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Does a magnetic field suppress the Coulomb gap?

B. Sandow[1], **K. Gloos**[2,3], **R. Rentzsch**[1], **A. N. Ionov**[4], **and W. Schirmacher**[5]

[1]Inst. Experimentalphysik, Freie Universität Berlin, D-14195 Berlin, Germany
[2]Inst. Festkörperphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany
[3]Max-Planck-Institut für chemische Physik fester Stoffe, D-01187 Dresden, Germany
[4]A. F. Ioffe Physico-Technical Institute, St. Petersburg, Russia
[5]Physik-Dept. E13, Technische Universität München, D-85747 Garching, Germany
sandow@physik.fu-berlin.de

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Abstract. We used electron-tunnelling spectroscopy to investigate the Coulomb correlation in n - type Germanium. The dopant concentration was smaller than the critical concentration for the metal-insulator (Anderson) transition. The tunnelling conductance, which probes the electronic density of states, was found to depend strongly on both voltage and temperature. At low temperatures it shows a conductance minimum at the Fermi energy as expected for the Coulomb correlation gap. Applying a magnetic field up to $B = 4\,\mathrm{T}$ at $T = 0.1\,\mathrm{K}$ reduces the magnitude of the tunneling conductance, but does not significantly change the shape of the spectra. At higher fields, the conductance minimum disappears, suggesting a suppression of the Coulomb gap. This could be due to the field-induced confinement of the electron wave functions, that strongly reduces the overlap between the localized electron states.

Keywords: disordered solids, metal-insulator transition, tunnelling spectroscopy
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1 Introduction

In disordered insulating systems like weakly doped semiconductors the low-temperature transport properties are dominated by the density of states (DOS) of the localized electrons. Due to the long-range Coulomb interaction between these localized electrons, the Efros-Shklovskii theory predicts a particularity – the Coulomb gap – in the single-particle density of states $N(E)$ [1].

The exact energy dependence of the DOS inside the Coulomb gap has not yet been settled. Usually, at the Fermi energy E_F the DOS is expected to follow a power law $N(E, T = 0) \propto (E - E_\mathrm{F})^{D-1}$, depending on the spatial dimension D [1, 2, 3, 4]. Other theories [5] predict an exponential dependence $N(E, T = 0) \propto \exp\{(E - E_\mathrm{F})^{D-1}\}$. For three-dimensional (3D) systems at finite temperature and with energy disorder, analytical and numerical results yield a power law $N(E_F, T) \propto T^\alpha$, with exponents α of about 2 [1, 6], 2.6 ± 0.2 [7], 2.7 ± 0.1 [8], and 1 [9]. The exponent α may also depend on the amount of structural disorder.

In the variable-range-hopping (VRH) regime the electrical resistance varies as $R = R_0 \exp\sqrt{T_0/T}$ when the Coulomb gap $N(E) \propto (E - E_\mathrm{F})^2$. Here $k_\mathrm{B}T_0 = C_2 e^2/4\pi\epsilon\epsilon_0 a$, a is the effective Bohr radius of the donors, ϵ the dielectric constant, e the electron charge, and $C_2 = 2.8$ [1]. Indirectly, this serves to identify the energy-dependence of the DOS.

In weak magnetic fields the hopping distance (at constant temperature), measured in units of the average distance between the impurities remains constant. This holds as long as the magnetic length $\lambda = \sqrt{\hbar/eB} \gg a$. At small fields the hopping resistance $\ln\{R(B)/R(0)\} \propto (B/B_0)^2$ increases exponentially with B because a magnetic field confines the wave function [4]. The parameter $B_0 = C_3 \left(\hbar/ea^2\right)^2 (T/T_0)^{3/2}$ with $C_3 = 288$. Above a characteristic field $B_C = n^{1/3}\hbar/ea$ the resistivity of weakly-doped semiconductors $\ln\{R(B)/R(0)\} \propto B \ln\sqrt{B/B_0}$. As discussed in Ref. [4], the field-dependence of the resistivity reflects the tunnelling factor of the hopping rate being exponentially reduced by the confinement of the wavefunctions. Using a semiclassical method, Ioselevich [10] derived an analytical formula for the tunnelling probability to interpolate between the high- and low-field limit.

So far the effect of the magnetic field on the Coulomb gap itself has been neglected. Here we report on tunnelling experiments on n-type Ge, that seem to indicate a strong suppression of the Coulomb gap in large fields.

2 Experimental

Our samples are neutron-transmutation doped [11] n-type Ge. Its shallow As donors are produced by a nuclear reaction with thermal neutrons ${}^{74}\mathrm{Ge}\,(n,\gamma)\,{}^{75}\mathrm{Ge} \to {}^{75}\mathrm{As}$. To obtain a small degree of compensation K, the original Ge crystal had been enriched by isotopic ^{74}Ge. The ratio between the concentration of acceptors and donors is $K = n_a/n_d = 12\,\%$ and the donor concentration is $n_d = 3.12 \cdot 10^{17}\,\mathrm{cm}^{-3}$. This is close to the disorder-driven metal-insulator (Anderson) transition [12] at the critical impurity concentration $3.4 \cdot 10^{17}\,\mathrm{cm}^{-3}$ of germanium.

We have measured the temperature dependence of the bulk resistance from 0.1 to 1 K and at $B = 0 - 3$ Tesla using the standard four-probe DC method with the magnetic field parallel to current flow I. The tunnelling experiments on mechanically-controllable break junctions were performed at $T = 0.1$ K in magnetic fields up to 8 Tesla using the setup described in Ref. [13]. The samples were glued electrically isolated onto a flexible bending beam. They were broken at low temperatures to avoid oxidation of the interface. The contact size could be adjusted by a micrometer screw and a piezo tube. The current-voltage reistance of the high-resistance junctions was recorded in the standard two-terminal mode. The bulk part of the samples contributed less than about 5 per cent to the total resistance. A magnetic field could be applied perpendicular to current flow. However, Ge is a rather isotropic compound, and we do not expect any strong dependence on the direction.

A note on 'tunnelling'. Usually tunnelling spectroscopy requires a tunelling barrier at the interface like a thin insulating layer or a vacuum gap, as reviewed for example in Ref. [14]. In contrast, the break-junction results presented here have been obtained on junctions that are small enough for a few hop processes to dominate the contact resistance. One can then take advantage of the fact that in the VHR regime charge transport is a (thermally activated) tunneling process [15]. The junctions are also sufficiently large that a depletion layer has not yet been formed at the interface [16].

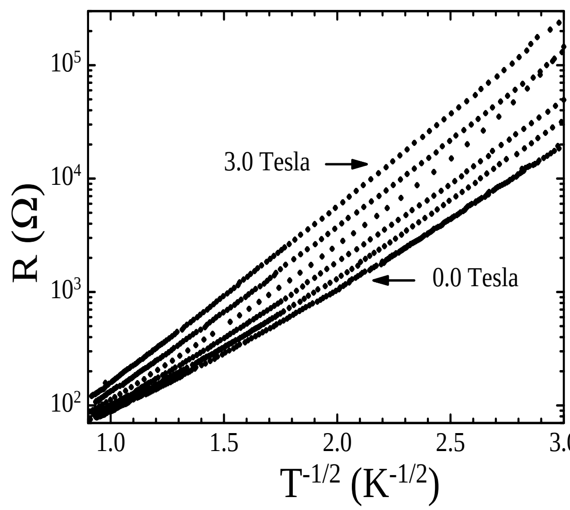

Fig. 1 Resistance R vs. $1/\sqrt{T}$ of n-type Ge at the magnetic fields of B(Tesla) = 0.0, 1.0, 1.5, 2.0, 2.5, and 3.0 (from bottom to top).

3 Experimental results

Fig. 1 shows the temperature dependence of the bulk resistance in a magnetic field. The $\ln(R) \propto 1/\sqrt{T}$ behaviour clearly supports the existence of a Coulomb gap with $N(E) \propto (E - E_\mathrm{F})^2$. The slight difference of the slope above and below about 0.2 - 0.3 K cold be attributed to the cross-over phenomenon of the DOS as discussed by Shlimak it et al. [17]. For the same data, the large positive magnetoresistance in Fig. 2 demonstrates the field-induced confinement of the wave function as described above (so far we have no bulk resistance data at higher fields).

Fig. 3 shows the tunnelling conductance dI/dU versus applied voltage U at $T = 0.1\,\mathrm{K}$ and in various magnetic fields. The junction of Fig. 3(a) has a larger conductance, and thus a larger cross-sectional area, than that of Fig. 3(b). It is therefore more in the regime of bulk transport, and has smaller spectral anomalies than the junction in Fig. 3(b). For both junctions, up to about 4 T the shape of the spectra does not change, although the conductance is considerably reduced with respect to the zero-field data. At about 5 T, the zero-bias minimum becomes smaller, and disappears at higher fields. Both the zero-bias contact resistance and $R_x = dU/dI$ at $U = 4\,\mathrm{mV}$ vary as B^2 up to about 4 Tesla, levelling off at larger fields (Fig. 4). This seems to indicate the transition from weak to strong fields at the characteristic field B_C, which is near the theoretical $B_C = \hbar n^{1/3}/ea \approx 1.4\,\mathrm{Tesla}$, at an effective Bohr radius $a \approx 30\,\mathrm{nm}$ of this Ge sample.

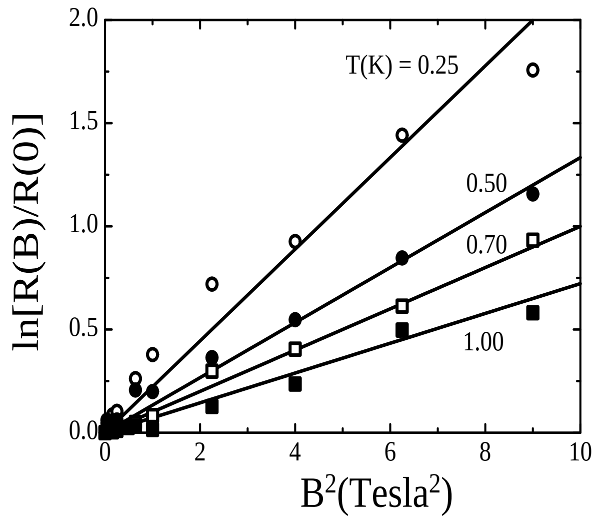

Fig. 2 Logarithm of the normalized magnetoresistance in weak fields at the indicated temperatures. Solid lines as guide to the eye.

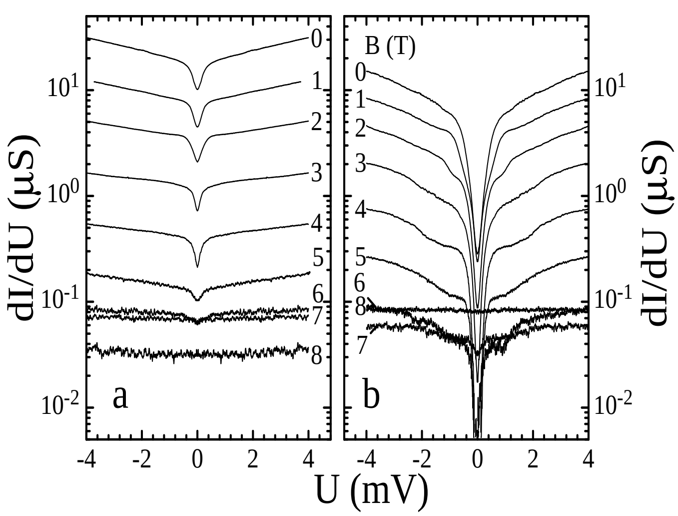

Fig. 3 Differential conductance dI/dU vs. voltage U of two Ge break junctions at the indicated magnetic fields. The temperature was $T = 0.1\,\mathrm{K}$.

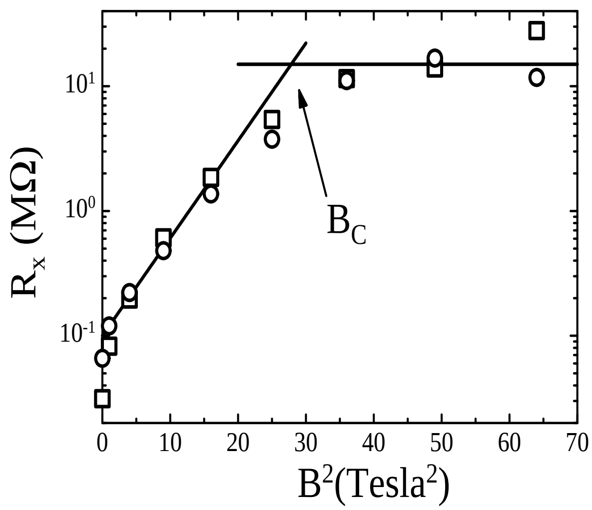

Fig. 4 Differential contact resistance $R_x = dU/dI$ at $U = 4\,\mathrm{mV}$ vs. B^2 of the junction in Fig. 3a (circles) and 3b (squares). Both junctions show a very similar behaviour.

4 Discussion

The close coincidence between the vanishing of the Coulomb-gap anomaly and the crossover from weak field to strong field may help to explain our results. According to Efros and Shklovskii [4], the crossover from weak to strong fields occurs when the magnetic potential $V_B(\mathbf{r}) = \hbar^2(x^2 + y^2)/8m\lambda^4$ is larger than the Coulomb potential $V_C(\mathbf{r}) = e^2/4\pi\epsilon\epsilon_0|\mathbf{r}|$. Here the field $\mathbf{B}$ is assumed to point in z direction. To excite an electron-hole pair (i, j) with energy Δ_{ij} at the Fermi level requires a minimum distance $r_{ij} = e^2/4\pi\epsilon\epsilon_0\Delta_{ij}$. Because of this condition, the DOS around the Fermi level is depleted and the Coulomb gap being formed. In a magnetic field the electron is affected by the Coulomb potential of the hole (and vice versa) only if the hole is located inside the cigar-shaped region in which $V_C(\mathbf{r}) > V_B(\mathbf{r})$.

The distances r_{ij}, responsible for the formation of the Coulomb gap, are much larger than the inter-donor separation $n_d^{-1/3}$. They are obviously of the same order of magnitude as the hop or tunnel distance in our break junctions. At some crossover field, the electron-hole interaction for hopping in the $x - y$ plane becomes inefficient. Therefore, the disappearance of the Coulomb-gap anomaly might be a similar crossover phenomenon as the low-field/high-field crossover due to the shrinking of the wave-functions. The crossover from a cubic to a linear integrated DOS considered by Shlimak *et al.* [17] is based on the same physical idea.

Furthermore, a strong magnetic field may not only make the Coulomb gap inefficient. The Coulomb gap could be completely suppressed since the field confines the wave function to a cigar-like shape along the $\mathbf{B}$ – direction. Therefore electrons can interact only in z direction, transforming the problem from three to one dimensions. And in one dimension a Coulomb gap cannot exist.

5 Summary

We have studied low-temperature transport and tunnelling in an Anderson insulator with long-range Coulomb interaction. Our most important finding is that at low temperature the minimum of the differential tunnelling conductance is suppressed when the applied field exceeds some characteristic field B_C. As explanation we propose a transition from 3D to 1D behaviour due to the field-induced confinement of the electron wave functions.

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