

Resistance Noise Scaling in a Dilute Two-Dimensional Hole System in GaAs

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(Received 24 September 2002; published 19 February 2003)

We have measured the resistance noise of a two-dimensional (2D) hole system in a high mobility GaAs quantum well, around the 2D metal-insulator transition (MIT) at zero magnetic field. The normalized noise power S_R/R^2 increases strongly when the hole density p_s is decreased, increases slightly with temperature (T) at the largest densities, and decreases strongly with T at low p_s . The noise scales with the resistance, $S_R/R^2 \sim R^{2.4}$, as for a second order phase transition such as a percolation transition. The p_s dependence of the conductivity is consistent with a critical behavior for such a transition, near a density p^* which is lower than the observed MIT critical density p_c .

DOI: 10.1103/PhysRevLett.90.076402

PACS numbers: 71.30.+h, 71.27.+a, 72.70.+m, 73.21.Fg

Two-dimensional (2D) dilute electronic systems at low temperature offer the unique opportunity to study the physical effects of strong Coulomb interactions. At low densities and in the limit of weak disorder, the correlations between the carriers should overcome the random motion of the electrons due to the fermions' confinement. The relative magnitude of these two effects is expressed by the ratio $r_s = E_{ee}/E_F$ between the Coulomb interaction (E_{ee}) and the Fermi (E_F) energies, which is proportional to $m^*/p_s^{1/2}$, m^* being the effective mass of the carriers, and p_s their areal density. For $r_s \gg 1$, one expects to observe a Wigner crystal [1], thus raising the question of the nature of the transition to this state by varying the density. The recent observations of a metallic behavior at intermediate r_s values, $4 < r_s < 36$, in 2D electron or hole systems (2DES or 2DHS) in high mobility silicon metal-oxide-semiconductor field effect transistors (Si-MOSFETs) and in certain heterostructures has raised the possibility of a new metallic phase due to the interactions [2]. The metallic behavior is defined by a decrease of the resistivity ρ for decreasing temperature T , for p_s larger than a critical density p_c . In contrast, an insulating behavior ($d\rho/dT < 0$) occurs for $p_s < p_c$. However, the nature of this metal-insulator transition (MIT) remains the subject of ongoing debate [2–17].

Real systems are subject to disorder, which makes the physical situation much richer. Experimentally, around the MIT, the physical observables depend significantly on the disorder [2,5–10]. Weak disorder could reduce the threshold for Wigner crystallization r_s^w from $r_s^w = 37 \pm 5$ [1] to $r_s^w \approx 7.5$ [18]. The system may also freeze into a glass [9,10,19,20] instead of crystallizing. In GaAs 2DHS, recent local electrostatic studies [11] and parallel magnetoresistance measurements [12] suggest the coexistence of two phases. Such a situation has been predicted by theories in which the disorder induces the spatial separation of a low and a high density phase [15–17]. In

these models, the transport and other physical properties result from the percolation of the most conducting phase through the insulating one. Such descriptions must be distinguished from the percolating network of Fermi liquid puddles connected by quantum point contacts [13]: In this case, only one phase is present due to the absence of interactions.

Resistance noise provides complementary information to that obtained from DC transport experiments, as shown recently in Si-MOSFETs close to the MIT [9,10]. In this paper, we present the first resistance noise measurements in a high mobility GaAs 2DHS at low densities, around the MIT. The density and temperature dependences of the normalized noise power S_R/R^2 indicate the onset of a new behavior as the density is decreased. We observe a clear scaling of the noise power vs resistance, suggesting the presence of a second order phase transition at a density lower than p_c , which could be a percolation transition. This possibility is supported by a scaling analysis of the conductivity vs density.

The samples are 2DHS created in Si modulation doped (311)A GaAs quantum wells. The front gate used to change the density is evaporated onto a 1 μm thick polyimide insulating film. This reduces leakage between the gate and the 2DHS to a negligible level and reduces the screening of the hole-hole interactions by the gate. The mobility at a density $p_s = 6 \times 10^{10} \text{ cm}^{-2}$ is $5.5 \times 10^5 \text{ cm}^2/\text{Vs}$ at 100 mK. The experiments were carried out on Hall bars 50 μm wide, with a distance of 300 μm between the voltage probes. The fluctuations of the voltage were measured as a function of time, for a fixed injected current I , low enough to ensure Ohmic conduction. The voltage noise power spectrum S_V (obtained in the $f = 0.01\text{--}3 \text{ Hz}$ interval) is calculated by using the cross-correlation technique [21] for the two voltage noise signals measured on opposite sides of the Hall bar [V_1 and V_2 in the inset of Fig. 1(b)]. This allows us to minimize

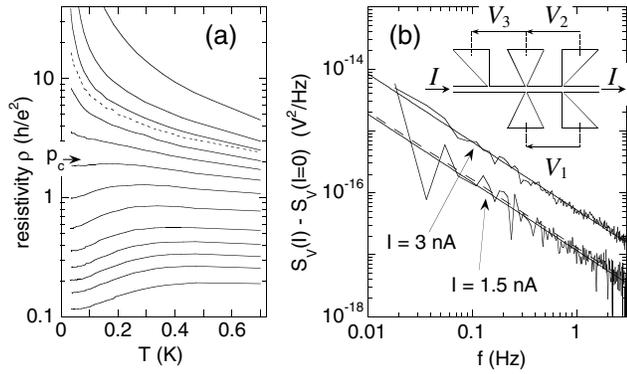


FIG. 1. (a) ρ vs T for densities $p_s = (1.30, 1.39, 1.43, 1.44, 1.48, 1.52, 1.57, 1.63, 1.74, 1.86, 1.96, 2.06, 2.16, 2.31) \times 10^{10} \text{ cm}^{-2}$ (from top to bottom). The dashed line is the $\rho(T)$ curve corresponding to the p_s limit $p'_c = 1.44 \times 10^{10} \text{ cm}^{-2}$, under which the activated law analysis is valid. (b) S_V vs frequency at $p_s = 1.75 \times 10^{10} \text{ cm}^{-2}$ and $T = 300 \text{ mK}$, for two currents $I = 3$ and 1.5 nA . The continuous straight lines are fits of the law A/f^α with $\alpha = 1.1$, and the dashed line is the fit for $I = 3 \text{ nA}$ divided by 4. Inset: Schematic view of the Hall bar, showing the three voltages used in the correlation measurements.

the noise due to the contacts and preamplifiers (LI75A, NF Instruments). We verified that $S_V(I) - S_V(0)$ was proportional to I^2 as expected for resistance noise [see Fig. 1(b)], and we define the resistance noise power as $S_R = [S_V(I) - S_V(0)]/I^2$. The possible contributions of external fluctuations (e.g., gate voltage, current, or temperature) were ruled out by measuring the correlation S'_V between the voltage noise along two different parts of the Hall bar [V_1 and V_3 in the inset of Fig. 1(b)]. $S'_V(I)$ and $S'_V(0)$ were independent of the frequency, contrary to $S_V(I)$, and their magnitudes were identical, well below $S_V(I)$. We verified that a correlation measurement on a single side of the Hall bar gives the same noise magnitude as for the standard measurement, and that S_V measured on a $600 \mu\text{m}$ bar made of two contiguous $300 \mu\text{m}$ sections is close to the sum of the values for each section, thus proving that possible geometrical effects due to the finite width of the bar are weak.

Figure 1(a) shows the temperature dependences of the resistivity ρ . The curves are similar to those obtained in other high mobility 2DHS in GaAs [2,5]. The change of slope from $d\rho/dT > 0$ to $d\rho/dT < 0$ attributed to the 2D MIT occurs at $p_c = (1.57 \pm 0.02) \times 10^{10} \text{ cm}^{-2}$ corresponding to $r_s^c \approx 24$ (assuming $m^*/m_e = 0.37$ [22]). At densities below $p'_c = (1.44 \pm 0.05) \times 10^{10} \text{ cm}^{-2}$, an activated law $\rho(T) \propto \exp(T_0/T)$ fits the data below a temperature $T_l(p_s)$ which increases when p_s decreases. Activated laws have been found in Si-MOSFETs [9,10,23,24]. T_0 depends linearly on p_s and vanishes at p'_c .

The resistance noise spectra have been measured for densities p_s ranging from 1.50 to $1.78 \times 10^{10} \text{ cm}^{-2}$ (thus, on both sides of the MIT at $p_c \approx 1.57 \times 10^{10} \text{ cm}^{-2}$), and for temperatures from 35 to 700 mK . They could be

satisfactorily fitted with a law $S_R(f) = A/f^\alpha$, A and α being the fit parameters. α does not show any strong variation as a function of p_s or T , and remains in the interval 0.9 – 1.3 . The normalized noise magnitude at 1 Hz , $S_R/R^2(1 \text{ Hz}) = A/R^2$ (R is the average resistance), increases strongly when p_s decreases [see Fig. 2(a)], indicating the onset of a new regime at low density. However, the continuous evolution as a function of p_s could indicate that this regime is already present at $p_s > p_c$, as suggested by local compressibility measurements in p -GaAs [11] and noise measurements in Si-MOSFETs [9,10]. The onset of a new regime at low density also appears in the temperature dependences: Their slopes go from positive to negative as p_s decreases [see Fig. 2(b)]. A decrease of the noise magnitude when the temperature increases is expected for a degenerate system at low temperature [25] or for localized electrons [26]. The increase we observe at high density is thus of strong interest. An increase is expected in the diffusive regime without quantum interference effects [27], at high temperature. In our case, it could be related to the temperature dependent screening [28] of the fluctuating disorder potential.

The temperature and density dependences of the noise are qualitatively similar to those in Si-MOSFETs [9,10], but we do not observe a comparable increase of α from 1 to 1.8 when p_s decreases. The low level and different nature of the disorder in p -GaAs in comparison to Si-MOSFETs may contribute significantly to this difference. Many studies have probed the physical importance of the disorder magnitude [2,5–10,18], but its nature could play a role also [15,17,29]. The very short sample geometry in Ref. [9] could also play a role, but similar behavior observed in much longer samples [10] seems to speak against this possibility [30].

Our main result is shown in Fig. 3. The normalized resistance noise S_R/R^2 scales as a function of the resistance R , whatever the density or the temperature, and the dependence is a power law. A fit of all the points gives $S_R/R^2 \sim R^{2.40 \pm 0.06}$. We verified that this power law dependence remained true for each temperature. This

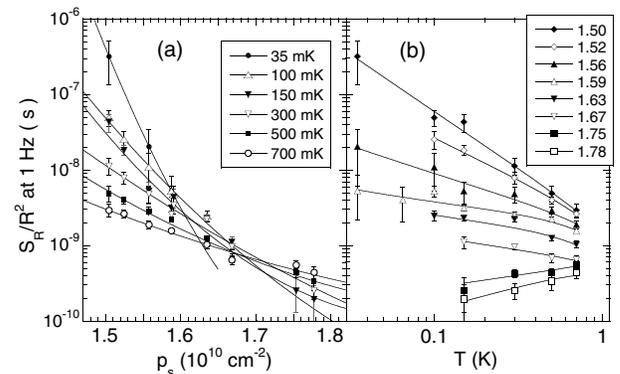


FIG. 2. (a) $S_R/R^2(1 \text{ Hz})$ vs density for six temperatures. (b) S_R/R^2 vs T , for eight densities indicated in units of 10^{10} cm^{-2} . In (a) and (b), the lines are guides to the eye.

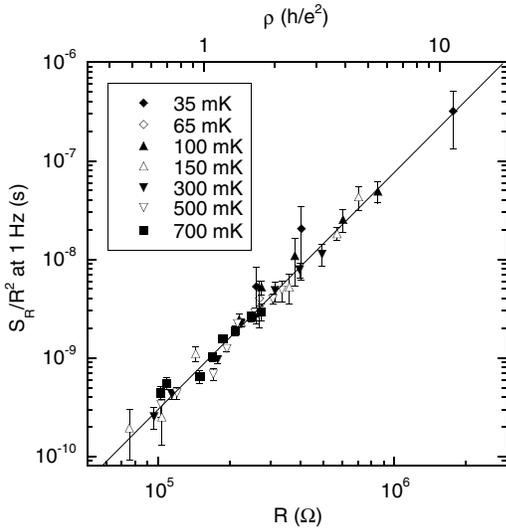


FIG. 3. Normalized noise power at 1 Hz as a function of the resistance at various temperatures, and for all the densities investigated between $1.5 \times 10^{10} \text{ cm}^{-2}$ and $1.78 \times 10^{10} \text{ cm}^{-2}$. The line is a fit with the power law $S_R/R^2 \sim R^{2.4}$.

scaling suggests the existence of a second order phase transition occurring at a critical density lower than $1.5 \times 10^{10} \text{ cm}^{-2}$, the minimum density at which the noise has been measured. It could be a percolation transition as suggested by the theoretical arguments given earlier.

For a percolation transition, with x the filling parameter of the network and x^* its critical value, the conductivity $\sigma \sim 1/R$ vanishes, and S_R/R^2 diverges when $x \rightarrow x^*$ and $x > x^*$. They follow the scaling laws [31]

$$\sigma \sim (x - x^*)^t \quad \text{and} \quad S_R/R^2 \sim (x - x^*)^{-\kappa}, \quad (1)$$

κ and t being, respectively, the critical exponents of the resistance noise and conductivity. Thus,

$$S_R/R^2 \sim R^w \quad \text{with} \quad w = \kappa/t. \quad (2)$$

As Eq. (2) is independent of x , it allows one to investigate the scaling if x is unknown. Our results would thus lead to $w = 2.40 \pm 0.06$. Simulations of percolation transitions in 2D yield $w = 1$ for a square lattice network [32], and $w = 3.2$ for a continuous random-void model [33]. Our case should be intermediate between these limits, as the distance between the sites should be neither constant nor completely random. Recent simulations of a 2D random resistance network yields $w = 2.6$ [34]. Such a scaling has been found in experiments on classical percolating 2D systems, with $w = 3.4\text{--}4.2$ for sand blasted metal films [35], and $w = 2.0 \pm 0.1$ for thin gold films [36].

We now consider the nature of the MIT we observe at $p_s = p_c$ in light of our results on the noise. Whether such a MIT is a “true” quantum phase transition has been discussed by many authors [2–17]. A similar situation has been already studied in three-dimensional systems, i.e., the behavior of the resistance noise close to the Anderson transition [37]. The noise was attributed to fluctuations of the system between the metal and the insulator due to the

fluctuations of the disorder potential. The authors have shown theoretically and experimentally that such a system presents an exponential increase of the relative noise magnitude as a function of the resistance. In our case, the exponential dependence is incompatible with the data. We can thus draw the important conclusion that such a type of transition is excluded in our 2DHS.

To examine further the data in terms of a percolation transition, we investigate the possible scaling of the conductivity, i.e., $\sigma \sim (x - x^*)^t$. The fact that our experimental points in Fig. 3 scale together whatever the temperature suggests that x is a function of both p_s and T . We consider the $x(p_s)$ dependence at a given low temperature. The simplest relationship $x \sim p_s$ is obtained in models where the disordered potential landscape is progressively filled by the Fermi liquid when the density increases [13]. Other models, in which the interactions play the major role, predict the percolation of a conducting phase in an insulating one [15–17]. In such models, x is a more complex function of p_s . To investigate the first class of models, we fitted the σ vs p_s dependences for $p_s > 1.5 \times 10^{10} \text{ cm}^{-2}$ with the law $\sigma = \lambda(p_s - p^*)^t$, t , p^* , and λ being the parameters of the fit. The result is shown on Fig. 4(a) for three temperatures. The fits are good, but the exponent t varies between 1.35 ± 0.1 and 1.9 ± 0.2 when the temperature is varied. The scaling of the noise whatever the temperature suggests on the contrary that t is universal and independent of the temperature. Moreover, a value close to 1.3 is expected in 2D systems [13]. We thus go to the second class of models. Shi *et al.* suggested that $x \sim p_s^\beta$ with $\beta > 1$, in order to account for the experimental compressibility measurements [17]. The fits of $\sigma(p_s)$ with $\lambda'(p_s^\beta - p^{*\beta})^t$ show that, for $\beta \approx 2$, the t values are rather close to each other and to 1.3 when T varies: They range from 1.2 ± 0.1 to

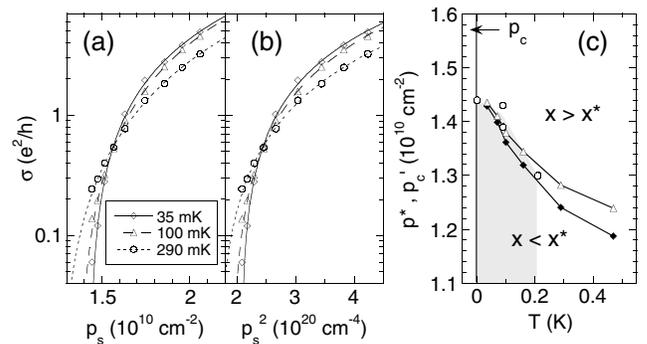


FIG. 4. (a) Conductivity vs density for three temperatures. The lines are fits with $\sigma \sim [p_s - p^*(T)]^t$. (b) The same data as in (a), plotted as a function of p_s^2 . The lines are fits with $\sigma \sim [p_s^2 - p^{*2}]^t$. (c) Temperature dependence of p_c^* . The closed diamonds (open triangles) correspond to $\sigma \sim (p_s - p^*)^t$ [$\sigma \sim (p_s^2 - p^{*2})^t$]. Open circles: p_s limit below which $\rho(T)$ can be fitted with an activation law $\propto \exp(T_0/T)$. At $T = 0$, this corresponds to $p_s = p_c^*$. The shaded area is the domain where the activation law is valid.

1.45 ± 0.15 . Figure 4(b) shows the quality of the fits with $\sigma = \lambda'(p_s^2 - p^{*2})^t$. The fact that t has a weaker T dependence and is closer to 1.3 thus favors the models in which the interactions govern a phase separation. The main conclusion of these σ vs p_s studies is that they are in agreement with a critical behavior of the conductivity, thus *supporting* the assumption that the noise vs resistance law is the signature of a phase (percolation) transition. As expected, the critical densities p^* extracted from the fits are lower than the minimum p_s value of the noise measurement range.

Figure 4(c) gives the possible phase diagram of the percolation transition, i.e., the temperature dependence of the critical density $p^*(T)$ extracted from the fits of $\sigma(p_s)$. The two lines correspond to $x \sim p_s$ (closed diamonds) and to $x \sim p_s^2$ (open triangles). They are close to each other and to the boundary (open circles) between the two domains where the activation law analysis $\rho(T) \propto \exp(T_0/T)$ is valid or not, i.e., the $T_i(p_s)$ line mentioned above. This result is consistent with the percolation interpretation: Below the percolation threshold, the system consists of isolated conducting regions between which the conduction electrons jump due to thermal activation. Such a description has been proposed to analyze the properties of the insulator close to the quantum Hall-insulator transition [38]. The experimental result that the $B = 0$ MIT is continuously connected to the quantum Hall-insulator transition [39] could thus be related to their common percolating nature.

In conclusion, the resistance noise of a high mobility gated p -GaAs quantum well at low density exhibits a huge increase of the noise power S_R/R^2 when the density decreases, accompanied by a change of its temperature dependence slope. The noise vs resistance dependence exhibits a scaling behavior for all densities and temperatures studied, $S_R/R^2 \sim R^{2.4}$. The corresponding critical behavior is confirmed by conductivity vs density analyses which allow one to extract the critical density $p^*(T)$ of a transition which could be of percolative nature. p^* is lower than p_c , the usual MIT critical density. The non-exponential S_R/R^2 vs R dependence does not favor a true MIT at $p_s = p_c$. The percolation could be that of a conducting phase in an insulating one as suggested by theories of interacting electrons.

The authors thank J.-P. Bouchaud, G. Deville, and D. C. Glattli for useful discussions, and are grateful to F. I. B. Williams for his help in initiating the project.

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