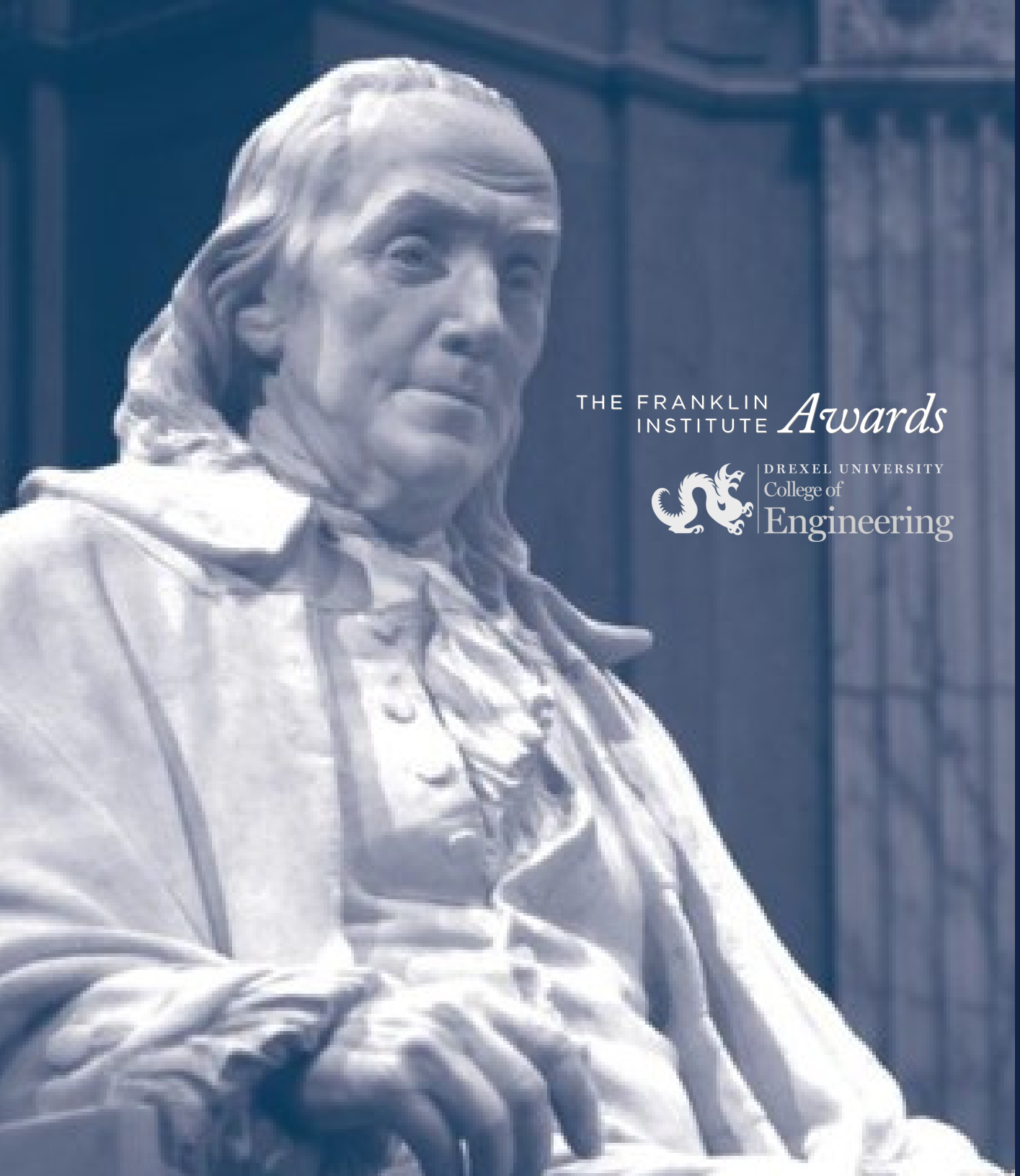

Layer by Atomic Layer:

MOCVD Growth for a Carbon Neutral Society

Symposium Honoring

Russell D. Dupuis. Ph.D. and
P. Daniel Dapkus, Ph.D.

Recipients of the 2022
Benjamin Franklin Medal in
Electrical Engineering

Wednesday, May 4th
9am-1pm ET

Event Speaker Schedule

09:00 Introduction and Welcome to the Benjamin Franklin Medal Symposium
Prof. Bahram Nabet, Drexel University-Electrical & Computer Engineering

09:05 Welcome Remarks
Dr. Darryl Williams, Senior Vice President, The Franklin Institute

09:10 Franklin Awards History (video)

09:15 Welcome Remarks*
President John Fry, Drexel University

09:20 **Prof. Hiroshi Amano***
Nagoya University, Japan
Title: "The MOCVD as the key technology for establishing a carbon neutral society."

09:50 **Prof. Chennupati Jagadish***
Australian National University-Canberra, Australia
Title: "Semiconductor Nanostructures for Optoelectronics Applications."

10:20 **Prof. Dieter Bimberg**
Technical University of Berlin, Germany
Title: "Quantum Dots for Green Quantum Technologies."

---Intermission---

11:00 **Prof. James Coleman***
University of Texas at Arlington
University of Illinois-Urbana, IL
Title: "The MOCVD Growth of Diode Lasers in Context--A Significant Challenge and an Elegant Solution."

11:30 **Prof. Shuji Nakamura**
University of California-Santa Barbara, CA
Title: "The importance of the MOCVD growth to the invention of the blue LED and solid-state light revolution."

12:00 **Prof. Dan Dapkus**
University of Southern California-Los Angeles, CA
Title: "Metalorganic Chemical Vapor Deposition--The Dominant Technology for Compound Semiconductor Devices."

12:30 **Prof. Russell Dupuis**
Georgia Institute of Technology-Atlanta, GA
Title: "Metalorganic Chemical Vapor Deposition--The Swiss Army Knife of III-V Epitaxy."

13:00 Conclusion, **Prof. Bahram Nabet**

previous*ly recorded*

Laureate

Russell D. Dupuis, Ph.D.

Steve W. Chaddick Endowed Chair in Electro-Optics
Georgia Institute of Technology,
Atlanta, GA USA

Title: Metalorganic Chemical Vapor Deposition – The Swiss Army Knife of III-V Epitaxy

Abstract: The challenges of future optoelectronic device technology can only be met with improved approaches to epitaxial growth. Over the past ~60 years, epitaxial growth of III-V compound semiconductor alloys has been developed to become an essential technology for the advancement of many large-scale commercial technological systems.

In 1967, Harold Manasevit, a chemist working at Rockwell International, first demonstrated the epitaxial growth of III-V semiconductors by a new process he called “metalorganic chemical vapor deposition” or MOCVD for short.

In 1975, Dupuis joined Rockwell International and further developed the MOCVD technology and using this improved process, demonstrated the first high-performance III-V semiconductor laser diodes and solar cells in 1977.These results were followed by the collaboration between Dupuis and Holonyak to demonstrate the first room-temperature “quantum-well” lasers in 1978. These results created a rapid expansion of research and development on MOCVD growth.

Today, there are well over 1,000 MOCVD reactors operating in the world, creating a variety of commercially important devices of all kinds, including LEDs, laser diodes, solar cells, photodetectors, transistors, high-power and high-speed electronics and photonic integrated circuits. I will review some of these advances in MOCVD technology in this talk.

Biography: n his early career, Professor Russell D. Dupuis worked in industry at Texas Instruments and Rockwell International. In 1979, he joined the Physics Research Division at Bell Laboratories, Murray Hill NJ as a Member of Technical Staff and was appointed a Distinguished Member of Technical Staff in 1986.

Dupuis was appointed a Chaired Professor in Electrical and Computer Engineering at The University of Texas at Austin in 1989. He joined Georgia Institute of Technology in 2003 as full Professor in ECE and Materials Science and the newly established the Steve W. Chaddick Endowed Chair in Electro-Optics and a Georgia Research Alliance Eminent Scholar. He was the first to demonstrate high-performance optoelectronic devices grown by metalorganic chemical vapor deposition (MOCVD), including the first injection laser diodes and solar cells and he developed improved MOCVD reactor designs. He has won many national and international awards for his work on MOCVD growth of III-V compound semiconductor materials growth and devices, including the US National Medal of Technology, the Charles Stark Draper Prize, the IEEE Edison Medal, Queen Elizabeth Prize in Engineering, and 2022 Benjamin Franklin Medal in Electrical Engineering.

Laureate

P. Daniel Dapkus, Ph.D.

Emeritus Distinguished Professor of Electrical Engineering, Material Science and Physics
University of Southern California,
Los Angeles, CA USA

Title: Metalorganic Chemical Vapor Deposition – The Dominant Technology for Compound Semiconductor Devices

Abstract: After its first demonstration in 1967 by Manasevit and its exploitation for heterostructure lasers and solar cells in the mid-1970's, metalorganic chemical vapor deposition (MOCVD) has emerged as the dominant technology for the myriad of applications for which compound semiconductors are uniquely suited. Semiconductor lasers, LEDs for lighting and displays, night vision sensors, high performance space solar cells, and cell phone output transistors are predominantly manufactured at high volume by MOCVD. Many hurdles have been surmounted and innovations produced to get to the point we are now. Technological issues such as source purity, unique heterostructure device designs, new materials and growth approaches, and new reactor designs have all helped to create the dominance of MOCVD as a technology of choice for compound semiconductor devices. In this presentation, we selectively discuss some of these areas to provide context for MOCVD's widespread use.

Biography: P. Daniel Dapkus is an Emeritus Distinguished Professor of Electrical and Computer Engineering, Materials Science, and Physics and Astronomy at the University of Southern California. He joined USC in 1982 after working as a Group Leader and Manager at Rockwell International (1976 – 1982) and as a Member of Technical Staff at AT&T Bell Laboratories (1970 – 1976). He received a BS in Engineering Physics in 1966, an MS (1967) and a PhD (1970) in Physics in from the University of Illinois at Urbana - Champaign. Dapkus has focused his career activities on the research and development of photonic materials and devices including semiconductor lasers, LEDs, solar cells and detectors. While at Rockwell International, he led the group that demonstrated the potential of metalorganic chemical vapor deposition (MOCVD) as the preferred technology for the growth of compound semiconductor devices.

As a Professor at USC, Dapkus' lab investigated MOCVD fundamental growth mechanisms and selective area growth. They contributed to the technology of long-distance fiber optic lasers, ultra-low threshold datacom lasers, vertical cavity surface emitting lasers (VCSELs) and photonic integrated circuits. Their quantum well material designs are widely employed in 1.55 micron emitting lasers for fiber optic systems and VCSELs for data communications and cell phone facial recognition. Fifty students received their PhD while studying under him. Dapkus has received several awards for innovations in photonic materials and devices including the IEEE Jun-Ichi Nishizawa medal, the John Tyndall Award, the IEEE David Sarnoff Award, Heinrich Welker Award of the ISCS, the Nick Holonyak, Jr. Award of OSA, the IEEE Photonics Society Engineering Achievement Award, and the SPIE Technology Achievement Award, 2022 Benjamin Franklin Medal, and was an IEEE Photonics Society Distinguished Lecturer. He was a co-founder of E2O and T-Networks, startup companies in the optical communications industry. Dapkus is a Member of the US National Academy of Engineering and the National Academy of Inventors and a Fellow of the IEEE, APS, Optica, and AAAS.

Hiroshi Amano, Ph.D.

Director, Akasaki Research Center,
Department of Electrical Engineering and Computer Science
Nagoya University,
Nagoya, Japan

Title: The MOCVD as the Key Technology for Establishing a Carbon Neutral Society

Abstract: When I just started my studies on GaN growth by metalorganic chemical vapor deposition (MOCVD) under the supervision of the late Professor Isamu Akasaki in 1983, I considered the papers written in Applied Physics Letters by Professors R. D. Dupuis, P. D. Dapkus, and their coworkers as my Bible and I read them again and again[1]-3. In the late 70s and early 80s, almost all the MOCVD researchers including nitride semiconductor researchers attempted to follow their path and implement their great achievements. After a long history of research and development, now, nitride semiconductors and their applications in devices become one of the most important key technologies for realizing a carbon-neutral society. For example, according to the US Department of Energy, the amount of energy saved from 2017 to 2035 through the use of LEDs for general lighting is estimated to be 2.3×1016 Wh, which is equivalent to around $890 billion.

Moreover, nitrides are considered to be semiconducting material systems that can be used in post-Si high-power devices. The energy loss of all-electric power circuits such as inverters and converters can be reduced to less than 1/100 by replacing Si-based MOSFETs and IGBTs with GaN-based transistors and diodes. In the future, the mobility of humans will be increasingly dependent on vehicles driven by electricity. Electric vehicles (EVs) are one of the most important tools for establishing a sustainable society. One of the problems of EVs is their short driving range owing to the insufficient capacity of the battery. Another is their long charging time. We succeeded in reducing the electricity consumption of traction inverters in EVs by 65.2% by replacing conventional Si-based IGBTs with GaN-based high-power HEMTs. In our newly developed EVs, IGBTs will be replaced with GaN-based power devices not only in traction inverters but also in all DC-DC converters. GaN-based systems will also be used in all the displays inside the car, and the headlights will be composed of GaN-based high-brightness LED/LD lamps. Thus, we call such a vehicle “all-GaN vehicle”.

[AlGaN-based UV-C LDs may replace conventional solid-state lasers with a fourth-harmonic generation system. In 2019, our group successfully fabricated a 271.8 nm LD on an AlN substrate. To realize current injection lasing, several issues should be overcome. One of the most serious issues is the low hole concentration in the P-type AlGaN cladding layer. From blue LDs to UV LDs, the threshold current density increases markedly with decreasing the emission wavelength. We realized efficient hole injection by using a polarization doping structure, thus reducing the threshold current density. The optimization of the active layer will lead to high-power operation, thus realizing efficient direct diode lasers for future low-carbon-emission laser processing

We are presently developing an open innovation platform to realize such novel power and optoelectronic devices and systems. We have established the Center for Integrated Research of Future Electronics (CIRFE). The purpose of CIRFE is to gather specialists in different fields such as those on the crystal growth of GaN, AlN, SiC, and carbon nanotubes, device fabrication and characterization, simulation, circuit design, module design, and system applications, thus contributing to realizing a carbon-neutralsociety. Our final goal is to realize the dream that was raised by Professors P. D. Dapkus and R. D. Dupuis. As one of the MOCVD researchers, I would like to thank both pioneers from the bottom of my heart.

Biography: Prof. Amano received Doctor of Engineering from Nagoya University. From 1988 to 1992, he was a research associate at Nagoya University. In 1992, he moved to Meijo University from 1998 till 2010. He moved to Nagoya University, where he was a professor of Graduate School of Engineering in 2010. On Oct. 1, 2015, he became a director of Center for Integrated Research of Future Electronics, Institute of Materials and Systems for Sustainability, Nagoya University.
Prof. Amano shared the Nobel Prize in Physics 2014 with Prof. Isamu Akasaki and Prof. Shuji Nakamura "for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources" He is currently developing technologies for the fabrication of high-efficiency power semiconductor development and new energy-saving devices at Nagoya University.

References:
[1] R. D. Dupuis, P. D. Dapkus, R. D. Yingling, and L. A. Moudy, “High-efficiency GaAlAs/GaAs heterostructure solar cells grown by metalorganic chemical vapor deposition”, Appl. Phys. Lett., 31, 201 (1977).
[2] R. D. Dupuis, and P. D. Dapkus, “Room-temperature operation of Ga(1-x)AlxAs/GaAs double-heterostructure lasers grown by metalorganic chemical vapor deposition”, Appl. Phys. Lett., 31, 466 (1977).
[3] R. D. Dupuis, and P. D. Dapkus, “Ga(1-x)AlxAs/ Ga(1-y)AlyAs double-heterostructure room-temperature lasers grown by metalorganic chemical vapor deposition”, Appl. Phys. Lett., 31, 839 (1977).

Dieter Bimberg, Ph.D.

Director, Bimberg Chinese-American Center for Green Photonics, Changun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences

Founding Director, Center of NanoPhotonics Technical University of Berlin, Germany

Member of German Academy of Sciences and American and Russian Academies of Engineering, Inventors and Sciences

Title: Quantum Dots for Green Quantum Technologies

Abstract: Universal self-organization at surfaces of semiconductors grown preferentially by MOCVD leads to the formation of self-similar quantum dots (QDs). Their electronic and optical properties are close to those of atoms in a dielectric cage. All their energy levels are however only twofold degenerate [1]. The few particle states like excitons are strongly Coulomb-correlated due to the carrier localization. Their energies depend on shape and size of the dots, such that positive, zero or negative biexciton binding energies and fine-structure splitting appear [2]. Applications of single, few and millions of QDs for novel Quantum Technologies will be elucidated.

a. Single QDs can be emitters of Q-bits on demand or entangled photons for future quantum cryptography systems. In electrically pumped RCLED structures, emission of q-bits at rates beyond 1 Gbit/s were shown [3, 4].

b. Hybridization of Flash and DRAMs, bringing together the advantages of both types of memories, is the “Holy Grail” of memories and ensures future memory development after the end of Moore’s law. The goal of non-volatility (i.e. storage time > 10 years) can be achieved for the storage of holes in type II (InGa)Sb QDs embedded in a (AlGa)P matrix [5].

c. The demand for higher data rates in optical networks, requires novel ultra-high bit rate, energy efficient sources. QD Lasers based on GaAs emit up to the O-band at 1.3 μm, showing record low jth and complete temperature stability up to 80°C. Passive mode-locking generates pulses in the sub-ps range at repetition rates up to 90 GHz. The hat spectrum of one single laser of several tens of closely spaced narrow lines is thus a potential pulse source for bit rates up to ≈6 TBit/s using higher order modulation formats like DQPSK [6]

Biography: Dieter Bimberg received the Ph.D. magna cum laude from Goethe University, Frankfurt, Germany. He held a Principal Scientist position at the Max Planck-Institute for Solid State Research, Grenoble, France, until 1979. After serving as a Professor of electrical engineering, Technical University of Aachen, Germany, he assumed the Chair of Applied Solid-State Physics at Technical University of Berlin. He is the Founding Director of its Center of NanoPhotonics. He was holding guest professorships at the Technion, Haifa, U.C. Santa Barbara, CA, USA, and at Hewlett-Packard in Palo Alto, CA. He was Distinguished Adjunct Professor at KAU, Jeddah 2012-2018. In 2018 he assumed the directorship of the "Bimberg Chinese German Center for Green Photonics" at the Changchun Institute of Optics, Fine Mechanics and Physics of the Chinese Academy of Sciences.
He is a member of the German Academy of Sciences Leopoldina, the EU Academy of Sciences, a Foreign Member of the Russian Academy of Sciences, the US Academies of Engineering and of Inventors, a Life Fellow of the American Physical Society and the Institute of Electrical and Electronics Engineers, IEEE, and a honorary member of the Ioffe Institute of the RAS. He is recipient of multiple international awards, like the UNESCO Nanoscience Award, the Max-Born Award and Medal of IoP and DPG, the Heinrich-Welker-Award, the Nick Holonyak Jr. Award, the Oyo Buturi and MOC Awards of the Japanese Society of Applied Physics, the Jun-Ichi Nishizawa Medal and Award of IEEE, the Stern-Gerlach Award of DPG to mention a few. He received honorary doctorates of the University of Lancaster, UK, and the St. Petersburg Alferov University of the Russian Academy of Sciences.
He has authored more than 1600 papers, 71 patents and patent applications, and six books. The number of times his research works has been cited exceeds 68,000 and his Hirsch factor is 113 (@ Google Scholar). His research interests include physics and technology of nanostructures, nanostructured photonic and electronic devices, and energy efficient data communication

References

[1] M. Grundmann, O. Stier and D. Bimberg: „Pyramidal Quantum Dots – Strain Distribution, Optical Phonons, and Electronic Structure", Phys. Rev. B52, 11969, 1995 and O. Stier, M. Grundmann and D. Bimberg: "Electronic and optical properties of strained quantum dots modelled by 8-band k.p theory", Phys. Rev. B 59, 5688, 1999.

[2] S. Rodt, A. Schliwa, K. Pötschke, F. Guffarth and D. Bimberg," Correlation of structural and few particle properties of self-organized InAs/GaAs quantum dots", Phys. Rev. B 71, 155325, 2005.

[3] A. Schliwa, M. Winkelnkemper, A. Lochmann, E. Stock, and D. Bimberg.: (InGa)As/GaAs quantum dots grown on a (111) surface as ideal sources of entangled photon pairs", Phys. Rev. B 80, 601307(R), 2009

[4] W. Unrau and D. Bimberg: "Flying q-bits and entangled photons" in "Laser Photonics Review" 8, 276, Wiley 2014

[5] L. Bonato, F. I. Arikan, L. Desplanque, C. Coignon, X. Wallart, Yi Wang, P. Ruterana and D. Bimberg, "Hole Localization Energy of 1.18 eV in GaSb quantum dots embedded in GaP", phys. stat. sol (b) 10, 1877, 2016

[6] G. Eisenstein and D.Bimberg, eds.: "Green Photonics and Electronics", Springer 2017

James Coleman, Ph.D.

Presidential Distinguished Professor of Photonics,
University of Texas at Arlington, TX

Intel Alumni Endowed Chair Emeritus,
University of Illinois, Urbana, IL USA

Title: The MOCVD Growth of Diode Lasers in Context – A Significant Challenge and an Elegant Solution

Abstract: The time period between the first demonstrations of the semiconductor diode laser in 1962 and its pervasive commercialization in the 1990s was one of rapid exciting developments in semiconductor laser device design, processing, characterization and especially the epitaxial growth of suitable materials. Here we try to provide context for the remarkable development of MOCVD epitaxial growth by outlining the state-of-the-art just prior to the work of Dapkus and Dupuis, and then highlighting some of the intended achievement, as well as some unexpected opportunities, that resulted.

Biography: James J. Coleman received his degrees in electrical engineering from the University of Illinois, Urbana. After working in industry at Bell Laboratories and Rockwell International, he joined the faculty at Illinois where he and his students were the first to define experimentally the ranges of wavelength, threshold current density, and reliability of 980 nm strained-layer InGaAs lasers. His research interest is MOCVD-grown diode lasers and other nanoscale photonic devices including narrow linewidth DBR lasers, integrated lasers and other photonic devices by selective-area epitaxy, and the growth processes for patterned quantum dot lasers. He is a member of the US National Academy of Engineering and a Fellow of the IEEE, OSA, SPIE, APS, and AAAS. He was awarded the 2021 IEEE Nishizawa Medal for “for contributions to the development of strained-layer semiconductor lasers.” His other awards include the IEEE/OSA John Tyndall Award, the IEEE David Sarnoff Award, the SPIE Technical Achievement Award, and the OSA Nick Holonyak, Jr. Award.

Chennupati Jagadish, Ph.D.

AC, MNAE (US), FAA, FTSE, FTWAS, FNAI, FNA, FNAE, FASc, FAPAS, FEurASc, FNAS
Distinguished Professor and Head of Semiconductor Optoelectronics and Nanotechnology Group,
Research School of Physics
Australian National University, Canberra, Australia
President-elect, Australian Academy of Science

Title: Semiconductor Nanostructures for Optoelectronics Applications

Abstract: Semiconductors have played an important role in the development of information and communications technology, solar cells, solid state lighting. Nanowires are considered as building blocks for the next generation electronics and optoelectronics. In this talk, I will present the results on optoelectronic devices such as lasers/LEDs, THz detectors, energy devices such as solar cells, photoelectrochemical (PEC) water splitting and Neuro-electrodes. Future prospects of the semiconductor nanowires will be discussed.

Biography: Professor Jagadish is a Distinguished Professor and Head of Semiconductor Optoelectronics and Nanotechnology Group in the Research School of Physics, Australian National University. Prof. Jagadish is the Editor-in-Chief of Applied Physics Reviews (IF:19.162), Editor of 2 book series and serves on editorial boards of 19 other journals including ACS Nano. He has published more than 1000 research papers (710 journal papers), holds 7 US patents, co-authored a book, co-edited 15 books and edited 12 conference proceedings and 20 special issues of Journals. He is a fellow of 11 Science and Engineering Academies (US, Australia, Europe, India) and 14 Professional Societies (IEEE, MRS, APS...). He received many awards including IEEE Pioneer Award in Nanotechnology, IEEE Photonics Society Engineering Achievement Award, OSA Nick Holonyak Award, IUMRS Somiya Award, UNESCO medal for his contributions to the development of nanoscience and nanotechnologies and Lyle medal from Australian Academy of Science for his contributions to Physics. He has received Australia's highest civilian honor, AC, Companion of the Order of Australia, for his contributions to physics and engineering, in particular nanotechnology. He has been elected as the next President of the Australian Academy of Science.

Shuji Nakamura, Ph.D.

Nobel Prize in Physics, NAE, NAI, NIHF, RAE
CREE Distinguished Professor
University of California Santa Barbara, CA.

Title: The importance of the MOCVD growth to the invention of the blue LED and solid-state light revolution

Abstract: I started a research of III-nitride based blue LED using a commercially available MOCVD in 1989. I had to spend one and half year to modify a reactor of the MOCVD to obtain a uniform GaN film over two-inch sapphire substrate. Finally, I could invent a novel MOCVD, called Two-Flow MOCVD in 1990 [1]. Up to 1990, the highest quality of undoped GaN was obtained by using other group's MOCVD. The electron mobility of their undoped GaN film was 50cm2/VS [2]. We obtained the electron mobility of 200cm2/VS by using the Two-Flow MOCVD. Since the invention of Two-Flow MOCVD, first p-GaN/n-InGaN/n-GaN double-heterostructure (DH) blue LEDs were demonstrated in 1993 [3]. In 1994, we demonstrated commercially available blue LEDs with an output power of 1.5mW, the EQE of 2.7% and the emission wavelength of 450nm [4]. At the same time, Nichia Chemical Industries Ltd. did a press release of mass production of the high brightness blue DH LEDs with a brightness of more than 1000 mcd on November 30th, 1993 [5], just one month later after a press release of metal insulating semiconductor (MIS) type LEDs with a brightness of 200 mcd by Toyoda Gosei Co. Ltd on October 20th, 1993 [6]. Finally, we demonstrated high brightness blue, green and yellow LEDs with InGaN quantum well (QW) structures in 1995 [7]. First laser diodes (LDs) were reported under RT pulsed operation in 1996 [8]. Currently, only a few companies could make the products of blue LDs as commercial base due to a problem of reliability and yield caused mainly by the MOCVD growth.

Biography:

Professor Shuji Nakamura is a Japanese-born American electronic engineer and inventor, specializing in the field of semiconductor technology. Professor Nakamura in Department of Materials and in the Electrical and Computer Engineering in the College of Engineering, University of California, Santa Barbara, also holds the Cree Endowed Chair in Solid State Lighting & Displays. Professor Nakamura is regarded as the inventor of the blue LED, a major breakthrough in lighting technology. He is a recipient of the 2014 Nobel Prize for Physics "for the invention of efficient blue light-emitting diodes, which has enabled bright and energy-saving white light sources." He is a fellow of the U.S. National Academy of Engineering, National Academy of Inventors, and the National Inventors Hall of Fame. He is a recipient of numerous international honors including the 2006 Millennium Technology Prize, The Harvey Award (2009), 2014 Order of Culture Award in Japan, the 2015 Global Energy Prize, the Technology & Engineering Emmy Award (2012), the 2018 Zayed Future Energy Prize, the 2020 National Academy of Science (NAS) Award for the Industrial Application of Science, 2021 Queen Elizabeth Prize for Engineering, and the 2002 Benjamin Franklin Medal in Electrical Engineering.

References:

1. S. Nakamura, Y. Harada, and M. Senoh," Novel metalorganic chemical vapor deposition system for GaN growth," Appl. Phys. Lett., vol. 58, 1991, pp. 2021-2023

2. H. Amano, N. Sawaki, I. Akasaki, and Y. Toyoda, "Metalorganic vapor phase epitaxial growth of a high quality GaN film using an AlN buffer layer," Appl. Phys. Lett., vol.48, 1986, pp. 353-355

3. S. Nakamura, M. Senoh, and T. Mukai," p-GaN/n-InGaN/n-GaN double-heterostructure blue-light-emitting diodes," Jpn. J. Appl. Phys., vol. 32, 1993, pp. L8-L11.

4. S. Nakamura, T. Mukai, and M. Senoh," Candera-class high-brightness InGaN/AlgaN double-heterostructure blue-light-emitting diodes," Appl. Phys. Lett., vol. 64, 1994, pp. 1687-1689.

5. "p-n junction DH Blue LEDs with a brightness of more than 1000mcd were developed by Nichia Chemical Industries Ltd.," November 30th, 1993, Nikkei Sangyo Shinbun (Japanese newspaper press release).

6. "MIS type Blue LEDs with a brightness of 200mcd were developed by Toyoda Gosei," October 20th, 1993, Nikkan Kogyo Shinbun (Japanese newspaper press release).

7. S. Nakamura, M. Senoh, N. Iwasa, and S. Nagahama," High-brightness InGaN blue, green and yellow light-emitting diodes with quantum well structures," Jpn. J. Appl. Phys. Vol. 34, 1995, pp. L797-L799.

8. S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita,H. Kiyoku, and Y. Sugimoto, "InGaN-based multi-quantum-well-structure laser diodes,"Jpn. J. Appl. Phys., vol. 35, 1996, pp. L74-L76.