Man-made Quantum Structures: From Superlattices to Quantum Dots

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Quantum structures with man-made superlattices, [1] were launched more than 30 years ago with compound semiconductor heterostructure and epitaxial growth, originally developed to improve the efficiency of injection lasers via charge confinement. [2] The NDC, negative differential conductance was thought to originate from domain oscillation. In order to distinguish quantum effects from Gunn-effect, [3] resonant tunneling in man-made DBRT was theoretically calculated, [4] and demonstrated. [5] While transport in these quantum devices was emphasized at IBM Research, optical properties were focused at Bell Laboratories. [6] Since then, the field has taken off rapidly and developed into Quantum Slab, QS; Quantum Wire, QWire; Quantum Dot, QD; and Nanoelectronics. We note that Quantum phenomena in devices, mainly from quantum interference, actually preceded heterojunctions and epitaxy. For example, the Aharonov-Bohm and Josephson effects in superconductors, [7, 8] the quantized 2-D electron gas in the silicon inversion layer at low temperatures, [9] appeared before superlattices. However, the nanoscale revolution in devices is propelled by the epitaxial growth of heterostructures. The advances in lithography, in fact, also play an important role. For example, the single electron transistor and memory [10, 11] involve the use of electrodes to produce quantum states. The multipole-electrodes in addition to heterojunctions form a hybrid system for the future generation of nanoscale electronics. [12] Incidentally, multipole shares some commonalities with heterojunctions, both being neutral, therefore short ranged, ideal for confinement of electrons.

Among these quantum devices, RTDs, Resonant Tunnel Diodes, have advanced to general applications in terahertz regime. [13] There are fundamental differences between a planar structure of QW-RTDs with conservation of both the transverse momentum and longitudinal energy [4] and QD where only energy is conserved. Since QDs are embedded in a matrix or supported on a substrate, the interface defects do couple with the quantum states. However, for QW, the coupling is rather small [14] because the wave functions do not overlap well. On the other hand, the wave functions of extremely confined states resembles those of the defects so that the coupling is much stronger resulting in trappings which manifest in switching and hysteresis with RT via QDs. [15,16] In the theory of resonant tunneling, the original treatment is based on the so-called coherent tunneling [4], while most of the RTD data were analyzed with the sequential tunneling model. [17] The two models manifest in very different ways as far as hysteresis is concerned, which is so important for tunneling via QDs. The situation is somewhat similar to the difference between hot luminescence and resonant Raman scattering.

All devices need input/output. For nanoscale devices, contacts must define an equal potential surface no larger than a fraction of one nm. Thus only highly doped n^+ semiconductors or metals can meet the requirement. Because of the extremely small mean-free-path for both, electrons basically originate from a spherical Fermi surface, having both transverse and longitudinal energies in tunneling via QDs. The transverse component reflects back resulting in low efficiency and losses, unless Q-wires are used. However, Q-wires are nothing but waveguides, which involves multi-modes in general. Each mode is represented by a conductance [18] $G_o = e^2 / h \sim 39\mu S$ per spin. Electrons originate from a spherical Fermi surface excite a given mode determined by the transverse degree of freedom. QD-RTD may serve as energy filter preferentially selecting a mode and rejecting others. As in circuits, the mode conductance serves the role of wave impedance in conventional waveguides.

Doping of QD runs into another issue because of the drastic decrease in the dielectric constant of QDs, [19] resulting in intrinsic behavior of doped QDs. [20] Although QD transport is via tunneling, but doping does affect the occupation of the states, controlled by symmetry consistent with Pauli's principle. If the electron mean-free-path is greater than the length of the Q-wire, doping is not even required! If not, one may still overcome random distribution of dopants by introducing dopants in a periodic fashion as in a superlattice.

To broaden the class of compound semiconductors, a new type of Semiconductor-Atom-SL [20] appeared few years ago which is not based on two compound semiconductors, allowing far more strain than the strain-layer SL [21] The challenge for the implementation of nanoelectronics is formidable. [22] My prediction is that it is within sights.

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1. R. Tsu and L. Esaki, Appl. Phys. Lett. **22**, 562 (1973).
2. H. Kroemer, Proc. IEEE, **51**, 1782 (1963)
3. J.B.Gunn, Solid State Comm. **1**, 88 (1963)
4. R. Tsu and L. Esaki, Appl. Phys. Lett. **22**, 562 (1973).
5. L.L. Chang, L. Esaki and R. Tsu, Appl. Phys. Lett. **24**, 593 (1974).
6. R. Dingle, W. Wigmann and C.H. Herry, Phys. Rev. Lett. **33**, 827 (1974)
7. Y. Aharonov & D. Bohm, Phys. Rev. **115**, 485 (1959)
8. B.D. Josephson, Phys. Lett. **1**, 251 (1962)
9. F.F. Fan and W.H. Howard, Phys. Rev.Lett.**16**, 797 (1966)
10 D.V. Averin and K.K. Likharev, J. Low Temp. Phys. **62**, 345 (1986)
11. Y.A. Pashkin et al Appl. Phys. Lett. **76**, 2256 (2000)
12. R. Tsu, in Adv. Semi. Heterostructures, M. Stroscio (World Scientific, Singapore, 2003) to be published.
13. E.R. Brown, W.D. Goodhue, TCLG Sollner, J. Appl. Phys. **64**, 1519 (1988)
14. V.J. Goldman, D.C. Tsui and J.E. Cunningham, Phys. Rev. Lett. **58**, 1256 (1987)
15. R. Tsu, X.L. Li, and E.H. Nicollian, Appl. Phys. Lett. **65**, 842 (1994).
16. A review in: R. Tsu, Appl. Phys. A**71**, 391 (2001).
17. M. P. Shaw, V.V. Mitin, E. Scholl and H. L. Grubin, Phys. of Instability in Solids State Electron Devices, (Plenum Press, N.Y.& London, 1992)
18. R. Webb, Rep. Prog. Phys. **55**, 1311, (1992)
19. R. Tsu, D. Babic, and L. Ioriatti, J. Appl. Phys. **82**, 1 (1997).
20. R. Tsu and D. Babic, Appl Phys. Lett. **64**, 1806 (1994)
21. J.W. Matthews and A.E. Blakeslee, J. Cryst. Growth **32**, 265-273 (1975)
22. R. Tsu, A. Filios, C. Lofgren, K. Dovidenko, C. G. Wang, Electroch & Solid State Lett., **1** (2) 80 (1999).
23. R. Tsu, Nanotechnology, **12**, 625(2002)