20 YEARS ANNIVERSARY

COMPOUND SEMICONDUCTOR

Connecting the Compound Semiconductor Community

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Handsets: The driver for GaAs

Scrutinising gains in chip reliability

A winning score for simulations

LEDs: Creating a lighting revolution

Lasertec

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AN ANGEL BUSINESS COMMUNICATIONS PUBLICATION

editorialview

by Dr Richard Stevenson, Editor

Happy anniversary

JUDGED FROM many different perspectives, an anniversary is a good thing.

For starters, it is great to have a celebration every now and then, and get the chance to spend some time with the people we love – whether celebrating many happy years of marriage, or the birthday of a friend or relative.

These milestones in life can also be a catalyst to reflect upon the ups and downs of the past, what we can learn from these experiences, and what are our aims and ambitions for the future.

In this issue of *Compound Semiconductor*, we celebrate 20 years of this magazine, with a range of features offering differing perspectives on how far we have come since 1995, and where we might be in 2035.

Tracking the evolution of the largest sectors in our industry, LEDs and GaAs microelectronics, are features from two of the most well-known market analysts of the III-Vs, Bob Steele and Eric Higham. Also in this edition you can get the lowdown on improvements in GaAs reliability from an expert in this field, Qorvo's Bill Roesch; read a review on droop, the biggest, most controversial mystery ever associated with the LED, that is co-authored by Hadis Morkoç from Virginia Commonwealth University; and hear the views of CPV specialist Sarah Kurtz on the progress of this technology.

To get an alternative perspective on how far we have come since 1995, you can see what we covered in our very first issue (see p.24). Back then, red LEDs were starting to win sales in the traffic light business, while blue VCSELs were struggling to deliver respectable output powers. So in some ways, everything has changed, as LED traffic lights are now commonplace – and in other ways we've hardly move on, as blue VCSELs are still confined to the lab.

If you prefer looking forwards then I recommend the feature "Positive vibes for 2035" (see p.26) that reports the views of experts on LEDs, power electronics and wireless communication. The next 20 years are tipped to be good ones, heralding ubiquitous solid-state lighting, ultra-fast wireless communication and electric vehicles – all underpinned by compound semiconductor devices.

So, whatever take you are looking for on the twentieth anniversary of *Compound Semiconductor*, I'm sure you'll find a feature worth reading.

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contents

CONNECTING THE COMPOUND SEMICONDUCTOR COMMUNITY
Volume 21 Issue VI 2015

features

22 Moving with the times: From silicon to SiC metrology

Lasertec, a supporter of semiconductor engineers for decades, continues to refine its SiC inspection and analysis tool that aids identification and minimization of various defects.

24 Going back to the beginning

Glance through the premier issue of *Compound Semiconductor* and you'll find articles about improving the efficiency of traffic lights, developing blue VCSELs and the birth of the GaN LED.

26 Positive vibes for 2035

The compound semiconductor industry will be even more healthy in 2035 than it is today, thanks to the emergence of ultrafast wireless, soaring sales of electric cars and ubiquitous LED lighting.

34 Two decades of glorious growth

During the last 20 years the LED has progressed from being a niche product to backlighting billions of screens and illuminating countless homes and offices.

42 The GaAs revolution

In the early 1990s, the US led the development of an infrastructure for GaAs MMIC manufacturing. The result: A technology that lies at the heart of the mobile wireless revolution.

48 Tracking CPV

Richard Stevenson quizzes NREL principle scientist Sarah Kurtz talks about the progress of CPV, the false dawns of this technology, and what must happen for this technology to truly take off.

22

54 Crosslight: 20 years and counting

Founded on the promise of delivering a superior tool for modelling laser diodes, Crosslight has blossomed into a provider of a range of software for understanding III-V technologies.

59 Improving reliability… the journey so far

The dot-com boom and the explosion in handset sales have ramped up the production of GaAs chips, and enabled their reliability to rival those made from silicon.

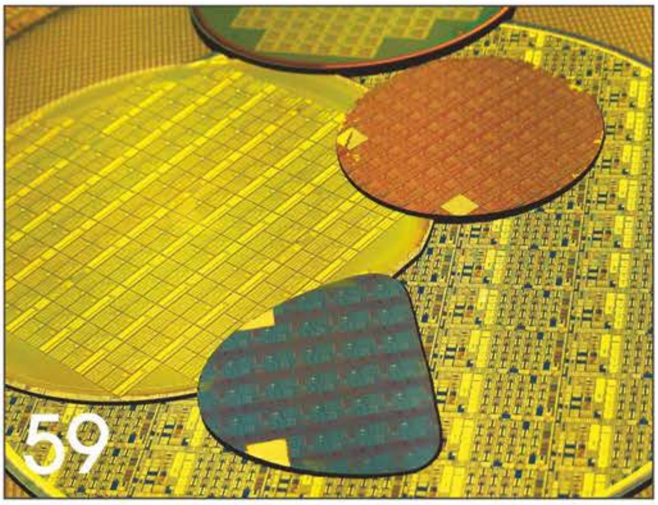
64 On the efficiency degradation in InGaN based LEDs: Mechanisms and remedies

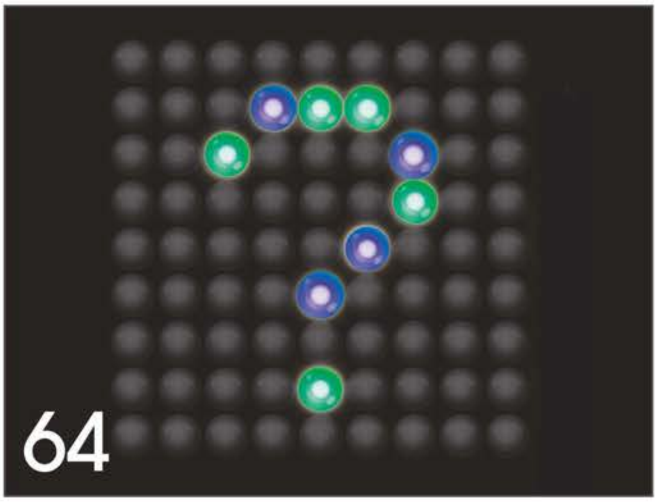
Researchers continue to debate the cause of the fall in LED efficiency at higher drive currents.

news

news analysis

research review





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Creating and strengthening links between chipmakers and network builders

AIM Photonics and UC Santa Barbara lead US photonics drive

IN A BID TO BOOST PHOTONICS manufacturing and bring more high-tech jobs to the US, as well as boost energy efficiency and performance in computing and communications, the Obama administration has announced that it has selected the American Institute for Manufacturing of Photonics (AIM Photonics) to lead research and manufacturing of integrated photonic technology. UC Santa Barbara is leading the West Coast division of this public-private partnership, in collaboration with the State University of New York – the lead university in this institute.

"AIM and UC Santa Barbara are leading a revolution that is integrating photonics and electronics for the benefits of both," said John Bowers, professor of electrical and computer engineering and of materials at UCSB, director of the campus's Institute for Energy Efficiency (IEE) and lead of the West Coast hub of AIM. Just as photonics has enabled the fibre optic communications which led to the Internet revolution, he said, the increased data capacity, speed and energy efficiency promised by photonics integrated circuits will result in enormous gains for everything from handheld devices to personal computing to data centres. "Our goal is to use complementary metal-oxide semiconductor processing to move photonics onto silicon and accelerate the integration of photonics and eliminate the data bottleneck that advanced silicon chips are facing during the next decade," said Bowers.

"UC Santa Barbara has been a leader in integrated photonics for the past 30 years," said UCSB Chancellor Henry T. Yang, "and this has been recognised in numerous ways, especially by three Nobel prizes: one in physics to Herb Kroemer, inventor of the double heterostructure laser, which is used in all data communications and telecom systems worldwide; one in chemistry to Alan Heeger, inventor of conductive polymers, which are widely used for displays and photovoltaic devices; and another one in physics to Shuji Nakamura, inventor of the blue LED, which is widely used for lighting." Add to this roster of ground-breaking UCSB researchers John Bowers – considered to be one of the world's authorities in optoelectronics – whose work in the IEE seeks to provide energy efficient solutions for computing while also improving performance.

With the $110 million in funding from the government, the new consortium aims to align research strength with development prowess to revitalise critical sectors of the country's manufacturing economy. Universities, including the Massachusetts Institute of Technology, University of Arizona, Stanford University, California Institute of Technology, UC Davis, UC Berkeley, UC San Diego, Columbia University and the University of Virginia will contribute their considerable research to the consortium. Meanwhile, major integrated photonics companies such as Intel, Hewlett Packard, Infinera, Agilent, Lockheed and Raytheon as well as design software companies Synopsys, Mentor and Cadence will lead the manufacturing charge.

Seoul Viosys acquires SETi

SEOUL VIOSYS, a subsidiary of Seoul Semiconductor specialising in UV LEDs, has recently secured the executive management share of SETi (Sensor Electronic Technology, Inc), a short-wavelength ultraviolet LED company in the US. SET developed the world's first short-wavelength ultraviolet LED and has the source technology for electronic devices (RF), since 2005.

Starting from an equity investment in SETi in 2005, Seoul Viosys has maintained close technical cooperation with SETi for more than 10 years to develop and commercialise UV LED chips with wavelengths below 350 nm. Since SETi's UV LED chip patents are critical components in the aerospace and defence industries, Seoul Viosys had to pass Ministry International Traffic Arms Regulations (ITAR) and to get approval from the US Committee on Foreign Investment in the United States (CFIUS).

For the past three years, Seoul Viosys has persistently persuaded the US Department of Defense and the Committee on Foreign Investments of the US and made many efforts to obtain the approval, and as a result, successfully took over the share and secured the executive management rights of SETi. Seoul Viosys was established in 2002 based on the proposal made by Nitride Semiconductor (NS), the Japanese venture company to Seoul Semiconductor in 2001 for the technical cooperation and joint development of long-wavelength UV LEDs (360 nm ~ 400 nm). It has the source technology for UV LED that is applied to bio, hardening, forgery detection, medical appliances, and sterilization, and the company has produced chip, package, and module covering the entire wavelength range of UV and provided the UV system solution as well.

"With all original patents and the mass-production system required for the development and manufacture of UV LED, Seoul Viosys will continuously develop UV LED technologies to contribute to the improvement of technical competitiveness and industrial development in Korea and take the lead for energy conservation and environmental protection through the expansion of distribution of UV LED over the world," said Jae-jo Kim, the representative of Seoul Viosys.

GaN market to grow at 15 percent over the next six years

TRANSPARENCY Market Research has published a report this year titled 'GaN Industrial Devices Market - Global Industry Analysis, Size, Share, Growth, Trends and Forecast 2015 - 2021'. According to the report, the market was valued at $481.8 million in 2014 and is expected to reach $1315 million by 2021, growing at a CAGR of 15.1 percent from 2015 to 2021.

By volume, the global GaN industrial devices market is expected to grow at a CAGR of 17.5 percent during the forecast period from 2015 to 2021 to reach a market size of 3427.2 million units by 2021. In 2014, volume of the market was 1099.6 million units.

Transparency has divided the global GaN industrial devices market into two main segments: power devices and opto electronics. By revenue, opto electronics was the largest contributor to the market in 2014, accounting for 78.0 percent of the overall market. The wide implementation of these devices in LEDs and laser diodes is majorly driving the market.

By application, the global GaN industrial devices market can be further classified into three sub-segments: RF, LEDs and power devices. According to the report, LED segment was the largest contributor to the market, both in terms of value and volume in 2014, accounting for a market share of 68.0 percent and 82.5 percent respectively This is due to the extensive usage of GaN-based LED devices in traffic signal lamps, vehicle lamps and liquid crystal displays among others. Moreover, there have been two major developments of GaN-based LED technology, such as development of GaN based devices on foreign substrates and the creation of bulk GaN substrate based LEDs.

The global GaN HEMT (RF) market is divided into seven application segments, namely WiMAX/LTE, wireless phone infrastructure: base stations (BTS), CATV, V-SAT, satellite, defence and others. By revenue, wireless phone infrastructure: base stations (BTS) segment was the largest contributor to the market in 2014, accounting for a market share of 26.0 percent. Rising adoption of GaN HEMT technology is leading to an increase in the number of base transceiver station installations.

In terms of value, North America acquired the largest share in 2014, accounting for 31.1 percent of the global market. This is mainly due to high penetration of GaN based transistors in military and defence applications. The penetration of GaN industrial devices is fueled by increasing demand for LEDs in computers, laptops, mobile tablets, gaming devices and televisions. Europe held the second largest market share and accounted for 28.9 percent in the global market in 2014 in terms of revenue.

GaN-based PAs used to transmit football in 4K ultra HDTV

ADVANTECH WIRELESS, a satellite broadband communications technology firm, has announced that its SapphireBlu Series GaN-based SSPAs (solid state power amplifiers)empowered 4K Ultra HDTV transmissions of a high profile international football tournament for national teams in South America.

Advantech Wireless SSPAs were selected for their higher performance and reliability combined with the smallest form factor and lowest power consumption on the market. "With the new requirements of HDTV and Ultra HDTV broadcasters need more power per feed, the second generation GaN based SSPAs deliver the best solution for DSNG [digital satellite news gathering] applications in terms of performance, quality and overall cost of ownership," stated Cristi Damian, VP Business Development at Advantech Wireless.

"Fleets of DSNG vehicles from our customers have been upgraded for full HDTV transmission capability in order to transmit uninterrupted feeds of these sports tournaments to all countries around the world."

The second Generation of GaN-based SapphireBlu SSPA/SSPB from Advantech Wireless offers very high linearity in a compact single package. These systems are designed for Ultra HD transmission broadcasting and are DVB-S2X ready. The increased linearity comes at the same time with no additional increase in size, weight and energy consumption.

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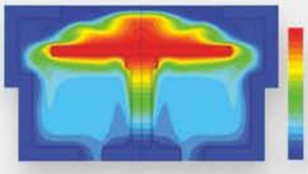

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GaN-on-silicon transferred to Epistar

TAIWANESE LED COMPANY Epistar and the German technology engineering and licensing company ALLOS Semiconductors have announced the successful conclusion of their project to establish ALLOS' mature 150 and 200 mm GaN-on-silicon technology at Epistar. The project was carried out with better than expected results and ahead of schedule (in less than six months) according to the companies. For example reproducible crystal quality was achieved with total dislocation density value of 2x10^{8}cm^2. With this performance Epistar says it has caught up with companies that have been developing GaN-on-silicon LED technology for a long time.

During the project ALLOS established its GaN-on-silicon epiwafer process on Epistar's epitaxy reactors. Epistar engineers were trained and worked in the integrated project team with ALLOS to gain full understanding and control over the GaN-on-silicon technology. Currently Epistar's own leading LED technology is been transferred to GaN-on-silicon structures.

"To conduct the technology transfer with ALLOS has proven to be the right decision for Epistar as it allowed us to quickly gain command over their leading GaN-on-silicon technology in a very cost-efficient and reliable way", says M. J. Jou, president of Epistar. He continues: "In a second phase we will now be focusing on realising the cost advantages of GaN-on-silicon LEDs and to unlock the application benefits."

"To accomplish a project of this size and complexity with such results is a complete success and a good reason to be proud of the teams from both parties", comments Burkhard Slischka, CEO and co-founder of ALLOS.

He explains: "This result underlines ALLOS' project execution skills as well as our technical capabilities to grow crack free wafers with market leading crystal quality. This is an example that our fast, cost-effective and successful implementation of GaN-on-silicon helps our customers to reduce development risk and to save time and money."

University of Arkansas wins $200K NSF grant to study GaN

RESEARCHERS at the University of Arkansas' GRid-connected Advanced Power Electronic Systems Centre (GRAPES) have received a $200,000 grant to study the modeling of GaN devices. Alan Mantooth, distinguished professor of electrical engineering and executive director of the centre, will lead the effort.

One of the barriers to the acceptance of GaN devices is a lack of high-quality models for circuit simulation that allow designers to evaluate them against silicon technology. Since the vast majority of all circuit design and simulation is done in computer programs, the lack of these models makes it very difficult for circuit designers to accurately portray how GaN devices will behave. This grant allows the Arkansas researchers to develop and evaluate a high-performance compact model for GaN power devices. Compact models are used by circuit designers to simulate the performance and behaviour of their designs before committing them to manufacture.

These models are especially important in power electronic applications where many real-world scenarios can be analysed safely. Further, statistical and failure mode analyses, which are practically impossible through experimentation, can be easily performed.

Veeco's Q2 revenue up

PROCESS equipment company Veeco Instruments has announced financial results for its second fiscal quarter ended June 30, 2015. It achieved revenue of $131.4 million, an increase of 38 percent compared with the same period last year. Non-GAAP adjusted EBITDA (Earnings before Interest, Taxes, Depreciation and Amortisation) was up to $12.8 million or around 10 percent of revenue. The company has also reported narrowing GAAP loss to ($0.21) per diluted share.

Non-GAAP earnings grew to $0.20 per diluted share and it generated $7.7 million in cash from operations. "We delivered solid second quarter results, achieving financial performance in line with our expectations across all P&L guided metrics. Revenue grew by around 38 percent year-over-year and adjusted EBITDA increased to nearly 10 percent of revenue. These results illustrate our continued focus on driving growth and operational execution," commented John R. Peeler, chairman and CEO.

"Our top line growth has been fueled by the rapid adoption of our TurboDisc EPIKTM700 MOCVD system. This latest generation product offers lower cost of ownership for our customers and improved margin contribution for Veeco, as compared with prior generation tools. We have now successfully demonstrated the tool's capabilities across multiple customers, which enabled us to begin recognising revenue upon shipment towards the end of the second quarter."

For Veeco's third fiscal quarter 2015: revenue is expected to be in the range of $135 million to $160 million; adjusted EBITDA is expected to be in the range of $14 million to $24 million; GAAP earnings (loss) per share are expected to be in the range of ($0.05) to $0.19; and non-GAAP earnings (loss) per share are expected to be in the range of $0.22 to $0.40.


GaN
InGaN
InAlN
AlGaN
GaSb
InSb
InP
InGaP
InAlGaN
GaAs
AlGaAs

GE to establish SiC packaging centre in New York State

ANDREW CU OMO, Governor of New York State, has announced that GE Global Research will serve as the anchor tenant of the Computer Chip Commercialisation Centre (QUAD C) on the campus of SUNY Polytechnic Institute's Colleges of Nanoscale Science and Engineering in Utica. Together SUNY and GE will create the first US based Power Electronics Manufacturing Centre with GE's SiC technology.

Mark Little, senior vice president and CTO of GE, said: "Together with New York State and SUNY Polytechnic Institute in Albany, and now Utica, we are creating a SiC Corridor that will be the epicenter of the next revolution in power. In Utica, it will expand the focus from computer chip commercialization to creating the first US based Power Electronics Manufacturing Center with GE's SiC technology."

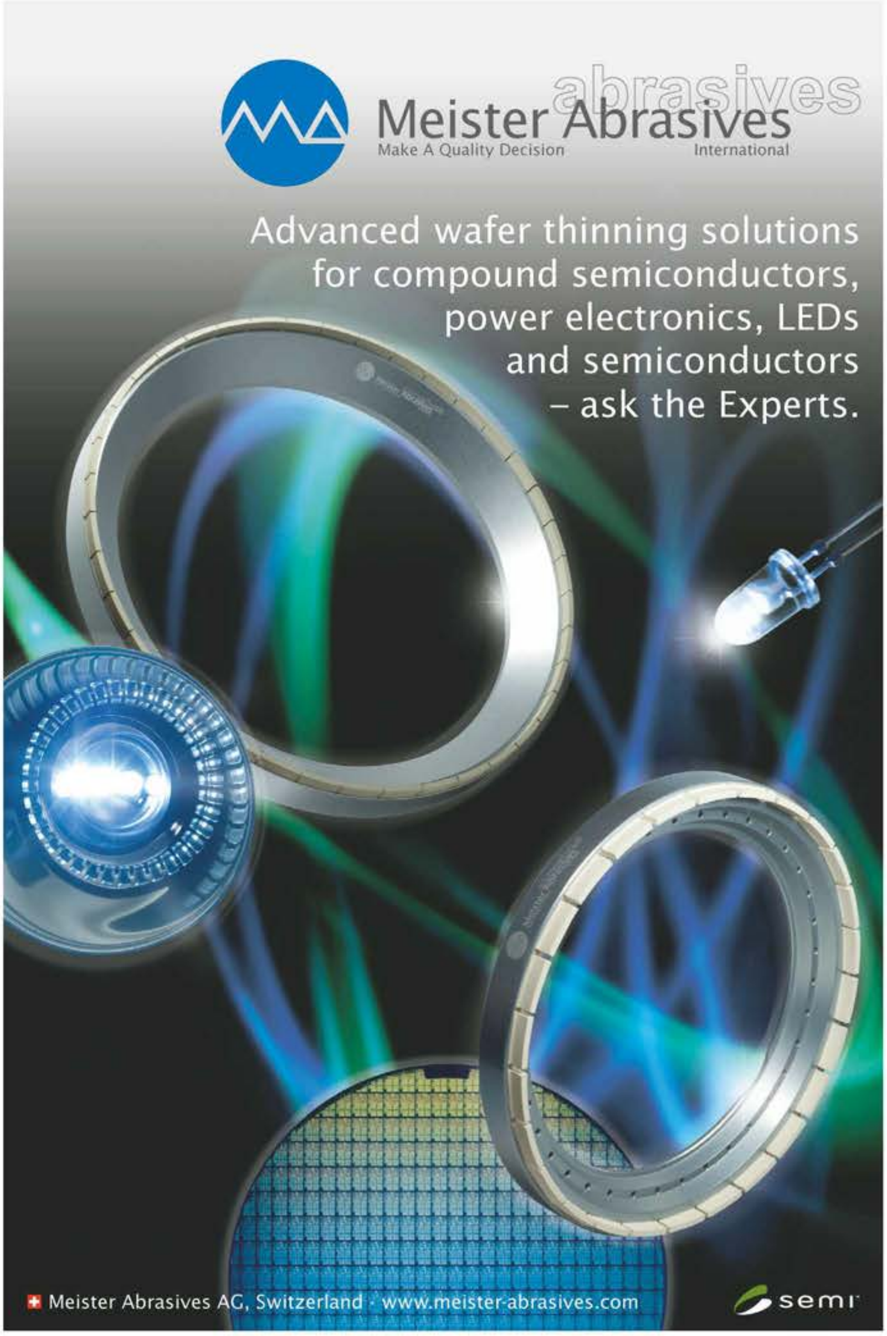
In addition, Cuomo revealed that analogue semiconductor and sensor company AMS AG, will invest over $2 billion to support a cutting edge, 360,000 square foot 200/300 nm wafer fabrication facility for making analogue chips to be constructed at the Nano Utica site in Marcy.

These public-private partnerships represent the launch of the next phase of the Governor's $1.5 billion Nano Utica initiative that is designed to replicate the success of SUNY Poly's Nanotech Megaplex in Albany and revitalise the Mohawk Valley.

Advanced packaging technologies are vital in the development of faster and more powerful computer chips, as well as SiC chips for power electronics applications. The packaging facility is a critical component of the New York Power Electronics Manufacturing Consortium, the governor's $500 million public-private semiconductor research partnership that includes over 100 companies. Based at the SUNY Poly Megaplex in Albany with lead partners including GE and IBM, the Consortium is driving coordinated materials research and job creation across the Upstate corridor.

The expansion of QUAD C includes state-of-the-art cleanrooms, laboratories, hands-on education and workforce training facilities, and integrated offices encompassing 253,000 square feet. The cleanroom will be the first-of-its-kind in the nation: a 56,000 square-foot cleanroom stacked on two levels that is now five times larger than initial plans.

In accordance with the governor's innovation-driven economic development model, no public funds will be given to private companies. New York will invest $250 million at QUAD C and the Marcy Nanometre to support critical equipment and infrastructure improvements at both locations. The state will own and manage these facilities through SUNY Poly and such state investment will catalyse the Mohawk Valley's high-tech economic ecosystem, attracting additional nanotechnology jobs and supply chain companies to support and contribute to Nano Utica initiative.



AXT acquires InP substrate maker Crystacomm

COMPOUND SEMICONDUCTOR substrate manufacturer AXT has acquired Crystacomm, a privately held Californian company that makes LEC-based InP substrates, in an all-cash transaction.

InP is rapidly emerging as a material of choice for both new and existing applications, including optoelectronic devices for fibre optic telecommunications, passive optical networks (PON), and data centre connectivity, as well as solar cells and next-generation wireless amplifiers.

Crystacomm, headquartered in Mountain View, was the first company to introduce 2-inch, 3-inch, and 4-inch InP substrates. It has also been a leader in the development of 6-inch InP technology, which has the capability to support the stringent requirements of 5G wireless communications.

"This technology acquisition is highly synergistic to our current InP business and provides further competitive differentiation and cost benefits," said Morris Young, AXT's chief executive officer. "It allows us to broaden our technology base, and gives us the flexibility to serve customers with varying technical requirements. While we are not expecting revenue from the acquisition in this calendar year, we believe that the additional capabilities will provide valuable and incremental business opportunities for AXT in the years to come."

While still relatively small, the InP market has seen considerable growth over the last two years, much of this driven by fibre-to-the-home network deployments. For example, China, Singapore, and Taiwan have invested heavily in nationwide PON, and network deployments are ongoing in countries such as Australia and New Zealand.

The landscape of InP substrate providers has been limited as a result of the relative technical difficulty in producing substrates that meet the stringent specifications for various optoelectronic and electronic applications. AXT has worked collaboratively with customers to overcome these challenges and has developed robust proprietary manufacturing processes over time, resulting in significant market share and leadership position in this expanding market.

The terms of the acquisition, which closed in the second quarter, are not being disclosed. The crystal-growth equipment and processes will be installed in AXT's Fremont, facility.

George Antypas, Crystacomm's founder and CEO, will stay on as a consultant to AXT, assisting the company in bringing up the Crystacomm LEC-InP crystal growth and poly-synthesis process. "I am very pleased to be able to leverage George's extensive expertise in what is emerging to be a very exciting and dynamic market," said Young. "George's groundbreaking research enabled the early commercialisation of InP, and Crystacomm has been at the forefront of the technology progression ever since. We are pleased to bring this valuable technology into our portfolio."

A new approach to making flexible white-light LEDs

RESEARCHERS from National Chiao Tung University in Taiwan have used pre-existing technologies to create flexible, efficient white LEDs with potential use in wearable displays and non-flat surfaces. "Compared to organic LEDs, this design of flexible LEDs can be very attractive, due to the low cost, prolonged lifetime and high efficiency.

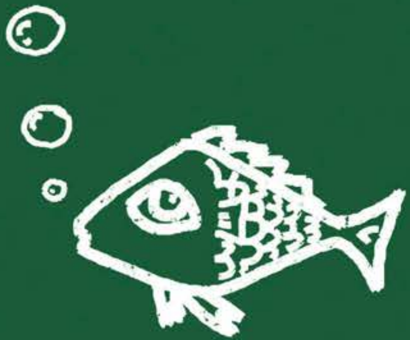
In addition, all of the technologies associated with this design are currently available," said Chien-Chung Lin, associate professor, College of Photonics, National Chiao Tung University, Taiwan. The paper by Lin, Hao-Chung Kuo, and their research team appears in *Optics Express*, a journal published by The Optical Society (OSA). The researchers' off-the-shelf LED device gets its flexibility from polyimide and polydimethylsiloxane. To construct it, Lin and his colleagues first covered a polyimide substrate with copper foil shielding tape. Then using flip-chip bonding, which reduces thermal resistance and results in higher heat dissipation than traditional wire bonding, they mounted 81 Blue LED chips, measuring 1.125 mm x 1.125 mm, to the foil in an upside down position.

To provide a warm white-yellow light, the researchers then added another layer consisting of a yellow phosphor film that had been mixed and spin-coated in polydimethylsiloxane, or PDMS, a widely used silicone-based organic polymer. It was chosen for its high degree of transparency, stability, and flexibility. The final film measured 5 x 5 cm, but there is no reasonable limitation to the size of the film.

The researchers ran the device for a standard 1,000 hours, to test its durability, finding that its emission decayed by only 5 percent. Its potential for use in wearables was demonstrated when subjected to bending tests. It held its power output when bent to a curvature with a 1.5 cm radius. It also exhibited a light efficiency of 120 lumens per watt. "Because the components are all available by current technology, the combined reliability can be very good," Lin said. "Most of the novel processes or materials require a lengthy procedure to verify their reliability, but our design uses only available parts to avoid this issue."

"Large-area, uniform white light LED source on a flexible substrate," by C. Sher *et al*; Optics Express **23**, 1167-1178 (2015).

SiC:
all systems go



Cree's recent APEI acquisition is set to unlock the true potential of silicon carbide. Rebecca Pool talks to company executives to find out more.

To say the last few months have been eventful for Cree's power and RF division would be something of an understatement.

In May, the US-based wide bandgap industry heavyweight unveiled plans to spin off this business as a separate company.

From word go Cree's LED and lighting sectors have overshadowed its power and RF arm, but this decisive move signalled the company's confidence in the growing SiC power device market.

And then in July, Cree acquired power module and electronics applications pioneer, APEI, US, to drive its high performance SiC module business forward.

Up until now, Cree's key four power markets have been switch-mode power supplies for servers, solar inverters, high frequency power supplies for industry applications and electric vehicle chargers. Clearly the company is now after more.

"We're trying to make a strong move into the power market," explains John Palmour, chief technology officer of Power and RF at Cree. "The larger, higher power markets really require power modules, and that's why we've acquired APEI."

As Palmour highlights, APEI has not only developed high-performance power modules, but has carried out extensive systems development to showcase its products.

"It's easy enough to talk about the electronics characteristics of silicon carbide but people don't often believe it until they see it in a system demonstration," he says "Only then do they fully realise, for example, the value of size reduction, weight savings, higher frequency operation."

"And whereas you see a lot of people dropping silicon carbide into pretty standard modules designed for silicon, APEI has started with the silicon carbide chip and built outwards to optimise everything about the module for this," he adds.

Packaging plans

While the merging of APEI with Cree is still very fresh in the minds of many industry players, the power pair has already collaborated on many government SiC power product-related contracts. In 2014, for example, the companies developed a SiC-based plug-in hybrid electric vehicle battery charger through an ARPA-E program. And right now, development of a traction drive for automotive applications is underway.

Crucially, as part of such module development, APEI has designed packaging specifically for SiC modules, a strength that company president and chief executive, Alex Lostetter, is quick to point out.

"In the overall industry, power packaging [for modules] has focused on more traditional [development] that's tied to silicon," he explains. "Somebody needs to come in and push development for SiC and wide bandgap semiconductors, to bring out the advantages of these technologies."

"There's not many people doing this, so this is now one of our focuses," he adds. "Cree already has its standard module products so we're looking at strengthening those and combining forces on future iterations; some [developments] will be optimisations while some will be novel. We'll see what the future holds."

Palmour concurs, but is reluctant to reveal details on development plans, simply saying, 'APEI has developed SiC packaging and we will be working on that together'. However, like Lostetter, he is keen to emphasise the importance of new packaging for SiC modules.

Wide bandgap devices operate at higher current densities than silicon equivalents,

but standard module packages do not provide the power dissipation demanded for such high-performance operation. At the same time, the higher frequencies and switching speeds of SiC semiconductors are hindered by the high loop inductance in standard modules.

"If you use a standard module design you still get a lot of the SiC benefits but you're also leaving a lot of the performance on the table," says Palmour.

So, Cree's latest acquisition looks set to drive the SiC market forward faster than ever. APEI is to be called Cree Fayetteville and will continue to operate in Fayetteville, Arkansas, as part of Cree's Power and RF business.

According to Losetter, the 'new' company will be developing SiC modules for higher voltage markets. As he says: "Right now, we see the real opportunities are in the 1200 V to 1700 V ranges."

At the same time, Palmour is confident the industry supply chain is now 'pretty healthy' and highlights the several substrate vendors and power MOSFET players that now exist.

"Multiple companies are developing power modules around these MOSFETs, so an early supply chain is in place... we can reinforce this with APEI," he says.

And right now, the two executives are rapidly integrating the two companies. While talking to *Compound Semiconductor*, both Palmour and Lostetter were together at Arkansas, to, in the words of Cree's chief technology officer, 'work out how to get things moving as quickly as possible'.

Acquisition celebrations: Cree's John Palmour (right) and Alex Lostetter, APEI, now intend to rapidly integrate the two companies.

Big wafers grand designs

With recent investment funds, Exagan gets ready to market GaN-on-silicon FETs on 200 mm wafers. Rebecca Pool reports

As investment into GaN power semiconductors gathers momentum, France-based Exagan is one of a raft of companies to receive funds.

Raising €5.7 million in June, this year, the fabless Leti-Soitec spin-out joins the likes of Transphorm, US and GaN Systems, Canada, now pumped up to produce power switching devices for photovoltaic, automotive and PC markets.

But unlike its contemporaries, Exagan intends to fabricate its first market-ready GaN-on-silicon devices on 200 mm, rather than 150 mm, wafers.

"By fabricating devices on 200 mm wafers, you reduce the processing costs, increase device yields but the biggest benefit is accessing the CMOS technology and manufacturing that exceed 150 mm [wafer sizes] capabilities," explains Frédéric Dupont, president and chief executive of Exagan. "You have access to a wider portfolio of technology and this all increases the attractiveness of GaN devices."

Exagan has already fabricated its first prototype 650 V FETs on 200 mm wafers, working with engineers at X-FAB Silicon Foundries' CMOS wafer fab in Dresden, Germany. The fabless French start-up now intends to use the latest cash injection to industrialise these products. According to Dupont, his company will now increase device quality and reliability, and deliver initial samples to customers by the end of this year.

"Looking at what the competition is doing, we believe there is still some work to be done on device reliability to meet market requirements at the right cost," he says. "This is why we're pursuing our 200 mm strategy and we intend to deliver the same quality and reliability of silicon devices, as requested by customers."

"GaN devices operate at much faster frequencies than silicon devices so characterising these devices is a challenge," he adds. "But we have very talented power engineers in our team, to address those challenges."

Secure supply chains

From word go, a critical part of Exagan's commercialisation strategy has been to secure a robust supply chain for GaN-on-silicon power devices, and so become Europe's primary supplier of GaN-based power switches.

According to Dupont, epitaxy is licensed from Soitec and will be retained within Exagan's own materials facility. XFAB will carry out all device processing, and partnerships are already formed for device testing.

"As well as smaller companies such as ourselves, and say EPC, we have some very big players in this market including International Rectifier that became Infineon," he highlights. "But I think it is important for new entrants like us to have a place in this market as we are bringing some flexibility and we are going to be pushing the technology very aggressively. The larger players are developing a broad product portfolio with alternative technology such as silicon carbide," he adds. "But we'll be pushing GaN-on-silicon vigorously and once our devices are qualified, customers will know there is no limitation to ramping up volumes."

Exagan's initial customers for its 650 V FETs are likely to be manufacturers of inverters for photovoltaic and electric vehicle applications as well as power supply and power-factor-correction players, keen to move away from the silicon IGBT. Devices will be offered as dies or with standard packages in a first step.

But what about rival technology SiC? The PV inverter sector has already started to embrace qualified SiC Schottky diodes and MOSFETs and more markets will follow.

Like the silicon IGBT, these transistors are normally-off devices, so replacing one device for the other, within a power system, is relatively straightforward. In contrast, the normally-on GaN-on-silicon FET demands different drivers and a system re-design.

To counter this, many GaN-on-silicon manufacturers are busy re-configuring the GaN HEMT as a normally-off device. Exagan is also developing normally-off approaches, but first products will be normally-on devices.
Dupont will not be drawn on applications

or markets, but is quite clear that he does not see SiC devices being a threat to GaN-on-silicon FETs.

"SiC has a clear advantage in terms of maturity, its proven and devices have reliability data," he says. "But for GaN-on-silicon, you're using silicon, you're using epi-reactors that can be bought everywhere and there's hundreds of fabs that can produce GaN-on-silicon at 200 mm."

"We will achieve the same performance as SiC devices, and then GaN will win because of the costs," he concludes.

Plessey eyes **eight-inch wafers**

Government cash will help UK LED manufacturer, Plessey, migrate more quickly to eight inch wafers. Rebeeca Pool finds out how

While Plessey Semiconductors is in the midst of fabricating GaN-on-silicon LEDs on 6-inch wafers at its UK-based Plymouth plant, a recent cash injection from the UK government is set to speed up its transition to 8-inch wafers.

In mid-July, the UK-based LED manufacturer won £1.3 million as part of the Advanced Manufacturing Supply Chain Initiative (AMSCI), to accelerate high volume manufacturing of its GaN-on-silicon LEDs in Plymouth. Working with partners, Aixtron and Bruker Nano Surfaces, the company intends to increase the yield of its current GaN-on-silicon process while getting ready for 8-inch commercial production.

"The grant will be used for a combination of buying new capital equipment, and research and development labour activity," says Plessey chief technology officer, Keith Strickland. "We're buying some measurement and metrology tools for the project and [spending] the rest on the labour and engineering associated with the use of those tools."

For starters, Plessey will invest in a Bruker LumiMap electroluminescence tool designed for optical and electrical characterisation on epiwafers for high-brightness LEDs.

Key measurements include forward and reverse IV characteristics, spectral intensity, wavelength and spectral width measurements. And as Strickland puts it: "This takes away the need for wafer processing so we can speed up wafer characterisation, when the wafer comes out of the MOCVD tool."

As part of the grant, Plessey is also working closely with Aixtron to address the necessary MOCVD reactor re-tooling issues of moving from 6-inch to 8-inch wafers. For example, the deposition equipment manufacturer will be designing and building new susceptors – the reactor plate that holds the substrates – so its MOCVD reactors can handle the larger wafer sizes.

"For example, how the wafers fit into the susceptor pockets is very critical to MOCVD growth," highlights Strickland. "The design of this and other aspects of the reactor will help with yields."

According to the chief technology officer, beyond re-tooling, no real technical hurdles exist for the move to 8-inch wafers, but the commercial timing has to be right.

"We have to re-tool our wafer processing [instrumentation] as well as our growth reactors so there are significant costs associated with this," he says. "When you reach certain volumes, then the economic case is made, but you can't just switch overnight, re-tooling takes time."

And while Strickland won't comment on exactly when Plessey will make the final move to 8-inch production, he confirms the grant will reduce the time until the transition.

"This [conversion] is an ongoing process," he says. "We are still working with six-inch wafers at the moment, but have started working on eight inch wafers, although the conversion won't be imminent, as in this year."

"But this grant is important as it will help us to migrate more quickly to eight inch wafers," he adds. "As the time approaches for migration, we will have done some of the engineering ahead of time, so this funding will certainly help us to knock months off commissioning."

Shorter time-frames aside, Plessey is also looking forward to the significant cost-savings that will ensue. An 8-inch wafer provides approximately 40 percent more area on which to grow devices.

Yet, as Strickland puts it: "The cost of sending that wafer down the production line to fabricate these devices is only a small increment more. You have to invest in new pieces of equipment but fabrication doesn't scale-up inordinately, so this is a big benefit."

And importantly for the UK government, this fabrication of these cheaper LEDs is kept onshore.

Plessey's latest government grant follows an initial £7 million AMSCI grant, won two years ago with UK LED developer, Zeta Controls, to build an indigenous sustainable manufacturing chain for solid-state lighting.

"It is very good that we still get this level of funding as our previous grant was also very useful in helping us to put our assembly line in place," he points out. "This type of government funding means we are not having to manufacture offshore, and can also maintain our expertise in areas that would also normally go offshore."

Commercialising GaN

Transphorm has won $70 million to bring GaN to mainstream markets. President, Primit Parikh, reveals his plans to Rebecca Pool

THIS SUMMER, California-based developer of GaN-based power conversion chips, Transphorm, received a hefty $70 million in funding from its latest investment round, led by global investment firm, KKR.

Known for its aggressive buyouts, KKR has a strong track record in the semiconductor industry. In 2005, alongside US private equity firm, Silver Lake Partners, it acquired Agilent's Semiconductor Products group, now Avago, for $2.66 billion. And in 2006, it was part of a massive leverage buyout, when it invested in ex-Philips semiconductor division, NXP Semiconductor.

For Transphorm, this latest industry investment brings much-awaited change. As president and co-founder Primit Parikh highlights: "We have KKRs large financial stability as well as its deep semiconductor expertise."

"We can leverage this with our GaN technology, IP and team; this combination is something we are very excited about."

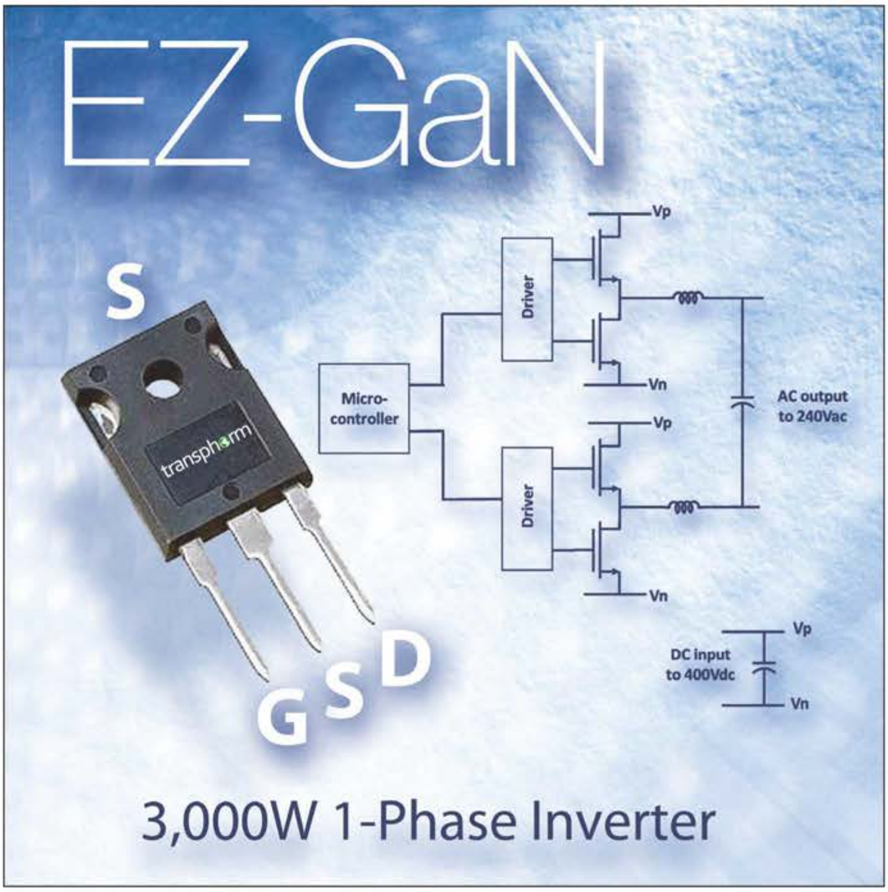
With KKR executives having now joined Transphorm's board of directors, the management team will focus on ramping up manufacturing. The company already has strong ties with key Japan-based industry heavyweights on its automotive-class wafer fab while Yaskawa Electric provides PV inverters, based on the very same modules, to Japanese markets.

Last year, the company also joined forces with India-based Tata Power Solar to develop PV inverters, and will now be looking to increase its presence in Japan and India, as well as Greater China, US and Europe.

"From here we are now going to go to full-scale, expanding our customer base worldwide," says Parikh. "We're very excited about the PV market in India and the US... and would like to see our finished solar inverter in the US market."

The plans are bold, but is the market ready for more GaN-based devices? Parikh thinks so.

As he asserts, he and colleagues have now spent three years proving GaN power semiconductor reliability and lifetimes. The company's GaN-on-silicon diodes and transistors were JEDEC qualified two years ago and it has



since demonstrated a high-voltage off-state lifetime of more than 10 million hours, at 600 V, with the very same chips.

"GaN is reliable, which is why we are getting traction from our customers in different market segments," says Parikh. "The technology is ready to take the next step into the mainstream, so this timing with KKR could not be better."

"We are very well positioned to [expand] in the next couple of years and this is a great launching pad," he adds.

Industry support

Parikh isn't alone in his conviction of GaN, and of course his company's ability to deliver. In a recent media report, blue laser diode pioneer and Nobel Laureate, Shuji Nakamura, said: "My invention of the GaN-based LED... has changed the world in illumination. Transphorm is the leading company producing GaN-based power conversion products that will have the same positive impact on energy that we saw with LED-based lighting."

And David Kerko, senior advisor to KKR, is equally confident. "Right now, Transphorm is the only place where customers can acquire reliable production-volume GaN products that meet or exceed required performance specifications for commercial products," he says.

"Long term, we believe [GaN] has the potential to replace all of the existing silicon-based technology used in high-voltage products," he adds.

Indeed, Transphorm aside, investment in GaN-based companies has, so far this year, flourished. In May this year, fabless developer of GaN-based power switching semiconductors, GaN Systems, Canada, raised $20 million in its latest funding round to ramp up sales and marketing worldwide, and expand manufacturing. And just last month, Leti and Soitec spinout, Exagan, France, won a little over $6 million in its first round of financing, to produce high-speed switching devices on 200 mm wafers.

So, even in the short-term, the future for GaN, and of course, Transphorm, looks bright as commercial activity gathers pace. To date, the company has garnered a grand total of $190 million in investment funds, with the immediate outlet for its power products being PV inverters.

However, Parikh believes data communications and telecom power supplies markets will come next, with non-critical automotive applications, such as air conditioning supplies, following.

"People are realising that GaN is here to stay and investors are investing in it," says Parikh. "Our goal has always been for the GaN field to expand and then for Transphorm to dominate in that field."

"These investments are good for GaN as a whole and we will work hard to maintain our leadership here," he adds.

Primit Parikh: Prior to Transphorm, Primit led GaN electronics at Nitres, as it was acquired by Cree. At Cree, he was head of Advanced Technology, leading GaN development.

Moving with the times:

From silicon to SiC metrology

Lasertec, a supporter of semiconductor engineers for decades, continues to refine its SiC inspection and analysis tool that aids identification and minimization of various defects.

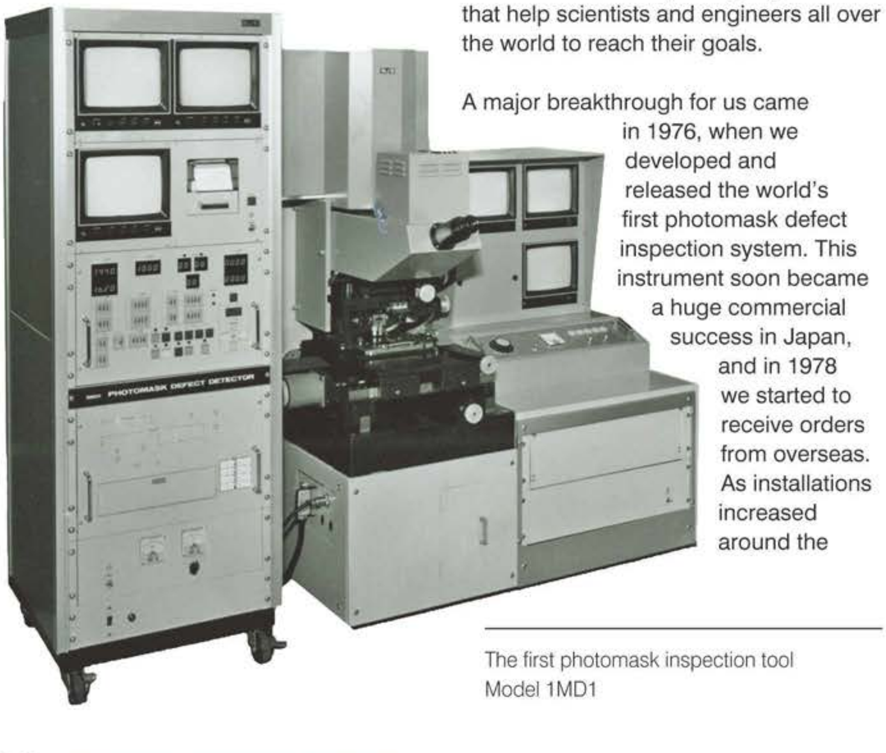
BY YUJI ASAKAWA FROM LASERTEC

IN THE PAGES OF this twentieth anniversary issue of *Compound Semiconductor*, you can find several features that look back over the last two decades of this industry. At Lasertec of Shin-Yokohoma, Japan, however, our origins can be traced back even further to our inception in 1960. Since then we have been serving the needs of various high-technology industries, including the semiconductor, compound semiconductor, renewable energy and flat panel display sectors.

We were founded by Yasushi Uchiyama, an innovative and entrepreneurial technologist. When he launched our company it initially traded under the name Tokyo ITV, designing and developing the imaging parts of an X-ray camera for Matsushita (Panasonic). But in 1962 our company switched its name to NJS (Nihon Jido Seigyo – Japan Automatic Control), and emerged as a fully independent entity.

Since our inception, we have followed the philosophy of our founder, which is to develop and release an innovative product every year. Pursuing this ideal has led us to develop many key tools that help scientists and engineers all over the world to reach their goals.

A major breakthrough for us came in 1976, when we developed and released the world's first photomask defect inspection system. This instrument soon became a huge commercial success in Japan, and in 1978 we started to receive orders from overseas. As installations increased around the globe, it made sense for us to expand our worldwide presence, a goal we accomplished by establishing three US offices – in California, New York and Texas.



The first photomask inspection tool Model 1MD1

In 1986 we developed and released yet another innovative product – the Color Laser microscope. Sales of this soared, prompting another name change to Lasertec Corporation. At that time, the word 'laser' had futuristic connotations, so it seemed an apt choice for a company with such a forward-looking technology roadmap.

During the intervening years we have developed and released many innovative product lines. Over this time we have strived to determine the technologies that will shape the future – and this has guided the directions we have taken, including our decision to place a great deal of emphasis and resource on the development of tools for the compound semiconductor industry. This includes metrology for SiC, a material for making power semiconductors that can enable greater efficiency in numerous electrical systems. For this reason, high quality SiC epitaxial wafers are a critical component in the supply chain.

Defect reduction is one of the most important factors for the mass production of high-quality SiC wafers. These imperfections are most often generated during grind and epitaxial processes, and it is critical to accurately and quickly detect and categorize them,

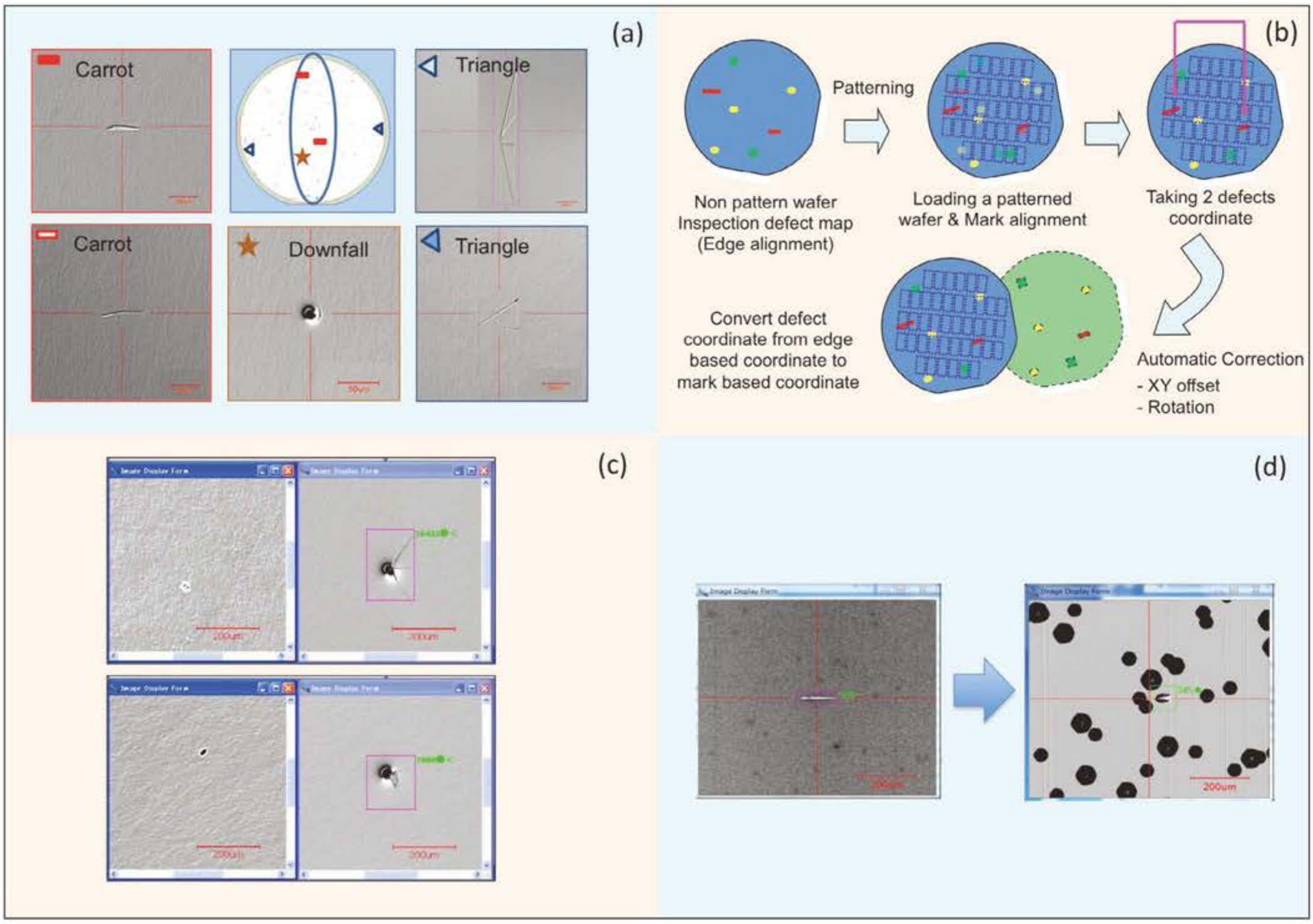


Figure 1 (a) The SICA tool can identify a range of defects, including carrots, triangles and downfalls. (b) The defect trace function can identify the exact location of random defects by compensating for misalignments caused by patterning and/or loading. (c) Imperfections uncovered in actual samples with the defect tracing function. (d) The photoluminescence capability being developed for the SICA tool can uncover defects that are confirmed by etching with potassium hydroxide.

as they impair device performance. By eliminating these killer defects early in the process, it is possible to ensure a high device yield in mass production. These defects can come in various forms, including scratches and epi-defects that arise on the wafer surface, and crystal-related defects, such as basal plane dislocations and stacking faults that are found inside the epilayers.

In 2009, we released our SiC inspection and analysis instrument, SICA. Since then we have undertaken a programme of continuous improvement, transforming this tool into a state-of-the-art system for defect inspection, review and analysis.

The SICA has been a noteworthy success, with installations taking place all over the world, thanks in part to the ability of this tool to deliver high-resolution defect images for highly accurate auto-defect classification.

SICA is capable of identifying a wide range of defects, including carrots, triangles and downfall (see Figure 1 (a)). It is possible to monitor these imperfections during processing with our defect tracing function (see Figure 1 (b)), which can uncover a relationship between defects in the substrate and in the epiwafer (see Figure 1(c)).

We are now exploring a photoluminescence-based technology that will allow the detection of crystal defects at a significantly higher throughput than before.

By combining this new feature with the existing surface defect capabilities, SICA will become one of the fastest and easiest defect detection and root cause analysis tools on the market. We have already made significant progress with the development of this new photoluminescence feature, with recent experiments involving a post-inspection etch in potassium hydroxide confirming the capability of this optical technique to accurately detect basal plane defects and stacking faults (see Figure 1(d)).

Our history of success shows that we have a great track record in identifying and delivering the tools that enable engineers to manufacture great products with high yields. SiC is a material that is destined to make a big impact in the power electronics industry, and we are here to support this effort with an inspection tool that can drive up yield and allow emerging devices to be more competitive with silicon incumbents.

Going back to the beginning

Glance through the premier issue of *Compound Semiconductor* and you'll find articles about improving the efficiency of traffic lights, developing blue VCSELs and the birth of the GaN LED.

IT'S SURPRISING what the first issues of some magazines are worth. If you want to get hold of the launch edition of a current affairs publication, such as *Time* or *Life*, you might have to fork out what you would pay for a reasonable meal in a restaurant. But if you want to get hold of the first edition of a particular comic, you might have to remortgage your house to pay for it.

Judged in these terms, *Compound Semiconductor*, which had its first-ever print run twenty year's ago, is worth peanuts. But viewed from a different perspective, it definitely has value, because it came out at a time when print ruled. Back then there wasn't an associated website or a digital edition, which means that the aging hardcopies of this magazine offer a unique view into the state of our industry in 1995.


COMPOUND SEMICONDUCTOR
July/August 1995
Volume 1 Number 1
PREMIER ISSUE
Blue and Green
Commercial Applications of Short Wavelength Light Emitting Devices
Also in this issue:
New
InP
Research Review - page 22
SAMPLE COPY
TIM WHITAKER 3
DRA
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One of the big news stories from that time was the uptake of red AlGaAs LEDs in traffic lights in Corona, California. The arguments propelling that move are detailed in the July&August 1995 edition and will be very familiar to those working in the LED business – reduced energy costs and longer lifetimes, which outweigh the higher outlay. In 1995, the red LED traffic light contained 500-750 emitting devices, cost $200, drew just 20 W and its widespread adoption promised to deliver an annual reduction in energy costs of $1 billion. In comparison, the major attraction of the 150 W incumbent incandescent source was its low cost. It sold for just $1-4.

Hindsight shows how difficult it is to predict the future. The story concludes 'Incandescent lights, however, will likely keep the yellow market – they are on for such short periods of time that the energy savings do not equal the cost of the LED array.' Drive around a city today, however, and there is good chance that you'll find yourself waiting at a traffic light with red, amber and green LEDs.

The rapid rate of progress in LEDs has not been matched by that in blue VCSELs. In the debut issue there is a brief report of state-of-the-art results presented at the Device Research Conference. A ZnSe-based VCSEL fabricated by engineers from Matsushita Electric and the University of Notre Dame could deliver emission at 490 nm when cooled by liquid nitrogen and driven in pulsed mode, under conditions of 17 V and 3 mA. Since then the choice of material for the blue VCSEL has switched from ZnSe to GaN, and devices are now capable of room temperature. However, output powers are still very limited.

Both of these materials were discussed in a feature reviewing the development of blue LEDs. In this balanced piece, Bob Johnstone tells the story of the breakthroughs of two Japanese researchers working independently: Isamu Akasaki from Nagoya University and Shuji Nakamura from Nichia.

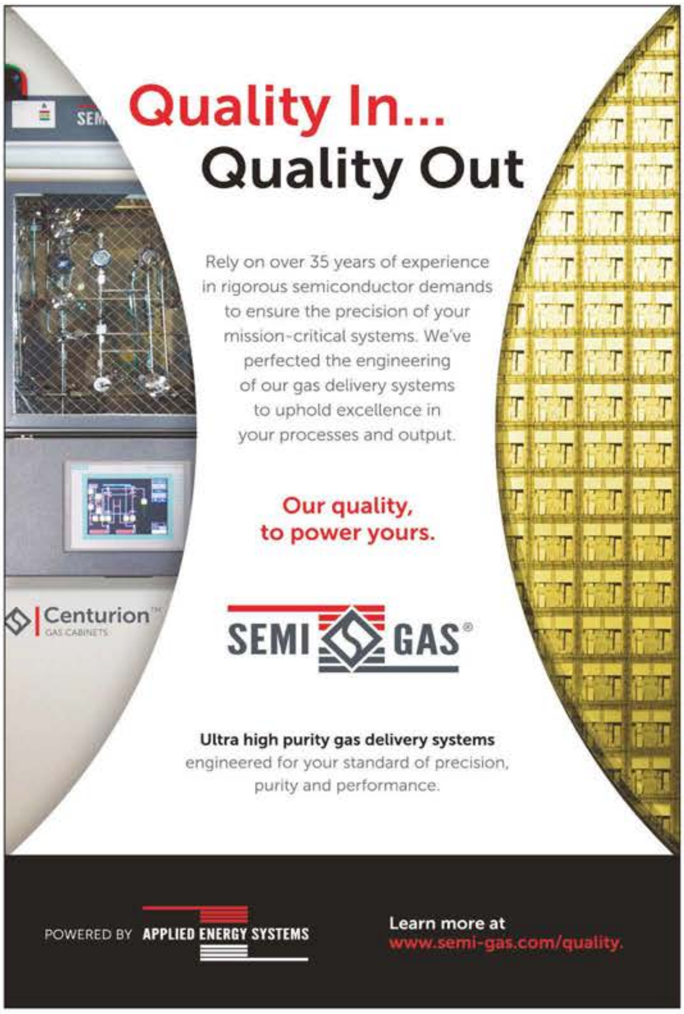
Akasaki's triumphs came at a time when interest in ZnSe vastly overshadowed that for GaN, so they received far less attention than they deserved. But now they win plaudits from all over the globe, and are even considered worthy of a Nobel Prize, thanks to the emergence of the multi-billion dollar LED industry.

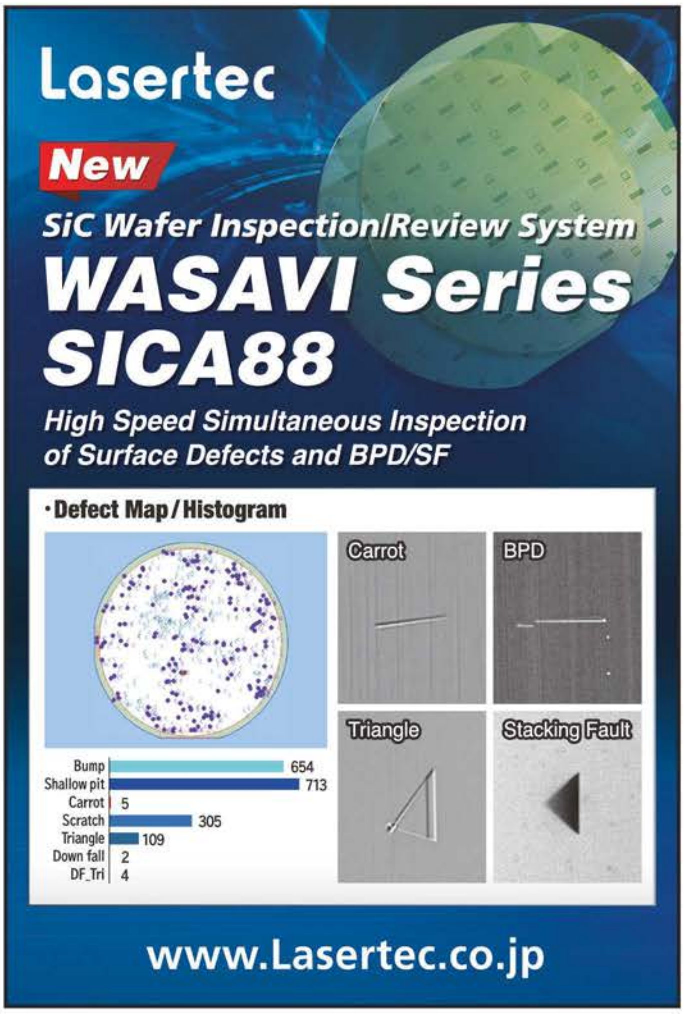
Key breakthroughs that have formed the foundation for the incredibly bright LEDs of today are the development of a buffer layer between sapphire and GaN, and the creation of *p*-type doping – and Akasaki has been a trailblazer in both these areas, developing the first successful buffer layers using AlN, and producing the first GaN with significant *p*-type doping, realised via electron bombardment of the material.

Refinements in both these areas were realised by Nakamura, a Tokushima University graduate who joined Nichia in 1975. He initially worked on purifying gallium and growing single crystals of GaAs and InP, but in 1989 he turned his attention to developing GaN LEDs.

After building his own MOCVD reactor, he produced epitaxial layers on sapphire with a GaN buffer, because this would circumvent any intellectual property issues associated with Akasaki's AlN approach. Then, after noticing that the exposure to an electron beam to promote *p*-type doping led to an increase in the temperature of the material, he showed that annealing GaN offered a more attractive approach to slashing its resistance.

With manufacturable approaches now in place for the growth of high-quality epistructures containing *p*-type layers, it did not take long for Nichia to launch its first LEDs. They came out, and the rest, as they say, is history – stories about our industry that have, and continue to be, reported within the pages of this publication.





Positive vibes
for 2035

The compound semiconductor industry will be even more healthy in 2035 than it is today, thanks to emergence of ultrafast wireless, soaring sales of electric cars and ubiquitous LED lighting.

IN 1995, the year *Compound Semiconductor* made its debut, our industry was far smaller than it is today. Back then the white LED and the GaAs transistor were yet to uncover their first killer application, and it would be more than five years before the first wide bandgap devices hit the market.

Fast-forward to today and it is clear that the last 20 years have been a tremendous period for compound semiconductors, with annual chip sales rocketing and now worth billions of dollars. And in this twentieth anniversary issue, many pages of this publication are devoted to recounting these successes and the reasons behind them. But will this continue, and where could the compound semiconductor industry be in 20 year's time?

Looking ahead to 2035 is a task that analysts tend to avoid, as predicting revenues for the mid 2020s and beyond involves too much uncertainty. But as Gordon Moore showed in his seminal paper from 1965, progressed can be predicted. There is no doubt that compound semiconductor chips will continue make strides in their bang-per-buck. And in sectors where change is slow and new technologies have to deliver proven reliability, it is not beyond us to see that the compound semiconductor chips that are delivering great promise today will be those that are deployed in a decade or so.

To gain a more detailed view of where the compound semiconductor industry might be heading in the long-term, here we talk to three leaders from our community: Fred Schubert, an academic from Rensselaer Polytechnic Institute, who gives his opinion on the future for LEDs; Cree co-founder John Palmour, who provides his take on the opportunities for wide bandgap power electronics; and Douglas Reep, Qorvo's Senior Director of Research, Infrastructure and Defense Products, who shares his views on the future of compound semiconductor devices for wireless communications.

In the LED industry, chip production is certain to increase in the coming years, spurred by the uptake of solid-state lighting. "For LED lighting, the cost is already below any comparable technology, if we take into account the purchase price, electricity price, environmental costs, replacement costs and environmental impact," says Schubert.

Convincing the public to part with their cash, however, hinges on the retail price, as many customers are not swayed by calculations considering the return-on-investment. This hampers sales today, as solid-state 60 W equivalent bulbs are currently far more expensive than the incumbents. However, prices should fall fast. "The LED cost of the bulb is $1, we add another $1 for the power supply and another 50 cents for the bulb and the sockets and the screw-in plug, so we are at a manufacturing cost of $2.50," explains Schubert. "So a selling price of $5 is very realistic – and we are going to have that over the next few years."

Cheaper LEDs should result from improvements in manufacturing efficiency, primarily related to refinements in packaging. 'Traditionally, 50 percent of the cost has been in the packaging field, because it has been a serial process," says Schubert, who expects costs to fall through the introduction of a parallel process involving the placing of LEDs on a foreign substrate – probably silicon – that is processed and diced up.

Improvements in LED performance are set to continue, and should lead to the availability of efficient devices that span the infrared to the ultraviolet. "I think blue LEDs will help green LEDs," says Schubert, who expects that in time there will be a reduction in the depth of the valley associated with the green gap. He is also predicting an increase in the efficiency of ultraviolet LEDs. "But I think it is going to be more difficult there, because of the high energies involved."

Shadowing silicon

One area where Schubert is not expecting a major change is in the architecture of the LED: It will have a *p-n* junction at its heart. However, there will be refinements. "Silicon technology has come a long way, and

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Connecting, informing and inspiring the compound semiconductor industry every detail in silicon technology – the gate, the dielectric, the interconnect, and so on – has been improved. We will see the same thing in LEDs: *p*-type doping, *n*-type doping, quantum wells, phosphors, packaging – all those things will improve." And thanks to this, by 2035 devices produced in a cost-effective manner should be delivering ultra-high efficiencies, such as 90 percent or more.

Of all the areas highlighted by Schubert for improvement, the most important one to address is *p*-type doping. "There are a lot of people who say that *p*-type doping is a problem, and we have also identified *p*-type doping as a problem in conjunction with our work on droop." Improving the doping in GaN is one solution, but more success might result from the introduction of a different material, such as InGaN, ZnO or another alternative.

The foundation for the chip is unlikely to change, according to Schubert: "I'm a big fan of GaN substrates, because they appear the better substrate, with fewer dislocations – but the price competition is so tough that GaN substrates cannot compete, at least for blue LEDs." It might be a different story for ultraviolet LEDs, however, which retail for more and can derive more benefit from a native platform.

Over the coming years we should expect to see increased deployment of systems that combine the selection of colour temperature with automation and colour-temperature dimming. These solid-state sources might also be used for wireless light communication. "The IEEE is working on that," says Schubert, who thinks this technology is promising, but more research is needed.

Predicting additional new applications for the LED is not easy, with Schubert warning that we should be ready for some surprises. He points out, for example, that large-scale photo-chemical reactions could be driven by LEDs.

In the long-term it is possible that the future of the LED is not actually that bright: Research at Sandia shows that it makes sense for solid-state lighting to be based on lasers, rather than LEDs, due to the lower cost-per-lumen associated with a droop-free device delivering high efficiencies at very high current densities.

Schubert believes that this work is a very interesting avenue, but one that may not be that successful. He argues that laser lighting was proposed in the 1990s, because lasers at that time were more efficient than LEDs. However, they did not have any success, due to the challenges of producing reliable devices operating at very high current densities.

GaN in smartphones?

In the wireless arena, the next few years are very easy to predict: The makers of smartphones will launch ever more sophisticated models, featuring more complex components that cater for the 4G and 4G LTE standards. Switches in these mobiles will be based on silicon-on-insulator devices, while the amplifiers will probably be made from GaAs.

"We will see GaAs amplifiers there for some time, due to their ability to do good power-added efficiencies – it's all about battery life – and very good linearity characteristics," argues Reep. Looking further ahead, there will be the introduction of mobile communication technologies that support ever-increasing data rates. This will support the seemingly insatiable appetite for greater global data consumption, which will initially allow improved streaming of video to mobile devices, before underpinning the growth of the Internet-of-things.

The first step will be the introduction of 5G, which is tipped to start its roll-out by the end of this decade. "The standards are very immature and currently being worked on," says Reep. "My personal belief is that we will see some demonstrations, if not standards, start to emerge in the Ka-band." Although there is no official allocation for mobile wireless in this spectral range, Reep believes that this situation could soon change – and he hopes that 5G could get a further boost from a successful demonstration of this technology at the next winter Olympics, which will be held in Pyeongchang, South Korea, in early 2018.

Next-generation smartphones sporting 5G capability will also have to be compatible with many existing standards. "It is likely that we'll see the older standards disappear within a relatively modest timeframe – perhaps that includes GSM. But it is likely that 3G and 4G will be around during the deployment of 5G – so the problem with multiple channels doesn't get easier."

Reep believes that this scenario can open the door to revolutionary product

> “The deivces that we have been working on for defence are high-voltage devices, and operate between 28 V and 48 V quite typically. The handheld needs 3 V, maybe a little less, up to 5 V, so we will need to see the emergence of a different class of GaN device that operates efficiently at low voltage.”
>
> Douglas Reep, Qorvo's Senior Director of Research, Infrastructure and Defense Products

development. "I think that this is where GaN will really shine for us – in compact, highly-efficient power amplifiers." These devices will be very attractive to the designers of smartphones, who will need to cram more radios into a fixed space, and are looking for amplifiers capable of operating at high power densities.

If the makers of GaN transistors are to grab this opportunity, they will have to develop new devices operating at lower voltages. "The devices that we have been working on today for infrastructure or defence are high-voltage devices, and operate between 28 V and 48 V quite typically. The handheld needs 3 V, maybe a little less, up to 5 V, so we will need to see the emergence of a different class of GaN device that operates efficiently at low voltage."

Carrier aggregation is viewed as another approach to handling higher data rates. This involves transmission over multiple channels, which can be managed with a software-defined radio.

"If we have the ability to, under software control, select the channel to support, then we can certainly simplify some of the hardware implementation within the phone," says Reep.

However, this approach is not easy, with those trying to develop software-defined radio for use by first responders having struggled for some time to find a solution.

To reach data rates that are beyond those that can be realised by 5G, one must go to even higher frequencies. One option is V-band. "It's in a bad spot from an atmospheric attenuation standpoint, but if I only want to communicate around my conference table, and not interfere with the folks in the conference room next door, then V-band can have some attributes," says Reep.

Head to even higher frequencies and the antenna needs to be pointed to the source. However, that inconvenience may not be a show-stopper, according to Reep: "I believe some of the researchers in Germany are convinced that for the data rates we need perhaps 300 GHz is the range for some of these short-hall communications."

"At that point I think that the competition will be light-based communication, because we will be in the sub-terahertz, as we would be taking a real beating on the atmospheric attenuation of the signal." The optical sources that could be used for this are either lasers or LEDs.

GaN for infrastructure

Underpinning the migration to faster data rates for smartphones will be the deployment of base stations operating at higher frequencies – and this spells good news for GaN. But this might not be the only use for this wide bandgap device in infrastructure, as it could also be used to provide connectivity for cars, trucks and other vehicles. As they move, links could be handed off between multiple access points, allowing adaptive traffic control. "If that vision occurs fairly rapidly, we'll have a proliferation of multiple platforms, and from an access standpoint, huge bandwidth demands," says Reep.

One area where he is predicting stability is in the material combination used for making GaN transistors for communication infrastructure and defense applications. He points out that GaN-on-silicon for high-power devices is not as appealing as it may seem initially, because the substrate is relatively expensive, due to the need for a high-resistivity foundation. "If one buys a GaN-on-silicon epiwafer from one of the current suppliers, it will cost more than a GaN-on-SiC wafer that we have in production today."

Although that may change with economies of scale, GaN-on-silicon may still fail to deliver significant success. Silicon has a significantly inferior thermal conductivity to SiC, and to prevent an increase in junction temperature, the devices must be spread further apart, which impairs cost-competitiveness.

Where GaN-on-silicon might have a role to play is in the power amplifiers of 5G phones. "We don't have the luxury of large current, because of the battery – and so in that arena, if we see a low-voltage device emerge, it will likely be a GaN-on-silicon technology."

GaN-on-silicon is already establishing itself in another market, by making

> "I think there are a whole lot of different technologies that can start being explored that did not make sense for silicon and will make sense for wide bandgap devices."
>
> John Palmour, Cree CTO, Power and RF

an impact in power electronics. "The performance has always been there," says Palmour, who believes that progress has been held back by uncertainty over how to use this material effectively. Engineers have spent time deliberating on whether the GaN transistor should either be a normally-on, cascaded device, or a normally-off device; there are still concerns over reliability; and widespread adoption of a repeatable manufacturing processes is still needed. But all these areas are being addressed, and GaN transistors are destined to be increasingly deployed in products requiring power devices operating between 30 V and 600 V.

At higher voltages, it is SiC that will displace the silicon incumbent, according to Palmour. These devices will become increasingly attractive as on-resistance falls, because this trims costs and increases switching speeds.

Palmour does not expect the voltage ranges where GaN and SiC products serve to shift with time, reasoning that although GaN-on-silicon can move to much larger wafers to cut costs, so can SiC, which could easily move to 8-inch lines. And although GaN-on-silicon is cheaper at the wafer level, that does not mean that it is superior when the cost of high-voltage devices is taken into account. "If we can get three times more amps per wafer than you do with GaN-on-silicon, it's a win," argues Palmour. "We're a GaN company, we do lots of transistors in GaN – we just don't think it's the best way for the high-voltage market."

Even more promising than GaN and SiC are devices made from ultra-wide-bandgap materials, such as AlN, Ga_2O_3 and diamond. However, unlocking the potential is challenging, because as the bandgap gets wider, it get harder to identify shallow dopants that enable acceptable on-resistances at normal operating temperatures. Another issue is that even for GaN and SiC, it is the package that limits the device performance. Areas to address include improving heat extraction and the current-handling capability of the wire bonds.

It is worth noting that there is still a considerable opportunity to improve the performance of today's GaN and SiC power devices. "Most of the designs that are around today are designed around the capabilities of silicon," argues Palmour, pointing out that the multi-level technologies widely used today create big, bulky, complex devices that have been constructed to get around the inherent slowness of the silicon IGBT.

"If you multi-level a bunch of lower-voltage IGBTs where you would have used a single level of a higher voltage, you get faster and simpler performance," explains Palmour, adding that this trade-off does not exist with the SiC MOSFET, due to its unipolar nature. "I think there are a whole lot of different circuit topologies that can start being explored that did not make sense for silicon and will make sense for wide bandgap devices."

Spurring investment in these new designs will be the increasing sales of wide bandgap devices. SiC chips are already being used in switched-mode power supplies, solar inverters, high-frequency power supplies and LED lighting power supplies, and they will see increasing deployment in uninterruptable power supplies and motor drives.

In the next decade, the big breakthrough for SiC, and possibly GaN too, will be its incorporation into electric vehicles. The relative sales of these two classes of wide bandgap devices will depend on the bus-voltage used in the vehicle. "There is also a lot of play as to whether it is an all-electric vehicle, a plug-in electric, or a hybrid," says Palmour. "But it's a pretty good bet that you'll see wide bandgap [devices] in electric vehicles past 2020, and obviously it would be a huge new market."

By then, SiC devices operating at very high voltages should have an opportunity to win sales in electrical grid infrastructure. "It is a long path to actually get it to market, because you have to convince a power company that this is a good thing to do – and that is going to take many years," says Palmour. But he believes that this could happen in the 2020s, beginning with the deployment of SiC MOSFETs and Schottky barrier diodes with 10 kV breakdown voltages.

Wind power is another potential market. Extracting power generated out of the tower requires a tremendous amount of copper, but, according to Palmour, this can be reduced by going to higher voltages into the nacelle, a move that is possible with SiC devices. To win adoption will require proving the reliability of the diodes and transistors, because any wind turbine downtime impacts its generating costs.

While silicon will not go away, by 2035 we can expect to see far greater adoption of wide bandgap devices than we do today, with devices deployed in electric cars, various forms of renewable energy systems and myriad power supplies. Compound semiconductors will also be serving mankind in many other ways – they will also be lighting our world and enabling communication at breath-taking speeds.

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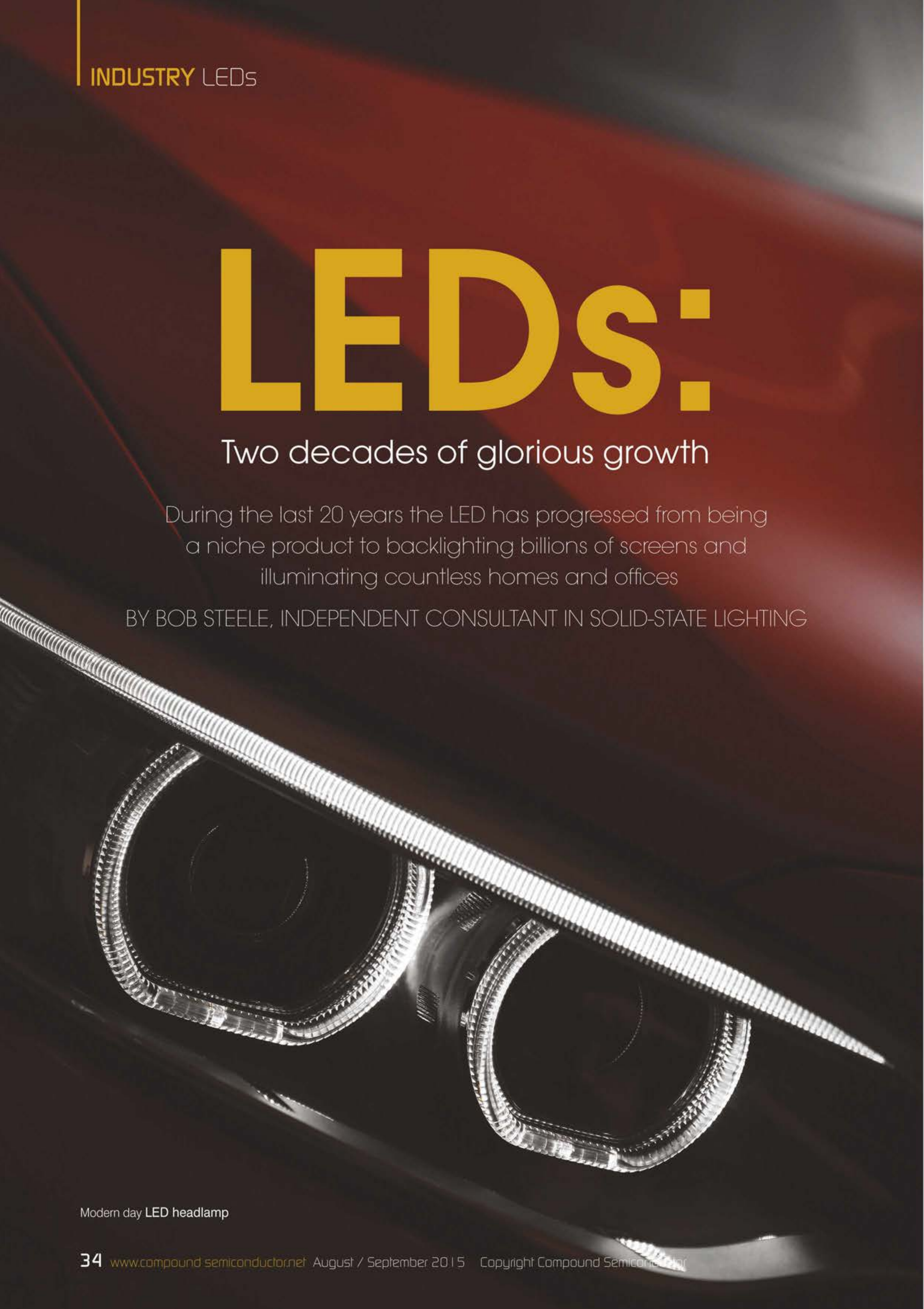
All speakers and presentations are subject to change.

LEDs:

Two decades of glorious growth

During the last 20 years the LED has progressed from being a niche product to backlighting billions of screens and illuminating countless homes and offices

BY BOB STEELE, INDEPENDENT CONSULTANT IN SOLID-STATE LIGHTING



Modern day **LED headlamp**

IN A HIGH-TECH INDUSTRY, a great deal can happen in 20 years. That's certainly the case for the LED: It has evolved from being deployed in low-brightness indicator lamps and alphanumeric displays to being incorporated in high-performance white-light sources that have captured more than one-third of the $80 billion global lighting market.

In this article, we attempt to summarize many of the major developments occurring over this timeframe – which spans the publication of the very first edition of *Compound Semiconductor* to this twentieth anniversary issue.

Technology

The LED predates this publication by many years, and its origins can be traced as far back as 1907, when British radio engineer Henry Joseph Round discovered the device completely by accident. While investigating the electrical properties of a metal-semiconductor SiC rectifier, he witnessed the first light emission from a solid-state material driven by an electrical current.

However, for the next fifty-five years or so, progress of this device was relatively slow, until the invention of the visible red LED in 1962, followed later by the commercialization of GaP-based and GaAsP-based yellow-green and red devices (see "The early years: LED development prior to 1995" for a more detailed history of this period). Making blue and true green LEDs proved particularly challenging. A major breakthrough came in the early 1990s, when Nobel-Prize winner Shuji Nakamura produced a film of low-resistance *p*-type GaN by annealing this material in a nitrogen atmosphere. In late 1993, Nichia announce the commercial introduction of AlGaN-InGaN-GaN double heterostructure, high-brightness blue LEDs with a luminous intensity 1 cd. At the same time Toyoda Gosei introduced metal-insulator-semiconductor blue GaN LEDs with a luminous intensity of 100 mcd.

By the following year Nichia's blue LEDs were selling at $15, for orders of reasonable quantity. However, significant sales only came in 1995, when volume pricing plummeted to $3. By then Toyoda Gosei had abandoned the metal-insulator-semiconductor devices in favour of the much-more-efficient double heterostructure configuration, and had started to sell these LEDs.

The development of InGaN technology for blue LEDs provided the foundation for making green variants. In 1996, Nichia launched true green (525 nm) InGaN LEDs with volume pricing at just over $2. These devices featured an indium content of up to 50 percent in the active layer. Around the same time, Nichia switched from a double heterostructure to a single-quantum-well structure to increase efficiency. Green LEDs were soon available from multiple sources, with Toyoda Gosei launching them on the market in 1997.

Japan's monopoly on the manufacture of GaN LEDs did not last long. Since the late 1980s, Cree had been quietly working on its own approach based on substrates made from SiC rather than sapphire, for which it received its first patent in 1989. Unlike Nichia and Toyoda Gosei, Cree supplied chips only, rather than packaged LEDs, releasing its first superbright GaN-on-SiC chip in June 1995.

Many lighting applications require white light, and equipping LEDs to do this via phosphor conversion represented the next big breakthrough for this solid-state device. First introduced by Nichia in 1996, the LED produced white light by colour-mixing blue emission with broad emission in the yellow, created by using a 455-nm blue chip to pump a Ce:YAG phosphor. The Japanese firm kept its technology in house, developing and producing its Ce:YAG phosphor and maintaining a very strong patent position in this technology.

Initially, white LEDs were only available in high colour temperatures, such as those greater than 5,000 K. It took until 2002 for customers in search of a warm-white to have their wishes fulfilled, when Lumileds launched devices with a colour temperature below 4,000 K. A combination of a red and Ce:YAG

Early electronic calculators featured an LED numeric display. Shown here is a HP-35, Hewlett-Packard's first pocket calculator and the world's first scientific pocket calculator. It was introduced at US$395 and was available from 1972 to 1975. Credit: Seth Morabito

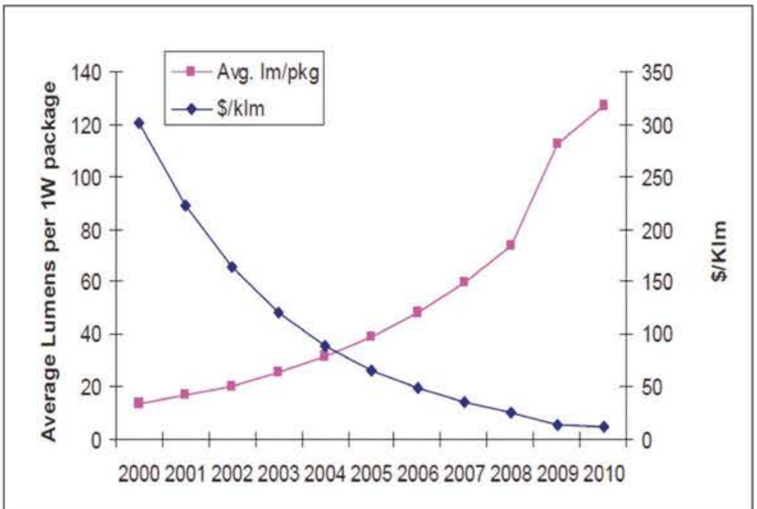


Figure 1. Developments in white LED light output and price (Typical 1-W cool-white LED package) Source: Strategies Unlimited.

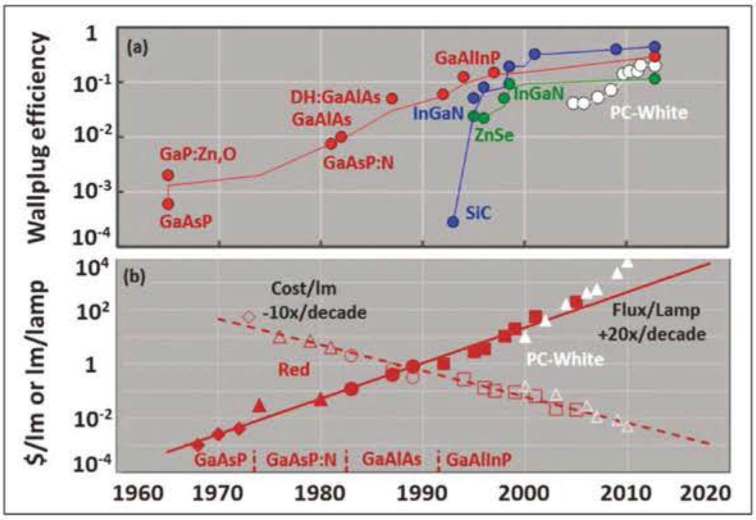


Figure 2 (a) Historical evolution of LED performance - red, blue, green and phosphor-converted white LEDs; (b) Haitz's Law. Source: M.H. Crawford et. al. "Solid-State Lighting: Toward Smart and Ultra-Efficient Materials, Devices, Lamps and Systems", published in D.L. Andrews, Ed., Photonics Volume 3: Photonics Technology and Instrumentation (Wiley 2013).

phosphor broadened the output of the blue-pumped device.

The number of manufacturers of GaN LEDs swelled throughout the late 1990s and beyond. The likes of Hewlett-Packard and Siemens Opto Semiconductors launched products, and a number of Taiwanese companies, such as Epistar, UEC, Epitech and Arima, focused on the production of chips (first InGaAlP, then GaN) rather than packaged devices. Other Taiwanese LED companies, such as Liteon and Everlight, packaged those chips. Many Japanese companies, including Stanley Electric, Matsushita, Toshiba, and Citizen also entered the packaged GaN blue, green and white LED market. However, the strong patent positions held by Nichia and Toyoda Gosei constrained them to buying GaN chips from Cree or Toyoda Gosei and packaging them, rather than manufacturing their own chips.

LCD TV with thin profile enabled by an LED backlight.

From this time to the late 2000s, the efficacy and lumen output of InGaAlP and InGaN devices increased dramatically. Milestones from this period include the introduction, in 1998, of the first high-power (1 watt) white LED by Hewlett-Packard that was based on a 1 mm x 1 mm chip. During this era, efficiency improvements resulted from several refinements to the device design: an improved epitaxial layer structure, including the introduction of multiple quantum wells; chip shaping to increase light extraction efficiency; and improvements in packaging to enhance heat removal from the chip. Throughout the 2000s a 'horse race' took place among the major LED manufacturers, as they all strived to announce the next improvement in efficacy, especially in white LEDs.

The remarkable progress in white LED efficiency and cost reduction during this period is illustrated in a plot of lumen output produced by a 1 W package (this is approximately equivalent to lumens/watt), and price, expressed in dollars-per-kilolumen (see Figure 1). Over a period of one decade, the price plummetted from $300 per kilolumen to $11 per kilolumen, while light output from a 1 W package shot up from 15 lumens to 130 lumens.

An alternative approach to considering the progress of the LED is to see the improvement in wall-plug efficiency over the years (see Figure 2a). This approach provides a superior measure of the relative performance of various types and wavelengths of LEDs, because it avoids considering the sensitivity of the human eye to the emission wavelength, which is incorporated in figures of luminous efficacy (lumens/Watt).

Yet another method for measuring the progress of the LED is the formulation that has come to be known as "Haitz's Law" (see Figure 2b). It was developed by LED pioneer Roland Haitz, a former R&D manager of Hewlett-Packard's Semiconductor Products Division who went on to hold the same position at the spun-out company, Agilent Technologies. In this remarkable analogue to Moore's Law for silicon semiconductors, Haitz's Law shows that the cost-per-lumen of LEDs declines by 90 percent per decade, while the output of LEDs (flux per lamp, measured in lumens) rises by a factor of 20 with every decade.

Advances in device efficiency have gone hand-in-hand with substantial improvements in packaging technology, especially in high-power LEDs, including dramatic reductions in material content. This, coupled with increasing production volumes, has spurred a rapid decline in the cost-per-lumen of LEDs in general, and in particular, white emitters. A move to chip-scale packaging, in which the entire package is barely larger than the LED die, has been a major accomplshment within this industry. Packaging technology has also evolved to address an increasing array of application requirements, especially in lighting. This evolution is evident in Lumileds' line of high-performance packages, which began with the standard 3 mm and 5 mm lamp packages that were driven at 20 mA, (<0.1 W), and now include ultra-high-power chip-on-board packages capable of handling input powers of more than 100 W (see Figure 3).

From mobiles to lighting

Increases in the brightness and range of colours produced by LEDs have enabled this device to serve more applications. Prior to the development of high-brightness LEDs, most applications were limited to indoor or quasi-indoor use, but the unfurling of new InGaN and InGaAlP high-brightness LEDs enabled the construction of full-colour outdoor signs, including video screens, in the mid-to-late 1990s.

Single-colour red and amber signs, including highway signs, also became a significant market. Although small at first, the use of red LEDs in traffic signals also began in the mid-1990s. This use of LEDs later expanded to include green and yellow signals, as well as amber and white pedestrian signals. By the early 2000s, the use of LEDs in traffic signals became mainstream, thanks to the higher energy efficiency and reduced maintenance of these solid-state sources compared to filtered incandescent lamps.

Later in the 1990s, the large-volume introduction of high-brightness LEDs into the automotive market began. LEDs were first used in interior automotive applications such as instrument panel lighting, primarily in Europe, with Siemens Opto Semiconductors (later Osram Opto Semiconductors) being the leading supplier.

In exterior automotive applications, Hewlett-Packard (later Lumileds) led the way with its high-flux InGaAlP products that were used in centre high-mounted stop lamps. In 1999, GM introduced the first all-LED rear combination lamp, using Lumileds LEDs, on its Cadillac DeVille model. During the decade that followed, exterior automotive applications extended to all functions, including stop, turn and tail lamps, daytime running lamps, and headlamps.

During the early 2000s, the use of LEDs in mobile phones – as backlights for LCD displays, keypad backlights and camera flash – became widespread, driving the growth of the market through 2005. LED backlights for LCD displays also spread to other portable electronics applications, such as digital music players, digital cameras, and laptop computers. And with time, LEDs won adoption in larger screens, with huge market growth beginning in 2010 as these

The early years:

LED development prior to 1995

ONE OF THE BIGGEST STEPS towards the commercialisation of the LED came in 1962, when Nick Holonyak and his team at GE Labs announced the invention of the first visible LED, which emitted in the red. Six years followed before significant commercial sales began, and from then on right up until 1995 the bulk of LED industry revenue was derived from the sale of yellow-green and red indicator lamps and alphanumeric displays based on GaP and GaAsP devices grown by LPE and VPE. These materials are indirect bandgap semiconductors, so they are inherently limited to low efficiency and low light output, and are consequently only suitable for indoor use. What's more, the colour spectrum is limited: These materials are incapable of producing blue or true green. (Although Cree began producing blue SiC LEDs in 1989, they were very low in brightness – around 10 mcd – and thus had limited applications.)

A big breakthrough came in 1982, when Hewlett-Packard in the US and Stanley Electric in Japan developed AlGaAs LEDs that produced a far higher brightness than those made from GaP or GaAsP. The major downside, however, was that they could emit only a single wavelength, 660 nm. Through the early 1990s this was the only LED material capable of being viewed in outdoor, full sunlight conditions. It was thus used in applications such as outdoor dot-matrix displays and signs and in the first LED-based centre high-mounted stop lamp on an automobile, the 1988 Nissan 300ZX.

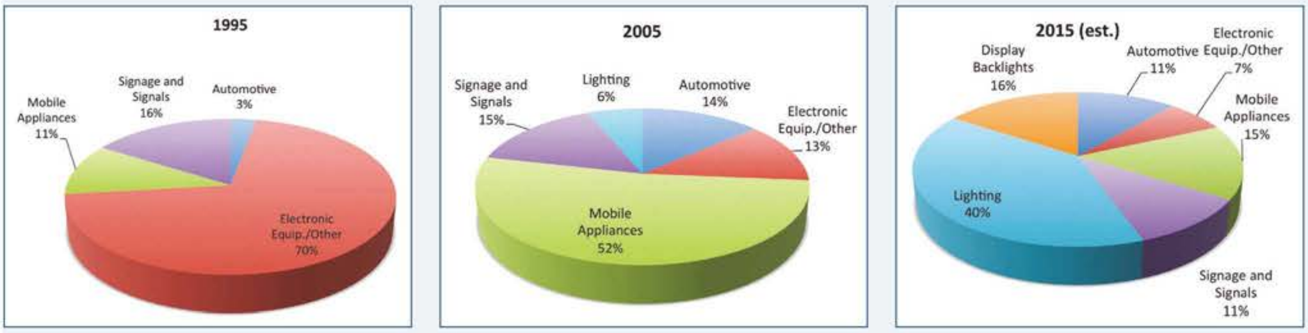
By 1995, work had been underway at a number of companies and laboratories to develop high-brightness materials across a broader spectral range, including blue and true green. In 1992 Hewlett-Packard and Toshiba completed development of the InGaAlP material system, producing, by MOCVD, devices with high-brightness emission in the red, orange and yellow. Initial devices were based on GaAs substrates, which absorb visible light, but a switch to transparent substrates made from GaP doubled performance and made InGaAlP LEDs the brightest devices on the market. They quickly replaced AlGaAs in outdoor applications, including automotive, partly because of their superior stability – AlGaAs has the tendency to deteriorate in outdoor conditions, due to oxidation of aluminium.

The next major development, a true breakthrough, came in late 1993 with the commercial introduction of GaN-based blue LEDs by Nichia Chemical and Toyoda Gosei. This is by now a well-known story, and the significance of this technical tour de force was recognized by the Royal Swedish Academy with their awarding of the Nobel Prize in Physics in November 2014 to the inventors of the blue LED – Shuji Nakamura at Nichia Chemical (now at UC Santa Barbara) and Isamu Akasaki and Hiroshi Amano at Nagoya University. (For further elaboration of the development of the blue LED see *Brilliant! Shuji Nakamura and the Revolution in Lighting Technology*, Revised Edition, Bob Johnstone, Prometheus Press, 2015.)

devices were deployed as backlights in LCD TVs and monitors.

As other applications have matured, lighting has taken over as the leading driver of growth for the LED market. The tipping point has been the passing of the 100 lm/W mark for white LEDs, which are getting cheaper with every year that passes. White LEDs started to be adopted in general lighting functions by most lighting manufacturers in 2009, and the growth in this sector since then has been nothing short of spectacular. Market research firm Strategies Unlimited predicts that the penetration, by revenue, of LED-based products into the lighting market will be 50 percent for lamps ($10.4 billion) and 39 percent for luminaires ($23.9 billion) in 2015. Adoption of LEDs in general lighting has grown so fast in recent years that lighting has outpaced all other LED applications, and is now the largest segment by a wide margin. In terms of LED component revenue, in 2015 lighting is projected to account for 40 percent of the market, equating to $6.9 billion (see Figure 4).

The evolution in LED applications



Over the last 20 years, the applications that the LED has served have changed considerably. Shown in the figure above is the breakout of LED applications in 1995, 2005 and 2015. Due to the very small market for high-brightness LEDs in 1995, the total applications breakout in that year includes conventional, low-brightness LEDs.

The definitions of the various market segments are as follows:
Mobile appliances – mobile phones, digital music players, digital cameras, laptop computers, tablet computers
Signage and signals – full-colour and single-colour outdoor signs, traffic signals, railroad signals, aircraft warning signals, etc.
Automotive – interior lighting, such as instrument panel lighting and dome lights; exterior lighting, including CHMSLs, stop, turn and tail lights, daytime running lamps and headlamps
Display backlights – backlights for LCD TVs and monitors
Lighting – lamps and luminaires for general lighting; specialty lighting such as machine vision; consumer portable lighting such as flashlights, headlamps and bicycle lights
Electronic equipment/other – primarily indicator lamps and alphanumeric displays used in electronic equipment; various niche applications too small to be categorized separately

At the beginning of the high-brightness era, the market was still dominated by conventional LED applications, particularly indicator lamps and alphanumeric displays used in electronic equipment. Signage was primarily limited to dot-matrix type displays used for indoor and quasi-indoor applications such as information displays in bus and train stations and airports. Mobile phone applications were mainly dot-matrix alphanumeric displays in handsets, such as those manufactured by Motorola.

By 2005, mobile appliances had become the dominant segment, accounting for 52 percent of the market. This success stemmed from the widespread adoption of mobile phones by consumers around the world, the ubiquitous use of white LEDs as backlights for LCD displays, and the use of blue and white LEDs as keypad backlights. A significant fraction of mobile phones included cameras, the majority of which featured white LEDs for the flash function.

Lighting also started to have a modest impact on the market, accounting for 6 percent of LED revenue in 2005. However, at that time the use of LEDs in lighting was limited to niche applications such as machine vision, channel letters and consumer portable devices such as flashlights.

A rapidly growing application was the use of red-green-blue LED systems in architectural lighting, particularly colour-changing systems. This application was pioneered by Color Kinetics in the late 1990s.

In 2015, most of the applications discussed above have matured, although some significant growth remains in the signage and automotive segments. General lighting has become the main growth driver and it now dominates the market.

Market growth

Prior to the introduction of high-brightness LEDs in the mid-1990s, the LED market had become mature, with very slow growth. With few new applications arising and the technology at a plateau, the conventional low-brightness market had stagnated at around \$1.7 billion. However, with the opening up of new applications in the late 1990s, based on the new high-brightness devices, the market began to accelerate. From a modest level of \$120 million in 1995 (see Figure 5) the high-brightness LED market grew at a compound annual growth rate (CAGR) of 59 percent to \$1.2 billion in 2000, and then on to \$3.9 billion in 2005, \$11.3 billion in 2010, and is projected to be \$17.5 billion in 2015. Following the initial 1995-2000 market ramp-up, the biggest 'growth spurts' took place in 2001-2004 (a CAGR of 45 percent), with the widespread adoption of LEDs in mobile phones; and in 2009-2010 (a CAGR of 110 percent) with the dramatic growth in the use of LED backlights in LCD TVs and monitors.

Over the last five years, the LED market has grown at a slower pace. For this period, the CAGR has been 9 percent, a figure that is representative of a more mature market. However, during this time the lighting segment has experienced a CAGR of 54 percent, driven by the robust rate of adoption of LEDs in lamps and luminaires for general lighting.

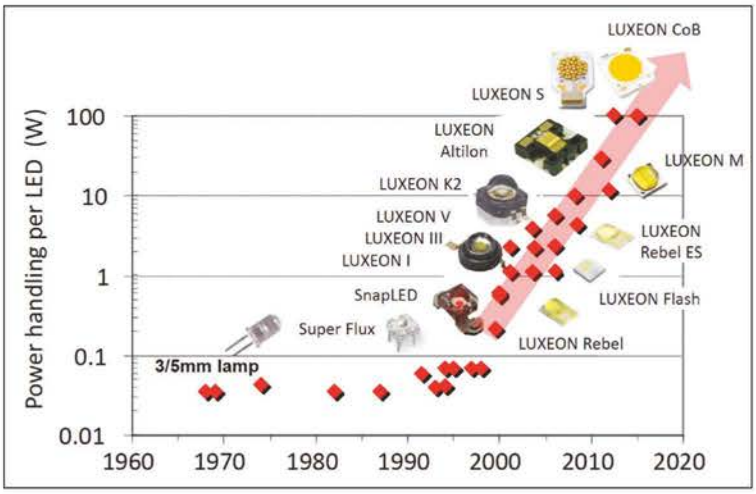


Figure 3. Evolution of LED package technology. Source: George Craford, Lumileds, "Innovations in LEDs", US Department of Energy Solid-State Lighting R&D Workshop, San Francisco, January 27, 2015.

Shifting suppliers

In addition to the dramatic changes in LED technology and markets over the last 20 years, there have been some major shifts in the structure of the LED industry (see Table 2). Companies that were leading the industry in 1995 have been displaced by those that were not even on the radar back then, and further changes to the industry landscape have resulted from mergers, acquisitions and spinoffs. Comparing the top ten firms in 1995 and 2015, only two crop up on both lists: Hewlett-Packard, in the form of its successor company Lumileds; and Siemens Opto Semiconductors, in the form of its successor company Osram Opto Semiconductors.

From a regional perspective, dominance by Japanese companies has disappeared. Seven firms were in the top ten in 1995, and now only Nichia is there – but it has held on to the top supplier spot since 2000, and with an estimated revenue of \$2.1 billion in 2014, its sales are far beyond those of its rivals. The last decade has witnessed a shift to success of other

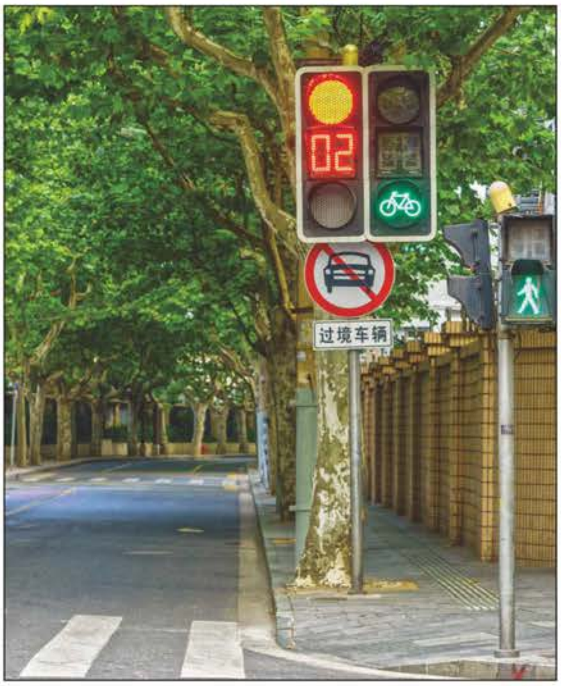
Milestones in LED technology and commercial developments

1962 – Nick Holonyak invents the first visible (red-emitting) LED using bandgap engineering (GaAsP) at GE Labs
1968 – First product introduction of visible LEDs by Monsanto (indicator lamps) and Hewlett-Packard (5 x 7 dot matrix displays)
Late 1960s-early 1970s - Litronix, Fairchild, TI, Toshiba, Sharp, and others begin production of visible LED indicator lamps and displays
1972 – Hewlett-Packard produces first large volume LED numeric (seven-segment) displays for the HP35 scientific calculator
1982 – Stanley Electric and Hewlett-Packard develop first 'high-brightness' LEDs based on AlGaAs
1989 – First production of a power (>20 mA) LED package by Hewlett-Packard, > 1 lumen
1989 – Cree begins first volume production of blue LEDs made from SiC
1992 – Hewlett-Packard and Toshiba introduce high-brightness red-orange-yellow LEDs based on InGaAlP
1993 – Nichia and Toyoda Gosei announce first high-brightness blue LEDs made from InGaN
1994 – Nichia begins first volume production of blue InGaN LEDs
1996 – Nichia introduces phosphor-converted white LEDs
1998 – Hewlett-Packard introduces first high-power (1W) LED, rated at more than 10 lumens
2002 – Lumileds introduces warm-white LEDs suitable for general lighting
2008 – Best commercial white LEDs reach 100 lm/W
2010 – Worldwide LED market passes the \$10 billion mark
2014 – Inventors of the blue LED (Nakamura, Akasaki and Amano) awarded the Nobel Prize in Physics

countries in the Far East, with Korean companies such as Samsung, LG Innotek, Seoul Semiconductor and Lumens emerging as major LED suppliers, and China starting to make a big impact. Last year, a Chinese company – Mulinsen – achieved top 10 supplier status for the first time.

The changes in the LED industry over the last 20 years have been nothing short of staggering: the size of the high-brightness LED market has shot up by a factor of 150; the conversion efficiency, evaluated for GaN blue LEDs, has increased by a factor of 10; the input power capability of LED packages is 1000 times higher than before; and the cost-per-lumen has plummeted by a factor of 100. Underpinning all these advances has been a combination of the efforts of key individual researchers and countless engineers, large corporate investments in R&D and manufacturing, and the support of government programmes and incentives. From being niche products, LEDs have become ubiquitous in all aspects of modern life – from mobile phones to cars, TV sets, and now lighting, including the common light bulb. It has been a great technological adventure, and for those who have been involved with it from the beginning, it has been a fascinating and rewarding journey.

Bob Steele is an independent consultant in solid-state lighting. He has been chair or co-chair of the *Strategies in Light* US conference since 2000 and chair of the *Strategies in Light Europe* conference since 2012. He was also a co-founder of the LED lighting startup QuarkStar LLC in 2010. From 1994 to 2010 he directed the LED market research programme at Strategies Unlimited, where he was responsible for all of the company's activities in LEDs, including conducting custom studies and preparing multi-client reports.



LED traffic and pedestrian signals

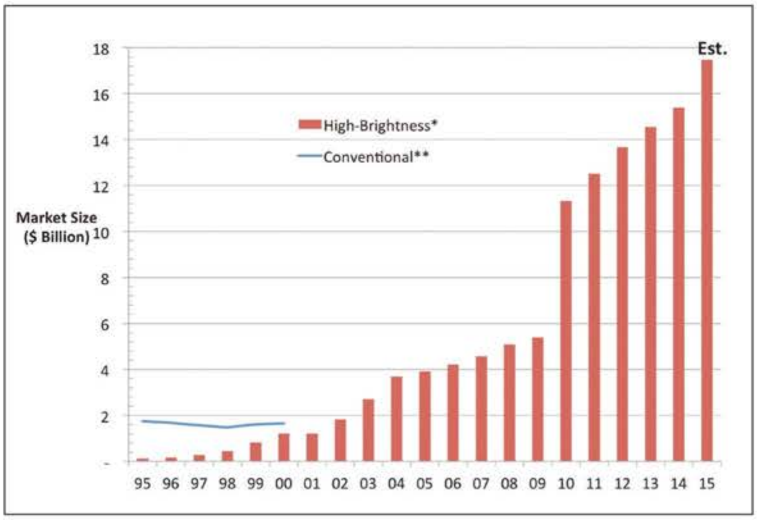


Figure 4: The market for conventional, low-brightness LEDs (based on GaP and GaAsP) declined slightly from 1995 until 2000, and data from beyond then is not available. Revenue for high-brightness LEDs (based on AlGaAs, InGaAlP and InGaN) has grown at a CAGR of 28.3 percent since 1995. Source: Strategies Unlimited

Top 10 packaged LED suppliers ranked by revenue 1995-2015

Rank	1995	2005	2015 (Est.*)
1	Hewlett-Packard	Nichia	Nichia
2	Stanley Electric	Osram Opto Semiconductors** (formerly Siemens Opto Semiconductors)	Osram Opto Semiconductors**
3	Matsushita Electric	Citizen Electronics	Samsung
4	Rohm	Stanley Electric	Lumileds***
5	Toshiba	Philips Lumileds (formerly Hewlett-Packard***)	LG Innotek
6	Sharp	Avago Technologies (formerly Hewlett-Packard***)	Cree
7	Taiwan Liteon	Everlight	Seoul Semiconductor
8	Siemens Opto Semiconductors	Rohm	Everlight
9	Citizen Electronics	Toyoda Gosei	Mulinsen
10	Sanyo Electric	Seoul Semiconductor	Lumens

*Based on 2014 revenues.

**Siemens transferred its Opto Semiconductor group to its wholly-owned lighting subsidiary Osram in 1999. Osram was spun out of Siemens as a public company in 2013.

***Hewlett-Packard spun out Agilent Technologies, which included its LED operation, in 1999. Agilent sold its Semiconductor Products Group, including the LED operation, to a private equity group in 2005, with the new company known as Avago Technologies. Hewlett-Packard formed a joint venture with Philips in 1997 known as Lumileds Lighting. After the spin-out of Agilent from Hewlett-Packard, Lumileds became a separate company focusing on high-power LEDs, with Agilent and Philips as 50/50 co-owners. Philips purchased Agilent's share in 2005. Philips announced the sale of 80 percent of its share in Lumileds to a private equity group in March 2015. Source: Strategies Unlimited.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The GaAs revolution

In the early 1990s, the US led the development of an infrastructure for GaAs MMIC manufacturing. The result: A technology that lies at the heart of the mobile wireless revolution.

BY ERIC HIGHAM FROM STRATEGY ANALYTICS

IN THE ARTS and the entertainment business, it can often be said that the more things change, the more they remain the same. That's certainly the case when comparing today with 20 years ago. Back then, Toy Story was a big hit at the box office, Bjork had a top ten album by the name of Post, and The Simpsons was an incredibly popular TV show. Fast-forward to today and there is much excitement surrounding the release of Toy Story 4, Bjork is in the top ten with her album Vulnicara, and many families are still sitting back and relaxing by watching the antics of Bart, Lisa, Homer and Marge (who don't seem to have aged at all!).

Within the GaAs industry, however, there has been monumental, profound change over the last two decades, which span the publication of the very first edition *Compound Semiconductor* to this twentieth anniversary issue.

The handset has been the killer-application for the GaAs power amplifier

The Early Days

The biggest driver for the advancement of III-V semiconductor technologies has been the US Department of Defense (DoD), which has funded many key programmes to improve the capability and manufacturability of GaAs devices.

When the semiconductor industry got its start in the late 1940s and early 1950s, III-Vs did not play a role, with efforts initially focusing on the development of germanium transistors, a promising alternative to vacuum tubes. However, it did not take long for silicon to replace germanium as the material of choice for high-volume manufacturing.

In the 1980s the DoD funded efforts to improve transistor performance through III-V semiconductor technologies. By the end of that decade, the DoD had funded a successful GaAs Pilot Line programme that sought to develop GaAs digital integrated circuits to compete with silicon. However, the advantages of silicon, such as an established infrastructure and lower cost, could not be denied.

This led the US government to switch its funding to the refinement of GaAs MESFET technology and the development of high-frequency GaAs amplifiers within the Microwave/Millimeter Wave Monolithic Integrated Circuits (MIMIC) programme.

Running until 1995, the MMIC programme had an incredible level of financial support, with DARPA pumping in an estimated $400 million. Although the initial focus was on microwave and

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Cardiff – UK
This position will lead the Group's U.K. Photonics R&D programs ensuring that they remain on budget while achieving required technical objectives. This role will serve as a technical point of contact with both internal and external customers for key technologies ensuring that IQE's product offering leads the market.

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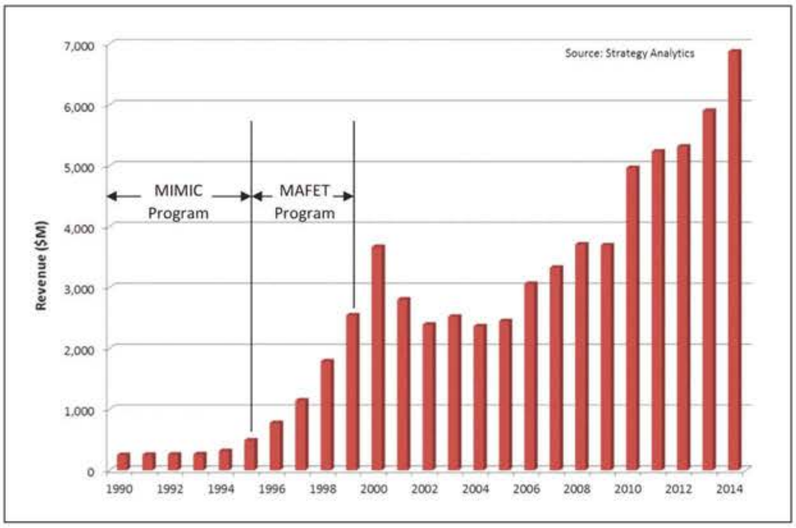


Source: Strategy Analytics

Figure 1: Global GaAs device revenue remained relatively flat in the early 1990s, but took off with the completion of the MMIC and the MAFET programmes.

millimetre-wave integrated circuits for defence applications, it also helped develop and refine test-and-measurement, assembly and manufacturing capabilities. Test and manufacturing capabilities were then propelled to a new level with the Microwave Analog Front End Technology (MAFET) programme, concentrated on developing multi-chip module manufacturing capability, improving GaAs device performance, and funding InP technology as a means of extending the operating frequency for solid-state components. While funding for these programmes came from the defence agency, and developments targeted defence applications, there can be no doubt that it is these two programmes that gave birth to the commercial wireless market.

This view is driven home by figures produced by our team at Strategy Analytics, which detail annual global GaAs device market revenue for each year from 1990 to 2015 (see Figure 1). In 1990, at the end of the GaAs Pilot Line programme, total revenue for GaAs was just $250 million, with a significant portion coming from the sales of GaAs-based digital circuits. While the MIMIC programme underpinned refinements to all the manufacturing, test and modeling capabilities, in addition to improving process and product performance, revenue remained fairly flat. However, after establishing this beachhead, GaAs device revenue rocketed from 1995 through to the conclusion of the MAFET programme in 1999, by which time MMICs accounted for the lion's share.

Growth continued after the conclusion of the MAFET programme, surging well past $3 billion in 2000. At that point in time, the entire electronics industry was caught up in the excitement of the 'dot com' era, with many working on the theory 'build it and they will come'. The majority of the major roads in the US were disrupted by contractors trenching multi-coloured spools of fibre into the ground, and tech companies throughout the land hoped that the bandwidth capability provided by the new fibre and network deployments would unleash a whole host of new services and benefits. Some of the GaAs products enjoying healthy sales back then were used for either conditioning signals, or deployed in modems and set-top boxes. Components sold included transimpedance amplifiers, RF amplifiers/attenuators and clock and data recovery type circuits.

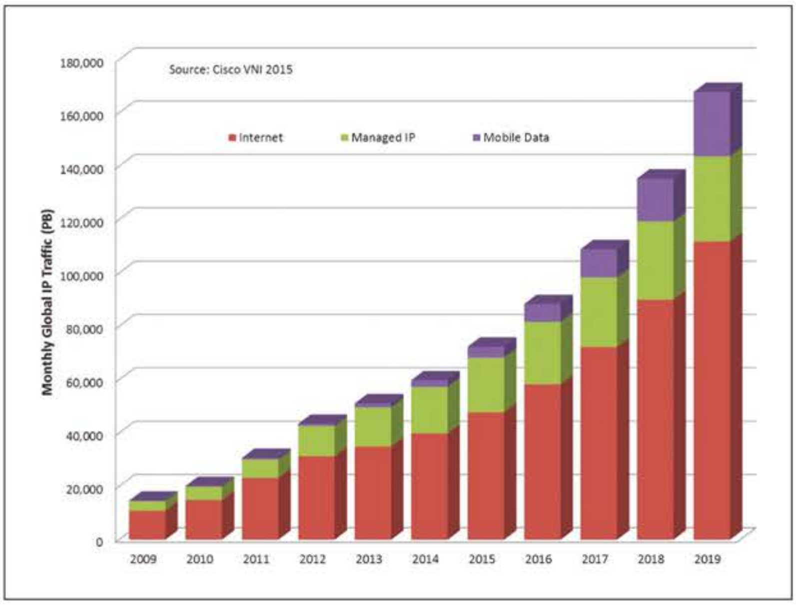
Unfortunately, the reality was that the dot com bubble burst; operators built networks, but no one came! In response, GaAs revenue dropped about as quickly as it rose, before floundering around at 1999 levels for several years.

The next inflection point began in 2004, a year that marked the start of what we now refer to as the wireless revolution. This kicked-off well after the beginning of mobile telephony in the 1980s – and at its start GSM accounted for about three-quarters of all mobile subscribers, but CDMA, with its higher data rates, was beginning to gain traction in North America. A turning point came in 2005, when operators introduced the first HSDPA (high-speed downlink packet access) networks into the GSM community, igniting a data arms race. Ignoring an almost flat year of 2009, when the global economy threatened to implode, GaAs device revenue has been on an upward trajectory ever since.

Market drivers

Between 2004 and 2014 GaAs revenue tripled to more than $7 billion. Early success of mobile

Figure 2: Data by Cisco shows that the ramp in data traffic is expected to continue throughout this decade.



Source: Cisco VNI 2015

communications initially spurred the rapid growth in GaAs sales, and this led on to the evolution of smartphones and increasing data traffic, which, according to Cisco, will grow at a compound annual rate of nearly 28 percent between 2009 and 2019 (see Figure 2).

Although that growth rate is impressive – it equates to an eleven-fold rise over a decade - it pales in comparison to the growth rate for mobile data. Analysts at Cisco are predicting that this will shoot up at a compound annual growth rate of 75 percent over the same time frame, equating to an 266-fold increase.

Several factors are behind this tremendous ramp in wireless data traffic. The top of the list is the increasing penetration of smartphones, which, in 2014, we estimate to account for two-thirds of all phone sales. This indicates that the wireless revolution is not only about communication, but entails a whole host of services and applications that users are accessing anywhere, at any time.

This anywhere, anytime connectivity is the engine for the entire RF market. It is welcomed by GaAs chipmakers, as it allows sales of their products to rocket. However, it also brings challenges, the biggest of which is how to build a network that is capable of handling the increase in data that is expected in future.

Essentially, there are three options for accommodating increases in wireless data. Equipment manufacturers can make radios that are more spectrally efficient; this means more data capability for a given bandwidth. However, the price to be paid for this is the combination of additional complexity of new wireless standards and more sophisticated modulation schemes.

One alternative is for operators to acquire more bandwidth, but this is a costly and potentially time-consuming process – and the third option is for operators to 'densify' networks by adding more, smaller wireless base stations. Benefits of this architecture, commonly called 'small cells', are fewer users per cell and more frequency reuse, but there are higher capital and operating expenses. Most of the evolving wireless networks are incorporating at least one of these three techniques, as they try to help operators fend off a wireless data tsunami.

Upgrades to data capacity that will occur through the introduction of new network architectures will provide many opportunities for the manufacturers of GaAs devices. They can aim to increase their sales of products that receive cellular signals in wireless base stations, are deployed in backhaul networks that aggregate the data, and featured in wired networks, which transport data to homes or enterprises and distribute this within the premises.

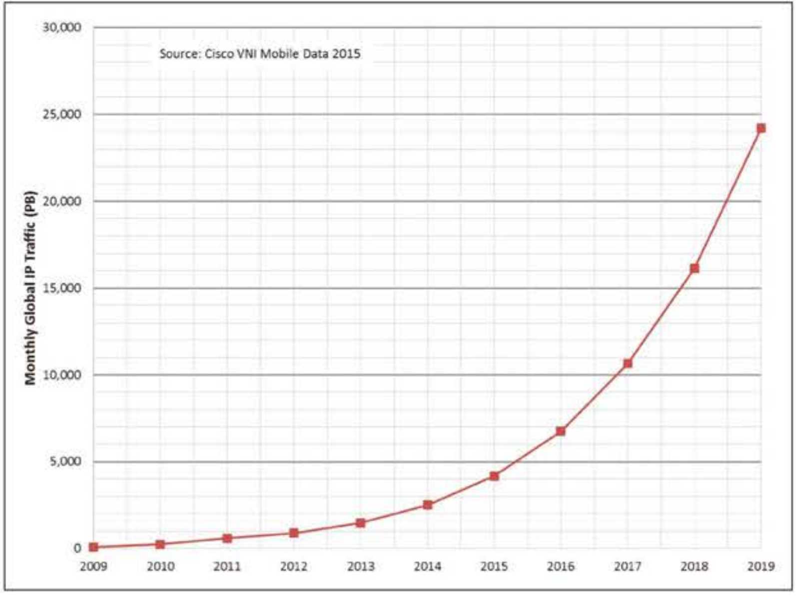
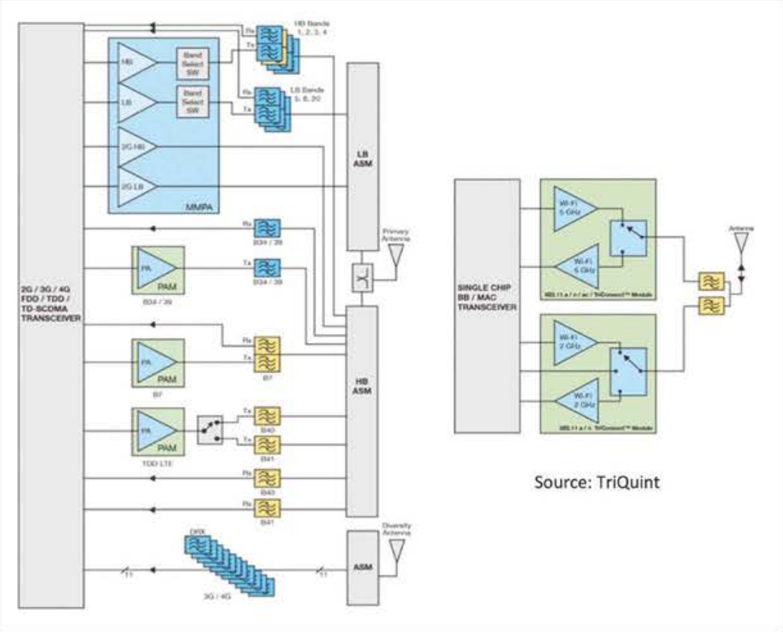


Figure 3: Mobile data traffic is increasing at a compound annual growth rate of 75 percent, according to Cisco Systems.

However, the single largest compound semiconductor opportunity comes from consumer cellular devices. Although mobile phones are the dominant wireless device of today, there are other opportunities that come under the 'cellular' umbrella, which have arisen due to the growing importance of applications such as tablets, e-readers and machine-to-machine communication.



Source: TriQuint

Figure 4: Today's typical smartphone contains many amplifiers, filters and switches for several cellular bands, along with Wi-Fi capability. Shown here is a mobile phone architecture for TriQuint, which merged with RFMD at the beginning of 2015 to form Qorvo.

Part of the reason why the cellular terminal market is so important to GaAs chipmakers is the volume that it offers – we estimate that 2.4 billion cellular devices were sold last year. That's not the full picture, however, as others factors are also at play in this industry. They are associated with efforts by operators to build more capacity into networks, by buying more bandwidth and deploying more LTE networks that offer higher data rates. Today there are more than 40 approved LTE bands that range from 700 MHz to 3.8 GHz, and operators also have to support legacy users on existing 2G/3G networks with different modulation schemes. From the perspective of a carrier, a 'world-phone' is wanted that accommodates all the regional frequency bands and modes, because this minimizes the number of different phone variants that have to be tracked.

The wide range of frequency bands and modes has prevented the semiconductor industry from introducing a single power amplifier that handles all the requirements. Instead, handsets tend to be equipped with a few amplifiers covering multiple bands and multiple modes. This results in a mobile architecture that contains many amplifiers, filters and switches for several cellular bands, along with Wi-Fi capability. This is good news for the chipmakers, because there is significant RF content in each smartphone (see Figure 4 for a representative block diagram from a leading maker of power amplifiers).

Thanks to the high degree of RF content in the handset, and sales of billions of them every year, revenue from the cellular sector accounts for more than half of all GaAs sales (see Figure 5). And if other wireless applications, such as Wi-Fi, wireless infrastructure, backhaul and VSAT are included, the wireless portion of GaAs device sales can account for 80 percent of total revenue. Meanwhile the military market, dominating GaAs revenue in 1995, now accounts for a tiny proportion of sales.

A shifting supply chain

Given the heavy dependence of GaAs device revenue on wireless applications, and in particular cellular, it is of no surprise that the largest GaAs device companies are those that are most closely associated with cellular devices. The four biggest device companies in 2014 were Skyworks, RFMD, TriQuint and Avago Technologies; and along with the largest pure-play GaAs foundry, WIN Semiconductors, they accounted for nearly 68 percent of GaAs device revenue. The top four companies for GaAs device revenue have not changed for several years, although there has been a tussle between RFMD and TriQuint for second-place.

The stasis at the top of the GaAs device-manufacturing pyramid belies what appears to be an accelerating trend of consolidation. This is seen in the 'merger of equals' that took place earlier this year: The marriage of RFMD and TriQuint to form Qorvo. A very top-heavy industry has resulted, and if 2014 revenue from TriQuint and RFMD is attributed to Qorvo, then between this firm and Skyworks, they account for 55 percent of last year's GaAs device sales.

Additional consolidation in the GaAs device industry includes: the acquisition of long-time industry stalwart, Hittite Microwave, by Analog Devices; and Avago Technologies expanding its presence by buying LSI Logic, and aiming to add Broadcom – the later is waiting for approval. Although the Avago activity will not make a big impact on its GaAs activity, these moves offer an interesting glimpse into the direction of that company. While it may appear that acquisition and consolidation is bigger than ever, it has been a staple of the GaAs industry since its inception.

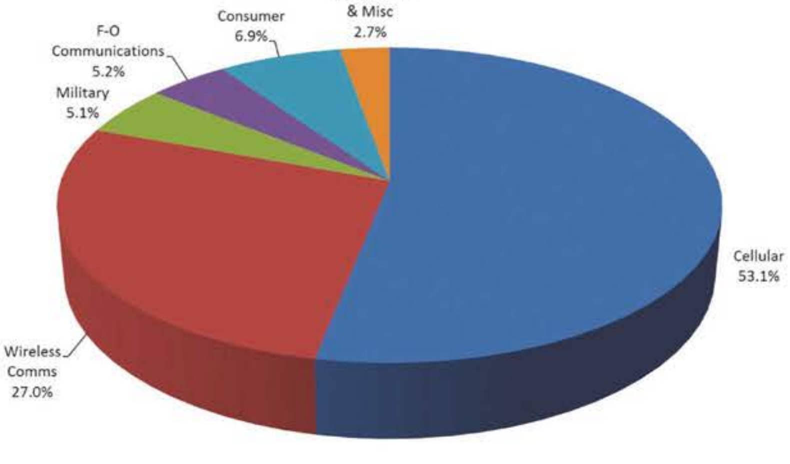


Figure 5: The majority of GaAs device revenue comes from the cellular sector.

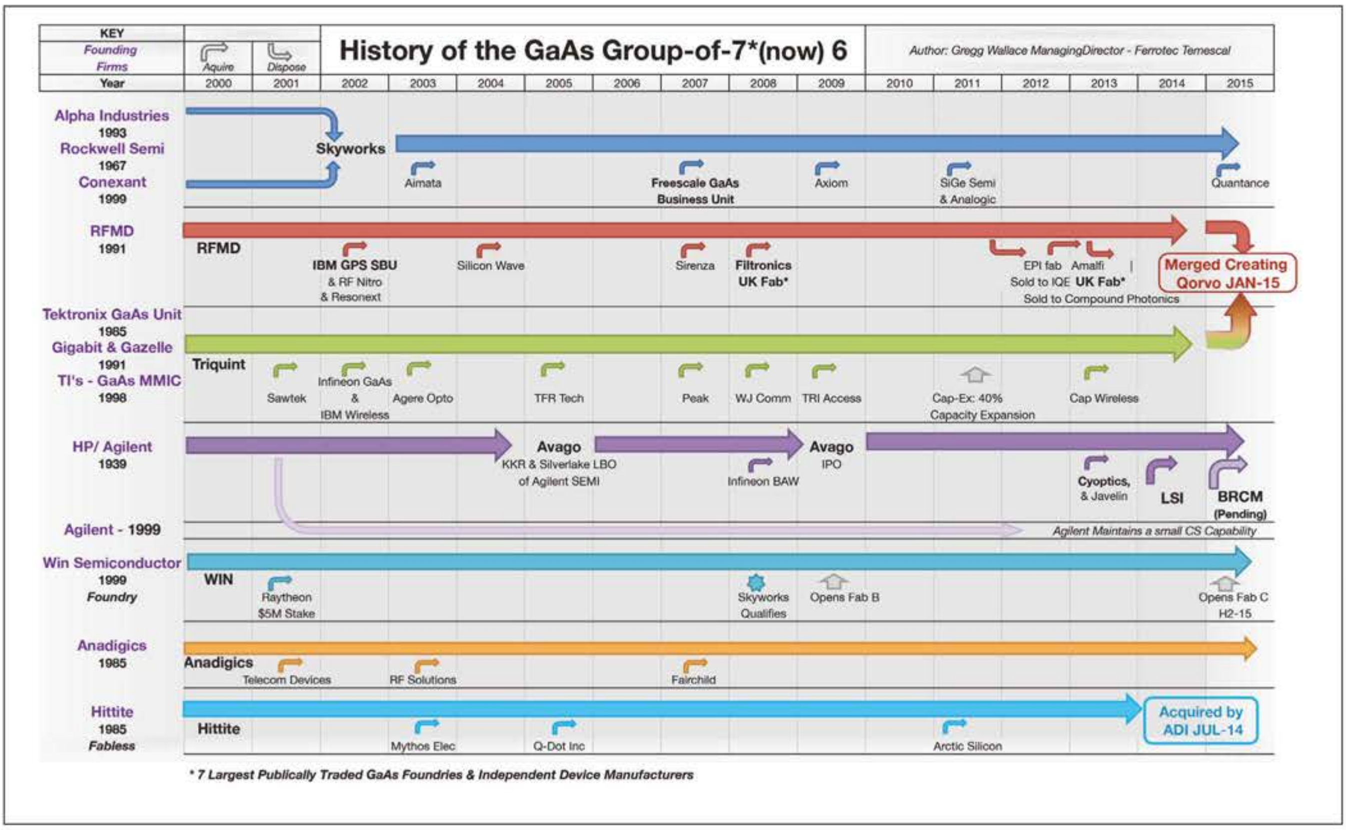


Chart compiled by Gregg Wallace of Ferrotec Temescal.

Figure 6: Since the turn of the millennium, there has been significant consolidation in the GaAs Industry.

This point is illustrated in Figure 6, which tracks the history of what were the seven largest publically traded GaAs device manufacturers. This chart reinforces the idea that GaAs development activities existed prior to the 1990s, and it also shows how the main players in the industry consolidated to acquire capability and reach scale as commercial applications have grown.

Those within this industry are now working feverishly to make the promise of 5G a reality. This communication standard is not well defined, but it promises to allow us to enter a mobile era where 'any place' and 'any time' are joined by a third attribute – 'any amount'.

History attests, in the form of the GaAs market of 1995, that it is important to continue developing manufacturing, test, process and design capabilities to realize the vision of 5G. What is encouraging for GaAs is that the network requirements that are under discussion seem to line up well with the performance advantages of this technology, so the emergence of 5G could propel chip sales to a new level.

During the lifetime of *Compound Semiconductor* magazine, the GaAs device evolved into a mature, dominant technology for most RF applications. However, this industry must not rest on its laurels. There will always be challengers to GaAs device revenue, and currently they are coming from various directions, due to developments associated with GaN, SiGe, InP and silicon CMOS technologies.

The introduction of new system architectures and performance requirements will provide challenges and opportunities for the industry, but the future looks very bright. For that reason, I look forward to future developments in the GaAs industry, along with continuing excellent, insightful coverage provided by *Compound Semiconductor*.

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Tracking CPV

Richard Stevenson quizzes NREL principle scientist Sarah Kurtz on the progress of CPV, the false dawns of this technology, and what must happen for this technology to truly take off

Q Twenty years ago, when the first issue of *Compound Semiconductor* went to press, there wasn't a CPV industry based on multi-junction cells. But research into CPV systems was under way. Who were the pioneers, what were their accomplishments, and what was the state-of-the-art at that time?

A Twenty years ago it was all silicon based. We had companies like ENTECH , which was one of the leaders for a low-X silicon concentrator. And Amonix was a leader for a high-concentration silicon concentrator.

Q What were the types of cells and the concentrations being used in those prototype systems?

A ENTECH was doing something on the order of 20X. There was another company called PV International that tried to launch something that was more like 7X,

Back in early 2009, the global financial crisis made it very tough for many of the fledgling CPV companies seeking to raise further investment. This included GreenVolts, which at that time was building a 2 MW CPV plant in Tracy, California. Fast-forward three years to 2012 and the company was laying off most of its staff and looking for a buyer of its assets or technology.

but that never got to the point of hundreds of kilowatts. Amonix then was using more like 200X, and they did get that deployed to a total of approaching 10 MW – it may have been 7 MW or 8 MW; I'm not sure what the final count was.

Q What were the key breakthroughs made by researchers in the late 1990s and early 2000s to enable CPV to be considered as a possible commercial solar technology?

A I think that the excitement that came with CPV was when the multi-junction cell passed 25 percent [efficiency], and then in the early 2000s as those crept up passed 40 percent. That inspired a whole different approach and attitude. If the cell efficiencies are comparable, then the advantage is only in terms of being able to use less semiconductor material. This is still a very valid approach, but this doesn't have quite the same level of excitement as when you are looking at module efficiencies that will eventually be 40 percent, and are now about 35 percent.

Q Which companies played a leading role in moving CPV from the demonstration of a technology to fledgling industry?

A Amonix was the first company to demonstrate multi-megawatts with silicon. They were also the first company to demonstrate [large-scale systems with multi-junction cells], they put in a 30 MW plant in Alamosa, [Colorado]. So I would say that they were a real leader. Soitec is then following after Amonix, and has surpassed its early lead. At this point in time Soitec would be considered the leader.

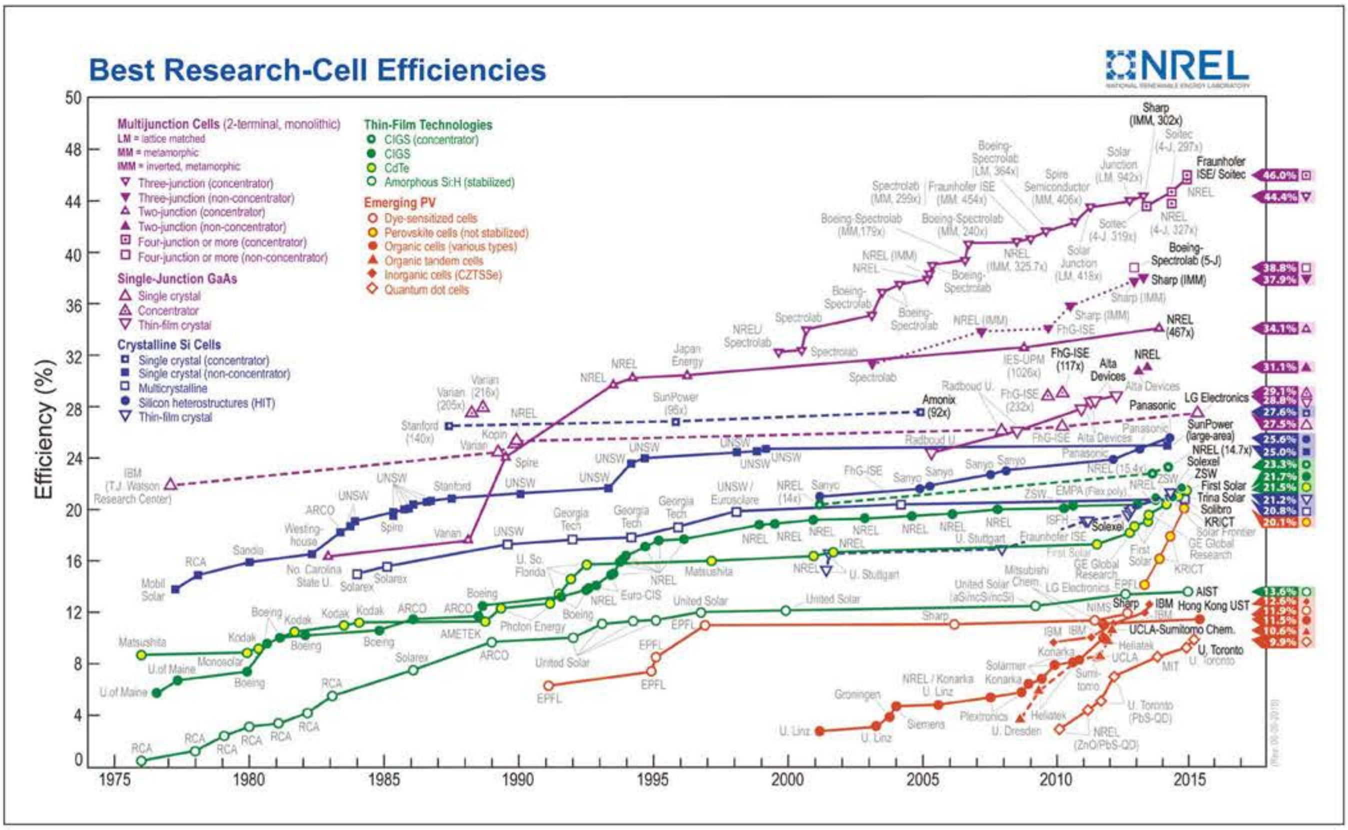
Q Towards the end of the last decade, the CPV industry suffered from a double whammy of plummeting prices for silicon PV and the global financial crash. Had neither of these occurred, do you think there would be a substantial CPV industry by now?

A If a CPV company had been ready to launch at the time when there was the silicon shortage – what you saw was that First Solar grew into that void – I'm fully convinced that they would have grown just as First Solar grew.

Q What lessons have been learnt from the failure of many players in CPV?

A I think the challenge of the scale-up being quite formidable is a lesson that is learned. [Another is] the need for a large investment in order to get over that hurdle – I'm not sure that it brings that hurdle down, but to understand that hurdle is high may help some companies plan.

Q How do you feel about the tough times that the CPV industry has faced?



In the 1990s, efficiencies at high concentrations for multi-junction cells surpassed those for silicon, igniting greater interest in this form of solar technology. Since then, cell efficiencies have continued to climb, with the current record standing at 46 percent for a four-junction cell made by Soitec.

A It is so sad to lose all the different companies, and the different approaches, when we haven't really figured out which approach works best.

Q In terms of cell architecture, what do you consider to be the big breakthroughs of the last 20 years?

A Solar Junction making dilute nitrides with antimony has laid out a path to high-efficiency multi-junction cells, but the metamorphic multi-junction structure is also laying out a path to be able to reach very high efficiencies. Soitec just announced another record efficiency, but whether the bonded approaches will yet take off is not yet clear. So those are three different approaches to the high efficiency, and they all are very promising, and which of them will turn out to be a winner in the long run is not clear to me.

Q Has the design of modules and tracker systems improved significantly during the last two decades?

A Certainly. Some of the biggest increases in efficiency in modules have come from improvements in optical design. There were a few years in particular where all the improvements were coming from that.

The tracker systems: It's such a straightforward technology in that it's not rocket science, but it definitely needs optimisation. In my observation, they are making progress.

Q Both lenses and mirrors have been used to date to focus the sunlight in CPV systems. Is one form of optics going to dominate in the years ahead?

A Whether lenses or mirrors will dominate is definitely still a fascinating topic. What I have observed was that in the US, back in the 1980s, they came to the conclusion that mirrors could not be used. So all of the investment for a number of years in the US was focused on lenses, whereas in other countries much of the work was focused on mirrors.

So it is fascinating to me that the decision that was made, based on the work that was done under the Department of Energy funding in the US, really split the directions of the community. There are advantages to both the lenses and to the mirrors, and in my mind it is not clear yet what direction it will go.

Q What are your thoughts on the suppliers of multi-junction cells today? Are there enough chipmakers that produce devices of sufficient quality to support a ramp in shipments of CPV systems?

A People have been worried about this for the last decade or so. I have told them that we have far too many cell suppliers. It is very difficult to believe that we could end up with a shortage of cell suppliers – there are so many different companies that would be capable of doing that, and would be able to ramp up. It is so easy for them to ramp up. The technology is now so well developed, and has so many different options.

The problem right now is that we don't have the business for them, so they are not going to invest. If we are trying to split a market that is not big enough for one company, and we're trying to split it between multiple companies, none of them will have a sustainable business model.

Q Since the birth of the CPV industry, is it now harder than ever to raise cash?

A Yes, by far. It is partly because there have been so many PV, thin-film companies and some CPV companies, and so many of them have been unsuccessful. The profit margins are now so small.

In the silicon space, silicon has moved so far down its learning curve that it is very difficult to compete with it. So the amount of funding that you need to get the scale up that is needed to get the price down to compete with silicon is very big. The biggest hope that the CPV industry has at this point in time is if we could develop another shortage of silicon, as happened once before. Then CPV could grow into that, and in that case they would be able to grow easily. But without that, it would take a company with very deep pockets to be able to get this over the hurdle.

The question is: Will one of today's companies demonstrate the technology, and the confidence in that, that a company with deep pockets would be willing to put money in and scale it up? Or will somebody come up with an approach that allows you to find an entry market, that allows it to be sold at a higher price as you make that transition?

The C7, [a system by SunPower that has been reported to have a 3 GW pipeline], is in my mind potentially one of the biggest developments that has happened in the last five years. It's almost like a big secret. I'm not sure how far along, or whether it could run into snags, but certainly the plans Sunpower has for the C7 are pretty spectacular.

Q A substantial proportion of CPV technology has been developed in Europe and the US. However, in recent times Chinese companies have acquired Emcore's CPV division in Albuquerque, the CPV part of Soitec, and the assets on Concentrix. So is the future of CPV now in Chinese hands?

A I think the future of CPV is in the hands of a company with deep pockets who is willing to make the investment. It is not clear to me that the Chinese companies have both the financial and technical capabilities to pass over that hurdle.

It's very clear to me that the CPV industry has the potential to be a major player within the industry, but the investment that will be needed to be taken to get from here to there will be substantial. It's not going to be done by a small company. It may start as a small company, but eventually it's going to have to have a very large company behind it to be able to be successful. Whether that is a Chinese company or a US company or a European company I don't know. All I know is that they'll have to have deep pockets.

Q Where could CPV be in 20 years' time?

A If there is a shortage that develops that allows an opening for CPV to grow into, I think it could be a substantial player in the locations that are hot with clear skies. A second scenario is that the C7-type approach may turn out to be a very important technology, and a third possibility is that it will lose all of its current people, and the multi-junction technology will be mostly used in space, including CPV in space.

> “A substantial proportion of CPV technology has been developed in Europe and the US. However, in recent times Chinese companies have acquired Emcore's CPV division in Albuquerque, the CPV part of Soitec, and the assets on Concentrix. So is the future of CPV now in Chinese hands?”

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ANALYST ○ **Eric Higham - Strategy Analytics**
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- **Duncan Pilgrim – Peregrine Semiconductor**
  CMOS: Game on!
- **Peter Gammel – Skyworks Inc**
  Technology requirements and initiatives for 5G smartphones
- **Takahisa Kawai – SEDI**
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ANALYST ○ **Pallavi Madakasira – Lux Research**
Hype versus reality: driving adoption of wide band gap power electronics

SPEAKERS

- **Peter Ward - Anvil Semiconductors**
  Driving down the cost of SiC devices for consumer applications
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  GaN on silicon – a truly revolutionary semiconductor technology matures
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  GaN normally-off devices for highly efficient power switching
- **Speaker TBC – Laytec**
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Exploiting opportunities for LEDs and lasers

Can LED bulbs meet the most demanding lighting applications, such as those found in the retail sector? And what are the opportunities for infrared and ultra-violet LEDs?

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Opportunities for IR LEDs

SPEAKERS

- **David Cheskis – Anadigics**
  6-inch VCSEL wafer fabrication manufacturing advances
- **Augustinas Vizbaras – Brolis Semiconductors**
  Mid-infrared light sources: manufacturability and applications
- **Paul Crump - Ferdinand-Braun-Institut**
  High-power, high-efficiency lasers for fiber lasers and other markets
- **Reinhard Windemuth – Panasonic**
  Presentation title TBC

Making heterogenous integration a hit

III-V channels are poised to make an introduction in next-generation logic circuits. But how will they be introduced, and what impact will they have?

KEYNOTE ○ **Yanning Sun – IBM**
III-V/Si integration: Moore and more

ANALYST ○ **Nadine Collaert – IMEC**
Heterogeneous integration of high mobility materials on a 300mm Si platform

SPEAKERS

- **Suresh Venkatesan– POET Technologies**
  A comprehensive technology platform for opto-electronic integration
- **Lukas Czornomaz – IBM**
  Hybrid IIIV/SiGe technology for CMOS and beyond, opportunities for 3D monolithic integration
- **Thomas Uhrmann – EVG**
  Heterogeneous integration enabled by advanced wafer bonding

Capturing light, generating cash

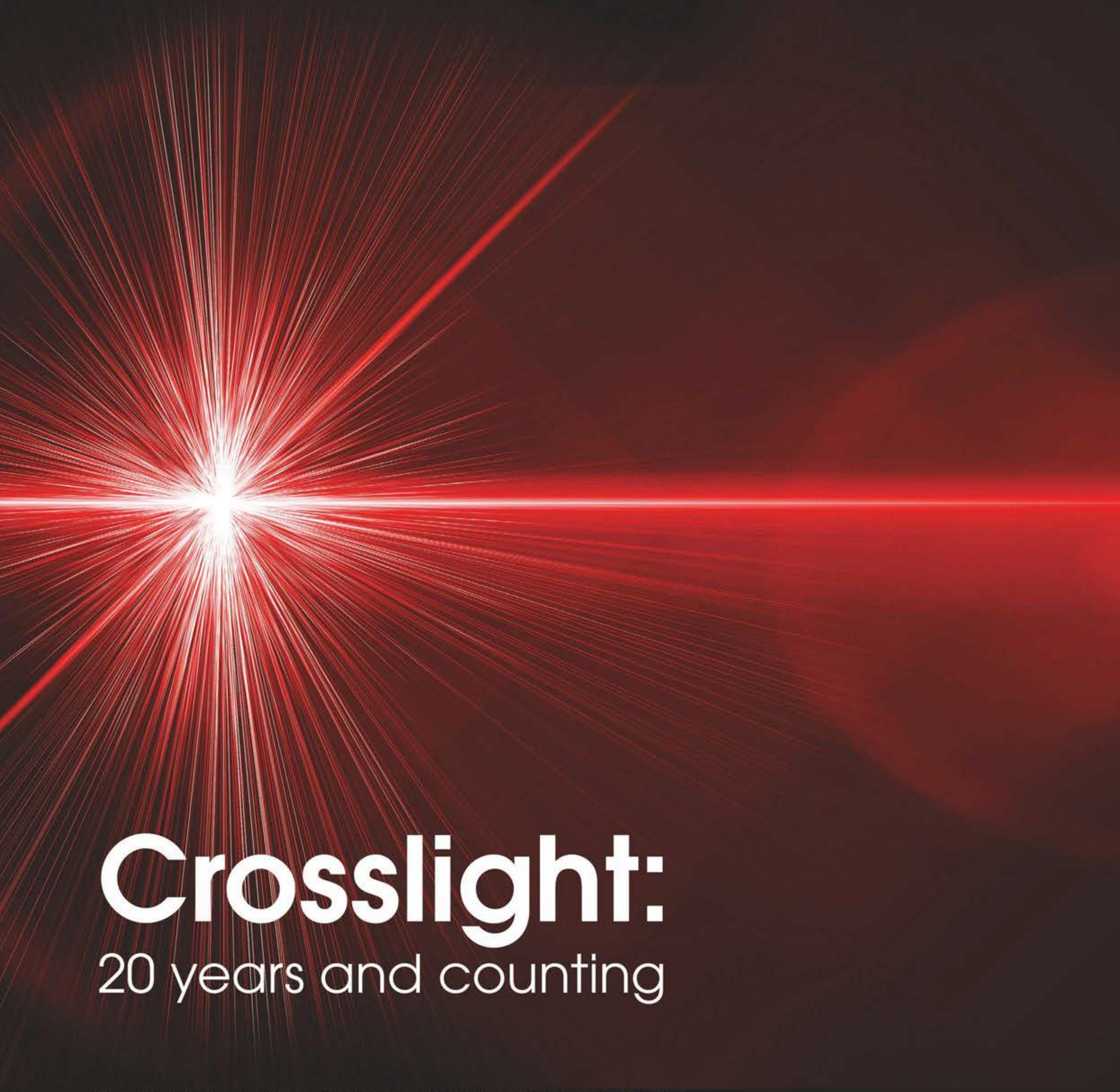
What is needed to kick-start significant deployment of concentrating photovoltaic technology? And what are the opportunities for III-V detectors operating in the infrared?

KEYNOTE ○ **Carlos Algora – Technical University of Madrid**
Perspectives of concentrator photovoltaic technology

ANALYST ○ **Frank Dimroth – Fraunhofer ISE**
Terrestrial III-V solar cells - challenges and opportunities

SPEAKERS

- **Paul Sharps – Solaerotech**
  High efficiency multi-junction solar cells - what's next?



Crosslight:
20 years and counting

Founded on the promise of delivering a superior tool for modelling laser diodes, Crosslight has blossomed into a provider of a range of software for understanding III-V technologies

1995 WILL GO DOWN IN HISTORY as a year when entrepreneurs made lasting contributions. For those in the aviation industry, it will be remembered for the launch of budget airline Easyjet by Greek Cypriot businessman Sir Stelios Haji-Ioannou; and for those working in pharmaceuticals, it was the year Indian law and commerce graduate Sanjiv Goyal founded NecLife, a maker of generic medical products for the US and Europe that is now employing more than 2000 staff.

In the compound semiconductor industry, success stories from this year might not be as big – but they have, without doubt, made a lasting impression. 1995 was the year that Marie Meyer produced the inaugural issue of *Compound Semiconductor* magazine; and it was the year Simon Li founded Crosslight, a pioneer of laser diode modelling software.

Since then, this Canadian firm has made many important contributions to our industry: It has trailblazed the modelling of lasers with quantum wells rather than double heterostructures; it has produced software for simulating VCSELs and integrated circuits incorporating III-Vs; and it has been a fervent supporter of NUSOD, by far the most important conference for the simulation and modelling of optoelectronic devices.

Getting going

Li began his life in China, studying Electrical Engineering at Zhongshan University and graduating at the age of 20. "At that time," says Li, "China was under Mr Deng Xiaoping, a man who opened up trade to the outside world."

What that meant for the most talented graduates of that time, including Li, is that they no longer had to study for higher degrees in China, but could head overseas. Numbers were limited for physicists, with selection based on the marks obtained in an exam. This was organised by Columbia University academic Tusng-Dao Lee, China's first winner of the Nobel Prize for Physics, for his work on the violation of the parity law in the weak interaction.

Li passed the exam, winning one of about 100 places for physics students. So, in 1982, he left his homeland for Vancouver, hoping to satisfy his interest in high-energy physics.

However, Li didn't get the chance to study the interactions of fundamental particles. "The government of Canada said that students should mostly work on experimental physics, because that is what China needed at the time," explains Li. He specialised sputtering, but didn't get very far as an experimentalist. "If a piece of equipment broke down and I

Crosslight has kept track of its sales, with products being bought from companies all over the world.

had to wait, I'd start to work on an optics problem." This suited him, as he had more success writing lines of Fortran than working in the lab.

One downside of this shifting of the emphasis of his research is that it spawned a thesis lacking a clear, coherent thread. "By the time I got the PhD written up, the examiners were confused. They didn't really know if the thesis was about sputtering, experimental physics, or optical problems." Fortunately, he convinced them that the various elements of his work were intertwined, allowing him to leave the university in 1988 with a Masters Degree and a PhD.

Li's sputtering expertise nearly landed him a job with the data storage firm Seagate Magnetics. However, he could not get a visa, so instead of moving from Vancouver to the US, he headed east to Ottawa, taking up a position at the National Research Council of Canada (NRC).

"I did a little bit of sputtering, but my group found out that I did very well with coding and modelling," says Li. His boss understood Li's strengths and put them to good use. So great was the research that followed that after one year of Li's two-year temporary post of research associate, he secured a permanent staff position.

Starting up

Although this gave Li a comfortable life as a scientist, he did not have high hopes for the future. He wanted to rise through the ranks, but knew that there were poor prospects for foreign-born researchers. Recently, one of his peers, Chander Gover, had been denied research funds, summer student assistance, and approval for conference participation (Gover took the NRC to a tribunal, winning the case in 1992, with the employer fined for discriminating against him on the grounds of race, colour and national origin).

By 1993, Li started to mull over the idea of starting his own company. "I didn't know anything about getting seed funding, getting licensing, or anything like that … [and] I didn't know if the idea would work." But he did start to plan for a possible launch: he wrote to authors of academic papers, asking if they would be interested in using his laser diode software; he started to squirrel away his earnings to fund a venture, amassing $20,000; and encouragingly, he managed to make his first sale, an order worth $3000 from the University of Tampere, Finland.

Li's success would hinge on winning more sales of his software for quantum well laser diodes. To succeed, he would need to set himself apart from his rivals – and he believed he could do this: "I was the first to put the modelling of the optical gain in the quantum well into a drift-diffusion solver." The two biggest challenges that he had to overcome to construct his code were: modelling the transport of carriers across a heterostructure; and providing data to describe the characteristics of compound semiconductors, which vary according to alloy composition. In comparison, the models made by Li's peers were analytical, and failed to include a drift-diffusion component.

Researchers often write code that is used just by them, so they don't need to make it accessible to others. But Li is of a different mindset – even in his days as an experimentalist, he took an approach that his colleagues could follow. "I started to make some forms that people in the lab can use," recollects Li. "You can think of it as a simple user interface."

It is not surprising, therefore, that the laser diode program he designed was very user-friendly. And to help the researchers make best use of it, the software includes a question and answer feature.

By 1995, Li had built up enough confidence in the venture to take the plunge. But to do so, he needed a license for the software. He overcame this obstacle, striking a deal with the NRC, and took leave without pay. Initially, he rented a 400 square feet of office space in a local business park.

At that time Li often wondered whether he could make enough money to survive. So, to give him the best possible odds, he responded to customers as fast as he could, regularly putting in 15-hour days. It did not take long to reap the rewards, and within two months Li had hired James Wu, an electrical engineer, to respond to swelling interest in the software.

Li's program was designed to run on Unix, because that was the type of machine owned by the NRC. But this limited potential sales, because many researchers worked on Sun stations. To right this wrong, Li hunted through advertisements, trying to pick up one of these machines for as little as possible. "Once I had that, I had to buy the Fortran compiler. They are not really universally available, so I had to look around."

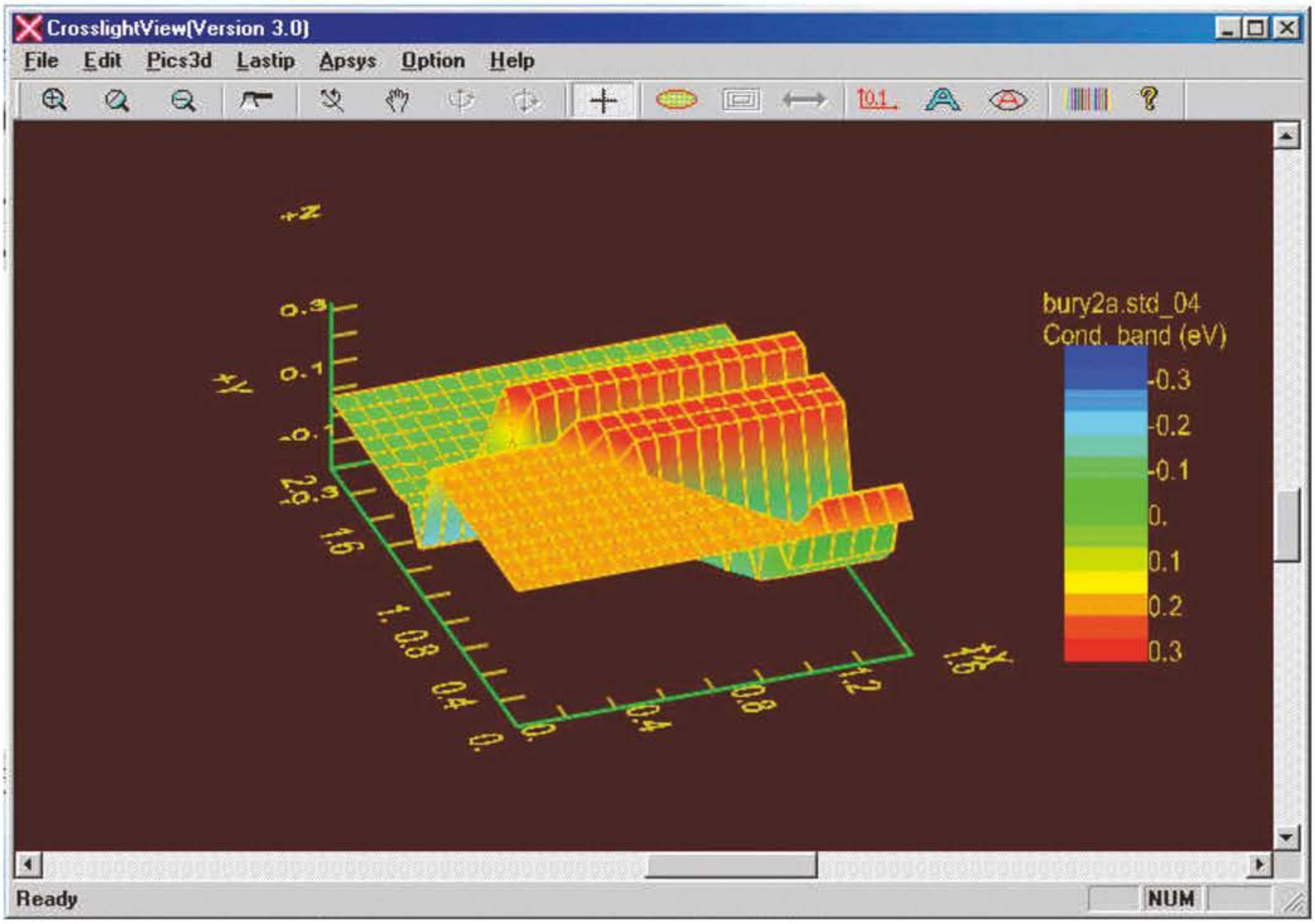
Linux then came out, forcing Crosslight to adapt its laser diode software once again, while trying to support customers as much as it could. "I recall that some people didn't want to install [Linux] themselves," says Li, "so I bought a PC and installed it on it. Somehow, when it passed US customs, they took it all apart. The customer was very mad. He returned the whole thing to Canada."

With a price tag at the time of $20,000 to $25,000, it was tough to persuade purchasing managers to invest in the software. So, to convince companies of the benefits of this modelling tool, Crosslight offered customers a two-month free trial. After this evaluation period, Li would leave the sales manager, Richard Rembaran, to tie-up the deal. His lack of a science background meant that he had very little knowledge of laser diodes – but his friendliness and ability to get on well with scientists and engineers meant that during his time at Crosslight – 1996 to 2001 – he had great success in this role.

Expanding the business

Rarely can a company survive and succeed on a single product. So Li directed efforts at expanding the product line, extending the capabilities of the existing software from handling two dimensions to three.

"At the time I had the opportunity of working on VCSELs," explains Li. "You



In the early years of Crosslight, a great deal of effort was devoted to improving the graphical user interface of the simulatrion software. By 1999, versions that coud run on 'Windows' were available.

can think of the VCSEL as a three-dimensional problem, because of the coupling of the longitudinal mode with the electrical current."

Back then sales of Crosslight software, particular in the US, were held back by a lack of a graphical user interface. To address this, Li hired some software engineers. He couldn't afford to recruit in Canada, so he started an operation in China, taking on a handful of employees from 1997. "Very few people knew how to make a graphical user interface program, but it didn't matter – I trained them."

Another milestone for Crosslight was the moving of its headquarters from Ottawa to Vancouver in 2001. Li preferred the climate on the west coast, and a location that is better suited for travelling to Japan and China, countries that account for a high proportion of Crosslight's sales.

At that time the software house had grown to 25 employees, sold its products to big-name firms such as Lucent Technologies, Nortel Networks, JDSU and Samsung; and its revenue, growing at around 30 percent per year, had hit $4 million. Since then, Crosslight has had further success, including establishing an office in Japan in 2002. This led to savings, with the elimination of agency commission fees.

One triumph from this era was the role Crosslight played in the launch of the NUSOD conference. Li had the idea for launching a modelling of optical devices conference that would have at its heart the delivery of tutorials for Crosslight software.

> "With a price tag at the time of $20,000 to $25,000, it was tough to persuade purchasing managers to invest in the software. So, to convince companies of the benefits of this modelling tool, Crosslight offered customers a two-month free trial"

This led Li to cofound NUSOD with Joachim Piprek, who was also keen to teach others how to make best use of the software. "In his own words, Lastip and Pics3D were the only programs that allowed you to do anything," says Li.

This freedom resulted from a material library that sits outside the program, allowing modellers to change material characteristics, such as bandgap and effective mass. Another highlight in the history of Crosslight came in 2005, when the company licensed process simulation software developed at the Integrated Circuits Laboratory of Stanford University.

"It was a difficult start, but now we've got it rolling out after ten years," says Li, explaining that the biggest challenges were to extend the simulator from two-dimensions to three, and to enable the software to cater for compound semiconductors.

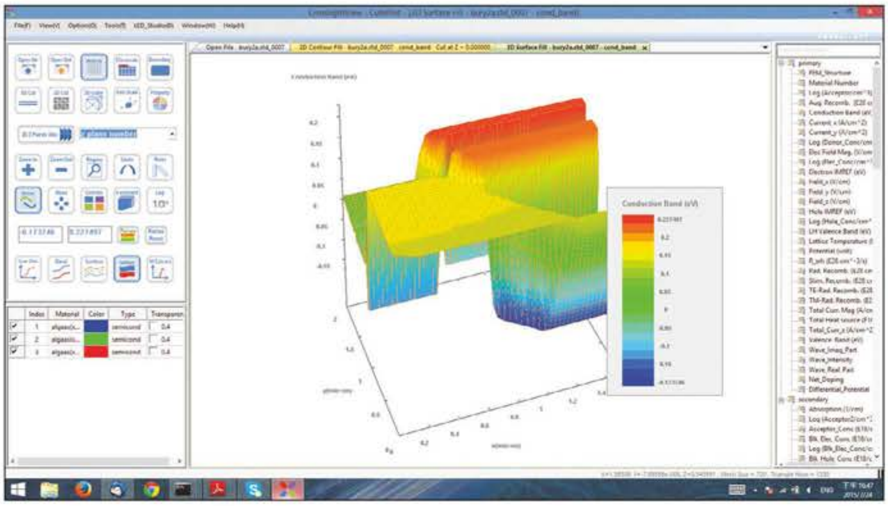
It is virtually impossible for any long-running company to have success in all its ventures. With Crosslight, it is the simulation software for MOCVD reactors that has failed to recoup its investment. Li hoped that epitaxial process engineers would buy this modelling tool, but the only interest came from the makers of MOCVD reactors.

Given the recent explosion in sales and shipments of LEDs, one would expect that Crosslight's software for modelling this particular device could deliver tremendous success. However, that's not the case: Technology computer-aided design software developed by the company includes terms related to diffusion, implying that it cannot account for the controversial, energy-sapping malady known as droop. "If you don't understand it, you can't model it. And if you can't model it, people are not going to buy your programs."

To grow sales, Li is now directing his company in the development of software for modelling power electronic devices, such as GaN HEMTs. "The simulation can predict more, because the physics is better known, compared to droop."

Such a move will be a significant step for Crosslight, which, for the last 20 years, has focused on modelling optical products.

"Maybe the name Crosslight is no longer appropriate," muses Li, "so maybe a name change, or call it Crosslight Compounds."



Today's software has an interface that is more sophicticated than that from 1999, but it has elements that can be traced back to its forerunner.

Improving reliability… the journey so far

The dot-com boom and the explosion in handset sales have ramped up the production of GaAs chips, and enabled their reliability to rival those made from silicon

BY BILL ROESCH FROM QORVO

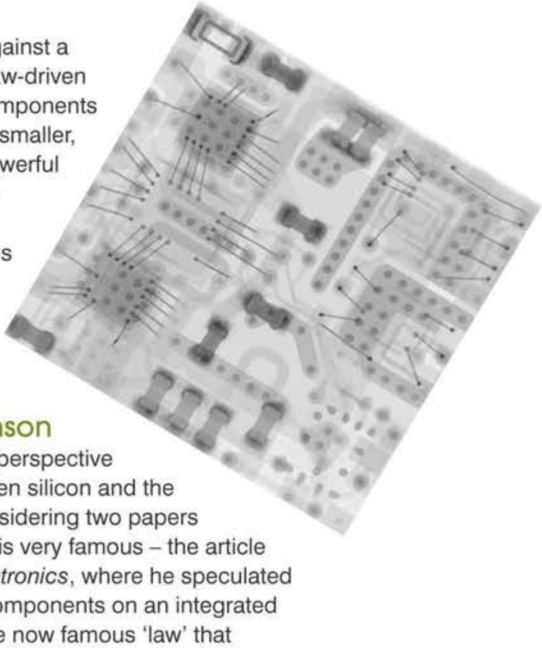
IN SEMICONDUCTOR FABS EVERYWHERE, there are engineers that are amassing and tormenting the ghostly skeletons of cell phones. The handsets that they interrogate have no cases, no screens, no processors, no memories, no batteries – they are just a vacant shell of the phone's radio section, often containing only a single piece of what wonderfully connects the phone to the rest of the world.

It is in these laboratories of torture that engineers evaluate nearly every type of component that makes a phone mobile; from switches, to filters, power amplifiers and everything in between. One dark truth of semiconductors, exposed and interrogated in these stress facilities, is that eventually even the very best products wear out. How long the integrated circuit can survive, however, is not the sole concern of the engineer – recently, they are also focusing their attention on the very small fraction of devices that could fail unexpectedly early.

For the compound semiconductor chips that lie at the heart of many mobile phones, amplifying signals that are transmitted to the local base station, the reliability journey has taken the same path as that for silicon, albeit with a delayed start.

One of the biggest challenges for any engineer trying to fully comprehend the reliability of III-V products is that it is deceptively difficult to understand circuit degradation. That's because it doesn't just depend on how customers use a product, but also on the intrinsic properties of each part – what it is made of and how those materials respond to wildly varying conditions. In addition to the materials; the package, the method of fabrication, the design, and the lay-out of the circuit can all influence reliability. Complicating matters further, it is getting tougher to estimate a product's infant fallout.

These difficulties arise against a backdrop of a Moore's-law-driven age, where electronic components are expected to get ever smaller, lighter, cheaper, more powerful and more efficient. To do this, studies are made, considering new materials and design techniques. All of this is great for innovation, but it can be terrible for reliability.



Moore versus Johnson

An interesting, insightful perspective on the differences between silicon and the III-Vs can come from considering two papers from 1965. One of these is very famous – the article by Gordon Moore in *Electronics*, where he speculated about cramming more components on an integrated circuit, and discussed the now famous 'law' that began the microminiaturization age. Lesser known is the piece by Edward Johnson in his company's *RCA Review*, where he discussed a figure of merit in the paper *Physical Limitations on Frequency and Power Parameters of Transistors*. Johnson argued "an ultimate limit exists in the trade-off between the volt-ampere, amplification, and frequency capabilities of a transistor". Like Moore, he had a theory that aimed to predict trends of future semiconductor developments.

Although there is not even a single mention of reliability in Johnson's publication, there is no doubt that he predicted that silicon devices deliver a superior performance to those made from germanium. One of the ingredients in the figure of merit is the bandgap, which accounts for claims that GaAs performs better than silicon, but is outclassed by GaN.

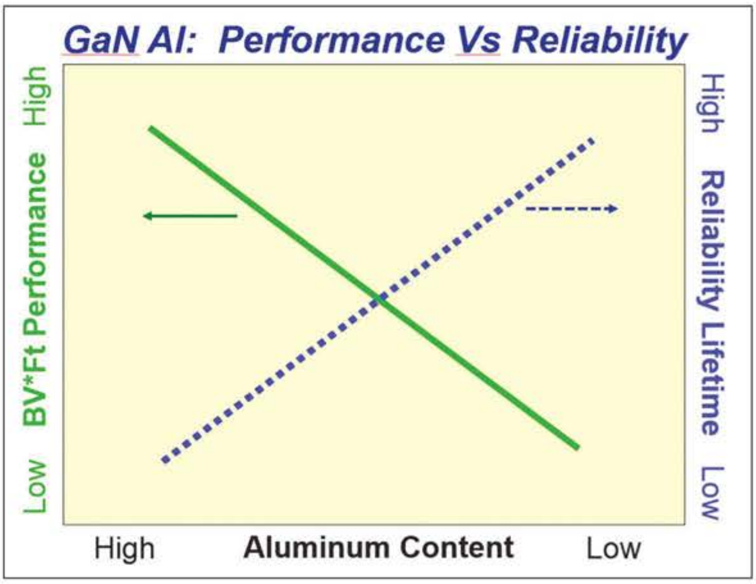


Figure 1. Performance versus reliability trade-offs caused by aluminum content in GaN.

Meanwhile, in Moore's paper reliability was prominent. He may have been fixated on cost, but he did discuss material performance aspects, writing: "Silicon is likely to remain the basic material, although others will be of use in specific applications. For example, gallium arsenide will be important in integrated microwave functions."

Despite the difference in impact between Moore's Law and Johnson's Figure of Merit, both are referenced 50 years later – with the particular citation depending on the preference for either microminiaturization or performance. However, integration and performance cannot stand alone, because if reliability is missing, the game is over.

From lab to fab

Compound semiconductors are not new. Researchers have been studying and experimenting with the likes of GaAs, InP, and GaN well before Moore and Johnson made their claims in 1965. However, the ensuing decade brought focus on initial reliability for silicon.

At that time, the Japanese had pressed quality to the forefront, setting the bar for automobiles and electronics. Shrinking eventually pushes reliability to the limitations of the materials, so to keep pace with Moore and the Japanese, semiconductor materials had to change. Compound semiconductor folks, on the other hand, were fixated on performance, with material changes underpinning gains in performance. The difference between technologies was cast. Semiconductor companies proliferated between 1975 and 1985. Intrigued by Johnson's performance promises, governments funded GaAs development programmes, helping to create more than a hundred labs throughout the world in the 1980s.

> "Reliability is defined as the absence of failure" Bill Roesch

For those working with silicon, the focus clearly included quality, and at this time GaAs was at least a decade behind – it was still proving viability, while trying to carve out a business niche that could unlock the door to mirroring the growth and profitability of silicon. Fast-forward to 1985 to 1995, and the reliability of compounds attracted attention, with efforts measuring lifetimes and showing that compared to silicon, GaAs was good enough. By now, the silicon industry had pushed through reliability difficulties, and identified the path that GaAs must follow.

For those engineers measuring semiconductor wearout, life was generally straightforward – they would simply stress the device until it fails. The three challenges that they faced were: determining the failure mechanism and degradation that defines a failure; measuring the distribution of time to failure; and understanding what stress is applicable, so that it is possible to evoke the failure mechanism faster than in normal use.

The work of these engineers could begin by obtaining an estimate of life – this is relatively easy, as all that it requires is to stress a single sample until it degrades. Estimating the variation of the lifetimes is not much harder, for it only requires replacing one sample with several. But determining a way to make a device fail faster is more challenging. Success on this front came in 1992, when Bob Yeats, working at Agilent Technologies, showed how to estimate an acceleration factor from a single GaAs MESFET.

The increased emphasis on reliability from 1985 to 1995 made this the decade of catch up for GaAs. Study after study, lifetest after lifetest, and product after product demonstrated adequate reliability for consumer, industrial, automotive, and even aerospace demands.

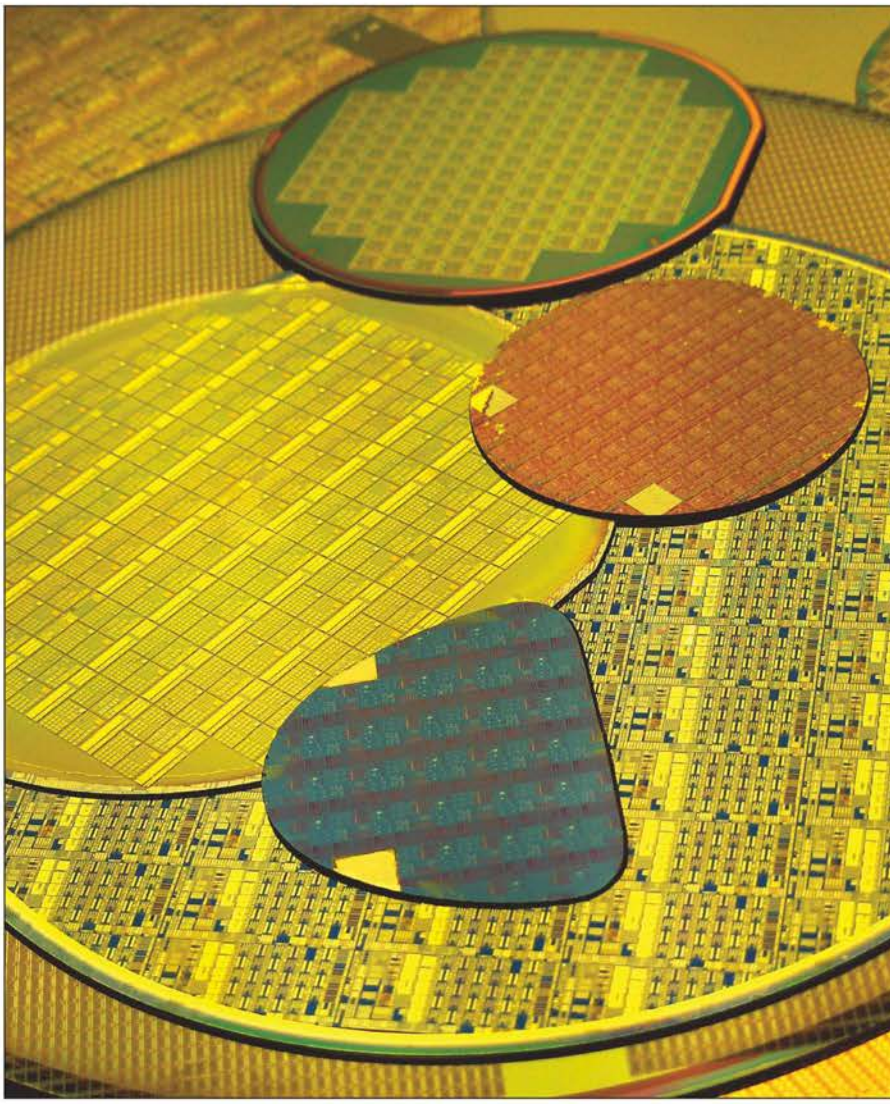
From 1995 onwards, efforts at estimating time to failure were combined with those to determine fallout distributions. Up until then, reliability studies had been limited to sample sizes of 1-100, and torture times of

1-1000 hours. But Walter Poole from Anadigics set an entirely new benchmark for the scale of a study of fallout distribution, interrogating 12,000 samples for 12,000 hours. This helped compound semiconductor labs to emerge as bona fide fabs – but the reliability of silicon wasn't standing still.

1995 was a bell weather year for compound semiconductors. Production volumes reached critical mass, with changes in product packaging arriving just in time. They were needed, because GaAs had been suffering from 'hydrogen poisoning', an infliction that diminished reliability. The incumbent, high reliability hermetic packaging produced an unintended consequence, with hydrogen desorbed from the package absorbed in the transistor, where it impacted device characteristics. These changes in performance were noted in aerospace applications and in long haul fibre channel distribution systems… all caused by hydrogen released from metal (typically kovar) employed on the lid or within connections inside of ceramic cavity packages.

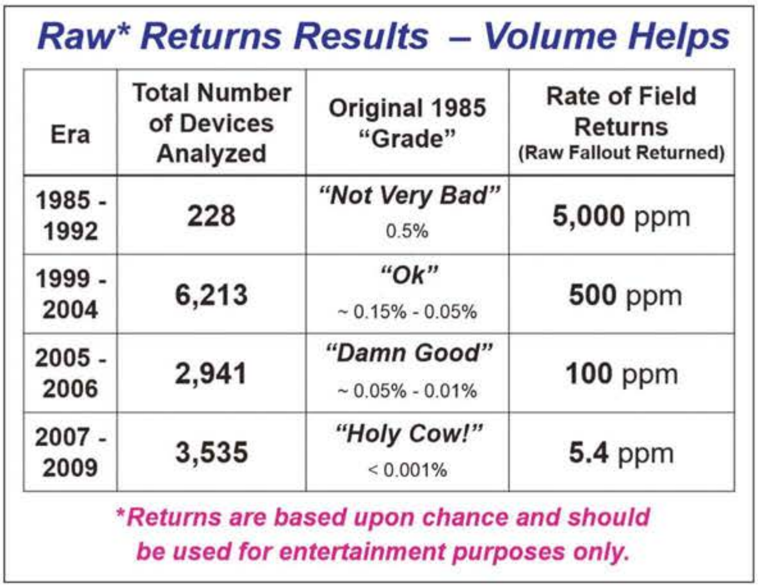
The solution was both obvious and non-trivial. Mainstream silicon devices – both commercial and industrial – had already moved to smaller surface-mount-plastic, epoxy-moulded packages, so switching to this was appealing. However, it was not so easily utilized for high-speed, power-guzzling digital GaAs. Nevertheless, the hydrogen phobia of 1989-1994 fuelled the switch to plastic for all but the most demanding applications. And in those particular cases, installing hydrogen getters mitigated the problem. Another milestone from 1995 was that this year marked the beginning of the end for digital GaAs. Cray ran out of time when massively parallel machines surpassed the computing power of his speedy machine, foretelling a fate that followed just a few years later with personal computers – where faster bus speeds, enabled by GaAs clock chips, gave way to faster and wider microprocessors.

However, back in the 1990s, the real champion of performance and reliability for compound semiconductors were the optoelectronic components that underpinned the beginning of the "dot-com" era in 1995. At that time fibre optic infrastructure exploded. System capacity doubled every six months, with the deployment of InGaAsP lasers and InGaAs photodiodes enabling the construction of links operating at up to 10 Tb/s. To cram thousands of communication channels onto the fibre, engineers turned to GaAs and then InP multiplexors and demultiplexors. This provided one of the first opportunities for compounds to reach production volumes that broke out of laboratory status and then to demonstrate reliability levels rivalling silicon.



Finally, in the late 1990s, Moore's 1965 prediction for GaAs came true. Driven by integration and miniaturization of cell phones, compound semiconductor reliability advanced like no other previous consumer gadget known to mankind. The first fashion phones came into being and a re-emphasis on quality and reliability followed. Makers of phones and their consumers redefined reliability with an expectation of seeing no failures – either in the handset factories or during the consumer's warranty period.

For the engineers working in the fabs, these expectations for components with longer and longer lifetimes led to an emphasis on finding and removing early fallout. By the end of the 1990s, phone-based annual volumes for III-Vs topped hundreds of millions, and reliability sampling and stressing exceeded



Raw* Returns Results – Volume Helps

Era	Total Number of Devices Analyzed	Original 1985 "Grade"	Rate of Field Returns (Raw Fallout Returned)
1985 - 1992	228	*"Not Very Bad"* 0.5%	**5,000** ppm
1999 - 2004	6,213	*"Ok"* ~ 0.15% - 0.05%	**500** ppm
2005 - 2006	2,941	*"Damn Good"* ~ 0.05% - 0.01%	**100** ppm
2007 - 2009	3,535	*"Holy Cow!"* < 0.001%	**5.4** ppm

***Returns are based upon chance and should be used for entertainment purposes only.**

Table 1. Example rates of field returns for GaAs-based compound semiconductor ICs.

millions per year. At this time, super heterodyne phone receivers evolved into digital radios – and the formative reliability methods of understanding mechanisms, distributions, and acceleration factors were enhanced by efforts to engineer reliability improvements and build in reliability throughout the communications sector.

Beating hero with zero

During the last ten years, the most exciting development in compound semiconductor reliability has been the shift from measuring wearout to quantifying early life failures. Taken to the extreme, this is like swinging focus from reliability to quality, since the earliest chance to detect failure is at the first measurement. In the journey to eliminate fallout, it makes sense for quality and reliability to be blurred together.

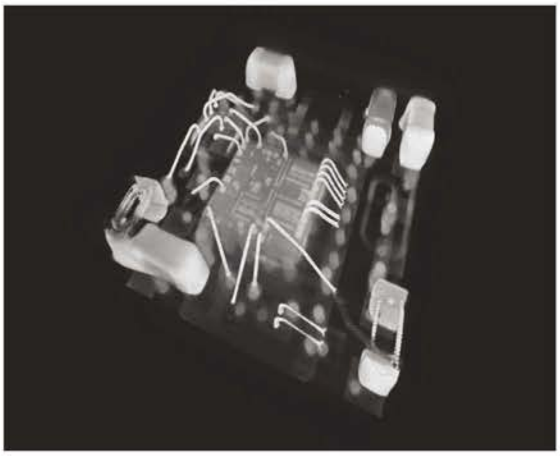
In 2006, Nien-Tsu Shen from Skyworks brought investigations on early life measurements that had been conducted in the previous decades into the public domain in a paper *Perfect Quality for Free*?!?, presented at the *Compound Semiconductor* Manufacturing Technology Conference. Makers of power amplifiers responded to the challenge, coming together to devise new methods of measuring reliability. Of course, the driver for measuring and reducing early failures is higher volume – but this was not an issue, with spending on phone microchips eclipsing that on computer microchips in 2011, and enabling III-Vs to finally find their niche.

Detecting early life fallout is far more challenging than estimating wear-out lifetimes because it is rare and getting scarcer. Of course, every semiconductor will eventually wear out – it just has to stressed hard enough and/or long enough to make an estimate of its life. But with mature technologies, early failures will occur in very few samples. Most failures are linked to defects, and occurrences of these are in a few parts per million.

One of the benefits of volume is that it drives down defects far better than anything else. The breakthrough in 1995 by Poole, who turned to 12,000 samples, enabled the detection of 100 parts per million. That's a rate of failure that is fine for the semiconductors of the 1980s and 1990s, but if it were occurring in 2014, it would have spawned around 4.5 million phone failures from last year's models! Now producers of GaAs chips in high volumes have (lower bound) early fallouts approaching 1 part per million, based on return rates measured over the earlier years.

In the current era, maverick events are behind the upper bound of early failure rates. An example, described in the January & February 2013 edition of *Compound Semiconductor*, involved 30,000 samples stressed by solder reflow simulations, thermal shock, and autoclave humidity saturation. This type of investigation provided unique information, because stressing continued until the samples *stopped* failing, and because mere detection wasn't the goal – the aim was to predict the occurrence and cumulative degree of fallout. In this case, the accumulated death toll was 0.5 percent, but the decreasing rate of failure throughout early life was the silver lining, demonstrating that the earliest measurements offer the best chance for detection.

What this means is that whether your measurement is described as quality, early life fallout, maverick anomalies, infant failures, or zero defects, this early assessment of reliability is just as critical as the electrical performance of a 'hero' device that stretches to the limit of Johnson's Figure of Merit.



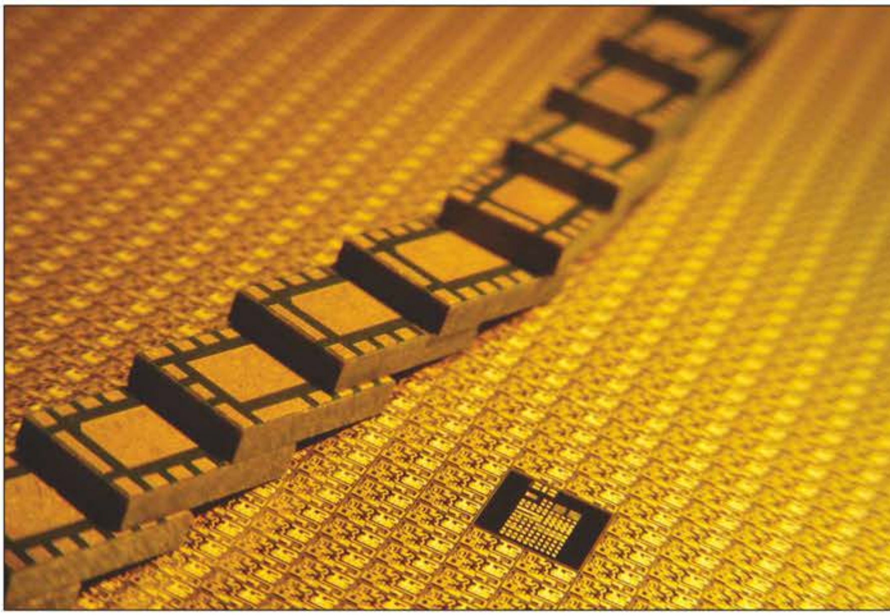
Turning full circle

For the most promising material of our time, GaN, reliability publications surfaced in 2002. Since then, there has been increasing interest in this material from government and academia. One would have expected that this technology would have delivered accepted lifetimes five years on from then, based on the reliability learning curves for silicon and compound semiconductor materials.

That's not been the case, however, with GaN reliability disputed and intensely debated to this day. This state-of-affairs is highlighted by the number of reliability publications on GaN published by the IEEE, which, since 2010, outnumbers those on GaAs by a factor of four. The 'building-in' reliability era for GaN has been problematic, with the material itself proving influential. Historically, adding more aluminium into the structures boosts performance, but at the expense of inferior reliability.

Fortunately, the slowdown of GaN RF circuit reliability has not impacted all GaN developments. Consider, for example, what has happened of late with the GaN LEDs that are lighting our world.

It is interesting to note that the silicon juggernaut has now developed a problem with reliability lifetimes. Since the introduction of the 180 nm node at the turn of the millennium, circuit lifetimes have plummeted, falling from 20 million hours to 200,000 hours for the 65 nm node reached in 2007. Now, the latest ICs sport transistors at the 14 nm node, and the reliability penalty to pay for this (if any) is yet to be determined. What this might mean at even smaller nodes is hard to say, for at nodes below 10 nm there is a need to introduce a new material – III-Vs have been mentioned as a possible saviour! Wouldn't it be ironic if the predictions of Moore and Johnson come together after 50 years to make both prophecies come to fruition, with reliability driving what neither could achieve independently?



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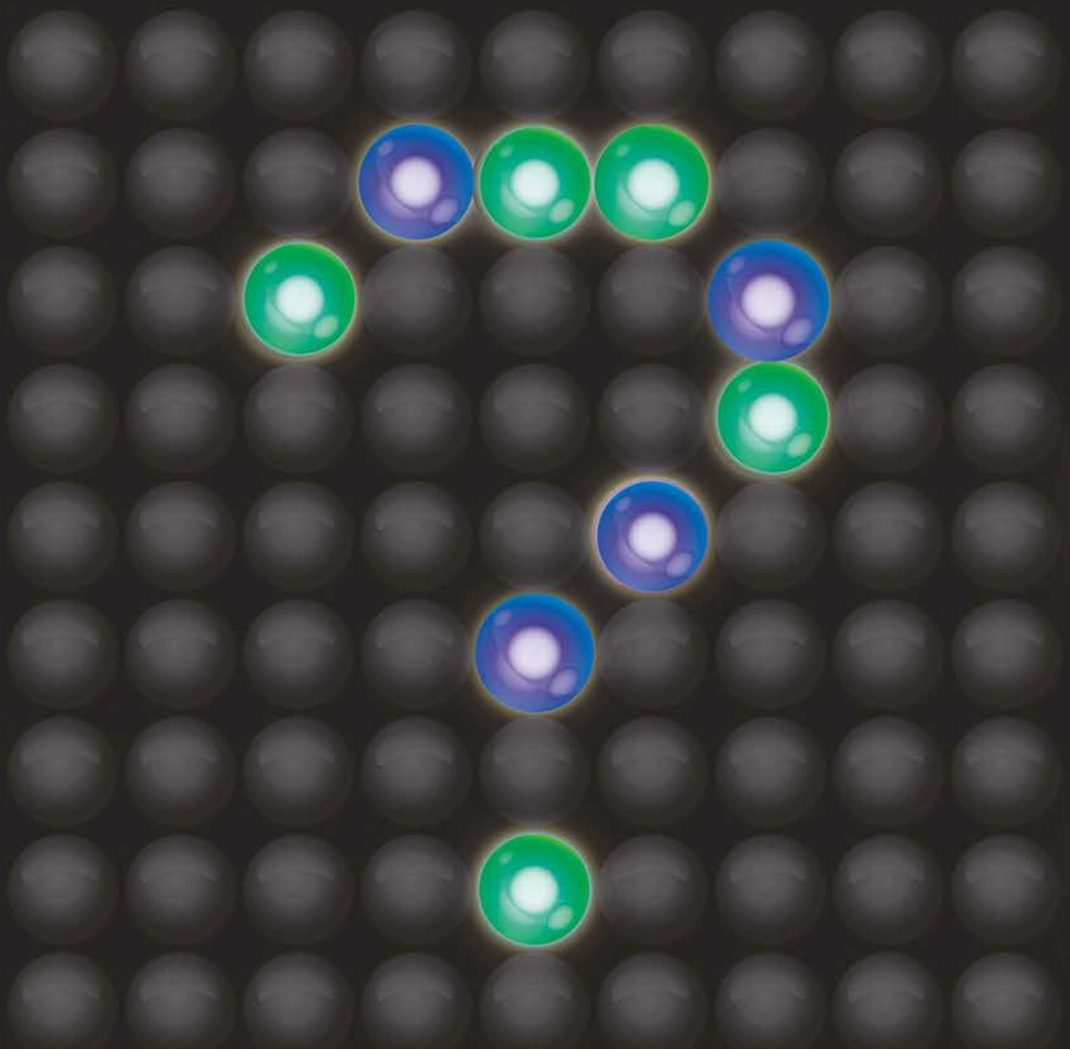

On the efficiency degradation in InGaN-based LEDs:

Mechanisms and remedies

Researchers continue to debate the cause of the fall in LED efficiency at higher drive currents

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LEDS HAVE BECOME indispensable in a variety of applications including displays, indicator lights, signs, traffic lights, printers, telecommunications, and the biggest of all, general lighting. In the centre of this blazing journey is the GaN based LED, which is somewhat mysterious in that the output does not scale linearly with the drive current at high injections aside from thermal issues. The injection route to increase the light output runs aground because of efficiency degradation, the causality of which has received a good deal of attention. More specifically, the internal quantum efficiency, IQE, typically peaks at levels as low as a few A/cm^2 and then drops with increasing injection to in some cases as low as 50 percent of the peak value. The reduction in IQE is also observed under pulsed injection with pulses having duty cycles and widths for which the heating effect can be ruled out as an origin[1], thus implying that the reduction in the IQE is related to the internal properties of the LED. Although this loss of efficiency is observed in UV LEDs, blue and, more severely, green LEDs are more prone to efficiency degradation at high injection.

For over a decade, some research efforts have been put forth for understanding the origin of the degradation mechanism and exploring possible remedies. Consequently, several technological modifications to the GaN-based LED structure has been proposed, some of which have been successfully implemented for laboratory prototype and commercial manufacture. The IQEs of blue LEDs are already in the high 90 percent range and attainment of packaging with efficient heat removal and cutting cost while retaining or even improving the performance are currently the key focus areas. However, unequivocal design rules are yet to be established to overcome efficiency degradation. This article reviews both the mechanisms of and remedies for the efficiency degradation, with the goal of providing the reader with an as complete as possible and updated picture of the present status of our current understanding of the efficiency loss and the mitigation efforts.

One characteristic of efficiency degradation in nitride LEDs is that it is more pronounced as the emission wavelength increases (see Figure 1). Possible explanations for more severe efficiency loss with increasing indium mole fraction in the active region are widely ranging and include a higher density of defects in the active region, more significant fluctuations in indium content, higher kinetic energy of the electrons due to increased conduction band offset, and the tendency to shift from direct to indirect Auger recombination processes.

Efficiency degradation is clearly caused by a non-radiative carrier loss mechanism that can be effective inside and outside the quantum wells (QWs) of the LED active region. If it is inside, the culprit might be a process governed by defect-related Shockley-Read-Hall recombination and Auger recombination, and enhanced by carrier delocalization and a reduction in the effective volume of the active region for injection. If it is outside, the origin of efficiency loss is either carrier leakage due to current crowding, inefficient hole injection, asymmetry of doping polarity, polarization charges or electron overflow from the active region. An overview of all these theories is provided in Figure 2, while an equation for internal quantum efficiency that accounts for all these mechanisms is provided in the panel "internal quantum efficiency".

Auger recombination

Auger recombination is one of the proposed mechanisms that lead to efficiency degradation in InGaN/GaN LEDs. This process involves recombination of an electron and a hole, with the energy that is released consumed by the excitation of a third carrier – an electron or a hole – rather than the emission of a photon.

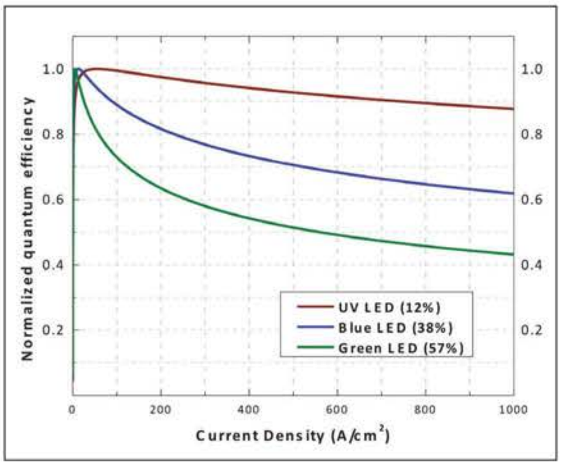

Figure 1: Efficiency versus current density curves of GaN-based UV, blue and green LEDs showing a decrease in efficiency with increasing injection current. Green LEDs have the largest efficiency degradation. The numbers in the brackets in the legend denote the efficiency degradation at 1000 A/cm2. (Simulation results for illustration purpose only, not actual experimental data).

In the GaN-based LEDs different Auger recombination processes are at play. In a direct Auger process, such as the *eeh* variety (see Figure 3, left panel), the energy given off by an electron dropping from the conduction band to the valence band is consumed to excite another electron to a higher state within the conduction band. This chain of events satisfies the requirements for the conservation of energy and momentum. The other direct Auger processes are less likely to occur, so they can be neglected[2].

Indirect Auger recombination, which can occur in parallel with the direct variety, encompasses phonon-assisted processes and/or many other scattering mechanisms (Figure 3, right panel). While the direct variety depends exponentially on temperature, the indirect variant exhibits a power law dependence. In general, the rate of Auger recombination is proportional to the third power of the free carrier density *n*. Consequently, if one assumes that the coefficients for Shockley-Read-Hall and radiative recombination do not depend on injection, the Auger recombination can be invoked to account for the efficiency loss with increasing injection depending upon the magnitude of the Auger coefficient *C*.

If this approach is taken, Auger coefficients should be greater than 10^{-31} cm^{6}s^{-1} to cause notable efficiency degradation[3,4]. However, such a large Auger recombination coefficient for III-Nitride systems has not been predicted so far by theoretical calculations except for the indirect and resonant processes that would take place only in LEDs emitting at 2.5 eV[5], assuming their presence. Yet, direct observation of Auger electron was made and it was postulated that the observed drop in electroluminescence efficiency corresponded to the detected high-energy Auger electrons, suggesting Auger recombination to be the sole contributor to the efficiency degradation[6]. One would then surmise that, if the nonradiative recombination due to Auger effect is to be the major (if not the sole) contributor to the observed efficiency degradation, indirect Auger processes have to be dominant as the direct variety is a very unlikely possibility. The likelihood of this is higher for relatively low quality material with alloy and compositional fluctuations. In general, the Auger coefficient extracted from the overly simplified *ABC* model is strongly dependent on quantum well properties such as the relative density of electrons to holes, the net polarization field, and the hot carrier escape ratio. A more rigorous approach than simple curve fitting plots of efficiency as a function of current density is required to obtain a consistent value for the Auger coefficient[7].

The proponents of Auger recombination as the major, if not the sole, mechanism for the efficiency degradation, have proposed different theories to reconcile the relatively small Auger coefficients with the strong efficiency loss effects. The most popular conjecture is that the effective optically-active volume is significantly reduced with respect to the nominal one. This could arise from strong non-uniformity of carrier-density distributions, which results in significantly higher local carrier densities in the optically active region than in the case of uniform distribution for the same driving current.

A relatively small C ($\approx 10^{-31}$ cm^6 s^{-1}) can then give rise to strong efficiency loss. Several explanations have been put forward as the genesis of the strongly non-uniform lateral carrier density distribution: polarization-field-induced electron-hole wave-function separation[8,9], carrier localization in the indium-rich areas of the active region[10], and lateral current crowding, which occurs in LEDs supporting lateral ohmic contact schemes[11].

Carrier-related theories

An internal non-radiative loss process that has been proposed is associated with carrier delocalization. The premise assumes carrier confinement at low current densities, associated with randomly distributed potential minima – these could be caused by energy-activated defects, or fluctuations in the indium content or width of the quantum well. These localized regions have low defect recombination and can be represented by a SRH recombination term characterized by a relatively small *A* coefficient, typically on the order of 10^7 s^{-1}. When the LED is operated at low current densities, carriers are confined in dislocation-free regions and have long non-radiative lifetimes, and the radiative recombination efficiency is relatively high; but as the current is increased, potential minima fill, with carriers spilling over, delocalizing, and diffusing to regions with a far higher defect density, leading to increased non-radiative recombination. A density-activated defect recombination (DADR) mechanism was proposed, wherein the loss rate is negligible below a certain threshold carrier density but rises with increased injection according to the quadratic dependence of the electron-electron scattering rates on the carrier concentration[12]. Detailed microstructure analyses seem to indicate fairly uniform quantum wells, however, in high quality LED structures. Therefore, carrier delocalization can be considered negligible in such structures.

The mechanisms of localization of carriers inside an LED active region are no different than those discussed under Auger recombination. However, the mechanism leading to degradation is different: carriers remain in the localized regions even at high current

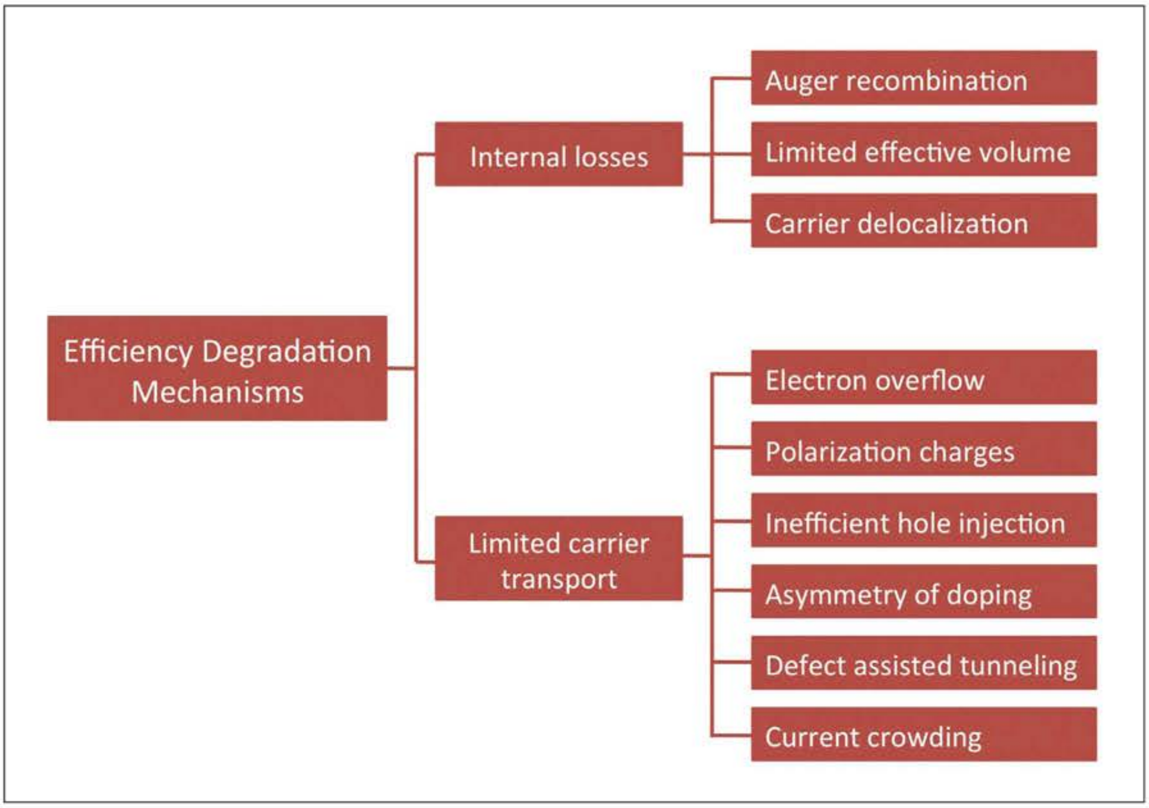

Figure 2: Mechanisms leading to efficiency degradation in InGaN LEDs.

densities and undergo strong Auger recombination according to the reduced-active-volume theory, whereas the energized carriers overflow from the localized regions and undergo defect-assisted recombination according to the carrier delocalization theory.

Another theory for explaining efficiency loss at high injection is that instead of recombining with holes in the quantum wells, electrons fly over the active region and undergo a non-radiative recombination process in the relatively low quality *p*-GaN, or recombine with holes in *p*-type GaN resulting in emission at unintended wavelengths, or collected at the *p*-type contact electrode. Electron overflow is by no means a new idea, having dogged LEDs since their inception, and inserting electron-blocking layers (EBLs) can reduce it, a practice that has been employed copiously in conventional III-V-based green LEDs and also in InGaN LEDs.

Inclusion of the electron overflow term into the rate equation was shown to represent the efficiency loss at high injection[13], which has been directly observed in LEDs confirming it as a source of the efficiency degradation in LEDs[14]. Electron leakage is indeed a family of degradation mechanisms rather than a single one, encompassing several different promoting factors: electron overflow, polarization-induced charges, poor hole injection, and asymmetry in doping.

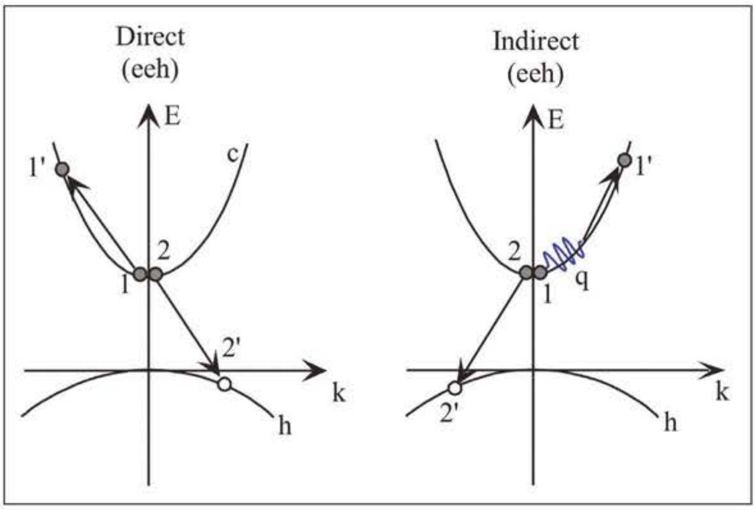

Figure 3: Direct (left) and indirect (right) eeh type Auger recombination processes.

The electron overflow in semiconductor heterostructures can originate from two processes. One is thermionic emission of equilibrium electrons from the bottom of the conduction band in the active region over the barrier into the *p*-layer. However, its effect in the InGaN system is negligible due to large band discontinuities[15]. The other possibility is ballistic or quasi-ballistic transport of the injected electrons, which can recombine in the *p*-GaN region instead of the active region, unless blocked by an EBL.

Upon injection, electrons acquire additional kinetic energy equal to the conduction band offset between *n*-GaN and InGaN. These hot electrons can either lose their excess energy mainly through interaction with LO-phonons; and thus contribute to recombination or they can avoid cooling altogether and leave the InGaN

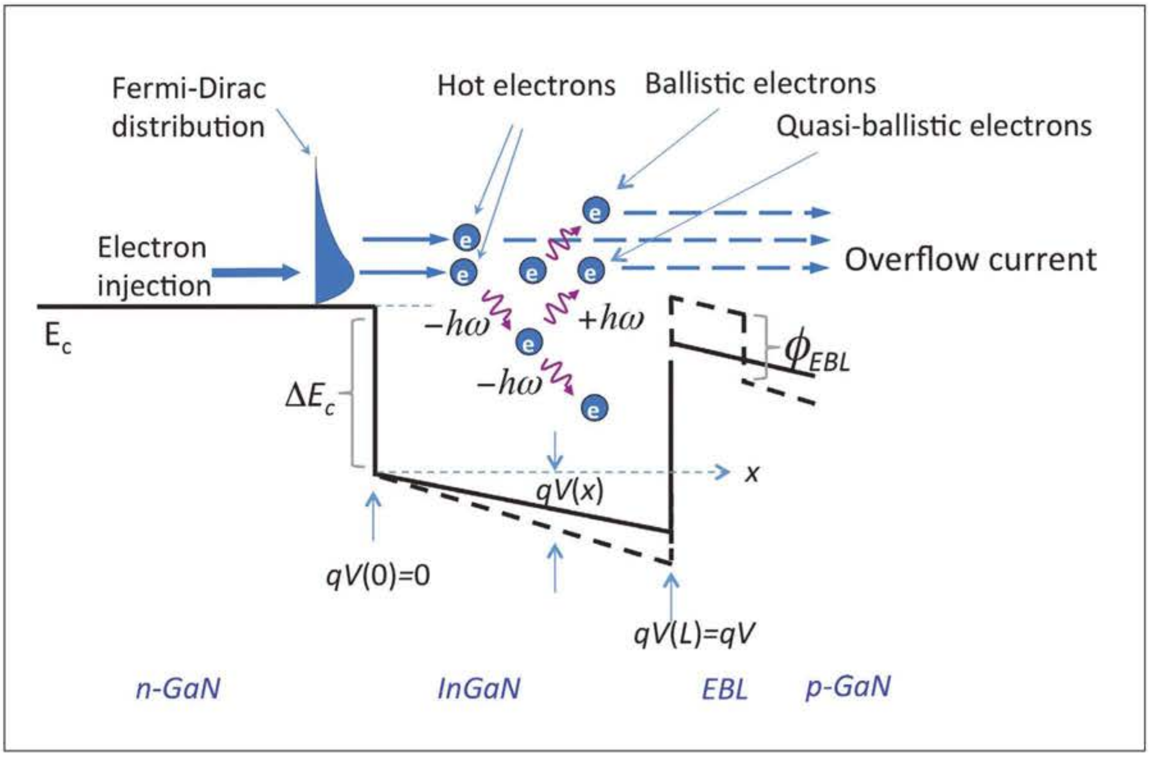

Figure 4: Schematic of electron overflow caused by ballistic and quasi-ballistic electron transport across the InGaN active region. The electrons gain a kinetic energy after being injected into InGaN, resulting in a total energy of $E + \Delta E_c + qV(x)$. Dashed lines in the band structure represent additional band bending caused by the piezoelectric field due to the EBL (redrawn after[3]).

region, contributing to electron overflow as depicted in Figure 4.

Alongside leakage due to highly energized electrons, another culprit may be the polarization-induced sheet charge at the interface between the AlGaN EBL and the spacer and at the quantum well/quantum barrier interfaces. The weakness associated with this conjecture is that in order for simulations to replicate experimental efficiency loss data, a multiplication factor ranging from 0.3 to 0.7 has to be introduced for the polarization charges. Without this factor, numerical device simulations can only reproduce sufficient efficiency degradation when the AlGaN/GaN band offset ratio ΔE_C: ΔE_V is reduced from normally accepted values of 70:30 to 60:40 or 50:50[16].

The AlGaN electron-blocking layer employed as a barrier for the electron overflow into the *p*-side of the LED device is to some extent a double-edged sword, as it results in a barrier for hole injection as well, due to the valence band offset between AlGaN and GaN. This unwanted barrier can be reduced by employing *p*-type doping in the AlGaN layer; however, *p*-type doping efficiency decreases as the aluminium mole fraction increases[17]. As a result, increasing aluminium content in the EBL for better confinement of electrons will lead to an increasing energy barrier for the holes. Hole injection is further hindered as compared to electron injection due to the fact that active regions are typically unintentionally or intentionally *n*-type doped.

Internal quantum efficiency

The overall power conversion efficiency (wall-plug efficiency) in an LED is the product of voltage conversion efficiency ($\eta_{voltage}$), internal quantum efficiency (η_{IQE}), and the light extraction efficiency ($\eta_{extraction}$).

$$\eta_{wall-plug} = \eta_{voltage} \, x \, \eta_{IQE} \, x \, \eta_{extraction}$$

The voltage conversion efficiency is fundamentally determined by band offsets of III-nitrides and the extraction efficiency is the function of LED design. Different mechanisms leading to efficiency loss can be encompassed in the following expression for the internal quantum efficiency of an LED, albeit with a plethora of assumptions, including injection independent A and B coefficients:

$$\eta_{IQE} = \frac{Bn^2}{An + Bn^2 = Cn^3 + k\,(n - n_0)^m + \frac{I_{leakage}}{qV_{QW}}}$$

where *An* and Cn^3 are the Shockley-Read-Hall and Auger recombination rates, $I_{leakage}$ is the electron leakage current, *q* is the electronic charge and V_{QW} is the volume of the active region. The term $k(n-n_0)m$ accounts for the non-radiative loss mechanism associated with the carrier delocalization with n_0 being the threshold carrier density triggering delocalization, *k* being a suitable constant, and $m \geq 2$.

The problem of limited hole transport has been found to be independent of material polarization and sheet charges at hetero-interfaces; therefore, this mechanism is relevant even in LEDs grown along non-polar and semi-polar orientations or polarization-matched LEDs grown on *c*-plane sapphire or (111) silicon. Moreover, poor hole transport through the active region leads to non-uniform hole distribution in a multiple-quantum-well LED. Appropriate structural designs mitigate this problem considerably.

Another proposition for the genesis of the electron overflow is the asymmetry in the free carrier concentration in the *p*- and the *n*-side of the LED device. In addition, the relatively low mobility (and thus diffusivity) of the holes compared to electrons contributes to a non-uniform hole distribution, particularly across a multiple-quantum-well LED active region.

In addition to all the explanations for electron leakage discussed above, there are suggestions that it can result from lateral current crowding and defect-assisted tunneling. Theoretical analyses of lateral and vertical LED structures support the view that the locally enhanced carrier densities induced by current crowding enhance electron leakage[18]. This is more pronounced in mesa-based lateral LED structures, but not a major impediment in vertical varieties where the substrates are removed. Defect-assisted tunnelling may also contribute to electron leakage, with electrons tunnelling from the quantum well to the defect sites, if present, in the *p*-doped barrier[19]. This is more likely to happen if the device contains a single, thin quantum well.

Combatting efficiency loss

The many and varied conjectures for the cause of efficiency loss have spawned a wide range of solutions. These aim to achieve one or more of the following: (i) reducing the carrier densities in the QWs, (ii) improving the electron confinement within the active region, (iii) enhancing the hole injection into the active region. See Figure 5 for an overview of the degradation alleviation mechanisms that are discussed below.

One popular option is to reduce the carrier density in the active region by increasing its effective volume via either employment of more or thicker quantum wells, or improved lateral current spreading and increased chip area. While the primary goal is to suppress the Auger recombination, this approach reduces electron leakage as well.

Turning to thicker wells is not a trivial solution, however. That is because dislocation generation is also a factor when determining the optimum thickness of the quantum well. For example, in a near-ultraviolet single-quantum-well LED emitting at around 400 nm, if GaN is grown on sapphire, the well should be 3 nm thick. However, if it is grown on a native platform, which has far fewer dislocations, an 18 nm-thick well works best[20]. These results indicate that, for good quality samples with a low defect density (both in terms of quality of the GaN epitaxial layer and the quantum wells), the dominant causes for efficiency degradation are Auger recombination and electron leakage. On the other hand, for LEDs grown on non-native substrates such as sapphire or silicon or emitting at longer wavelengths, defect-related mechanisms such as carrier delocalization and defect-assisted tunneling come into play.

To reduce the carrier density with thicker quantum wells, a relatively uniform carrier distribution must be achieved across the active region. If the LEDs have wells with low indium content, making them thicker reduces the internal electric field, leading to a spread of wavefunctions and thus an enhanced electron-hole overlap, which results in mitigation of the degradation in radiative recombination. However, thicker quantum wells may introduce other issues; and if they are rich in indium, material quality may suffer. The best solution appears to be increasing the number of wells, while keeping the thickness of each of them low enough to avoid drawbacks associated with the quantum confined Stark effect due to internal electric fields.

A variant of this approach is to employ short-period superlattice (SPSL) InGaN/GaN active region[21]. Such a structure increases the number of QWs and introduces quantum mechanical coupling between them. This results in carrier delocalization among the QWs through the formation of minibands, leading to increased uniformity of electron and hole distributions and reduced peak carrier densities.

Improved LED performance via reduction of electron leakage is promised through modifications to the design of the active region, electron-blocking layer, and electron injector. Varying degrees of success can also result from a reduction in the polarization field, which can be accomplished through the introduction of polarization-engineered multi-quantum well and electron-blocking structures, and the switch to non-polar and semi-polar planes for the LED. Although they are appealing, the technology for these unconventional planes has not yet matured to the extent of the *c*-plane variety. Significant emission efficiency has hinged on the use of very high quality bulk GaN substrates, which are expensive and very small, and thus unsuitable for LED production. Thanks to the superior quality of material grown on the *c*-plane, it is this orientation that still sets the benchmark for LED performance.

A straightforward approach to reduce the electron leakage from the LED active region is to increase the barrier height of the electron-blocking layer. Switching from AlGaN to $In_xAl_{1-x}N$ both increases the band offset with GaN and InGaN and allows lattice-matching with $In_yGa_{1-y}N$ layers of the active region. An InAlN EBL has been shown to be more effective than AlGaN EBL for reduction in efficiency degradation[22,23], but at the expense of an increase in the barrier for holes in *p*-GaN, which hampers hole injection. Magnesium-doped InAlN can be used to mitigate this problem

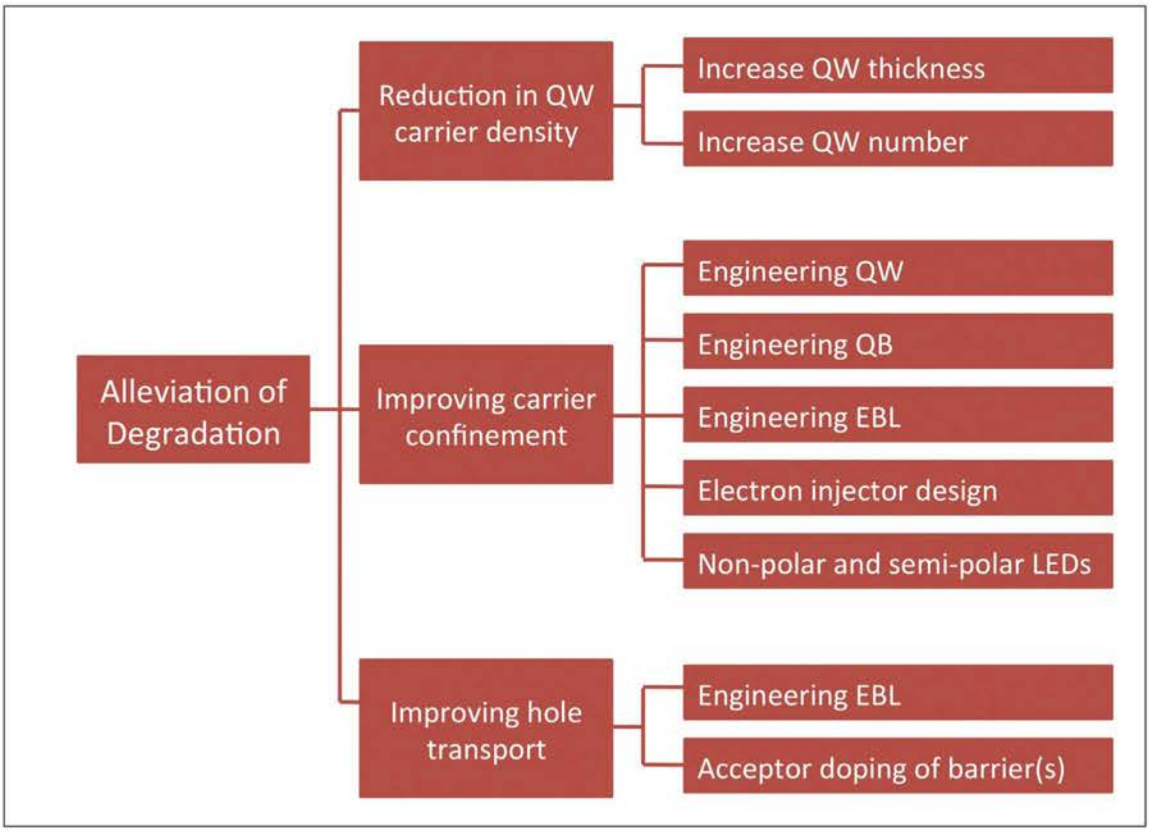

Figure 5: Overview of the approaches to alleviate the efficiency degradation problem.

some; but, *p*-type doping of InAlN with sufficient thickness is difficult. One proposed solution is to use an electron blocking structure composed of a *p*-doped InAlN/GaN superlattice[24].

Some researchers have attributed efficiency loss to polarization effects that result in electron leakage. To address this problem, reduction of polarization charges in the MQW region by polarization-matching quantum wells and barriers have been proposed. Using AlInGaN[25] or InGaN[26] as barriers instead of GaN has been shown to lower efficiency degradation. These approaches as well as multilayer and graded barriers also have the potential to provide more uniform hole density across the active region[27].

According to the hot electron model, another source of leakage is the high energy of electrons injected into the active region. Upon injection, their potential energy is converted to kinetic energy and while they diffuse from the *n*-GaN side to the active region they gain additional energy from any field present. To reduce this effect, and thus alleviate electron leakage and the associated efficiency degradation, an 'electron cooler' has been introduced[28]. This layer consists of compositionally graded (from lower to higher indium content in the growth direction) InGaN known as staircase/graded electron injection (SEI/GEI) layers between the *n*-GaN region and the quantum wells. A great strength of this approach is that it allows the removal of the electron-blocking layer, which acts as a barrier for holes. Each energy step would ideally be equal to or slightly larger than the LO phonon energy (92 meV in GaN). The composition can also be graded continuously, in which case the step height requirement is removed.

Most of the approaches aiming to enhance the hole injection into the active region focus on the optimization of the EBL. Other usually employed approaches include linearly grading the aluminium mole fraction (increasing along the growth direction) in an AlGaN EBL. The idea behind this proposition is to compensate the band bending associated with the polarization charges at the EBL/spacer interface, leading to enhanced hole density at the interface and in the spacer; and to improved hole injection into the QWs. Experimentally, this approach has shown to reduce the efficiency degradation significantly. AlGaN/GaN or InAlN/GaN super-lattice EBLs have also been used to improve hole injection into the active region of the LED[29]. Ultimately, increased hole concentration beyond the current 10^{18} cm^{-3} or slightly higher would boost the LED performance.

One route to improve the hole injection into the active region is to dope the barriers with magnesium[30]. This delays the onset of efficiency degradation, but drags down LED efficiency, with band-edge emission diminishing as magnesium content in the active region increases. Alternatively, delta-doping the barriers with magnesium has been proposed as a solution to reduce possible magnesium diffusion into the QWs[31].

There are clearly many options for reducing the impact of efficiency loss in InGaN LEDs, the origin of which has been attributed to several mechanisms. Auger recombination and electron leakage are the two leading contenders, and there is a great deal of theoretical and experimental evidence supporting both hypotheses. However, the industry operates on a very rigorous slope and continually improves the LED performance by optimizing growth and device design schemes. The LED performance is consistent with very high internal and external quantum efficiencies to the point where the mechanisms discussed in this report for degrading the efficiency can be safely assumed to be reasonably countered. After all these measures to alleviate the degradation are taken, ultimately, the hole concentration should be improved to boost the nitride LED performance.

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LEDs shine on $ScAlMgO_4$ substrates

Switching from sapphire to $ScAlMgO_4$ reduces the strain in GaN LEDs while increasing extraction efficiency

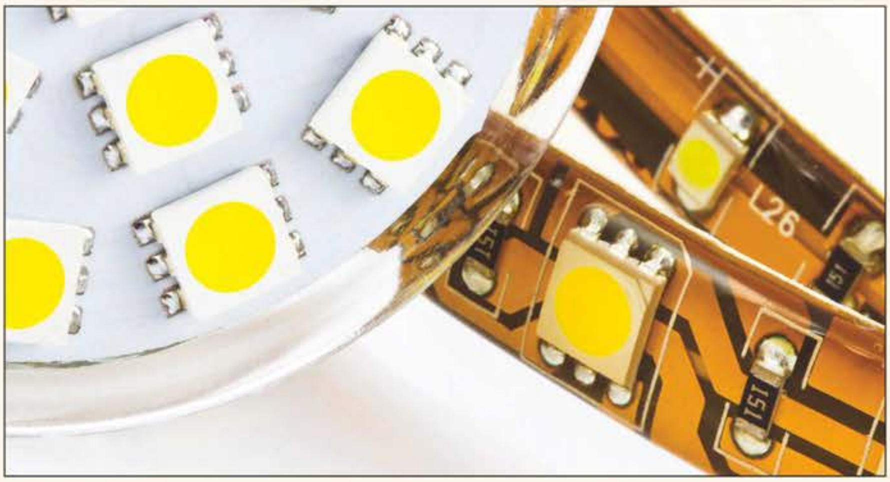
ALTHOUGH SAPPHIRE has proved itself as a suitable foundation for making myriad GaN LEDs, it has its weaknesses: There are significant lattice and thermal mismatches between it and the epilayers, and this leads to a high degree of dislocations, epiwafer bow and large residual strain.

To address all these issues, a team from Kyoto University, Japan, has turned to $ScAlMgO_4$ substrates for making LEDs. Ingots of $ScAlMgO_4$ can be grown by the well known and widely used Czochralski method, which is employed for forming many types of compound semiconductor boule, and the substrates that are sliced from it have a lattice mismatch with GaN of only 1.8 percent.

That is not the only advantage that $ScAlMgO_4$ has over sapphire for making LEDs. This oxide is transparent down to 196 nm, so it can be used for making visible and ultraviolet LEDs; and it has a relatively high refractive index, improving light extraction.

Typical refractive indices for GaN and sapphire are 2.56 and 1.77, respectively, and this large difference between them can cause a high proportion of the light that is emitted from the active region of the LED to be trapped within this device by total internal reflection. This issue is not prevalent in devices grown on $ScAlMgO_4$, because it has refractive index is 2.2, according to spectroscopic ellipsometry measurements by the team. Calculations based on these values for refractive index suggest that switching from sapphire to $ScAlMgO_4$ propels light extraction efficiency from 28 percent to 49 percent.

Another benefit of $ScAlMgO_4$ over sapphire is that its coefficient of thermal expansion is much closer to that of GaN. This enables a reduction in the compressive strain in the LED, and thus a decrease in the polarisation field and an increase in the critical-layer thickness. To demonstrate these theoretical benefits in real devices, the researchers from Kyoto University have compared the performance of LEDs grown on $ScAlMgO_4$ and sapphire.


Switching from sapphire to ScAlMgO4 reduces the strain in GaN LEDs and boosts extraction efficiency

Photoluminescence from a 4 μm-thick film of GaN on $ScAlMgO_4$ is at a longer wavelength than that from a 3 μm-thick film of GaN on sapphire, indicating less residual strain. This strain is quantified by examining the exciton energies, which are uncovered by reflectance spectroscopy. Results indicate a reduction in the strain-induced blue shift by an order of magnitude.

Plugging numbers obtained by these measurements into calculations reveals that switching from sapphire to $ScAlMgO_4$ for the growth of GaN enables an increase in critical thickness of overgrown $In_{0.2}Ga_{0.8}N$ by 10 percent, and a commensurate fall in the polarisation-induced field.

The LEDs formed on $ScAlMgO_4$ consist of a low-temperature buffer, a 4 μm-thick layer of silicon-doped GaN, a three-period multi-quantum well with 3 nm-thick $In_{0.16}Ga_{0.84}N$ wells and 10 nm-thick barriers, a magnesium-doped *p*-type GaN layer, and a heavily-doped, 20 nm-thick GaN capping layer. Devices with dimensions of 350 μm by 350 μm were created by conventional photolithography and reactive-ion etching, before vacuum evaporation added an *n*-type electrode of Ti/Al and a *p*-type electrode of Ni/Au.

The team compared the performance of these LEDs with sapphire-based variants that were identical, aside from a 3 μm-thick layer of undoped GaN grown beneath the *n*-type GaN.

Current-voltage measurements revealed that the turn-on voltage for the GaN-on-$ScAlMgO_4$ LED is 3 V, 0.2 V higher than that for the control devices. This is due to the higher series resistance – it is 50 Ω, compared to just 18 Ω for the LED on sapphire. This higher resistance is believed to stem from the absence of the unintentionally doped *n*-type GaN underlayer.

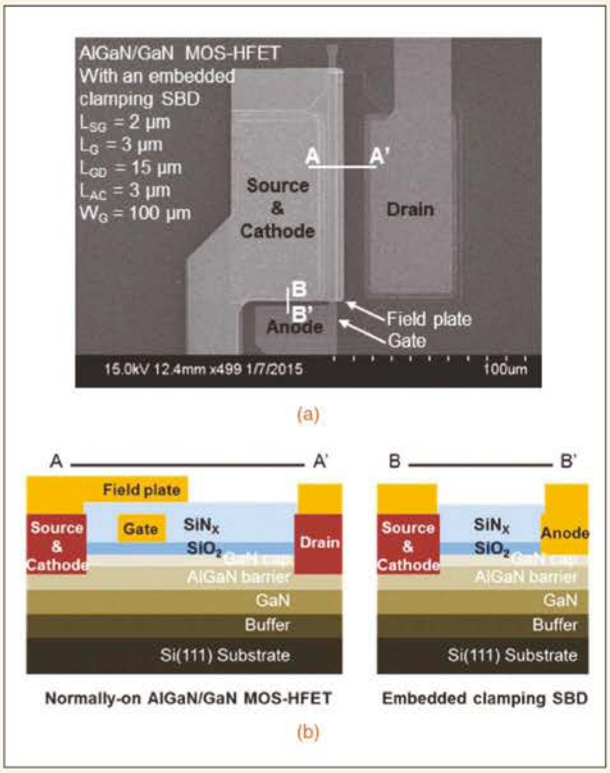
Electroluminescence measurements with a pulsed source show that when driven at 100 mA, the intensity of the emission from the LED grown on $ScAlMgO_4$ is about 40 percent higher than that formed on sapphire. In the low-current regime, increases in the intensity of both types of LED are linear with current, but for that formed on $ScAlMgO_4$, efficiency declines in the high current regime.

The researchers believe that this weakness stems from a combination of the inferior thermal conductivity of $ScAlMgO_4$, which is about four times lower than that of sapphire, and the higher input power required to reach a given current. Turning to a flip-chip configuration could address these issues.

T. Ozaki *et. al.* Appl. Phys. Express **8** 062101 (2015)

A makeover for the normally-off HEMT

Inserting an embedded clamping diode leads to the fabrication of a high-performance, normally-off, GaN-based HEMT



Incorporating a Schottky barrier diode into a HEMT enables the formation of a normally-off device.

ADDING A DIODE to an AlGaN/GaN HEMT has enabled a Korean team to lay the foundations to low-cost production of high-performance, normally-off transistors.

The device that they have made is a novel form of GaN-based HEMT, which is a promising class of device for power electronics due to its combination of fast switching speeds and extremely high breakdown fields.

One of the merits of the Korean team's device is that it is normally-off, which equips it with safe operating characteristics – GaN HEMTs tend to be normally-on, due to the polarization-induced two-dimensional electron gas at the interface between AlN and GaN.

Several groups have modified devices to create normally-off HEMTs, using either fluorine treatment or the introduction of either a recessed gate or a *p*-type gate. However, all these changes limit the transistor's current density, according to corresponding author Ho-Young Cha from Honik University.

He argues that the only alternative to their approach that is capable of realising a normally-off HEMT with a high current density is to pair a normally-on HEMT with a silicon MOSFET, which is used as a switching device and connected in a cascode configuration. However, using two devices to form a normally-off HEMT adds cost.

The Korean team's device features a Schottky barrier diode, which is embedded at the input of a normally-on HEMT with a MOS gate.

Connecting an external capacitor to the embedded diode shifts the input signal down, enabling the normally-on HEMT that has a negative threshold voltage to be operated as a normally-off HEMT with a positive threshold.

"The diode integration does not increase the cost because it barely requires extra space or processing steps," says Cha, adding that only a few additional steps are needed to bring the capacitor onto the device.

"If a chip capacitor is integrated in a power device package, instead of the monolithically integrated wafer level capacitor, the cost will be much lower than adding a silicon MOSFET. So, production-cost-wise, our approach is better than the cascode configuration."

Engineers fabricated their devices from GaN-on-silicon epiwafers featuring a *p*-type conductive substrate, a 3.9 µm-thick carbon-doped GaN buffer layer, a 0.4 µm-thick GaN channel, a 20 nm-thick $Al_{0.25}Ga_{0.75}N$ barrier, and a 2 nm-thick layer of undoped GaN. After defining the active area via etching, wafers were cleaned with acid and a solvent, before they were loaded into a plasma-enhanced CVD chamber. That tool was used to deposit a 30 nm-thick layer of SiO_2.

After defining an ohmic contact region via etching, a metal stack was added and annealed, and then additional etching defined the Schottky contact region.

A Ni/Au stack formed the Schottky anode, before the quality of the oxide and the interface was improved via annealing under oxygen at 400 °C for 20 minutes. Finally, a field plate was added to suppress trapping effects.

Current-voltage measurements on this novel HEMT revealed an off-state breakdown voltage exceeding 900 V, an on-resistance of 2.34 mΩ cm^2, a gate threshold voltage of -14 V and a maximum drain current density of 600 mA/mm at a gate voltage of 0 V. This current density is nearly double that for normally-off HEMTs formed by either fluorine treatment, or the introduction of either a recessed gate or a *p*-type gate.

The connection of a capacitor to the HEMT may raise concerns related to the possibility of a decline in high-speed, high-efficiency switching capability, which would hamper the chances of this device from displacing silicon incumbents.

Cha is reassuring in this regard: "Once the capacitor is charged at the start-up condition, the clamp circuit does not limit the switching frequency as long as the capacitor is not discharged."

S.-W. Han *et. al.* Appl. Phys. Express **8** 091001 (2015)

Simulations dismiss electron leakage as the cause of droop

Modelling LED efficiency at different temperatures rules out electron leakage as the primary cause of droop

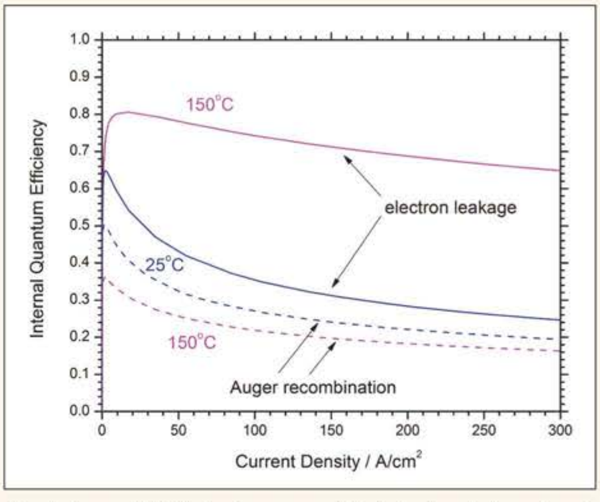
ONE OF THE MOST hotly debated issues within the nitride community concerns the cause of droop, the mysterious malady behind the reduction in LED efficiency at higher drive currents.

Using simple models to try and identify which of the two leading contenders – electron leakage and Auger recombination – is behind droop has had limited success, because they only consider one mechanism. Turning to more complex models does not pay dividends, either, because they are held back by a lack of known material characteristics to use in the calculations.

But it is possible to gain an insight into the plausibility of the leading candidates for droop when temperature-dependence is considered, according to Joachim Piprek from NUSOD. After recently modelling the efficiency of blue LEDs at different temperatures and currents, he concluded: "I am confident that the droop in these blue LEDs is not caused by leakage." LED behaviour at 25 °C and 150 °C could be replicated, however, with the Auger recombination element of the model.

Piprek's efforts involved modelling LED behaviour with Crosslight's APSYS software. This solves semiconductor carrier transport equations that are coupled to a quantum-mechanical model for photon emission from strained InGaN quantum wells.

Two different material parameters were used for Piprek's simulations: One favoured electron leakage from quantum wells, and the other gave prominence to Auger recombination. These two conditions were realised by varying the Auger recombination coefficient and the acceptor density inside the electron-blocking layer.



Simulations of LED behaviour suggest that electron leakage is not the primary cause of droop, because in real devices, internal quantum efficiency falls at elevated temperatures.

The NUSOD theorist is fully aware of the uncertainty surrounding both these parameters. He points out in his paper that the proportion of atoms that become AlGaN acceptors is unknown, and that there is great uncertainty surrounding the value of the Auger recombination coefficient.

He has compared the results of his calculations with measurements made on 440 nm LEDs by Fred Schubert's group from RPI. These experiments, reported in a paper in 2008, involved a device that featured five 3 nm-thick InGaN quantum wells and an electron-blocking layer made from *p*-type $Al_{0.13}Ga_{0.87}N$.

Piprek selected this experimental data for his work because it included current-voltage plots and high-temperature internal quantum efficiency data. "I first focused on the I-V characteristic, but this did not result in a decisive difference."

When he assumed that the majority of magnesium atoms formed AlGaN acceptors, a condition that virtually stops electron leakage, he could replicate plots of LED efficiency as a function of current density at room temperature. But when he reduced the acceptor density and the Auger coefficient, measured characteristics were also reproduced fairly well. The upshot: At this stage, he could not eliminate either of the leading candidates for the primary cause of droop.

The breakthrough came from considering changes to LED efficiency with increases in temperature. Modelling shows that at higher temperatures, electron leakage falls, due to enhanced hole transport. So, if electron leakage is the cause of droop, LEDs would be more efficient at elevated temperatures – but the opposite is true, according to measurements on real devices.

In stark contrast, simulations where Auger recombination is prevalent are able to reflect the decline in LED efficiency witnessed at lower temperatures. Simulations suggest a drop in peak efficiency of 30 percent when the LED temperature is increased from 25 °C to 150 °C, while measurements indicate a decline of just 20 percent. This difference may be explained by a decline in the Auger coefficient with increasing temperature, or minor contributions from thermionic emission leakage.

Piprek describes the Auger recombination in the quantum wells as "surprisingly strong", and would like to see efforts directed at understanding the reasons for this. He will not be embarking on such studies, however, arguing: "Other groups have better tools for that."

J. Piprek Appl. Phys. Lett. **107** 031101 (2015)

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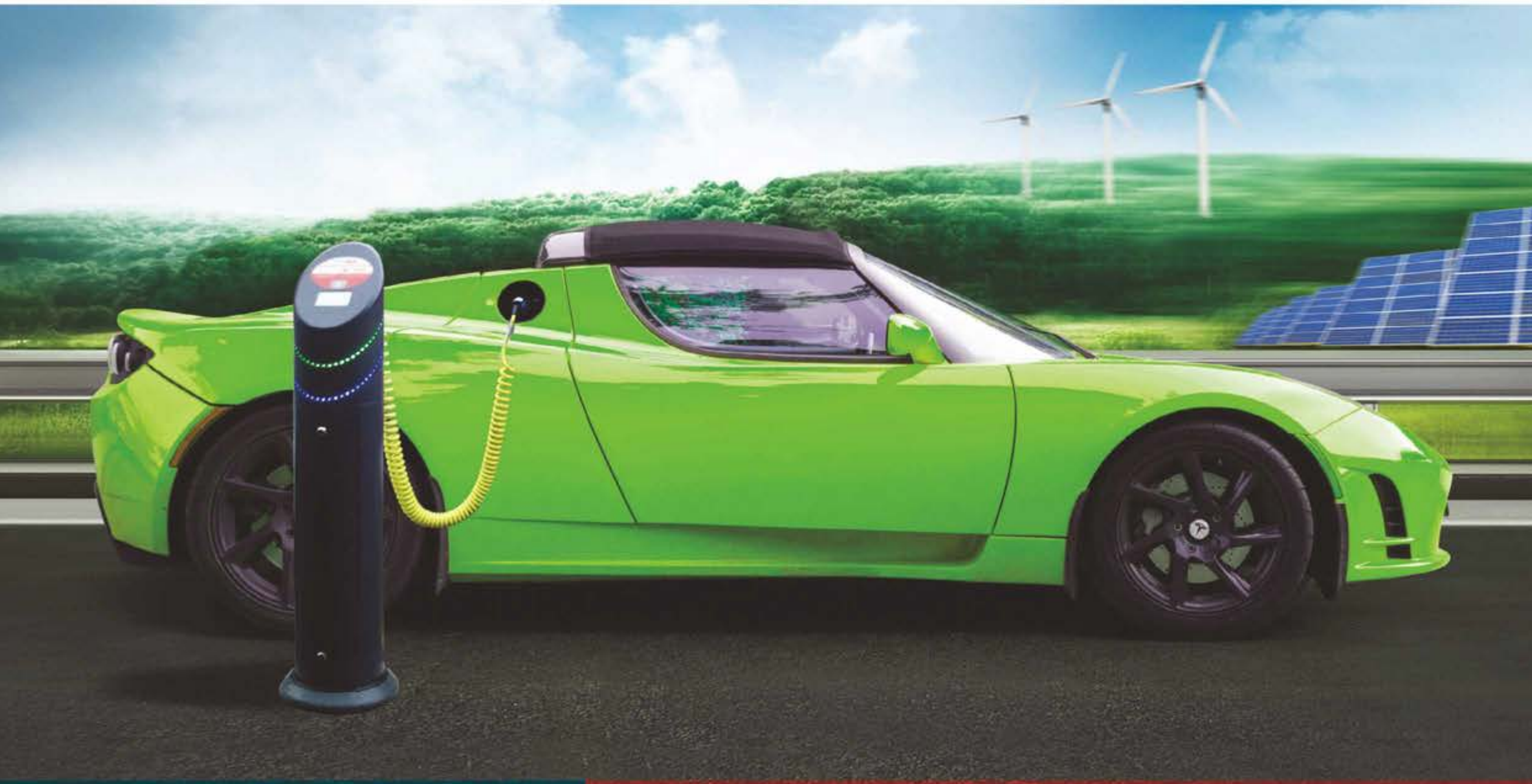


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