Application of Quantum-Based Devices: Trends and Challenges

Gerald J. Iafrate, Fellow, IEEE, and Michael A. Stroscio, Fellow, IEEE

(Invited Paper)

I. INTRODUCTION

As semiconductor technology continues to drive the scaling of electronic device dimensions into the ultrasmall, nanodimensional regime, many concepts and phenomena appropriate for ultrasmall and ultrafast devices will continue to be put forth for notional consideration. The stunning achievements of nanofabrication in the last decade now facilitate band-engineering and atomic-level structural tailoring not heretofore available or explorable except through naturally occurring atomic and molecular processes. In fact, the techniques of atomic layer epitaxy facilitate the growth of structures atomic layer by atomic layer; as well, advanced lithographic techniques are capable of defining "lateral" structures with an accuracy of about 50 Å.

These revolutionary nanofabrication techniques and trends have opened the way to fabricating quantum wells, quantum wires and quantum dots that may provide the basic building blocks for future nanoelectronic and mesoscopic (quantum) device technologies. Furthermore, these trends lead to new opportunities for realizing quantum-based information processing devices but many challenges must be addressed and intensive international basic research is essential for the full exploitation of these revolutionary devices.

II. HIGHLIGHTS OF SELECTED CHALLENGES

A principal challenge in the application of quantum-based devices arises from the molecular feature-size considerations implicit in mesoscopic and nanoelectronic technology; to be sure, many interesting questions arise concerning fluctuations, tolerances, robustness, and other statistical considerations which might conceivably wash-out many of the seemingly fragile characteristics of nanodevices. There are numerous illustrative examples in which inherent statistical variation in composition and device dimensions produce substantial deviation from the desired nanostructure electrical response. Such examples include: 1) minimum metal-oxide-semiconductor transistor size as determined by a combination of gate oxide breakdown, drain-source punch-through, and substrate doping fluctuations [1]; 2) minimum planar bipolar transistor size as determined by a combination of collector junction breakdown, base punch-through and base doping fluctuations [2]; 3) effects of structural and alloy disordering on the electronic states in quantum wires [3]; and 4) the effect of fabrication-related dimensional variations on carrier scattering rates in quantum wires [4], [5].

An obvious challenge for nanoelectronic and mesoscopic device communities is to explore concepts and designs that optimize robustness and suppress device fragility. In meeting this challenge it will be necessary to circumvent statistical phenomena which typically exacerbate the scaling of conventional device technologies to reduced feature sizes; as well, it will also be essential to exploit phenomena specific to the nanoscale regime which are known to suppress noise and related fluctuations in "small" and mesoscopic devices.

On a more positive note, a related challenge—and opportunity—for nanoelectronic and mesoscopic device communities is to explore concepts and designs that optimize robustness and suppress device fragility.

III. ILLUSTRATIVE RESEARCH REQUIREMENTS AND TRENDS

The exploration of conceptual options for achieving robustness is an essential ingredient for the successful exploitation of quantum-based information processing devices and systems. As well, several phenomena which play critical roles in nanoelectronic and mesoscopic devices provide important opportunities to realize robustness in such nano-dimensional devices.
Especially promising avenues for achieving robustness include the application of Coulomb blockade effects, design through quantum control theory, and emulation of biological and chemical systems where phenomena such as neuron networking and self-organization finesse disordering processes. As an example, many potential applications of quantum control theory to "small" and mesoscopic electronic devices are motivated on the basis of past uses of robust optimal control theory for the selective excitation of quantum mechanical vibrational states of molecules [6]-[10]. In addition, a number of the recent developments in the field of Coulomb blockade are potentially important and highly encouraging; such developments include: the observation of Coulomb blockade effects at temperatures which are an appreciable fraction of room temperature [11]; theoretical prescriptions for enhancing the reliability of single-electron switches operating on the basis of Coulomb effects [12]; and recent progress in understanding how mesoscopic Coulomb blockade effects may be used to greatly suppress noise in electron emission processes in p-i-n semiconductor junctions [13]. The observation of Coulomb blockade effects at 100 K [11], have been extended recently by the principal authors of [11] who report the observation of Coulomb blackade effects in silicon-based quantum wires at 110 °K for the case of holes and 170 °K for electrons. In order to expand on the progress made in some of these areas, this paper places particular emphasis on two specialized topics: the simulation of the capacitance of quantum dots [14]; and the tailoring of deformation potential and piezoelectric scattering in mesoscopic devices in order to maintain de Broglie wave coherence [15].

The impressive trends in both the design and fabrication of quantum-based devices motivate and lead to the need for circuit design tools for integrated circuits with quantum-based component devices. In recent years there has been substantial progress in the development of design tools for ultrafast and compact circuits using heterojunction bipolar transistors and negative differential resistance (NDR) devices such as resonant hot-electron transistors, resonant tunneling transistors, and resonant tunneling diodes; a few examples of these works are summarized in [16]. These efforts are realized, in part, based on a new circuit simulator, NDR-SPICE, which has been developed by extending the Berkeley SPICE simulator to the domain of NDR circuits. Such tools have been used to design a wide variety of circuits including: multiple-valued multiplexers and demultiplexers; totally parallel multiple-valued logic adders; four-valued up/down counters; analog-to-digital converters; and a 32-bit parallel correlator. Many more such applications of codes such as NDR-SPICE will be made in the next few years.

Recent contributions to defining quantum logic gates that are potentially suited as the building blocks of quantum logic networks [17]-[19] portend new vistas and enormous payoffs through the realization of quantum computers. This possibility has not been the focus of extensive attention within the nanoelectronics and microelectronics communities but these communities have created fabrication and design technologies that may provide the basis for realizing quantum computers.

IV. QUANTUM CAPACITANCE

Through the dramatic advances in nanofabrication technology it is now feasible, indeed routine, to produce nanoscale
devices that exhibit electrical properties that are determined principally by the laws of quantum physics rather than classical physics. From the point of view of possible applications of quantum-based devices, it is critical that the electronic properties of such nanoscale devices be understood fully. Extremely revealing simulations of the capacitance of quantum dots reveals a rich atomic-like structure for the capacitance of two-dimensional circular quantum dots modeled on the basis of a self-consistent solution of the Schrödinger equation; in these studies many-body effects were included using a local density approximation as well as the optimized Kreiger-Li-Iaf rate (KLI) exchange potential. Fig. 1 shows how the capacitance varies with electron number for a two-dimensional gallium arsenide quantum dot with a radius of 200 nm (empty squares), 100 nm (solid circles), and 50 nm (empty circles) in the presence of a conducting backgate located at a distance of 1/10 of the radius. At these short separation distances, it was demonstrated [14] that the presence of a backgate significantly increases the capacitance. As is illustrated in Fig. 1, the capacitance exhibits pronounced minima corresponding to the shell filling just as in the case of an atom. These shell-like groupings were shown previously [14] to be due to degeneracies introduced by symmetry and the dips are the consequence of the increased difference between the chemical potential values for consecutively accumulating electrons as each new set of degenerate orbitals starts to be filled. As a second example, these shell-like groupings are illustrated clearly in Fig. 2 where the capacitive energy calculated with the KLI exchange potential is plotted as a function of the electron number of atoms with nuclear charge number Z. These nonclassical effects in the quantum capacitance should prove to be important in a variety of applications of quantum-effect devices including quantum-dot memory cells for compact high-density data-storage devices.

V. TAILORING SCATTERING RATES IN MESOSCOPIC DEVICES

In order to modify and control the strengths of deformation potential and piezoelectric scattering in mesoscopic devices it is essential that the spectrum of acoustic phonons in these mesoscopic devices be understood. Acoustic phonons have been quantized for a variety of mesoscopic and nanoscale structures in order to assess to role of electron–acoustic-phonon scattering in limiting the performance of mesoscopic and nanoscale electronic devices. These structures include quantum wells, quantum wires with cylindrical and rectangular cross sections, as well as quantum dots with spherical, cylindrical and rectangular boundaries [20]. Many of these modes have symmetries that are dramatically different from those of bulk phonon modes as shown in Fig. 3 for the case of a spherical quantum dot. Such quantized phonons have been studies for the two cardinal boundary conditions of classical acoustics: free standing boundary conditions (FSBC’s) for the case of open boundaries where the phonon displacements are unrestricted and allowed to balance all normal traction forces to zero; and clamped surface boundary conditions (CSBC’s) for the case of rigid boundaries where phonon displacements are required to vanish at the boundaries. An example of the deformation potential scattering rates in a cylindrical quantum wire [21] is given by the results depicted in Fig. 4.

In general, for the case of quantum wires, scattering rates have been calculated only for the case of infinitely long quantum wires and, as appropriate for this case, the acoustic phonons have been quantized in only the lateral dimensions. In contrast, for realistic mesoscopic device designs, the quantum wire input and output “leads” as well as the active regions of the devices with quantum-wire geometries have finite lengths. For such realistic cases, deformation and piezoelectric scattering rates must be based on acoustic phonons that are quantized in all three spatial dimensions.

The mesoscopic device community does not appear to have considered the role of three dimensional confinement of acoustic phonons in mesoscopic devices but it is clear from the solutions of classical acoustics that boundary conditions imposed at the ends of wire-like regions can have a profound effect on the properties of acoustic modes. Based on the present understanding of such finite wire-like structures, it should be possible to “engineer” mesoscopic structures so that electron–acoustic-phonon scattering is reduced.

As an illustrative example, the standing-mode pattern for acoustic modes in a free-standing quantum wire with cylindrical cross section and finite length has a simple analytical form

Fig. 3. Displacement patterns for the breathing and torsional acoustic modes in a spherical quantum dot.
which facilitates the selection of device geometries and dimensions that minimize electron-acoustic-phonon scattering rates. Such an "engineered" reduction is most likely to be most important in mesoscopic devices which operate on the basis of "coherent" electron-wave interference effects.

VI. CONCLUSION

The challenges before the nanoelectronic and mesoscopic device communities are, on the one hand, to explore designs and concepts that optimize robustness and, on the other hand, to exploit quantum effects that portend unique means of information processing that have no counterparts in the classical domain. Through this dual approach the nanofabrication technology revolution can be exploited fully by the architects of future generations of quantum-based information processing systems and devices. As envisioned by the famed physicist Richard Feynman in his 1959 talk entitled "There's Plenty of Room at the Bottom," we shall realize the "bottomless" possibilities of "manipulating and controlling things on a small scale."

REFERENCES


Gerald J. Iafrate (F'93) was born April 8, 1941. He holds B.S., M.S., and Ph.D. degrees in physics. He is currently with the U.S. Army Research Office, Research Triangle Park, NC.

He was named an IEEE Fellow for technical leadership, contributions to quantum transport, and pioneering concepts in solid-state electronics. He was an Invited Speaker at the 1983 IEEE/Cornell University Symposium on High-Speed Semiconductor Devices and Circuits, and the 1987 IEEE New Jersey Coast Sector Charter Meetings, and an Invited Panelist at the 1987 IEEE International Electron Devices Meeting, was Chairman of Electro '89 Professional Program on Nanoelectronics, and was Editor of the December 1991 Special Edition of the IEEE Aerospace and Electronic Systems Magazine.

Michael A. Stroscio (F'92) was born June 1, 1949, in Winston-Salem, NC. He received the B.S. degree in physics from the University of North Carolina, Chapel Hill, and the M.Phil. and Ph.D. degrees, both in physics, in 1972 and 1974, respectively, from Yale University, New Haven, CT. He is currently with the U.S. Army Research Office, Research Triangle Park, NC.

He was named an IEEE Fellow for contributions to the understanding of quantum and relativistic phenomena in solid-state and laser-produced plasmas. He is also a Fellow of the Yale Science and Engineering Association. He received the Director’s Research Initiative Award from Los Alamos Scientific Laboratory in 1977. He has been a Member of the Program Committee as well as Organizer and Chairman of the IEEE International Conference on Plasma Science, a referee for the IEEE Circuits and Devices Magazine, a Member of the sub-committee on Quantum Electronics for the IEEE International Electron Device Meeting (IEDM) in 1990-1991 and 1995-1996, Session Chairman 1990-1991, Organizing Committee Member in 1991 and 1993, and Session Chair in 1993 and 1995.