Perspectives in Quantum Devices and Computational Nanotechnology

by Jean-Pierre Leburton

JEAN-PIERRE LEBURTON

JEAN-PIERRE LEBURTON WAS born in Liège, Belgium, 4 March 1949, to Edmond Leburton and Charlotte Joniaux. His father was a well-known Belgian statesman who served in various positions as a minister in the king's government from 1954 to 1971 and ultimately as his prime minister in 1973. His mother was the daughter of a civil engineer, Charles Joniaux, who was involved in the construction of the Peking–Hankow railroad in China at the beginning of the 20th century. He had a younger brother, Eddy, who passed away in 1993.

Leburton started elementary school at the Athénée Adolf Max in Brussels in 1954 during his father's first tenure as the Minister of Public Health to finish in 1960 at the Athénée Royal in Waremme, Belgium, where his father was the mayor and a house representative. He entered middle and high school in the same institution, where he studied Latin, mathematics, and basic sciences among his main courses. His decision to study physics at the University of Liège, Belgium, was sparked by his reading of two comprehensive volumes, "Contemporary Sciences," edited by Louis Leprince-Ringuet, as a gift from his father when he was in the 11th grade. In 1971, he obtained his license (bachelor of science) in physics with grande distinction (magna cum laude).

After two years as a teaching assistant in the Experimental Physics group at the University of Liège, he spent a year as a coopérant technique universitaire at the Mohammadia School of Engineers in Rabat, Morocco, where he taught thermodynamics, statistical physics, and mechanics for freshman and sophomore students. In 1975, he came back to the University of Liège to pursue a doctorate in theoretical physics and graduated in 1978 with la plus grande distinction (summa cum laude) for his thesis "Theory of Electrical Conductivity in Polar Semiconductors."

One year later, he joined the Department of Halbleiter Technik (semiconductor techniques) with Siemens A.G. in Munich, Germany, where he worked for two years on modeling hot carriers in short-channel metal–oxide semiconductor transistors in Gerhard Dorda's group. During that time at a group seminar, he met Dr. Klaus von Klitzing, who had just published his seminal paper on the quantum hall effect. Anecdotally, the sparse audience at the time, including members of the research laboratory's upper management, missing the work fundamentals, focused instead on its potential for electronic applications. On that, Dr. von Klitzing diligently emphasized its importance in metrology, which, in addition to associating his name with a new resistance standard, propelled him to being awarded the Nobel Prize in Physics four years later.

In September 1981, Leburton was invited by Dr. Karl Hess to join the Coordinated Science Laboratory at the University of Illinois as a visiting assistant professor to work on modeling ballistic transport in semiconductor devices. Two years later, he accepted a tenure-track position with the Department of Electrical and Computer Engineering. One of his first undertakings was the investigation of the effects of periodicity and aluminum (Al) composition on the dielectric constant of gallium arsenide (GaAs)/AlGaAs superlattices, for which he developed a full-band theory approach. Hence, he was able to explain the variations of the index of refraction observed among the patterned regions of GaAs-AlAs superlattices and the AlGaAs alloys obtained by the selective zinc interdiffusion achieved by the Holonyak group [1]. Simultaneously, he theoretically explored the possibility of producing high-efficiency energy conversion with periodically N- and P-doped structures by proposing a new type of solar cell, which, as of today, still draws attention in the photovoltaic community [2].

Leburton's interest also extended to quantum devices to achieve negative differential resistance (NDR), which led him to propose the first vertical tunneling field-effect transistors (FETs) for high-speed applications, where the NDR onset is controlled by a metal gate [3]. Of a similar vein was his prediction of a new tunneling mechanism for real-space transfer in modulation-doped structures, evidenced a couple of years later [4]. It is during that time that he also focused on the effect of quantum confinement on charge-carrier scattering affecting electronic transport in semiconductors, especially in quantum wires. To validate his approach, he developed the first multisubband Monte Carlo simulation of 1D systems [5], predicting various new effects, such as optic-phonon-enhanced mobility with anomalous carrier cooling, optic-phonon-induced resonant intersubband scattering with population inversion, and later, the onset of antiresonant-hopping conductance and negative

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magnetoresistance in a linear chain of quantum boxes.

In 1992, he spent a year of sabbatical at the Research Center for Advanced Science and Technology in Tokyo, Japan, where he held the Hitachi Ltd. Quantum Material Chair, collaborating with Hiroyuki Sakaki's group on transient transport in quantum wires. During his visit, he gave numerous seminars, such as "Lattice Vibrations and Phonon Scattering in Semiconductor Structures," at the Hongo Campus at the University of Tokyo. Upon his return from Japan, he pursued his research on quantum confinement in nanostructures by focusing on the electronic properties of quantum dots. He and his group developed sophisticated, 3D computer tools, which integrated quantum mechanics with the electrostatic and structural properties of materials, including the disorder due to doping fluctuations in a self-consistent scheme [6]. In September 1992, he co-organized the North Atlantic Treaty Organization (NATO) Advanced Research Workshop "Phonons in Semiconductor Nanostructures" in Spain. The following year, the French government, through its Chicago Consulate, awarded him the title "Chevalier (Knight) dans l'Ordre des Palmes Académiques," for his dedication and service to French science.

In parallel, Leburton pursued the investigation of charge-carrier dynamics in 2D structures by suggesting a new electron transport via Fraunhofer diffraction through the periodic arrays of antidots in FETs [7]. Furthermore, he carried on the simulation of optical semiconductor devices, such as electro-optic modulators made of a Barrier Reservoir and Quantum Well Electron Transfer (BRAQWET) structure, in collaboration with Bell Labs, Holmdel, New Jersey [8], and developed the physical models for a mid-infrared Quantum Fountain Laser in asymmetric, quantum-well structures during a long-lasting collaboration with the University of Paris, France, and the Hebrew University of Jerusalem, Israel [9].

In 1996, he had the privilege to chair and organize the International Conference of Superlattices, Microstructures and Microdevices (ICSMM) in Liège, Belgium, as a satellite conference of the International Conference of the Physics of Semiconductors (ICPS), which, as of today, is one of the most attended and successful ICSMM's. Under his active participation and leadership, the conference was later renamed the *International Conference of Superlattices, Nanostructures and Nanodevices* (*ICSNN*), thereby keeping on the natural evolution of semiconductor technology. He continues to serve as the chair of the ICSNN Steering Committee, held every other year as an ICPS satellite conference. That same year, he cochaired a NATO Advanced Study Institute on the "Optical Spectroscopy of Low-Dimensional Semiconductors" in Ankara, Turkey, and saw his reputation rewarded by being elected a Fellow of IEEE while also being named a member of the New York Academy of Science.

FIGURE 1 Jean-Pierre Leburton (left) with King Albert II of Belgium in 2001 (right).

In 2000, after spending a semester of sabbatical at the École Polytechnique Fédérale de Lausanne, Switzerland, Leburton focused his activities on quantum dot modeling from first principles. His models, implemented through several generations of graduate and postdoctoral students, shone considerable light on the physical properties of various types of quantum nanostructures from GaAs lithographically defined planar, and vertically confined quantum dots for applications in single-electron charging effects, and spin-qubit operations in quantum information processing, to self-assembled InGaAs quantum dots for applications in single-photon sources. His simulation expertise placed him in an ideal position to lead a team of international spintronic experts supported by the Quantum Information Science and Technology program at DARPA with the mission of building a scalable quantum gate based on the electric manipulation of individual spins in GaAs artificial molecules. Concurrently, he continued to explore the properties of charge-carrier confinement in silicon nanocrystals for single-electron memory applications in collaboration with the University of Fortaleza in Brazil [10], [11].

At that time, as one of its distinguished citizens, the Belgian government honored him with an invitation from King Albert II to serve on a panel on researcher mobility, organized by the European Sciences and Technology Commission to discourse on his scientific experience abroad (see Figure 1). In 2004, he was selected for the Quantum Device Award by the International Symposium on Compound Semiconductors, a leading conference in his field, "for his contribution to the development of simulation tools and physical models for quantum wires and quantum dots." That same year, he was awarded the Gold Medal for Scientific Achievement at the 75th anniversary of the alumnus association of his Belgian alma mater, Les Amis de l'Université de Liège. From 1999 to 2008, he also lectured at the European School for Advanced Study in Material Science at the Collegio Borromeo in Pavia, Italy (see Figure 2). In 2007, he was invited to China to deliver distinguished seminars at the Chinese Academy of Sciences in Beijing, at Peking University, and at Fudan University in Shanghai.

However, Leburton's interest was not restricted to the investigation of solid-state electro-photonic devices. At the turn of the century, advances in nanotechnology had enabled the manipulation of semiconductor structures at scales comparable to biomolecules. He immediately recognized the tremendous potential offered by merging the research of both fields of science, i.e., the physical and living sciences for vast societal benefits. In this prospect, he explored the use of ultrathin, semiconductor membranes containing a tiny hole, or nanopore, for biosensing. In this scenario, the DNA molecules basking in salted solutions are threaded through the nanopore to detect their molecular structures by monitoring the blocked ionic current flowing through the pore. The idea of using biological membranes with ion channels for the same purpose had been proposed in the 1990s by Daniel Branton at Harvard University.

However, in Leburton's and his collaborator's minds, although solid-state membranes offer additional advantages in terms of pore shape and size design as well as in robustness to the environment, their semiconducting properties add a new component to the sensing mechanism by driving an electronic current along the membrane. This mechanism can now detect the biomolecules passing through the pore by monitoring electric resistance variations. In this context, he first proposed the making of bipolar, multilayer semiconducting membranes, such as p-n junctions to control the flux of ions and biomolecules through the nanopore [12]; he later suggested to create a constriction around the pore, and add a metallic layer acting as an FET gate to control the electronic conductivity of the semiconducting membrane, thereby enhancing pore sensitivity [13]. In the meantime, the emergence of 2D materials, such as graphene and transition metal di-chalcogenides, opened new opportunities to enhance the membrane sensitivity that Leburton did not miss the chance to exploit in a series of patented inventions for varieties of biomedical applications like cancer detection, but also for big data processing [14].

However, his interest in conventional semiconductors did not abate. He continued to implement his modeling techniques to provide a comprehensive theory of dissipative transport in metallic carbon nanotubes [15] and to harness new photonic device operations, such as the three-terminal transistor laser invented by his colleagues Nick Holonyak Jr. and Milton Feng at the University of Illinois at Urbana-Champaign, for which he developed the Zhang–Leburton model, and the transistor-injected quantum cascade laser used to simulate high-frequency operations [16].

For all of these matters, Leburton's reputation did not go unnoticed by his Belgian colleagues, who elected him to the Royal Academy of Sciences, Letters and Fine Arts in 2011, "for his worldwide leadership in the field of nanoscale device simulation." In the meantime, his involvement with the IEEE Nanotechnology Council (NTC) since its creation in 2000 led him to serve on various committees, such as the Technical Subcommittee on Spintronics; the Technical Subcommittee on Modeling and Simulation, which he chaired for more than 10 years; the Editorial Board of the Transactions on Nanotechnology; the Fellow Evaluation Committee; and very recently, the Fellow Search Committee. He was also appointed an NTC Distinguished Lecturer for several years and is the 2021 recipient of the NTC Pioneer Award.

Leburton is the author or coauthor of more than 350 technical papers in international journals; books as well as of several patents in device electronics. He has been invited to deliver more than 200 presentations, several of them as the keynote or plenary speaker at worldwide meetings and international research institutions. He has also served as chairman and on the advisory and program committees of numerous international conferences. He has been a Life Fellow of IEEE since 2016; and a fellow of the American Physical Society, the Optical Society of America, the American Association for the Advancement of Science, the Electrochemical Society, and the Institute of Physics. Among his many

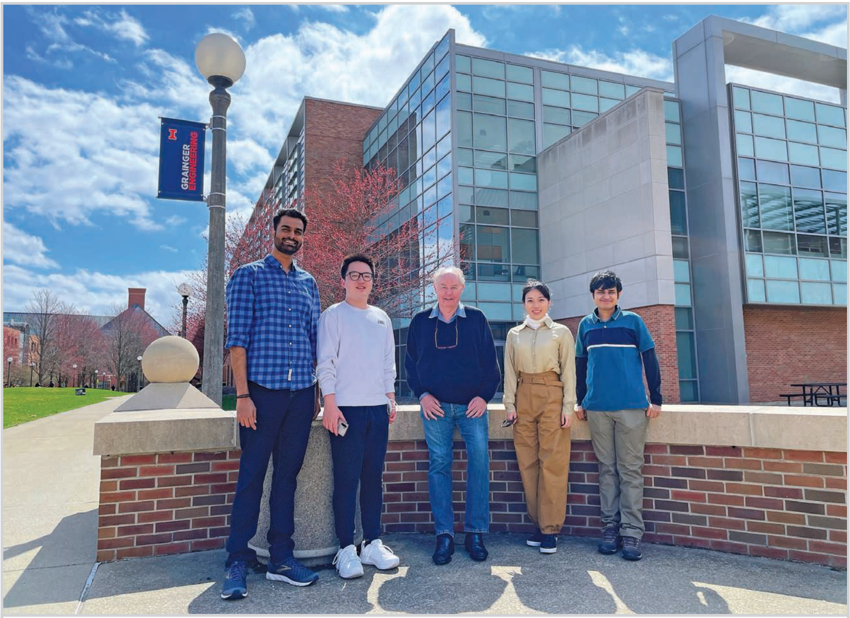

FIGURE 2 Jean-Pierre Leburton (center) with his current students. From left to right: Nagendra Athreya, Bohao Wu, Mingye Xiong, and Rajat Chakraborty.

honors, he is also the recipient of the Collaborative Conference on Materials Research Serendipity Award, Seoul, South Korea (2019).

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Applications (NANO RF)," FP7 ICT (2012–2016); and "Multilayered Sandwich Graphene Devices (MILESAGE)," GRAPHENE FLAGSHIP (2014–2016). PI of the Project "Wireless Devices Based on Carbon Nanotubes Traveling Wave (TW-CNT)," QUÉBEC-ITALIE Project (2011–2012). He is the author or coauthor of approximately 250 peer-reviewed papers in journals and at conferences.

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