Future Nanometer Electronics

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The main impacts in the field of nanoelectronics have come from the combination of lateral patterning techniques together with advanced material growth techniques. The present state of the art gives considerable opportunities for the fabrication of nanostructured devices. New phenomena as quantization of resistance and ultra small capacitance effects have the potential for new device applications. Single electron electronics becomes feasible.

New tunneling devices, infrared detector and lasers have evolved from high performance crystal growth. The impacts of reduced dimensionality have still to come.

1. Introduction

Nanoelectronics involves the study of the basic science and material technology when semiconductors are structured at a scale of nanometers. It deals on the one hand with the investigation of the miniaturization limits of todays semiconductor device technology and on the other hand it explores quantum effects which become apparent when dimensions are pushed to the fabrication limits. On the material technology side, the advances in MBE and MOCVD-growth together with the progress in lithography techniques (E-beam lithography and reactive ion etching) led to the perception of new classes of electronic structures [1]. The development has been driven mainly by the GaAs-System, however, most recent results in Si/Ge based systems have given strong impact also from the main stream Si-technology. The future nanoelectronics will influence other fields, which have interest in artificial structures on the nanometer scale. The emerging fields of supramolecular chemistry [2] and molecular electronics [3] are good examples.

Basic to all electronic devices is the ability to switch an element from one electronic state to another in a controlled manner within a very short period of time. Conventional semiconductor technology is either based on the injection of minority carriers or field effects, which are governed by classical transport effects. And still, further reductions in device dimensions will enable a further continuous growth for 10 more years. It is clear that current VLSI technologies will eventually reach their limits at device dimensions of 0.1 µm, which may be mainly limited by interconnects.

The size-quantization has not given rise to drastic changes in device performance yet since the basic laws of transistor functions are still governed by the requirement of charge neutrality. In fact, size quantization leads only to modifications in effective masses and electron transport. However, quantum effects such as tunneling through barriers and quantum interference effects become only apparent at low temperatures [4]. The appearance of these effects at room temperature would require device dimensions with feature sizes in the 10 nm range. The exploration of quantum effects for the realization of new device function is one of the main goals of future nanoelectronics.

2. Quantum Transport

The starting point for heterostructure nanoelectronics is the ability of growth techniques (mainly MBE) to produce extremely high quality two dimensional electron gas systems [5]. In the last years significant progress has been achieved in extending the growth technique for further reducing the electronic dimensions. Delta doping migration-enhanced epitaxy and selective overgrowth techniques [6-7] have enabled the realization of quantum wire [8] and quantum dot structures [9] with significant confinement energies.

Fig. 1: Heterostructure potential and probability density for two different energy levels.

Semiconductor devices are based on the control of carrier flow by variable energy barriers. In homostructure pn-junctions, barriers extend over a depletion length in the order of 100 nm and are limited by doping levels. In the well controlled MBE-grown heterostructures with large energy barrier variations on an atomic scale the carrier flow can be restricted to a layer thickness in the order of 10 nm. Highly improved device performance in TEGFET and Quantum Well Lasers are documentations of this improvement [5].

The basic features of the barrier induced confinement is demonstrated in Fig. 1, which shows a heterostructure potential together with the probability density of the confined electrons in two different subbands. In the lowest subband where the depletion field is still high the electrons are confined within about 10 nm. Electrons within the third subband are confined only within 50 nm extending mainly into the bulk due to the weaker depletion field. The figure clearly demonstrates the strong confinement ability of an atomic scale barrier as compared to a depletion field.

Size quantization becomes important when it is applied in a further dimension. The most simple implementation of an one-dimensional channel is the patterning with a split-gate structure as shown in Fig. 2. If the phase coherence of the electron is not broken over its dimensions up to its electrical contacts, the resistance appears quantized under certain conditions. For a geometry, where the main free path is considerably larger than W and L the resistance is given by $R_S = h \cdot \lambda_F/(2eW)$ and is thus dependent on the sample geometry. However, for the case that the distance between the contacts W is in the order of the Fermi wavelength ($\lambda_F = (2\pi/n_S)^{1/2}$ with n_S the 2D density) one-dimensional quantum channels are formed within the restriction and the conductivity G becomes quantized: $G = \frac{2e^2}{h} \cdot N_c$. N is the number of occupied quantum channels.

Fig. 2: Split gate geometry (a), quantized conductance (b).

Fig. 3: Two quantum point contacts in series form a 0D state (a). Coupled quantum dots representing a 1D crystal (b).

This behavior has been predicted by Landwehr and Buttiker [10] and observed first by Wees et al. [11]. This means resistance comes in quantized amounts of 13 kΩ per channel (neglecting spin, Fig. 2b). For an arbitrary constriction this value has to be multiplied by the transmission coefficient.

Quantum interference devices can be realized by putting two or more quantum point contacts in series: In Fig. 3(a), a quantum dot state is formed which results in pronounced interference effects (Aharonov-Bohm effect) due to alternation of the phase difference between a split coherent electron flow [12]. In Fig. 3(b), a finite one-dimensional crystal is demonstrated. The resistance for this case contains quantized steps which are modified by the interference of the five restrictions [12]. By changing the form of just one finger a significant change of the resistance can be achieved. At present, all these concepts are realized only at very low temperatures. However, with decreasing dimensions these interference effects may be maintained up to liquid nitrogen temperatures.

Fig.4: Comparison between the tunneling characteristics of a 2D-2D and a 1D-2D system. The temperature behavior is also shown.

Tunneling processes between a wet-chemically etched multiple quantum wire (MQW) system and a two-dimensional electron gas (2DEG) system, realized on GaAs-AlGaAs-GaAs heterostructures, have also been investigated [13-15]. As can be seen in Fig. 4, the nanostructured samples exhibit a large number of extra resonances in the dI/dV characteristics compared to the unstructured sample. In this system, both the initial and the final states involved in a tunneling transition are quantized in a way that no free momentum component exists in the direction of the tunneling current. Under these conditions, the tunneling probability and selection rules are mainly influenced by the profile and the character of the 1D wave function. Using a model based on the transfer Hamiltonian formalism, calculations for a series of one-dimensional (1D) quantum wire potentials of varying shape we performed. For a square well potential, only one resonance position is of significance, whereas in the case of a smooth cosine shaped potential all 1D states give rise to a multitude of resonance structures in the tunneling current. From the experimental results it was concluded that in wet-chemically etched quantum wires, the bottom part of the potential can qualitatively be described by a harmonic oscillator profile. In addition, the temperature behavior of the resonance structures was used to determine the subband energies in the quantum wires.

3. Single Electron Effects

All the above phenomena based on size quantization of the electronic motion have been observed via measurements on large ensembles of electrons. Significant effects due to individual electrons were first reliably reported in gated quantum wire structures in Si [16], in which the trapping and detrapping of single electrons was observed as telegraph noise. Recently, there have been spectacular observations of the tunneling of single electrons (normal materials) and cooper pairs (superconducting materials) in very small metal insulator tunnel junctions (areas 50 nm × 50 nm) at low temperatures [17-19].

Effects related to the so-called Coulomb blockade are observed, when the junction capacitance C is sufficiently small so that the charging energy of a capacitance $\Delta E = e^2/2C$ exceeds the thermal fluctuations. A tunneling current can not flow for small applied voltages; the tunneling is blocked by the Coulomb interactions equivalent to an energy gap. Note that this gap can be engineered as it is inversely proportional to C. The effect has been experimentally found recently [20]. The next step is to construct a "single electron transistor" as shown in Figure 5. The single electron transistor consists of two Coulomb blockade tunnel junctions in series. The center electrode (gate) determines the charge Q that is crucial for the transfer through the horizontal tunnel junctions. It has been experimentally proved that the transfer of single electrons can be controlled in this way and that in principle a single electron can carry one bit of information certainly the most economic way of information storage and transfer.

Fig. 5: Single electron transistor

If an ac-voltage is supplied to the gate a current standard is obtained [20]: For every cycle of the voltage exactly one electron is transferred between the electrodes. The current becomes directly related to the frequency: $I = e \cdot \frac{\omega}{2\pi}$.

4. Novel Devices

The possibility to engineer the heterostructure bandgap in the growth direction has led to many new physical systems and devices [21]. The first demonstrated device was the Resonant Tunneling Double Barrier Diode (RTDBD) [21], where both the controlled tunneling and the artificially designed energy level structure between the barriers is used. Many other band-engineering structures and concepts have been introduced by Capasso [20]. One application, the Resonant Hot Electron Transistor (RHET), has been persuaded by Yokohama [22]; single device operation up to 120 GHz has been demonstrated. In addition, the high functionality of such non-linear electrical devices allows the replacement of five standard devices by a single RHET in logic IC applications.

Another example are Quantum Well Infrared Photodetectors (QWIP) which can be engineered to any frequency in long wavelength infrared region with the GaAs/GaAlAs system. The first demonstration of an array has been reported by Levine [23]. Extremely high performance and response at selective wavelength has been demonstrated by Köck et al. [24]

One of the main goals of future devices is to use the lateral structuring techniques to improve basic transport properties. One such system is the quantum wire. Significantly higher drift velocities than in a regular 2D-system are predicted since the phonon scattering is significantly reduced [25]. In the case that only the lowest subband is occupied an electron can only scatter by changing its wavevector in the opposite direction.

In a weakly coupled quantum dot system optical phonon emission should be almost eliminated resulting in nearly scattering free transport at high electric fields. This may well leas to the first realization of Bloch-oscillations and other coherent phenomena even at higher temperatures.

In the optical field, the tendency has also been to reduced dimensions going from 3D bulk to 2D quantum wells and to 1D and 0D structures. A variety of improvements are expected based on sharper resonances, stronger phase space filling effects, larger exciton binding energies and higher oscillator strength [5]. Whereas good luminescence of 1D structures has been obtained leading to good Quantum Wire Laser performance, quantum box properties have so far not been able to improve device performances.

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References

[1] M. Reed and N. P. Kirk (eds.), Nanostructure Physics and Fabrication, Academic Press, New York, 1989.

[2] J. M. Lehn, Science, 227 (1985) 849.

[3] F. Carter (ed.), Molecular Electronic devices II, Dekker, New York, 1987.

[4] M. Reed (ed.), Semiconductor and Semimetals, Academic Press, New York, 1990.

[5] for a general review see e.g. C. Weisbuch and B. Vinter, Quantum Semiconductor Structures, Academic Press, Boston, 1991.

[6] Y. Arakawa and H. Sakaki, Appl. Phys. Lett., 40 (1982) 939.

[7] S. Tsukamoto, Y. Nagamune, M. Nishioka and Y. Arakawa, J. Appl. Physics, 71 (1992) 533.

[8] S. Tsukamoto et al., to be published in Proc. of the 19th Intern. Symposium on GaAs and Related Compounds (1992).

[9] Y. Nagamune et al., to be published in Proc. of the 19th Intern. Symposium on GaAs and Related Compounds (1992).

[10] R. Landauer and M. Buettiker, Phys. Rev. Lett., 54 (1985) 2049.

[11] B. J. van Wees, L. P. Kouwenhoven, M. van Houton, C. W. Beemakker, J. E. Mooij, C. T. Foxxon, J. J. Harris, Phys. Rev. B, 348 (1988) 3625.

[12] H. van Houten, C. W. Beenakker, B. J. van Wees, M. A. Reed (ed.), Semiconductor and Semimetals, Academic Press, New York, 1990.

[13] J.Smoliner, F.Hirler, E.Gornik, G.Weimann, M.Hauser, and W.Schlapp, Semicond. Sci. Technol. 6, 389, (1991)

[14] J.Smoliner, W.Demmerle, F.Hirler, E.Gornik, G.Weimann, M.Hauser, G.Weimann, M.Hauser, and W.Schlapp, Phys.Rev.B, 43, 7358 (1991)

[15] J.Smoliner, W.Demmerle, E.Gornik, G.Böhm, G.Weimann, Proc. Int. Workshop on Quantum electronics physis and applications, Luxor 6-10. Jan.92, Inst. Phys. Conf. Ser. 127, 213 (1992)

[16] W. J. Skopol, M. Kelly (ed.), The Physics and Fabrication of Microstructures and Microdevices, Springer Verlag, Berlin, 1986.

[17] T. A. Fulton, G. J. Dolan, Phys. Rev. Lett., 59 (1987) 109.

[15] P. Delsing, K. K. Likharev, L. S. Kuzmin, T. Claeson, Phys. Rev. Lett., 63 (1989) 1861.

[18] L. J. Geerlings et al., Phys. Rev. Lett., 64 (1990) 2691.

[19] for a review see: L. J. Geerlings, J. H. Davies and A. R. Long (eds.), Physics of Nanostructures, IOP Publishing, Bristol, 1992.

[20] F. Capasso (ed.), Physics of Quantum Electronics, Springer Verlag, Berlin, 1990.

[21] L. Esaki and L. L. Chang, Phys. Rev. Lett.; 33 (1974) 495.

[22] N. Yokoyama et al., F. Capasso (ed.), Physics of Quantum Electronics, Springer Verlag, Berlin 1990.

[23] B. F. Levine, Appl. Phys. Lett. 56, (1990), 2354.

[24] A. Köck, Appl. Phys. Lett. 60, (1992), 2011.

[25] H. Sakaki, Surface Science, 267 (1992) 623.