Perspectives on III-V Semiconductor Nanowire Optoelectronics and Beyond

Lan Fu and Chennupati Jagadish

PROFESSOR CHENNUPATI JAGADISH (see Figure 1) is a Distinguished Professor at the Department of Electronic Materials Engineering, Research School of Physics, the Australian National University (ANU). He is also currently the President of the Australian Academy of Science.

He obtained the B.Sc. degree in physics from Acharya Nagarjuna University (VSR College, Tenali) in 1977, the M.Sc. (Tech) in Applied Physics from Andhra University in 1980, and the M.Phil. and Ph.D. degrees in Physics from the University of Delhi in 1982 and 1986, respectively. After completing his Ph.D., he worked at Sri Venkateswara College, New Delhi, as a Lecturer in Physics and Electronics during 1985–1988 and then took up a post-doctoral position working on Barkhausen noise in ferromagnetic steels at Queen's University Physics Department. He moved to the ANU in 1990, and since then, he has been working in the fields of compound semiconductor optoelectronics, nanotechnology, photovoltaics, and neurotechnology. His wide range of outstanding research achievements has led to the election of him as a Fellow of 12 Science and Engineering Academies in Australia, India, the United States, U.K., and Europe, and a Fellow of more than 14 professional societies, including Fellow of the Australian Academy of Science and the Australian Academy of Technological Sciences and Engineering, a Fellow of IEEE, APS, OSA, SPIE, AAAS, TWAS, etc., a Foreign Member of the US National Academy of Engineering, a Foreign Fellow of the Indian National Science Academy and

FIGURE 1 Professor Chennupati Jagadish.

Indian National Academy of Engineering, and, most recently, in September 2022, International Fellow of the United Kingdom's Royal Academy of Engineering (see Figure 2). He has also won numerous internationally acclaimed awards, including the IEEE Pioneer in Nanotechnology, IEEE Photonics Society Engineering Achievement Award, the Welker Medal, the IUMRS Somiya Award, the UNESCO medal for the development of nanoscience and nanotechnologies, the Lyle Medal, the Boas Medal, the Beattie Steel Medal, to highlight a few. With his wife Vidya Jagadish, he created an Endowment Fund in 2015 to support students and young scientists from developing countries to travel to the ANU to pursue collaborative research for up to 12 weeks (see Figure 3).

Following his early pioneering work on novel delta doping and bandgap engineering of quantum structures in thin film III-V compound semiconductors, such as quantum wells, quantum wires, and quantum dots that have led to innovative optoelectronic devices with several world records for device performance, his research has been focused on the development of new materials and devices based on the one dimensional semiconductor nanostructures, i.e., nanowires, with a number of seminal work significantly advancing the fundamental understanding and development of the field. He has been a great advocate for Nanoscience and Nanotechnology and was the former President of IEEE Nanotechnology Council. In this Highlights Section of INM, we are very pleased to feature a review of Prof. Jagadish's outstanding research achievements and perspectives on III-V semiconductor nanowire optoelectronics and beyond.

Since the early 1990s, III–V semiconductor nanowires have emerged as an exciting new research field due to their potential to reveal new fundamental physics and to stimulate new device designs for a wide variety of applications ranging from interconnects, waveguides to functional device elements in electronic, optoelectronic, and sensor applications. One of the challenges of nanowire research is the synthesis of nanowires with well-controlled dimensions, orientation, structure, phase purity, and chemical composition [1]. In early 2000, Prof. Jagadish's group extended his well-known III-V semiconductor epitaxial growth expertise by metal organic chemical vapour deposition (MOCVD) to nanowire growth and demonstrated a variety of III-V nanowire materials grown via vapor liquid solid (VLS) mechanism,

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FIGURE 2 Prof. Jagadish receiving scroll from the HRH princess royal and signing charter book at the Royal Academy of Engineering as an International Fellow in London, U.K., in Nov. 2022.

including InGaAs [2], GaAs [3], GaAs/AlGaAs [4], InAs [5], InP [5], and GaAsSb [6], etc. By employing a two-temperature growth procedure, containing an initial high-temperature step for obtaining straight, vertically aligned epitaxial nanowires on the (111)B GaAs substrate and a lower temperature step to minimize radial growth and eliminate twinning defects, they successfully demonstrated VLS GaAs nanowires with superior morphology and crystallographic quality [3]. In 2010, Prof. Jagadish's group demonstrated growth of phase-perfect zinc blende (ZB) and wurtzite (WZ) VLS GaAs nanowires, of arbitrary diameter, by tailoring basic growth parameters: temperature and V/III ratio [7]. This ability to tune crystal structure between twin-free zinc blende and stacking-fault-free wurtzite not only will enhance the performance of nanowire devices but will also open up new possibilities for engineering nanowire devices without restrictions on nanowire diameters or doping. By properly designing the Fabry–Pérot cavity, optimizing the material quality and minimizing surface recombination, Prof. Jagadish's group has achieved room-temperature operation at low threshold for the smallest-volume bulk GaAs nanolasers [8], taking a major step towards incorporating (Al)GaAs nanowire lasers into the design of nanoscale optoelectronic devices for on-chip integration. Based on the VLS grown III-V nanowires, Prof. Jagadish's group has demonstrated a series of high performance single nanowire based IR photodetectors [9], THz detectors [10], and solar cells [11].

Among different types of III-V semiconductor nanowires, InP based materials are shown to have very low surface recombination velocity [5], which is particularly critical to their applications for optical telecommunications, solar cells, and high-speed electronics. Although small diameter Au-seeded InP NWs with high crystalline quality and limited tapering have been demonstrated by various epitaxial techniques, the VLS method does show complexity and compromised optical properties for InP NW growth with up-scaling diameters and impurity (Au atoms) incorporation. To address these issues, in 2015, Jagadish's group developed the SiO_2 template based selective area epitaxy (SAE) technique, demonstrating the successful growth of stacking-fault-free WZ InP NWs with a wide range of diameters, varying from 80 to 600 nm [12]. As a result of the excellent structural and optical quality that are equivalent to the best quality 2D layers, these SAE grown InP nanowires have led to the demonstration of room-temperature lasing from conventional guided modes [12], broadband THz detectors [13], and two-channel polarization resolvable THz detectors [14]. The SAE InP NW based material and growth platform has further led to the capability of design and growth of a variety of nanowirestructures with different geometries [15] and quantum structure (such as quantum wells) incorporation [16] through shape and crystal facet engineering, opening up further opportunities for device performance enhancement and on-chip integration. For example, through careful cavity design and lasing mode engineering, efficient room-temperature lasing from InP micro-ring lasers by optically pumping has been recently achieved [15]. By changing the MOCVD growth window to grow InP nanowires with mixed ZB and WZ phases so as to rotate the hexagonal NW facets to lower the surface energy for InGaAs growth, multiple InGaAs/InP quantum wells with uniform morphology and room temperature optical lasing have been achieved [16].

With the deep insight into the NW material properties and device physics, Prof. Jagadish's group has also shown that NW arrays fabricated by top-down etching approach, without relying on epitaxial growth, offer alternative flexibility in device design with potentially reduced cost and complexity. By utilizing a radial p–n junction nanowire architecture, a p-InP/n-ZnO/AZO radial heterojunction nanowire solar cell has been designed and fabricated from a p-type InP substrate to achieve a photovoltaic conversion efficiency of 17.1%: a record value for radial junction nanowire solar cells at the time [17]. On the other hand, owing to the strong built-in electric field (exceeding 3×10^5 V cm^{-1}), such device design has further led to a broadband light sensitivity which can distinguish a single photon per pulse at 0 V, providing a new pathway toward low-cost, high-sensitivity, self-powered photodetectors for numerous future applications.

Beyond optoelectronics, Prof. Jagadish has further led the research on III-V nanowires into new areas and applications. By using the top-down etched InP nanowire array as scaffolds, neurite growth with the spontaneous neuronal network activity was monitored and evaluated by his group using functional calcium imaging. It was found that multiple neurons, with neurites guided by the topography of the isotropic arrangement of InP nanowires, exhibit synchronized calcium activity, implying intercellular communications

FIGURE 3 Professor Chennupati Jagadish with wife Vidya and students supported by the Chennupati and Vidya Jagadish endowment fund.

via synaptic connections. This new discovery reveals the role of nanotopographical cues in the formation of functional neuronal circuits in the brain, which is important for the future development of neuroprosthetic scaffolds [18]. Also, by carefully engineering the NW geometry (i.e., diameter and pitch) and developing a novel NW sensor device design, Jagadish's group has demonstrated InP nanowire array chemiresistive NO_2 sensor with performance superior than those previously reported semiconductor-based sensors, obtaining a limit of detection of 3.1 ppb at room temperature, with outstanding selectivity, and long-term stability [19]. These have been attributed to the unique nanoscale structures and material properties of the InP NW arrays and indicate that III-V compound semiconductor NWs present a new and promising chemical sensing platform for the development of future high performance, miniaturized on-chip sensing systems.

With the continuous progress of nanoscience and nanotechnology, III-V semiconductor materials and devices present enormous opportunities for a wide range of emerging technologies. Currently, Prof. Jagadish and his team are working towards developing single photon sources and detectors for quantum communication applications, flexible electronic, and optoelectronic devices, including flexible solar cells, sensors, nonlinear optics, and meta-optical systems, as well as nanolasers and detectors for miniaturized optical systems for next generation holography, augmented reality, LiFi, and LIDAR applications.

ABOUT THE AUTHORS

Lan Fu (lan.fu@anu.edu.au) is with the ARC Centre of Excellence for Transformative Meta-Optical Systems, Department of Electronic Materials Engineering, Research School of Physics, The Australian National University, Canberra, ACT 2601, Australia.

Chennupati Jagadish (corresponding author: chennupati.jagadish@anu.edu.au) is with the ARC Centre of Excellence for Transformative Meta-Optical Systems, Department of Electronic Materials Engineering, Research School of Physics, The Australian National University, Canberra, ACT 2601, Australia.

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