Institution:	**UNIVERSITY OF CAMBRIDGE**
Unit of Assessment:	**B13** Electrical and Electronic Engineering, **Metallurgy and Materials**
Title of case study:	**Low-cost high-efficiency LEDs for lighting**

1. Summary of the impact

Research on the growth of gallium nitride (GaN) light-emitting diode (LED) structures has led to the creation of two spin-out businesses (subsequently sold), has assisted *Forge Europa Ltd* in expanding its sales of LED-lighting products, has helped *AIXTRON* to achieve sales of related GaN-growth equipment [text removed for publication] , & has enabled *Plessey Semiconductors Ltd* to manufacture the world's first commercially available LEDs on 6-inch Si (& the first LEDs to be manufactured in the UK).

2. Underpinning research

Sir Colin Humphreys, Professor in the Dept of Materials Science & Metallurgy (**DMSM**) at the University of Cambridge (**UCAM**) since 1990, has a long record of research (grants listed in Section 3) on GaN LEDs, in which the light-emitting layers are quantum wells (QWs) of InGaN sandwiched between GaN barriers. The QWs emit blue light & a covering phosphor converts this to white. Bright emission is obtained for dislocation densities as high as 10^9 cm^{-2}, while for all other light-emitting semiconductors the dislocation density has to be less than 10^3 cm^{-2}, or dislocations, as non-radiative recombination centres, quench light emission. It was thought that nm-sized In-rich clusters in the QWs localized the carriers (electrons & holes) & prevented them from diffusing to the dislocations. Such clusters, observed in electron microscopy, were shown by Humphreys' group to be an artefact of electron-beam damage [1], changing the accepted understanding of why GaN LEDs are so efficient with high dislocation densities, & underpinning the group's subsequent work on high-efficiency GaN LEDs.

In collaboration with Manchester University (performing optical studies), Humphreys' group showed that carriers in the InGaN quantum wells are localized within a few nanometres, & suggested a localization mechanism [2]: monolayer-height QW thickness fluctuations, which the group observed in high-resolution electron microscopy in device structures grown in DMSM.

Although the efficiency of GaN LEDs is not highly sensitive to the dislocation density, the efficiency is reduced if the dislocation density is very high. To study this, Humphreys' group invented a novel, fast method for assessing dislocation densities in GaN [3], followed by a breakthrough [4] on how to reduce the dislocation density of GaN grown on sapphire, using porous silicon nitride interlayers. The group was able to transfer this method to growth of GaN LEDs on 6-inch Si substrates — very difficult, compared to growth on smaller-diameter sapphire or SiC substrates. The large (54%) difference in the thermal expansion coefficients of GaN & Si leads to wafer bowing on cooling from the growth temperature (~1000°C); the GaN is in tension & cracks. Humphreys' group inserted four graded AlGaN layers, carefully tailored so that their compressive stress compensates the tensile stress upon cooling, crucially ending with a flat, crack-free LED. The large (17%) lattice mismatch between GaN & Si would result in an unacceptably high dislocation density, & Humphreys' group solved this problem using a sub-monolayer SiN mask with natural holes; epitaxial lateral overgrowth from these reduces the dislocation density by two orders of magnitude.

To protect know-how, only a little (eg [5] & a patent pending [6]) has so far been published on the commercially important processing to achieve GaN LED growth on 6-inch Si.

Humphreys' group members taking up specialist roles drawing on their research:
Tim Smeeton (PhD student), 2001–4. Joined *Sharp Europe* in 2004.
Lixia Zhao (PDRA), 2006–8. Joined *Forge Europa* in 2008.
Matt Charles (PhD), 2002–5. Joined *AIXTRON* in 2007.
Clifford McAleese (PhD student, then PDRA), 2001–9. Joined *AIXTRON* in 2009.
Dandan Zhu (PhD then PDRA), 2003–12. Joined *Plessey* in 2012.
Lewis Liu (PhD student), 2007–11. Joined *Plessey* in 2012.
David Wallis (PDRA), 2011–12. Joined *Plessey* in 2012.

Other key researchers in Humphreys' group:
Rachel Oliver (Royal Comm for 1851 Exhibition Fellow, then Royal Society URF, Univ Lecturer in

DMSM, & now Reader in DMSM), 2002–present.
Menno Kappers (Senior Research Associate in DMSM), 2000–present.

3. References to the research

1*. TM Smeeton, MJ Kappers, JS Barnard, ME Vickers & CJ Humphreys: Electron-beam-induced strain within InGaN quantum wells: False indium 'cluster' detection in the transmission electron microscope, *Applied Physics Letters* **83** (2003) 5419; DOI: 10.1063/1.1636534. [129 citations as of October 2013]

2*. DM Graham, A Soltani-Vala, P Dawson, MJ Godfrey, TM Smeeton, JS Barnard, MJ Kappers, CJ Humphreys & EJ Thrush: Optical and microstructural studies of InGaN/GaN single-quantum well structures, *Journal of Applied Physics* **97** (2005) 103508; DOI: 10.1063/1.1897070. [87 citations]

3*. RA Oliver, MJ Kappers, J Sumner, R Datta & CJ Humphreys: Highlighting threading dislocations in MOVPE-grown GaN using an in-situ treatment with SiH_4 and NH_3, *Journal of Crystal Growth* **289** (2006) 506; DOI: 10.1016/j.jcrysgro.2005.12.075. [72 citations]

4. MJ Kappers, R Datta, RA Oliver, FDG Rayment, ME Vickers & CJ Humphreys: Threading dislocation reduction in (0001) GaN thin films using SiN interlayers, *Journal of Crystal Growth* **300** (2007) 70; DOI: 10.1016/j.jcrysgro.2006.10.205. [64 citations]

5. D Zhu, C McAleese, KK McLaughlin, M Haeberlin, CO Salcianu, EJ Thrush, MJ Kappers, WA Phillips, P Lane, DJ Wallis, T Martin, M Astles, S Thomas, A Pakes, M Heuken & CJ Humphreys, GaN based LEDs grown on 6-inch diameter Si (111) substrates by MOVPE, in 'LEDs: Materials and Devices for Solid-State Lighting XIII', *Proc. SPIE* **7231** (2009) 723118; DOI: 10.1117/12.814919. [9 citations]

6. UK Patent Application Number 1019301.9: "Semiconductor wafer comprising gallium nitride layer having one or more silicon nitride interlayers therein", filed 15/11/2010; application now in public domain, application now in progress to grant. International (PCT) application, PCT/GB2011/001474, filed 12/10/2011. International searches by European Patent Office received and citations assessed. Liaising with patent agents & inventors to best determine in which countries to file under an International Patent Application.

*<u>references best indicating the quality of the underpinning research</u>. The distinction of Humphreys' research in this area has been widely recognised: since 2008, he has been invited to give 10 Plenary, 4 Keynote & 33 Invited talks at international conferences. He was awarded the Platinum Medal (IOM3) in 2013. He has given 4 named lectures (Kelly, 2013; Finniston, 2012; Winegard, 2012; Cowley, 2011).

Key Research Grants (all to Humphreys as PI, or as Cambridge PI)**:**

1. "Exploratory proposal to grow and characterise gallium nitride on silicon", EPSRC, 01/02/2003–30/04/2003, £53,664.
2. "Next generation GaN-based materials", EPSRC, 01/05/2003–30/06/2006, £1,217,962.
3. "Materials challenges in GaN-based light emitting structures", EPSRC, 01/11/2006–30/04/2010, £1,362,143.
4. "A low-cost manufacturing route for gallium nitride based solid-state lighting", DTI, 01/04/2007–30/06/2010, £582,665.
5. "Nitrides for the 21st Century", EPSRC Platform Grant, 01/11/2009–31/10/2014, £826,500.
6. "Lighting the Future", EPSRC Programme Grant, 01/12/2010–30/11/2015, £3,166,773 (UCAM part of a total of £6.3M shared with Bath, Manchester & Strathclyde).

4. Details of the impact

The research of the Humphreys' group has had impact on three companies: *Forge Europa Ltd*, *AIXTRON Ltd* and *Plessey Semiconductors Ltd.*

The impact on *Forge Europa* has been from the Humphreys' group research on LED reliability, & it was highlighted in the EPSRC Annual Report 2010-2011 [1] under the heading "Economic Success for Gallium Nitride LEDs": "Professor Sir Colin Humphreys and his team at Cambridge University… have delivered positive outcomes for businesses in the lighting industry… For

example, Forge Europa, an SME in Cumbria… received the Queens Award for Innovation in 2009. Its Managing Director Peter Barton writes, '*The excellent work of the Cambridge group has proved to be of great benefit to Forge Europa and assisted our business to grow by over 100% in a 3-year period… A great deal of our knowledge is directly attributed to our links with Cambridge.*'…" Of the impact on *AIXTRON*, its Managing Director, Tony Pearce (in October 2013), writes "*Our collaboration with Professor Humphreys' group in Cambridge has been hugely valuable to AIXTRON. The research carried out by the Cambridge group not only advances understanding of the material technology, but helps us build deposition systems to meet these demands. AIXTRON remains in a dominant position, with significant revenues generated by this technology of* [text removed for publication]

. Furthermore, AIXTRON continues to develop next-generation products that will serve the future semiconductor material challenges, and our collaboration with the team at the University of Cambridge will continue to help us steer this technology."

Humphreys & two colleagues (Dandan Zhu & Lewis Liu) set up spin-offs to exploit their research, *CamGaN* in 2010 & *Intellec* in 2011, to which UCAM transferred the patent noted in Sections 2 & 3, that provides a framework for a considerable amount of know-how that was deliberately not patented. The patent & know-how provide a method for growing low-cost high-efficiency GaN LEDs on 6-inch Si. *Plessey* acquired *CamGaN* & *Intellec* in February 2012 for [text removed for publication] & hired Zhu & Liu (Fig. 1), & another Humphreys group member, David Wallis. Plessey raised funds to permit this acquisition of patent & know-how, to purchase a commercial-scale GaN growth reactor from *AIXTRON* & other equipment, & to revive a mothballed 6-inch Si processing line in its factory in Plymouth. Zhu & Wallis successfully transferred the UCAM recipe for growing GaN LED structures to the new reactor at *Plessey* in December 2012. This has enabled *Plessey* to sustain ~12 manufacturing jobs, & it is currently in the process of hiring additional staff to support the production of GaN LEDs on 6-inch Si. *Plessey* is addressing a global market: this is a clear indication of the cost savings the UCAM technology brings. The LEDs are already on the market (Fig. 2; product data sheet at: [www.plesseysemiconductors.com/doc/?id=292040]). Sales of [text removed for publication] . Until now, all the LEDs in the UK are manufactured in China or Taiwan. *Plessey* has recently raised additional funding to purchase nine more commercial-size GaN growth reactors.

Fig. 1. Vince Cable, Secretary of State for Business, Innovation and Skills, visits Plessey (15 April 2013) and hears about the GaN-on-silicon technology from Lewis Liu.

Fig. 2. Plessey's *Magic LED PLW111010* LEDs shown on vendor site *Saelig Co Inc*. [http://www.saelig.com/pr/plw111010.html]

The impact of Humphreys' group research on *Plessey* has been highlighted in: *Inside: Technology* [2]; *The Economist* [3]; & *Ingenia* [4]. *The Economist* [3] states: "Plessey's other big venture is light-emitting diodes (LEDs) for lighting homes and offices… Plessey is up against mighty competitors like GE, Philips, Samsung and Siemens. Mr LeGoff (Managing Director, Plessey) says Plessey has an edge. It can make LED lights at a fraction of the cost of rivals, thanks to a unique process developed at Cambridge University."

David Willetts, the Universities & Science Minister, writes in *Eight Great Technologies* [5]: "The team led by Professor Sir Colin Humphreys at Cambridge has developed a new cost-effective way of growing gallium nitride on silicon, which in turn increases the cost effectiveness and energy efficiency of LED lighting. Since lighting accounts for today 20% of all electricity generated in the UK, widespread adoption of LED lighting would reduce electricity consumption by 10-15%. And moreover, these are being manufactured in the UK (using the technology) by Plessey. Plessey acquired this technology in 2012 and plan to produce 500 million LEDs a year in Plymouth — the first manufacturer of LEDs in the UK".

Electronics Weekly [6] states: "Plessey got into white LEDs by buying University of Cambridge GaN-on-Si spin-out *CamGaN*… this is the first production of GaN-on-Si LEDs from any company, and Plessey has gone from never having made an LED to manufacturing with this advanced technology in 15 months."

The research of the Humphreys' group has revolutionized the manufacturing of low-cost high-efficiency LEDs and we expect that the impact of this work will continue to grow.

Main types of impact

Economic — Performance of existing business improved through new products & processes (*Plessey*, establishing the UK's first manufacture of LEDs); Spin-out business created (*CamGaN* & *Intellec*, now bought by Plessey with financial benefit for UCAM & the inventors); Business sector adopted new or significantly changed technology or process (*AIXTRON*, market leader through innovation in GaN-growth technologies); Performance improved through highly skilled people taking up specialist roles that draw on their research (members of Humphreys' group joining *AIXTRON*, *Forge Europa* and *Plessey*).

Society — Research has contributed to community regeneration (*Forge Europa* investment, creating jobs in Cumbria; *Plessey* investment, sustaining & creating jobs in Devon).

Environment — Improved through introduction of new products or processes (much broader use of LED lighting will significantly reduce electricity consumption & CO_2 emissions).

5. Sources to corroborate the impact

AIXTRON (headquartered at Herzogenrath, Germany) — claims about the impact on this company can be verified by the Managing Director at AIXTRON Ltd, Swavesey, Cambridgeshire (see also http://www.aixtron.com/en/home/).

Forge Europa Ltd — claims about the impact on this company can be verified by its Managing Director (see also http://www.forge-europa.co.uk/).

Plessey Semiconductors Ltd — claims about the impact on this company can be verified by its CEO (see also http://www.plesseysemiconductors.com/index.php).

1. *EPSRC Annual Report* 2010-2011, p. 20 (http://www.epsrc.ac.uk/newsevents/news/2011/Pages/annualreport10-11.aspx).
2. *Inside:Technology*, journal of The Technology Partnership: 3 linked articles in Issue 8 (http://www.gan.msm.cam.ac.uk/2012/08/inside-technology-issue-8/).
3. "Chips with everything" *The Economist*, 13 October 2012 (http://www.economist.com/node/21564614).
4. "Changing Lightbulbs" by Richard Stevenson, in the journal of The Royal Academy of Engg: *Ingenia*, iss 54, March 2013 (http://www.ingenia.org.uk/ingenia/articles.aspx?index=820).
5. David Willetts, *Eight Great Technologies*, Policy Exchange, 2013, p.44 (http://www.policyexchange.org.uk/publications/category/item/eight-great-technologies).
6. *Electronics Weekly*, 8 April 2013 (http://www.electronicsweekly.com/news/components/led-lighting/plessey-gan-on-silicon-led-sampling-2013-04/).
7. More media linked articles in (http://www.gan.msm.cam.ac.uk/media/).