Part III
Quantum Wires

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In the following Sections, experiments on single semiconductor quantum wires, lateral superlattices, and semiconductor rings performed and published since the outset of this very active research area are briefly described. The order in which the descriptions of the experiments are given is according to the submission dates of the corresponding publications.

Each section begins with a brief introduction into the phenomenon or the phenomena described in that section. The references given are not meant to represent an overview of the available theoretical literature. The cited publications contain additional references on the theoretical background, though. The main theoretical results on the theory of quantum transport are summarized in Section 12 (written by the editor).

In nearly all of the experiments described here, more than one question was addressed. Hence, a given experiment is described once as a whole in one of the Sections. In another Section also related to that particular experiment, a short reference is given including the number of the page where the complete description may be found.

6 Overview over systems

Semiconductor quantum wires may be defined using a large number of different materials and fabrication techniques. A very brief overview of the materials and the techniques used in the experiments described in the following chapters is given here.

6.1 Si–based systems

Si–based systems (see for example [82A, 91F1, 96S2, 98T2] and references therein) have been employed in order to study the transport properties of single wires (first reported by Fowler et al in [82F], see page 125), lateral superlattices (first reported by Skocpol et al in [82S1], see page 228) and connected rings (first reported by Gao et al in [94G1], see page 272). preparation and characterization may be found in the conference proceedings [80F, 84B1, 84C, 86B1, 86K1, 86V, 87D, 87L1, 88G1, 88L1, 88M1, 89A, 89D1, 89F1, 89L1, 89M1, 89N, 90B1, 90F1, 90K2, 91C, 91K1, 92B1, 92M1, 92P1, 93L1, 93L2, 93S, 94G2, 94I1, 95A1, 95C, 95E1, 95F1, 96B1, 96J1, 96K1, 97A1, 97S1, 97S2, 98G1].

6.2 AlGaAs/GaAs–heterostructures

AlGaAs/GaAs–heterostructures (see for example [82A, 91F1, 91W1, 96S2] and references therein) have been used in order to measure the transport properties of single wires (first reported by Choi et al in [85C], see page 168), lateral superlattices (first reported by Brinkop et al in [88B1], see page 244), isolated rings (first reported by Mailly et al in [93M1, 94M1], see page 252), and connected rings (first reported by Timp et al in [87T1], see page 264). on materials, preparation and characterization may be found in the conference proceedings [80F, 84B1, 84C, 86B1, 86K1, 86V, 87D, 87L1, 88G1, 88L1, 88M1, 89A, 89D1, 89F1, 89L1, 89M1, 89N, 90B1, 90F1, 90K2, 91C, 91K1, 92B1, 92M1, 92P1, 93L1, 93L2, 93S, 94G2, 94I1, 95A1, 95C, 95E1, 95F1, 96B1, 96J1, 96K1, 97A1, 97S1, 97S2, 98G1].

6.3 Quantum wires based on other III-V and II-VI materials

Transport in single wires has been examined in systems of InGaAs/InP (first reported by Menschig et al in [90M1, 90M2], see page 116), InAs/AlGaSb (first reported by Haug et al in [92H1], see page 180), HgCdMnTe and PbMnTe (first reported by Dietl et al in [93D], see page 191, for information on the material see [88F1], and CdMnTe (first reported by Jaroszyński et al in [95J], see page 181, see also [88F1]). Transport properties of lateral superlattices have been measured in systems of InSb (first reported by Alsmeier et al in [88A], see page 244), InGaAs/InAlAs/InP (first reported by Kern et al in [90K1], see page 225), AlGaAs/InGaAs/GaAs (first reported by Carpi et al in [93C1], see page 243), InGaAs/InP (first reported by Kreschuk et al in [94K1], see page 289), InAs/AlGaSb (first reported by Sasa et al in [96S1], see page 226), and $(InP)_2/(GaP)_2$ (first reported by Tang et al in [98T1], see page 229). investigated in systems of GaInAs/AlInAs (first reported by Kurdak et al in [92K1], see page 256), InO (first reported by Chandrasekhar et al in [94C1], see page 275), InGaAs/InP (first reported by Appenzeller et al in [95A2], see page 258), and InGaAs/AlGaAs (first reported by Bykov et al in [96B2], see page 291). Additional information on materials, preparation and characterization may be found in the conference proceedings [80F, 84B1, 84C, 86B1, 86K1, 86V, 87D, 87L1, 88G1, 88L1, 88M1, 89A, 89D1, 89F1, 89L1, 89M1, 89N, 90B1, 90F1, 90K2, 91C, 91K1, 92B1, 92M1, 92P1, 93L1, 93L2, 93S, 94G2, 94I1, 95A1, 95C, 95E1, 95F1, 96B1, 96J1, 96K1, 97A1, 97S1, 97S2, 98G1].

6.4 Preparation and structuring

Semiconductor heterostructures are usually grown by *molecular beam epitaxy* (MBE) or *metal organic vapour phase epitaxy* (MOVPE) (see for example [82S2, 84C, 85J, 91F1, 91W1, 92P1, 94T, 96S2] and references therein). In order to define a specific structure, a layer of resist is spun onto the wafer. Then, *optical lithography*, *holographic lithography*, *electron beam lithography* (EBL), and *focused ion beam* (FIB) *lithography* may be employed in order to write the pattern into the resist (see for example [88H1, 90B1, 91F1, 91W1, 92P1, 92V, 94G2, 94T, 96S2, 97F] and references therein). The resist is developed and is either washed away where it was exposed (positive resist) or where it was not exposed (negative resist) (see for example [92P1] and references therein).

Different processing steps may follow. First, a thin metal film may be evaporated onto the patterned and developed resist. When the resist is dissolved away, the metal film only remains in places where the resist was washed away during development. This process is called *lift–off* and is used to deposit metallic gates and contacts (see for example [88H1, 90B1, 91W1, 92P1, 96S2, 97F, 98T2] and references therein). Second, the resist pattern may be used as a mask for selective etching (affecting the bare semiconductor but not the resist). One uses either *wet chemical etching* or *dry etching* including *plasma etching*, *reactive ion etching* (RIE), and *reactive ion beam etching* (see for example [88H1, 90B1, 91F1, 91W1, 92P1, 96S2, 97F, 98T2] and references therein).

Alternatives to the above fabrication techniques are, for example, implantation to form local *p-n* junctions (see for example [98T2] and references therein), direct writing of the pattern into the semiconductor using *focused ion beam implantation* (see for example [91F1, 92P1, 96S2, 98T2] and references therein) or *cleaved edge overgrowth* where two orthogonal quantum wells form a T–shaped wire (see for example [92S1, 97A1] and references therein).

Additional information on materials, preparation and characterization may be found in the conference proceedings [80F, 84B1, 84C, 86B1, 86K1, 86V, 87D, 87L1, 88G1, 88L1, 88M1, 89A, 89D1, 89F1, 89L1, 89M1, 89N, 90B1, 90F1, 90K2, 91C, 91K1, 92B1, 92M1, 92P1, 93L1, 93L2, 93S, 94G2, 94I1, 95A1, 95C, 95E1, 95F1, 96B1, 96J1, 96K1, 97A1, 97S1, 97S2, 98G1].

6.5 Characterization

A sample is characterized by its spatial dimensions, i. e. *thickness* t, *width* w and *length* L. The amount of disorder in a sample determines the *mean free path* l, which is related to the *elastic scattering time* τ and the *Fermi velocity* of the electrons v_F by $l = v_F\tau$. When electrons are accelerated in an electric field E, they assume a *drift velocity* $v_D = -eE\tau/m^*$, where m^* is the *effective mass* and $e\tau/m^*$ is the *drift electron mobility* μ_D. The mobility together with the *carrier concentration* n yields the *Drude conductivity*, $\sigma = en\mu_D$. The product of the Hall resistance, R_H, and the conductivity is called *Hall mobility*, $\mu_H = |R_H\sigma|$. The *diffusion constant* $D = v_F^2\tau/2$ is a measure of the area in which an electron may be found after it has performed many elastic scattering events (see for example [81S1, 96S2] and references therein).

After the fabrication of a quasi 1D channel, the actual width of the wire may be determined from a fit to the negative magneto resistance using weak–localization theory, from a fit to reproducible aperiodic conductance fluctuations or via magnetic depopulation of 1D subbands. The electron density may either be determined from Hall measurements or from Shubnikov–de–Haas oscillations. The drift mobility may be inferred from conductivity measurements and the Hall mobility from Hall measurements. The carrier concentration yields the Fermi energy and thus the Fermi velocity. Further, knowing carrier concentration and mobility, the mean free path may be derived (see for example [98T2] and references therein).

Additional information on materials, preparation and characterization may be found in any of the conference proceedings [80F, 84B1, 84C, 86B1, 86K1, 86V, 87D, 87L1, 88G1, 88L1, 88M1, 89A, 89D1, 89F1, 89L1, 89M1, 89N, 90B1, 90F1, 90K2, 91C, 91K1, 92B1, 92M1, 92P1, 93L1, 93L2, 93S, 94G2, 94I1, 95A1, 95C, 95E1, 95F1, 96B1, 96J1, 96K1, 97A1, 97S1, 97S2, 98G1].

6.6 References for Section 6

[80F] Physics of Nonlinear Transport in Semiconductors, NATO ASI Series B: Physics Vol. 52, edited by Ferry, D.K., Barker, J.R., Jacoboni, C. (Plenum Publishing Corporation, 1980).

[81S1] Sze, S.M.: Physics of Semiconductor Devices, second edition (John Wiley & Sons, 1981).

[82A] Ando, T., Fowler, A.B., Stern, F.: Rev. Mod. Phys. **54** (1982) 437.

[82F] Fowler, A.B., Hartstein, A., Webb, R.A.: Phys. Rev. Lett. **48** (1982) 196.

[82S1] Skocpol, W.J., Jackel, L.D., Hu, E.L., Howard, R.E., Fetter, L.A.: Phys. Rev. Lett. **49** (1982) 951.

[82S2] Stringfellow, G.B.: Rep. Prog. Phys. **45** (1982) 469.

[84B1] Two–dimensional systems, heterostructures and superlattices, Solid–State Sciences 53, edited by Bauer, G. (Springer Verlag, 1984).

[84C] Molecular Beam Epitaxy and Heterostructures, NATO ASI Series E: Applied Sciences Vol. 87, edited by Chang, L.L., Ploog, K. (Nijhoff, 1984).

[85C] Choi, K.K., Tsui, D.C., Palmateer, S.C.: Phys. Rev. B **32** (1985) 5540.

[85J] Joyce, B.A.: Rep. Prog. Phys. **48** (1985) 1637.

[86B1] Two–dimensional systems: physics and new devices, Solid–State Sciences 67, edited by Bauer, G. (Springer Verlag, 1986.)

[86K1] The physics and fabrication of microstructures and microdevices, edited by Kelly, M.J. (Springer Verlag, 1986).

[86V] Heterojunctions and semiconductor superlattices, edited by Voos, M., Allan, G. (Springer Verlag, 1986).

[87D] The Physics of the Two-Dimensional Electron Gas, NATO ASI Series B: Physics Vol. 157, edited by Devreese, J.T., Peeters, F.M. (Plenum Publishing Corporation, 1987).

[87L1] Semiconductor interfaces: formation and properties, edited by Lelay, G., Derrien, J., Boccara, N. (Springer Verlag, 1987).

[87T1] Timp, G., Chang, A.M., Cunningham, J.E., Chang, T.Y., Mankiewich, P., Behringer, R., Howard, R.E.: Phys. Rev. Lett. **58** (1987) 2814.

[88A] Alsmeier, J., Sikorski, Ch., Merkt, U.: Phys. Rev. B **37** (1988) 4314.

[88B1] Brinkop, F., Hansen, W., Kotthaus, J.P., Ploog, K.: Phys. Rev. B **37** (1988) 6547.

[88F1] Semiconductors and Semimetals, Volume 25, Diluted Magnetic Semiconductors, edited by Furdyna, J.K., Kossut, J. (Academic Press, 1988).

[88G1] The Physics of Submicron Semiconductor Devices, NATO ASI Series B: Physics Vol. 180, edited by Grubin, H.L., Ferry, D.K., Jacoboni, C. (Plenum Publishing Corporation, 1988).

[88H1] Physics and Technology of Submicron Structures, Solid–State Sciences 83, edited by Heinrich, H., Bauer, G., Kuchar, F. (Springer Verlag, 1988).

[88L1] Interfaces, Quantum Wells and Superlattices, NATO ASI Series B: Physics Vol. 179, edited by Leavens, C.R., Taylor, R. (Plenum Publishing Corporation, 1988).

[88M1] Physics and Applications of Quantum Wells and Superlattices, NATO ASI Series B: Physics Vol. 170, edited by Mendez, E.E., von Klitzing, K. (Plenum Publishing Corporation, 1988).

[89A] Band Structure Engineering in Semiconductor Microstructures, NATO ASI Series B: Physics Vol. 189, edited by Abram, R.A., Jaros, M. (Plenum Publishing Corporation, 1989).

[89D1] Physics, Fabrication, and Applications of Multilayered Structures, NATO ASI Series B: Physics Vol. 182, edited by Dhez, P., Weisbuch, C. (Plenum Publishing Corporation, 1989).

[89F1] Properties of Impurity States in Superlattice Semiconductors, NATO ASI Series B: Physics Vol. 183, edited by Fong, C.Y., Batra, I.P., Ciraci, S. (Plenum Publishing Corporation, 1989).

[89L1] Microelectronic Materials and Processes, NATO ASI Series E: Applied Sciences Vol. 164, edited by Levy, R.A. (Kluwer Academic Publishers, 1989).

[89M1] Growth and Optical Properties of Wide–Gap II–VI Low–Dimensional Semiconductors, NATO ASI Series B: Physics Vol. 200, edited by McGill, T.C., Sotomayor Torres, C.M., Gebhardt, W. (Plenum Publishing Corporation, 1989).

[89N] Heterostructures on Si : One Step Further with Silicon, NATO ASI Series E: Applied Sciences Vol. 160, edited by Nissim, Y.I., Rosencher, E. (Kluwer Academic Publishers, 1989).

[90B1] Science and Engineering of One– and Zero–Dimensional Semiconductors, NATO ASI Series B: Pyshics Vol. 214, edited by Beaumont, S.P., Sotomayor Torres, C.M. (Plenum Publishing Corporation, 1990).

[90F1] Spectroscopy of Semiconductor Microstructures, NATO ASI Series B: Pyshics Vol. 206, edited by Fasol, G., Fasolino, A., Lugli, P. (Plenum Publishing Corporation, 1990).

[90K1] Kern, K., Demel, T., Heitmann, D., Grambow, P., Ploog, K., Razeghi, M.: Surf. Sci. **229** (1990) 256.

[90K2] Localization and confinement of electrons in semiconductors, Solid–State Sciences 97, edited by Kuchar, F. (Springer Verlag, 1990).

[90M1] Menschig, A., Forchel, A., Roos, B., Germann, R., Pressel, K., Heuring, W., Grützmacher, D.: Appl. Phys. Lett. **57** (1990) 1757.

[90M2] Menschig, A., Roos, B., Germann, R., Forchel, A., Pressel, K., Heuring, W., Grützmacher, D.: J. Vac. Sci. Technol. B **8** (1990) 1353.

[91C] Electronic Properties of Multilayers and Low–Dimensional Semiconductor Structures, NATO ASI Series B: Pyshics Vol. 231, edited by Chamberlain, J.M., Eaves, L., Portal, J.-C. (Plenum Publishing Corporation, 1991).

[91F1] Ferry, D.K., Grondin, R.O.: Physics of Submicron Devices (Plenum Publishing Corporation, 1991).

[91K1] Quantum Coherence in Mesoscopic Systems, NATO ASI Series B: Pyshics Vol. 254, edited by Kramer, B. (Plenum Publishing Corporation, 1991).

[91W1] Weisbuch, C., Vinter, B.: Quantum Semiconductor Structures, Fundamentals and Applications (Academic Press, 1991).

[92B1] Low–dimensional electronic systems: new concepts, Solid–State Sciences 111, edited by Bauer, G. (Springer Verlag, 1992).

[92H1] Haug, R.J., Munekata, H., Chang, L.L.: Jpn. J. Appl. Phys. **31** (1992) L127.

[92K1] Kurdak, C., Chang, A.M., Chin, A., Chang, T.Y.: Phys. Rev. B **46** (1992) 6846.

[92M1] Optical Properties of Semiconductors, NATO ASI Series E: Applied Sciences Vol. 228, edited by Martinez, G. (Kluwer Academic Publishers, 1992).

[92P1] Low–Dimensional Structures in Semiconductors: From Basic Physics to Applications, NATO ASI Series B: Physics Vol. 281, edited by Peaker, A.R., Grimmeiss, H.G. (Plenum Publishing Corporation, 1992).

[92S1] Nanostructures and Mesoscopic Systems, edited by Kirk, W.P., Reed, M.A. (Academic Publishing Corporation, 1992).

[92V] Valiev, K.A.: The Physics of Submicron Lithography (Plenum Press, 1992).

[93C1] Carpi, E.L., van Hove, M.: Superlatt. Microstruct. **14** (1993) 53.

[93D] Dietl, T., Grabecki, G., Jaroszyński, J.: Semicond. Sci. Technol. **8** (1993) 141.

[93L1] Phonons in Semiconductor Nanostructures, NATO ASI Series E: Applied Sciences Vol. 236, edited by Leburton, J.-P., Pascual, J., Sotomayor Torres, C. (Kluwer Academic Publishers, 1993).

[93L2] Optical Phenomena in Semiconductor Structures of Reduced Dimensions, NATO ASI Series E: Applied Sciences Vol. 248, edited by Lockwood, D.J., Pinczuk, A. (Kluwer Academic Publishers, 1993.)

[93M1] Mailly, D., Chapelier, C., Benoit, A.: Phys. Rev. Lett. **70** (1993) 2020.

[93S] Semiconductor Interfaces at the Sub–Nanometer Scale, NATO ASI Series E: Applied Sciences Vol. 243, edited by Salemink, H.W.M., Pashley, M.D. (Kluwer Academic Publishers, 1993).

[94C1] Chandrasekhar, V., Webb, R.A.: J. Low Temp. Phys. **97** (1994) 9.

[94G1] Gao, W.X., Ismail, K., Lee, K.Y., Chu, J.O., Washburn, S.: Appl. Phys. Lett. **65** (1994) 3114.

[94G2] Nanolithography: A Borderland between STM, EB, IB, and X–Ray Lithographies, NATO ASI Series E: Applied Sciences Vol. 264, edited by Gentili, M., Giovannella, C., Selci, S. (Kluwer Academic Publishers, 1994).

[94I1] Interaction and Scattering Phenomena in Nanostructures, Semicond. Sci. Technol. **9, 11S** (1994) 1853-2030.

[94K1] Kreschuk, A.M., Kulagina, M.M., Novikov, S.V., Savel'ev, I.G., Shik, A., Kipshidze, G.D.: Superlatt. Microstruct. **16** (1994) 153.

[94M1] Mailly, D., Chapelier, C., Benoit, A.: Physica B **197** (1994) 514.

[94T] Thornton, T.J.: Rep. Prog. Phys. **57** (1994) 311.

[95A1] Mesoscopic quantum physics, edited by Akkermans, E., Montambaux, G., Pichard, J.-L. (Elsevier Science Publishing, 1995).

[95A2] Appenzeller, J., Schäpers, Th., Hardtdegen, H., Lengeler, B., Lüth, H.: Phys. Rev. B **51** (1995) 4336.

[95C] Quantum Dynamics of Submicron Structure, NATO ASI Series E: Applied Sciences, Vol. 291, edited by Cerdeira, H., Kramer, B., Schön, G. (Kluwer Academic Publishers, 1995).

[95E1] Low Dimensional Structures Prepared by Epitaxial Growth or Regrowth on Patterned Substrates, NATO ASI Series E: Applied Sciences, Vol. 298, edited by Eberl, K., Petroff, P.M., Demeester, P. (Kluwer Academic Publishers, 1995).

[95F1] Quantum Transport in Ultrasmall Devices, NATO ASI Series B: Pyshics Vol. 342, edited by Ferry, D.K., Grubin, H.L., Jacoboni, C., Jauho, A.-P. (Plenum Publishing Corporation, 1995).

[95J] Jaroszyński, J., Wróbel, J., Sawicki, M., Kamińska, E., Skośkiewicz, T., Karczewski, G., Wojtowicz, T., Piotrowska, A., Kossut, J., Dietl, T.: Phys. Rev. Lett. **75** (1995) 3170.

[96B1] Nanostructure physics and technology, edited by Bauer, G.: Semicond. Sci. Technol. **11S** (1996).

[96B2] Bykov, A.A., Litvin, L.V., Moshchenko, S.P.: Surf. Sci. **361/362** (1996) 747.

[96J1] Frontiers in Nanoscale Science of Micron/Submicron Devices, NATO ASI Series E: Applied Sciences, Vol. 328, edited by Jauho, A.-P., Buzaneva, E.V. (Kluwer Academic Publishers, 1996).

[96K1] Quantum Transport in Semiconductor Submicron Structures, NATO ASI Series E: Applied Sciences, Vol. 326, edited by Kramer, B. (Kluwer Academic Publishers, 1996).

[96S1] Sasa, S., Sugihara, T., Tada, K., Izumiya, S., Yamamoto, Y., Inoue, M.: Physica B **227** (1996) 363.

[96S2] Smith, C.G.: Rep. Prog. Phys. **59** (1996) 235.

[97A1] Optical Spectroscopy of Low Dimensional Semiconductors, NATO ASI Series E: Applied Sciences, Vol. 344, edited by Abstreiter, G., Aydinli, A., Leburton, J.-P. (Kluwer Academic Publishers, 1997).

[97F] Ferry, D.K., Goodnick, S.M.: Transport in Nanostructures (Cambridge University Press, 1997).

[97S1] Nanowires, NATO ASI Series E: Applied Sciences, Vol. 340, edited by Serena, P.A., Garcia, N. (Kluwer Academic Publishers, 1997).

[97S2] Mesoscopic Electron Transport, NATO ASI Series E: Applied Sciences, Vol. 345, edited by Sohn, L.L., Kouwenhoven, L.P., Schön, G. (Kluwer Academic Publishers, 1997).

[98G1] Nanoscale Science and Technology, NATO ASI Series E: Applied Sciences, Vol. 348, edited by Garcia, N., Nieto–Vesperinas, M., Rohrer, H. (Kluwer Academic Publishers, 1998).

[98T1] Tang, Y., Rich, D.H., Moy, A.M., Cheng, K.Y.: Appl. Phys. Lett. **72** (1998) 55.

[98T2] Thornton, T.J.: Superlatt. Microstruct. **23** (1998) 601.