Transport signatures of correlated disorder in a two-dimensional electron gas

T. Heinzel†, R. Jäggi, E. Ribeiro†, M.v. Waldkirch, and K. Ensslin
Solid State Physics Laboratory, ETH Zürich, 8093 Zürich, Switzerland

S. E. Ulloa
Department of Physics and Astronomy, Ohio University, Athens, OH 45701-2979, USA

G. Medeiros-Ribeiro†, and P. M. Petroff
Materials Department, University of California, Santa Barbara, CA 93106, USA
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We report electronic transport measurements on two-dimensional electron gases in a Ga[Al]As heterostructure with an embedded layer of InAs self-assembled quantum dots. At high InAs dot densities, pronounced Altshuler-Aronov-Spivak magnetoresistance oscillations are observed, which indicate short-range ordering of the potential landscape formed by the charged dots and the strain fields. The presence of these oscillations coincides with the observation of a metal-insulator transition, and a maximum in the electron mobility as a function of the electron density. Within a model based on correlated disorder, we establish a relation between these effects.

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The optical and electronic properties of self-assembled quantum dots (SAQDs) have been widely studied in the past few years. These experiments have been performed on individual SAQDs or on two-dimensional dot arrays. Recently, however, substantial progress in fabrication technology has led to self-ordered growth of such quantum dots in twod and even three-dimensional geometries. The ordering has been detected by scanning force microscopy as well as by X-ray diffraction. These studies suggest that designing electronic minibands by self-ordered growth of SAQDs may be feasible.

Here, we report experimental evidence in electronic transport, that InAs SAQDs embedded at the heterointerface of a Ga[Al]As heterostructure are capable of creating a potential landscape with substantial spatial and amplitude correlations. In our samples, the SAQDs have been grown on an atomically flat GaAs [100] surface. The charged SAQDs, combined with the induced strain fields, act as repulsive scatterers in a two-dimensional electron gas (2DEG). At sufficiently high dot densities, several effects are observed to occur in concert: (1) Magnetoresistivity measurements show pronounced, periodic oscillations, which are interpreted as Altshuler-Aronov-Spivak oscillations. In addition, under certain parametric conditions, a resistivity minimum around zero magnetic field is observed, superimposed with the weak localization peak. (2) We observe a maximum in the electron mobility as a function of the electron density. (3) The temperature dependence of \( \rho_{xx} \) as a function of electron density shows a transition from metallic behavior to insulating behavior; an effect that has been interpreted as a signature of a metal-insulator transition in two dimensions. We emphasize that in the samples under study, these transport features always occur together. As we describe below, this complex experimental behavior is a signature of the potential correlations provided by the SAQD potential landscape.

The samples have been grown by molecular beam epitaxy. A layer of InAs SAQDs has been embedded in the GaAs buffer layer 3 nm below a GaAs \(-\text{Al}_{0.3}\text{Ga}_{0.7}\text{As} \)-heterointerface, at which the 2DEG resides. The density \( n_{QD} \) of the InAs SAQDs varies across the wafer. \( n_{QD} \) has been determined, within a factor of two, by transmission electron microscope (TEM) studies, as well as by low-temperature transport experiments. For details of the sample growth and characterization, see Ref. 11. The wafer was cleaved into pieces, and conventional Hall bar geometries were patterned by optical lithography. Voltages applied to a homogeneous top gate electrode were used to tune the electron density \( n_e \) of the 2DEG. Transport experiments were carried out in a \(^3\text{He}/\text{\textit{He}}\) dilution refrigerator and in a standard \(^4\text{He} \) cryostat at temperatures between 60 mK and 20 K. The resistivity was measured in a standard 4-terminal setup, probing sample areas of \( 40 \mu m \times 100 \mu m \). For \( n_{QD}\leq 2 \times 10^{14} m^{-2} \), the electron gases behave like ordinary low-mobility samples, in which the mobility is dominated by the SAQDs. At higher dot densities of \( n_{QD}\approx 2.5 \times 10^{14} m^{-2} \) (i.e. the samples labelled by 14a, 14b and 24b, see inset in Fig. 1a), we find pronounced oscillations as a function of a magnetic field \( B \) applied perpendicular to the plane of the 2DEG. The oscillations are periodic in \( B \), with a period of \( \delta B = 400 \pm 20 \) mT in sample 14a, which increases to \( 560 \pm 20 \) mT in sample 24b. The period is independent of \( n_e \) (Fig. 1a). The relative oscillation amplitude \( \delta \rho/\rho \) increases as \( n_e \) is increased, with a maximum of \( \delta \rho/\rho \approx 0.12 \). Measurements in tilted magnetic fields show that the oscillations are determined solely by the magnetic field component perpendicular to the plane of the 2DEG, and have therefore a purely dynamical (no spin) origin. These oscillations are superimposed on a broad resistivity background, which vanishes around
We do not observe Shubnikov-de Haas oscillations for filling factors larger than 4.

In addition to a weak localization peak, we observe for large electron densities a well-pronounced minimum in the magnetoresistivity around $B = 0$, which extends up to a few hundred mT. In contrast to the magneto-oscillations, this minimum shows no significant temperature dependence up to about 2.5 K (Fig. 1b). Figure 2, shows additional observations that coincide with the presence of the features discussed above: (i) a fixed point is observed in the temperature dependence of $\rho_{xx}(n_e)$ at $B = 0$, separating a region of high electron density ($n_e > 1.2 \times 10^{15} m^{-2}$) with a metallic temperature dependence, from a low density region showing an insulating temperature dependence. (ii) the electron mobility $\mu$ shows a maximum as a function of $n_e$ (upper inset in Fig. 2).

The presence of these effects depends on the cooldown cycle. Hence, the arrangement of charges in the potential landscape during cooldown is a crucial factor. However, we have been unable to establish a systematic dependence on the cooldown speed or on the biasing conditions during cooldown. The simultaneous occurrence of the transport features described here indicates a possible unifying explanation which is developed below.

In the following, we focus on sample 14a and interpret its behavior, starting with the periodic magneto-oscillations. The experiments clearly suggest a magnetic flux effect as its origin. It is well-known that Aharonov-Bohm oscillations with period $\Delta B = h/eA$ ($A$ denotes the enclosed area) ensemble-average to zero, since the phase of each interference loop at $B=0$ is loop-specific.

In contrast, Altshuler-Aronov-Spivak (AAS) oscillations always show zero phase shift at $B=0$, and consequently

**FIG. 1.** (a) Magnetoresistivity of sample 14b for $n_e = 2.37 \times 10^{15} m^{-2}$ ($\bigcirc$), $1.16 \times 10^{15} m^{-2}$ ($\bullet$), and $0.97 \times 10^{15} m^{-2}$ ($\triangle$); the resistivity data for the two lower electron densities are scaled as indicated. Pronounced magneto-oscillations are observed for $|B| < 2T$. Their period and phase is independent of $n_e$. In addition, a positive magnetoresistivity is observed for $|B| < 0.5T$, with the weak localization peak superimposed. The inset shows a sketch of the wafer under study. $n_{QD}$ increases from top to bottom (edge of the wafer), and has been estimated by TEM studies as $n_{QD} = 2.5 \times 10^{14} m^{-2}$ in sample 23, and $n_{QD} = 3.0 \times 10^{14} m^{-2}$ in sample 25, respectively. The magneto-oscillations are observed on samples shown in dark gray. (b) Temperature dependence of the magnetoresistivity in samples 14b and 24b.

**FIG. 2.** Metal-insulator transition as observed as a function of $n_e$ and temperature in two samples. The upper inset shows the electronic mobility $\mu$ as a function of $n_e$ for two samples. Sample 24b shows a maximum in the electron mobility, in contrast to sample 24a. Lower inset: localization length vs correlation length $y_0$ for the correlation function discussed in text in a 1D system, and selected energy values. $l_{loc}$ increases rapidly for larger $y_0$, with a rate that depends on the energy $E$ of the state. An even faster enhancement of $l_{loc}$ is anticipated for a 2D system. Algorithm to calculate $l_{loc}$ is described in Ref. 19.
survive ensemble-averaging. We thus conclude that the observed oscillations are AAS oscillations with a characteristic enclosed area of $5.2 \times 10^{-15} \text{m}^2$.

Similar oscillations have been recently detected in hexagonal antidot lattices, while no signature of such oscillations has been found in rectangular lattices with otherwise comparable parameters. In Ref. [16], the authors explain this observation in terms of semiclassical trajectories of the electrons around the antidots: in the hexagonal array, the probability for the electrons to be scattered in loops around the antidots is greatly enhanced, leading to a significant AAS oscillation amplitude, in contrast to the more open geometry of rectangular lattices.

Let us, based on this knowledge and our observations, assume that the potential landscape generated by the charged SAQDs and the strain fields reveals at short range hexagonal ordering to a significant degree. The measured AAS period would then suggest an inter-dot separation of $a \approx 78 \text{nm}$, corresponding to a density of SAQD points of $1.9 \times 10^{14} \text{m}^{-2}$. This is in reasonable agreement with $2 \times 10^{14} \text{m}^{-2} \lesssim n_{QD} \lesssim 3 \times 10^{14} \text{m}^{-2}$, as determined in TEM studies, although $n_{QD}$ is determined from resistivity studies is somewhat higher. Further estimates are consistent with this picture. We have determined the phase coherence length $\ell_\phi$ from fits of the weak localization peak for $\rho_{xx} < \hbar/e^2$ and find $\ell_\phi \approx 500 \text{nm}$ at $n_e = 1.8 \times 10^{15} \text{m}^{-2}$, and increasing slightly as $n_e$ increases. The electrons are thus clearly able to eclipse the area of the locally hexagonal ordered cells in a phase coherent fashion. As a further consequence, quantum point contacts are formed in between the lattice points, with a maximum of two occupied 1D spin-degenerate subbands at the electron densities under investigation. This explains the quenching of the Shubnikov-de Haas oscillations above filling factor 4. Using these numbers and assuming that the hexagonal arrangement contains approximately circular scatterers of electrostatic radius $r_{QD}$ at the Fermi energy, we can estimate $r_{QD} \approx 20 \text{nm}$. Hence, $2r_{QD} \approx \frac{\pi}{\sqrt{3}}$, which has been shown to be a particularly effective geometry for observing AAS oscillations in hexagonal antidot lattices. We must emphasize that this analysis does not rely on truly long-range order, but rather only on the local hexagonal relative arrangement of the charged SAQDs. Nor do we know unambiguously that the ordering is really hexagonal: other types of correlations in the disorder potential, e.g. possibly a random trimer superlattice, may give rise to B-periodic coherent backscattering as well. Note, however, that the relative amplitude of the oscillations is comparable to that one observed in Ref. [16], which suggests a similar degree of ordering.

We proceed by constructing the relation between the AAS oscillations, the “metal-insulator transition” (MIT), and the maximum in $\mu(n_e)$. If the density of SAQDs is low, there is no positional short-ranged order, and even homogeneous charging of the dots results in a potential landscape dominated by the disordered dot distribution of charged scattering centers. As the inter-dot separation is still large, the backscattering processes inherent to the AAS effect are unlikely, and no magneto-resistance oscillations occur. Similarly, the mobility of the system is dominated by random scattering events from the dots, yielding an insulating behavior for all values of electronic density. As the density of dots increases, there is an effective repulsive interdot interaction which facilitates the appearance of short-ranged order so as to relax the local elastic stress in the system. Upon formation of the 2DEG, the dots do formed acquire charge with a distribution which is likely correlated to the loading state of nearby dots (notice that dot-dot interaction is quite large, as $(2e)^2/k\alpha \approx 6 \text{meV}$, for doubly-charged dots embedded in GaAs, $\kappa \approx 12$). The short-range order yields enhancement of backscattering and AAS oscillations, as well as the appearance of relatively extended states due to the effectively weaker, more correlated, potential disorder. As the electron density increases, the AAS oscillations become more prominent, indicating increasing population of the corresponding states. The resulting electronic states are then capable of exhibiting a drastically different transport behavior as a function of electron density: insulating for low densities, and metallic for higher concentrations. This change is the result of the Fermi level sweeping through the density of states, sampling ever more extended states. It is worth mentioning that our experiments show a sharp transition to such a correlated state as a function of $n_{QD}$, given the fact that $n_{QD}$ varies by 15 % between sample 24a and 24b (or sample 13 and 14a) at most. Sample 15 shows conventional behavior, which, however, may be due to its proximity to the wafer edge.

The observed transport behavior is qualitatively consistent with the appearance of ‘extended’ states in the 2DEG (with localization lengths much longer than a few SAQD spacings), and reminiscent of the situation recently analyzed in disordered but correlated 1D systems. Izrailev and coworkers have demonstrated that even in a 1D system, potential correlations in a disordered structure can give rise to true mobility edges, where the localization length would diverge over a certain energy window. Although the situation for 2D is not as firmly established, one expects that the higher connectivity of electronic paths in 2D would give rise to mobility edges even with weaker potential correlations than in a corresponding 1D case. Numerical evidence in a variety of systems suggests.

In this context, it is instructive to estimate the potential correlations produced by the scattering centers (the charged dots) on the 2DEG carriers. The entire SAQD charged array generates a disordered Coulomb potential given by $V(\mathbf{r}) = \sum_j \frac{q_j}{|\mathbf{r} - \mathbf{r}_j|} e^{-\gamma|\mathbf{r} - \mathbf{r}_j|}$, where each dot has effectively trapped a charge $q_j$ and the bare dot potential is assumed screened by the 2DEG (the full potential surely includes also local strain components).
Correspondingly, the potential correlations are given by 
\( \langle V(x)V(x+y) \rangle \), where the angular brackets denote an average over the dot population. For a random charge distribution, \( \langle q_i q_j \rangle = \delta_{ij} q^2 \), and a random distribution of dots, the potential correlator has an asymptotic behavior given by \( v_0^2 e^{-y/y_0(a/y)} \), where the correlation length \( y_0 \) is a monotonically decreasing function of the screening length \( \gamma^{-1} \), which in turn is a function of electron density in the system, and \( a \) is the mean dot separation. One expects that as the electron density increases and provides better screening, the characteristic length \( y_0 \) also increases, resulting in stronger (longer range) correlations in the system.

As this expression neglects the built-in effective interaction between dots introduced by the strain fields, as well as the correlations in potential strength of the charged-dots landscape, this result provides a pessimistic estimate of the true correlator in our system. Nevertheless, even such a ‘weak’ exponential correlator in a 1D system can be shown to result in increasing localization lengths for larger \( y_0 \) values, as shown in the lower inset of Fig. 2.

The rather strong potential correlations that exist in our 2D system are then anticipated to yield long localization lengths which clearly exceed the phase coherence length of the system, and explain the complex behavior we observe.

Within this interpretation, the character of the MIT observed in our system is quite different from those reported in other systems. One striking feature of the MIT observed in, e.g., Si-MOSFETs is its suppression in magnetic fields applied parallel to the plane of the electron gas. This suppression has been attributed to complete spin alignment. This is in sharp contrast to our system, where the MIT is present up to the strongest magnetic field accessible to us, i.e. 12 T.

A positive magnetoresistivity around \( B = 0 \) is also present in the metallic regime. This resistivity minimum is robust as the temperature is increased (Fig. 1b), indicating a classical origin. Furthermore, the minimum vanishes as \( n_e \) is reduced into the insulating regime (Fig. 1a). Similar effects are well-known from electron gases with double subband occupancy due to the different densities and mobilities of the electrons in the two subbands, a positive magnetoresistance evolves. Since we cannot determine the individual electron densities in the two types of states, we cannot fit \( \rho_{xx}(B) \). Qualitatively, however, it is known that this effect is strong if the difference in the mobilities is significant, and consistent here with the presence of a ‘band’ of high mobility (extended states) next to another ‘band’ with low mobility.

In conclusion, the following qualitative picture emerges: the presence of AAS oscillations indicates some degree of short-range ordering, possibly in a hexagonal geometry, of the potential landscape induced by the InAs SAQDs. This leads to the formation of a different class of states, which may be seen as an extended-state “mini-band” arising from the local ordering in the dot potential. These states become populated as \( n_e \) is increased above a threshold density, which corresponds approximately to the fixed point of the MIT. For higher electron densities, scattering between two bands with quite different mobilities can occur, which reduces the overall mobility. The positive magnetoconductivity around \( B = 0 \) indicates such a scenario. Our data thus represent the first transport signature that two-dimensional, correlated potential landscapes can be formed by self-ordering of charge between self-assembled quantum dots, and raises several questions about mobility edges and miniband design by self-ordering in two dimensions, which will hopefully be addressed in future experiments and theoretical studies.

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This estimation of $n_{QD}$ from transport experiments assumes that two electrons are captured per dot. Higher occupation numbers are possible and reduce the value extracted for $n_{QD}$.

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