50th Anniversary of the Light-Emitting Diode (LED): An Ultimate Lamp

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The light-emitting diode (LED) has found its way into almost every electrical gadget on our planet and is currently elbowing aside all other forms of lighting, including the iconic incandescent light bulb that Thomas Edison created ~130 years ago. Today, LEDs are all around us. Some of the most common applications include general lighting, architectural lighting, traffic lights, automotive lighting, flashlights, remote controls, large-scale displays, signage, LED TVs and computer displays, and status indicators on devices such as cell phones, and even in "picoprojectors." The year 2012 marked the 50th anniversary of the 1962 demonstration of the first visible LEDs (Fig. 1) and semiconductor diode lasers (Fig. 2) composed of alloy compound semiconductors [1].

Dedicated to the celebration of the 50th anniversary of the LED, the articles in this special issue provide a historical perspective as well as current and future trends in LEDs.

LEDs possess many advantages over conventional light sources, including efficiency, light/power density, reliability, and form factor (for styling and efficiency). As a result, LEDs comprise a growing > \$10 billion business and either are or are rapidly becoming the dominant lighting source in many applications. LEDs are providing enormous value in energy savings and are on track to reduce the world's total electricity consumption by > 10% as they displace conventional lighting sources over the next few decades. The efficiency improvement in commercial LEDs has been dramatic over the last 50 years, increasing over three orders of magnitude from 0.1 lm/W and now is at a level that is competing with conventional lighting sources, as shown in Fig. 3.[1] Warm-white LEDs have been demonstrated in the laboratory with

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[1] Data courtesy of M. Krames of Soraa, Inc. (Fremont, CA, USA).

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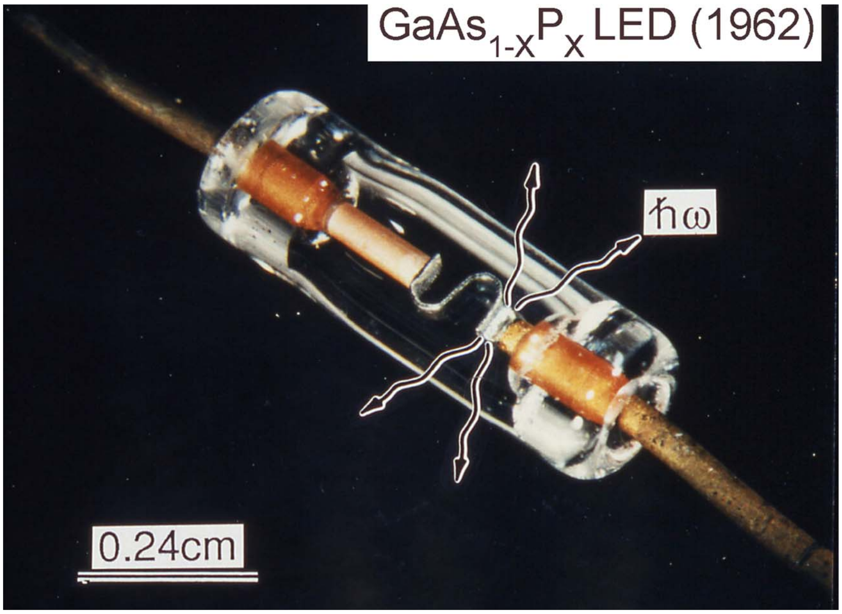

Fig. 1. ***Photograph of one of the first practical LEDs: A GaAsP red-emitting LED developed by Nick Holonyak, Jr. while working at General Electric.***

efficiencies $>$ 200 lm/W [2], a much higher efficiency than any other man-made high-quality white light source available today.

Moreover, the historical demonstration of the first visible LED and visible diode lasers (made in GaAsP) demonstrated the viability of alloy compound semiconductors [1]. The alloy compound semiconductor is the foundation for virtually every III–V optoelectronic device and many electronic devices, including: lasers, photodetectors, semiconductor optical amplifiers, heterostructure bipolar transistors, and high electron mobility transistors. All of these devices critically rely on the III–V alloy as a basis for their design. Furthermore, these components form the foundation and basis for much of today's communications infrastructure (wired and wireless) and connect billions of people across the globe.

This Special Issue of the Proceedings of the IEEE is dedicated to the celebration of "The 50th anniversary of the LED: An ultimate lamp" [3]. The invited contributors provide a historical perspective as well as current and future trends in LEDs and the associated enabling technologies that impact the realization of "an ultimate lamp." The volume begins with a historical perspective on the III–V alloy diode laser and LED by Holonyak, Jr., who describes why the LED is an "ultimate lamp." This is followed by a paper in which Craford describes the development of LEDs, starting with Holonyak's $<$ 0.1-lm/W red-emitting LED and progressing to $>$ 100-lm/W white sources that are now competing with conventional illumination sources. Like the alloy compound semiconductor, the heterostructure is a ubiquitous element of almost every optoelectronic device. In separate papers, Alferov and Kroemer provide their perspective on the development and impact of the heterostructure on optoelectronic devices.

The development of some of the critical technologies for LEDs is described in the next series of papers. The development of metalorganic chemical vapor deposition (MOCVD) and quantum-well heterostructures is described by Dupuis. This is followed by separate papers by Akasaki, and Nakamura and Krames that describe the development of GaN technology and LEDs. The later paper also describes a new emerging area of GaN LED technology wherein the LEDs utilize a native GaN substrate. The development of GaN substrate technology is further described in a subsequent paper by Nakamura and Motoki.

Several major extensions of the alloy semiconductor and LED and diode laser technology have been developed that offer, or have done so already, the potential to substantially impact the world. The development, physics, and progress of the vertical-cavity surface-emitting laser (VCSEL) are described in a paper by Iga. This is

Fig. 2. ***Photograph of the first (1962) red-spectrum GaAsP alloy diode laser developed by Prof. Nick Holonyak, Jr. at General Electric.***

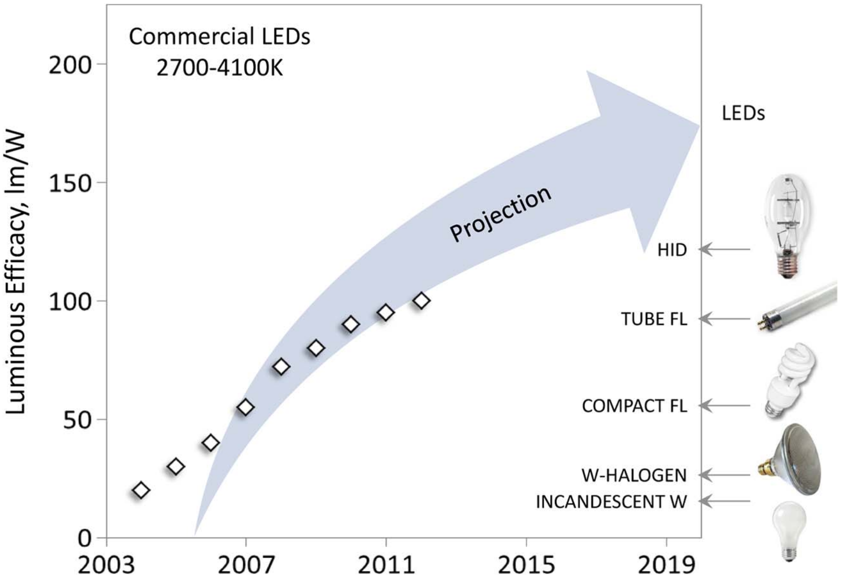

Fig. 3. *Evolution of luminous efficiency versus time (lumens per electrical watt) for commercial "warm white" (2700–4100 K) LED products as well as a projected performance based on information compiled for the U.S. Department of Energy. At right, typical luminous efficiencies are indicated for conventional lighting technologies. Over the next several decades, the efficiency of LEDs is expected to outpace most conventional lighting technologies, making the LED "an ultimate lamp," [3].*

followed by a paper by Dallesasse and Deppe that describe one of the key enabling technologies for many high-performance VCSELs: the oxidation of III–V Al-bearing alloys. Subsequently, Kumagai *et al.* describe the history of alloy diode laser development and mass production for optical storage systems at Sony Corporation. Kish *et al.* describe the key advances which enabled the progression from the first visible alloy semiconductor LEDs to today's most sophisticated III–V photonic integrated circuits (PICs). The issue concludes with a paper by Then *et al.* that reviews the emerging three-terminal laser technology which provides the coherent light emission in the transistor, the transistor laser.

Since the first demonstration of the visible alloy LED 50 years ago, exponential progress has been made in the performance of these devices as well as diode lasers and optoelectronic devices, including PICs. This progress has and continues to transform the display, lighting, optical storage, and communication industries. Nonetheless, there is still much work to be done to realize the full potential of the alloy semiconductor and LED as an "ultimate lamp." The editors hope the papers in this issue provide the readers with some of the key historical developments, status, and challenges in these very impactful fields. ■

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ABOUT THE GUEST EDITORS

M. George Craford (Fellow, IEEE) received the Ph.D. degree in physics from the University of Illinois at Urbana–Champaign, Urbana, IL, USA.

He began his professional career as a Research Physicist at Monsanto Chemical Company, and became Technical Director of the Electronics Division, before joining the Hewlett Packard Company in 1979. He is currently the Solid State Lighting Fellow at Philips Lumileds Lighting Company, San Jose, CA, USA. His research has been mainly focused on the development of visible LEDs, using a variety of compound semiconductor materials.

Dr. Craford is a member of the National Academy of Engineering. He has received technical achievement awards from a variety of organizations and shared the 2002 National Medal of Technology with Nick Holonyak Jr. and Russell D. Dupuis.

Russell D. Dupuis (Fellow, IEEE) received the Ph.D. degree in electrical engineering from the University of Illinois at Urbana–Champaign, Urbana, IL, USA, in 1973.

He was a Member of Technical Staff (MTS) at Texas Instruments, Dallas, TX, USA, from 1973 to 1975. From 1975 to 1979, he was an MTS at Rockwell International, Anaheim, CA, USA, where he was the first to demonstrate that MOCVD could be used for the growth of high-quality semiconductor thin films and devices, including the first room-temperature quantum-well diode lasers. He was an MTS (1979–1986) and a Distinguished MTS (1986–1989) in Physics Research at AT&T Bell Laboratories, Murray Hill, NJ, USA, where he extended his work to the growth of InP–InGaAsP lasers by MOCVD. From 1989 to 2003, he was a Chaired Professor in Electrical and Computer Engineering at the University of Texas at Austin, Austin, TX, USA. From 2003 to present, he has been a Chaired Professor in Electrical and Computer Engineering at the Georgia Institute of Technology, Atlanta, GA, USA. He is currently studying the growth of III–V compound semiconductor devices by MOCVD, including materials in the InAlGaN/GaN, InAlGaAsP/GaAs, InAlGaAsSb, and InAlGaAsP/InP systems.

Prof. Dupuis received the IEEE Edison Medal in 2006 and the IEEE Lasers and Electro-Optics Society (LEOS) Award for Engineering Achievement in 1995. He also received the 2002 National Medal of Technology for contributions to the development of the LED and was elected a Member of the National Academy of Engineering in 1988.

Milton Feng (Fellow, IEEE) received the B.S. degree in electrical engineering from Columbia University, New York, NY, USA, in 1973 and the M.S. and Ph.D. degrees in electrical engineering from the University of Illinois at Urbana–Champaign (UIUC), Urbana, IL, USA, in 1976 and 1979, respectively.

From 1979 to 1983, he was Head of the GaAs Material and Device Group at Torrance Research Center, Hughes Aircraft Company, where he was in charge of ion implantation, $AsCl_3$ vapor-phase epitaxy (VPE), metal-organic chemical vapor deposition (MOCVD), and molecular-beam epitaxy (MBE) technology. In 1983, he developed a direct ion-implanted low-noise and power metal–semiconductor field-effect transistor (MESFET) and monolithic microwave integrated circuits (MMICs) for X-band phase array radar application. He demonstrated the first 60-GHz GaAs amplifiers in 1983. From 1984 to 1986, he worked for Ford Microelectronics, Inc., Colorado Springs, CO, USA, where he managed the advanced digital integrated circuit development program in 1-K SRAM and 500 gate array. Since 1991, he has been a Professor of Electrical and Computer Engineering and a Research Professor at the Microelectronics Laboratory, UIUC. He invented the pseudomorphic heterojunction bipolar transistor (PHBT), ''pushed'' the transistor speed boundary toward terahertz, and demonstrated InP PHBTs with the world's fastest speed performance ($>$ 800 GHz). He, along with Prof. N. Holonyak, Jr., demonstrated the first laser operation of a quantum-well-based light-emitting transistor (QWLET), a transistor laser (TL). A transistor laser opens up a rich domain of integrated circuitry and high-speed signal processing that involves both electrical and optical signals. He has published over 200 papers and 200 conference talks, and has been granted 27 U.S. patents in semiconductor microelectronics.

Dr. Feng is a Fellow of the Optical Society of America (OSA), and serves on many executive and strategy committees both in industry and at conferences. In 1989, he received the Ford Aerospace Corporate Technology Award and the Ford Motor Innovation Award. In 1997, he received the IEEE David Sarnoff Award, and in 2000, he received the Pan Wen Yuan Outstanding Research Award in Microelectronics. In 2006, his transistor laser research paper was selected as one of the top five papers in the 43-year history of *Applied Physics Letters*, and also was selected as one of the top 100 most important discoveries in 2005 by the *Discover* magazine. In 2005, he was chosen as the first Holonyak Chair Professor of Electrical and Computer Engineering. In 2013, Prof. Feng received the OSA R. W. Wood Prize for the co-invention and realization of the transistor laser.

Fred A. Kish (Fellow, IEEE) received the B.S., M.S., and Ph.D. degrees in electrical engineering from the University of Illinois at Urbana–Champaign (UIUC), Urbana, IL, USA, in 1988, 1989, and 1992, respectively. His Ph.D. degree was obtained under the direction of Prof. N. Holonyak, Jr. on ''Native oxides on aluminum-bearing III–V semiconductors with applications to high-performance laser diodes.'' This work is part of the core Al-bearing III–V native-oxide technology that has enabled the development of the highest performance vertical-cavity surface-emitting lasers (VCSELs) and has been licensed to VCSEL manufacturers throughout the world.

From 1992 to 1999, he was at Hewlett-Packard's Optoelectronics Division where he coinvented and led the commercialization of the highest performance (efficiency) red–orange–yellow visible LEDs produced at the time (wafer-bonded transparent-substrate AlGaInP LEDs). The efficiencies of these devices exceeded those of incandescent and halogen lamps with products based on this technology resulting in over $2 billion in revenue to date. From 1999 to 2001, he was with Agilent Technologies Fiber Optics Components Division as the III–V Department Manager. There he led the department that developed commercially viable 2.5-Gb/s VCSELs and VCSEL/detector arrays (12 × 2.5 Gb/s) for next-generation fiber-optic transceivers and the first multi-gigabit per second parallel fiber-optic transmitter/receiver products. In 2001, he joined Infinera Corporation, Sunnyvale, CA, USA, as Vice President of Photonic Integrated Circuit (PIC) Development and Manufacturing Department, and later, as Senior Vice President of the Optical Integrated Components Group. At Infinera, he coinvented and led the effort to research, develop, and commercialize the first practical (commercially deployed) large-scale PICs. The large-scale PICs are at the core of Infinera's optical network products and have been the enabling technology behind over $2.5 billion in PIC-based networking product sales. He has coauthored over 100 U.S. patents, over 60 peer-reviewed publications, and four book chapters on optoelectronic devices and materials.

Dr. Kish is a Fellow of the Optical Society of America (OSA). His awards include the IEEE David Sarnoff Award, the IEEE LEOS Engineering Achievement Award, the OSA Adolph Lomb Award, and the International Symposium on Compound Semiconductors Young Scientist Award.

Joy Laskar (Fellow, IEEE) received the B.S. degree in computer engineering (*summa cum laude*, with physics and math minors) from Clemson University, Clemson, SC, USA, in 1981, and the M.S. and Ph.D. degrees in electrical engineering from the University of Illinois at Urbana–Champaign, Urbana, IL, USA, in 1989 and 1991, respectively.

He is the Vice President of Advanced Technology at InSite Partners, an investment and advisory group in Silicon Valley and an Adjunct Professor of Electrical and Computer Engineering at Hong Kong University of Science and Technology, Hong Kong. From 1992 to 2011, he held various faculty positions at the University of Hawaii and at Georgia Tech. His technical expertise and research contributions are at the intersection of radio-frequency electronics, analog electronics, and electromagnetics. Since 1995, he has cofounded four companies, coauthored five textbooks, published more than 600 peer-reviewed journal and conference papers, more than 60 patents (issued or pending), and graduated 42 Ph.D. students. As a result of the these efforts, four product/technology segments have been invented and developed: GaAs high-performance error vector magnitude (EVM) power amplifiers (designed on the Intel Centrino Platform), complementary metal–oxide–semiconductor (CMOS) equalizer/retimer solution (designed on the Apple Thunderbolt), CMOS radio-frequency (RF) amplifier, antenna impedance tuner for LTE (designed on the Qualcomm LTE platform), and low-power millimeter-watt gigabit wireless (for backhaul and wireless docking). The economic impact of these developments is more than $1 billion.

Dr. Laskar is an elected member of the PROCEEDINGS OF THE IEEE Editorial Board, an elected member of the IEEE Microwave Theory and Techniques Society (MTT-S) Administrative Committee (AdCom), and General Co-Chair for the IEEE International Wireless Symposium.