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EXPERT OPINION

The Blue LED Nobel Prize: Historical context, current scientific understanding, human benefit

Jeffrey Y. Tsao, Jung Han, Roland H. Haitz, and P. Morgan Pattison

The paths that connect scientific understanding with tools and technology are rarely linear. Sometimes scientific understanding leads and enables, sometimes tools and technologies lead and enable. But by feeding into each other, they create virtuous spirals of forward and backward innovation [1].

In perhaps no area of human knowledge has this been more evident than in semiconductors [2]: the interactive progress in semiconductor science and technology has transformed and continues to transform both our scientific understanding of the universe and the technologies with which we live our daily lives. A testament to this are the seven Physics Nobel Prizes listed in Figure 1 that have been awarded in the broad area of semiconductors. Some of the Prizes were for technology breakthroughs – as with research surrounding Si planar processing and the integrated circuit. Some of the Prizes were for science breakthroughs – as with research surrounding the integer and fractional quantum Hall effects. And some were for nearly simultaneous science and technology breakthroughs – as with the transistor.

The most recent 2014 Physics Nobel Prize, for the blue light-emitting diode (LED), is clearly for a technology breakthrough. Indeed, it is an extreme example in which the then-prevailing scientific un-

derstanding appeared to *discourage* continued effort. All the more amazing, then, was the perserverence of Isamu Akasaki, Hiroshi Amano and Shuji Nakamura (“AAN” for short), who in the late 1980’s and early 1990’s braved seeming impossibilities and skeptics with an undaunted spirit.

In this Opinion piece, we give an informal tour through: (1) the historical context of semiconductor science and technology breakthroughs that preceded the most recent blue LED breakthrough; (2) our current scientific understanding of the blue LED breakthrough; and (3) the massive human benefit the blue LED breakthrough is unleashing.

1 The historical context [3]¹

Up until the AAN breakthroughs, the four successive semiconductor technology generations could be thought of as: Ge, Si bipolar, Si MOS, and the “conventional” III-V’s. Each generation followed a similar pattern of manufacturing process development from substrates to chips, and built and improved on hard-won knowledge from the previous generation. And each generation became part of a long chain of semiconductor innovations that continue to transform the world.

1.1 Ge: Diodes and Transistors

The first semiconductor technology was based on Ge, and its foundation [4] was laid by a Bell Laboratories team led by William Shockley, whose goal was a field-effect amplifying device to replace the triode tube.

Laying that foundation was not without its challenges. It was only after repeated failures to achieve power gain in Ge that Walter Brattain and John Bardeen finally turned to the use of a cat-whisker contact on a bar of n-type Ge, and the week before Christmas in 1947 discovered power gain. Shockley, familiar with work by Richard Haynes and Gerald Pearson also at Bell Laboratories, was ultimately able to explain the observed gain not as due to a field effect but instead due to minority carrier injection, a realization that later led to the much more manufacturable bipolar junction transistor [5].

The combined discovery and explanation by Bardeen, Brattain and Shockley of the transistor is the most foundational and important breakthrough in the history of semiconductor science and technology, and was awarded the Physics Nobel Prize in 1956. If measured by economic or social benefit to mankind, then it might also be the most important breakthrough of the 20th Century. It initiated a now 6⁺-decade chain of ever-more-powerful semiconductor

¹ For some of the early history, see, e.g., [3].

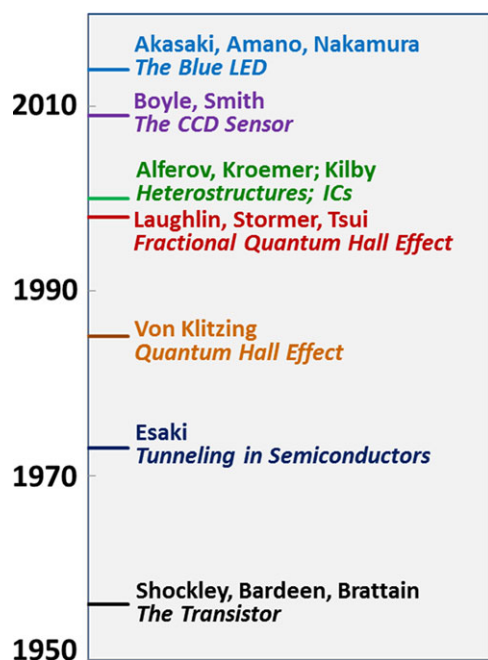


Figure 1 Timeline of Physics Nobel Prizes in semiconductor science and technology.

technologies, including those that eventually circled back to include field-effect amplifying devices.

1.2 Si Bipolar: Planar Processing & ICs

A significant handicap of Ge is its limited operating temperature range because of its narrow 0.69 eV band gap. Si, with its wider band gap of 1.1 eV, expands the operating temperature range, and thus became an intense focus of research.

Initially, slight variations on the bag of fabrication tricks developed for Ge – crystal growth, grown/alloyed/diffused junction formation, alloyed contacts and cleaved or sawed chip cutting – were used for Si. These early Si devices were good enough to replace tubes in consumer applications, [6]² but

² The first commercial Si transistor was introduced by Texas Instruments in 1954, as described in [6].

the more demanding computer, telephone and military applications could not tolerate the effects of contamination introduced at the pn junction edges.

This led, in 1958-9, to the development by Jean Hoerni at Fairchild of the native oxide (SiO₂) both for passivation and as a mask for dopant diffusion. Combined with photolithography, the resulting “planar process” became the most important combination of steps in Si processing. This in turn led almost immediately to the practical integrated circuit, by Robert Noyce (also at Fairchild), that enabled the interconnection of multiple circuit elements which Jack Kilby at Texas Instruments had earlier demonstrated in Ge.

Ultimately, Kilby (though neither Hoerni, who died in 1997, nor Noyce, who died in 1990) was awarded half of the Physics Nobel Prize in 2000 for the invention of the integrated circuit (IC). But the implementation by Noyce using Hoerni’s planar

transistor process³ was a necessary precondition to take integration beyond the range of a handful of circuit elements interconnected by flying wires, and to initiate what is now known as the Moore’s Law evolution of IC density and performance.

1.3 Si MOS: CMOS & VLSI

Continued mastery of the planar process, especially clean, controlled oxidation, eventually led to the metal-oxide-semiconductor field-effect transistor (MOSFET) – the solid-state version of the triode tube that Brattain, Bardeen and Shockley were trying to replicate.

In retrospect, MOS transistors would have been practically impossible to implement in the Ge technology available in 1947. Even in Si, it took Fairchild and Intel nearly a decade to clean up their Si crystal growth and oxidation processes to the point where MOS transistors could match the stability of bipolar transistors. Even after reaching

³ Note from R.H.H. regarding the contents of Reference [3]. For this special issue, G.L. Pearson and I tried to cover two aspects of the invention of the IC via two articles. First, an article by Kilby on the first reduction to practice in 1958 – a practice which was revolutionary but whose flying wire-bond interconnects would clearly become a nightmare with just 10 transistors in a random logic circuit. Second, an article by Hoerni on the planar process he developed in 1958-9 – a process whose multilayer interconnect capability was a necessary ingredient for ICs with thousands, then millions, then the ~10 billions of transistors on a chip that Intel will likely introduce in 2015. Unfortunately, Hoerni cancelled shortly before our deadline for health reasons, too late to invite others (especially Robert Noyce or Gordon Moore) to tell the Fairchild story.

acceptable performance and yields in both p-MOS and n-MOS transistors, it took another half decade to make *complementary* MOS (CMOS), the work-horse technology whose low power consumption enabled scaling to ever higher densities and very large scale integration (VLSI).

Enroute, a variant of the MOS-FET, the charge-coupled device (CCD), was developed, with the Physics Nobel Prize in 2009 awarded to Willard Boyle and George Smith of Bell Laboratories for its invention and use as a solid-state image sensor.

Ultimately, it is CMOS and VLSI technology that have enabled the explosion of computing power that has transformed the world to one in which smartphones and the Internet feed each other information 24/7. And, to come full circle, that computing power in turn enables science breakthroughs of even the most fundamental sort – including the recent data-analysis-rich experimental confirmation of the Higgs Boson, whose prediction was awarded the Physics Nobel Prize in 2013.

1.4 “Conventional” III-Vs: LEDs, Lasers and Transistors

Though the most important, Si is by no means the only important semiconductor material. III-V semiconductors, materials which are compounds of elements from column III and V of the periodic table, have found utility as well. The easier of these materials to work with, the III-P’s, III-As’s and III-Sb’s, are mostly so-called direct-bandgap semiconductors. Thus, they emit and absorb light much more efficiently than Si does, hence are useful for optoelectronics; and they have much higher electron and hole mobilities than Si has, hence are useful for low-noise and high-speed electronics.

These III-V semiconductors could build to some extent on the fabrication processes developed for Si. Most importantly, they have more degrees of compositional freedom than Si. The binary III-V compound GaAs is nearly completely miscible with the binary III-V compound AlAs and so the ternary alloy $\text{Al}_x\text{Ga}_{1-x}\text{As}$ is possible, as are a zoo of other ternary, quaternary and even pentanary III-V alloys. With these additional degrees of compositional freedom come the ability to fabricate devices with tailored spatial variations not only in doping but in bandgap.

Thus, the development of precision composition-tailoring epitaxy techniques – liquid-phase epitaxy (LPE), vapor-phase epitaxy (VPE), molecular beam epitaxy (MBE) and metal-organic vapor-phase epitaxy (MOVPE) – was critical. And heterostructures – whose development by Herb Kroemer (at Varian) and Zhores Alferov (Ioffe Physico-Technical Institute) was awarded half of the Physics Nobel Prize in 2000 – were also critical.

Indeed, precision epitaxy and “bandgap engineering” via heterostructures are used in virtually all modern III-V semiconductor devices. Among them are the critical forerunners to the blue LED: the red and yellow LEDs pioneered by Nick Holonyak (University of Illinois) and George Craford (Monsanto and Hewlett Packard) that are useful in their own right for signaling and displays. Also among them are the single-mode laser diodes that enable the broadband dense-wavelength-division-multiplexed optical fiber networks that are the backbone of the Internet, and the low-noise high-speed transistors used for “last mile” wireless communications to and from smartphones.

And, again to come full circle, precision epitaxy and bandgap engi-

neering technology enabled the scientific discovery of quantum fluids with fractionally charged excitations by Robert Laughlin (Lawrence Livermore National Laboratory), Horst Stormer (Bell Laboratories) and Dan Tsui (Bell Laboratories), awarded the Physics Nobel Prize in 1998.

2 III-N’s: The Blue LED

The one III-V semiconductor materials system that had remained elusive through the years of intense development of Ge, Si and the “conventional” III-V technologies were the “unconventional” III-N semiconductor materials. Early work at RCA had established a plausibility proof in the 1965-70 period that some blue light could be coerced out of GaN. But the sheet resistance of the p-layer was atrociously high ($V_f = 20\text{--}30\text{ V}$) and the conversion efficiency was unacceptably low. The major challenges: no substrate in sight that was reasonably lattice-matched to GaN so as to keep dislocation density acceptably low (seemingly a must for any minority carrier device); and no dopant process for low-sheet-resistance p-layers.

Indeed, by the 1980’s the challenges seemed insurmountable, and most researchers had abandoned the field. All the more amazing and unexpected then were the three pivotal AAN breakthroughs in the late 1980’s and early 1990’s: (a) the “magic” AlN and GaN buffer layers on sapphire with reduced dislocation densities; (b) an unexpected method to activate p-type Mg doping of GaN; and (c) the unexpected resistance of InGaN quantum well luminescence to defects. Indeed, one can see, from the citation plot in Figure 2, how these breakthroughs unleashed huge subsequent worldwide efforts in III-N semiconductor research.

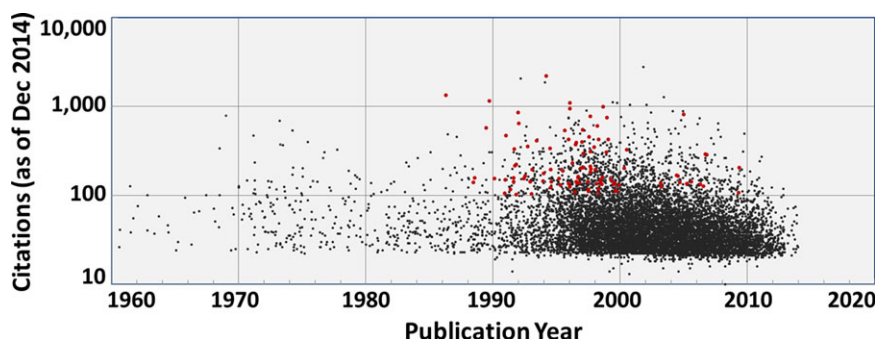


Figure 2 Scatter plot of Web of Science articles associated either with the AlInGaN materials family or with solid-state lighting, with cumulative citations plotted versus year of publication. The density of articles explodes after the initial 1986–1994 wave of AAN articles (AAN articles over all years are shown in red).

Even AAN themselves, though, fantastic as their intuition was, did not fully understand the mechanisms underlying their breakthroughs. Those mechanisms took 1–2 more decades to unravel; and here we discuss briefly our best current scientific understanding of those mechanisms.

2.1 The “Magic” AlN and GaN buffer layers on sapphire

The first breakthrough, the discovery of the low-temperature (LT) AlN buffer layer on sapphire, [7] is undoubtedly the critical foundational step in the history of III–N materials. In the absence of bulk GaN substrates, sapphire is one of the few available substrates that is compatible with the severe growth conditions associated with GaN MOVPE. But, given their mismatch both in crystallography and lattice constant, growth of GaN on sapphire is an extreme exercise in heteroepitaxy by any measure. By the early 1980s, the task was taken by most to be at best quixotic – Akasaki might very well have been the only researcher persevering in this journey, joined by a handful of associates and assistants in his group (including Amano who was then a graduate student).

Even for these two talented experimentalists, countless growth ex-

periments failed, but eventually led them to reformulate the problem as the difficulty of nucleation of GaN on highly lattice-mismatched sapphire. In the inventors’ own accounts, Akasaki described the need for “a softer or flexible thin layer” while Amano considered the insertion of Al-containing layers, based on the empirical finding that “AlGaIn layers tend to have a better morphology.” Ultimately, they circumvented the nucleation barrier through the use of an AlN buffer layer grown at an (at first accidental) much-reduced temperature. Then, a few years later, Nakamura discovered that a GaN buffer layer grown at a reduced temperature in a homebuilt “cross-flow” or “two-flow” MOVPE reactor gave yet improved results [8]. Throughout the 1990s there were debates and much confusion at major conferences regarding the choice of buffer layer from the two leading Japanese groups, as well as the role of reactor design. Substantial portions of the GaN Symposia at the Fall Materials Research Society Meetings were devoted to studies of buffer layers.

In hindsight, we now know that two phenomena were and are at play in what has come to be the standard and widely used “two-step” growth procedure.

The first phenomenon is the production of GaN nuclei on sapphire both with a high degree of crystallographic registry with the underlying sapphire, and in a narrow and optimal range of densities. To nucleate at all, an initial reduced growth temperature produces a supersaturation of precursors in the vapor phase – a phenomenon not too different from forming a thin layer of frost by breathing warm moist air on a cold window in winter. Then, because GaN has a weaker chemical bond than AlN does, GaN is “softer” and its nuclei are more susceptible to kinetic mass-transfer processes such as desorption, ripening, and solid-phase epitaxy [9]. These processes enable the crystal quality and density of the nuclei to be tuned over a wide range by growth parameters.

The second phenomenon is the lateral expansion of the GaN nuclei during a subsequent high-temperature growth phase. The lateral GaN expansion that fills the space in between the nuclei occurs without much interaction with the underlying sapphire substrate and is therefore defect free, a process now called epitaxial lateral overgrowth (ELO). Moreover, many of the residual defects (due to the nuclei themselves being imperfect) redirect and annihilate with one another during the lateral expansion

and subsequent coalescence. The full understanding of these growth dynamics is fascinating and invokes nearly all the important theories and models in crystal and thin-film growth science, including the Burton-Cabrera-Frank (BCF) theory [10], orientation selection [11], Wulff constructions [12], grain growth/ripening [13], heteroepitaxial strain relaxation [14], and adatom transport [15], to name just a few.

We also mention a less-appreciated yet significant contribution from Nakamura's work on the LT GaN buffer: his report of apparent fluctuations in temperature [16] as monitored by infrared pyrometry. In his growth geometry, the black-body radiation of the sample holder was transmitted through and modulated by the GaN layer growing on sapphire. The setup provided an invaluable record regarding the procedure he developed, and conveyed to the world the rich complexity of the growth evolution of GaN on sapphire. Nowadays, in-situ diagnostics of reflectance [17] and stress [18] are standard and indispensable in GaN epitaxy research.

2.2 Unexpected ability to activate p-type doping of GaN

The second breakthrough, the achievement of consistent p-type conductivity, is no less astounding than the first. In the late 1980's, even with a much-improved GaN layer from the two-step process, p-type doping was elusive. Akasaki and Amano tried several p-type dopants, but samples always turned out highly resistive or oppositely n-type. Adding to the pessimism, a prevailing theory was that Mother Nature's resistance to conductivity control in wide-bandgap semiconductors was fundamental and due to so-called "self-compensation" by native point

defects [19] – some wide-bandgap semiconductors, notably ZnO, have not been made p-type even to this day.

A first sign of life came when Amano observed in a scanning electron microscope that Zn-doped GaN, though showing no trace of p-type conductivity, gave a distinct blue luminescence under electron beam irradiation. This accidental discovery became an invaluable guidepost in the coming years to gauge the effectiveness of any p-doping attempt, even when concrete electrical confirmation was unavailable. Eventually, Akasaki and Amano tested the winning element, Mg, and demonstrated p-type conductivity with a treatment now called low-energy electron-beam irradiation (LEEBI). A few years later, Nakamura carried the torch further by replacing LEEBI activation with a more controllable thermal-annealing process, while also identifying hydrogen passivation as the culprit for the observed high resistivity [20]. The GaN light-emitting diode was dawning in 1992.

In hindsight, we now know that hydrogen is indeed key to the p-type doping breakthrough, but plays a complex *dual* role.

The first role is beneficial. During MOVPE of GaN, there is an abundance of hydrogen from precursors and carrier gas. As the smallest atom, hydrogen is able to diffuse freely in GaN during growth and is able to interact with impurities and dangling bonds to "passivate" these otherwise active sites. Unbeknownst to Akasaki and Amano, by forming Zn-H or Mg-H complexes, hydrogen prevents the formation of native defects which would otherwise compensate p-type doping. Hydrogen is a "Trojan horse" that allows the incorporation of Zn and Mg acceptors into GaN without triggering the "self-compensation" defense.

The second role is non-beneficial. Because hydrogen prevents self-compensation by itself passivating the Mg acceptors, immediately upon growth there is no p-type doping. The hydrogen must be removed, either through LEEBI or through thermal annealing. Moreover, the thermal annealing must take place in a hydrogen-deficient ambient, and it must be at a high enough temperature not only to break the Mg-H bond, but to enable H to out-diffuse and then overcome a significant surface barrier to recombination and release [21].

Interestingly, the general phenomenon of hydrogen passivation was well studied in silicon (especially for a-Si solar cells) and GaAs in the 1970s and 80s [22]. While these studies may or may not have influenced AAN's thinking, they did anticipate [23] the dual beneficial/non-beneficial role of hydrogen, and the possibility of post-growth activation as a general principle for circumventing self-compensation. The importance of this topic is attested to by the international patent litigation it caused in the early 2000s [24].

2.3 The unexpected insensitivity of InGaN luminescence to defects

The first two breakthroughs, however remarkable as seen from today's rear-view mirror, were greeted by the larger science and technology community with only cautious optimism. This is reflected in both Amano and Nakamura's Nobel Lectures, in which they lamented single-digit attendees at the GaN sessions at technical conferences.

The reason? The conventional wisdom at the time, from GaAs-based optoelectronics, was that defects act as non-radiative centers, like tiny black holes in semiconductors, consuming injected electrons

and holes and preventing them from interacting to emit light [25]. GaN epilayers on sapphire, even with the newly developed magic AlN and GaN buffer layers on sapphire, were more defective than GaAs by at least six orders of magnitude. The heavy favorite for bright blue light emitters was ZnSe materials with low defect density and high efficiency, albeit a questionable reliability [26]. It was by no means clear whether meaningful light emitting devices could be made from GaN.

The paradigm shift came in 1994. During that year, Nakamura began to publish results of record and increasingly higher efficiency blue-light-emitting InGaN LEDs. Many of us remember vividly his rock-star presentations, mesmerizing standing-room-only crowds of thousands of conference attendees with the blindingly bright LEDs he brought. There is no question that Nakamura was singularly responsible for transitioning InGaN-based LEDs from laboratory possibility to overnight commercial success. Once his discovery was made, GaN technology was destined to dominate all others. ZnSe materials were quickly dropped.

Nevertheless, for many years, the science and technology community remained puzzled. Nakamura's terse comment at countless conferences, "no indium, no photon!" left the community in awe, but did little to reduce their perplexedness. In the subsequent few years, the GaN community expanded exponentially along two prongs: a technology-driven prong hoping to catch up with and replicate Nakamura's results, and a scientific prong aiming to unravel the mechanisms underlying the many "gravity-defying" phenomena in GaN.

Perhaps the most memorable puzzle [27] emerged from electron micrographs from reverse-

engineered high-brightness LEDs showing dense dislocations, and the implied insensitivity of luminescence efficiency of InGaN to the presence of those defects. It took at least ten years of probes, techniques, models and revisions, to weave together a partial unravelling of this puzzle, with many detailed mechanisms still under debate.

The current prevailing theory is that alloy clustering is responsible [28]. Because Indium (In) atoms are much larger than gallium (Ga) atoms, adding InN into GaN creates local stretching (for Ga atoms) and squeezing (for In atoms). Under particular growth conditions discovered by Nakamura, the InGaN alloy tends to decompose into InN-rich and GaN-rich regions in order to reduce total strain energy. This kind of phenomenon is somewhat analogous to the un-mixing of immiscible solutions such as oil and water. Because InN-rich InGaN has a narrower energy bandgap than GaN-rich InGaN, injected electrons and holes see an energy landscape of hills and valleys that impedes their free motion, and prevents them from being consumed by the tiny black holes. Thus, one of Nakamura's most important discoveries was a procedure under which InGaN is synthesized at an exceptionally slow rate, [29] which moves the synthesis condition closer to equilibrium and likely promotes the thermodynamically driven InGaN alloy clustering. Such a spontaneous clustering process became the antidote to a defective material system.

3 Lighting the World and Beyond

The blue LED breakthrough led first and foremost to solid-state lighting (SSL), which is in the midst of transforming how we light our

world. Here, we discuss the current and potential benefits of SSL. Moreover, the blue LED breakthrough was really a series of breakthroughs in the foundational III-N semiconductor materials system, so we also discuss other transformative technologies that this materials system might enable.

3.1 Solid-State Lighting: Enormous Energy Savings

The most obvious feature of the blue LED is that it is on the short-wavelength (high-energy) side of the white light spectrum that the human eye can perceive. Thus, unlike the yellow, red, and infrared LEDs that were possible in the conventional III-V's, photons from these blue LEDs can be both energy down-converted into green, yellow and red photons via phosphors and also mixed with those downconverted photons. Thus, blue LEDs enable white light that can be used for general illumination – what we now call solid-state lighting (SSL).

Progress in the past two decades since the AAN breakthroughs has been nothing short of spectacular, for a number of reasons. Because III-N blue LEDs are similar to yellow, red and infrared LEDs in the conventional III-V's, they could leverage the epitaxy, chip and packaging infrastructure developed previously for those III-V technologies. Because artificial light has so many uses, SSL benefited from learning curves associated with a multitude of stepping-stone applications, such as displays, signage, signaling and flashlights, enroute to general illumination [30, 31]. Most importantly, because SSL is a semiconductor technology, it has the potential for very high efficiency and an exponential "Haitz'-Law" [31] evolution in key attributes such as lumens/package and cost/lumen.

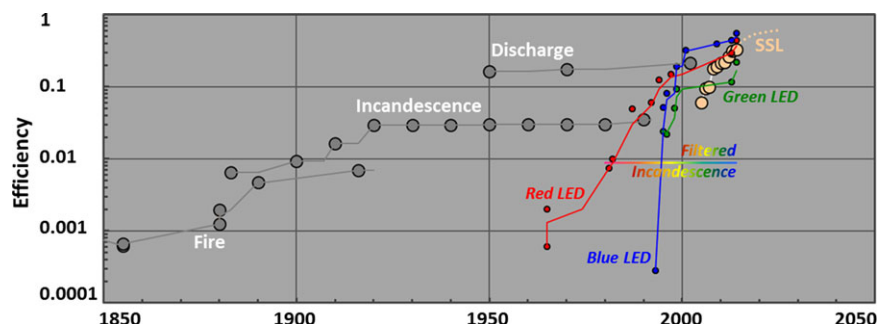


Figure 3 200-year timeline of efficiencies of lighting technologies: fire, incandescence, discharge, and SSL. Warm-white SSL past data (filled peach circles) and projected future targets (dashed peach lines) are from the U.S. Department of Energy SSL R&D Multi-Year Program Plan. Red, green and blue LED efficiencies are also shown, along with a rainbow bar indicating the efficiency of color-filtered incandescence which those LEDs compete with in monochrome (not-lighting) applications.

At this point in time, SSL's efficiency (~40% for commercial products, ~60% for research devices [32]) is already much higher than those of historical technologies such as fire (~0.025%), incandescence (~4%) and plasma discharge (~20%). And because artificial lighting is so critical to humanity and consumes so much energy (approximately 6.5% of the world's primary energy and 16% of the world's total generated electrical energy [33]), the energy savings potential of SSL is huge. A recent study [34] by the U.S. Department of Energy, based on conservative estimates for future SSL efficiency, cost and market penetration, projects energy savings in 2030 in the U.S. alone of ~3 Quads/year of primary energy: equivalent to ~260 TWh of electrical energy and ~US\$30B/year of consumer electricity cost, and to the time-averaged output of ~30 1-GW-scale power plants. World energy savings would be these scaled by 3–4x – a huge benefit to humanity attributable to any single technology (Fig. 3).

Note that these energy savings far exceed those possible for increases in the already-fairly-high efficiencies of most other energy-intensive technologies. Like increases in the efficiency of other energy-intensive technologies, though, these energy

savings are not just “one-shot,” but accumulate year-after-year.

3.2 Solid-State Lighting: More to Come

SSL has made stunning progress in efficiency and cost, but is far from “done.” Not only are further improvements in efficiency and cost likely, but new features that make SSL more *functional* are just as likely.

With respect to efficiency, SSL efficiency, as mentioned above, is already 10x higher than incandescence and 2x higher than plasma discharge. But at 40% there is yet room for improvement [35]. Blue LED efficiency decreases as electron injection density increases – an “efficiency droop” which, if better understood and mitigated, would enable major cost and efficiency benefits. III-N LED efficiency also decreases as wavelength increases from the blue to the green – a “green-gap” which if better understood and mitigated would enable all-III-N direct-emitting white light without phosphor downconversion losses. Better matching of phosphor spectra with the human eye response is a final challenge – particularly the elimination of the deep red light emitted by current commercial

phosphors to which the human eye is insensitive.

With respect to functionality, SSL lighting technology can offer much more than just raw efficiency [36]. Because LEDs are essentially point sources of light, they can in principle be precisely controlled in space (architected light). Because LEDs can be mixed and combined with phosphors or other LEDs, their chromaticity can be precisely controlled (spectral tailoring). Because LEDs have very little operating inertia, their brightness can be easily modulated in time (on/off/dimming and communication). Because LEDs are DC devices, they can be efficiently coupled with DC renewable energy sources or DC power grids, eliminating DC-AC-DC electrical inversion losses (DC compatibility). Because of the long lifetime of LEDs, bulb-fixture modularization can be eliminated, leading to deeper and more functional/artistic integration of lighting into building structures (lighting-environment integration).

To elaborate on just the example of chromaticity control: tailoring spectra to match plant response will open up new opportunities for local urban agriculture; tailoring spectra to match animal response will open up new opportunities to maximize livestock production and minimize

the impact of light on the ecosystem; and tailoring spectra to match human eye response will open up new opportunities for visual acuity and information transfer. All this is leading to a rethinking of lighting science and a re-engineering of the physiological impact of light. Recent research has even yielded an unexpected surprise: the human eye contains a *non-visual* blue-light receptor [37] that helps regulate melatonin and the Circadian rhythm, with implications for new ways to optimize sleep patterns, alertness, productivity, and general health.

To come full circle back to energy, such high-functionality lighting has the potential to decrease the consumption of light and energy further, via lights that are on only where and when needed. And to go beyond energy, such high-functionality lighting will, just as did previous generations of semiconductor technologies, almost certainly create uses that today we cannot even imagine. Some have said, and we agree, that SSL and its future variants will be so ultra-efficient and smart as to likely never be superseded by another lighting technology [31].

3.3 Beyond Solid-State Lighting

Just as the blue LED led to SSL, SSL in turn leads to other spin-offs. Three examples stand out in particular.

First, light fixtures are the most common grid-connected appliance both indoors and outdoors, so they could also become the distributed “last-meter” for sensors, actuators, communications, and intelligence for the Internet of Things.

Second, since III-N materials emit light over such a wide wavelength range, they enable current and potential-future applications such as: purple/blue lasers for blue-ray DVDs and plastic optical

fiber communications; blue/green lasers for digital projection; and UV LEDs and lasers for water purification, chemical sensing, atomic clocks, and free-space secure optical communications.

Third, because AlGaN materials have very wide bandgaps, they are useful for power electronic devices requiring high “off” voltages and high “on” currents, and which can operate efficiently at high temperature. These are key attributes for switching electrical power across the smart grid of the future and for transforming electrical power within and amongst the various distributed energy sources and appliances that will reside on that smart grid: solar cells, batteries, electric vehicles, motors, etc.

4 Epilogue

On behalf of a large and growing community of scientists and technologists working in III-N semiconductor materials, physics and devices, and of users of the applications they enable, we congratulate Professors Akasaki, Amano and Nakamura. We also pay our respects to the many researchers on whose work AAN built and benefited from – including those awarded previous Physics Nobel Prizes in semiconductor science and technology. And we cheer those whose ongoing and future work, standing on the shoulders of *all* this accumulated work, will enable yet more surprises, breakthroughs, and human benefit.

Perhaps most importantly, we cheer *both* scientists and technologists.

As noted at the beginning of this Opinion piece, the path that connects scientific understanding with tools and technologies is rarely linear. Prevailing scientific understanding often enables and unleashes new

tools and technologies. But prevailing scientific understanding is imperfect, and technology researchers must often step, as did AAN, *outside* its confines for their breakthroughs. When this happens, scientific understanding plays catch up but ultimately benefits, as it is itself often limited by the tools and technologies it uses in the “doing” of science. *Scientific understanding and tools/technologies form a deeply symbiotic system which feed, challenge and are indispensable to one another.*

Also as noted at the beginning of this Opinion piece, the importance of technology breakthroughs is particularly evident in semiconductors: in recent decades, more and more Physics Nobel Prizes have been awarded for technology breakthroughs, and of these by far the most have been for semiconductors. We live today in the information age, and the critical enablers of the information age are semiconductor technologies. We gather data with imaging and sensor chips; we manipulate data with processing and memory chips; we communicate data over long and short distances with laser diode and radio-frequency transceiver chips; and we visualize data through active-matrix flat-panel displays. Increasingly, we use data to manipulate the world via transducer chips, the most recent and important of which are SSL chips for illumination. *Semiconductor technologies aren't just conferring great benefit to mankind, they are transforming the very patterns of mankind's daily life.*

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References

- [1] J. Y. Tsao, K. W. Boyack, M. E. Coltrin, J. G. Turnley, and W. B. Gauster, *Research Policy* **37**, 330–352 (2008); L. Vinsel, T. Odumosu, and V. Narayana-murti, *Issues in Science and Technology* XXIX.2 (Winter 2013); H. Brooks, *Research Policy* **23**(5), 477–486 (1994).
- [2] J. R. Chelikowsky and M. L. Cohen, *J. Appl. Phys.* **117**, 112812 (2015).
- [3] G. L. Pearson and R. H. Haitz, Eds., *IEEE Transactions on Electron Devices* **ED-23**(7) (July, 1976).
- [4] M. Riordan, "Crystal Fire: The Birth of the Information Age" (W.W. Norton & Company, 1998).
- [5] W. Shockley, *IEEE Transactions on Electron Devices* **ED-23**(7), 597 (July, 1976).
- [6] W. A. Adcock, M. E. Jones, J. W. Thornhill, and E. D. Jackson, *Proc. IRE* **42**, 1192 (July, 1954).
- [7] H. Amano, N. Sawaki, I. Akasaki, and Y. Toyoda, *Appl. Phys. Lett.* **48**(5) 353–355 (1986).
- [8] S. Nakamura and Y. Harada, M. Seno, *Appl. Phys. Lett.* **58**, 2021–2023 (1991).
- [9] X. H. Wu, D. Kapolnek, E. J. Tarsa, B. Heying, S. Keller, B. P. Keller, U. K. Mishra, S. P. DenBaars, and J. S. Speck, *Appl. Phys. Lett.* **68**, 1371–1373 (1996).
- [10] W. K. Burton, N. Cabrera, and F. C. Frank, *Phil. Trans. R. Soc. Lond. A* **243** 299–358 (1951).
- [11] A. Van der Drift, *Philips Res. Rep.* **22**, 267–288 (1967).
- [12] C. Herring, *Phys. Rev.* **82**, 87–93 (1951).
- [13] C. V. Thompson, *Annu. Rev. Mater. Sci.* **20**, 245–268 (1990).
- [14] J. W. Matthews, A. E. Blakeslee, and S. Mader, *Thin Solid Films* **33**, 253–266 (1976).
- [15] J. A. Venables, *Philos. Mag.* **27**, 697–738 (1973).
- [16] S. Nakamura, *Jpn. J. Appl. Phys.* **30**, 1620–1627 (1991).
- [17] J. Han, T.-B. Ng, R. M. Biefeld, M. H. Crawford, and D. M. Follstaedt, *Appl. Phys. Lett.* **71**, 3114–3116 (1997).
- [18] S. Hearne, E. Chason, J. Han, J. A. Floro, J. Figiel, J. Hunter, H. Amano, and I. S. T. Tsong, *Appl. Phys. Lett.* **74**, 356–358 (1999).
- [19] G. Mandel, *Phys. Rev.* **134**, A1073–A1079 (1964).
- [20] S. Nakamura, N. Iwasa, M. Senoh, and T. Mukai, *Jpn. J. Appl. Phys.* **31**, 1258–1266 (1992).
- [21] S. M. Myers, A. F. Wright, G. A. Petersen, C. H. Seager, W. R. Wampler, M. H. Crawford, and J. Han, *J. Appl. Phys.* **88**, 4676–4687 (2000); and S. M. Myers and C. H. Seager, *J. Appl. Phys.* **95**, 520–527 (2004).
- [22] S. J. Pearton, J. W. Corbett, and T. S. Shi *Appl. Phys. A* **43**, 153–195 (1987).
- [23] G. F. Neumark Rothchild, *US Patent* 5,252,499 (1993).
- [24] See, e.g., W. Grimes, Gertrude Rothschild, Dies at 83; *Advanced LEDs*, *New York Times Business Day* (November 17, 2010).
- [25] R. J. Roedel, A. R. Von Neida, R. Caruso, and L. R. Dawson, *J. Electrochem. Soc.* **126**, 637–641 (1979).
- [26] A. Salokatve, H. Jeon, J. Ding, M. Hovinen, A. V. Nurmikko, D. C. Grillo, Li He, J. Han, Y. Fan, M. Ringle, R. L. Gunshor, G. C. Hua, and N. Otsuka, *Electron. Lett.* **29**, 2192–2194 (1993).
- [27] S. D. Lester, F. A. Ponce, M. G. Craford, and D. A. Steigerwald, *Appl. Phys. Lett.* **66**, 1249–1251 (1995).
- [28] S. F. Chichibu, A. Uedono, T. Onuma, B. A. Haskell, A. Chakraborty, T. Koyama, P. T. Fini, S. Keller, S. P. DenBaars, J. S. Speck, U. K. Mishra, S. Nakamura, S. Yamaguchi, S. Kamiyama, H. Amano, I. Akasaki, J. Han, and T. Sota, *Nat. Mater.* **5**, 810–816 (2006).
- [29] S. Nakamura, *Microelec. J.* **25**, 651–659 (1994).
- [30] S. W. Sanderson and K. L. Simons, *Research Policy* **43**, 1730–1746 (2014).
- [31] R. H. Haitz and J. Y. Tsao *Physica Status Solidi (a)* **208**, 17–29 (2011).
- [32] Y. Narukawa, M. Ichikawa, D. Sanga, M. Sano, and T. Mukai, *Journal of Physics D: Applied Physics* **43**(35), 354002 (2010).
- [33] J. Y. Tsao and P. Waide, *LEUKOS* **6**(4), 259–281 (2010).
- [34] U.S. Department of Energy, SSL Program, *Energy Savings Forecast of Solid-State Lighting in General Illumination Applications* (August, 2014).
- [35] U.S. Department of Energy, *Solid-State Lighting Research and Development Multi-Year Program Plan* (2014); P. Pust, P. J. Schmidt, and W. Schnick, *Nature Materials* **14**, 454–458 (2015).
- [36] E. F. Schubert and J. K. Kim, *Science* **308**, 1274–1278 (2005); J. Y. Tsao, M. H. Crawford, M. E. Coltrin, A. J. Fischer, D. D. Koleske, G. S. Subramania, G. T. Wang, J. J. Wierer, and R. F. Karliceck, *Adv Optical Materials* **2**, 809–836 (2014).
- [37] G. C. Brainard, J. P. Hanifin, J. M. Greeson, B. Byrne, G. Glickman, E. Gerner, and M. D. Rollag *The Journal of Neuroscience* **21**(16), 6405–6412 (2001).