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# Coulomb pseudogap caused by partial localization of a three-dimensional electron system in the extreme quantum limit

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Scanning tunneling spectroscopy is applied to a three-dimensional electron system in the extreme quantum limit (EQL). A parabolic pseudogap of a width of $\pm 2.5$ meV is found at $E_F$ and interpreted as the Coulomb gap predicted by Efros and co-workers [J. Phys. C **8**, L49 (1975); Sov. Phys. Semicond. **14**, 487 (1980)] for localized particles. The fact that the depth of the gap is markedly above zero and fluctuates in space is interpreted as evidence for partial localization supporting our previous assumption that a distinct electron phase exists in the magnetic-field range between the transition to the EQL and the magnetic freeze-out.

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The extreme quantum limit (EQL) of a three-dimensional electron system (3DES) is particularly interesting, since the occupation of only the last spin-polarized Landau level with electrons allows to quench the kinetic energy of the system according to $\overline{E_{kin}} \propto 1/B^2$, which increases the importance of interactions.[1] In normal metals, the EQL cannot be reached, since the transition field $B_{EQL}$ scales with the electron density $n$ as $B_{EQL} = [h^4 n^2/(16e\mu_b g m_{eff})]^{1/3} \propto n^{2/3}$ and turns out to be several thousand of teslas.[2] In degenerately doped semiconductors, i.e., at doping levels above the zero-field metal-insulator transition, the electron density is considerably reduced and the EQL can be reached. Since metallic behavior at low density requires a large Bohr radius $a_B$, low-gap III-V materials with $a_B \geqslant 10$ nm are appropriate to reach the EQL. These materials have the additional advantage of a high $g$ factor, reducing $B_{EQL}$ further according to $B_{EQL} \propto g^{-1/3}$.[2]

On the high $B$-field side, the EQL region is confined by the so-called magnetic freeze-out, where all electrons become bound to donors.[3] The condition for magnetic freeze-out is $n a_B (2 l_B)^2 / ln(a_B/l_B)^2 = 0.04$, with $l_B$ being the magnetic length. The corresponding field is called $B_{MIT}$.[4]

It has been shown that the system is a metal below $B_{EQL}$ and an insulator above $B_{MIT}$.[5] Between those fields, the transport properties are found to be anisotropic, i.e., the conductivity parallel to $B$ decreases with decreasing temperature $T$, while the conductivity perpendicular to $B$ increases with $T$.[6] In this case the electron system is obviously neither a metal nor an insulator, which makes it likely that a third electron phase besides metal and insulator exists in the EQL. This phase, sometimes called a Hall insulator or a Hall conductor,[7,8] also exhibits an unusual Hall resistance $R_H$ appearing as a kneelike structure in the $R_H(B)$ curve.[9]

In a previous paper we have shown that the local density of states (LDOS) in the EQL exhibits drift states along equipotential lines of the sample.[10] Such states are usually expected for two-dimensional (2D) systems in the integer quantum-Hall regime,[11] which implies a quasi 2D-character of the 3D system. The density of drift states increases with increasing $B$ field, decreasing temperature, and decreasing energy,[12] but we always found that only part of the states are transformed into drift states. The remaining states still exhibit a smooth LDOS implying the usual metallic 3D character. We interpret our results by partial localization of the electronic states, induced itself by the increased backscattering of the electrons along the $B$ field.[6,12] The basic idea is that the localized electrons feel an effective 2D potential across the magnetic field as long as the localization length is larger than the magnetic length. This naturally explains the observed drift states.

The question arises as to how the partial localization modifies the DOS close to the Fermi level $E_F$. Such a modification is expected if the localized electrons interact by their Coulomb potentials. The influence of Coulomb correlations on the DOS at $E_F$ has previously been studied for 3D and 2D systems across density or disorder driven metal-insulator transitions.[13] All results could be straightforwardly explained by relatively simple models requiring a cusp at $E_F$ on the metallic side and a smooth gap $S(E) \propto |E - E_F|^{D-1}$ on the insulating side in a $D$-dimensional system,[14] where $S(E)$ is the DOS at energy $E$. Also a magnetic-field induced metal-insulator transition has been studied, revealing basically the same results,[15] but none of the previous measurements are done in the EQL. Here, we present the investigation of the DOS at $E_F$ in the EQL, where the situation is less clear, since the system is neither a metal nor an insulator.

Nevertheless, the arguments given by Efros *et al.* and Shlovskii *et al.* to deduce the $|E - E_F|^{D-1}$ shape of the gap should still apply, since they do not require complete localization, but only the existence of localized particles.[14] Therefore, we expect a soft parabolic gap in the EQL. To be more precise we expect a pseudogap, i.e., the minimum of the gap at $E_F$ should not be zero, but should reflect the ratio of metallic and localized states. Morever, we expect that the depth of the gap should spatially fluctuate, since the ratio of localized and metallic density of states spatially fluctuates. These two properties are indeed found, establishing the existence of a parabolic pseudogap also in the mixed phase of the 3DES EQL and giving additional evidence that our previous interpretation of a partially localized phase is correct.

Details of the experiment are given elsewhere.[12,16] In short, a low-temperature scanning tunneling microscope (STM) operating in ultrahigh vacuum and in magnetic fields up to 6 T perpendicular to the surface is used. We image the

 

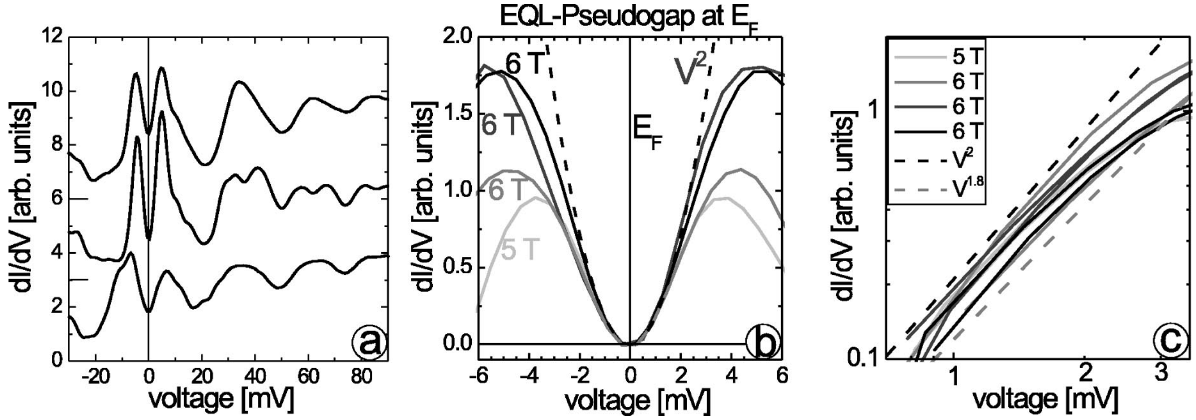


FIG. 1. (a) $dI/dV(V)$ spectra of $n$-InAs(110) obtained with different microtips, $B=6$ T $I_{stab}=500$ pA, $V_{stab}=100$ mV, $V_{mod}=1$ mV; the curves are offset by 2 units for clarity. (b) Pseudogap region of spatially averaged $dI/dV(V)$ spectra displayed after subtracting a linear background, $B$ as indicated, different microtips are used, $I_{stab}=500$ pA, $V_{stab}=100$ mV, $V_{mod}=1$ mV; $V^2$ curve is added for comparison. (c) Same data as in (b), but on a double-logarithmic scale.

differential conductivity $dI/dV(V,x,y)$ at the InAs(110) surface of an $n$-doped sample ($N_D=1.1\times10^{16}$ cm$^{-3}$). Since surface states of InAs(110) are about 1 eV away from the band edges,[18] we effectively probe the LDOS of the bulk conduction band. We calculate $B_{EQL}=3.3$ T and $B_{MIT}=9$ T; thus our $B$ field covers a large range of the EQL regime. The $dI/dV(V)$ curves are recorded by a lock-in technique using a modulation voltage $V_{mod}$ after stabilizing the tip at voltage $V_{stab}$ and current $I_{stab}$. It is known that $dI/dV(V,x,y)$ recorded at low $V$ is proportional to $S(E,x,y)$.[17] Since we have shown that the influence of the probe on the spatial fluctuations of the $dI/dV$ signal is small,[12] we attribute the measured spatial variation of $dI/dV$ directly to the spatial dependence of the sample LDOS. However, the voltage dependence of $dI/dV$ is found to be influenced by the probe.[12] It exhibits peaks, which correspond to quantized states of the so-called tip-induced quantum dot (QD). The tunneling current proceeds from the tip via the QD to the 3DES LDOS. Consequently, $dI/dV(V)$ measures a convolution of the QD and 3DES LDOS. Since the QD is moved with the tip, its influence on the spatial distribution of $dI/dV$ and LDOS is negligible, while its influence on the voltage dependence of $dI/dV$ is significant.

Three $dI/dV$ spectra taken with different microtips at $B=6$ T are shown in Fig. 1(a). They exhibit a number of peaks caused by the Landau and spin levels of the QD.[19] Moreover, a dip close to $V=0$ mV is visible in all spectra. This dip is apparent in about 90% of the $dI/dV$ curves recorded in the EQL. In the other 10% of the curves, the dip is barely visible, since it coincides with a voltage in between the QD peaks. Because the dip does not correlate with QD features and since we are not aware of any reason explaining such a dip at $E_F$ in a QD spectrum, we conclude that the dip is caused by the sample LDOS. However, the shape of the dip is influenced by the adjacent QD peaks. To deduce the correct shape of the dip as present in the 3DES, we subtract a linear background. In other words, we make the gap symmetric as required from particle-hole symmetry in the 3DES. After doing that, all dips exhibit the minimum exactly at $V=0$ mV. Some resulting curves deduced from spatially averaged $dI/dV$ data are shown in Fig. 1(b). The spatially averaged $dI/dV$ curves refer directly to the sample DOS. Different magnetic fields are applied and the data are recorded with different microtips. For comparison, the expected $V^2$ shape of the soft gap is added, revealing good correspondence close to $V=0$ mV. Figure 1(c) shows the same data on a double logarithmic plot. This allows to deduce the exponent more quantitatively resulting in $1.9\pm0.1$ up to about $V=2.5$ mV. The agreement with the exponent of 2 expected from the Efros-Shlovskii model is good. The width of the Coulomb gap of about 2.5 meV is also in good agreement with the predicted value $\Delta E=e^3[S(E_F)/(4\pi\epsilon\epsilon_0)^3]^{1/2}=2.8$ meV with $S(E_F)$ being the sample DOS at $E_F$ in the noninteracting case.[14] Thus, the dip has exactly the properties of an Efros-Shlovskii gap expected for localized particles. In accordance with previous studies performed on very different samples,[13] we do not find any indications of many-particle excitations, which would modify the shape of the gap. In particular, these excitations are predicted to result in a stronger energy dependence of the DOS.[20] The absence of many-particle excitations is not surprising, since the localized particles in the EQL are rather isolated. From the dopant

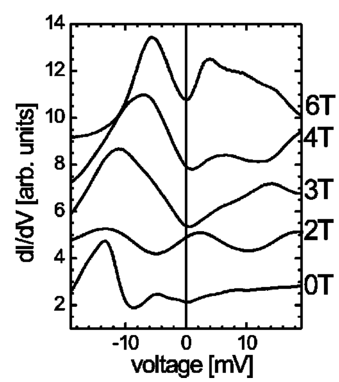


FIG. 2. Spatially averaged $dI/dV(V)$ spectra obtained with the same microtip at different $B$ fields as indicated, $I_{stab}=500$ pA, $V_{stab}=100$ mV, $V_{mod}=1$ mV; the curves are offset by two units for clarity.

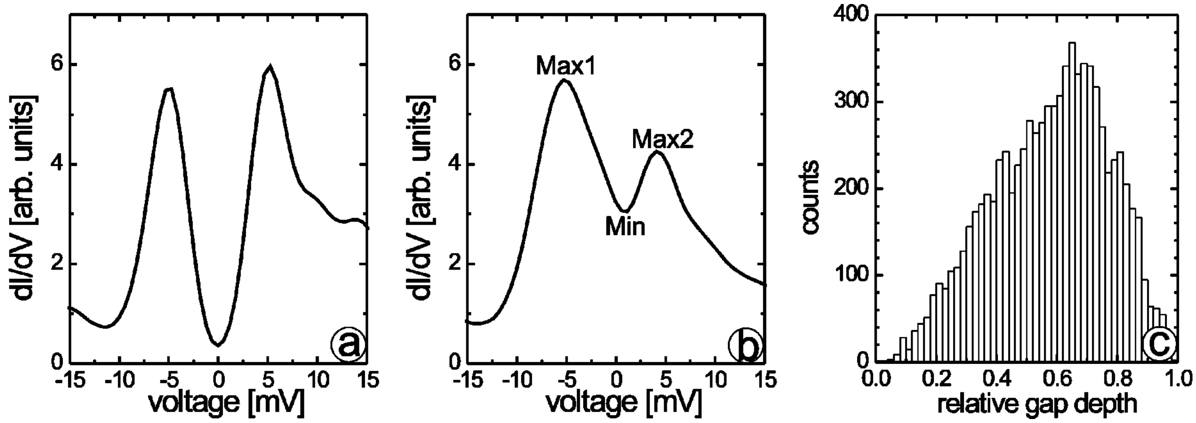


FIG. 3. (a) and (b) $dI/dV(V)$ spectra of $n$-InAs(110) obtained with the same microtip on different sample positions, $B=6$ T, $I_{stab}=500$ pA, $V_{stab}=100$ mV, $V_{mod}=1$ mV; marked maxima and minima serve to calculate the relative gap depth according to $[0.5(\mathrm{Max1}+\mathrm{Max2})-\mathrm{Min}]/[0.5(\mathrm{Max1}+\mathrm{Max2})]$. (c) Histogram of relative gap depth obtained from 8300 $dI/dV$ spectra recorded in an area of $(160\ \mathrm{nm})^2$.

concentration and the measured energy dependence of the drift states, we deduce that individual potential troughs are about 50 nm apart. On the other hand, we found that only about 65% of the electrons (density of $1.1\times10^{16}\ \mathrm{cm}^{-3}$) are localized,[12] resulting in an average distance of localized particles of 50 nm. Consequently, the localized electrons are well separated and similar to point charges as assumed in the derivation of the parabolic pseudogap by Efros and Shlovskii.[14]

Figure 2 shows that the pseudogap is only observed in the EQL. Spatially averaged $dI/dV$ curves recorded on the same sample area at different $B$ fields are shown. A small cusp is visible at $B=0$ T, while a pseudogap appears only above $B=3$ T, i.e., within the EQL regime. This result provides additional evidence that the gap is related to the 3DES, since the EQL field does not coincide with a special filling factor of the QD. Obviously the depth of the gap increases with increasing $B$ field as expected from the increasing localization.[12]

Using an STM as the tunneling probe has the additional advantage that the spatial variation of the pseudogap depth can be measured. Such a variation is not expected in the insulating case but in the case of the EQL, where localized and metallic states coexist. While the metallic states give only a small cusplike and spatially constant contribution, the spatially fluctuating localized states dominate the gap at $E_F$. Hence, the depth of the gap corresponds to the percentage of localized states contributing to the LDOS. The two curves shown in Figs. 3(a) and 3(b), which are taken at different positions of the same sample, show that the gap depth indeed fluctuates. However, the presence of the QD states complicates the quantitative determination of the local gap depth, since also the energy and intensity of the QD states slightly depend on position.[19] A reasonable way to estimate the gap depth as present in the 3DES is to divide the measured gap depth by the averaged height of the two maxima adjacent to the gap. Referring to the points marked in Fig. 2(a), we, thus, define a relative gap depth as $[0.5(\mathrm{Max1}+\mathrm{Max2})-\mathrm{Min}]/[0.5(\mathrm{Max1}+\mathrm{Max2})]$. The procedure removes the influence of the intensity of the QD states by assuming that without the gap, the QD state would have had an intensity at $E_F$ interpolated between the two maxima. The resulting relative gap depth is basically equal to the percentage of localized particles contributing to the sample LDOS.

A histogram of the relative gap depth obtained from $dI/dV$ curves at about $10^4$ different positions is shown in Fig. 3(c). Of course, we checked that the microtip has not changed during the data recording by reproducing individual curves. We find that the relative gap depth strongly fluctuates between 5% and 95%. From previous studies performed on a 2DES and a 3DES without a magnetic field, we know that localized particles typically exhibit LDOS corrugations of $60-90\,\%$, while metallic particles only show slight corrugations of 3% caused by scattering induced interference.[21] Thus, we conclude that the gap depth fluctuation is mainly caused by the spatial fluctuation of the density of localized particles. Note that the observation of a spatially fluctuating relative gap depth is direct evidence for the presence of metallic states. Otherwise the relative gap depth would be 100% at each position.

In summary, we analyzed the pseudogap at $E_F$ in the peculiar phase of a three-dimensional electron system in the extreme quantum limit. We found that the gap is parabolic in shape and has a width of about 2.5 meV, both in accordance with predictions from Efros and Shlovskii for localized particles. The adequately normalized gap depth fluctutates between 5% and 95%, which is in disagreement with a phase consisting completely of localized particles, but in agreement with our previous model that only part of the states are localized.

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