PHYSICAL REVIEW B **85**, 041304(R) (2012)

Nonactivated transport of ultradilute two-dimensional hole systems in GaAs field-effect transistors: Interaction versus disorder

Jian Huang,[1,2] L. N. Pfeiffer,[2] and K. W. West[2]

[1]*Department of Physics and Astronomy, Wayne State University, Detroit, Michigan 48201, USA*

[2]*Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, USA*

(Received 2 December 2011; revised manuscript received 30 December 2011; published 17 January 2012)

Very strongly interacting high-purity two-dimensional (2D) electron systems at temperatures $T \to 0$ demonstrate certain nonactivated insulating behaviors that are absent in more disordered systems. By measuring in dark the T dependence of the conductivity of ultrahigh-quality 2D holes with charge densities down to 7×10^8 cm^{-2}, an approximate power-law behavior is identified. Moreover, the exponent exhibits a linearly decreasing density dependence which suggests an interaction-driven nature. Such an electron state is fragile to even a slight increase of disorder, which causes a crossover from nonactivated to activated conduction. The nonactivated conduction may well be a universal interaction-driven signature of an electron state of strongly correlated (semiquantum) liquid.

DOI: 10.1103/PhysRevB.85.041304 PACS number(s): 71.27.+a, 71.30.+h, 71.55.Eq, 72.15.Rn

Most transport experiments on dilute electron systems at low temperatures demonstrate activated conduction: $\sigma(T) \sim e^{(T^*/T)^\mu}$, with T^* being the characteristic energy, and $\mu = 1/3, 1/2$ corresponding to Mott[1] and Efros-Shklovskii variable range hopping (VRH)[2] and $\mu = 1$ for Arrhenius conductivity. Generally, such a phonon-assisted hopping behavior is consistent with the Anderson localization[3] model developed for noninteracting electrons. On the other hand, electron-electron interaction is expected to also bring significant changes to the electron states. The metal-to-insulator transition (MIT)[4] in two dimensions (2D) is a good example of the important role of interaction that significantly modifies the scattering of electrons by disorder. Nevertheless, the usual disorder level dominates when the carrier concentration is low when both the Fermi energy E_F and the Coulomb energy E_{ee} are suppressed. This is why most transport results for the insulating side of MIT have shown activated conduction, confirming the same disorder domination. To understand whether stronger interaction effects bring about qualitative changes, such as the Wigner transition[5–7] or strongly correlated liquids, it is fundamentally important that experiments be performed in cleaner electron systems at lower charge densities. This will allow one to capture the altered transport behaviors from the usual hopping conductance.

Recently, measurements of higher-quality devices, e.g., p-GaAs heterojunction-insulated-gate field-effect transistors (HIGFETs) and SiGe, revealed a nonactivated behavior that persists to very low carrier densities.[8–10] The results for measuring SiGe demonstrate an approximately linear $\sigma(T)$ for a r_s value close to 20 (with a minimum charge density of 3×10^{10} cm^{-2}). For the GaAs cases, for a larger r_s range from 35 to 90, the temperature dependence of the conductivity $\sigma(T)$ exhibits an almost linear dependence when the charge density p is lowered just into the insulating regime and $\sigma(T)$ then becomes power-law-like for lower p. These indications of change of transport behaviors as interaction becomes progressively stronger should provide clues for identifying the contribution due to interaction. Meanwhile, how this peculiar nonactivated insulating behavior ($d\sigma/dT > 0$) qualitatively differs from hopping is also ambiguous. It is then also crucial to vary disorder and observe the transport characteristic changes that will distinguish it from a disorder-dominated scenario. The purpose of this Rapid Communication is to present a study of the density dependence of the nonactivated conductance that demonstrates an interaction-driven origin through a density-dependent scaling. In addition, by slightly increasing disorder within the same system, we show a drastic crossover to activated conduction, thus distinguishing the nonactivated behaviors from a disorder-dominated insulator. A possible strongly correlated semiquantum liquid is also discussed.

The devices used are the undoped GaAs HIGFETs (Fig. 1). The charge carriers are two-dimensional (2D) holes that are capacitively induced at the GaAs/AlGaAs interface without any intentional doping. The disorder level, typically short-ranged impurities in the conduction plane, is greatly suppressed. A change in the interaction is realized through tuning the charge density, ranging from 8×10^{10} cm^{-2} down a record low value of 6×10^8 cm^{-2}, via a metal gate (Fig. 1). No magnetic field is used to preserve the natural carrier wave-function forms. The sample preparation and measurement details for the p-HIGFET are provided in Refs. 11–14. The measurement was made in a dilution refrigerator with the sample placed in a 3He/4He mixing chamber. The density of the 2D holes (p) was determined by measuring the quantum oscillations of the magnetoresistance $R_{xx}(B)$ in a B field. For measurements in the high impedance range, dc techniques with low-level drives (pA and 0.05 μV) were adopted. Results obtained from a standard four-terminal measurement with both current drive setup and voltage drive setup are in agreement. For the low-density, high-impedance cases, T-dependence measurements were repeated a few times with different low current drives ranging from 50 pA to 1 nA, corresponding up to 400 times the power variation in the range of 10^{-12} W. The results produced with different drives remain consistent, indicating that Joule heating is less significant.

The measurements include two steps. First, the T dependence of the conductivity (σ) is measured in dark for a number of charge densities down to 8×10^8 cm^{-2}. Then, a slight light illumination is briefly introduced via a light-emitting diode

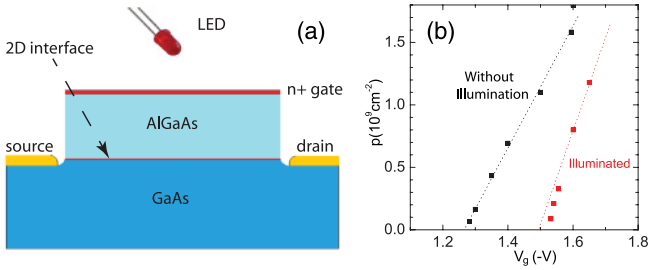

FIG. 1. (Color online) (a) Schematics of the HIGFET structure under LED illumination. (b) HIGFET charge density vs turn-on voltage before and after illumination.

(LED) that provides photons of 1.9–2 eV. The in-dark measurement is then repeated after a sufficient wait time. The results obtained before illumination exhibit nonactivated power-law-like $\sigma(T)$ for charge densities below 2.5×10^9 cm^{-2}, with an exponent that scales with charge density. In contrast, the postillumination results show a suppressed conduction that is activated in nature due to an increase of disorder by light, thus supporting the interaction-driven nature for the nonactivated conduction.

The T dependence of the conductivity before the illumination is shown in Fig. 2. Figure 2(a) shows the $\ln\sigma$ (before illumination) plotted against $\ln T$ for various fixed densities p ranging from 8×10^8 to 6.1×10^9 cm^{-2}. Each curve is for a fixed charge density indicated in the graph. The critical density p_c of the apparent metal-to-insulator transition (MIT) is $\sim 4 \times 10^9$ cm^{-2}. For $p < 4 \times 10^9$ cm^{-2}, the system exhibits an insulating behavior indicated by $d\sigma(T)/dT > 0$. The decrease of $\sigma(T)$ with cooling is stronger for lower charge densities. For the lowest densities, $\sigma(T)$ becomes apparently power-law-like. As shown in Fig. 2(b), fitting to $\sigma(T,p)/(e^2/h) = A + (T/T^*)^B$ for the lowest densities yields that A is approximately zero, within an error bar of 0.02, for p below 2.5×10^9 cm^{-2}. The corresponding r_s value varies between 32 and 58 even if $m^* = 0.2m_0$ is assumed. The exponent $B(p)$ decreases with increasing p in an approximately linear fashion at -0.3 per 1×10^9 cm^{-2} and it varies roughly between 1.6 and 1.2. The fitting parameter T^* shows an increase with decreasing density as shown in Fig. 2(d). The values for T^* are 388, 376, 355, and 346 mK for $p = 0.8$, 1.2, 1.6, and 1.8×10^9 cm^{-2}. When $\sigma^{1/B}$ is then plotted versus (T/T^*) in Fig. 2(c), all four curves for $p < 2 \times 10^9$ cm^{-2} collapse into a single curve. We note that accurate power-law fitting with $R^2 \geqslant 0.9995$ is found only for T below some temperatures $\sim$220 mK. As seen in Fig. 2(c), $T/T^* \sim 0.5$ corresponds to a temperature of $\sim$220 mK, where a slight break is found. This is the characteristic temperature at which a conductivity kink has been recently reported.[15]

We note that the disorder present in HIGFETs is predominantly short ranged, making the system an ideal candidate for an Anderson insulator. Weaker disorder, i.e., the weak-localization scenario, with moderate interaction corrections should result in logarithmic T dependence.[16] However, none of the disorder-dominated behaviors was present. Instead, the power-law-like behavior suggests a collective nature of the carrier state. As shown below, this nonactivated behavior is fragile to the increase of disorder which qualitatively alters the conduction behavior.

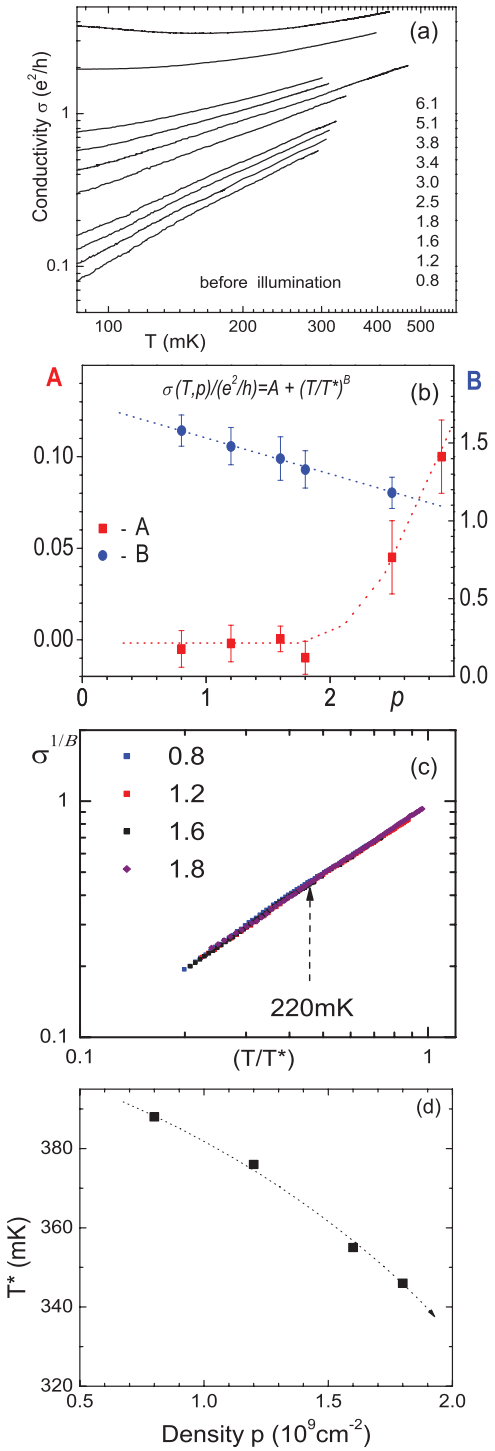

FIG. 2. (Color online) (a) Preillumination T dependence of the conductivity σ for a number of densities (in units of 10^9 cm^{-2}). (b) Fitting parameters $A(p)$ and $B(p)$. (c) Collapse of the $\sigma^{1/B}$ for the lowest four densities plotted against T/T^*. (d) T^* vs charge density p.

Following the measurement in dark, light is briefly introduced to modify the disorder level. The typical way of studying variable disorder effects is through preparing multiple devices, each having a different fixed disorder configuration.[17,18] Both

the type and amount of disorder can be quite difficult to control since the samples are taken from different wafers that are grown through different processes (i.e., doping and temperature). Plus, different samples have to go through different cooling cycles. That adds another cause of disorder variation due to the different quenching processes. We utilize LED illumination to reconfigure disorder by adding long-ranged disorder within the *same system and the same cooling cycle*. The procedure is as follows: The sample is first lowered to a base temperature of 25 mK. The LED was mounted 1.5 cm away from the top of the sample (Fig. 1) and powered by a current source with its output set to 0.1 μA. The LED was turned on for 1 s while the top gate was biased at -1.2 V. After turning the device off and grounding all sample leads, there was a 24-h waiting time before the in-dark measurement was resumed. The data collected thereafter are consistent. As shown in Fig. 1(b), the turn-on or threshold voltage ($V_{\rm th}$) is shifted from roughly -1.2 to -1.55 V by the light. $V_{\rm th} = -1.55$ V is indeed the expected value from calculations. This suggests that there exist charged impurities, most of which are neutralized by the electrons and holes produced during illumination. The effective capacitance is also increased as expected.

The change in the density-mobility (μ) relationship due to the illumination is recently reported as a result of the long-range disorder introduced by light. What is remarkable about the changes in $\mu(p)$ is that it exhibits little change for $p \geqslant 2 \times 10^{10}$ cm^{-2}, but differed by orders of magnitudes for densities below. This can be explained by the diminishing of the nonlinear screening of long-ranged disorder when the charge concentration is tuned to such a dilute limit.[14,19,20] Screening becomes weakened overall as the charge density is decreased. Eventually, at sufficiently low charge densities, disorders become unscreened as the screening length is exceeded by the average charge spacing ($2a$, a being the Wigner-Seitz radius), resulting in maximum scattering. Such a drastic change in $\mu(p)$ should not be present if the disorder were short range in nature. Thus, the change in $\mu(p)$ before and after LED illumination helps to identify the long-range nature of the disorder. The average charge spacing varies approximately from 100 to 400 nm for the measured charge densities from 7 to 0.7×10^9 cm^{-2}. Theoretical calculations on the p and T dependence of the screening length are not yet available.

Contrast to the power-law-like $\sigma(T)$ observed before illumination, the postillumination $\sigma(T)$ for $p < p_c$ shown in Fig. 3(a) exhibits severely suppressed conductivity with cooling. Note that the solid curves, which are the ac measurement results, are connected with the scattered points, which are the dc results, by artificial dotted lines for the same densities. The critical density p_c of the apparent metal-to-insulator transition (MIT) is estimated as $\sim 1 \times 10^{10}$ cm^{-2} after the illumination, significantly higher than the p_c of $\sim 4 \times 10^9$ cm^{-2} obtained before the illumination. This is expected since p_c is sensitive to the effect of disorder-interaction interplay.

Replotting the postillumination $\sigma(T)$ for two randomly picked charge densities in semilog scales, $\ln\sigma$ vs $1/T$, Fig. 3(b) confirms the phonon-activated nature of the transport which signifies a disorder domination in contrast to the preillumination scenario. Taking $p = 2.8 \times 10^9$ cm^{-2} as an

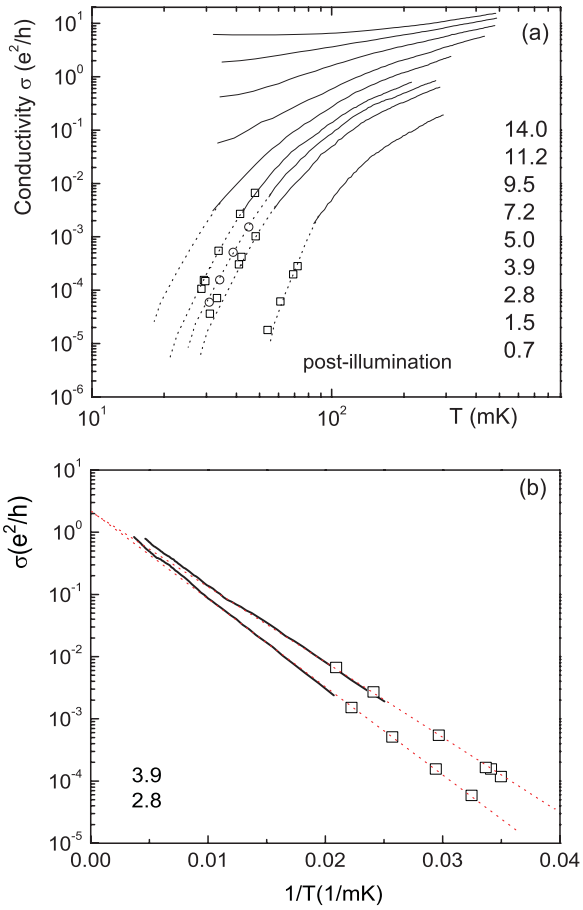

FIG. 3. (Color online) (a) $\ln\sigma$ vs T for densities from 14 to 0.7×10^9 cm^{-2}. (b) $\sigma(T)$ vs $1/T$ for $p = 2.8$ and 3.9×10^9 cm^{-2}.

example, fitting to the Arrhenius conductivity $\sigma(T,p) = \sigma_0 \exp(-T^*/T)$ e^2/h produces $R^2 = 0.9997$, $\sigma_0 = (2.1 \pm 0.1)e^2/h$, and $T^* = (264 \pm 11)$ mK. $\sigma \sim \sigma_0 \sim 2e^2/h$ in the limit of $T^*/T \ll 1$ is in agreement with a previous observation obtained in doped GaAs heterostructure 2D systems.[21] Meanwhile, $T^* = 264$ mK is significantly less than the characteristic temperature found previously for the variable range hopping cases,[4,21] confirming a lower disordered environment.

The results from both parts of the measurements support a strongly correlated regime that is not well understood. Generally, lowering of the charge density should drive a system away from a Fermi-liquid state into a Wigner crystal state given T below the melting point of the Wigner crystal and disorder is sufficiently small. Even if the two conditions are met, there exists another fundamental question regarding the nature of the phase transition, whether a first-order liquid-to-solid phase transition or intermediate phases,[22] that are still under debate. The density range corresponding to such a transition (with r_s from 25 to $\geqslant$40) is within the density range of this measurement. However, the charge state is also subject to the finite experimental temperature which competes with the Coulomb energy E_{ee} and Fermi energy E_F, especially at the lowest charge densities. For instance, the estimated Fermi temperature T_F for p from 0.8 to 2×10^9 cm^{-2} is from 0.09 to 0.27 K assuming $m^* \sim 0.2m_0$. The corresponding

Coulomb energy varies between ∼7 and 15 K. This T_F is much smaller than the Debye temperature, but comparable to the experimental temperatures. On the other hand, although the melting temperature of a Wigner crystal for the quantum case, in contrast to the classical Wigner crystal observed by Grimme and Adams, is yet another known factor, it is expected to be lower than the classical melting temperatures, which are already comparable to the experimental temperatures. Thus, the system we measured is probably a semiquantum liquid.[22,23]

The transport of a strongly correlated semiquantum liquid is an interesting area of physics that is little known. A relevant model for the transport is the semiquantum hydrodynamical viscous flow calculated originally for the high-frequency response of neutral particles.[23] An important prediction from Andreev's model for the transport characteristic is the linear temperature dependence of the conductivity $\sigma(T,p) \propto (1/\eta) \propto T$ (η viscosity), which is weaker than the exponential law. This seems to be similar to our experimental results of $\sigma(T) \sim T^B$ with $B \sim 1.2$, given the charge density is not too low. Nevertheless, applying the model to electrons, as was recently adopted to describe the conductance of an intermediate electron microemulsion phase, must be justified. This hydrodynamic model should be expanded to incorporate Coulomb force and disorder, both of which should give rise to η and result in a stronger T dependence than the linear prediction. This is in qualitative agreement with the exponents (of the power-law-like σ) that is larger than 1 in our observation.

The long-range disorder introduced by light makes the postillumination system a better candidate for percolation[24,25] than for an Anderson insulator, even though the Arrhenius behavior is somewhat unexpected due to the presence of a strong interaction effect.[26] The smallness of T^* is due to the lower disorder level present in the system. Further studies on the light effect are needed to determine how the transport varies as a function of the illumination time and the photon energy.

We note that the interaction parameter r_s is difficult to be determined exactly due to the complex effective mass, specifically the nonhyperbolic dispersion relation at such dilute charge concentrations. It is only estimated as $m^* \sim 0.2m_0$ by considering that only the lowest heavy-hole (HH) subband[27] is occupied. Nonetheless, r_s reaches beyond 40 for the lowest densities.

To summarize, we have observed a charge-density-dependent nonactivated transport of the ultraclean 2D holes in a strongly correlated regime with charge densities down to 8×10^8 cm^{-2}. The corresponding r_s values are beyond 40. The remarkable density-dependent scaling of the $\sigma(T)$ captures the interaction-driven nature of the charge states. The LED illumination is proved to be effective in introducing long-ranged disorder. Moreover, it brings a crossover to a disorder-dominated activated conductivity as a qualitative distinction from the nonactivated conductivity obtained before the illumination. The interaction-driven nature of the carrier is further confirmed. Whether the nonactivated behavior is a universal indication of a strongly correlated semiquantum liquid needs to be further explored.

[1] N. F. Mott, J. Non-Cryst. Solids **1**, 1 (1968).
[2] A. L. Efros and B. I. Shklovskii, J. Phys. C **8**, L49 (1975).
[3] P. W. Anderson, Phys. Rev. **109**, 1492 (1958).
[4] S. V. Kravchenko, Whitney E. Mason, G. E. Bowker, J. E. Furneaux, V. M. Pudalov, and M. DIorio, Phys. Rev. B **51**, 7038 (1995).
[5] E. P. Wigner, Phys. Rev. **46**, 1002 (1934).
[6] B. Tanatar and D. M. Ceperley, Phys. Rev. B **39**, 5005 (1989).
[7] E. Abrahams, S. V. Kravchenko, and M. P. Sarachik, Rev. Mod. Phys. **73**, 251 (2001).
[8] Hwayong Noh, M. P. Lilly, D. C. Tsui, J. A. Simmons, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **68**, 241308(R) (2003).
[9] Jian Huang, D. S. Novikov, D. C. Tsui, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **74**, 201302(R) (2006).
[10] K. Lai, W. Pan, D. C. Tsui, S. Lyon, M. Muhlberger, and F. Schaffler, Phys. Rev. B **75**, 033314 (2007).
[11] B. E. Kane, L. N. Pfeiffer, and K. W. West, Appl. Phys. Lett. **67**, 1262 (1995).
[12] Harrell *et al.*, Appl. Phys. Lett. **74**, 2328 (1999).
[13] Jian Huang, D. C. Tsui, L. N. Pfeiffer, and K. W. West, Int. J. Mod. Phys. B **21**, 1219 (2007).
[14] Jian Huang, L. N. Pfeiffer, and K. W. West, Appl. Phys. Lett. **98**, 092105 (2011).
[15] Jian Huang, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **83**, 081310(R) (2011).
[16] B. L. Altshuler, A. G. Aronov, and P. A. Lee, Phys. Rev. Lett. **44**, 1288 (1980).
[17] W. Li, C. L. Vicente, J. S. Xia, W. Pan, D. C. Tsui, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **102**, 216801 (2009).
[18] W. R. Clarke *et al.* Nat. Phys. **4**, 55 (2007).
[19] S. Das Sarma, M. P. Lilly, E. H. Hwang, L. N. Pfeiffer, K. W. West, and J. L. Reno, Phys. Rev. Lett. **94**, 136401 (2005).
[20] D. S. Novikov, Phys. Rev. B **79**, 235304 (2009).
[21] M. Y. Simmons, A. R. Hamilton, M. Pepper, E. H. Linfield, P. D. Rose, and D. A. Ritchie, A. K. Savchenko, and T. G. Griffiths, Phys. Rev. Lett. **80**, 1292 (1998).
[22] B. Spivak, S. V. Kravchenko, S. A. Kivelson, and X. P. A. Gao, Rev. Mod. Phys. **82**, 1743 (2010).
[23] A. F. Andreev, JETP Lett. **28**, 5571978 (1978) [Sov. Phys. JETP **50**, 12181979 (1979)].
[24] A. L. Efros, Solid State Commun. **70**, 253 (1989).
[25] S. Das Sarma, M. P. Lilly, E. H. Hwang, L. N. Pfeiffer, K. W. West, and J. L. Reno, Phys. Rev. Lett. **94**, 136401 (2005).
[26] D. M. Basko, I. L. Aleiner, and B. L. Altshuler, Ann. Phys. (NY) **321**, 1126 (2006).
[27] R. Winkler, E. Tutuc, S. J. Papadakis, S. Melinte, M. Shayegan, D. Wasserman, and S. A. Lyon, Phy. Rev. B **72**, 195321 (2005).