Special Issue on Optoelectronic Devices Based on Quantum Dots

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In the past few years, increasing interest has been focused on nanoscience and nanotechnology and, in that context, on semiconductor nanostructures. This is mainly due to their low-dimensional character, which allows one to tailor carrier quantum confinement as well as coulomb interaction. The most significant scientific and technological advancement in the field was the introduction of quasi-zero-dimensional (OD) systems, called semiconductor quantum dots, or *semiconductor macroatoms*. Such quantum dots (QDs) are now realized as coherently strained, defect-free islands during the self-organized epitaxial growth of mismatched semiconductor heterostrucures, e.g., InAs/GaAs. The areal density of islands, which exhibit properties of quantum dots, or boxes, can be varied from $10^9 - 10^{12}$ cm^{-2} and multiple layers of these dots can be vertically stacked. The peak wavelength of the luminescence from the dots can be tuned over a wide range—0.5–2.0 μm by varying the heterostructure composition or the dot size. Apart from their relevance in terms of basic physics, self-organized quantum dots have attracted a great deal of attention because of their technological applications, including lasers, infrared detectors, optical amplifiers, charge storage devices, and quantum information processing devices. This special issue will provide a comprehensive overview of the explosive growth of quantum dot devices for present-day and future applications in optoelectronics. Significant emphasis is placed on the unique device functions and performance that can be derived from quantum dot active regions.

> This issue provides a snapshot of current research and development in the area of quantum dot optoelectronic devices, including a comprehensive overview of present and future applications.

Three-dimensional quantum confinement in semiconductors and quantum boxes, or dots, has been investigated theoretically for some time. It is only recently that defect-free quantum dots, whose structural, electronic, and optical properties can be measured and with which devices can be fabricated reliably and reproducibly, have been experimentally realized. The three-dimensional quantum confinement gives rise to singular localization of electrons and holes and a discrete spectrum with density of states. Although many of the predicted properties arising from 3-D confinement were experimentally verified with quantum dots realized by controlled etching of epitaxially grown quantum wells, such quantum dots

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were not suitable for the fabrication of most devices due to the high density of surface states created during etching. Fortunately, advances in mismatched or strained-layer epitaxy with III-V compound semiconductors led to the elucidation of near-equilibrium growth conditions under which defect-free islands were formed. By virtue of their size and shape, these self-organized or self-assembled islands have become the material of choice for the realization of a host of optoelectronic devices. More importantly, quantum dots and their unique properties have quickly transcended the realm of curiosity and have emerged as active regions of high-performance and novel devices.

Since the first demonstration of quantum dot laser operation at cryogenic temperatures, rapid progress has been made in the understanding and control of self-organized epitaxy and in device development. Room-temperature quantum dot edge-emitting lasers, first demonstrated more than a decade ago, now surpass quantum well lasers in performance. This finding was quickly followed by the demonstration of quantum dot vertical cavity surface-emitting lasers (VCSELs). Large electrooptic coefficients have been measures in the dots. New devices such as the quantum dot infrared photodetector (QDIP), which takes advantage of the possibility of normal incidence operation, have been conceived and demonstrated. QDIPs have now demonstrated high-temperature (200 K–300 K) operation, large responsivity ($\sim$1 A/W), and high detectivity ($D^* \sim 10^{11}$ cm$\sqrt{\text{Hz}}$/W). The characteristics of quantum dot optical amplifiers exceed those of other semiconductor optical amplifiers in terms of ultrabroad gain, ultrafast nonlinear gain response, low noise figure, and high saturation output power. Self-organized quantum dots also offer more exciting possibilities. The observation of cavity quantum electrodynamics phenomena in semiconductor systems is made possible by a single quantum dot lasing in a single-mode optical cavity with a high-quality factor, such as a single-defect microcavity in a photonic crystal. These devices have been fabricated and characterized for the first time. While most of these developments have taken place with GaAs and InP-based quantum dots, rapid progress is also being made with nitride-based and silicon-based self-organized quantum dots. The current state of the art of such research and development is the subject of the 12 papers in the present Special Issue of the PROCEEDINGS OF THE IEEE.

The first paper, titled "Quantum Dot Optoelectronic Devices," is written by one of the guest editors (Bhattacharya) and his colleague, Mi, and serves as an introduction to the special issue. The article provides a comprehensive overview of the development of self-organized In(Ga)As/Ga(Al)As quantum dots and their application to existing and novel optoelectronic devices, thereby providing the reader with a glimpse of the tremendous strides made with these fascinating nanostructures. The epitaxy, structural, and optical characteristics are briefly described, followed by a short description of carrier scattering and hot-carrier dynamics in the quantum dots. Understanding of these aspects was crucial in the realization of high-performance devices. The characteristics of edge-emitting quantum dot lasers emitting at various wavelengths are described in some detail, with emphasis on special techniques used to enhance device performance. The article also provides an introduction to the contents of the rest of the papers in the Special Issue, with additional references. Thus, the characteristics of vertical cavity surface emitting lasers (VCSELs), optical amplifiers, microcavity devices for quantum information processing, and infrared photodetectors, all with self-organized quantum dot active regions, are briefly described. It is hoped that the readers will get the sense of the complementary efforts in theory, modeling, epitaxial growth, materials characterization, and device design and characterization, which have all been effective in transforming quantum dots from scientific curiosity to a versatile technology.

The remaining 11 papers in the special issue are organized in four sections, each describing the current state of understanding and development: a section on lasers and amplifiers, a section on devices for quantum information processing, a section on QDIPs, and finally a section on devices with nitride-based and silicon-based quantum dots. These are now briefly discussed.

I. LASERS AND AMPLIFIERS

The present section includes four papers. In the first paper of this section, "High Speed Quantum Dot Vertical Cavity Surface Emitting Lasers," Ledentsov *et al.* report on recent progress in quantum dot high speed VSCELs. Advanced techniques of quantum dot epitaxy and device design lead to 20 Gb/s operation under direct modulation and bit error rates better than 10^{-12}. A unique approach of high-speed electro-optic modulation of the QD VCSELs is described, which leads to 60 GHz electrical and $\sim$35 GHz optical bandwidths. Future challenges to further improve device performance are also discussed.

In the next paper, "Quantum-Dot Semiconductor Optical Amplifiers," Akiyama *et al.* review recent progress of quantum dot semiconductor optical amplifiers developed as ultra-wideband polarization-insensitive high-power amplifiers, high-speed signal regenerators, and wideband wavelength converters. The paper describes how these unique attributes are made possible by utilizing isotropically-shaped quantum dots and by exploiting their ultra-broad gain and ultra-fast non-linear gain response. The authors describe QD semiconductor optical amplifier (SOA) operation with a gain > 25 dB, noise figure < 5 dB, 3-dB saturation output power of > 20 dBm, record widest bandwidth of 90 nm among all categories of optical amplifiers and > 40 Gb/s operation. The authors conclude that such performance characteristics will lead to low-cost realization of regenerative transmission systems.

In the third paper of the section, "High Speed Mode Locked Quantum Dot Lasers and Optical Amplifiers," Kuntz *et al.* review recent results on GaAs-based high-speed mode-locked quantum dot lasers and optical amplifiers for 1.3 μm operation. Hybrid and passive mode-locking of QD lasers with repetition frequencies between 5 and 80 GHz, sub-picosecond pulse widths, ultra-low timing jitter of 190 fs, high output peak power > 1 W and suppression of Q-switching are demonstrated and show the potential of these devices for O-band optical fiber applications. The authors also predict their application in future 100 Gb ethernet networks.

In the last paper of the section, "InAs/InP Quantum Dash Lasers and Amplifiers," Reithmaier *et al.* describe devices made with InAs *quantum dashes* on InP substrates. Under typical group V stabilized surface conditions during epitaxy, indium atoms have a longer surface diffusion length along the [110] direction compared to the [110] direction. The resulting anisotropic stress relaxation typically leads to the formation of elongated quantum dashes. The luminescence output peak from the dashes ranges from 1.4 to 1.65 μm, thereby covering the 1.55 μm telecom wavelength. The authors report multi-wavelength amplification without any cross-talk at data rates of 10 Gb/s and pattern-free and noise reduced signal amplification at saturation conditions up to 40 Gb/s.

II. DEVICES FOR QUANTUM INFORMATION PROCESSING

Two papers, both of which describe quantum dot single photon sources, are grouped together in this section. These are non-classical light emitters which have applications in quantum cryptograpy and quantum information processing. In the paper titled "InP/GaInP Quantum Dots as Single Photon Sources for Quantum Information Processing," Aichele *et al.* review different demonstrations of quantum applications using a deterministic single photon source. Self-organized InP quantum dots in a GaInP matrix are used in the active region of the devices as their emission wavelength around 690 nm allows the highest detection efficiency of single photons. In addition to single photons, the authors demonstrate photon pairs and triplets, as well. The applicability of the non-classical sources is demonstrated in a quantum key distribution experiment and in encoding of quantum information.

Young *et al.* in the second paper titled "Quantum Dot Sources for Single Photons and Entangled Photon Pairs" describe triggered quantum dot light sources of both single and polarization entangled photons for Quantum Information applications. The authors describe a process and a device to form a sub-micron current aperture within a p-i-n diode in which embedded InAs quantum dots are addressed electrically and individually.

III. QUANTUM DOT INFRARED PHOTODETECTORS (QDIPs)

Three papers are grouped in this section. The first, titled "Quantum Dot Infrared Photodetectors," serves as introduction to the operating principles, fabrication and characteristics of these unique infrared detection devices. The authors, Campbell and Madhukar, describe these aspects in great detail. The device active (absorption) region consists of InAs self-organized quantum dots with GaAs, InGaAs, or AlGaAs capping layers, which allow tuning of the operating wavelength by changing the electron inter-sublevel spacing in the dots. Normal incidence operation with high detectivity in the mid (3–5 μm) and long (8–12 μm) wavelength regimes and the potential for multi-color operation are demonstrated.

In the second paper of the section, titled "High-Temperature Tunneling Quantum Dot Intersublevel Detectors for Mid-Infrared to Terahertz Frequencies," Bhattacharya *et al.* describe a novel variation of the QDIP active region, which enables a significant reduction of the dark current and consequent high temperature operation. Essentially, resonant tunneling is utilized to separate the electrons contributing to the dark- and photo-current. Operation of devices is demonstrated in the wavelength range of 6 to 80 μm at temperatures up to 300 K with acceptable values of peak responsivity and specific detectivity.

In the third paper, "Quantum Dot Based Infrared Focal Plane Arrays," Krishna *et al.* describe the characteristics of normal incidence imaging arrays made with QDIPs. The authors demonstrate the use of a novel dots-in-a-well (DWELL) design in the active region of the detectors, which allows bias tunability and multicolor operation in MWIR, LWIR and VLWIR wavelength ranges. The authors describe the fabrication and characteristics of mid-format 320 $\times$ 256 and 640 $\times$ 512 focal plane arrays (FPAs). The paper concludes with a discussion on future prospects in terms of enhanced functionality and high temperature operation.

IV. DEVICES WITH NITRIDE-BASED AND SILICON-BASED QUANTUM DOTS

The last section of this special issue includes two papers which describe the developments with quantum dots of other heterostructure systems. Grandjean and Ilegems in "Visible InGaN/GaN Quantum Dot Materials and Devices" describe the general properties of nitride-based quantum dots and provide an excellent review of the developments with this material system. A unique feature in this heterostructure system is the presence of a large built-in internal electric field of several MV/cm. Starting with a description of GaN/AlN QDs, the authors move on to describe the epitaxy and optical properties of InGaN/GaN QDs. The properties of light-emitting diodes are next illustrated. The article concludes with the present status of nitride QD based lasers and their future prospects.

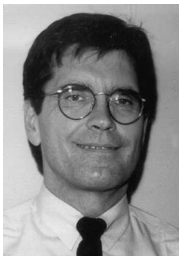
In the last paper, Cha *et al.* in "Ge/Si Self-Assembled Quantum Dots and Their Optoelectronic Device Applications," discuss the epitaxy, properties and device applications of the Group IV-based nanostructures. Ge/Si quantum dots exhibit a type-II band lineup. By replacing Ge with $Si_{1-x}Ge_x$ as the dot material and by changing the dot size, great tunability of emission and absorption wavelengths of interband and intersublevel devices can be obtained. Molecular beam epitaxy of the dots and their structural and optical properties are presented in great detail. Characteristics of light emitting diodes and QDIPs are presents. The results indicate that Ge/Si quantum dots are potentially applicable for 8–12 μm infrared detectors as well as 1.3–1.55 μm optoelectronic devices for fiber-optic communications.

This special issue aims to provide the reader with a picture of current research and development of quantum dot optoelectronic devices. The researchers who have contributed to the present special issue have made pioneering contributions to this development. They have also invested significant time and effort in writing the articles. We would like to thank the numerous reviewers, whose help and feedback have been invaluable. Finally, we would like to thank the Managing Editor Jim Calder and Acting Publications Editor Jo Sun for their help and continuing support. ■

ABOUT THE GUEST EDITORS

Pallab Bhattacharya (Fellow, IEEE) is the Charles M. Vest Distinguished University Professor of Electrical Engineering and Computer Science and the James R. Mellor Professor of Engineering in the Department of Electrical Engineering and Computer Science at the University of Michigan, Ann Arbor. He received the M. Eng. and Ph.D. degrees from the University of Sheffield, U.K., in 1976 and 1978, respectively. Professor Bhattacharya was an Editor of the IEEE Transactions on Electron Devices and is Editor-in-Chief of *Journal of Physics D*. He has edited *Properties of Lattice-Matched and Strained InGaAs* (U.K.: INSPEC, 1993) and *Properties of III-V Quantum Wells and Superlattices* (U.K.: INSPEC, 1996). He has also authored the textbook *Semiconductor Optoelectronic Devices* (Prentice Hall, 2nd ed.). His teaching and research interests are in the areas of compound semiconductors, low-dimensional quantum confined systems, nanophotonics and optoelectronic integrated circuits. He is currently working on high-speed quantum dot lasers, quantum dot infrared photodetectors, photonic crystal quantum dot devices, and spin-based heterostructure devices. From 1978 to 1983, he was on the faculty of Oregon State University, Corvallis, and since 1984 he has been with the University of Michigan. He was an Invited Professor at the Ecole Polytechnic Federale de Lausanne, Switzerland, from 1981 to 1982.

Prof. Bhattacharya has received the John Simon Guggenheim Fellowship, the IEEE (EDS) Paul Rappaport Award, the IEEE (LEOS) Engineering Achievement Award, the Optical Society of America (OSA) Nick Holonyak Award, the SPIE Technical Achievement Award, the Quantum Devices Award of the International Symposium on Compound Semiconductors, the IEEE (Nanotechnology Council) Nanotechnology Pioneer Award and has been selected to receive the 2008 TMS John Bardeen Award. He has also received the S.S. Attwood Award, the Kennedy Family Research Excellence Award, and the Distinguished Faculty Achievement Award from the University of Michigan. He is a Fellow of the IEEE, the American Physical Society, the Institute of Physics (U.K.), and the Optical Society of America.



Dieter Bimberg (Member, IEEE) received the Diploma in physics and the Ph.D. degree from Goethe University, Germany, in 1968 and 1971, respectively.

From 1972 to 1979 he held a Principal Scientist position at the Max Planck-Institute for Solid State Research in Grenoble/France and Stuttgart. In 1979 he was appointed as Professor of Electrical Engineering, Technical University of Aachen. Since 1981 he holds the Chair of Applied Solid State Physics at Technical University of Berlin. Since 1990 he is Executive Director of the Solid State Physics Institute at TU Berlin. Since 2004 he is director of the Center of Nanophotonics at TU Berlin. In 2006 he was elected as chairman of the German National Centers of Excellence of Nanotechnologies.

Dr. Bimberg's honors include the Russian State Prize in Science and Technology 2001, the Max-Born-Award and Medal 2006, awarded jointly by IoP and DPG, and in 2004 his election to the German Academy of Natural Sciences Leopoldina and as Fellow of the American Physical Society. He has authored more than 800 papers, patents, and books resulting in more than 16000 citations worldwide. His research interests include the physics of nanostructures and photonic devices, like quantum dot lasers and amplifiers, single photon emitters, wide gap semiconductor heterostructures and ultrahigh speed photonic devices.

Yasuhiko Arakawa (Fellow, IEEE) received B.S., M.S., and Ph.D. degrees in electrical engineering from the University of Tokyo, in 1975, 1977, and 1980, respectively.

In 1980, he started his academic carrier by joining University of Tokyo as an assistant professor and was promoted to a full professor in 1993. He is now Professor of Research Center for Advanced Science and technology, University of Tokyo. He is also the director of Nanoelectronics Research Center at Institute of Industrial Science, University of Tokyo as well as Research Professor at NTT. His current research includes growth and physics of semiconductor nanotechnologies for optoelectronic device applications such as quantum dot lasers and various nanostructure devices.

Dr. Arakawa is the recipient of many awards including Niwa Memorial Award, Excellent Paper Award from IECE, Young Scientist Award, International Symposium on GaAs and Related Compound Semiconductors, IBM Award, Distinguished Achievement Award from IEICE, Hattori Hoko Award, Sakura-Kenjiro Award from OITDA, Electronics Award from IEICE, and Nissan Science Award. He has been serving several distinguished international conferences as general chairs including the 17th IEEE Semiconductor Laser Conference. He was Associate Editor of IEEE JOURNAL OF QUANTUM ELECTRONICS and Editor in Chief of the *Journal of Japanese Society of Applied Physics*, and he is currently Editor in Chief of *Solid State Electronics* and Regional Editor on *New Journal of Physics* (IOP). He is in charge for planning the optoelectronics technology-roadmap at the OITDA.