Recent surprises in magnetotransport in 2D electron systems

A. D. Mirlin
Institut für Nanotechnologie, Forschungszentrum Karlsruhe, 76021 Karlsruhe, Germany
Institut für Theorie der Kondensierten Materie, Universität Karlsruhe, 76128 Karlsruhe, Germany
Petersburg Nuclear Physics Institute, 188350 Gatchina, St Petersburg, Russia

1. Oscillatory photoconductivity and zero-resistance states

Recent experiments have discovered [1] that the resistivity of a high-mobility two-dimensional electron gas (2DEG) in GaAs/AlGaAs heterostructures subjected to microwave radiation of frequency ω exhibits magnetooscillations governed by the ratio ω/ω_c, where ω_c is the cyclotron frequency. Subsequent work [2, 3, 4, 5, 6, 7] has shown that for samples with a very high mobility and for high radiation power the minima of the oscillations evolve into zero-resistance states (ZRS). These spectacular observations have attracted much theoretical interest.

In this lecture I will present the key experimental observations and the recently developed theory of the oscillatory photoconductivity (OPC) and of the ZRS. According to our theory, the parametrically largest contribution to the effect is governed by the microwave-induced change in the distribution function [8, 9, 10]. More specifically, because of the oscillations of the density of states related to the Landau quantization, the distribution function acquires an oscillatory structure, both as a function of the energy and of the microwave frequency. This generates a contribution to the *dc* conductivity which oscillates with varying ω/ω_c. A distinctive feature of the photoconductivity generated in this way is that its magnitude is proportional to the inelastic relaxation time $\tau_{\rm in}$ and thus strongly increases (as T^{-2} or T^{-1}, depending on the relation between T and ω) with lowering temperature T, as observed in experiment.

We use the kinetic equation approach and calculate the non-linear (both with respect to *dc* and the microwave fields) photoresistivity. For a sufficiently strong microwave power the linear-in-*dc*-field photoconductivity becomes negative. This induces an instability leading to the formation of domains with spontaneous currents and Hall fields [11]. As a result, the observable resistivity is zero, in agreement with experiments showing regions of ZRS. Using the microscopic theory of the effect, we calculate the threshold power at which this zero–resistance state is formed and the spontaneous *dc* field in the domains.

An alternative mechanism of OPC, which is based on the effect of microwave radiation on electron scattering by impurities was in fact proposed a long ago [12] (for the case of a strong *dc* electric field). In the context of recent experiments this contribution was studied in [13, 14, 15]. A comparison of the two contributions shows that the one related to the change of the distribution function is dominant provided $\tau_{\rm in} \gg \tau_{\rm q}$ (where $\tau_{\rm q}$ is the quantum, or single-particle, relaxation time due to impurity scattering), which is the case for the experimentally relevant temperatures.

In the end of this part of the lecture, I briefly review most recent developments, as well as some directions of current and future research. In a number of recent papers the theory was developed in a variety of contexts: propagation of surface-acoustic waves [16], photoconductivity of laterally-modulated structures [17], local compressibility of irradiated samples [18]. The authors of Ref. [19] analyzed the nature of the non-equilibrium phase transition into the zero-resistance state. In [20] the effect of long-range inhomogeneities on zero-resistance states and the underlying domain structure was studied. On the experimental side, a strong suppression of resistivity by microwave radiation for B above the cyclotron resonance was observed in [21] and explained by the theory of citedmitriev04, dmitriev05 applied to this range of magnetic fields. Weak oscillations of the Hall component of the resistivity induced by the radiation were observed in [22]. Experimental activity in the directions of thermodynamic signatures of the ZRS (considered theoretically in [18]), as well as of the evolution of the effect with further increase in frequency (when the effect shifts into the range of B corresponding to well separated Landau levels) is currently underway [23].

2. Coulomb drag

Coulomb drag between two barrier-separated parallel 2DEG's was theoretically predicted a long ago [24]. However, only in the beginning of 90s the progress in nanofabrication made the drag an experimental reality [25, 26]. The drag signal is the voltage V developing in the open-circuit passive layer when a current I is applied in the active layer. The drag resistance (also known as transresistance) is then defined by $R_D = V/I$. In the last few years, the Coulomb drag has developed into a powerful probe of quantum-Hall systems [27, 28, 29, 30, 31, 32, 33, 34], providing information which is complementary to conventional transport measurements.

The recent activity concentrated on two ranges of B: (i) vicinity of filling factor $\nu = 1/2$ of the lowest Landau level (LL) in each layer, and (ii) the regime of high LLs, $\nu \gg 1$. While the first regime encompasses beautiful and rich physics, I will only briefly touch it here. In the vicinity of $\nu = 1/2$ the low-energy physics in each layer is described in terms of composite fermions (CF's) — quasiparticles consisting (roughly speaking) of an electron and two flux quanta. It was theoretically predicted [35, 36, 37] that a gauge-field interaction between the CF's leads to an unconventional $T^{4/3}$ temperature dependence of the drag, as was confirmed by experiment [30, 34]. Furthermore, for smaller interlayer separation a superconducting pairing of CF's in the both layers leads to formation of a highly correlated state (which can be also viewed as an excitonic condensate) [32, 33]. Vanishing of the longitudinal component of the drag and quantization of its Hall component serve as indicators of this novel state with spontaneous inter-layer phase-coherence.

In the sequel, I concentrate on the range of high LL's assuming weak interlayer coupling. In a simple picture of Coulomb drag, the carriers of the active layer transfer momentum to the carriers of the passive layer by interlayer electron-electron scattering. Due to the open-circuit setup, a voltage V develops in the passive layer, which balances this momentum transfer. The phase space for interlayer scattering is proportional to the temperature T in either layer predicting a monotonous temperature dependence $R_D \propto T^2$ of the drag resistance. Moreover, the signs of the voltages in active and passive layer are expected to be opposite (the same) for carriers of equal (opposite) charge in the two layers [38]. It is conventional to refer to the sign resulting for like (unlike) charges as positive (negative) drag. It is worth stressing that the non-zero value of drag in the regime of weak interlayer interaction is entirely due to the violation of the particle-hole symmetry.

Remarkably, experiments show that Coulomb drag behaves very differently from these simple expectations when a perpendicular magnetic field B is applied. Several experiments [29, 31] in the regime of weak interlayer coupling observed negative drag when the filling factors in the two layers are different. A more recent experiment [34] also reveals a non-monotonic dependence on temperature. While the drag resistivity shows a quadratic T-dependence at sufficiently high T, where drag is always positive, an additional peak develops at low T which can have both a positive or a negative sign depending on the filling-factor difference between the two layers. These results came as a surprise since they were in strong contradiction with preceding theoretical work [39, 40] that predicted strictly positive drag resistivity.

A systematic diagrammatic theory of the Coulomb drag in moderately strong magnetic fields, when the Landau bands are already separated but the Landau level index is still large, was developed in [41]. Depending on the relation between the cyclotron radius R_c and the interlayer distance a several regimes should be distinguished. In [41] we concentrated on the experimentally most relevant ballistic regime, when R_c/a is large. In this case the theoretical analysis of the drag requires special care, in view of a cancellation between leading-order contributions. We also briefly considered the evolution of the drag resistivity in the whole range of R_c/a, from the diffusive to the ultra-ballistic regime.

The theory shows that Coulomb drag in strong magnetic fields is an interplay of two contributions. At high T, the leading contribution is due to breaking of particle-hole symmetry by the curvature of the zero-B electron spectrum. This "normal" contribution to the drag is always positive and increases in a broad temperature range as T^2. At low T, we find that a second, "anomalous", contribution dominates, which arises from the breaking of particle-hole symmetry by the energy dependence of the density of states related to Landau quantization. This contribution is sharply peaked at a temperature $T \sim \Delta$ (where Δ is the LL width) and has an oscillatory sign depending on the density mismatch between the two layers. These results for the T dependence and sign of the drag resistivity $\rho_{xx}^D(T)$ are in good agreement with recent experimental findings [34], and thus explain the remarkable features of Coulomb drag in high LL's observed experimentally. I will close the lecture with a discussion of some prospects for future research.

Bibliography

[1] M. A. Zudov, R. R. Du, J. A. Simmons, and J. L. Reno, Phys. Rev. B **64**, 201311(R) (2001); P. D. Ye, L. W. Engel, D. C. Tsui, J. A. Simmons, J. R. Wendt, G. A. Vawter, and J. L. Reno, Appl. Phys. Lett. **79**, 2193 (2001).

[2] R. G. Mani, J. H. Smet, K. von Klitzing, V. Narayanamurti, W. B. Johnson, and V. Umansky, Nature **420**, 646 (2002).

[3] M. A. Zudov, R. R. Du, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **90**, 046807 (2003).

[4] R. G. Mani, J. H. Smet, K. von Klitzing, V. Narayanamurti, W. B. Johnson, and V. Umansky, Phys. Rev. B **70**, 155310 (2004); Phys. Rev B **69**, 193304 (2004); Phys. Rev. Lett. **92**, 146801 (2004).

[5] C. L. Yang, M. A. Zudov, T. A. Knuuttila, R. R. Du, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **91**, 096803 (2003).

[6] S. I. Dorozhkin, JETP Lett. **77**, 577 (2003).

[7] R. L. Willett, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **93**, 026804 (2004).

[8] I. A. Dmitriev, A. D. Mirlin, and D. G. Polyakov, Phys. Rev. Lett. **91**, 226802 (2003).

[9] I. A. Dmitriev, M. G. Vavilov, I. L. Aleiner, A. D. Mirlin, and D. G. Polyakov, cond-mat/0310668; Physica E **25**, 205 (2004).

[10] I. A. Dmitriev, M. G. Vavilov, I. L. Aleiner, A. D. Mirlin, and D. G. Polyakov, cond-mat/0409590, to appear in Phys. Rev. B (2005).

[11] A. V. Andreev, I. L. Aleiner, and A. J. Millis, Phys. Rev. Lett. **91**, 056803 (2003).

[12] V. I. Ryzhii, Sov. Phys. Solid State **11**, 2078 (1970); V. I. Ryzhii, R. A. Suris, and B. S. Shchamkhalova, Sov. Phys. Semicond. **20**, 1299 (1986).

[13] A. C. Durst, S. Sachdev, N. Read, and S. M. Girvin, Phys. Rev. Lett. **91**, 086803 (2003).
[14] V. Ryzhii and R. Suris, J. Phys. Cond. Matter **15**, 6855 (2003); V. Ryzhii, A. Chaplik, and R. Suris, JETP Lett. **80**, 363 (2004).
[15] M. G. Vavilov and I. L. Aleiner, Phys. Rev. B **69**, 035303 (2004).
[16] J. P. Robinson, M. P. Kennett, N. R. Cooper, and V. I. Fal'ko, Phys. Rev. Lett. **93**, 036804 (2004) and cond-mat/0410064.
[17] J. Dietel, L. Glazman, F. Hekking, and F. von Oppen, Phys. Rev. B **71**, 045329 (2005); C. Joas, J. Dietel, and F. von Oppen, cond-mat/0501394.
[18] M. G. Vavilov, I. A. Dmitriev, I. L. Aleiner, A. D. Mirlin, and D. G. Polyakov, Phys. Rev. B **70**, 161306(R) (2004).
[19] J. Alicea, L. Balents, M. P. A. Fisher, A. Paramekanti, and L. Radzikhovski, cond-mat/0408661.
[20] A. Auerbach, I. Finkler, B. I. Halperin, and A. Yacoby, cond-mat/0501170.
[21] S. I. Dorozhkin, J. H. Smet, V. Umansky, and K. von Klitzing, cond-mat/0409228.
[22] S. A. Studenikin, M. Potemski, P. T. Coleridge, A. Sachrajda, Z. R. Wasilewski, Solid State Comm. **129**, 341 (2004); R. G. Mani, V. Narayanamurti, K. von Klitzing, J. H. Smet, W. B. Johnson, and V. Umansky, Phys. Rev. B **69**, 161306 (2004).
[23] J. Smet, A. Yacobi, private communications.
[24] M. B. Pogrebinskii, Fiz. Techn. Poluprovodn. **11**, 637 (1977) [Sov. Phys. Semicond. **11**, 372 (1977)].
[25] T. J. Gramila, J. P. Eisenstein, A. H. MacDonald, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **66**, 1216 (1991); Phys. Rev. B **47**, 12957 (1993).
[26] U. Sivan, P. M. Solomon, and H. Shtrikman, Phys. Rev. Lett. **68**, 1196 (1992).
[27] N. P. R. Hill, J. T. Nicholls, E. H. Linfield, M. Pepper, D. A. Ritchie, A. R. Hamilton, and G. A. C. Jones, J. Phys.: Condens. Matter **8**, L557 (1996).
[28] H. Rubel, A. Fisher, W. Dietsche, K. von Klitzing, and K. Eberl, Phys. Rev. Lett. **78**, 1763 (1997).
[29] X. G. Feng, S. Zelakiewicz, H. Noh, T. J. Ragucci, and T. J. Gramila, Phys. Rev. Lett. **81**, 3219 (1998).
[30] M. P. Lilly, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **80**, 1714 (1998).
[31] J. G. S. Lok, S. Kraus, M. Pohlt, W. Dietsche, K. von Klitzing, W. Wegscheider, and M. Bichler, Phys. Rev. B **63**, 041305 (2001).
[32] M. Kellogg, I. B. Spielman, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **88**, 126804 (2002); M. Kellogg, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **90**, 246801 (2003); Phys. Rev. Lett. **93**, 036801 (2004);
[33] R. D. Wiersma, J. G. S. Lok, S. Kraus, W. Dietsche, K. von Klitzing, D. Schuh, M. Bichler, H. P. Tranitz, and W. Wegscheider, cond-mat/0407591.
[34] K. Muraki, J. G. S. Lok, S. Kraus, W. Dietsche, K. von Klitzing, D. Schuh, M. Bichler, and W. Wegscheider, Phys. Rev. Lett. **92**, 246801 (2004).
[35] I. Ussishkin and A. Stern, Phys. Rev. B **56**, 4013 (1997).
[36] S. Sakhi, Phys. Rev. B **56**, 4098 (1997).
[37] Y.-B. Kim and A. J. Millis, Physica E (Amsterdam) **4**, 171 (1999).

[38] L. Zheng, and A. H. MacDonald, Phys. Rev. B **48**, 8203 (1993);
A. Kamenev and Y. Oreg, Phys. Rev. B **52**, 7516 (1995);
K. Flensberg, B. Y. Hu, A.-P. Jauho, and J. M. Kinaret, Phys. Rev. B **52**, 14761 (1995).
[39] M. C. Bønsager, K. Flensberg, B. Y. Hu, and A.-P. Jauho, Phys. Rev. Lett. **77**, 1366 (1996); Phys. Rev. B **56**, 10314 (1997).
[40] A. V. Khaetskii and Yu. V. Nazarov, Phys. Rev. B **59**, 7551 (1999).
[41] I. V. Gornyi, A. D. Mirlin, and F. von Oppen, Phys. Rev. B **70**, 245305 (2004).