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GIANT GROWTH OF QUANTUM OSCILLATIONS IN AN INHOMOGENEOUS 2D ELECTRON SYSTEM

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We experimentally detect for the first time that the connection of 2D electron systems with different electrochemical potentials results in long-range (> 50 μm) electron density disturbances. When a gated region of the Corbino sample is strongly depleted, the amplitude of the magneto-resistance oscillations caused by high density ungated regions is found to increase proportionally to the sample resistance which is dominated by low density regions with small conductivity. The experiments on the samples with an artificial potential profile (antidots and etched rings) below the gate show that the observed effects are not due to contact effects.

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In the pioneering work of Ref. [1] Tsui and Allen found quantum oscillations in the magneto-resistance of low-mobility silicon MOSFET's that persist in the activated regime at low electron densities. Recent studies using high-mobility Si MOSFET's [2–6] and lowmobility AlGaAs/GaAs heterostructures [7–9] confirm the existence of the effect and establish the oscillating behaviour of the metal-insulator phase boundary with magnetic field (also called reentrant behaviour of the insulating and metallic phase). The origin of this phenomenon remains unclear, although two theoretical approaches have been formulated over the years. In the case of short-range random potential, Refs. [11, 12] predict quantum oscillations in the dirty-metal regime due to floating-up of extended Landau-states with decreasing magnetic field. Alternatively, in the case of an inhomogeneous 2D system (random long-range potentials) it has been suggested that chemical potential oscillations may affect percolation phenomena that determine the sample conductance [13, 14]. Thus, the first approach implies a change of mobility threshold as the main cause for the phenomena while in the other the chemical potential plays the dominant role.

Here we investigate the quantum oscillations in high-mobility AlGaAs/GaAs heterostructures with an artificial potential landscape, so that they consist of regions of high and low electron density. We find that also in these high-mobility samples resistance oscillations in an insulating phase do occur. The periodicity of these oscillations corresponds to the *high* electron density region. Remarkably,

the amplitude of the oscillations is proportional to the total sample resistance which is dominated by the *low* electron density region. The results prove that in either region there occur macroscopic electron density redistributions with changing magnetic field.

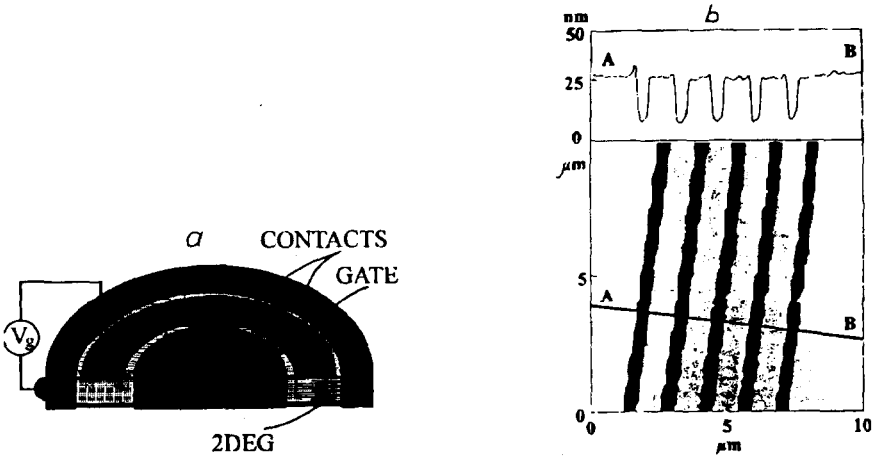

Fig.1. (*a*) Schematic view of the sample. Additional structure in a gated region is not shown; (*b*) Image of the relief in the form of etched rings, observed using an atomic force microscope

In our experiments we use Corbino samples made of an AlGaAs/GaAs heterostructure containing a 2D electron gas (2DEG) with electron density $1.7 \cdot 10^{11}$ cm^{-2} and mobility $\mu \approx 1.2 \cdot 10^6$ cm^2/Vs (at temperature $T = 4.2$ K). A sketch of the sample is shown in Fig.1. The spacer layer thickness is 410 Å, the dimensions of Corbino ring are $r_1 = 0.2$ mm, $r_2 = 0.5$ mm. The samples have a circular gate restricted by radii $r_{1g} = 0.3$ mm and $r_{2g} = 0.4$ mm so that the gated region of the 2DEG is separated from the contacts by guarding rings. By applying a dc voltage to the gate it is possible to vary the electron density in the gated region independently of that in the guarding rings. Some of the samples have an additional artificial potential profile below the gate. We employ two types of the potential relief: (i) five coaxial rings consisting of antidots in the middle of the gated region. The geometrical diameter of antidots is about 0.5 μm, their spacing along the ring perimeters is equal to ≈ 1.8 μm; (ii) five coaxial rings formed by etching the wafer to a depth of ≈ 180 Å (Fig.1), whereas the distance between the gate and the 2D layer is equal to $d \approx 960$ Å. The rings are located in the middle of the gated area, their geometrical dimensions in the plane are displayed in Fig.1.

The samples are mounted in the mixing chamber of He^3/He^4 dilution refrigerator with a base temperature of ≈ 25 mK. The measurements are made using a low frequency ($f = 3$ Hz) lock-in technique. An ac current of about 2.5 pA is passed through the samples. At very strong depletion of the 2DEG in the gated region the resistance of the sample becomes comparable with the input resistance of lock-in; in this regime the measurements are done using dc techniques. All our data presented below are obtained in the linear regime.

We measure the resistance, R, of our device (which is equal to $R = \sigma_{xx}^{-1}\ln(r_2/r_1)/2\pi$ in the case of homogeneous electron density) under depletion of the 2DEG in the gated region. Evidently, the total resistance of the 2D layer should be the sum of resistances of the depleted region and the guard rings. One may anticipate that the magnetic-field dependences in these two parts of the sample are entirely independent, so that the sample resistance as a function of magnetic field is the combination of quantum oscillations in the guard-rings and the background resistance of the gated region. Such behaviour is indeed observed in our samples when the conductivity in the gated region is metallic.

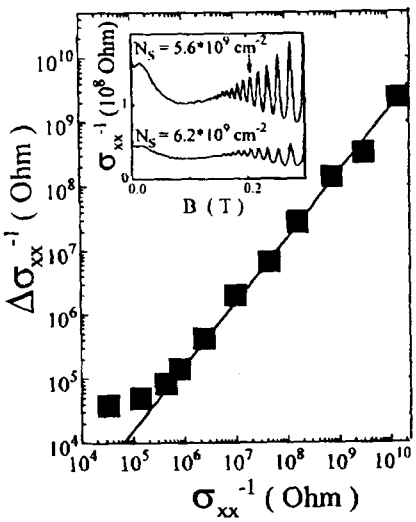

Fig.2

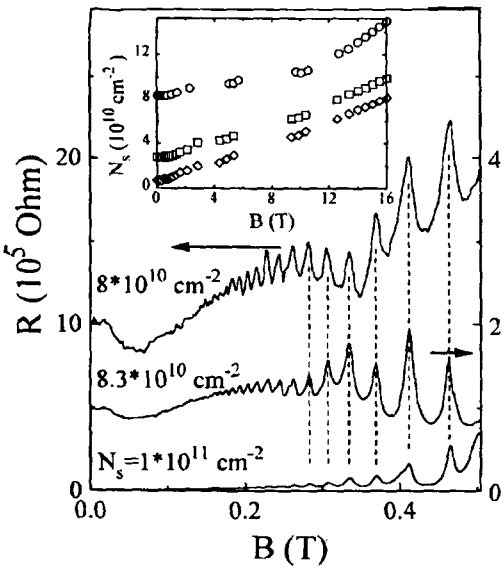

Fig.3

Fig.2. Resistance oscillation amplitude as a function of sample resistance on the device without structure below a gate at $B = 0.21$ T and $T \approx 30$ mK. Inset: behaviour of the magnetoresistance for two different electron densities in the gated region

Fig.3. Resistance oscillations on the sample structured with antidots at strongly different degrees of depletion of the gated region: in an insulating phase (upper and middle curve) and in the case of metallic conductivity in the gated region (lower curve). Electron densities in the unpatterned region below the gate are indicated near the dependences. Vertical lines are guides to the eye. Inset: Metal-insulator phase boundary in the (B, N_s) plane corresponding to a fixed value of sample resistance 10 MΩ per square (see the text and Ref. [15]) for devices structured with antidots (circles), rings (squares) and without additional structure (diamonds)

However, and to our surprise, we find a quite different behaviour of the quantum oscillations in the limit of strong depletion when the resistance R is largely determined by the poorly conducting low-density region of 2DEG. An example of this behaviour is shown in Fig.2 for a sample without artificial potential modulation below the gate. The inset of Fig. 2 displays the experimental traces for two values of electron density in the gated region. We recognize a series of quantum oscillations due to the (high-density) guard-rings, the amplitude of which increases with sample resistance. In a wide range these two quantities turn

out to be roughly proportional to each other, as can be seen from this Figure[1]. Using the current-voltage technique of Ref. [15], we have verified that also in the present samples the metal-insulator transition point corresponds (at $T \approx 25$ mK) to $\sigma_{xx}^{-1} \approx 10$ MΩ; It is exactly for resistivities σ_{xx}^{-1} of around and above this value that the growth of the quantum oscillations can be observed (Fig. 2). At the lowest temperatures the transport in the insulating phase is due to variable range hopping, except in the vicinity of the transition point, where activated transport prevails. This change of transport mechanism (in the range of σ_{xx}^{-1} from 10^8 to 3×10^8 Ω) is not found to result in appreciable deviations in the linear dependence of the oscillation amplitude on sample resistance (*cf.* Fig. 2). However, we have found in additional experiments that, at constant electron density, the oscillation amplitude drops more rapidly with increasing temperature than the sample resistance.

We observe a very similar behaviour in samples that have an additional artificial potential profile, with one noteworthy distinction: in these samples the metal-insulator phase boundary (see inset of Fig. 3) is pushed to higher electron densities. This implies that an insulating state arises first in the patterned area covering only a small part of the gated region. In this case we detect an increase of the amplitude of the oscillations caused by both the gated region of the sample without structure and the guarding rings (Fig. 3) [2] In this figure we compare the phase of the quantum oscillations with that of the Shubnikov-de Haas oscillations (Fig. 3) in the metallic regime; we find that the phases of both types of oscillations strictly coincide.

We explain the observed effects by an influence of the chemical potential, μ_h, in the high electron density regions on the chemical potential, μ_l, in depleted regions. For the simple case of electrically neutral systems the equilibrium state should obey the lever-arm equation. In our case charge transfer caused by the oscillating chemical potential μ_h to bring the 2D system into equilibrium results in the appearance of a difference in contact potential between the high and low density regions. In principle, when the density of states is small, also the electrostatic energy contribution to a change of the electrochemical potential is small, and the system is close to an electrically neutral one. Usually, however, the opposite limit occurs: the electrostatic energy is much larger than the change of either chemical potential. As a result, the latter can be detected if the measured resistance is very sensitive to the level of the chemical potential, which is the case, e.g., in the activated regime.

We note that in 3D systems the charge redistribution caused by a variation of the chemical potential in either region occurs in the vicinity of the junction only, i.e., on the scale of the Thomas-Fermi length. In the 2D case the characteristic scale is given by the distance d from the 2D layer to the gate which is, in general, large compared to the Thomas-Fermi length but is much smaller than the macroscopic dimensions of the 2D system. Therefore one could tentatively expect that the observed phenomenon is a contact effect. In fact, this can be

[1] We note that the symbol dimensions in Fig. 2 do not reflect the accuracy of our measurements. There is ambiguity what resistance should be used as a characteristics of the device: either zero field resistance or the resistance at a magnetic field corresponding to the oscillation given. The size of symbols in Fig. 2 is chosen to cover this uncertainty.

[2] One of the two samples structured by rings was made of wafer with lower mobility $\approx 8 \times 10^5$ cm^2/Vs. The growth of the oscillation amplitude in this case is also observable, though less pronounced compared to that in the other samples.

checked experimentally: the measurements on patterned samples show the growth of oscillations due to the guarding rings (Fig. 3). Since the distance between the patterned area and the guarding rings is about 50 μm *we do not believe that the observed effects are due to contact effects.* The obvious contradiction can be resolved when considering the equations describing the screening problem. For the sake of simplicity let us consider a gate in the form of an infinite strip of width $-L < x < L$ separated from the 2DEG by the distance d. Applying a negative voltage V_g to the gate produces changes in the charge density $N_g(x)$ on the gate and $N(x)$ on the 2D plane. We have from the electro-neutrality condition

$$\int_{-\infty}^{\infty} \Big(N(x) + \Theta(x+L)\Theta(L-x)N_g(x)\Big)\mathrm{d}x = 0. \tag{1}$$

Besides, in equilibrium the electrochemical potentials of both the 2DEG and the gate should be constant and the difference between them is equal to eV_g

$$\int_{-\infty}^{\infty} \Big(N(x')\ln \mid x-x' \mid \; + \; \Theta(x'+L)\Theta(L-x')N_g(x')\ln\sqrt{(x-x')^2+d^2}\Big)\mathrm{d}x' - \\ - \kappa N(x)/2e^2D = \mathrm{const}, \tag{2}$$

$$\int_{-\infty}^{\infty} \Big(N(x') \; - \; \Theta(x'+L)\Theta(L-x')N_g(x')\Big)\ln\Big(1+d^2/(x-x')^2\Big)\mathrm{d}x' + \\ + \kappa N(x)/e^2D_l = \kappa V_g, \quad -L < x < L. \tag{3}$$

Here κ is dielectric permeability, the thermodynamical density of states $D = D_l$ if $-L < x < L$ and $D = D_h$ otherwise, $\Theta(x) = 1$ when $x \geq 0$ and $\Theta(x) = 0$ when $x < 0$.

Analysis of Eqs. (1-3) shows that only in the limiting case $L \to \infty$ the charge density change in a gated region is given by the expression $N = V_g/(4\pi d/\kappa + 1/e^2D_l)$. In a finite system the change of charge density below the gate is smaller and it is influenced by the density of states D_h in the guarding rings in a similar way to the lever-arm equation. Indeed, the solution $N(x)$ represents a nearly flat maximum in the gated region which, after an abrupt drop on the scale $\sim d$ near the gate edges, is followed by slowly decaying (without a characteristic scale) "tails" in the ungated regions. Decreasing D_h suppresses the "tails", thereby giving rise to an increase of the maximum. As a result, the electron density below the gate diminishes, which implies an increase of the sample resistance R. One concludes that a maximum in R is observed whenever D_h is minimum, in agreement with the experiment. Hence, the oscillations of the resistance R are controlled by *the modulation of the density of states D_h rather than by the variation of μ_h itself.* As follows from the solution of Eqs. (1)-(3), in the activated regime the relative oscillation amplitude $\Delta R/R = \Delta\mu_l/kT$ is expected to be close (at constant temperature) to a constant value because at small relative variations of V_g the magnitude of $\Delta\mu_l$ is basically determined by the modulation of D_h. The corrections in the variable range hopping regime as well as those caused by a change of temperature are in qualitative agreement with the experimental observations.

Thus, we can describe our experiment in the framework of chemical potential oscillations owing to oscillations in D_h. At this point it is interesting to compare the oscillations observed here with those of the metal-insulator phase boundary in

the case of Si MOSFET's [2–6] low-mobility AlGaAs/GaAs heterostructures [7–10]. Analyzing the behaviour of the phase boundary in these studies we find that in the insulating phase the resistance has minima at integer filling factors when one can expect minima in the density of states. Therefore the oscillation phase is different by 180^0 from that observed here. This allows us to discriminate between the two theoretical approaches mentioned above. We argue that the behaviour of the metal-insulator phase boundary is determined by oscillations of the mobility edge when the extended states leave the centers of the Landau levels, shifting-up in energy (*i.e.*, floating up [5, 6, 10]) with decreasing magnetic field.

In summary, we have studied the quantum oscillations in high-mobility AlGaAs/GaAs heterostructures with an artificial potential profile. We find that in an insulating phase the amplitude of the oscillations caused by high density regions increases linearly with the sample resistance which, in turn, is dominated by the low density regions. This means that a variation of the chemical potential in some region of the 2DEG leads to the redistribution of electrons over the whole 2D plane. A model invoking chemical potential oscillations is capable of describing the experimental data. Our results also give evidence that the reentrant behaviour cannot be explained in terms of chemical potential oscillations.

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