Measurement of Coulomb drag between Anderson insulators

K. Elsayad, J. P. Carini and D. V. Baxter

Department of Physics, Indiana University, Bloomington, Indiana 47405

(Dated: February 26, 2008)

We report observations of the Coulomb drag effect between two effectively 2-d insulating a-Si$_{1-x}$Nb$_x$ films. We find that there only exist a limited range of experimental parameters over which we can measure a sizable linear-response transresistivity ($\rho_d$). The temperature dependence of $\rho_d$ is consistent with the layers being Efros-Shklovskii Anderson insulators provided that a 3-d density of states and a localization length smaller than that obtained from the DC layer-conductivity are assumed.

Materials such as a-Si$_{1-x}$Nb$_x$ which exhibit a disorder driven $T = 0$ (Quantum Critical) Metal-Insulator Transition (MIT) have presented many challenges to condensed matter physics: in particular understanding the role of long ranged electron-electron interactions in the insulating phases and in the vicinity of the MIT. Since the interplay between disorder and electron-electron interactions in such systems will determine the dominant transport mechanism, the development of experimental techniques to separately measure these is useful. In this letter we show that the Coulomb drag effect allows us to directly study long ranged electron-electron interactions in insulating a-Si$_{1-x}$Nb$_x$ thin films. We find that although linear-response Coulomb drag is only observable over a limited range of sample parameters, when obtainable, it offers unequivocal distinction to be made between alternative models for the electronic transport in such systems.

Coulomb drag arises from the Coulomb scattering of charge carriers in spatially separated layers, in the absence of charge transfer between the layers. Experimentally, the Coulomb drag effect between two layers (layer-$1$ and $2$) can be observed by measuring the electric-field ($E_2$) created in one, open circuited, layer due to a parallel applied current-density ($j_1$) in the other. The (longitudinal) transresistivity, or linear-response Coulomb drag coefficient, is defined as $\rho_d = -E_2/j_1$; whilst the measured total-transresistivity is the ratio of the induced voltage in layer-$2$ to the applied current in layer-$1$, i.e. $-V_2/I_1$. Theoretical analyses agree that the linear-response transresistivity between two identical 2-d layers is given by,

$$\rho_d \sim \frac{\hbar^2 \beta}{2e^2 n^2} \int d\omega \int \frac{dq}{(2\pi)^2 q^3} \frac{\text{Im}\chi(\omega, q) U(\omega, q)}{\sinh(\hbar \omega / \beta / 2)} \right)^2 \tag{1}$$

where $\beta = (k_B T)^{-1}$, $T$ is the temperature, $n$ is the carrier density in a layer, $\chi(\omega, q)$ is the density-density response function of a layer, and $U(\omega, q)$ is the screened interaction potential between the layers, $\text{Im}\chi(\omega, q)$ may be obtained from the finite wavevector conductivity via:

$$\text{Im}\chi(\omega, q) = q^2(e^2 \omega)^{-1}\sigma(\omega, q). \tag{2}$$

The motivation for this study comes from predictions that the temperature dependence of the transresistance can be used to differentiate insulating states. In particular, for the case of (2-d) Mott Anderson insulator bilayers the low-$T$ transresistivity should vary as $\rho_d \propto T^2$, whilst for (2-d) Efros-Shklovskii (ES) Anderson insulators it should diverge when $T \to 0$ as $\rho_d \propto T^3 \exp[(T_0/T)^{1/2}]$, where $T_0$ is the ES characteristic temperature given by $k_B T_0 \approx 2e^2/\kappa \xi$ and $\kappa$ is the dielectric constant of the layers. This opposite behavior of the transresistivity as $T \to 0$ (diverging for ES-Anderson insulator bilayers, and vanishing for Mott Anderson insulator bilayers) allows for a more transparent distinction between the two insulating states over a narrow $T$ range than intra-layer transport measurements do—where one would obtain different functional $T$ or $\omega$ dependencies with the same trend.

In our study, samples consisted of two U-shaped $200\AA$ thick insulating a-Si$_{1-x}$Nb$_x$ layers, separated by a SiO barrier (see upper left inset in figure). All layers were fabricated using standard RF magnetron sputtering techniques, with the a-Si$_{1-x}$Nb$_x$ layers being deposited using the co-sputtering technique with a rotating sample-holder outlined in Ref. Samples were all grown on polished glass slides in an inert (argon) environment at ambient temperature and a pressure of $\approx 0.50$kPa. Prior to the layers being deposited, $600\AA$-thick silver connections and a silver bridge, that would connect the two layers, were sputtered. The latter would prevent the barrier from breaking due to electrostatic discharge/breakdown during handling, characterization and cooling. Connections to the signal generating and measuring apparatus were made with sputtered silver layers on the arms of the U-shaped layers several millimeters from the interacting-region. To prevent oxidation the top layer was covered with a $\approx 50\AA$-thick SiO film prior to atmospheric exposure. Thicknesses were inferred from the sputtering rate (measured using a quartz crystal thickness monitor), and were within $\approx 5\%$ of those obtained from optical interferometry measurements on samples of similar compositions and thicknesses. Estimates of the uncertainty in the thickness due to fluctuations in the deposition rate and uncertainties in the exposure time are $< \pm 10\AA$ and $< \pm 15\AA$ for the case of the a-Si$_{1-x}$Nb$_x$ and the barrier layers respectively. The barrier layer was deposited in discrete stages to reduce the formation of pinholes. High sputtering powers and brief atmospheric exposure be-
The layers have different resistivities, the condition that remains the same on interchanging the layers (even if every DC current source was programmed to flip polarity were performed using a quasi-AC technique in which transresistance measurements were performed using standard 4-wire techniques, for which it was assured that driving currents were small enough to give linear-response effects from ground-leakage and -loops. Single layer resistance measurements were performed using standard 4-wire techniques, for which it was assured that driving currents were small enough to give linear-response coefficients. The indifference of the layer resistances to the direction of driving current is decreased, was used as a test for the linear-response regime. The transresistance at driving currents \( I = 1 \text{nA} \) for samples with average Nb concentrations per layer \( \rho \) of \( x = 0.07 \rightarrow 0.08 \) and layer separations of \( 50 \rightarrow 200 \text{A} \) were found to, on average, increase with decreasing temperature between \( T \sim 20 \rightarrow 3 \text{K} \). At lower temperatures the transresistance would saturate or decrease in magnitude. This is shown in figure 1 for a selection of samples. In what follows we will present data for sample 1B, where the transresistance entered the linear-response regime for \( I \leq 1 \text{nA} \). Due to the multitude of competing size effects (see below), it was unclear, based on the temperature dependence of the DC resistance alone, whether the layers are better described by the ES Variable Range Hopping (VRH) model \( \sigma \), which predicts: \( \ln(\sigma_{dc}) \propto T^{-1/2} \), or the Mott VRH model \( \sigma \), which, for effectively 2-d films, predicts: \( \ln(\sigma_{dc}) \propto T^{-1/3} \), at low temperatures. This can be seen in figure 2 where we present \( T^{-1/2} \) and \( T^{-1/3} \) plots of the layer-resistances of sample 1B. In the temperature range \( 4 \text{K} < T < 15 \text{K} \), ES VRH with a characteristic temperature of \( T_0 = 145(\pm 6)\text{K} \), 2-d Mott VRH with a characteristic temperature of \( T_0 = 1890(\pm 60)\text{K} \), and 3-d Mott VRH with a characteristic temperature of \( T_0 = 36,000(\pm 1000)\text{K} \), all describe the T-dependence reasonably well. The localization length determined from the ES characteristic temperature is \( \xi \approx 105(\pm 6) \text{A} \). For each case the DC VRH transport in the layers should be effectively 2-d for \( T \leq 20 \text{K} \)—on account of the resonant hopping distance \( r_c \) being larger than the width of each layer \( (W) \). At these temperatures the resistance

![Figure 1](image1.png)

**FIG. 1:** Plot of the low-\( T \) transresistance per square \((R_{drag}/\text{square})\) for various samples, at a driving-current of \( I_1 = 1 \text{nA} \). (The right-vertical axis shows the ratio of the total measured voltage to the total driving current). Samples 1A, 1B and 1C have an average Nb concentration of \( x = 0.070 \) and layer separations of \( 200 \text{A}, 100 \text{A} \) and \( 55 \text{A} \) respectively. Samples 2C and 3C have the same geometry as sample 1C but with \( x \approx 0.076 \) and \( \approx 0.080 \).

![Figure 2](image2.png)

**FIG. 2:** Resistance per square of layers 1 (triangles) and 2 (circles) in sample 1B. Open symbols are plotted against the \( T^{-1/2} \) axis and closed symbols against the \( T^{-1/3} \) axis. Upper inset: sketch of sample geometry. Lower inset: resistances of layers-1 and -2 (triangles and circles) compared to lower bounds of the barrier resistance (squares). The dashed horizontal line represents the maximum resistance that could be measured using \( V_{\text{induced}}(I_{\text{applied}}) \) techniques with existing apparatus.

The samples were cooled to \( T \approx 1.2 \text{K} \) using a standard liquid helium cryostat. The low-\( T \) \((\leq 20 \text{K})\) resistance of the barrier layer was obtained by measuring its conductance, i.e. by applying a small DC potential difference between terminals on either layer, and then measuring the induced current. Measurements were performed from several terminals on each layer and with various terminals and connections grounded to rule out any effects from ground-leakage and -loops. Single layer resistance measurements were performed using standard 4-wire techniques, for which it was assured that driving currents were small enough to give linear-response coefficients. The indifference of the layer resistances to the grounding of terminals in the second layer provided further verification that inter-layer leakage and tunneling was not significant. Transresistance measurements were performed using a quasi-AC technique in which a DC current source was programmed to flip polarity every \( \sim 1 \text{ second} \). Since in linear-response theory \( \rho \) remains the same on interchanging the layers (even if the layers have different resistivities), the condition that \((R_{drag}/\text{square})_{2 \rightarrow 1} = (R_{drag}/\text{square})_{1 \rightarrow 2} \) as the driving-current is decreased, was used as a test for the linear-response regime. The transresistance at driving currents of \( I = 1 \text{nA} \) for samples with average Nb concentrations per layer \( \rho \) of \( x = 0.07 \rightarrow 0.08 \) and layer separations of \( 50 \rightarrow 200 \text{A} \) were found to, on average, increase with decreasing temperature between \( T \sim 20 \rightarrow 3 \text{K} \).
of the barrier—obtained by measuring the tunneling current (see above)—is found to be approximately two orders of magnitude larger than the resistance of layers-1 and -2 (see lower inset in figure 2).

The observed decrease of the layer-resistance and transresistance observed at $T \leq 2.5\,K$ is (based on the tests outlined above and in Ref[11]) neither due to grounding loops/leaks or tunneling/leakage through the barrier. It is unlikely that they are due to thermoelectric effects (as in e.g. [8]), given that all connections were far away from the interacting region. Furthermore, it is unlikely to be due to the layers undergoing a superconductor-insulator transition—which is known to occur in thin a-Si$_{1-x}$Nb$_x$ films with large Nb concentrations ($x \approx 0.15 - 0.18$ [10])—based on the high resistance per square of the layers and the high temperature at which the transition appears to occur. We will present a comprehensive study of this phenomenon elsewhere, and focus on the temperature range $2.5\,K < T < 15\,K$ in this letter.

As the driving current is increased the transresistance decreases (see inset in figure 3), and for $I \approx 100\,nA$, the transresistance is found to be more than 3 orders of magnitude smaller than at $I = 1\,nA$. This is likely due to larger driving currents both increasing the effective sample temperature and producing significant non-linear responses. For $I < 1\,nA$ the drag voltage becomes noisier, but its average value changes by less than $\pm 5\%$ between 1, 0.75 and 0.5nA (see figure 3). We thus believe that at this point we have reached the linear-response regime. It is unlikely that phonon [12] and plasmon [13] contributions are significant at these temperatures on account of the small layer separations and the strong insulating nature of the layers.

In order to limit the number of fitting parameters in analysing these data, we find it convenient to plot the ratio $(R_{\text{drag/square}})/(R_{\text{layer/square}})$ as a function of temperature. Doing so we find that our data is best described (see figure 4) by the 2-parameter equation: $(R_{\text{drag/square}}) = aT^b(R_{\text{layer/square}})$, with $a = 1.1(\pm 0.1) \times 10^{-4}\text{K}^{-b}$ and $b = 2.0(\pm 0.1)$. The latter parameter deviates from the predictions of Ref[6], which suggest that $b = 3$ for a bilayer system comprised of 2-d ES Anderson insulators.

The observed discrepancy can be explained if the screening in the layers is not 2-d in the studied regime—i.e. if the response is dominated by a finite wave-vector $q > W^{-1}$ (where $W \approx 200\,A$) for which the layers will be effectively 3-d. Since $\xi^{-1} > W^{-1} > r_c^{-1} = \xi^{-1}(T_0/T)^{-1/2}$, at the temperatures of interest, this occurs at momentum transfers ($q > r_c^{-1}$) that dominate the transresistance (see Ref[6]).

Repeating the calculations for the finite-$\omega, q$ conductivity in Ref[14] for 3-d systems, we find it takes the asymptotic forms:

$$\sigma_{3d}(\omega, q \ll r_\infty^{-1}) \sim C_1(\epsilon^2/\hbar)(\omega/\omega_0)r_\infty^{-1}$$

(3)

![FIG. 3: Temperature dependence of linear-response transresistance observed at driving currents $I \leq 1\,nA$ for sample 1B. Inset: At driving currents $I \geq 1\,nA$. The anomalous low-$T$ increase of the $I < 1\,nA$ transresistance is consistent with the layers being Efros-Shklovskii Anderson insulators and not Mott Anderson insulators](image3)

![FIG. 4: Plot of the $T$-dependence of the ratio $(R_{\text{drag/square}})/(R_{\text{layer/2/square}})$ at $I = 1\,nA$ for sample 1B (circles), the predicted slope for the case of two 2-d Mott-Anderson insulator layers (dotted line), the predicted slope for the case of two 2-d Efros-Shklovskii Anderson insulator layers (dash-dotted line), and the predicted slope for two effectively 3-d Efros-Shklovskii Anderson insulator layers (solid line). As can be seen, the last prediction describes the data best. Inset: $T^2$-scaled transresistance per square for the same sample.](image4)
\[ \sigma_{3d}(\omega, r_\omega^{-1}) \ll q \ll \xi^{-1} \sim C_2(e^2/\hbar)(\omega/\omega_0)q^{-2}r_\omega^{-3} \] (4)

where \( r_\omega = \xi(\omega_0/\omega), \omega_0 = k_B T/\hbar, \) and \( C_i, i = 1, 2 \) are numerical constants of order unity. Substituting equations (3) and (1) into (2) and then (1), we find that the dominant contribution to the transresistance, if the layers are treated as effectively 3-d for \( q > r_c^{-1} \) and we can assume weak static screening, would change with \( T \) as: \( \rho_d \propto T^2 \exp[(T_0/T)^{1/2}] \). The observed \( \rho_d \propto T^2 \exp[(T_0/T)^{1/2}] \) temperature dependence can however arise if one or both of the following are the case:

(1) The relevant localization length is much smaller than that obtained from the \( T \)-dependence of the DC conductivity so that:

\[ \xi(T_0/T)^{1/2} < d. \] (5)

In this way the \( r_c^{-1} < q \) momentum transfers (which are otherwise dominant) are suppressed, and the \( q < r_c^{-1} \) contribution determines the low-\( T \) transresistance. Substituting equation (1) into (2) and then (1), the transresistance would now change with temperature as: \( \rho_d \propto T^2 \exp[(T_0/T)^{1/2}] \).

(2) Finite-\( \omega \) transport is effectively 3-d due to pair-arms \( (r_c) \) reaching into the barrier and the second layer. From the strongly localized nature of electrons in the barrier layer, the effective \( \xi \) would be much smaller and condition (5) may be satisfied, even if the effective layer separation also decreases significantly.

We note that since several of the relevant length scales are comparable \( (r_c \sim \xi \sim W \sim 2d) \), a small modification of the effective values that these parameters take (due to e.g. finite-size effects, correlated hopping or surface effects) could cause a change between the \( \xi > d \) and \( \xi < d \) regime in the temperature range probed, resulting in a different \( T \)-dependence than that predicted. We also note that we do not observe the expected transition from the \( q < r_c^{-1} \) to the \( q > r_c^{-1} \) regime, as the temperature is increased. However, if the apparent change in the \( T \)-dependence of the transresistance (see figure[3] at \( T \approx 4K \) occurs when the \( q > r_c^{-1} \) regime kicks in, then we predict that \( \xi \approx (4K\beta R/e^2)d^2 \sim 3\AA \). This would give a transresistance that goes as \( \rho_d \propto T^2 \exp[(T_0/T)^{1/2}] \) for \( T > 4K \), or \( q < r_c^{-1} \), as we have observed.

In conclusion, we have observed the Coulomb drag effect between two 200\AA thick insulating a-Si\(_{1-x}\)Nb\(_x\) films (with 0.07 \( \leq x \leq 0.08 \)) separated by a 50 – 200\AA thick SiO\(_x\) based barrier. We were able to retrieve accurate linear-response data for \( x = 0.070(\pm 0.002)\% \), and layer separations of 100(\pm10)\AA. The temperature dependence of the transresistance in such samples was found to be in agreement with that predicted for ES Anderson Insulator films, provided that the localization length in the a-Si\(_{1-x}\)Nb\(_x\) layers is smaller than that inferred from the temperature dependence of the DC layer-resistances. Our study suggests that whilst theoretically the Coulomb drag effect is a useful technique for distinguishing the insulating states of thin films, it is experimentally challenging due to the complex dielectric properties of disordered thin films at low energies, which result in non-linear inter- and intra-layer excitations becoming dominant at practical temperatures and sample dimensions. Experimental studies of the non-linear crosstalk regime between thin insulating films, along with simulations of the non-linear (current-dependent) transresistance in such systems, may prove to be the most productive method of studying the detailed nature of the observed excitations.

We would like to thank Prof. E. Shimshoni for fruitful discussions, and D. Sprinkle and M. Hosek for help with the experiments.

* jpcarini@indiana.edu

[1] S.L. Sondhi, S.M. Girvin, J.P. Carini, and D. Shahar, Rev. Mod. Phys. 69, 315 (1997).
[2] D.J. Bishop, E.G. Spencer, and R.C. Dynes, Solid State Electron. 28, 73 (1985); H.-L. Lee, J.P. Carini, D.V. Baxter, W. Henderson, and G. Gruner, Science 287, 633 (2000).
[3] E. Helgern, G. Gruner, M.R. Ciofalo, D.V. Baxter, and J.P. Carini, Phys. Rev. Lett. 87, 116602 (2001).
[4] P.M. Solomon, P.J. Price, D.J. Frank, and D.C. La Tulipe, Phys. Rev. Lett. 63, 2508 (1989).
[5] L. Zheng and A.H. MacDonald, Phys. Rev. B 48, 8203 (1993).
[6] E. Shimshoni, Phys. Rev. B 56, 13301 (1997).
[7] Average niobium concentrations were estimated by comparison of the deposition rate and characteristic ES and Mott temperatures to that of a-Si\(_{1-x}\)Nb\(_x\) films for which \( x \) was determined from Electron microprobe analysis.
[8] A.L. Efros and B.I. Shklovskii, J. Phys. C: Solid State Phys. 8, L49 (1975).
[9] N.F. Mott, Phil. Mag. 22, 7 (1970).
[10] H. Aubin, C.A. Marrache-Kikuchi, A. Pourret, K. Behnia, L. Berge, L. Dumoulin, and J. Leseueur, Phys. Rev. B 73, 094521 (2006).
[11] T.J. Gramila, J.P. Eisenstein, A.H. MacDonald, L.N. Pfeiffer, and K.W. West, Phys. Rev. Lett. 66, 1216 (1991).
[12] T.J. Gramila, J.P. Eisenstein, A.H. MacDonald, L.N. Pfeiffer, and K.W. West, Phys. Rev. Lett. 47, 12957 (1993).
[13] K. Flensberg and B. Y-K. Hu, Phys. Rev. Lett. 73, 3572 (1994).
[14] L.L. Aleiner and B.I. Shklovskii, Intern. Journ. of Mod. Phys. B 8, 801 (1994).