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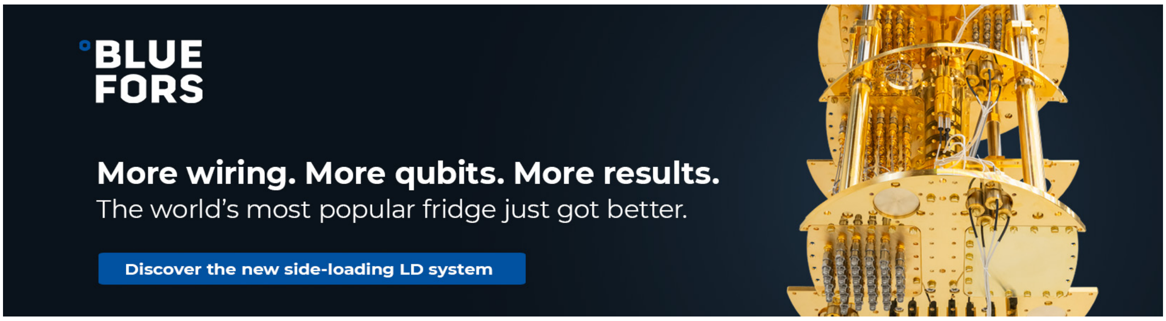

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ABSTRACT

Historically, in measurements of electron transport in disordered two-dimensional systems, an Arrhenius Hall carrier density has never been observed alongside an Arrhenius conductivity, when the Fermi level is below a mobility edge. This has long been an issue with respect to claiming observation of transport via activation to a mobility edge. In this work, an Arrhenius conductivity and Arrhenius Hall carrier density have been observed alongside one another in such a system. Measurements were made of a two-dimensional electron gas hosted in a gated GaAs/$Al_{0.33}Ga_{0.67}As$ heterostructure. Furthermore, in the regime of Arrhenius conductivity and Arrhenius carrier density, the mobility is shown to be independent of the position of the Fermi level below the mobility edge. A transition between carrier density and mobility dominating the resistivity temperature dependence has been observed, as the Fermi level is varied.

Given arbitrary disorder, all single-particle states are predicted to be localized in a two-dimensional electronic system.[1,2] However, at finite temperature, a mobility edge exists due to incoherent scattering events disrupting quantum interference, giving the appearance of a metal-insulator transition. In the case that the Fermi level is below the mobility edge, the conductivity is typically highly temperature dependent and has the following form:

$$\sigma(T) = \sigma_0 \exp\left[-\left(\frac{T_0}{T}\right)^{\gamma}\right]. \quad (1)$$

Here, T_0 is a characteristic temperature and σ_0 is a temperature independent constant. For transport via activation to the mobility edge[3] or nearest neighbor hopping,[4] $\gamma = 1$, and the conductivity has an Arrhenius form. In the case of activation to a mobility edge, σ_0 was predicted by Mott to be equal to a minimum metallic conductivity. In two dimensions, Mott's predicted value is $0.7e^2/h$.[5] The transport typically becomes dominated by Mott variable range hopping at lower temperatures.[6] In this case, in two dimensions, $\gamma = 1/3$; in general $\gamma = 1/(d+1)$, where d is the dimensionality. It is also possible to observe Efros-Shklovskii hopping, in which $\gamma = 1/2$ irrespective of dimensionality. This is due to the effect of a Coulomb gap at the Fermi level.[7]

In theory, if transport is via activation to a mobility edge, the expected form of the measured Hall carrier density is

$$n(T) = n_0 \exp\left(-\frac{T_0}{T}\right). \quad (2)$$

That is, the number of carriers activated into extended states above the mobility edge has the same form as the conductivity with the same characteristic temperature, T_0. Here, n_0 is a temperature independent constant that depends on the density of states above the mobility edge. The form of Eq. (2) follows when assuming that only the carriers activated to extended states are responsible for the Hall effect, and that their finite lifetime above the mobility edge has no bearing on the effect. The mobility, $\mu = \sigma/ne$, in this case, will be a temperature independent constant. This behavior, however, has never been reported in a two-dimensional system. Instead, the carrier density, measured using the Hall effect, has historically been observed as being temperature independent when conductivity has an Arrhenius form. Until now, there has never been any evidence of an Arrhenius conductivity and corresponding Arrhenius carrier density, when considering two-dimensional disordered electronic systems in which the Fermi level is below a mobility edge. It is the mobility, not the carrier density, that has been consistently reported as being activated,

$$\mu(T) = \mu_0 \exp\left(-\frac{T_0}{T}\right). \quad (3)$$

This has been reported in silicon inversion layers[8–10] and more recently in Ge-Sn quantum wells.[11,12] The concept of a thermally activated mobility is difficult to explain satisfactorily. One explanation for this behavior involves the electron system acting as a viscous liquid and the Lorentz force being shared among all carriers.[13]

In this Letter, evidence of an Arrhenius carrier density when transport is via activation to a mobility edge in two dimensions will be presented. In recent years, there has been a resurgence of interest in the field of localization due to the prediction that the many-body localized phase is possible in a disordered electronic system.[14] It has been suggested that electron-phonon decoupling,[15] a necessary condition for many-body localization, is easier to observe in systems displaying Arrhenius behavior than in those exhibiting Mott variable range hopping and Efros-Shklovskii hopping.[16] There is, thus, renewed interest in understanding Arrhenius behavior in disordered electronic systems.

A gated GaAs/$Al_{0.33}Ga_{0.67}As$ heterostructure, hosting a two-dimensional electron gas (2DEG), was used in this work to study localized transport. The 2DEG is formed at a GaAs/$Al_{0.33}Ga_{0.67}As$ interface, 90 nm below the surface of the wafer. The wafer is modulation doped. The disorder in the wafer is due to ionized dopants, alloy disorder associated with the $Al_{0.33}Ga_{0.67}As$ layer, and background impurities associated with the growth. Square devices, of dimensions 300 μm $\times$ 300 μm and suitable for van der Pauw measurements,[17] were defined via wet etching using an H_2SO_4-H_2O_2-H_2O etch.[18] Au/Ge/Ni Ohmic contacts were fabricated via thermal evaporation and a 430 °C anneal for 80 s. A Ti/Au gate was also deposited via thermal evaporation. This allowed the Fermi level to be manipulated below the mobility edge. Zurich MFLI lock-in amplifiers were used to make four-terminal Hall and longitudinal resistance measurements. A 16-bit DAC was used to vary gate voltage, V_g. Carrier density and mobility were 1.53×10^{11} cm^{-2} and 1.90×10^6 cm^{2}V^{-1}s^{-1}, respectively, when $V_g = 0$ at 1.5 K. The minima of the Shubnikov-de Haas oscillations fell to zero, confirming the absence of parallel conduction. When measuring in the resistive state, a 100 μV AC excitation was applied at 2 Hz. When making Hall resistance measurements, magnetic fields of $\pm$ 0.5 T were applied. Mixing of the longitudinal signal was removed by anti-symmetrising the Hall resistances. Longitudinal resistance measurements were also made at $\pm$ 0.5 T so as to compare with Hall resistances at the same field magnitude.

Resistivity, ρ, against the reciprocal of temperature, T^{-1}, for different gate voltages, is shown in Fig. 1(a). Straight lines indicate agreement with Eq. (1), with $\gamma = 1$, indicating the transport is an Arrhenius process. The fitted straight lines converge to the same conductivity intercept, $\sigma_0 = 3e^2/h$, at the lowest gate voltages. This convergence is indicative of a minimum metallic conductivity and is in agreement with previously observed values.[9,11,19,20] The effect of the gate voltage, as it decreases, is to push the Fermi level further below the mobility edge and increase the characteristic temperature, T_0, which varies between 43 and 90 K. Figure 1(b) displays a plot of $W = -d\log\rho/d\log T$ against T on a log-log scale, for $V_g = -0.213$ V. If conductivity is of the form (1), $W = \gamma T_0^{\gamma} T^{-\gamma}$ and the plot should be a straight line with slope equal to $-\gamma$. This is observed with a slope of -1.07 ± 0.15, which is again supportive of an Arrhenius transport mechanism.

Hall carrier densities, at the same gate voltages, are plotted against temperature in Fig. 2(a). They too are Arrhenius. The Hall mobility, as seen in Fig. 2(b), is gate independent. This indicates that the position of the Fermi level does not affect mobility, which itself can be explained if all transport takes place above the mobility edge. The gate independence is striking and arguably the strongest evidence presented here of transport via activation to a mobility edge. If transport was not via activation to a mobility edge, reducing the Fermi level would be expected to reduce mobility. As the Fermi level is pushed deeper into the band tail, it is expected that mobility at the Fermi level reduces. This is due to both the density of states and localization length decreasing as the Fermi level moves further into the band tail. However, if the dominant transport mechanism is that of activation to the mobility edge, the transport naturally takes place at the mobility edge. The Fermi level, thus, has no influence on mobility, which itself depends only on the states at the mobility edge. Due to the observation of an Arrhenius conductivity, an Arrhenius carrier density, and a Fermi level independent mobility, a central claim of this Letter is that transport via activation to a mobility edge has been observed.

The mobility does retain a temperature dependence. When considering activation to the mobility edge, one may expect $\mu = \sigma/ne$ to be a temperature independent constant, due to σ and n being expected to share the same characteristic temperature. It is, however, reasonable to suggest that the properties of the states just above the mobility edge

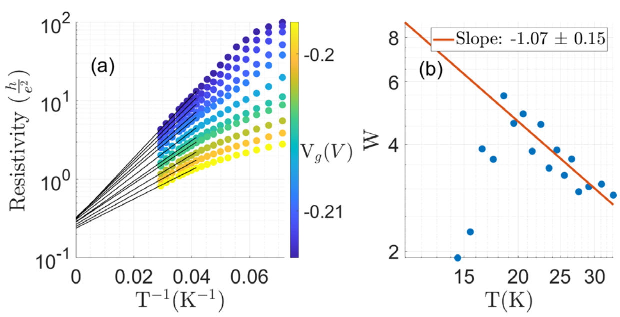

FIG. 1. (a) Resistivity against T^{-1} at various gate voltages. The straight lines indicate Arrhenius behavior. At the lowest gate voltages, the fitted straight lines converge to the same infinite temperature conductivity intercept of $3e^2/h$. (b) Plot of $W = -d\log\rho/d\log T$ against T on a log-log scale at $V_g = -0.213$. The slope is -1.07 ± 0.15 indicating Arrhenius behavior.

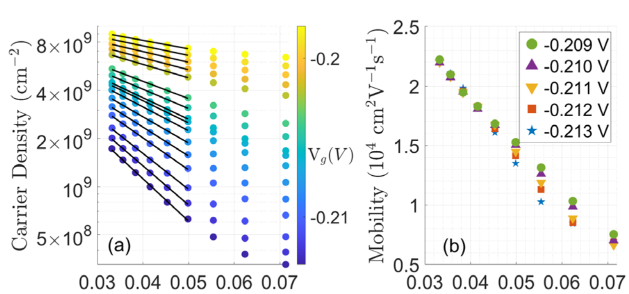

FIG. 2. (a) Hall carrier density against T^{-1} for the same gate voltages shown in Fig. 1(a). The straight lines indicate Arrhenius behavior. (b) Hall mobility against T^{-1}. The mobility is independent of gate voltage. This is striking and indicative of conduction taking place at the mobility edge.

have a significant temperature dependence, given that the very presence of a mobility edge in two dimensions is due to finite temperature effects. The temperature dependence of the mobility could, therefore, be related to quantum coherence, which decreases as temperature rises. This leads to a reduction of quantum interference, thus a reduction of localization effects at the edge. Note that as the mobility is independent of Fermi level, it does not depend on the number of electrons above the mobility edge; the effect must be a single electron effect.

The Arrhenius characteristic temperatures of both carrier density and resistivity, taken from the straight line fits shown in Figs. 1(a) and 2(a), are plotted against gate voltage in Fig. 3(a). As expected, these characteristic temperatures are shown to increase as the Fermi level is pushed further below the mobility edge, by decreasing gate voltage. The value of $k_B T_0$, in the case of the carrier density, is just the energy difference between the Fermi level and the mobility edge. Also plotted in Fig. 3(a) is the difference between the resistivity and carrier density characteristic temperatures. This value is seen to be approximately constant. As $\mu = \sigma/ne$, this difference is responsible for the Hall mobility temperature dependence. As previously discussed, the Hall mobility is determined by the mobility of the extended states just above the mobility edge. This difference can, thus, be interpreted as the characteristic temperature of the extended state mobility. This interpretation explains why the difference is gate independent. Furthermore, Fig. 3(a) indicates a transition between the activated carrier density behavior, reported in this Letter, and the previously reported activated mobility regime. The transport is always via activation to mobility edge; what is different between the two regimes is what dominates the resistivity temperature dependence. At the most negative values of V_g, the temperature dependence of the resistivity is primarily determined by the Arrhenius carrier density. However, as the Fermi level is raised, the resistivity temperature dependence becomes relatively more dependent on the temperature dependence of the states above the mobility edge and not the gap between the Fermi level and the mobility edge. As can be seen in Fig. 3(a), at the most positive gate voltages, it is the mobility of these extended states, and not the carrier density, that now has the stronger temperature dependence. One of the central claims of this Letter is that a transition between the two different regimes has been observed. It is also claimed here that the previous works in the literature, which claim an activated mobility, are associated with the latter regime in which the extended states just above the mobility edge dominate the resistivity temperature dependence.

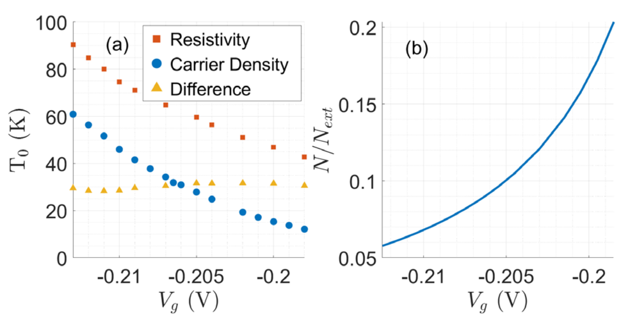

FIG. 3. (a) Characteristic temperatures of the Arrhenius carrier densities and resistivities against gate voltage. The difference, responsible for the mobility temperature dependence, is also plotted. (b) Ratio of the density of states, N, to the extended state density of states, $N_{ext} = m^*/\pi\hbar^2$, against gate voltage. The density of states was found by first fitting to T_0 against V_g and then evaluating $N = (C_g/k_B)dV_g/dT_0$, where T_0 is the carrier density characteristic temperature and C_g is the change in 2DEG density per unit gate voltage.

It is expected that the lifetime at the mobility edge will depend exponentially on the difference between the Fermi level and mobility edge, $\tau \propto \exp(-[E_\mu - E_F]/k_B T)$. Given that the temperature dependence of the mobility is invariant with the Fermi level, the finite lifetime at the mobility edge does not appear relevant. The elastic scattering time is, thus, expected to be less than the edge lifetime. This is true regardless of whether it is mobility or carrier density that dominates the temperature dependence of the resistivity.

The density of localized states can be found using $N = (C_g/k_B)dV_g/dT_0$, where T_0 is the carrier density characteristic temperature and C_g is the change in 2DEG density per unit gate voltage.[21] The derivative, dV_g/dT_0, is evaluated after fitting to T_0 against V_g. Figure 3(b) shows the ratio of N to the extended state density of states, $N_{ext} = m^*/\pi\hbar^2$, plotted against V_g. Here, m^* is the effective electron mass. As expected, the density of states reduces as the Fermi level is pushed further into the band tail. That it has been possible to observe the Arrhenius carrier density and transition could be explained by the low values of N/N_{ext} observed in this work, 0.05–0.2. Previous values in the literature, when making similar measurements, typically have $N \approx N_{ext}$.[21] The fact that it has been possible to make measurements deeper into the band tail could be related to the high quality of the material used. This is a significant difference between our work and previous works.

In summary, an Arrhenius Hall carrier density has been observed alongside an Arrhenius conductivity in a two-dimensional system in which the Fermi level is below a mobility edge. Furthermore, the Hall mobility has been shown to be independent of the Fermi level. The conclusion of these findings is that transport is via activation to the mobility edge, and the measured Hall effect is due to the activated carrier density above the mobility edge. It is argued that the temperature dependence of the resistivity is due to both the energy difference between the Fermi level and mobility edge, and the mobility of the extended states just above the mobility edge. Notably, a transition between which of these dominates the resistivity temperature dependence has been observed. If it is the latter, the Hall mobility has a stronger temperature dependence than that of the Hall carrier density.

See the supplementary material for the results at lower temperatures, whereby the transport was via Efros-Shklovskii hopping.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Robert Carroll: Conceptualization (equal); Data curation (lead); Formal analysis (lead); Investigation (lead); Methodology (lead); Visualization (lead); Writing – original draft (lead); Writing – review & editing (lead). **Gregory Auton:** Investigation (equal); Supervision (equal); Writing – review & editing (supporting). **Stuart N. Holmes:**

Investigation (equal); Supervision (equal); Writing – review & editing (equal). **Chong Chen:** Investigation (supporting); Resources (equal). **David A. Ritchie:** Investigation (supporting); Resources (equal). **Michael Pepper:** Conceptualization (equal); Funding acquisition (lead); Project administration (lead); Supervision (lead); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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