AIP | Low Temperature Physics

Valentin Peschansky and the puzzles of magnetotransport

V. M. Pudalov

Citation: Low Temperature Physics **37**, 771 (2011); doi: 10.1063/1.3670032
View online: http://dx.doi.org/10.1063/1.3670032
View Table of Contents: http://scitation.aip.org/content/aip/journal/ltp/37/10?ver=pdfcov
Published by the AIP Publishing

Articles you may be interested in

Quadratic temperature dependence of magnetoresistivity of pure tungsten single crystals under static skin effect
Low Temp. Phys. **37**, 852 (2011); 10.1063/1.3670029

Valentin Grigor'evich Peschansky (On his eightieth birthday)
Low Temp. Phys. **37**, 733 (2011); 10.1063/1.3665884

Role of boundary roughness in the electronic transport of Bi nanowires
J. Appl. Phys. **104**, 123704 (2008); 10.1063/1.3041491

Spin relaxation in a germanium nanowire
J. Appl. Phys. **100**, 044303 (2006); 10.1063/1.2230012

Spin-orbit interaction in thin bismuth films
Low Temp. Phys. **31**, 326 (2005); 10.1063/1.1884436

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 35.8.11.3 On: Sat, 30 Jan 2016 01:21:53

Valentin Peschansky and the puzzles of magnetotransport

V. M. Pudalov[a)]

P. N. Lebedev Physical Institute, 53 Leninskii Ave., Moscow 119991, Russia
(Submitted May 12, 2011)
Fiz. Nizk. Temp. **37**, 970–976 (September–October 2011)

Since the 1950's, the Kharkov school of theoretical physics has been a world leader in the theory of metals. In particular, the research by V. G. Peschansky for many years has focused on the relationship between the magnetic field dependence of components of the resistivity and the electron energy spectrum. Peschansky developed an elegant theory of magnetoresistance that took surface scattering of electrons into account. The physics of bulk 3D metals was almost exhausted by the end of 1970's and Peschansky extended his research to low-dimensional electron systems. Throughout his scientific life, V. G. Peschansky has advocated the idea that magnetoresistance is a powerful tool for exploring the rich physics of electron systems. The many experimental and theoretical studies of magnetoresistance behavior in various systems, from simple to the most complex, have, by now, confirmed the fruitfulness of this idea.
© *2011 American Institute of Physics*. [doi: 10.1063/1.3670032]

I. INTRODUCTION

As I grew older, I occasionally feel obliged to write memoirs in order to reward distinguished scientists whom I have met. I appreciate them for sharing with students an overview of the architecture of science, for object lessons in creativity and, quite importantly, for lessons in respect toward students. This latter ingredient creates an especially favorable and friendly atmosphere in physical research. In particular, I greatly appreciate Professor Valentin Peschansky, not only for his remarkable contributions to the theory of metals, but also for his perpetual benevolence. Physics is made by people, and without knowing their personalities, the physics would be colorless, like boring black-and-white textbooks. Young scientists must know the biographies of outstanding personalities because major scientific achievements often appear to be linked with events in their lives.

I met Valentin Peschansky for the first time at the Kapitza Institute for Physical Problems (named after Kapitza after his death), in Moscow, where I was a graduate student of Professor M. S. Khaikin. The period from the 1950's to the 1970's was a time of triumph for metal physics. Experimentalists succeeded in purifying materials and growing state-of-the-art single crystals of almost all metals. There was certainly a sort of competition among them to achieve record values of the resistance ratio $R_{300}/R_{4.2}$ or the electron mean free path. The high quality of these samples inspired respect for the published data.

The research in experimental laboratories at the Kapitza Institute was in a full swing: Yu. V. Sharvin did beautiful experiments on electron focusing with point contacts. M. S. Khaikin with his young co-workers discovered numerous effects in microwave resonant electron transport in Bi, Sn, In, Pb, and W, including size effects related to the cyclotron motion of electrons. N. E. Alexeevskii and collaborators studied magnetoresistance anisotropies in Be, V, and Nb. N. V. Zavaritskii studied phonon drag and acousto-magnetic effects in Sn and Al. The next generation of experimentalists, V. F. Gantmakher, V. S. Edelman, Yu. P. Gaidukov and others, grew up in these parent laboratories and started their own research on metal physics.

The period from the 50s to the 70s was also a golden age for the Kharkov school of theoretical physics. We must recall that Mark Ya. Azbel, Moissei I. Kaganov, Arnold M. Kosevich, Ilya M. Lifshitz, and Valentin G. Peschansky were highly creative, working at the same time and the same place. This short list of distinguished theorists would be an honor to a university anywhere in the world. The Kharkov theorists were welcome at the Kapitza Institute; they often came to give talks at the famous Kapitza seminars and visited the experimental laboratories. Their activity in the 1950's and 1960's was focused on studying the relationship between observable features of electron properties in magnetic fields and electron energy spectra.[1,2] The nearly-free-electron approach had just emerged and the Fermi surfaces of the majority of metals remained to be explored.

Needless to say, there was a plethora of novel experimental data at the Kapitza Institute for the theorists to explain; in their turn, theorists were eager to have their predictions tested experimentally. The mutual attraction of Moscow experimentalists and Kharkov theorists has made the Kapitza Institute a center for meetings and discussions, particularly concerning the electronic properties of normal metals. After Landau's death, Kapitza wanted to strengthen the theory department of his Institute, and, soon after, Ilya Lifshitz (in 1969) and Moissei Kaganov (in 1970) joined the Kapitza Institute. Even earlier, in 1966, Emmanuil Rashba, also an originally Ukrainian theorist, joined the Landau Institute for Theoretical Physics. Peschansky, Azbel and Kaner kept working and lecturing in Kharkov, but I saw them very often in Moscow at the IPP.

Valentin Peschansky stood out among the Ukrainian theorists for his friendly attitude and benevolence toward other people. He spoke with a soft voice and never put his opponent in an awkward situation. My own graduate research was also related to the electron energy spectrum of metals, so that when the time came to defend my PhD thesis, my

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 35.8.11.3 On: Sat, 30 Jan 2016 01:21:53

scientific supervisor M. S. Khaikin suggested Peschansky as official opponent. As usual, he kindly agreed. This was indeed a good choice and has left me with many pleasant memories.

As the result of experimental efforts in crystal growth, the quality of metal samples reached a level where the electron mean free path at low temperatures became comparable to the sample size. It was found unexpectedly that electron scattering at the surface of a sample is an elastic, almost mirror-reflection process. As an example, M. S. Khaikin observed quantum transport of electrons skipping at the surface; Yu. V. Sharvin and V. S. Tsoi studied focusing of the electrons undergoing mirror reflection at surfaces; and, V. S. Edel'man, V. F. Gantmakher, and Yu. P. Gaidukov also discovered various size effects owing to mirror reflection of electrons at the surfaces of samples.

Also at the Institute for Physical Problems, Yu. P. Gaidukov studied magnetoresistance anisotropy and, using the theory of Peschansky *et al*., reconstructed the Fermi surface topology.[3] When Gaidukov moved to the Low-Temperature Department of Moscow State University, he extended his research from bulk to whisker crystals of metals. These tiny specimens, with typical dimensions of $1 \times 10 \times 100$ μm, were extraordinary. They could easily be charged electrostatically and bent into a spiral with no loss of quality and with no residual defects. Gaidukov and collaborators succeeded in growing whisker crystals of Bi, Sb, Zn, and Cd from the vapor phase. (He even found whisker crystals of tin which grew on his old tin-lined skates.)

Besides their extreme mechanical properties, whisker crystals were the ideal object for studies of size effects owing to their small thickness and mirror-flat natural surfaces. Experimental studies of magnetoresistance in Gaidukov's laboratory were very fruitful. To handle the tiny objects under a microscope one had to have perfect vision and strong nerves, because moving the crystals, fixing them, and making tiny contacts took many hours of delicate work using eye-surgery tools. In Gaidukov's laboratory this research was performed by young female PhD and graduate students. One of the Gaidukov's PhD students, Elena Goliamina, became my wife, and for this reason I also became indirectly involved in the "whisker business," have read Peschansky's papers, and have even done some research on tiny whisker crystals grown by Gaidukov.[4]

Semimetals such as Bi and Sb were good test objects for experimentalists because of their low melting point, high purity, and extremely small and almost cylindrical electronic pockets at the Fermi surface. The latter led to huge amplitudes of quantum oscillatory effects, resonant effects, etc.

On the theoretical side, Valentin Peschansky and his collaborators also actively studied the kinetic properties of semimetals.[5,6] The most elegant effect, elaborated theoretically by Peschansky and collaborators was the "static skin effect".[5,7,8] It appeared that the contribution of ordinary "bulk" electrons (which are not scattered by the surface) to the conductivity could become much smaller than the contribution of electrons mirror-reflected by a sample surface. In other words, for a given sample thickness d and a given mean free path l, with $d > l$, one can apply a strong magnetic field, such that the current will be concentrated within a thin layer near the surface; the thickness of this layer is on the order of the cyclotron radius, r. This concept radically changed our understanding of conduction in thin samples and led to such interesting observable effects as a novel type of magnetoresistance, magnetoresistance anisotropy, and oscillation-dependent nonuniform conductivity in the bulk. The "static skin effect," however, was expected to be very sensitive to the existence of a small diffusivity in the electron scattering at the surface, a drawback that made experimental verification of the theoretical prediction rather difficult.

Experiments at the Moscow State University were motivated in part by the predictions of the "static skin effect" theory. Thus, a paper by Peschansky *et al*.[5] became one of the "handbooks" in Yurii Gaidukov's laboratory. Over the period from 1973 to 1978, Gaidukov and collaborators studied the size effect in the magnetoresistance of Cd, Sb, and Zn whisker crystals.[9–11] Some features of the observed magnetoresistance agreed qualitatively with Peschansky's theory. In particular, the magnetoresistance data scaled for samples with different thicknesses, and in weak magnetic fields the "parallel" magnetoresistance ($B \| I$) exhibited a maximum. However, quantitatively, the maximum didn't agree with the theory, for it was observed at fields $r(B) \propto d$, while in the theory it should obey $r(B) \propto \sqrt{d}$. The disagreement with the theory was sample dependent: it was minor for Sb, but more substantial for Zn and Cd. The experimental results thus indicated an insufficiently smooth surface and a lack of ideal mirror reflection at Zn and Cd surfaces.

Despite a lack of quantitative agreement with theory, the experimental data have revealed unambiguously the striking difference between the magnetoresistance for thin samples ($d \sim r$) and that for thick 3D samples ($d \gg r$). The most direct confirmation of the theory has been obtained in experiments with Sb. Whereas bulk Sb samples showed almost isotropic magnetoresistance, thin plate-like whiskers of Sb have an anisotropic magnetoresistance that is a factor of 10 higher. This clearly confirmed the contribution of surface scattering to electron transport in thin 3D samples, which was the central point of the Peschansky theory.

As often occurs in experiments, besides the desired monotonic magnetoresistance, Gaidukov and Goliamina unexpectedly discovered a novel oscillatory size effect: cutoff of Shubnikov-de Haas oscillations in magnetic fields[11,12] so low that the cyclotron orbit becomes larger than the whisker thickness. Remarkably, even before this, Peschansky had written a theoretical paper[13] on the Shubnikov-de Haas effect in thin conductors, where he predicted a cutoff of the oscillations, but did not consider the case of mirror reflections. The experiments were done with Sb, a material in which electron scattering at the surface is of the mirror type, and the monotonic magnetoresistance of which yields the best agreement with the "static skin effect" theory. The experiments, however, revealed more rich physics that had not been predicted by the theory: in magnetic fields lower than the cyclotron orbit cut-off, new series of oscillations emerged owing to quantization in magnetic fields of truncated electron orbits with mirror reflected trajectories.

Soon afterward, Elena Goliamina had her PhD thesis ready and Peschansky, as the major expert in the field, was invited to act as opponent. After the official defense he was very surprised to learn that he had played the same role twice for one family.

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 35.8.11.3 On: Sat, 30 Jan 2016 01:21:53

II. MAGNETORESISTANCE IN LOW DIMENSIONAL SYSTEMS

The golden age of research on the electronic properties of three-dimensional metals was over by the end of the 1970's. In 1979, Peschansky published comprehensive reviews on kinetic size effects in metals.[6,7] Five years later, he and several other Russian "metal physicists," including the author, wrote a book[8,14] surveying their earlier research on the physics of 3D metals. These and many other reviews summarize the results of 20-years of active research on the physics of metals. The bulk metals appeared to be rather simple and their physics was quickly exhausted. Besides knowledge of the Fermi surfaces for the majority of metals,[15] the net result of these studies was the development of a number of milestone concepts, including approaches involving nearly-free-electrons, strong and weak coupling, the Fermi liquid paradigm, and the Fermi surface. Another key result was the development of a number of powerful experimental and theoretical tools for studying electronic systems.

Right at this time the physics of low-dimensional systems started to emerge worldwide and the seeds of the 3D metal physics fell on fertile soil. With the development of semiconductor technology and the advent of high quality low-dimensional systems, many "metal physicists" in the 1970's and 1980's switched to the physics of "low-dimensions." Some of them started studying two-dimensional (2D) electron systems at semiconductor interfaces, and others, layered (1D and 2D) crystals.

As mentioned above, the twenty years of research on the electronic properties of 3D metals resulted in a number of well-developed and powerful concepts and tools. These include, the Shubnikov-de Haas and de Haas-van Alfven effects, cyclotron resonance, and magnetoresistance. In bulk metals, and even in thin conductors, magnetoresistance was used as a probe to test electron orbital motion. The spin degree of electron freedom was considered almost irrelevant. Much later, researchers encountered the effects of electron-electron (exchange) interactions governed by physics of spin. Now, it is well recognized that magnetoresistance can also be used to probe electron- electron interactions, i.e., the physics of spin. With this interesting change of viewpoint, the physicists came back to Peschansky's original idea that magnetoresistance can be a key tool for probing unknown electron systems and for understanding their microscopic architecture.

A. Magnetoresistance and cyclotron resonance in organic low-dimensional systems

Searching for a new field of research, the author also started studying low-dimensional systems: in 1980, 2D electron systems in semiconductors, and in 1998, quasi-one-dimensional organic conductors. The latter objects, in particular, compounds of the $(TMTSF)_2X$ family, are very interesting: at low temperatures, their physics is related to a spin density wave state[16] in low or zero magnetic fields, whereas at elevated pressure the spin density wave state is suppressed and $(TMTSF)_2PF_6$ behaves as a quasi-1D layered metal at finite temperatures.

$(TMTSF)_2PF_6$ has a quasi-one-dimensional electron system confined in a three dimensional host lattice. The electron system is, therefore, highly sensitive to external parameters and, depending on the pressure, magnetic field, temperature, etc., exhibits properties characteristic of 1D, 2D, and 3D systems.[16] The unique property of $(TMTSF)_2PF_6$ is that its *P-B-T* phase diagram contains numerous phases such as a spin density wave (SDW) state, a field induced spin density wave (FISDW) state, a quantum Hall effect, and a superconducting state (at temperatures below ≈ 1 K). This is because the paramagnetic metallic state of the quasi-1D electronic system is unstable and, because of electron-electron interactions, as the temperature is reduced, it undergoes a transition to the SDW state, which is an antiferromagnetic (AF) spin-ordered state (an insulator). Increasing the pressure destroys the SDW order and makes the paramagnetic metallic state more favorable.[16] Again, as in bulk 3D metals, the magnetoresistance appears to be a most powerful experimental tool for studying the origins of the various phases and phase transitions in this quasi-1D material.

It is a coincidence that Valentin Peschansky also switched from 3D metals to quasi-two dimensional conductors in his theoretical studies.[17–19] In particular, in Ref. 19, he studied cyclotron resonances in layered materials. At almost the same time, we were seeking the cyclotron resonance, but in quasi-one-dimensional $(TMTSF)_2PF_6$. At first sight, the idea of cyclotron motion in 1-dimensional systems sounds odd. However, because of the transfer integrals are finite, the system under study is quasi-one-dimensional. In the metallic state it has an open Fermi surface; a magnetic field (below the onset of the field-induced spin-density wave state, FISDW (Ref. 16)) applied perpendicular to the conducting plane causes one-dimensionalization of the electron motion. Nevertheless, the finite transfer integrals (perpendicular to the most conductive direction) lead to a periodic motion of the electrons in the magnetic field. This motion was detected in our experiments by observing the cyclotron resonance in the mm-wave range.[20] The measured cyclotron mass exceeded the theoretical prediction; the discrepancy motivated theorists to revise the existing "standard" models of the field-induced spin density wave state.[16]

B. Magnetoresistance in two-dimensional systems

Historically, the physics of 2D systems emerged in 1966 when Allan Fowler, Frank Fang *et al*., observed Shubnikov-de Haas oscillations in a silicon MOSFET (metal- oxide-semiconductor field effect transistor).[21] By tilting the sample in a magnetic field they found the period of quantum oscillations to be governed solely by the perpendicular field component, and, thereby, proved that these electron systems are two dimensional. At first, the theoretical ideas that had been developed earlier for 3D metals were applied to 2D systems and they seemed to work, at least to the first approximation. For about twenty years the 2D physical community used the conventional Lifshitz-Kosevich formulas for 3D systems with minor and obvious modifications for a 2D density of states. V. G. Peschansky also contributed to this research and published a paper on magnetotransport effects in organic layered conductors in 2002.[17]

In the 1980s, experiments with high perpendicular magnetic fields revealed huge effects owing to electron-electron interactions, which were negligibly small in 3D metals and had, therefore, been ignored previously. The dimensionless

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 35.8.11.3 On: Sat, 30 Jan 2016 01:21:53

ratio r_s of the potential Coulomb interaction energy to the kinetic Fermi energy is commonly used to parametrize the electron-electron interaction. In 2D systems, r_s can easily be as high as $\sim$10 on decreasing the electron density in high quality samples. The presence of electron-electron interactions makes the 2D system much more complex, and its physics much more profound. Over only 30 years of research this has led to the award of three Nobel prizes for the discovery of unexpected phenomena in 2D electron systems: integer and fractional quantum Hall effects, and the physics of graphene. Surely, more discoveries are still waiting to be so recognized.

The most familiar interaction effect is the negative compressibility, κ, of the electron system, where κ changes sign at $r_s \approx 1.4$. This effect was predicted theoretically by A. L. Efros,[22] observed in the 2D system of an Si-MOSFET,[23] and later on, by J. Eisenstein in a double-layer GaAs/AlGaAs heterostructure.[24] The physics of this effect is straightforward: as one adds new electrons to the 2D interacting system, the gain in electron potential (exchange interaction) energy overpowers the growth in kinetic (Fermi) energy. The total system (2D electrons + lattice + gate) remains neutral because of the presence of the metallic gate, or owing to dopants embedded near the interface. In this way, the classical electrostatic energy maintains the stability of the system, in contrast to the black holes in cosmology which also have negative compressibility.

It turns out that the interaction effects are greatly enhanced in a perpendicular field; this effect was initially described in terms of an interaction between resolved Landau levels. Effects such as quantum oscillations of the Landau level splitting, enhanced and oscillatory spin splitting, and Landau level broadening are the best known consequences of interaction effects in perpendicular fields.

III. MAGNETORESISTANCE IN THE IN-PLANE FIELD

The more subtle physics of inter-electron interactions can be revealed in magnetic fields parallel to the 2D plane. In this geometry, the field does not couple to the electrons' motion but only to their spins. For a noninteracting ideal 2D system, the in-plane field does not create magnetoresistance. When the thickness of the 2D layer becomes comparable to the magnetic length l_H, a diamagnetic shift of the energy levels must be taken into account. Here we ignore these strong field and finite thickness effects and focus only on the magnetoresistance induced by electron-electron interactions.

Applying an in-plane magnetic field to a strongly interacting and clean 2D electron system was found to cause a dramatic increase in the resistance, by more than two orders of magnitude, as seen in Fig. 1.[25,26] At high fields, the resistance saturates. This kind of behavior was found in all high-mobility 2D samples with strongly interacting carrier systems. Thus, the magnetic field simply destroys the metallic state. At fields higher than a density dependent value B^*, the magnetoresistance saturates; the saturation field corresponds approximately to full spin polarization of the 2D electron system, $g\mu_B B^* = 2E_F$.

This remarkable magnetoresistance effect was observed in 1997; it took about 5 years to understand the interaction-induced magnetoresistance in the $B_{\parallel}$ field. In 2002, Zala,

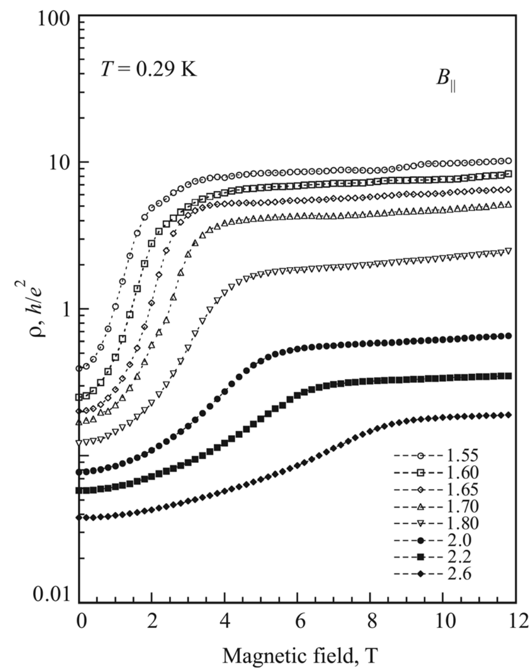

FIG. 1. Resistivity as a function of parallel magnetic field for $T = 0.29$ K in an Si-MOSFET sample. The different symbols correspond to gate voltages ranging from 1.55 to 2.6 V, or, equivalently, to densities from 1.01 to $2.17 \cdot 10^{11}$ cm^{-2}. Taken from Ref. 26.

Narozhny, and Aleiner (ZNA) (Ref. 27) developed a theory that took into account all the interaction contributions to the conductivity, including exchange interactions. This theory offers a unified approach to both the ballistic ($T\tau \gg 1$) and diffusive ($T\tau \ll 1$) interaction regimes by considering quantum interference between electron waves scattered off a short-range random potential "dressed" by Friedel oscillations of the electron density. The theory was extended to the case of a long-range scattering potential by Gornyi and Mirlin (GM).[28] These theories[27,28] naturally incorporate the Altshuler-Aronov (AA) results for the interaction corrections to the conductivity in the diffusive regime.[29]

These theories[27,28] predict that the magnitude and sign of the interaction correction to the conductivity, $\Delta\sigma(T,B)$, is determined by the Fermi-liquid parameter F_0^{σ}, so that F_0^{σ} can be derived from measurements of $\Delta\sigma(T,B)$.[30] This parameter was also found independently by measuring Shubnikov-de Haas (18) oscillations in weak magnetic fields tilted relative to the plane of a 2D structure.[31,32]

A. Modern ideas regarding magnetoresistance in interacting 2D systems

An in-plane magnetic field, being coupled mostly to electron spins, provides a useful tool for exploring interaction effects in the low-temperature conductivity of 2D systems.[25,26] When the Zeeman energy $E_Z = g_b \mu_B B$ ($g_b = 2$ is the bare g-factor, μ_B is the Bohr magneton) is much greater than T, the number of triplet terms contributing to the interaction correction $\Delta\sigma_{ee}(T)$ is reduced from 15 to 7. A similar reduction in the triplet terms is expected for a valley splitting $\Delta_V > T$. These two effects have been included in a theory for the interaction corrections.[27,33] In the presence of a magnetic field and/or valley splitting, the interaction correction to the conductivity can be expressed as follows:[33]

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 35.8.11.3 On: Sat, 30 Jan 2016 01:21:53

$$\Delta\sigma_{ee}(T,\tau,F_0^\sigma,B_\parallel,\Delta_V) = \Delta\sigma_{ee}(T) + 2\Delta\sigma^Z(E_Z,T) + 2\Delta\sigma^Z(\Delta_V,T) + \Delta\sigma^Z(E_Z+\Delta_V,T) + \Delta\sigma^Z(E_Z-\Delta_V,T), \qquad (1)$$

where $\Delta\sigma_{ee}(T)$ is given by

$$\Delta\sigma_{ee}(T) = \delta\sigma_C(T) + 15\delta\sigma_T(T). \qquad (2)$$

Here $\delta\sigma_C$ is the so-called "charge" contribution, which combines the Fock correction and the singlet part of the Hartree correction, and $\delta\sigma_T$ is the "triplet" contribution due to the triplet part of the Hartree term. The valley index can be treated as a pseudo-spin in multi-valley systems, and the valley degeneracy increases the number of triplet terms through spin exchange processes between electrons in different valleys. For a (100) Si-MOSFET system with two degenerate valleys, the total number of interaction channels is $4\times4=16$, with 1 singlet and 15 triplet terms (for comparison, there are 1 singlet and 3 triplet terms for a single-valley system).

All the terms $\Delta\sigma^Z(Z,T)$ are of the form

$$\Delta\sigma^Z(Z,T) \equiv \sigma(Z,T) - \sigma(0,T) = \delta\sigma_b(Z) + \delta\sigma_d(Z) = \frac{1}{\pi}\left\{\left[\frac{2F_0^\sigma}{1+F_0^\sigma}(T\tau)K_b\left(\frac{Z}{2T},F_0^\sigma\right)\right] + \left[K_d\left(\frac{Z}{2\pi T},F_0^\sigma\right)\right]\right\} \qquad (3)$$

if the relevant energies $Z \ll E_F$ (Z stands for E_Z, Δ_V, and the combinations $E_Z \pm \Delta_V$). Explicit expressions for the functions K_b and K_d are given in Ref. 27. In particular, Eq. (3) describes the interaction-driven magnetoconductivity in magnetic fields much weaker than the field corresponding to full spin polarization of a system. In Eq. (3), we omit the crossover function which is numerically small and does not change $\Delta\sigma(Z,T)$ by more than one percent outside the ballistic-diffusive crossover region.

B. Magnetoconductivity. Comparison of experiment and theory

Since the theory calculates corrections to the conductivity rather than to the resistivity, here we switch to the magnetoconductivity (MC). To test the theoretical predictions regarding the magnetoconductivity induced by in-plane magnetic fields, the $\sigma(B_\parallel)$ dependences have been measured at fixed temperatures.[34] The MC of sample Si6-14 for fields of -4.5 T $< B_\parallel <$ 4.5 T is plotted in Fig. 2 for different densities and temperatures.

The theoretical $\Delta\sigma(B_\parallel)$ given by Eqs. (1) and (3) are plotted in Fig. 2 as solid curves; these fit the observed MC very well for magnetic fields that are not too strong, i.e., such that $g_b\mu_B B_\parallel < 0.2E_F$. The only adjustable parameter was $F_0^\sigma(n)$ determined for each density by fitting the MC at high temperatures (≈0.7 K), where the effects of valley splitting or intervalley scattering on $\Delta\sigma_{ee}(T, B)$ can be neglected. The fitted values of $F_0^\sigma(n)$ agreed with previous independent measurements based on beating of Shubnikov-de Haas oscillations in tilted magnetic fields.[32]

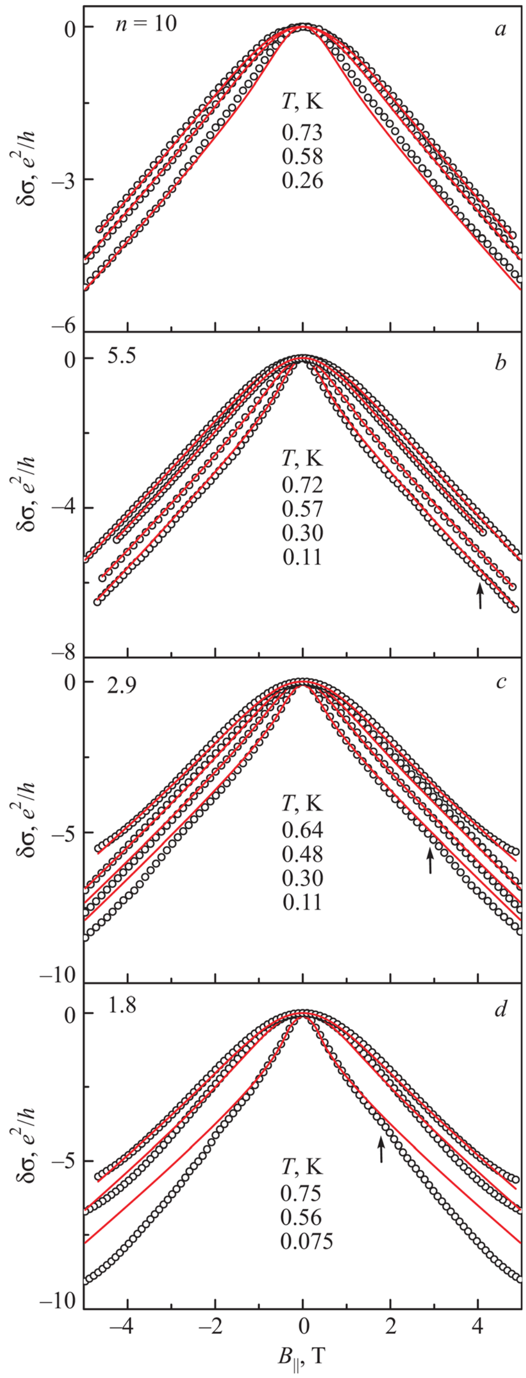

FIG. 2. Magnetoconductance of an Si-MOSFET sample at different electron densities and temperatures. Experimental data are indicated by dots and the theoretical dependences according to Eqs. (1)-(3), by solid curves. The value of F_0^σ is the only fitting parameter in the comparison with the theory (Ref. 27); the corresponding values of $F_0{}^\sigma$ are given in Fig. 5 of Ref. 34. The arrows indicate the fields corresponding to the condition $g\mu_B B_\parallel/2E_F = 0.1$. The values of n are shown in units of 10^{11} cm^{-2}. Taken from Ref. 34.

As $B_\parallel$ is increased and/or the density decreases, the data start to deviate from the theoretical curves (see Fig. 2(d)); this deviation can be attributed to failure of the condition $g_b\mu_B B \ll E_F$ for applicability of Eqs. (1) and (3).

IV. CONCLUSION

Experiments show that the low-T behavior of the magnetoconductivity of interacting 2D electron systems in Si MOSFETs is well described by the theory of interaction effects in systems with short-range disorder.[27] Over a wide

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 35.8.11.3 On: Sat, 30 Jan 2016 01:21:53

range of intermediate temperatures ($g_b\mu_B B < T \ll E_F$), the interaction effects are strongly enhanced in Si MOSFETs owing to the presence of two valleys in the electron spectrum. This factor, in combination with the interaction-driven renormalization of the Fermi-liquid parameter F_0^σ, makes σ increase with decreasing T. The F_0^σ values obtained by fitting the experimental data to the theory[27] agree well with F_0^σ found by analyzing the oscillations of these samples. This example confirms the continuing validity and productivity of Peschansky's central concept of magnetoresistance as a powerful tool for exploring the complex physics of electron systems.

[a]Email: pudalov@sci.lebedev.ru

[1] I. M. Lifshitz, M. Ya. Azbel, and M. I. Kaganov, *Electron Theory of Metals* (Nauka, Moscow, 1971).
[2] I. M. Lifshitz and V. G. Peschansky, Zh. Eksp. Teor. Fiz. **35**, 1251 (1958).
[3] N. E. Alekseevskii, Yu. P. Gaidukov, I. M. Lifshitz, and V. G. Peschansky, Zh. Eksp. Teor. Fiz. **39**, 1201 (1960).
[4] V. M. Pudalov and S. G. Semenchinskii, J. Phys. **39**, 1199 (1978); Prib. Techn. Exp. **4**, 203 (1978).
[5] M. Ya. Azbel and V. G. Peschansky, Zh. Eksp. Teor. Fiz. **55**, 1980 (1968).
[6] V. G. Peschansky, Sov. Sci. Phys. **16**, 1 (1992).
[7] O. V. Kirichenko, V. G. Peschansky, and S. N. Savel'eva, Zh. Eksp. Teor. Fiz. **77**, 2045 (1979) [JETP **50**(5) (1977)].
[8] V. G. Peschansky, "Static skin-effect," in *Conduction Electrons (Electrony provodimosti)* (Nauka, Moscow, 1985).
[9] Yu. P. Gaidukov and N. P. Danilova, Zh. Eksp. Teor. Fiz. **64**, 921 (1973); **65**, 1541 (1973).
[10] Yu. P. Gaidukov, E. M. Goliamina, and N. P. Danilova, Pis'ma Zh. Eksp. Teor. Fiz. **22**, 231 (1975).
[11] Yu. P. Gaidukov and E. M. Goliamina, Pis'ma Zh. Eksp. Teor. Fiz. **23**, 336 (1978).
[12] Yu. P. Gaidukov and E. M. Goliamina, Zh. Eksp. Teor. Fiz. **74**, 1426 (1978).
[13] V. G. Peschansky and V. V. Sinolitskii, JETP Lett. **16** (1972) [Pis'ma v Zh. Eksp. Teor. Fiz. **16**, 484 (1972)].
[14] V. M. Pudalov, "Dilatometric studies of electron spectrum in tin," in *Conduction Electrons* (*Electronu provodimosti*) (Nauka, Moscow, 1985), p. 254.
[15] Yu. P. Gaidukov, Usp. Fiz. Nauk **100**, 449 (1970).
[16] A. V. Kornilov and V. M. Pudalov, "Magnetic field-induced spin-density-wave and spin-density-wave phases in (TMTSF)2PF6, in *The Physics of Organic Superconductors and Conductors*, edited by A. G. Lebed (Springer-Verlag, Berlin-Heidelberg, 2008), p. 487.
[17] V. G. Peschansky, Zh. Eksp. Teor. Fiz. **121**, 1204 (2002).
[18] V. G. Peschansky, Phys. Rep. (Amsterdam) **288**, 305 (1997).
[19] V. G. Peschansky, Zh. Eksp. Teor. Fiz. **118**, 485 (2000).
[20] A. V. Kornilov, P. J. M. van Bentum, J. S. Brooks, J. S. Qualls, J. A. A. Perenboom, and V. M. Pudalov, Synth. Met. **103**, 2246 (1999).
[21] A. B. Fowler, F. F. Fang, W. E. Howard, and P. J. Stiles, Phys. Rev. Lett. **16**, 901 (1966).
[22] A. L. Efros, Solide State Commun. **65**, 1281 (1988).
[23] S. V. Kravchenko, V. M. Pudalov, and S. G. Semenchinsky, Phys. Lett. A **141**, 71 (1989).
[24] J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **68**, 674 (1992).
[25] D. Simonian, S. V. Kravchenko, M. P. Sarachik, and V. M. Pudalov, Phys. Rev. Lett. **79**, 2304 (1997).
[26] V. M. Pudalov, G. Brunthaler, A. Prinz, and G. Bauer, Pis'ma Zh. Eksp. Teor. Fiz. **65**, 887 (1997) [JETP Lett. **65**, 932 (1997)].
[27] G. Zala, B. N. Narozhny, and I. L. Aleiner, Phys. Rev. B **64**, 214204 (2001); **65**, 020201 (2002).
[28] I. V. Gornyi and A. D. Mirlin, Phys. Rev. B **69**, 045313 (2004).
[29] B. L. Altshuler, A. G. Aronov, and P. A. Lee, Phys. Rev. Lett. **44**, 1288 (1980); B. L. Altshuler and A. G. Aronov, in *Electron-Electron Interactions in Disordered Systems*, edited by A. L. Efros and M. Pollak (North-Holland, Amsterdam, 1985).
[30] A. A. Shashkin, S. V. Kravchenko, V. T. Dolgopolov, and T. M. Klapwijk, Phys. Rev. B **66**, 073303 (2002).
[31] T. Okamoto, K. Hosoya, S. Kawaji, and A. Yagi, Phys. Rev. Lett. **82**, 3875 (1999).
[32] V. M. Pudalov, M. E. Gershenson, H. Kojima, N. Butch, E. M. Dizhur, G. Brunthaler, A. Prinz, and G. Bauer, Phys. Rev. Lett. **88**, 196404 (2002).
[33] S. A. Vitkalov, K. James, B. N. Narozhny, M. P. Sarachik, and T. M. Klapwijk, Phys. Rev. B **67**, 113310 (2003).
[34] N. N. Klimov, D. A. Knyazev, O. E. Omel'yanovskii, V. M. Pudalov, H. Kojima, and M. E. Gershenson, Phys. Rev. B **78**, 195308 (2008).

This article was published in English in the original Russian journal. Reproduced here with stylistic changes by AIP.

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 35.8.11.3 On: Sat, 30 Jan 2016 01:21:53