Article

Metal-to-Insulator Transitions in Strongly Correlated Regime

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Abstract: Transport results from measuring ultra-clean two-dimensional systems, containing tunable carrier densities from $7 \times 10^8 \text{ cm}^{-2}$ to $\sim 1 \times 10^{10} \text{ cm}^{-2}$, reveal a strongly correlated liquid up to $r_s \approx 40$ where a Wigner crystallization is anticipated. A critical behavior is identified in the proximity of the metal-to-insulator transition. The nonlinear DC responses for $r_s > 40$ captures hard pinning modes that likely undergo a first order transition into an intermediate phase in the course of melting.

Keywords: electron-electron interaction; metal-insulator transition; strongly correlated phenomena; Wigner crystal; liquid-solid phase transition; non-Fermi liquid

1. Introduction

Anderson insulators [1] describe a quantum localization effect of non-interacting electrons due to random disorders. Such an insulator is expected to prevail in two-dimensional (2D) systems even in the low disorder limit [2], as long as the sample size L and the electron coherence length l_ϕ are beyond the localization length ζ . As far as the experimental results are concerned, Anderson localization provides a partial description of the transport behaviors because a 2D system can be a metal or an insulator as demonstrated extensively via the metal-insulator transition (MIT) [3,4] when the carrier density n is reduced below a critical value n_c . While the disorder manifests in metals via the weak-localization (WL) [5] (with perturbation corrections from interaction [6,7]), it usually, as most results support, drives an Anderson insulator for $n < n_c$ where the low- T conduction is realized through hopping [7,8] among the localized states. Thus, this scenario of MIT is characterized by the prominent disorder effect, with perturbation influences from interaction. However, this picture is radically altered if disorder is sufficiently reduced. This paper is aimed to demonstrate an MIT arising from strong interaction effects.

Strong interaction in the low disorder limit causes correlated electron states to emerge. Examples range from the long sought-after Wigner crystal (WC) [9] to the non-Fermi liquids [10]. The effect of interaction is reflected in a ratio $r_s = E_{ee}/E_F$ as a function of the carrier density n : $r_s = m^* e^2 / \epsilon \hbar^2 \sqrt{\pi n}$. $E_{ee} = e^2 / \epsilon a$ is the Coulomb energy, $E_F = n \pi \hbar^2 / m^*$ is the Fermi energy, and m^* is the effective mass. Continuous increase of r_s should eventually cause a liquid-solid phase transition (LSPT). Since a WC is always pinned by disorder [11], this LSPT manifests a distinctive MIT accompanied by a symmetry breaking. The predicted critical point for the LSPT is $r_s^{WC} \approx 37$ [12]. Therefore, it implies a considerable range for a strongly correlated non-Fermi liquid (non-FL) [10] and even possible intermediate phases (i.e. liquid crystals [13]) whose breakdown precedes the onset of a WC. Such an LSPT composes unknown manybody effects that are fundamentally important to a broad spectrum of strongly correlated phenomena. However, rigorous demonstration of a WC state and the LSPT are still lacking.

Realization of a large r_s in a zero magnetic field requires the lowering of n which necessarily reduces both E_{ee} and E_F . The rising effect from disorder at dilute n tends to drive an Anderson localization (or percolation transition depending on the nature and the amount of the disorders) and breaks long-range orders. Most systems do not have sufficiently low disorders so that they become Anderson insulators (or a glass or mixed phases) before reaching r_s^{WC} . This is evidenced by the activated low- T conductivity $\sigma(T) = \sigma_0 \exp(-T^*/T)^{1/\gamma}$ ($\gamma = 2, 3$) occurs whenever r_s is raised beyond 20. Consequently, the value of n_c (or r_s^c) is sensitive to the disorder levels [14,15].

Adoption of ultra-clean 2D systems is crucial to avoid disorder-driven localization at large r_s . For this study, the samples are p -type 2D systems in (100) GaAs/AlGaAs heterojunction-insulated-gate field-effect-transistors (HIGFETs). The carrier density p is tunable between $7 \times 10^8 \text{ cm}^{-2}$ to $3 \times 10^{10} \text{ cm}^{-2}$, corresponding to $70 > r_s > 25$. Without any intentional doping, the carriers accumulate at the hetero-interface in response to a voltage bias on the metal gate beyond a threshold ($V_{th} \sim -1.3 \text{ V}$). The sample contains a $6 \text{ mm} \times 0.8 \text{ mm}$ Hallbar fabricated with a self-align technique [16,17]. Ohmic contacts are realized via annealing AuBe alloys. Measurement is made inside a dilution refrigerator. The carrier density p is determined by the quantum Hall measurement. The carrier mobility μ reaches $1.04 \times 10^6 \text{ cm}^2/\text{V}\cdot\text{s}$ at $p = 1.2 \times 10^{10} \text{ cm}^{-2}$.

2. Results

An MIT associated with an interaction-driven phase transition should occur around r_s^{WC} . The actual r_s^{WC} is not yet well determined though a somewhat higher value is anticipated considering the thermal, quantum, and disorder fluctuations. The presentation of the results starts with the metallic phase which indeed confirm a conductor up to $r_s^c \sim 40 \sim r_s^{WC}$ where signatures supporting a critical behavior emerge. The critical r_s is found to settle around r_s^{WC} , showing little dependence on the samples. At $r_s > r_s^c$, the transport is nonactivated over a range of T which contrasts the disorder-driven localization. Finally, the nonlinear response for $r_s > r_s^c$ reveals prominent pinning modes characterized by a large translational correlation length ξ . The dependence on the temperature and the external bias display a behavior supporting an LSPT mediated by an intermediate phase.

2.1. Metal Behaviors at Large r_s and a Critical Behavior

Though most 2D metallic behaviors are well described by the Fermi liquid (FL) [18], the breakdown of the FL is inevitable in both disorder- and interaction-dominated regimes. Indications of non-FL states are mostly documented for the metallic states in the proximity of n_c corresponds to a $r_s \sim 10$ –20. Evidence includes T -dependence of the resistivity [19–22], the magnetoresistance (ρ_{xx}) in a parallel $B_{||}$ field [22,23], and the Coulomb drags [24], etc. The suppression of disorder reduces r_s^c and opens up a range for the non-FL regime. Verification of a metallic state persisting up to the anticipated r_s^{WC} is crucial to establish a LSPT. The results below confirm a metal state up to a r_s that is in fact approximately the r_s^{WC} .

The metallic state is determined by the T dependence of the resistivity $\rho(T)$ measured with a four-probe AC lock-in technique. Figure 1a shows the $\rho(T)$ for $p = 5.9 \times 10^9 \text{ cm}^{-2}$ (or $r_s = 37$) which unambiguously confirms a metal behavior: $\rho(T)$ is below the quantum of conductance h/e^2 and $d\rho/dT \sim 3 \text{ k}\Omega/100 \text{ mK}$ has a positive sign below a characteristic temperature T_{max} where $\rho(T)$ peaks. $T_{max} \sim 125 \text{ mK}$ is $\ll T_F = E_F/k_B \sim 400 \text{ mK}$. Figure 1c confirms the same metal behavior in a different sample with a carrier density of $p = 5.2 \times 10^9 \text{ cm}^{-2}$ (or $r_s = 40$) down to $T = 4 \text{ mK}$. Note that the ac current excitation is kept under 0.5 nA so that Joule heating at $< 1 \times 10^{-17} \text{ W}$ is negligible. $\rho(T)$ is studied for multiple carrier densities and the characteristics related to a critical behavior are found through the r_s dependence of T_{max} .

Figure 1. (a) T dependence of the sheet resistance for $r_s = 37$ down to 40 mK and (b) The p dependence of T_{max} in comparison to E_F . (c) $\rho(T)$ for $r_s = 40$ down to 4 mK. (d) DC-IV for $p = 5.2 \times 10^9 \text{ cm}^{-2}$ measured at 25 mK for a current range between 0 and ± 0.4 nA. Inset: dV/dI based on the IV result.

T_{max} is sometimes associated with a renormalized Fermi energy $E_F^*(p)$ [11]. As shown in Figure 1c where the p or (r_s) dependence of T_{max} is shown, T_{max} is indeed below $T_F = E_F/k_B$ which is qualitatively correct from the stand point of a strong renormalization [10]. However, the nonlinear fall of T_{max} with decreasing p is far too rapid to be accounted for by FL renormalization: a nearly three-fold drop from $p = 8.5$ to $5.8 \times 10^9 \text{ cm}^{-2}$. In fact, the trend of diminishing T_{max} suggests a critical behavior. A nonlinear three-free-parameter fit to a scaling $T_{max}(r_s) = T_0(r_s^c - r_s)^\alpha$ produces $T_0 = 116.4 \pm 5.3$ mK, $r_s^c = 41.08 \pm 0.6$, and $\alpha = 0.488 \pm 0.25$, with a $R^2 \approx 0.9987$. $r_s^c \sim 41$ corresponds to a critical density $p_c \sim 5 \times 10^9 \text{ cm}^{-2}$. Carrier density dependent scaling has been reported in Si-MOSFETs where a similar exponent is found [25]. Note that the value of $m^* = 0.35m_0$ used for extracting r_s values is based on the cyclotron resonant studies [26,27] obtained for similar carrier densities.

In addition, the DC-IV reveals a nonlinear response incompatible with a FL. As shown in Figure 1d, the DC-IV for $r_s = 40$ (or $p = 5.2 \times 10^9 \text{ cm}^{-2}$) is nonlinear within a current window of just ± 0.4 nA. The derivative dV/dI shown in the inset figure varies continuously from 6.3 kΩ at $I = 0$ to 3.5 kΩ at $I = \pm 0.4$ nA. The nonlinearity is easily resolved down to tiny drives below $I \sim 0.1$ nA where the Joule heating dissipates negligibly at $< 5 \times 10^{-17}$ W. Nonlinear DC response associated with interaction has been extensively reported for both the insulating regime, in connection to the finite pinning effects [28], as well as in the metallic regime, as identified in mesoscopic systems in a B -field [29]. As shown later for larger r_s , the nonlinear DC-IV becomes increasingly prominent and eventually manifests as a threshold similar to the pinned charge density waves (CDWs) [30]. The weak nonlinear response indicates the onset of a possible intermediate phase which is further discussed later in this report.

2.2. Critical Density and the Influence of the Disorder

As confirmed by most experiments [3,4,11,14,31,32], the r_s^c in more disordered systems is well below r_s^{WC} and it varies with the changes in the disorder levels. This is, however, contrasted by results obtained from ultra-clean systems where the r_s^c observed among various samples tends to settle approximately at a large $r_s^c \sim 40$. Figure 2a shows $\rho(T)$, on semi-logarithmic scales, obtained from one of the samples for a number of carrier densities from 1.2 to $12.5 \times 10^9 \text{ cm}^{-2}$. Note that the four curves from 10 K to 300 mK (in black) are obtained in a 3-Helium cryostat and 1 K to 30 mK results are obtained in a dilution refrigerator. For $p \leq 4 \times 10^9 \text{ cm}^{-2}$ (blue curve), only insulators are found. p_c is estimated as $\sim 4.5 \times 10^9 \text{ cm}^{-2}$ (or $r_s^c \sim 43$ assuming $m^* = 0.35m_0$) which is in good agreement with the T_{max} extrapolation [Figure 1b]. Consistent p_c has been found in multiple HIGFET samples from four different wafers. Some of the results are reported in Refs. [19,20]. The histogram of p_c shown in the inset figure is based on results collected from seven different samples.

Figure 2. (a) T dependence of the resistivity $\rho(T)$ for a carrier density range from $7 \times 10^8 \text{ cm}^{-2}$ to $1.25 \times 10^{10} \text{ cm}^{-2}$. (b) Comparison of the nonactivated conductance (in blue) of a clean system to the activated hopping conductance (in red) of a more disordered system for $p \sim 1.5 \times 10^9 \text{ cm}^{-2}$. (c) The nonactivated behavior is turned into an activated behavior as a result of increase of disorders. p is from $7 \times 10^{10} \text{ cm}^{-2}$ to $5 \times 10^9 \text{ cm}^{-2}$. Solid lines are the AC results and the scattered points are the DC results. Dotted lines are a guide to the eye. Inset: comparison between an Arrhenius hopping and the Efros-Shklovskii variable range hopping.

Meanwhile, the transport of the insulator draws a distinction from the activated behavior. Figure 2b displays on double-logarithmic scales the qualitative differences in the conductivity $\sigma(T)$ ($=1/\rho$) between the non-activated T dependence in an ultra-clean case, with $p = 1.5 \times 10^9 \text{ cm}^{-2}$, and the activated T dependence in a more disordered case, with $p = 1.6 \times 10^9 \text{ cm}^{-2}$. Though similar values of $\sigma(T)$ are found for both cases beyond 200 mK, an activated behavior is only observed for the more disordered system whose $\sigma(T)$ plummets by more than three orders of magnitude compared to the clean case. A power-law fit, $\sigma(T) \propto T^\alpha$, to the low T nonactivated results produces an $\alpha \sim 1.35$. These striking differences are also observed in other studies [19,20].

The influences of the disorder is demonstrated in Figure 2c. When extra disorders are introduced, through LED illumination in our case, the nonactivated behavior diminishes and an Arrhenius activated transport is recovered as shown by the $\sigma(T)$ versus $1/T$ on semi-logarithmic scales. Consequently, p_c rises substantially to nearly $p = 9.2 \times 10^9 \text{ cm}^{-2}$. A comparison to the variable range hopping (VRH) is provided in the inset of Figure 2c.

2.3. Nonlinear Responses and the Liquid-Solid Phase Transition

Detection of collective modes of possible WCs has been carried out in both the quantum Hall regime, with respect to pinning [28,33–35], resonant absorption (via RF (Radio frequency), microwaves, acoustic waves [36–39], and tunneling [40]), as well as in a zero magnetic field (B) [14,41–43]. Nevertheless, a WC phase is not yet well supported for a number of reasons. First, the correlation length ξ is rather small ($\leq 1 \mu\text{m}$) and decays exponentially with increasing T . As the pinning strength scales with ξ [44,45], it explains why the observed differential resistance is not as robust as expected. These findings favor an intermediate or a mixture of liquid and solid phases. Second, the reported melting [37,38,40] is reflected via a smooth crossover [28,37,38,40], lacking a singularity that reflects the changes in the free energies across the phase boundary [46]. Some of the experimental challenges can be understood by the sensitive nature of the WC on the disorder, T , the magnetic field (for WC studies in the fractional quantum Hall regime), and even the experimental conditions. Suppression of disorder is key to not only reducing the chances of glass [47–49] or mixed phases, but also to maintaining an accessible critical temperature T_c which can be suppressed substantially by disorder fluctuations [50–52]. The results presented below are based on the DC response as a probe to both pinning and melting effects.

Figure 3a shows the DC-IV obtained for $r_s \sim 50$ where a contrast is found between two close-by temperatures: 32 and 43 mK. The DC response at 43 mK or higher T (not shown) is approximately linear up to 50 pA and is invariant when switching the leads to different orientations. This finding

is consistent with the previous results [28,34] interpreting an isotropic liquid. On the other hand, the DC-IV exhibits a nonlinear response at 32 mK, indicating the presence of pinning. The differential resistance r_d measured with a current I below 5 pA is ~ 18 M Ω . r_d approaches a linear behavior with increasing I and reaches the same r_d as for the 43 mK case. Assuming collective pinning of $N = p\zeta^2$ carriers by a periodic potential after the CDW model, previous studies [28,34] adopted the following equation to estimate ζ :

$$I(E) \propto \sinh(NeEa/T) \exp[-(2NeE_{th}a/\pi T)] \quad (1)$$

$E_{th} = V_{th}/L$ (L is the length between the voltage contacts) is the threshold electric field. At the threshold, $eE_{th}a$ is ~ 0.01 μ eV (or 0.1 mK) $\ll k_B T$, confirming a collective nature. As shown in Figure 3a, fitting the 32 mK curve to equation (1) produces $N \sim 200$ or $\zeta \sim 14a \sim 1.4$ μ m at $R^2 = 0.9995$. Nevertheless, this fitting makes an assumption that N is only affected by T and is independent of V . This, however, is incorrect if a melting instead of depinning occurs. Note that these results associated with soft pinning are qualitatively consistent with the previous results [28].

Figure 3. (a) Nonlinear and linear DC-IV for $r_s = 53$ at 32 and 43 mK within a current window up to 50 pA. Dashed line is a guide for the eye. (b) Threshold DC-IV obtained at 29 mK for the same r_s (c) Piecewise behavior of $r_d(T)$ displayed in $\log(r_d)$ vs. $1/T$.

Figure 3b shows the DC-IV obtained for the same r_s at 29 mK where a threshold behavior appears. The sub-threshold pinning increases substantially as indicated by $r_d = dV/dI \sim 100$ M Ω . As shown by previous studies [28,34], ζ is estimated by balancing the total potential energy $N\epsilon$ and the pinning energy $-(1/2)\kappa a$. $\kappa = 0.245e^2p^{3/2}/4\pi\epsilon_0\epsilon$ is the shear modulus and $N = p\zeta^2$ is the particle numbers in the domain. For our case, this yields $N \geq 10^5$ or $\zeta \geq 50$ μ m. As clearly shown by the results below by the general nonlinear IVs up to 43 mK, ζ decreases with increasing V . Therefore, the estimated ζ reflects a lower limit.

The pinning effect depends on both T and the external bias. Thus, to probe a thermal melting, the external bias signal must be limited to the lowest levels. Figure 3c shows the r_d measured with $I \leq 0.5$ pA at several temperatures. $r_d(T)$ exhibits a piecewise behavior, supporting a phase transition at $T_c \sim 30$ mK where a sharp jump of nearly 60 M Ω appears. The jump can be viewed as a potential energy loss if ζ is suddenly reduced. Because a pinned WC is characterized by the potential energy, r_d scales with ζ . By limiting I below 0.5 pA, the nonlinear effect related to the level of excitation diminishes. Thus, this result implies a piecewise T dependence of ζ which is proportional to the energy within a WC domain. A recent Monte Carlo study indeed predicts a discontinuity in the free energy across the phase boundary between a WC and a quantum hexatic phase [51]. As a finite pinning [53] is retained above T_c , this transition indeed ends up in an intermediate phase instead of a liquid. Melting through intermediate phases has been modeled for hexatics [51,54–57], stripes, bubbles, and microemulsions [58]. For the T dependence of r_d above T_c (or for $1/T \leq 0.033$ in Figure 3c), r_d falls exponentially with increasing T , which is qualitatively consistent with the exponential T dependence of ζ predicted for the hexatic phases [52,55,56].

3. Discussion

In addition to a thermal melting, a phase transition can also be triggered by the external bias. The threshold in the DC-IV behavior for $r_s > r_s^{WC}$ at $T < T_c$ is often associated with the depinning of a WC which is perhaps influenced by the sliding CDW picture. However, there is possibly a more energetically-favorable alternative—the onset of an intermediate phase whose correlation length decreases with increasing bias until reaching a liquid phase. The critical behavior demonstrated in the r_s dependence of T_{max} suggests a relevant energy scale of which the origin needs to be better understood. r_s^c being larger than the estimated r_s^{WC} is likely due to the finite disorder effect which can not be quantified at this point. The discontinuity [46] in the thermal melting is consistent with a recent theoretical work [51]. $T_c \sim 30$ mK is only 25% of the classical melting point $E_{ee}/137$. This may be an indication to the fact that a quantum melting differs from the classical process such as the Kosterlitz-Thouless transition [59] due to an extra degree of freedom. In this preliminary report, several important questions are left unanswered. Subjects such as the nature of the intermediate phase, the free energy differences between the phases, effects from the spin-orbit coupling, etc. need further exploration.

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Abbreviations

The following abbreviations are used in this manuscript:

MDPI	Multidisciplinary Digital Publishing Institute
DOAJ	Directory of open access journals
TLA	Three letter acronym
LD	linear dichroism

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