Manipulating Electrons in Nanostructured Semiconductors

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A brief overview of electron manipulations in nanostructured semiconductors is given. Such manipulations go down to average transfer of less than a single electron per controlled step. The applications to nanodevices beyond the scaled down silicon microelectronics is also discussed.

I Introduction

Fabrication technologies with nanometer resolution enable us now to realize nanostructured semiconductor devices in which the artificial geometric confinement dominates the laws of transport and storage of electrons. This gives rise to novel electronic behavior quite in contrast to the diffusive electron motion that governs electron transport even in todays small semiconductor devices. Three distinct examples of electron manipulation in such nanostructures are discussed in the following and serve to explore the possibilities for future storage and sensing devices.

II Electronic Shell Structure and Excitations in Self-Assembled Quantum Dots

Several nanofabrication techniques have made it possible to create semiconductor quantum dots with cage-like potentials in which the number of confined electrons can be voltage-tuned. One route uses molecular beam epitaxy of strained layers to create quantum dots via self-organized Stransky Krastanov growth. Embedding such self-assembled InAs quantum dots into suitable field-effect devices allows to inject few electrons into these dots one by one [1]. The few-electron ground states in their dependence on electron occupation and magnetic fields can be studied with high resolution capacitance spectroscopy which allows us to sample also small ensembles of quantum dots [2,3]. The evolution of the electronic ground state energies with electron number and magnetic field reveals single electron charging via Coulomb blockade as well as a clear shell structure caused by spatial quantization of the electronic motion. The electronic structure can be well described by a simple parabolic model [3]. Capacitance spectroscopy can also be employed to study self-assembled nanorings in which the threading of a single flux quantum causes observable changes in the electronic ground state [4]. On larger ensembles of about 10^8 quantum dots the intraband electronic absorption in the far-infrared [1,4,5] as well as the excitonic absorption in the near infrared [6] can be investigated with transmission experiments. In particular we observe qualitative changes in these spectra that reflect the filling of the atom-like shells by single electrons and again can be well described by theory. Recent luminescence experiments on single quantum rings reveal the detailed dependence of the excitonic excitations on charge and spin states of the stored carriers [7].

III Electromechanical Nanodevices

Nanofabrication employing high resolution electron beam lithography combined with selective etching of sacrificial layers makes it possible to manufacture nanobeams and –levers out of Si or GaAs crystalline films grown on a sacrificial layer [8]. Using the excitation via the Lorentz force that is experienced by a current carrying wire in the presence of a magnetic field one can study the resonant mechanical and electromechanical behavior of conducting nano-beams. Because of their small size typical mechanical resonance frequencies of such wires lie in the regime of radio frequencies up to several 100 MHz. The successful excitation of mechanical motion can then be detected either by measuring the rf power absorbed by the device or by capacitively detecting the motion of the wire with respect to a close by electrode. At low power typical Si-beams exhibit a simple harmonic motion and the mechanical quality factor can easily be deduced from the width of the frequency spectrum to be typically several thousand. At higher excitation power the nano-beams behave increasingly non-linear until one eventually can observe hysteresis and bistability at the highest power level /9/. This non-linear behavior can be employed to improve the sensitivity with which any additional forces that act on such resonantly vibrating nano-beams can be detected. Using a close by electrode we have demonstrated that such vibrating beams can e. g. act as sensitive charge sensors that are able to detect changes of fractions of electrons if influenced on a neighboring electrode [10].

Nanomechanical devices fabricated on silicon can also be employed as fast electrical switches or as shuttles for small amount of charges. In Ref.11 a suspended silicon clapper acts as a mechanical switch between two electrodes, source and drain. The switch can be driven by the electric force exerted via voltages applied across two additional gate electrodes, which cause a mechanical motion of the clapper. Because of its very small mass the resonance frequency of the clapper is in the regime of 10^{th} of MHz. If the tip of the clapper is fabricated as a small metallic island deposited on an isolating clapper the device can also be used as a shuttle for small parcels of charges. Presently we thus can thus transfer on average less than a single electron with each motion of the clapper. We study such a "quantum bell" as a possible device to transfer and count electrons in quantized units by operating the metal island on he clapper as a mechanically controlled single electron transistor /8,9/.

IV Tunable Potential Landscape as Photonic Conveyor Belts and Memories

Another novel mode of combing mechanical motion with electron manipulation allows to process optical signals in quantum wells. Usually photoluminescence in quantum wells is a very efficient process by which incoming light with energy above the effective band gap of a quantum well is absorbed and generates electron-hole pairs, which recombine within nanoseconds to reemit photons at the band gap energy. We use the piezoelectric potential of sufficiently strong surface acoustic waves (SAW) propagating on GaAs quantum wells to spatially separate electron and holes and trap them in adjacent extrema of the potential superlattice created by the SAW. With separations in the micrometer regime this easily extends the recombination lifetimes by orders of magnitude. Furthermore the separation can be reversed and thus can be employed for intermediate storage of optical signals. The dramatic suppression of recombination allows the trapped electron-hole pairs to surf across the devices. Locally flattening the potential wave in which the electron and hole are trapped, e. g., by a screening metal electrode or by an array of quantum dots again induces efficient recombination and emission of monochromatic light. In such a dynamic optical memory device photonic signals have been successfully stored up to 10ths of microseconds, only limited by the time it takes for the SAW to travel across the chip. In a related quasi-static photonic memory we have recently achieved storage times for photonic signals up to seconds.

Saws propagating across piezoelectric heterostructures can also be used to transform a two-dimensional electron system into a grid of electron wires propagating with sound velocity /15/ or as sensors for optical signals and electrical charges as these modify the phase and amplitude of the propagating SAW. Based on such concepts we have recently realized a very simple and fast position detector for photonic signals /16 /. Similar device can be employed as a fast and cheap camera.

V Conclusion

The above examples should have demonstrated that electrons in nanostructures can be manipulated in ways quite different from those used in classical charge transport. The new forms of electron transport and storage can contribute to finding semiconductor devices for information processing and sensing beyond the area of scaled down silicon microelectronics. I want to acknowledge the essential contributions from many collaborators as identified in the references and continuous support from the German Science Foundation (DFG). The German ministry of education (BMBF), and the Volkwagen Foundation.

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