Women in Electron Devices Society

Manijeh Razeghi, Doctorate d'état ES Sciences Physiques

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Professor Manijeh Razeghi is a pioneering leader in the area of III-V compound semiconductor materials and optoelectronic devices. For more than 40 years she has been blazing a trail, developing new semiconductor materials and then using them to realize practical semiconductor optoelectronic devices including a wide range of light emitting diodes and lasers emitting at wavelengths from the terahertz, to the infrared, all the way to the deep ultraviolet. Prof. Razeghi performed her graduate studies at Université de Paris where she obtained her M.S. in Materials Science in 1976, her Ph.D in Solid State Physics in 1978, and her Docteur ès Sciences in Physics in 1980. From 1981 to 1992 she was a Senior Research Scientist and then Head of the Exploratory Materials Laboratory at Thomson-CSF (Orsay, France). There she pioneered the scientific study, development, and implementation of most major modern epitaxial growth techniques., Prof. Razeghi is especially known as a pioneer in the development of the MOCVD (Metal-Organic Chemical Vapor Deposition) crystal growth technique for the growth of InP, GaInAs/InP and GaInAsP/InP based materials. This semiconductor growth technique is still the leading method for mass production of telecommunication optoelectronics. The key to successfully taking advantage of these materials is that the physical properties and quantum structures need to be truly dominated by the physics of the material and not by uncontrolled defects, dislocations and surface states. This is exactly where Razeghi's artistry for materials magic comes into play. She, for the first time, managed to produce the material quality with MOCVD that was good enough to observe the subtle quantum-physical effects predicted and calculated by theoreticians with such excitement.

She was able to use this material to investigate basic semiconductor physics. This included the first quantum well heterostructures, the first superlattices, observation of the quantum Hall effect in this material system, the first demonstration of two-dimensional electron gas and two-dimensional hole gas in this material, and the first observation of room temperature excitons in GaInAs/InP superlattices. These contributed to the realization of a plethora of novel optoelectronic devices including lasers, optical waveguides, InP based Gunn diode for radar systems, a number of field effect transistors, InP-based photodiodes, and their monolithic integration. The capstone of these transformative discoveries was the realization of the important 1.3 and 1.55 µm laser diodes and photodetectors necessary to fuel the coming optical fiber telecommunication revolution.

Her scholarly work in France both generated and stimulated scientific research in this field for many years and was being relentlessly studied by world scientists from all over the Americas to Asia and Europe. This early work leading up to, and including, the development of the first 1.3 and 1.55 μm laser diodes was documented in what has become one of the most seminal volumes ever written on MOCVD growth: "The MOCVD Challenge: Volume 1: A Survey of GaInAsP-InP for Photonic and Electronic Applications" (1989) Adam Hilger Publishing and Institute of Physics Publishing. This book received rave reviews, with Pierre Aigrain in the Foreword of this book writing: *"Manijeh Razeghi has been recognized all over the world for her ability to achieve astonishingly brilliant results with MOCVD technologies. Simply reading the book may not be quite enough for every engineer to do fully as well as she does. But it is a necessary step in that direction."*

Then in 1991, Manijeh Razeghi left France and came to the United States, where she joined Northwestern University in Evanston, Illinois, from among a long list of major US institutions attempting to attract her. She was appointed as a Walter P. Murphy Chair Professor of Electrical Engineering and Computer Science. There, she founded the Center for Quantum Devices to continue her pioneering works, and devoted her research activities to studying III-V semiconductor materials for a wide range of quantum optoelectronic devices, including lasers, LEDs, photodetectors, and focal plane arrays, covering a very wide spectral band from the deep ultraviolet (down to a wavelength of ~0.2 μm) to the very long wavelength infrared (~32 μm), and most recently all the way out into the terahertz (the elusive boundary between radio and photonic sources).

Within a few years of joining Northwestern University, Prof. Razeghi established herself anew and continued generating a whole impact on optoelectronics. Within three years, she had used her MOCVD skills to develop GaInAsP/GaAs semiconductor materials and designs for the first high-power aluminum-free diode lasers emitting at 808 and 980 nm. There were existing AlGaAs designs at these wavelengths, but they were inherently unable to meet all the stringent requirements imposed by modern applications. The main failing was that aluminum oxidizes very easily, and during laser fabrication and high-power operation these oxides would form dark defects that absorbed power and destroyed the laser. The crucial technology was the development of the material and design to eliminate aluminum from the lasers ("aluminum-free"). The lasers that Manijeh Razeghi developed did not suffer from aluminum oxidation, and thus showed long-lifetime and very high output power. The availability of these lasers revolutionized the high power diode laser industry and their applications in the early 1990's, including diode pumped solid-state lasers and erbium doped optical fiber amplifiers for telecommunications. She also used the GaInAsP/GaAs material system to realize heterostructures and superlattices, demonstrating for the first time a two-dimensional electron gas in this system. This discovery led to the first heterojunction field effect transistor (HFET), modulation-doped FET (MODFET), two-dimensional electron gas FET (TEGFET) based on this material. She also started to use the GaInAs/InP material system to realize the first Quantum Well Infrared Photodetectors (QWIPs), the first multi spectral QWIPs, and the first focal plane array, based on this material system.

Based on the pioneering work leading up to and including this discovery, Prof. Razeghi released her second major book: "The MOCVD Challenge: Volume 2: A Survey of GaInAsP-GaAs for Photonic and Electronic Applications" (1995), Adam Hilger Publishing and Institute of Physics Publishing. The content of this volume, like Volume 1, is her own work and achievements for the MOCVD growth, characterization and fabrication of optoelectronic devices, including high-power aluminum-free lasers, based on the GaAs-GaInAsP material system. Again this is book received rave reviews with Jerome B. Cohen, the Dean of the McCormick School of Engineering at Northwestern, writing: *"This book is another example of her ability to do cutting-edge research and her desire to educate. It is a text of the fundamentals of semiconductor crystal growth and materials characterization leading into many of the important concepts in advanced device design and fabrication."*

Since then Manijeh Razeghi has continued to demonstrate herself as a world renowned pioneer of III-V semiconductor materials research, quantum device physics, and photonic source technology. In every material system she has worked, she has not only developed the fundamental material, but has created a wide array of practical optoelectronic devices, many of which have required new physics—pushing the boundaries of what was thought possible using III-V semiconductors.

Speaking of new physics, Razeghi has also become a world leader in the pioneering development of Quantum Cascade Lasers (QCLs). QCLs are based on the same InP material system which she first developed while working in France. These devices are unipolar lasers that use intersubband transitions in quantum structures, the novel physicals effects which have become possible with the growth of complex hetero-structures. They have made it possible to produce lasers emitting at nearly arbitrary wavelengths ranging from the mid-infrared all the way into the THz spectral regions. These spectral regions have been utilized in industry for many years for chemical/biological spectroscopy, but the old source technologies (like gas lasers and parametric oscillators) were bulky and far from mass manufacturability. The QCL technology is transformative in that QCLs are capable of ultrasensitive chemical/ biological detection but have the size, weight, and power of standard semiconductor laser diodes. This has ushered in a new era of portable sensing. In addition, thanks to other beneficial properties of this wavelength range, there has been a significant development of these sources for free-space communications and as an infrared countermeasure to safeguard aircrafts from heat-seeking missiles.

Soon after QCLs had been introduced as only a cryogenically-cooled laboratory curiosity, Manijeh Razeghi drove the technology forward, maturing it into a commercial technology capable of room temperature, high power, continuous-wave operation over a wide range of wavelengths (3–12 μm). This included both the highest power and highest efficiency QCLs ever demonstrated. Other novel developments included two-dimensional photonic crystal distributed feedback (PC-DFB) sources for high power, single-frequency operation and multi-wavelength QCL arrays for wide wavelength coverage and rapid tunability.

Based on this pioneering quantum cascade laser work, Prof. Razeghi developed recently novel THz sources operating at room temperature. The terahertz is a novel region of the electromagnetic spectrum situated between the infrared and microwave. The unique properties of materials at these wavelengths allow new sensing applications that will revolutionize chemical/biological sensing and airport/border security, as well as applications for a non-destructive package inspection and astronomy. However, up until recently, the lack of convenient, compact diode laser sources has prevented realization of these applications. Razeghi developed the highest power terahertz lasers, and though still in development, she projects that mW-class, compact, room temperature THz sources will be available soon. Once realized the inherent mass production potential of semiconductor lasers will enable many new exciting applications. Finally, Razeghi played a crucial role in the development of the wide bandgap AlInGaN semiconductor material system. This material system has revolutionized visible photonics sources with the recent introduction of blue LEDs and lasers. For the first time, it has become possible to have practical high-efficiency, long-lifetime, semiconductor-based, solid-state lighting. Razeghi played a role in the development of this material system for blue lasers, which have gone on to be used in next generation data storage. Her contributions have more recently focused on LEDs in the deep ultraviolet (<280 nm), leading to the first demonstration of LEDs at 280 nm or shorter. All wavelengths are at the heart of the next generation of fast and reliable chemical and biological agent sensors, and portable water purification systems.

In addition to her pioneering work on photonic source technology, Prof. Razeghi has also found time to pursue detectors and focal plane array imagers based upon these novel III-V compound semiconductor materials. She realized the first InAs and InGaAs Quantum Dot Infrared Photodetectors and focal plane arrays. In parallel, she pioneered in the area of QWIPs on InP for mid, long and very long wavelength spectral bands (4~19 μm) and demonstrated the first multi spectral QWIP on InP. Moreover, she developed the molecular beam epitaxy of InAs/GaSb type II quantum heterostructures, photodetectors and even focal plane arrays operating in the mid, long, and very long wavelength infrared spectral bands (3~32 μm). This pioneering work enabled the demonstration of the first infrared camera based on this material system. This technology is beginning to reshape the infrared sensing industry and it is possibly leading to a technological revolution, with a direct impact on medical applications, manufacturing thermal imaging, firefighting, pollution monitoring, surveillance, law enforcement, as well as dense applications. In the deep ultraviolet spectral band (200–400 nm), Razeghi's innovative ideas concerning wide bandgap AlInGaN based semiconductors and their quantum structures led her to demonstrate high efficiency photodetectors, Geiger-mode avalanche photodiodes, and solar-blind focal plane arrays with world record characteristics.

In addition to her unparalleled contributions to basic and applied research related to photonic source technology, Prof.Razeghi has also demonstrated herself as an accomplished educator. She has created and manages the Graduate and Undergraduate Programs in Solid State Engineering (SSE) at Northwestern University. She directly oversees many assistant and research professors, and many adjunct professors. She regularly takes time out of her tireless research schedule to teach fundamental undergraduate courses and generate interest and motivate the next generation of scientists. She prepared several text books, including *Fundamentals of Solid State Engineering* (4th edition), *Technology of Quantum Devices*, *Introduction to Carbon Atom*, to name a few.

Manijeh Razeghi received the Doctorate d'état ES Sciences Physiques from the Université de Paris, France, in 1980. She was the Head of the Exploratory Materials Laboratory at Thomson-CSF (France) during the 80's where she developed and implemented modern metalorganic chemical vapor deposition (MOCVD), vapor phase epitaxy (VPE), molecular beam epitaxy (MBE), GasMBE, and MOMBE for entire compositional ranges of III-V compound semiconductors for spectrum range from deep UV to THz. Developing these tools was fundamental in enabling her to achieve high purity semiconductor crystals with a consistency and reliability that was often unmatched, thereby leading to new physics phenomena in InP, GaAs, GaSb, and AlN based semiconductors and quantum structures. She realized the first InP Quantum wells and Superlattices and demonstrated the marvels of quantum mechanics in the low dimensional world. She joined Northwestern University, Evanston, IL, as a Walter P. Murphy Professor and Director of the Center for Quantum Devices in Fall 1991, where she created the undergraduate and graduate program in solid-state engineering. She has authored or co-authored more than 1000 papers, more than 34 book chapters, and 20 books, including the textbooks Technology of Quantum Devices (Springer Science Business Media, Inc., New York, NY U.S.A. 2010) and Fundamentals of Solid State Engineering, 4th Edition (Springer Science Business Media, Inc., New York, NY U.S.A. 2018). Two of her books, MOCVD Challenge Vol. 1 (IOP Publishing Ltd., Bristol, U.K., 1989) and MOCVD Challenge Vol. 2 (IOP Publishing Ltd., Bristol, U.K., 1995), discuss some of her pioneering work in InP-GaInAsP and GaAs-GaInAsP based systems. The MOCVD Challenge, 2nd Edition (Taylor & Francis/CRC Press, 2010) represents the combined updated version of Volumes 1 and 2. She holds more than 60 U.S. patents and gave more than 1000 invited and plenary talks. Her current research interest is in nanoscale optoelectronic quantum devices. Dr. Razeghi is a Fellow of MRS, IOP, IEEE, APS, SPIE, OSA, Fellow and Life Member of Society of Women Engineers (SWE), Fellow of the International Engineering Consortium (IEC). She received the IBM Europe Science and Technology Prize in 1987, the Achievement Award from the SWE in 1995, the R.F. Bun shah Award in 2004, IBM Faculty Award 2013, the Jan Czochralski Gold Medal in 2016, the 2018 Benjamin Franklin Medal in Electrical Engineering, and many best paper awards. She is an elected life-Fellow of SWE, IEEE, and MRS.