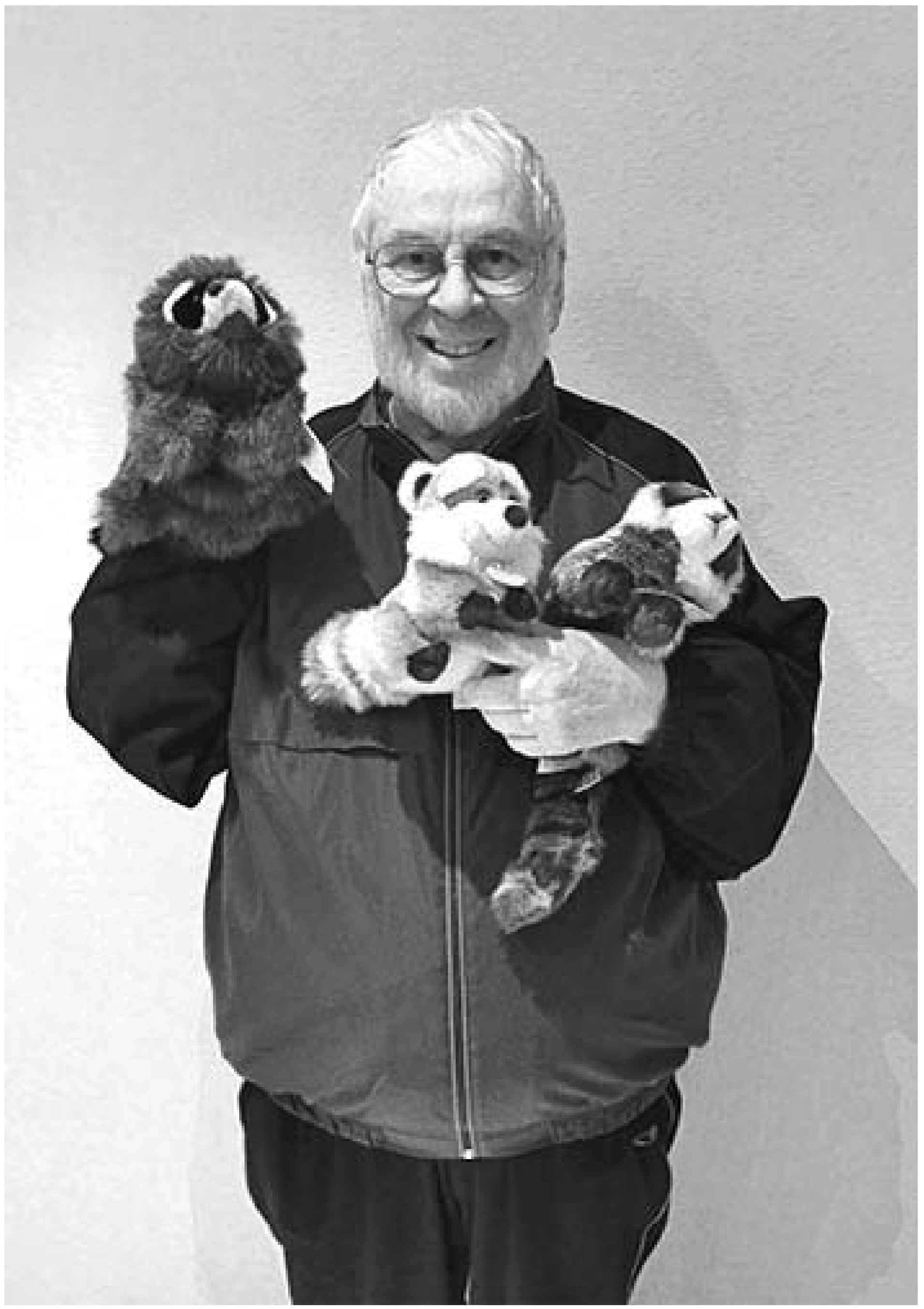
Roland

1935 - 2015



Roland Haitz

A Life of Creativity

For more on Roland Haitz, visit:

http://quarkstar.com/roland_haitz.html

Coming soon:

http://haitzs-law.com

http://quarkstar.com
info@quarkstar.com

Foreword

Louis Lerman, Jacqueline Teng
QuarkStar

We, as visual creatures, are so dependent on our sense of sight to comprehend the world around us, that the core of our imagery and metaphor for thought, discovery, epiphany, and realization has a fundamental relationship with light and vision. We use phrases such as, "I see!" or "shedding light" on a topic, or icons of old-fashioned light bulbs to indicate a "bright" idea.

And then there are descriptors such as "visionary" – one marked by foresight and imagination – and "luminary" – a person who inspires or influences others, or a body that gives light. Both seem to have been tailored for Roland in every sense and shading of the words. After all, through his insight, vision, actions and guidance, he literally helped to bring a new light to the world.

Presented here are snapshots of some of the seminal moments in his remarkable journey. His official biography as researched by the noted writer Bob Johnstone and ourselves follows the broad strokes of his life, from its modest beginnings on a farm in WWII Germany and onward through a storied career. Jeff Tsao, a long-time collaborator of Roland's, provides an up-close and personal view of his professional life in solid-state lighting.

We also selected two of Roland's papers to excerpt here. The first is the well-known collaborative white paper that was the first public cry-to-arms for an SSL revolution. The second is based on an unprinted segment of a recently published *Annalen der Physik* article – a magnificent historical technical perspective on the 2014 Nobel Prize for solid-state lighting. (The published piece was written by Roland, Jeff, and friends and printed alongside the official addresses of the three Nobel recipients.) These two papers stand as brilliant bookends to both Roland's career and the rise and establishment of the SSL industry.

Roland had been an eager and enthusiastic explorer; actively inventing, analyzing, and critically observing into his last days. Truly, he deserved the titles of "luminary" and friend. He is sorely missed.

Roland Haitz: A Life
The Official Biography

Bob Johnstone, Louis Lerman

History will remember Roland Haitz as the prophet of the last great revolution in lighting. Haitz's Law, the metric he formulated, is the equivalent for LEDs and lighting what Moore's Law is for transistors and integrated circuits. It correctly predicted the time-scale and degree to which light-emitting diodes (LEDs) would triumph over all other lighting technologies in efficiency and cost. The accuracy and utility of these predictions initiated and sustained the on-going transformation in lighting that has progressed from his vision and imagination to unstoppable revolution – in just 15 years.

But, as well as being the prophet of what is now being called the solid-state lighting (SSL) revolution, Dr. Haitz was also its catalyst. He was the first to grasp the potential of LEDs for massively reducing energy consumption, and personally led the way in securing much-needed government support for the nascent SSL industry. An early green pioneer, Roland Haitz was one of very few visionaries who was equally fundamental in creating the technologies upon which his vision would be based.

A productive scientist throughout his long and illustrious career, at age 76 he joined a startup – QuarkStar – in a collective mission to radically rethink the fundamental design of LED light sources and lighting fixtures. Dr. Haitz posed to QuarkStar the following challenge: The LED is to the incandescent light bulb what the transistor is to the vacuum tube. Just as the integrated circuit unlocked the transistor's full potential, can one create lighting's equivalent of the integrated circuit with all the power and newfound capabilities that would result from such an integrated system?

Ever the seer and prophet, the answer turned out to be a resounding 'yes'. As recently stated by

Dr. Haitz, "Everyone else is integrating the electronics. In QuarkStar, we have integrated the optics. Together we will create wonderful things that nobody can even imagine at this time."

Dr. Haitz played an active role in the creation of these solutions. Indeed, the last of his many patent applications was filed just three months before his death at age 80. With 10 patents filed in just the past four years, Dr. Haitz filed more than 50 patent applications over a professional lifetime of 50 years.

He was the recipient of many honors and awards, including (together with his former HP colleague Dr. George Craford) the prestigious Economist Innovation Award for Energy and Environment in 2007. In the week following his passing, his most recent paper was published in the prestigious European journal Annalen der Physik, an invited co-authorship presenting technical commentary and historical context on this year's Nobel Prize in Physics for the invention of the bright blue LED.

Roland Haitz was unique in being able to offer such insights and context. His seminal work with LEDs spans more than four decades, and his involvement with lighting and semiconductors dates back over 50 years to the very beginning of Silicon Valley and its legendary startups.

* * *

Roland Haitz was born in Germany in 1935 and grew up in a village between Karlsruhe and Baden-Baden in the Rhine Valley. On his father's side, the family was all farmers for whom the fruits of the industrial revolution remained scarce. Their farm still depended on horses to pull logs to the sawmill in winter and to plow fields in summer. His maternal great-grandfather had been a school principal, while his grandfather started a small grocery store. It was from watching his grandmother tally items that Dr. Haitz learned basic arithmetic, well before he started school. Fascinated by numbers, he was always top of his class in mathematics.

At Munich Technical University, Roland Haitz graduated with a diploma in physics a full two years ahead of his peers. His farm-bred willingness for hard work, coupled to a grounded sense of humor, acted as a magnet for the most exacting and challenging of teachers and mentors. Dr. Haitz enjoyed the irony that, at the height of the Cold War, he could claim a Stalin Prize winner and an American Nobel Prize winner as his scientific 'fathers'. His scientific 'grandparents' were equally impressive.

His principal advisor in Munich was Nikolaus Riehl, a student of the discoverers of nuclear fission, Lise Meitner and Otto Hahn. Riehl himself worked on the German atomic bomb projects during WW2. Captured by the Russians at the end of the war to work on their atomic bomb (hence, the Stalin Prize), Riehl was repatriated to Germany just in time to become Roland Haitz's first great mentor.

But Riehl was also a world expert on luminescence and one of the inventors of the modern fluorescent lamp. Riehl patented the concept of coating the inside of a glass discharge tube with fluorescent materials, producing a light source more efficient than the filament bulb by an order of magnitude. Done in conjunction with Osram, Riehl's work catalyzed the early efforts of GE, eventually leading to the fluorescent tube's widespread commercialization. Through Riehl, Roland Haitz was almost certainly made aware of the idea that a new, more efficient, physics of light generation can have a global impact on lighting.

But the far greater influence was Nobel Prize winner William Shockley, co-inventor of the transistor. For his graduate work, Roland Haitz wanted to work on the most promising field, which at the time was semiconductors. But America beckoned as well. Should he do a PhD? Or go to America?

An entrepreneurial solution presented itself when he met Dr. Shockley on a visit to Munich. Shockley had just won the Nobel Prize four years before, and the young Roland Haitz had not even graduated. Neither spoke the other's language. But communicating for hours via pencil and paper, by the end of their lunch, he was hired as Shockley's new graduate student. "Being in the right place at the right time with a little luck can have big effects," was how Dr. Haitz modestly described this meeting 50 years later.

In 1961, Shockley's newest graduate student left Germany and moved to Mountain View, California, to work at the world's first semiconductor startup, Shockley Semiconductor Lab. (Later changed to Shockley Transistor, it is from this startup that Silicon Valley's legendary semiconductor companies are descended, including Fairchild, Intel, National Semiconductor, AMD, and even the VC firm Kleiner, Perkins.) From Shockley, Dr. Haitz learned how to take a complex subject and translate it into language people could understand. "I always try to bring things down to the least complicated issue," he said, "and if you can write a formula, then great." Haitz's Law is the classic example of this ability.

Having received his PhD under Shockley, with his first patent co-invented with Shockley himself, Dr. Haitz moved to Texas Instruments in 1964. But Dallas summers were too hot for him, so after five years he moved back to Palo Alto to work for Hewlett Packard. There, Dr. Haitz found "a nearly ideal job," managing optoelectronics research and development. It was a role that allowed considerable scope for his creative abilities. One early product he was responsible for, an optocoupler (an LED-based device used to isolate electrical circuits), proved extremely profitable. In 1983, Dr. Haitz was promoted to CTO of HP's Semiconductor Products Group, a position he held for the next 19 years.

Managing, leading, and personally innovating in both optoelectronics and semiconductor R&D, he was responsible for many of HP's early LED products from printer heads to display technologies. One in particular was the alphanumeric display for HP's pocket-sized scientific calculators – it was Dr. Haitz's ideas that allowed the calculators to be hand-held in size, yet have highly legible displays. HP's calculators turned out to be a huge global hit. They were one of the earliest pioneers in what has become the portable hand-held revolution, owned by most every professional in any field involving computation. Another display innovation that Dr. Haitz set the global standard for is the ubiquitous seven-segment display still seen everywhere today, from microwaves to elevators.

Dr. Haitz was also the instigator of the high-power LED market. Initial attempts in the late 1980s to implement solid-state car brake lights lined up dozens of low-power LEDs. He took one look and snorted, "This is an unnatural act!" (a favorite expression). Better to make one big chip and then stick it in a package that could handle the heat. The resulting high-power LEDs would come to dominate the automobile signals market, now a multi-billion dollar a year industry.

"He was not one for systematic engineering management," a former co-worker recalled. "Organization and documentation systems and training did not appeal to him." "Roland was very often wandering around, checking up with the engineers and looking to see what they were working on," another ex-colleague remembered.

With his guttural growl and crusty, no-nonsense manner, Dr. Haitz made his presence felt. But behind the gruff exterior he proved a generous mentor, always willing to take the time to teach useful lessons and surprising people with his idiosyncratic sense of humor.

Roland Haitz's influence and leadership ranged well beyond Silicon Valley and engineering. In 1991, in response to the threat from Japanese competitors, he co-founded the Washington-based Optoelectronic Industry Development Association (OIDA). His 1993 OIDA strategic roadmap paper on *Opportunities in Optoelectronics* clearly demonstrates a farsighted leadership and global perspective in both technology and business. For someone whose background was R&D, Dr. Haitz was very committed to business. In his last years at HP and its spin-off Agilent, he saw himself as much a financial analyst as a physicist. He would attempt to inculcate basic business principles into the young engineers he supervised, with many of his junior researchers later starting their own firms. His proud boast was that the Optoelectronics Division at HP was as influential in seeding the solid-state lighting industry as the Shockley Lab and Fairchild had been in semiconductors.

With respect to lighting, the pivotal point in Dr. Haitz's career came in 1994. Following a tour of Philips Lighting's laboratories in Holland, Roland Haitz's key insight was that the future of LEDs lay in general lighting, a huge market. By 1999 he had persuaded HP's management to establish Lumileds, a joint venture with Philips, the company quickly becoming a leading manufacturer of high-power LEDs.

Dr. Haitz had tracked the progress of LEDs since the early 1970s. In 1999 he plotted his data as a graph, from which he then derived the formula that bears his name. Haitz's Law states that every decade, the amount of light output by an LED (measured in lumens) increases by a factor of twenty, while the price per lumen falls by a factor of ten. Extrapolating the lines, Dr. Haitz estimated that by around 2005, LEDs would begin to compete with conventional light sources.

The implications went far beyond scientific curiosity. LEDs use about eighty percent less power than incandescents. When he calculated the potential energy savings nationwide, the numbers were huge … as much as $20 billion dollars saved per year, just by replacing America's incandescent and halogen lamps. Global savings would be much larger. This is what convinced him: "We have to do something!"

Compelling an argument as it was, a serious financial and engineering catch threatened its realization. The LED industry could not afford, by itself, to make the improvements to LED technology and increases in production capacity necessary to achieve such savings. The only solution, Dr. Haitz saw, was to devise a strategy for eliciting support and funding from the federal government.

To help make this happen, Dr. Haitz joined forces with others from Hewlett-Packard and Sandia National Laboratories (Jeff Tsao, Fred Kish, and Jeff Nelson) for the writing of a white paper, *The Case for a National Research Program on Semiconductor Lighting*. In October 1999 Dr. Haitz then presented it in Washington DC. This is considered a seminal work in the history of solid-state lighting – the gauntlet was thrown. Light emitting diodes were already displacing incandescent bulbs in colored-light applications like traffic signals. With proper funding, he predicted, rapid improvements in brightness were possible that would ultimately create the ideal light source.

Worldwide, the electricity consumed by lighting would drop by more than half, Dr. Haitz forecast: "This new light source will change the way we live, and the way we consume energy." Based on Dr. Haitz's rigorous analysis, within months of the paper's publication, calls for similar national government-industry initiatives went out in Korea, Taiwan, China, and in particular, Japan.

In 2002, Dr. Haitz retired after 35 years at Hewlett Packard/Agilent Technologies, where the products developed under his leadership – the LEDs, optocouplers, and display technologies – continued to evolve. These in turn significantly contributed to the ongoing profits of the HP-derived companies Avago (originally the semiconductor division of HP at which Roland Haitz was the CTO and now a top 20 global semiconductor company) and Lumileds (a top 5 global LED company where much of Dr. Haitz's work was done in conjunction with his HP friend and colleague, former Lumileds CTO Dr. George Craford).

Dr. Haitz 'retired' in order to start the next stage of his career – overseeing, catalyzing, and lobbying for the industry he had done so much to nurture. For the next few years, Dr. Haitz was relentless in his writing and speaking engagements, taking every opportunity to communicate his vision for the lighting industry. His appeal to the US government was ultimately successful – the US Energy Policy Act of 2005 authorized funding of around $500 million over ten years, just as Dr. Haitz and his colleagues had proposed in 1999.

In 2010, Dr. Haitz paused to take stock of progress. Dramatic developments had occurred in the decade since the 1999 white paper. This resulted in another seminal paper with Jeff Tsao, *Solid-State Lighting: Why it will succeed, and why it won't be overtaken*. Unexpected new applications had popped up, like LEDs as backlights on mobile phones and flat screen televisions. Such large markets massively boosted LED production and lowered costs, continuing to follow Haitz's Law.

Yet the biggest change was the attitude of the otherwise staid lighting industry. Fixture makers had initially regarded LEDs as mere novelty. Filament and gas-filled bulbs and tubes had sufficed for over a hundred years. But fueled by Shuji Nakamura's Nobel-prize winning innovations, white light solid-state sources kept getting brighter (as Haitz's Law predicted) until they became impossible to ignore.

"Of all the green energy technologies … solid state lighting is clearly the sleeping beauty," Roland Haitz liked to say. Eventually, he felt confident, all conventional lighting technologies were headed for the history books.

But it was going to take some time. Invited to London in 2011 to participate in the *Economist's* annual technology forum, Dr. Haitz explained, with characteristic humor, why the prophet of the solid-state lighting revolution did not yet have any LED lights in his own home:

"I know how good they can be, and they are not yet there; I know how cheap they can be, and they are not yet there; and I know they will outlast me, and I don't want to be annoyed for the rest of my life that I have bought such stupid junk!"

To solve these birthing problems of technical performance and system economics, Dr. Haitz joined forces with QuarkStar, a start-up that combined fellow luminaries in the solid-state lighting community with up-and-coming younger talent. He ended up spending four years with QuarkStar, a full quarter of the 16 years of professional efforts he dedicated solely to making the solid-state lighting revolution a reality. Frequently turning down family vacation trips because he was having 'as much fun' as in his early days at HP with 'Bill and Dave', Dr. Haitz synthesized and extrapolated all that he had learned and conjectured about LEDs, lighting, and solid-state optics from the previous 50 years.

A Life: The Official Biography

His stated ambition: to help define what that "Promised Land of Lighting" should be. "We are now rapidly approaching the end of the incandescent light bulb. We are not only sending the Edison bulb into the museum – we are booting out all conventional light bulbs, including linear fluorescent and metal halides, in the transition to integrated and smart SSL components." (As befits a prophet, he signed his early communications 'Moses', walking the line between whimsy and insightful experience.)

Dr. Haitz was well aware that the electronics revolution of the 20th Century came not from the individual transistor by itself, but from the IC – the integrated circuit brought into being in large part by fellow Shockley alums. Dr. Haitz challenged QuarkStar to address what he saw as the next overarching challenge to the entire lighting industry: "As the LED replaces filament bulbs and fluorescent tubes, what is the integrated circuit equivalent for lighting? Just like the IC did for the transistor, what is the integrated system of lighting that will liberate the true potential of the LED?"

The quest to answer this challenge became Dr. Haitz's next contribution to lighting. Focusing on "herding photons" at the LED package level, Dr. Haitz personally led a small team within QuarkStar, composed of HP veterans and Hertz Fellows. Their mission was to understand the journey of every individual photon on its outward path from the LED itself, so that not a single one would be wasted.

According to Dr. Haitz, "I've been thinking about photon herding since I've been doing optoelectronics, which started in the late sixties. I was doing photon herding with the seven-segment display forty years ago. What I did there became the production standard for the rest of the world for this class of products. And I learned a few tricks that I never talked about because they were so subtle, and that's what I'm re-applying now." This has led his team to new designs for LED packages that approach theoretical efficiencies, and suggests previously unheard-of capabilities that integrate the functionality of modules at the package scale.

Dr. Haitz similarly inspired QuarkStar's younger engineers. Their answer to his challenge was the creation of a second, completely independent approach of integrated systems on the fixture level, one that was even more congruent to the modular and scalable nature of integrated circuits. This new lighting technology was first unveiled in public only a few weeks before Dr. Haitz's passing. QuarkStar's Moses, like his namesake, was unable to attend in person, but he was present in spirit as prophet and guide.

This integrated systems approach brings the entire light fixture closer to the scale of LEDs. It is such a fundamental game-changer that, even while the company was cloaked in the 'stealth-mode' common to Silicon Valley startups, QuarkStar won awards from the US Department of Energy and the international lighting industry.

These technologies elegantly solve many of the technical and economic problems of conventional LED lighting, reducing the size and cost of light fixtures by multiples while commensurately increasing their functional capabilities. This congruency to Haitz's law for LED chips is no accident. The parallel reduction in size and cost of LED fixtures and increased performance is not only a direct consequence of the standard Haitz's Law at the LED scale, but also suggests that 'the law' can be extended to the scale of LED modules and fixtures. Considering all that has come from the original chip-scale version of Haitz's law, this is exciting indeed. Roland Haitz's Law continues to lead the future.

Dr. Haitz's last remarks on solid-state lighting underscore the progress to come. They were made just one week before his passing: "Solid-state lighting is where the internet was in the 1980's. Just as we could not then have predicted what the internet is now, 30 years later -- we cannot foresee all that light and lighting will become in the next decades. We know simply that it will be wondrous and beautiful."

Dr. Haitz is survived by his wife of 49 years, Bente Haitz, who was a true partner in the remarkable journey of all that he did and accomplished. He has two children, a son Lars and a daughter Kirsten, and three grandchildren.

Roland Haitz: 20 Years of Mentorship, Collaboration & Inspiration

Jeff Tsao
Sandia National Laboratories

Roland Haitz had by any measure a rich life. Others can speak better to his formative pre-professional years, and to the two early phases of his professional career: his "semiconductor device electronics" phase while at the Shockley Semiconductor Lab and Texas Instruments, and his "low-power optoelectronics" phase while at Hewlett-Packard. I had the privilege of working with Roland during the third phase of his career, in what might be called his "power optoelectronics" phase while at Hewlett-Packard, Agilent and QuarkStar. These were the two decades spanning roughly 1995 through 2015 – major chunks of both his and my careers. Throughout this period, I benefited enormously from his mentorship, collaboration and inspiration, and it is a pleasure to reminisce about these.

Our Papers Together

Let me start with the papers we co-authored together. There were only four, so not many, but I like to think we made each one "count" -- and behind each paper are stories that shed light both on Roland's character as well as on some of the history.

1999: "The Case for a National Research Program on Semiconductor Lighting"[1]

I sometimes think of this as the "solid-state lighting goes from impossible to possible" paper. It was "just" a white paper: at the time it was too forward-looking and too much of a call to action to be published in a scholarly journal. Instead, it was sponsored and distributed by the Optoelectronics Industry Development Association, whose then-President, Arpad Bergh, knew both Roland and me and encouraged us to put our heads together to write it. We enlisted help from two collaborators, Fred Kish (then at Hewlett-Packard) and Jeff Nelson (then at Sandia), and got to work. The theme of the paper, that solid-state lighting for general illumination was someday possible and could lead to massive energy savings, was not totally new: in 1998, Japan had initiated their "Light for the 21st Century" national project with just such a theme.[2] But our paper provided the first *quantitative* data and projections in support of the theme. The data were from Roland's diligent and prescient collecting of quantitative cost and performance benchmarks from many years of light-emitting-diode (LED) technology:[3] when plotted logarithmically versus year, it showed a Moore's-Law-like exponential progress that has since come to be known as Haitz' Law; and when extrapolated out a couple of decades into the future, it suggested that LED technology would someday out-compete traditional technologies for general illumination. The projections were from Roland's quantitative analysis of the co-evolution of industry revenue, research and development (R&D) investment, technology evolution, market penetration, and global energy savings. Of course, even buttressed by quanitative data and projections, it took courage[4] to extrapolate out so far into the future – LEDs circa 1999 were so wimpy – so it is a testament to Roland's courage and vision that he was willing to call so boldly for a national research program to help turn that extrapolation into reality.

1 R. Haitz, F. Kish, J.Y. Tsao, J.S. Nelson, "The Case for a National Research Program on Semiconductor Lighting," presented at the Annual Forum of the Optoelectronics Industry Development Association (1999).

2 See, e.g., the "Light for the 21st Century: The Development of Compound Semiconductors for High Efficiency Optoelectronic Conversion" Year 2000 Report of Results (Japan Research and Development Center of Metals' National Project, 2000), English translation by K.V. Sereda and J.Y. Tsao in 2002. The target of this program was "an energy efficiency twice that of traditional fluorescent lamps, through the use of long-life, thin, lightweight, GaN-based high-efficiency blue and ultraviolet LEDs."

3 The data were from the famous optoelectronics division of Hewlett-Packard that Roland headed for many years. This division was to LED technology in the 1990's-2010's what Fairchild was to silicon integrated circuit technology in the 1950's-1970's: the organization from which a diaspora of alumni went on to distinguish themselves at LED companies throughout the world.

4 That courage didn't come from thin air, but as is often the case with Roland came from a combination of theory and data: first was our understanding from theory that the extrapolation was not forbidden by fundamental physics; second was Sandia's recent experimental demonstration of a semiconductor light emitter with an efficiency, 50%, of the order of what we were extrapolating to [K.L. Lear, K.D. Choquette, R.P. Schneider, S.P. Kilcoyne, K.M. Geib, "Selectively oxidised vertical cavity surface emitting lasers with 50% power conversion efficiency," Electronics Letters 31, 208 (1995)]. Note that Sandia's demonstration was a powerful existence proof, but was in the infrared rather than the visible, and at power levels much lower than what would eventually be needed for general illumination.

Roland Haitz: 20 Years of Mentorship, Collaboration & Inspiration

2010: "Solid-State Lighting: 'The Case' 10 Years After and Future Prospects"[5]

I sometimes think of this as the "solid-state lighting goes from possible to certain" paper. The ten years from 1999 to 2010 were full of surprises, and this "ten years later" paper gave us the opportunity to discuss where we went right and where we went wrong with our original predictions. Perhaps where we were most right was that Haitz' Law did indeed continue, not just for the red LEDs that the original Haitz' Law data had been collected for, but for the white LEDs that were necessary for the holy grail of general illumination. That continuation of Haitz' Law triggered a virtuous spiral of industry and government R&D investment, technology improvement, penetration of existing (and development of new) markets, and industry revenue available for further R&D investment. Nonetheless, we were surprised by some of the details of the virtuous spiral. For example, we were surprised that the "green-yellow gap" hadn't been closed, and that phosphor approaches to white light ended up prevailing. We were also surprised at some of the stepping-stone markets that the industry was using to drive progress enroute to general illumination – in particular the increasing importance of the market for LED-backlit liquid-crystal displays. Indeed, because of the magnitude of these stepping stone markets, industry R&D investment was both larger than we had anticipated and larger than the government R&D investment that was important but ended up smaller in scale than we had originally called for. Nonetheless, through both the non-surprises and surprises, incredible progress *was* made, and by 2010-2011 one could for the first time say that the displacement of traditional by solid-state lighting had become a future certainty.

2011: "Solid-State Lighting: Why It Will Succeed, and Why It Won't be Overtaken"[6]

I sometimes think of this as the "solid-state lighting goes from now to forever" paper. It was

5 R.H. Haitz, J.Y. Tsao "Solid-state lighting: 'The case' 10 years after and future prospects," Physica Status Solidi (a) 208, 17-29 (2011).

6 R. Haitz and J.Y. Tsao, "Solid-state lighting: why it will succeed, and why it won't be overtaken," Optik & Photonik 6.2, 26-30 (2011).

one thing to be convinced that solid-state lighting had become a certainty. But, in trademark bold Roland fashion, this paper went further, and made the prediction that, in the end game, the characteristics of solid-state lighting would make it difficult if not impossible for it to be overtaken by *any* subsequent technology. Those characteristics are: continued headroom for efficiencies to 75% and beyond; easy compatibility with digital control for increased functionality and especially increased efficiency of light *use* (not just light creation);[7] and a lighting element whose purchase cost was negligibly small compared to its operating cost.[8] Even with these powerful characteristics the prediction is bold, but, again, with his trademark courage Roland was willing to make it.

2015: "The Blue LED Nobel Prize: Historical Context, Current Scientific Understanding, Human Benefit"[9]

This was our last paper together, and the last paper of Roland's life. With the awarding of the 2015 Nobel Prizes in physics to the inventors (Isamu Akasaki, Hiroshi Amano and Shuji Nakamura) of the blue LED, it was clear to the world how important solid-state lighting was going to be to humanity. This paper was an opportunity to put solid-state lighting into a much larger historical perspective. We enlisted help from two collaborators, Jung Han (Yale University) and Morgan Pattison (advisor to the Department of Energy), and got to work. The paper ended up having three major parts: an overarching historical context consisting of the many other semiconductor science and technology breakthroughs that preceded the blue LED breakthrough; our current scientific understanding of the blue LED breakthrough itself; and the massive human benefit the blue LED breakthrough was just beginning to unleash. Having been a student of William Shockley, and having either participated in or watched unfold in close proximity virtually every semiconductor science and technology breakthrough, Roland was uniquely positioned to write the overarching historical context.[10] He chose to divide the

7 Roland was fond of saying that photons from near-point-source semiconductors, unlike those from traditional incandescent and gas-discharge lamps, are "trained early" and thus would be more easily directed in space ("photon herding," he would often call it). Combined with easy control of the intensity of semiconductor light emitters, Roland was a big fan of the digital control of solid-state lighting in time and space for enhanced efficiency of use. He was also a big fan of other kinds of digital control, e.g., of the chromaticity of solid-state lighting for human health.

8 This last characteristic was one that Roland often came back to in his thinking. Because lighting-device purchase cost would ultimately be small compared to lighting-device operating cost, Roland argued in 1999 that the return on industry investment in solid-state lighting R&D would be both insufficient as well as incommensurate with benefit to society, hence industry R&D investment needed to be augmented by national R&D investment. Using exactly the same argument, Roland argued in 2011 that the return on industry R&D investment in any newer technology would likely also be insufficient to enable that newer technology to develop to the point of being competitive with solid-state lighting.

9 J.Y. Tsao, J. Han, R.H. Haitz, and P.M. Pattison, "The Blue LED Nobel Prize: Historical context, current scientific understanding, human benefit," Annalen der Physik 527, A53-A61 (2015).

10 During the first, semiconductor device electronics, and second, low-power optoelectronics, phases of his career,

breakthroughs into five periods: Ge diodes and transistors, Si bipolar, Si MOS (metal-oxide-semiconductor), "conventional" III-V's, and "unconventional" III-N's. Having myself only lived through the latter two of these periods, I would not have had the confidence to place either the "conventional" III-V's or the "unconventional" III-N's at the same level as Si. But Roland did have that confidence, and his accounting of why, and his recounting of the key breakthroughs of each period, were done with his characteristic attention to truth, detail, and sense of historical context.

My Lessons Learned

Throughout these twenty years, I had the privilege of many conversations with Roland. Some conversations were during the co-authoring of our papers – we debated pretty intensely both the validity and presentation of the various arguments. But many conversations were in between the co-authoring of our papers – particularly during the last few years of his life when we tried to have chats, whenever his health permitted, every few weeks. These were our "catch up" conversations: Roland was intensely interested in the latest breakthroughs in research; I was intensely interested in Roland's unfailingly interesting insights into the importance (or unimportance!) of those breakthroughs. Space and my memory are too short to enumerate all that I learned from Roland. But if I were to try to capture a few of the "big" lessons I learned – lessons I wish I had learned at a younger age and indeed lessons that I would most wish to pass on to a younger generation of researcher – it would be these.

Truth. I think, first and foremost, Roland was after truth. He wasn't fussy about how it came: if through data, he was happy; if through deep analytical thinking, he was happy; if through unimpeachably credible sources, he was happy. But his bar for what he would take to be truth was set very high. As those who have interacted directly with him can attest, Roland was not shy to interrogate, to criticize, and to counter-argue – until his very high bar was met.[11] Conversations with Roland were rarely "feel-good" conversations filled with social niceties; they were intended to reveal truth. Never would an emperor with no clothes have gotten past Roland. And never would Roland have made a technical decision driven by artificial social consensus; he insisted always on deep intellectual debate. His confrontational style was not for everyone, but to me it was refreshing and inspiring.

Roland served as editor of the well-known IEEE Transactions on Electron Devices. In 1976, he invited Gerald Pearson to co-edit with him a special issue that he was quite proud of. It contained historical accounts of the most important semiconductor science and technology breakthroughs up until that time: G.L. Pearson, R.H. Haitz, Eds., "Special Issue: Historical Notes on Important Tubes and Semiconductor Devices," IEEE Transactions on Electron Devices ED-23(7) (July, 1976).

11 Or woe to the person he was interacting with if it were not met!

Courage. I think, second, Roland was courageous. Maybe this is connected to his desire for truth. Sometimes the truth leads you to conclusions that are difficult to believe on the face of it, and then it takes courage to follow those truths. Sometimes people call that kind of follow-through "vision," and certainly the outcome can be visionary. But, more than anything else, I think it represents courage. Roland had critics. Certainly it was easy for those who hadn't thought through the arguments to view his call for a national research program in solid-state lighting as simply a ploy to get government funding for a research area of parochial self-interest. But Roland's call for such a national research program was by no means parochial self-interest – he would not have tolerated that for even a nanosecond. His respect for truth and his courage to follow truth to its logical conclusion was what led him to his call for a national research program in solid-state lighting.

Work. I think, third, Roland placed enormous value on work, and on the contributions to society that followed from work. Even after he retired formally from Agilent, and even as he struggled with the cancer that he ultimately passed away from, his passion for work was enormous. During the four months before he passed away, he spent much effort, despite severe pain, co-authoring the Blue LED Nobel Prize paper discussed above. During the four years before he passed away he had also been hard at work at QuarkStar on "asymmetric light valves," an ingenious new concept that may form the basis for a future generation of very-high-extraction-efficiency blue and white LED light engines. For many, work is the means someday to not work. For Roland, my sense is that work was not that at all; it was something to embrace because it is an integral part of life and gives it purpose.

Engineering. I think, fourth, and perhaps it should be higher up in this list, Roland had a genius for engineering, and by that I mean a genius for understanding the interfaces between engineered products and, on the one side, their scientific working principles and, on the other side, the economics of their markets. Roland was a master of those interfaces. An example of his exercising of the former interface was the asymmetric light valve mentioned above, in which he elegantly brought together geometric ways of looking at light propagation and scattering in the presence of curved interfaces. An example of his exercising of the latter interface was his projections in 1999 of the likelihood of future energy savings due to solid-state lighting. He carefully modeled industry return on R&D investment before counterintuitively concluding that, for an energy service such as lighting, the long-term return to the manufacturer of the device would be insufficient to justify the investment to improve the efficiency of the device – an "externality" that required government investment. I didn't always appreciate it at the time, but in hindsight I realize that what he was doing in these and other examples is really the essence of engineering.

Roland Haitz: 20 Years of Mentorship, Collaboration & Inspiration

Behind Every Great Person ...

I close by mentioning that, through the years I worked with Roland, I also had a few times the privilege of interacting with his wife, Bente. Their devotion to each other was inspiring to me. Roland would often joke, when he was retiring from HP, about the "honey do" projects that Bente had lined up for him, always with a sense of pride and affection.[12] I am reminded that a community of support is essential to all great people; Bente certainly provided that for Roland.

12 Of course, the changing of light bulbs in high places was on his list to someday eliminate, by replacing light bulbs with long-lived solid-state lighting!

The Case for a National Research Program on Semiconductor Lighting

This white paper was first presented publicly at the 1999 Optoelectronics Industry Development Association (OIDA) forum in Washington DC on October 6, 1999.

Roland Haitz[1], Fred Kish[1], Jeff Tsao[2], Jeff Nelson[2]

[1]Hewlett-Packard Company, [2]Sandia National Laboratories

Executive Summary

Dramatic changes are unfolding in lighting technology. Semiconductor light emitting diodes (LEDs), until recently used mainly as simple indicator lamps in electronics and toys, have become as bright and efficient as incandescent bulbs, at nearly all visible wavelengths. They have already begun to displace incandescent bulbs in many applications, particularly those requiring durability, compactness, cool operation and/or directionality (e.g., traffic, automotive, display, and architectural/directed-area lighting).

Further major improvements in this technology are believed achievable. Recently, external electrical-to-optical energy conversion efficiencies exceeding 50% have been achieved in infrared light emitting devices. If similar efficiencies are achieved in the visible, the result would be the holy grail of lighting: a 200*lm/W* white light source two times more efficient than fluorescent lamps, and ten times more efficient than incandescent lamps.

This new white light source would change the way we live, and the way we consume energy. The worldwide amount of electricity consumed by lighting would decrease by more than 50%, and total worldwide consumption of electricity would decrease by more than 10%. The global savings would be more than 1,000*TWh/yr* of electricity at a value of about US$100B/year, along with the approximately 200 million tons of carbon emissions created during the generation of that electricity. Moreover, more than 125*GW* of electricity generating capacity would be freed for other uses or would not need to be created, a savings of over US$50B of construction cost.

Bringing about such revolutionary improvements in performance will require a concerted national effort, of the order $0.5B over ten years, tackling a broad set of issues in semiconductor lighting technology. The effort would also require harnessing the most advanced high-technology companies, the best national laboratory resources, and the most creative university researchers in this area.

Introduction

Energy is the lifeblood of our economy, and a critical building block for global peace and security. Its generation incurs huge costs: both direct economic costs as well as indirect environmental costs (smog and particulate emissions, acid rain, global warming, waste disposal, etc). And, the direct economic costs will only increase as concern heightens over how to reduce the indirect environmental costs.[1] As a consequence, there is great benefit to enhancing the efficiency with which energy is used -- virtually all major energy consumers from transportation to heating to the various users of electricity are constantly being examined for energy saving opportunities.

Among the most widespread, important, and *growing* uses of energy is the electricity used for lighting. As illustrated in Figure 1, in the U.S., about 20% of all electricity consumed,[2] and about 7.2% of all energy consumed, can be estimated to be used for lighting. In 1998, the cost

1 In the Kyoto Protocol of 1997, e.g., the developed nations agreed to limit their greenhouse gas emissions, relative to the levels emitted in 1990. The United States agreed to reduce emissions from 1990 levels by 7% during the period 2008 to 2012.

2 According to a recent EPRI report (TR-106196), the four top electricity-consuming applications in the U.S. in 1995 were: electric motors (24%), cooling/refrigeration (18%), lighting (17%), and space/water heating (16%). These percentages include the three major market segments -- residential, commercial and industrial -- but not street lights, traffic signals, nor the use of electricity to remove the heat generated by lighting in air-conditioned buildings. The Industrial Lighting handbook estimates that it takes 1 kW of electricity in the air-conditioning system to remove 3 kW of heat generated by lighting. After including the above omissions, it is safe to say that, in the U.S., lighting consumes at least 20% of electricity and ranks a close second to the 24% consumed by electric motors.

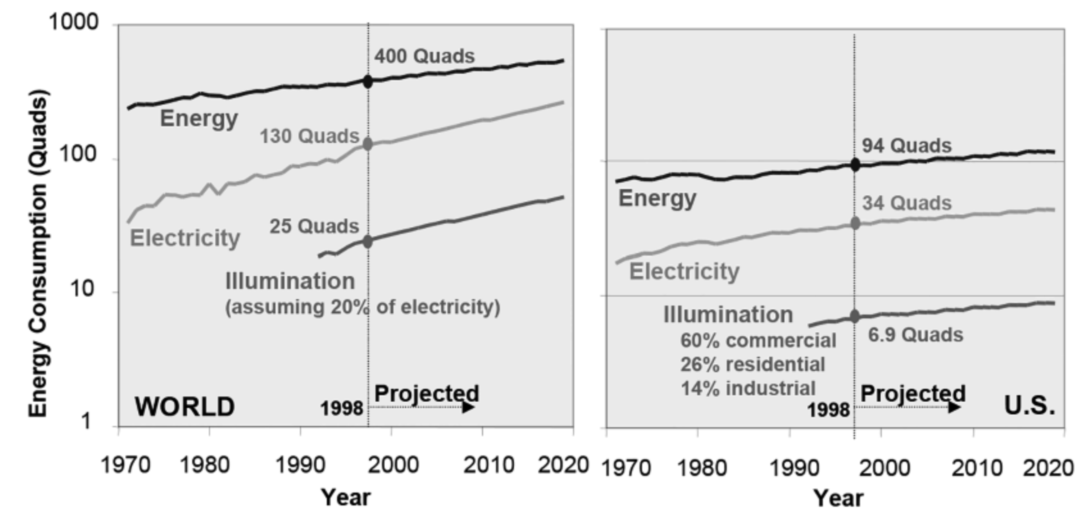


Figure 1. World (left) and U.S. (right) consumption of energy for use in all forms (blue), for use in electricity generation (pink), and for use in illumination (green).[3] One Quad (one quadrillion BTUs) of primary energy consumed is roughly equivalent, after energy conversion and transmission losses, to 92TWh of electricity at the wall plug.

was about 6.9 quads of primary fuel energy (with an associated 112 million tons of carbon emissions), and about 637*TWh* of actual electricity consumed at a cost of about US$63B. Worldwide, about 3.4% of all energy consumed can be estimated to be used for lighting, a percentage that is expected to increase with standard of living. In 1998, the worldwide cost was about 25 quads of primary fuel energy (with an associated 410 million tons of carbon emissions), and about 2,350*TWh* of actual electricity consumed at a cost of about US$230B.

Because of this large contribution of lighting to worldwide energy consumption, it is no wonder that the lighting industry receives its fair share of inquiries regarding energy reduction. In 1995, the three major US lighting manufacturers – GE Lighting, Osram/Sylvania and North American Philips – sponsored a three-day workshop to identify promising research areas for improving the efficiency of white light sources. This workshop confirmed that “lighting consumes about 20% of the electric power production of the nation.” One of the most revealing figures in the resulting EPRI report[4] is a graph of luminous efficiency vs. time for the major “true” white light sources: incandescent, halogen, and fluorescent lamps. As illustrated in Figure 2, none of these workhorse technologies has shown any significant efficiency improvements during the preceding 20 years!

3 World data taken from the International Energy Agency (http://www.iea.org), and assuming projected energy, electricity and illumination growth rates of 1.6%, 3.5% and 3.5%. U.S. data taken from the Energy Information Administration (http://www.eia.doe.gov), and assuming projected energy, electricity and illumination growth rates of 1.2%. We acknowledge Gerald Hendrickson and Arnold Baker at Sandia National Laboratories for assistance interpreting the data.

4 The workshop is summarized in EPRI report TR-106022.

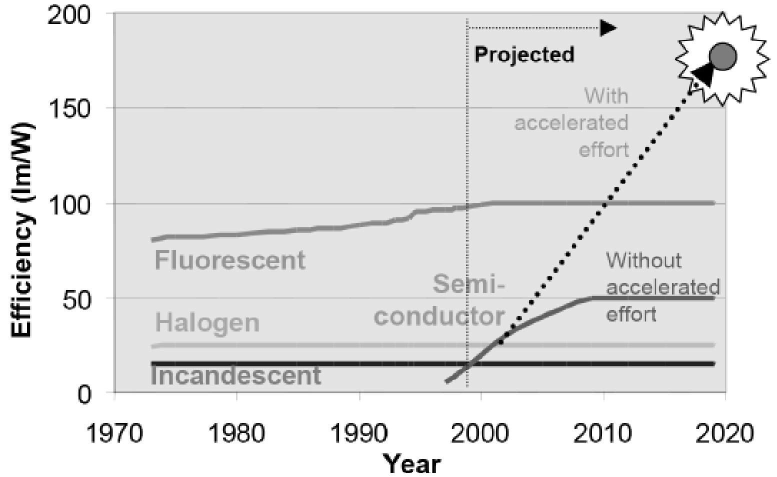


Figure 2. Condensed history and projection of efficiencies (in lm/W) of vacuum tube (incandescent, halogen and fluorescent) and semi-conductor (LED) white lighting technologies.

There is, however, one striking exception. Light emitting diodes (LEDs), a 40-year-old semiconductor technology, have steadily improved their efficiencies and power levels to the point where they are knocking incandescent and halogen lamps out of such traditional monochrome lighting applications sockets as traffic lights and automotive tail lights. And, a recent breakthrough in the green and blue makes LEDs a serious contender for conventional white lighting.

It is the purpose of this white paper to call attention to this new lighting technology and to the potential impact of a concerted national effort to advance it further. Such an effort would fill a need identified by the U.S. Department of Energy for research in advanced lighting technologies.[5] And, such an effort would target the technology we believe has the highest potential to create an ideal lighting source, both in quality and in cost. LEDs and their semiconductor variants are visually appealing, convenient and environmentally friendly, and it is our assessment that they have a realistic shot at reaching the industry nirvana of an efficiency of 200*lm/W*.

If semiconductor lighting can achieve this goal through a concerted national effort, the lighting industry would be revolutionized. An efficiency of 200*lm/W* would be more than 2x better than that of fluorescent lamps (80*lm/W*), and more than 10x better than that of incandescent lamps (15*lm/W*). If current lighting, with an aggregate efficiency of roughly 50*lm/W* (in between the efficiencies of fluorescent and incandescent lamps), were replaced by semiconductor lighting with an aggregate efficiency of 150*lm/W* (somewhat less than the target), then the electricity currently used for illumination would decrease by a factor of three, from 2,350*TWh* to 780*TWh*. This would represent a decrease in global electricity use of about 13%, and a decrease in global energy use and associated carbon emissions of 2.3%.

5 This need has been identified in the Department of Energy's ongoing "Vision 2020" lighting technology roadmapping activity. It has also been identified separately by the Department of Energy's Office of Building Technology, State and Community Programs, whose program plan consists of three overall goals: (1) Accelerate the introduction of highly efficient technologies and practices through research and development; (2) Increase minimum efficiency of buildings/equipment through codes, standards and guidelines; and (3) Encourage use of energy efficient technology through technology transfer and financial assistance.

The Case for a National Research Program on Semiconductor Lighting

In some ways such a revolution in lighting could be compared to the revolution in electronics that began 50 years ago and is only now reaching maturity. Just as for electronics, glass bulbs and tubes would give way to semiconductors. And, just as for electronics, the increased integrability, density, performance, and mass manufacturability of semiconductors may drive an explosion of additional, not-yet-thought-of uses for lighting. One can even speculate on visionary concepts in which information and illumination technologies combine to create ultra-fast wireless local-area networks that are mediated through building lights!

We begin this white paper in Section 2 with a brief history of LED technology, and compare its current and projected performance and cost with those of conventional technology. In Section 3, we discuss its penetration (and replacement of conventional technology) in signaling and lighting applications. We expect LED penetration into signaling applications, currently dominated by inefficient filtered incandescent lamps, to be rapid, and to drive continued improvements in performance and cost. These improvements will, in turn, enable gradual penetration of LEDs into lighting applications, currently dominated by a mix of incandescent and fluorescent lamps. Although the penetration will be gradual, its global impact will already be very significant, since lighting represents such a large fraction of global energy consumption. In Section 4, we describe an economic model for that global impact.

We believe much more dramatic improvements to be possible. In Section 5 we discuss such improvements, the resulting acceleration of the penetration of semiconductor lamps into lighting applications, and the resulting huge impact on global energy consumption. Finally, in Section 6 we discuss in general terms the daunting technical challenges, and the magnitude and nature of a national research program that might enable these challenges to be overcome.

To view the entire white paper, visit
http://wwww.quarkstar.com/roland_haitz.html

Solid-State Lighting: Innovation & Nobel Goals

Roland Haitz
QuarkStar

This essay was being worked on by Roland, in conjunction with Louis Lerman, at the time of his passing. It began as unpublished addendum to his 2015 Annalen der Physik article with Tsao et al.[1]

The 2014 Nobel Prize in Physics was given to Isamu Akasaki, Hiroshi Amano, and Shuji Nakamura explicitly for the enablement of solid-state lighting (SSL) and its role in energy conservation … i.e. "for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources"[2]. This exclamation point of utility is itself a useful starting point for evaluating SSL's future impact, especially in the context of technological innovation. Indeed, it is a fascinating exercise to use as a metric, Alfred Nobel's own

1 Jeffrey Y. Tsao, Jung Han, Roland H. Haitz, and P. Morgan Pattison **The Blue LED Nobel Prize: Historical Context, Current Scientific Understanding, Human Benefit.** Ann. Phys. (Berlin) 527, No. 5–6, A53–A61 (2015) / DOI 10.1002/andp.201570058

2 The Nobel Prizes discussed in this essay are further described at the Nobel Prize website: http://www.nobelprize.org/nobel_prizes/physics/laureates/

selection criteria: "Prizes [are to be given] to those who, during the preceding year[3], shall have conferred the greatest benefit on mankind".

Historically, as specified in his will, the three science prizes in physics, chemistry and medicine have been given to discoveries, inventions and improvements. Now, the definition of a discovery is usually non-controversial – but how does one measure "benefits on mankind" of one or even a string of inventions and improvements? And how can we apply this usefully to solid-state lighting, its past and its future?

In the broad field of semiconductors we have identified four subfields that are antecedent to SSL: (1) Ge and Si transistors, (2) CMOS integrated circuits, (3) conventional III-V compound transistors, LEDs and lasers, and (4) III-V nitride compounds for blue LEDs and lasers and high voltage transistors. Each subfield used existing processing and tools and then added field-specific new processes and tools. Indeed, alternative developments and processes likely did not happen because they could not be justified ab–initio on an economic basis. For instance, the early LED manufacturing processes used photolithography and assembly tools from obsolete transistor lines, sometimes with slight modifications. Also, the blue LEDs used the same assembly lines and proven processes developed for red and yellow LEDs.

The conventional definition of a benefit encompasses three distinctly different categories:

Type I: These inventions or improvements of existing products, or processes used in existing applications, usually fall into the following measurable categories: higher performance, smaller size (portability), lower manufacturing cost, longer operating life, lower operating/maintenance cost, etc. Examples include: A transistor replacing a vacuum tube in a radio or TV set (Nobel Prize 1956), a small-scale IC replacing one or several gates in a computer (Nobel Prize 2000) or a blue laser based on GaInN increasing the storage capacity of a DVD (Nobel Prize 2014).

Type II: This category is dominated by discoveries that enable new applications that previously did not exist or were not anticipated. Examples include: Penicillin (Nobel Prize for Medicine, 1945), X-Rays (Nobel Prize 1901). Both discoveries saved untold lives or reduced pain and misery from broken bones to cancer diagnosis and treatment.

Type III: This category contains contributions that started as Type I inventions and then took on an unprecedented dynamic growth phase of their own. A star example is the evolution from discrete Si transistors with a price in the range of $100 in the late 1950s to a quad core microprocessor with >10^9 transistors for the same $100 today!

3 The time frame "during the preceding year" was later dropped or modified.

Another star example is the Internet itself, combining half a dozen critical Type I inventions: (1) CMOS ICs as processors in cloud computing, PC, tablet and smart phone (Nobel Prizes to Shockley, Brattain, and Bardeen 1956, and Kilby 2000); (2) single-mode fiber for the backbone of the long distance communications network (Nobel Prize to Kao 2009) (3) conventional III-V compounds for single-mode lasers for transmitters in the network; (4) conventional III-V compounds for low noise receivers and high efficiency power transmitters in the last mile wireless part of the network (Nobel Prize to Alferov, Kroemer, 2000); (5) CCD and CMOS imaging arrays for digital graphics, photographs and video (Nobel Prize to Boyle, Smith 2009) and (6) active matrix based flat panel displays either in combination with LCD cells or OLED arrays to achieve portability for note-pads and smart phones. *All of these six technologies are necessary for the Internet to function as we know it. Take one of these technologies out and the Internet would either be dysfunctional or severely reduced in value.*

Coming back to GaInN, blue LEDs and their use in SSL: How does SSL, the latest revolution in semiconductors, measure up to the formidable milestones[4] set by the other semiconductor technologies and their "benefits on mankind" via the Internet?

The answer is: Quite well!

Here are our arguments: SSL has started out as Type I innovation with its classical benefits such as (1) higher performance (source efficiency of ~40% vs 20% for the best conventional lamps); (2) smaller size (lower etendue translates into lower light distribution losses in the luminaire); (3) longer operating life (integrate source into luminaire, no need for lamp replacement and sockets, lower maintenance cost); (4) dimming without reduction in efficiency (incandescent lamps still operate at 85% of full power when dimmed to half brightness, most other conventional lamps cannot be dimmed at all); (5) instant relighting (An extreme example of the importance of this was the 34 minute interruption of the Super Bowl because of a brief power failure. To an economist...with 100 million watchers of the Super Bowl, the 34 minutes to relight the stadium's HID lamps was a loss of 50 million man-hours of individual productivity.)

4 My interest in using historical economics for the evaluation of technology and the potential value of its underlying R&D effort goes back a considerable time. See G. L. Pearson and R. H. Haitz, Eds., Historical Notes On Important Tubes And Semiconductor Devices. A special issue of the IEEE Transactions on Electron Devices ED-23(7) (July, 1976).

"This special Bicentennial Issue of the IEEE Transactions On Electron Devices: "Historical Notes on Important Tubes and Semiconductor Devices" is appearing in July 1976 to commemorate the two hundredth anniversary of the founding of the United States of America. The content of this issue is somewhat different from usual in that all of the articles highlight the history of the most important inventions in the field of tubes and semiconductors. Rather than asking historians to describe the evolution and growth of these inventions, we have asked one of the original inventors to describe the story as he saw it…. In selecting topics, we limited ourselves to devices which proved to have significant economic impact."

This list could go on and on. But let's put the inconveniences and smaller benefits aside and only look at integrated power savings. A recent DoE study[5] estimates the US energy savings in 2030 of 30GW, equivalent to $30B per year savings at retail electricity prices. I believe that this is an underestimate for several reasons: Somewhere in the 2030s, even the most efficient fluorescent tubes and halide lamps will not be competitive with SSL and will be phased out; and the efficiency of SSL will keep increasing to 50% multiplying the energy savings by a factor 1.5x.

Furthermore as SSL transitions from a Type I to a Type III category (smart lighting), many smaller power savings will emerge, i.e. light-on-demand. Multiplying the 2030 energy savings of $30B with the increased efficiency of 1.5x and a global to US ratio of 3.5 gets us to an energy savings worth $160B per year. Adding to that the inevitable cost increases for renewable energy and other non-energy related benefits, our estimate could conceivably reach $180B-$200B per year in the early 2030s. Even with potential errors of 10-20%, these remain big numbers. And with the lighting industry itself estimated to asymptote at around $100 billion/year the integrated economic impact of the global transformation to SSL is considerable.

Although Internet benefits are substantially larger than the SSL benefits, in a conventional return on investment analysis, it is the benefit/investment ratio that counts. Let's take a high altitude look and normalize the six Internet technology cumulative investments (R&D, Marketing, Machinery & Equipment, Buildings w/o Land) to the SSL investments: CMOS ICs 10x, Single Mode Fiber 0.3x, Conventional III-V 1x, WiFi 0.3x, CCD 0.1x and Active-Matrix Flat Panel Display 3x. This very crude estimate says that we invested at least 15x the SSL investment in getting to the Internet capability of today.

With the SSL investment we have a bird-in-the-hand with $2T in mostly energy savings between 2030 and 2040 that are real and tangible. Hence the GaInN based blue LED development contribution by the Nobel-prize winning team of Akasaki, Amano, and Nakamura measures up well in comparison with the other major developments from semiconductor research and industry. The developments benefitted greatly from previously developed semiconductor technologies. They developed processes that, against all odds, were critical to success and led to completely unexpected levels of conversion efficiency for blue LEDs. The timing for their discovery was perfect to effect a global impact: The concern for global warming demanded coal based electricity reduction and the SSL based savings are second to none.

But on the optical hardware side of the internet – flat panel displays (and not considering mobile devices) – the rumor mill says that the industry has not made an adequate return in the last 25 years. And for the last few years, probably none at all. Why else are the non-Asian CMOS IC companies such as IBM, Motorola, Philips and Siemens divesting from their CMOS black

5 U.S. Department of Energy, SSL Program, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (August, 2014).

holes? And why else are those major Asian corporations heavily weighted towards displays (like Sharp, Sony, and Panasonic) increasingly stressed financially?

So we return to Alfred Nobel: If the return on investment is too low, the "benefits on mankind" are quite shaky. Yet with all of the above, the *risk-weighted return* of SSL over the next two decades could well be superior to the return on the majority of Internet investments.

But profitability in SSL will depend on two things that are only now becoming realized: differentiation and scale-integration. The differentiation is of the classic two attributes – function and form. Each needs to evolve beyond the simple substitution of LEDs into physical envelopes that have been optimized for light sources based on completely different and far less efficient physics. Otherwise, the true potential, opportunities, and even real-world market share will irredeemably suffer at the hands of consumers and users who have successfully learned to understand what is genuine progress by 'feel', without a care for technical detail.

Most importantly this mutual evolution of function and form will be driven by the scaling that occurs through the vertical integration of solid-state lighting, congruent to that of solid-state electronics itself — for the LED is to the incandescent light bulb what the transistor is to the vacuum tube. Remember that only 20 years ago we were all calling it *semiconductor lighting.*

And just as the IC has replaced transistors… integrated lighting systems will replace current SSL solutions. This is currently occurring with chip-scale packages, integrating the previously distinct categories of chips and packages. The next steps will include integrating modules and luminaires on one hand, and these in turn will be integrated with the package level. This is what we predicted years ago in our initial efforts[6] to bring about the birth of solid-state lighting; and this is what I, and the rest of the team, have focused on these last four years at QuarkStar.

My interest in this approach goes back to my earliest days in the Valley, just as it was becoming Silicon Valley through the collective efforts of my fellow Shockley alumni. Just as "system on a chip" further revolutionizes modern electronics, the IC-equivalent of lighting will make possible complete luminaires up to an order of magnitude smaller than current ones. And this will be coupled to brand new system variables whose control will power the improvements,

6 Roland Haitz, Fred Kish, Jeff Tsao, Jeff Nelson, **The Case For A National Research Program On Semiconductor Lighting.** This white paper was first presented publicly at the 1999 Optoelectronics Industry Development Association (OIDA) forum in Washington DC on October 6, 1999, and then again presented at Strategies in Light, Burlingame, CA (February 2000). It was published in revised form by Sandia (Sandia 2000 – 1612).

"In some ways such a revolution in lighting could be compared to the revolution in electronics that began 50 years ago and is only now reaching maturity. Just as for electronics, glass bulbs and tubes would give way to semiconductors. And, just as for electronics, the increased integrability, density, performance, and mass manufacturability of semiconductors may drive an explosion of additional, not-yet-thought-of uses for lighting. One can even speculate on visionary concepts in which information and illumination technologies combine to create ultra-fast wireless local-area networks that are mediated through building lights!"

new capabilities, and customization leading to a further congruence with that of electronics – the personalization of light(ing). In so doing platforms uniquely suited for integration into larger, networked systems will be enabled, along with radically new applications for light itself. What we talked about as far-reaching dreams 16 years ago is increasingly being realized: "One can even speculate on visionary concepts in which information and illumination technologies combine ... "[7]

But there is so much more to come. Solid-state lighting is just beginning. It's what the internet looked like in the 1980's. What lighting will be in 30 years is unimaginable now — we know only that it will be wondrous and beautiful!

- Roland Haitz
June 12, 2015

7 *Ibid.* (For those who wish to see this in context, see page 23 of this booklet.)

Patents

Roland has been named inventor on more than 50 patents and patent publications categorized into 23 patent families[1] which are summarized on the following pages.

The first families represent his early patents, issued during the 1960s and 1970s, the first of which was co-invented with his PhD advisor William Shockley. These first five patents all focus on his early work with diode development at the Shockley labs and then Texas Instruments. After that, starting in the mid-1970's, came his work at Hewlett Packard with a wide range of applications that are still, in some form, being used today.

The seven patent families representing patents issued during the 1990s show a diversity of applications which underlined his professional leadership in optoelectronics innovation. This was demonstrated in the early 1990's when he cofounded the national Optoelectronic Industry Development Association (OIDA), now a part of the OSA (Optical Society of America).

The last nine listed families are a part of Roland's work with QuarkStar, a total of 10 patent families in just three years of effort. This is over twice the rate of patent production that he'd demonstrated in his two past periods of IP innovation. The last of his patent applications was submitted only a few months before his passing.

This is a strong testament to the unwavering spirit of exploration and creativity that powered Roland throughout his life, and a clear-cut demonstration that, even at the end of his 50 year professional life, he was exuberantly excited for what else was out there, what else could be understood, and what new innovations could be created to contribute to the well-being of the world. Roland never felt 'old', he said, "just a little tired on occasion".

1 Per INPADOC

Roland Hermann Haitz

A shortlist of patents

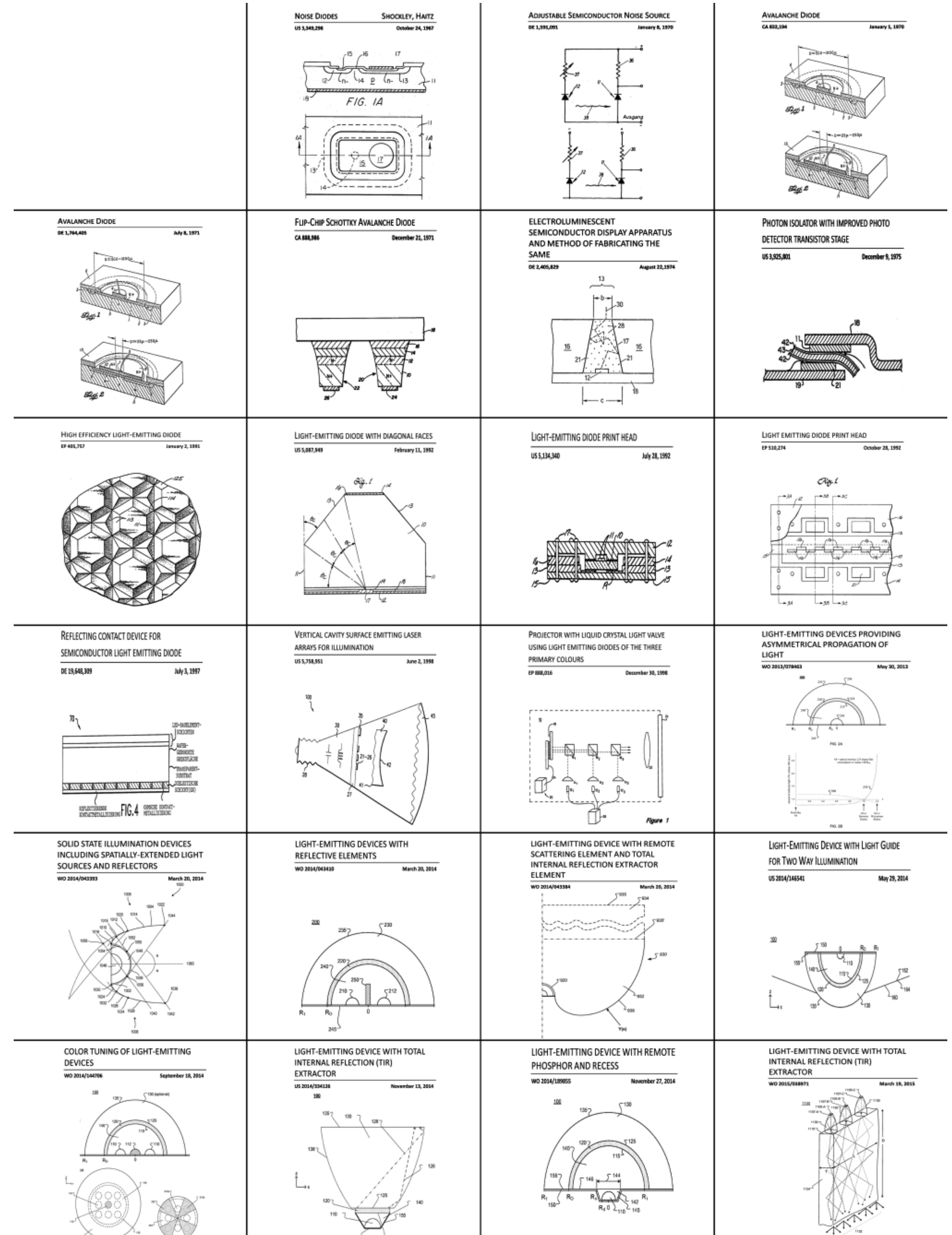
1967 Noise Diodes (inventors: Shockley, Haitz)
1970 Adjustable Semiconductor Noise Source
1970 Avalanche Diode
1971 Avalanche Diode
1971 Flip-Chip Schottky Avalanche Diode
1974 Electroluminescent Semiconductor Display Apparatus and Method of Fabricating the Same
1975 Photon Isolator with Improved Photo Detector Transistor Stage

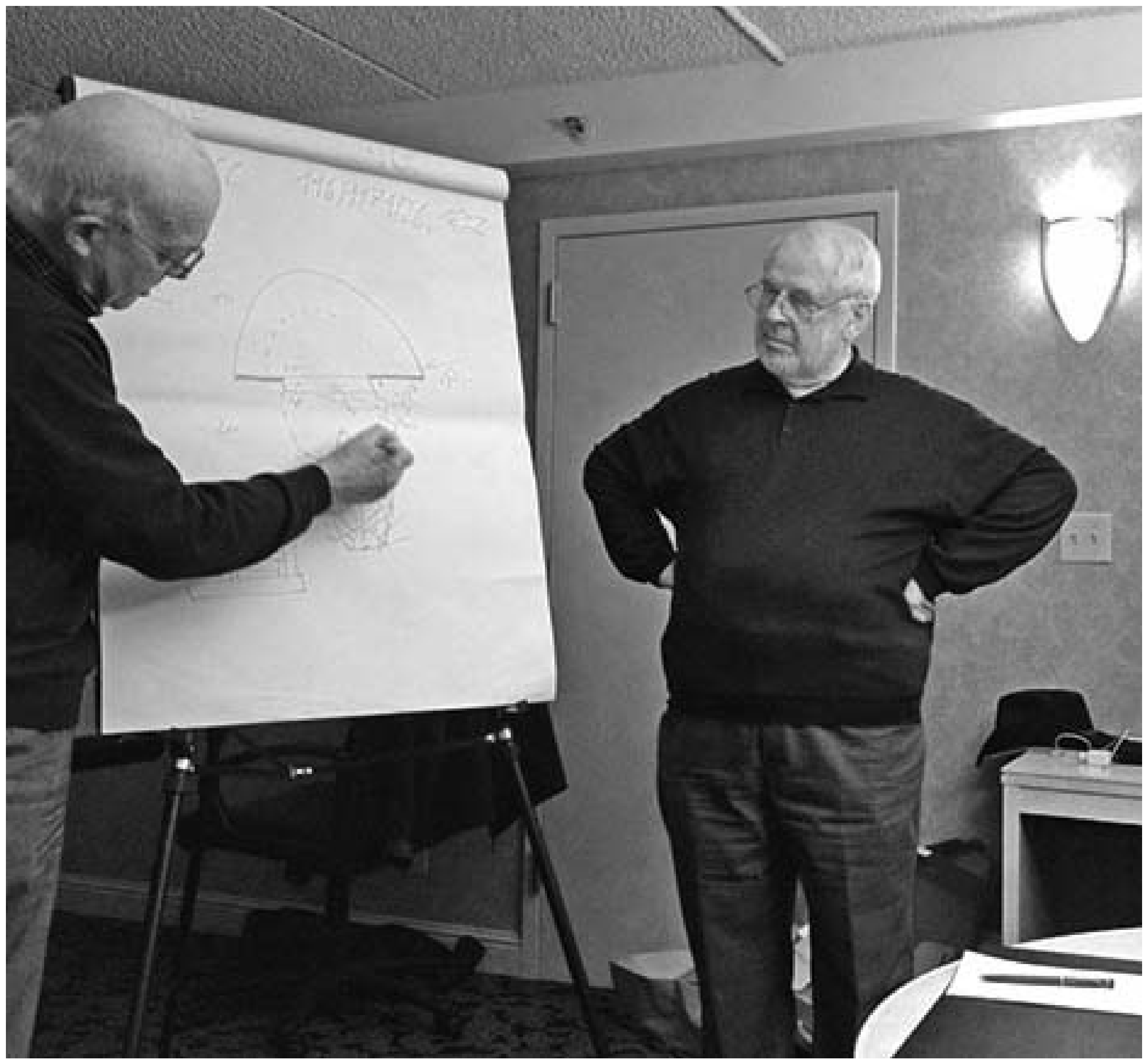
---

1991 High Efficiency Light-Emitting Diode
1992 Light-Emitting Diode with Diagonal Faces
1992 Light-Emitting Diode Print Head
1992 Light Emitting Diode Print Head
1997 Reflecting Contact Device for Semiconductor Light Emitting Diode
1998 Vertical Cavity Surface Emitting Laser Arrays for Illumination
1998 Projector with Liquid Crystal Light Valve Using Light Emitting Diodes of the Three Primary Colours

---

2013 Light-Emitting Devices Providing Asymmetrical Propagation of Light
2014 Solid State Illumination Devices including Spatially-Extended Light Sources and Reflectors
2014 Light-Emitting Devices with Reflective Elements
2014 Light-Emitting Device with Remote Scattering Element and Total Internal Reflection Extractor Element
2014 Light-Emitting Device with Light Guide for Two Way Illumination
2014 Color Tuning of Light-Emitting Devices
2014 Light-Emitting Device with Total Internal Reflection (TIR) Extractor
2014 Light-Emitting Device with Remote Phosphor and Recess
2015 Light-Emitting Device with Total Internal Reflection (TIR) Extractor





Papers

Roland’s published work on solid-state lighting did not just parallel the history of the field, but provided the necessary catalysis at critical points of its development. The listed papers and presentations reveal the stages of the evolution of SSL, and in the process display the extraordinary intellect and pioneering insights of Roland Haitz.

But not listed here are another 30 technical papers he published in professional journals, while also serving a stint as editor of the IEEE Transactions on Electron Devices. They too describe his evolution as scientist and innovator, and offer useful perspective on the antecedents of his pioneering work on solid-state lighting.

Roland’s early work, until 1970, followed his PhD under William Shockley and dealt with diodes, microplasmas, and avalanche discharges. (In addition, five patents were granted on related inventions.) But in 1969 Roland moved from Texas Instruments to Hewlett Packard, and began to publish on electroluminescent materials and LED displays. (Coincident with this were patent filings on specific implementations.)

Of particular pride to him was his creation and editorship of a special Bicentennial Issue of the IEEE Transactions On Electron Devices: “Historical Notes on Important Tubes and Semiconductor Devices” that appeared on July 1976 to commemorate the two hundredth anniversary of the founding of the United States of America, his adopted country. The included articles highlight the history of the most important inventions in the field of tubes and semiconductors. It is apparent from this early effort that Roland, from the beginning, was focused on technologies that had maximal societal and economic impact.

With all the above the stage was set for Roland’s eureka moment in the late 1990’s – that LEDs could foment a revolution to displace the hundred year-old light bulb and fifty year-old fluorescent tube (co-invented by Roland’s German mentor, Nickolas Riehl).

Phase 1: The LED Before SSL
(pre-1999)
- [1976] Historical Notes on Important Tubes and Semiconductor Devices
- [1993] Opportunities for Optoelectronics: A Strategic Roadmap
- [1994] Handbook of Optics: Chapter 12 Light-Emitting Diodes

Phase 2: The Challenge Is Issued: Haitz's Law Ushers In the SSL Era
(1999)
- [1999] The Case for a National Research Program on Semiconductor Lighting

Phase 3: Another Semiconductor Revolution: This Time It's Lighting!
(2000 - 2003)
- [2000] Sandia: Transforming the Lighting Sector with Semiconductor Lighting Technologies
- [2000] The Cost to Reduce CO2 Emission: Energy Savings through Solid-State Lighting vs. Emission Reduction through Photovoltaic Generation
- [2001] Sandia: A Market Diffusion and Energy Impact Model for Solid-State Lighting
- [2001] Physics Today: The Promise and Challenge of Solid-State Lighting
- [2002] Compounds Semiconductor Magazine: Another Semiconductor Revolution: This Time It's Lighting!
- [2003] Advances in Solid State Physics: Another Semiconductor Revolution: This Time It's Lighting!

Phase 4: Why SSL Won't Be Overtaken
(2003 - 2011)
- [2011] Lighting Technology: Solid-State Lighting: Why It Will Succeed, and Why It Won't Be Overtaken
- [2011] Physica Status Solidi A: Solid-State Lighting: 'The Case' 10 Years After and Future Prospects
- Invited Plenary Presentations Globally

Phase 5: Securing the Future of SSL
(2011 - 2015)
- QuarkStar Technical Papers
- [2015] Annalen der Physik: The Blue LED Nobel Prize: Historical Context, Current Scientific Understanding, Human Benefit

Papers may be downloaded at http://quarkstar.com/roland_haitz.html

For more on Roland Haitz, http://quarkstar.com/roland_haitz.html

Coming soon: http://haitzs-law.com

"Solid-state lighting is where the internet was in the 1980's. We cannot foresee all that light and lighting will become in the next decades, but know simply that it will be wondrous and beautiful."

- Dr. Roland Haitz

Photographs by Michael Collopy & Louis Lerman
Designed by Jacqueline Teng & Louis Lerman

Sponsored by QuarkStar