Department of Physics and Measurement Technology

Quantum Transport in Semiconductor Nanostructures and Nanoscale Devices

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Zhen-Li Ji

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This licentiate thesis consists of an introduction and the following four papers,

I. Numerical study of ballistic conductance in parallel configuration
Zhen-Li Ji and Karl-Fredrik Berggren
Semicond. Sci. Technol. **6**, 63 (1991).

II. Resonant tunneling via quantum bound states in a classically unbound system of crossed, narrow channels
Karl-Fredrik Berggren and Zhen-Li Ji
Phys. Rev. B **43**, 4760 (1991).

III. Resonant tunneling via bound states in T-shaped electron waveguide structures
Karl-Fredrik Berggren and Zhen-Li Ji
Superlatt. Microstruct. **8**, 59 (1990).

IV. Effect of impurities on the conductance of nanostructures
Zhen-Li Ji
Submitted for publication

In addition, the following papers are relevant to the work but not included in the thesis,

1. Bound states at intersections of lateral narrow channels
J. Rundquist, Zhen-Li Ji, and K.-F. Berggren
in *Nanostructures Fabrication and Physics,* edited by H. G. Craighead, D. Kern, T. P. Smith III and S. D. Berger Proceedings of Symposium Y, 1989 Fall Meeting of the Materials Research Society Publ. by Materials Research Society (Pittsburg 1990), P87.

2. Transition from laminar to turbulent flow in quantum ballistic transport in a model semiconductor nanostructure
C. Besev, Zhen-Li Ji, and K.-F. Berggren
To be published

INTRODUCTION

Only a decade ago the study and fabrication of electron devices whose smallest features were just under 1 micron represented the forefront of the field. Today that position has advanced an order of magnitude to 100 nanometers and has given rise to a new terminology based on the prefix *nano*, in turn derived from the Greek word for dwarf: nanoscale devices, nanolithography, nanofabrication. *Nano* indicates one-billionth of a unit.

Quantum effects are unavoidable in devices with dimensions smaller than 100 nanometers. A variety of quantum effects have been discovered over the years, such as tunneling, resonant tunneling, weak and strong localization, and the quantum Hall effect. Since 1985, experiments on nanostructures (dimensions < 100 nm) have revealed a number of new effects such as the Aharanov-Bohm effect, conductance fluctuations, non-local effects and the quantized resistance of point contacts. For nanostructures at low temperature, these phenomena clearly show that electron transport is influenced by wave interference effects similar to those well-known in microwave and optical networks.[1] New device concepts now being proposed and demonstrated are based on these wave properties.

This thesis discusses our study of electron transport in nanostructures. All of the quantum phenomena that we address here are essentially one-electron phenomena, although many-body effects will sometimes play a more significant role in the electronic properties of small structures[2]. Most of the experimental observations to date are particularly well explained, at least qualitatively, in terms of the simple one-particle picture.

Vertical and lateral quantum devices

The development of molecular-beam epitaxy, pioneered in the late 1960s by Alfred Cho and John Arthur at AT&T Bell Laboratories, has made it possible to grow ultra-thin layers (on the order of 20 Å) of different materials with atomically sharp interfaces. This has led to the development of *vertical* quantum devices, in which the current flows *perpendicular* to the layers instead of in parallel (Fig. 1(a)). Changes in the material composition give rise to variations in the conduction band edge, sensed as an effective potential by the electrons. Alternatively, modulations in the doping profile during film growth can be used to tailor the electrostatic potential through space-charge transfer. Some of these vertical structures have recently reached a high level of maturity and proved to be potentially useful as resonant tunneling diodes or transistors.

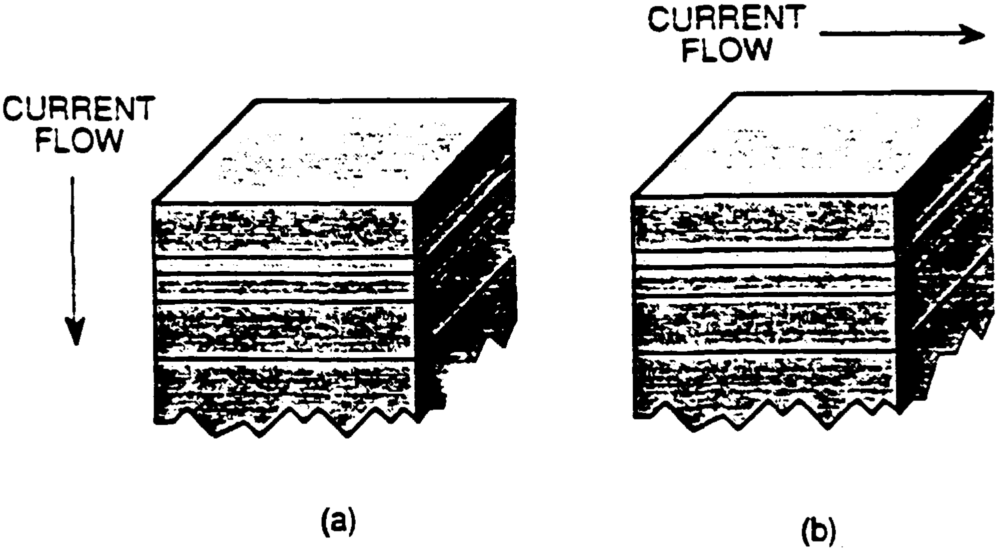

FIG. 1. *(a) Vertical quantum device based on e.g. GaAs/AlGaAs and Si/SiGe layers. (b) lateral quantum device.*

By contrast, the development of *lateral* quantum devices, in which current flows *parallel* to the layers, is still in its infancy, except where HEMTs (High Electron Mobility Transistor) are concerned. In these structures, the potential can be defined through patterned electrodes which deplete selected regions. This opens a possibility to create lateral confinement in addition to the vertical one. Such structures have only recently been made possible by the advances in nanolithographic techniques [3-6]. It will probably be many years before devices based on such effects become practicable. However, since 1985, there has been a flood of experiments revealing novel quantum effects at low temperatures; these have caused considerable excitement in the communities of both basic and applied physicists. Such experiments open new ways to study the fundamental questions of physics. They raise the possibility of obtaining radically new electronic devices that operate by controlling the phase of the wavefunction (one example is shown in Fig. 2), rather than by controlling the carrier density, as in present-day devices.

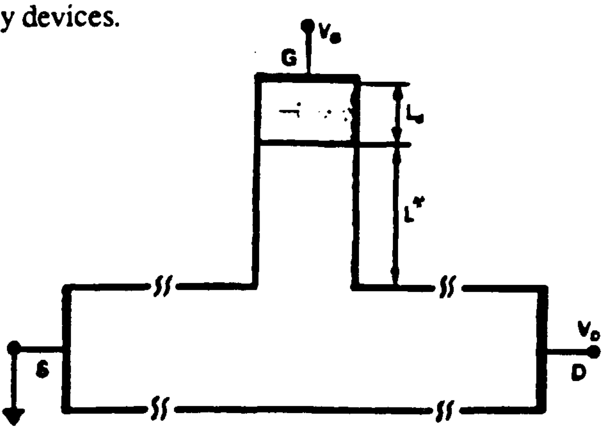

FIG. 2. *A proposed Quantum Modulated Transistor (QMT) structure[7]. The transmission coefficient T between the source S and drain D of the device is a sensitive function of the electron energy E and the transverse stub length L^*, which may be adjusted by changing the depletion length L_d.*

Vertical devices (Fig. 1(a)) usually have cross-sectional dimensions on the order of several microns, allowing transport to be described in terms of plane waves; however, with advances in nanolithography, vertical devices with submicron cross-sections are also be investigated[8]. Lateral devices (Fig. 1(b)) are formed by lithographically patterning a modulation-doped heterostructure, where current flow is confined to a two-dimensional (2D) electron gas. Therefore, one of the transverse dimensions is always so small that only a few modes (commonly called subbands) need be involved, making it more appropriate to view transport in terms of discrete waveguide modes. Within the scope of the present thesis, studies of quantum transport are restricted to lateral quantum devices.

Lateral confinement and ballistic wires

As mentioned above, the current in a lateral device flows parallel to the layers. We will now briefly describe the lateral confinement. Fig. 3 shows the qualitative feature of GaAs/AlGaAs heterostructures. Suppose that the AlGaAs side of the junction is heavily doped with shallow donors, i.e., we may regard the electrons as initially occupying the bulk conduction band. Since the conduction-band edge is lower on the GaAs side, electrons will try to lower their energy by flowing into that region. The donor ions, however, being immobile, will remain on the AlGaAs side. As a consequence, an electrostatic potential will be set up, counteracting the transfer of electrons and confining them to the interface as shown in Fig. 2(b). If the confining potential is narrow, the motion perpendicular to the interface becomes quantized.

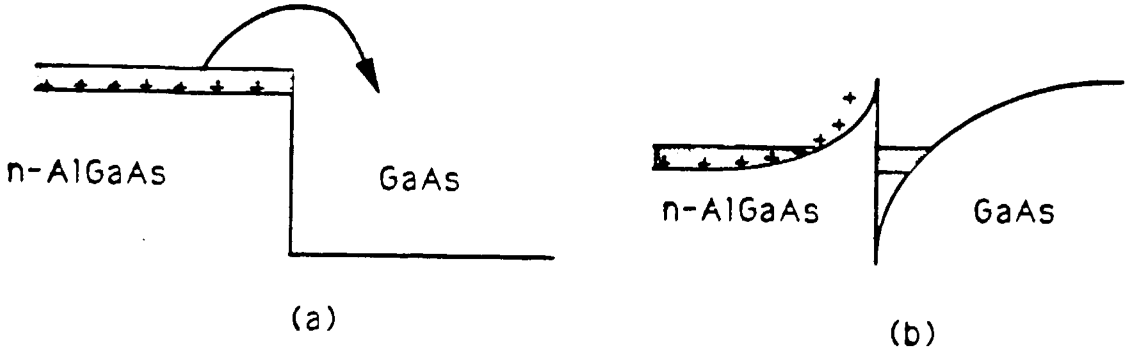

FIG. 3. *A heterojunction in which the material with wider bandgap is n-doped. (a) Electrons try to lower their energy by flowing to the material with lower conduction-band edge. (b) An electrostatic potential is then set up which confines electrons to the interface in the form of a 2D electron gas.*

It is common that only the lowest quantum state or sublevel is occupied at low temperatures. Then the electron gas residing at the interface responds dynamically to weak perturbations as a two-dimensional system.

Using electron-beam lithography, a patterned metal gate is formed on top of the heterostructure. The density of 2D electron gas may be varied continuously by a gate voltage. At sufficiently large bias, the 2D electron gas is totally depleted under the gate. This opens the possibility of creating lateral confinement.

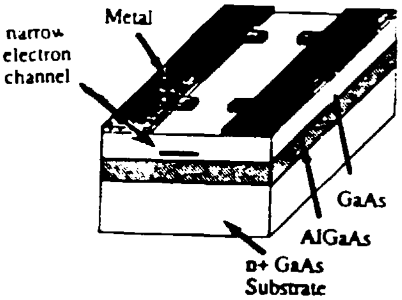

FIG. 4. *Schematic drawing of a lateral device structure. A 2D electron gas forms at the interface between the top layer of undoped GaAs and the AlGaAs layer. A negative voltage* V_g *applied to the metal depletes the 2D electron gas underneath. The patterned electrodes on top define a narrow channel.*

If the gate is split, a stripe is formed where electrons collect; other regions are drained when gate voltage is applied. A narrow conducting channel is thus achieved at the interface (Fig. 4). The channel is not only narrow but also so short that the mean free path exceeds the length of the channel and electrons travel through the channel ballistically. The permissible modes in the channel are "waveguide" modes which are quantized. The conductance is also quantized, increasing by $2e^2/h$ whenever the Fermi energy is raised to the point where the next-higher-order waveguide mode is allowed[9-11].

The question which naturally arises is how do conductances of two parallel channels combine when their separation is less than the elastic and phase coherence mean free paths. Under these dictates, the electron waves should pass along the stripes of both split gates coherently, and double parallel channels will form a coupled one-quantum system[12-14]. Paper I of this series investigates a parallel arrangement of ballistic channels. We find that the system of two channels behaves like a classical system of two conductors added in parallel. The conductance structures are dominated by quantized plateaus and regular oscillations.

Bound states and resonant tunneling

Rather than thinking of the gate as being scored in a simple slit, we may imagine a pattern. Thus the 2D electron gas at the interface may be shaped into a simple network, grid, dot, ring, etc. One of the more remarkable features of nanostructures has been the recent subject of theoretical study. Quantum-mechanical calculations show that it is possible to obtain resonant tunneling through bound states when the construction is caused by geometrical effects[15-20]. This offers the possibility of obtaining a tunnel structure without having to tunnel through potential barriers. Resonant tunneling devices have generated a great deal of interest among applied physicists as being candidates for high frequency and fast switching applications. For vertical devices, resonant tunneling diodes have been used as mixers up to 1.8 THz and as oscillators up to 400 GHz [21,22]. Switching operations with a rise time as short as 2 ps have been reported[23]. Where lateral devices are concerned, it is still an open, but fascinating question if the resonant tunneling and interference effects of nanostructures may be utilized for device purposes. On the other hand, resonant tunneling as a phenomenon is also useful as a probe in studying basic transport phenomena and is deserving of study on its own merits.

In Paper II, we investigate a structure which consists of two perpendicular channels, one of which connects two reservoirs of 2D electron gases. Our calculations show that two bound states reside at the intersection. Sharp resonances are associated with these bound states. For a T-shaped structure, there is one bound state (described in Paper III of this series). In addition to these bound states, there are resonances which resemble delta functions and which are very hard to find by calculating the conductance of the constrictions. Visualization of spatial current distributions and electron densities clearly shows the presence of the resonances. This most unusual type of localized quantum states appears for potentials which are classically open, i.e., are unable to trap classical particles. One may, at least in principle, now achieve resonant tunneling through the described states by means of geometry.

Impurity effects on conductance

The effect of an impurity on conductance on nanostructures is investigated in Paper IV. It is shown that the conductance is lowered due to the presence of an impurity[24-28]. For a single channel, the conductance is reduced below the unperturbed plateau values, and where strong scatterers are concerned, the plateaus disappear. The presence of an

impurity in a crossbar geometry suppresses the resonant tunneling associated with bound quantum states. The position of the impurity also plays a role in suppressing the resonant tunneling. Because of the interference and scattering, the current density in the construction displays very complex behavior in the form of volatile vortex structures.

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References

1. M. L. Roukes, A. Acherer, S. J. Allen, H. G. Craighead, R. M. Ruthen, E. D. Beebe, J. P. Harbison, Phys. Rev. Lett. **59**, 3011 (1987); G. Timp, A. M. Chang, P. Mankiewich, R. Behringer, J. E. Cunningham, T. Y. Chang, R. E. Howard, Phys. Rev. Lett. **59**, 732 (1987).

2. U. Meirav, M. A. Kastner, and S. J. Wind, Phys. Rev. Lett. **65**, 771 (1990) and references cited therein.

3. *Physics and Technology of Submicron Structure*, edited by H. Heinrich, G. Bauer and F. Kuchar (Springer-Verlag, New York, 1988).

4. *Nanostructure Physics and Fabrication*, edited by M. A. Reed and W. P. Kirk (Academic, New York, 1989).

5. Phys. Today **43** (2) (1990).

6. *The Physics and Fabrication of Microstructures and Micro devices*, edited by M. J. Kelly and C. Weisbuch (Springer-Verlag, Berlin, 1986); *Two-Dimensional Systems: Physics and New Devices*, edited by G. Bauer, F. Kuchar, and H. Heinrich (Springer- Verlag, Berlin, 1986).

7. F. Sols, M. Macucci, U. Ravaioli, and Karl Hess, Appl. Phys. Lett. **54** 350 (1989).

8. A. M. Reed, R. W. Frensley, J. R. Matyi, N. J. Randall, and A. C. Seabaugh, Appl. Phys. Lett. **54** 1034 (1988).

9. D. A. Wharam, T. J. Thornton, R. Newbury, M. Pepper, H. Ahmed, J. E. F. Frost, D. G. Hasko, D. C. Peacock, D. A. Ritchie, and G. A. C. Jones, J. Phys. C **21**, L209 (1988).

10. B. J. van Wees, H. van Houten, C. W. J. Beenakker, J. G. Williamson, L. P. Kouwenhoven, D. van der Marel, and C. T. Foxon, Phys. Rev. Lett. **60**, 848 (1988).

11. G. Kirczenow, Phys. Rev. B **39**, 10453 (1989).

12. C. G. Smith, M. Pepper, R. Newbury, H. Ahmed, D. G. Hasko, C. D. peacock, J. E. F. Frost, D. A. Ritchie, G. A. C. Jones, and G. Hill, J. Phys.: Condens. Matter **1** 6763 (1989).

13. Y. Avishai, M. Kaveh, S. Ahatz, and Y. B. Band, J. Phys.: Condens. Matter **1** 6907 (1989).

14. E. Castano and G. Kirczenow, Phys. Rev. B **41** 5055 (1990).

15. F. M. Peeters, in Science and Engineering of One- and Zero-Dimensional Semiconductors, edited by S. P. Beaumont and C. M. Sotomajor Torres (Plenum, New York, 1990), p. 107.

16. R. L. Schult, D. G. Ravenhall, and H. W. Wyld, Phys. Rev. B **39**, 5476 (1989).

17. K.-F. Berggren and Zhen-Li Ji, Phys. Rev. B **43**, 4760 (1991).

18. E. Tekman and S. Ciraci, Phys. Rev. B **40**, 8559 (1989).

19. F. Sols and M. Macucci, Phys. Rev. B **41**, 11887 (1990).

20. F. M. Peeters, Superlatt. Microstruct. **6**, 217 (1989).

21. T. C. L. G. Sollner, W. D. Goodhue, P. E. Tannenwald, C. D. Parker, and D. D. Peck, Appl. Phys. Lett. **43** 588 (1983).

22. T. C. L. G. Sollner, E. R. Brown, H. Q. Le, Lincoln Laboratory Journal **1** 89 (1988).

23. J. F. Whitaker, G. A. Mourou, T. C. L. G. Sollner, W. D. Goodhue, Appl. Phys. Lett. **53** 385 (1988).

24. E. G. Haanapel and D. van der Marel, Phys. Rev. B **39**, 5435 (1989).

25. C. S. Chu and R. S. Sorbello, Phys. Rev. B **40**, 5941 (1989).

26. J. Masek, P. Lipavsky, and B. Kramer, J, Phys. Condens. Matter **1**, 6395 (1989).

27. E. Tekman and S. Ciraci, Phys. Rev. B **42**, 9098 (1990).

28. J. Faist, P. Gueret and H. Rothuizen, Superlatt. Microsstruct. **7**, 349 (1990).

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