Phase coherent transport in SrTiO$_3$/LaAlO$_3$ interfaces

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The two dimensional electron gas formed between the two band insulators SrTiO$_3$ and LaAlO$_3$ exhibits a variety of interesting physical properties which make it an appealing material for use in future spintronics and/or quantum computing devices. For this kind of applications electrons have to retain their phase memory for sufficiently long times or length. Using a mesoscopic size device we were able to extract the phase coherence length, $L_{\phi}$ and its temperature variation. We find the dephasing rate to have a power law dependence on temperature. The power depends on the temperature range studied and sheet resistance as expected from dephasing due to strong electron-electron interactions.

Oxides interfaces have recently attracted considerable scientific attention due to their potential for implementation in oxide based electronics and for basic science. One of the most studied examples is the interface between LaAlO$_3$ and SrTiO$_3$ (LAO/STO). In this interface a highly conducting two dimensional electron gas (2DEG) appears above a critical thickness of 4 unit cells.

Magnetotransport in the 2DEG formed at the interface between STO and LAO exhibits quite rich behavior in low and high magnetic fields in both perpendicular and parallel orientations. The magnetoresistance at low magnetic fields was described in terms of suppression of weak localization. However, it is difficult to sort out the contribution of quantum corrections to the magnetoresistance from other possible mechanisms such as two types of charge carriers and inhomogeneities. There is therefore a need for a different type of measurement sensitive solely to the mesoscopic phase coherence, such as universal conductance fluctuations (UCF) and root mean square (RMS) value of the UCF and the width of these fluctuations should have a universal value upon changing the impurity configuration. For two dimensions these fluctuations should have a universal value of the order of $\sqrt{\ln T}$. An experimental realization simulating such a configuration modification is achieved by an application of external magnetic field. In this case the magneto-conductance will produce a reproducible fluctuating curve. In order to observe this effect the size of the sample should be comparable with the low temperature length scales: $L_{\phi}$, the phase breaking length and/or $L_T = \sqrt{\frac{\kappa_D}{\kappa_B T}}$ the so-called thermal length. The root mean square (RMS) value of the UCF and the width of the typical oscillation provide information on $L_T$ and $L_{\phi}$ when the length and the width of the sample exceed the above microscopic lengths.

For a macroscopic sample the UCF average out. However, coherent back scattering also known as weak localization (WL) still affects the conductance. The latter quantum corrections as well as the UCF depend on the same microscopic length-scale, $L_{\phi}$. The observation of both the WL and UCF with a similar $L_{\phi}$ gives a strong evidence that the low field magnetoresistance in macroscopic samples is governed by quantum interference effects.

In this paper, we report studies of magnetoconductance fluctuations in mesoscopic samples of the 2DEG at the STO/ LAO interface as well as WL in a macroscopic sample. The analysis of the UCF suggests that the low field magnetoresistance for macroscopic samples at the low carrier densities is governed by quantum corrections, namely weak localization. In addition, we show that for these densities the dephasing mechanism is mainly due to electron-electron interactions.

8 and 20 unit cell (uc) samples of LAO were epitaxially grown on atomically flat TiO$_2$ terminated STO substrate using pulsed laser deposition. The growth parameters are described elsewhere. The 8uc sample was patterned into a Hall-bar geometry using a combination of photo- and
electron-beam lithography. The LAO was dry-etched using Ar ions. The etching was followed by a short oxygen treatment at 200°C in order to anneal out oxygen vacancies created in the substrate during the etching. The dimensions of the Hall bar are 4μm×1.5μm. The 20uc sample was measured in a Van der Pauw configuration. The samples were measured in 4He cryostat (8uc) and 3He refrigerator (20uc).

The typical magnetoresistance curve of the bridge is shown in Fig 1. The field was cycled from -4 to 4 T for several times at 1.3 K and at 4.2 K. Two of these traces at 1.3 K are shown. A reproducible fluctuating signal is clearly seen. These are the universal quantum fluctuations. Fig 1b shows conductance deviations from its average as a function of field. The subtracted average value is given by

\[ \delta G = \frac{N_c \alpha}{\beta} \cdot \frac{e^2}{h} \cdot \sqrt{\frac{4W}{\alpha^2 L^3}} \cdot L_\phi \]  

where \( \beta \) represents the effect of SO coupling on the size of the fluctuations. \( \beta \) goes to 2 at the strong coupling limit. The \( N_c \alpha \) factor stands for the effect of valley degeneracy and is the same as the factor that appears in weak localization theory. Consequently \( \alpha \) has been theoretically predicted to be of order 1. From this relation using our measured RMS value and the known sample dimensions we find \( L_\phi = 1570 \pm 300 \) Å at 1.3 K. Here we assume that spin-orbit scattering length, \( L_{so} \) is much shorter than the dephasing length \( L_\phi \) and therefore \( \beta \approx 2 \). This is reasonable in view of the strong spin-orbit coupling observed in this material. The valley degeneracy \( N_c \) is assumed to be 3 as in bulk STO. The consistency of this assumption as well as the assumption \( L_\phi \approx L_T \) will be addressed further below.

The dependence of \( B_c \) on \( L_\phi \) has been calculated.\(^\text{16}\)

\[ L_\phi = \sqrt{\frac{h/e}{B_c}} \]  

For \( L_\phi \approx L_T \). Substituting the obtained value for \( B_c \) we find \( L_\phi = 1650 \pm 320 \) Å, consistent with the value estimated from the RMS value of the fluctuation amplitude.

The conductance-correlation function:

\[ F(\Delta B) = \langle \delta g(B) \delta g(B + \Delta B) \rangle \]  

was calculated from the data in Fig 1b. \( F(\Delta B = 0) \) gives the RMS value of the fluctuations. The magnetic correlation field \( B_c \) is found from

\[ F(\Delta B = B_c) = \frac{1}{2} F(\Delta B = 0) \]  

For sample dimensions \( L > L_\phi \approx L_T \) the RMS value is given by\(^\text{14, 16}\)

\[ \delta G = \frac{N_c \alpha}{\beta} \cdot \frac{e^2}{h} \cdot \frac{1}{\sqrt{\pi L^3}} \cdot L_\phi \]  

where \( \beta \) represents the effect of SO coupling on the size of the fluctuations. \( \beta \) goes to 2 at the strong coupling limit. The \( N_c \alpha \) factor stands for the effect of valley degeneracy and is the same as the factor that appears in weak localization theory.\(^\text{15}\) \( \alpha \) has been theoretically predicted to be of order 1. From this relation using our measured RMS value and the known sample dimensions we find \( L_\phi = 1570 \pm 300 \) Å at 1.3 K. Here we assume that spin-orbit scattering length, \( L_{so} \) is much shorter than the dephasing length \( L_\phi \) and therefore \( \beta \approx 2 \). This is reasonable in view of the strong spin-orbit coupling observed in this material.\(^\text{17}\) The valley degeneracy \( N_c \) is assumed to be 3 as in bulk STO. The consistency of this assumption as well as the assumption \( L_\phi \approx L_T \) will be addressed further below.

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The magnetococonductance dip at zero magnetic field was analyzed in the framework of WL theory in the presence of spin-orbit interactions.\(^\text{14, 16}\) The data and the theoretical curves using equation (5) are presented in fig 2.

\[ \Delta \sigma(H, T)_{WL} = \frac{e^2}{\pi h} N_c \alpha \langle \Psi(x_1) \rangle + \frac{1}{2\sqrt{1 - \gamma^2}} \langle \Psi(x_2) \rangle - \frac{1}{2\sqrt{1 - \gamma^2}} \langle \Psi(x_3) \rangle \]  

where

\[ \Psi(x) = ln(x) + \psi \left( \frac{1}{2} + \frac{x}{H} \right), x_1 = \frac{H}{H_i + H_{so}}, \]

\[ x_2 = \frac{H}{H_i + H_{so}(1 + \sqrt{1 - \gamma^2})}, x_3 = \frac{H}{H_i + H_{so}(1 - \sqrt{1 - \gamma^2})}, \]

\( \gamma = g \mu H/(4eDH_{so}) \) and \( N_c \approx 3 \). We used \( \alpha \approx 1 \) as theoretically predicted for inter-valley scattering rate smaller than the dephasing one.\(^\text{21}\) and \( g = 2.25 \) consistent with Ref.\(^\text{19}\) for sample with a similar sheet resistance. \( L_\phi(T) \) and \( L_{so} \) are used as the fitting parameters.\(^\text{22}\) From the fit we find \( L_\phi = 1300 \pm 260 \) Å consistent with the values found from UCF and \( L_{so} \approx 200 \) Å. It is indeed significantly shorter than \( L_\phi \) at 1.3 K as we assumed earlier in the analysis of the UCF data. It is important to stress that the value of \( L_\phi \) deduced from the fit to the WL calculations is similar to that extracted from the UCF. This provides an important evidence that weak localization corrections play an important role in the low field magneto-transport.

At 4.2K \( L_\phi = 640 \pm 100 \) Å. It is much shorter than at 1.3 K. We note that the ratio of the diffusion coefficient
for these temperatures is \( \frac{D(4.2K)}{D(1.3K)} = \frac{\tau(1.3K)}{\tau(4.2K)} = 1.5 \). Since \( L_\phi = \sqrt{D\tau_\phi} \) we obtain \( \tau(4.2K)/\tau(1.3K) = 6 \), much higher than the ratio between the phase coherence lengths. In order to elucidate the mechanism responsible for dephasing we carefully studied the temperature dependence of the magnetoresistance. We used the macroscopic 20uc sample since in such a sample the analysis of the central weak localization feature is less affected by the UCF themselves, which can alter the conductance at low fields. In principle, one could study a mesoscopic sample but for our case the number of fluctuations is too small to provide an accurate measurement for the temperature dependence of \( L_\phi \).

In fig 3 we present the magnetoconductance curves for the 20uc sample for temperatures ranging from 0.35 K to 20 K. The solid lines are the theoretical fits using equation (5). Here we also used \( L_\phi(T) \) and \( \tau_\phi(T) \) as the fitting parameters. The data was fit for a field range between -5 T to 5 T (or more). The higher field region was not included in the fit to avoid high field contributions due to electron-electron interactions and other possible corrections. The fit is excellent for \( T < 5K \) where quantum corrections dominate the low field behavior. For this sample we used \( g = 0.6 \pm 0.1 \) (consistent with Ref 21 for similar sheet resistance). We allowed \( g \) to vary within the error bar for the various temperatures to obtain a better fit for the higher field regime. This small variation does not affect the value of \( L_\phi \). The data could not be fit with \( \alpha N_v = 3 \) but with \( \alpha N_v = 1 \). The diminished role of the valley degeneracy for this sample can be explained by a stronger inter-valley scattering. We should keep in mind that this sample has mobility \( \approx 6 \) times lower than the 8uc sample. In addition, \( \alpha N_v = 1 \) was also used in Ref 21 for samples with similar sheet resistance. We note that while the magnetoresistance can be well explained by equation (5) the temperature dependence of the resistivity is more complicated. Other effects not included in our simple analysis may be involved. However, since the localization peak is seen together with the UCF we can be sure that quantum corrections are dominate the magneto-conductance at low temperatures.

The quasi-elastic electron-electron scattering time is known to be dependent on disorder. At low temperatures, in most cases, this is the major mechanism for the dephasing. This can explain the difference in dephasing between the two samples. To verify this assumption we plot the dephasing rate as function of temperature for both samples.

In fig 4 the dephasing rate calculated from \( L_\phi = \sqrt{D\tau_\phi} \) is plotted as a function of temperature on a logarithmic scale for both samples. The diffusion coefficient was calculated from Einstein relation \( D = \frac{\pi \hbar^2}{2m_e v_F^2} \). We used an effective mass of \( m^* = 3m_e \) (\( m_e \) the bare electron mass) and \( N_v = 3 \) as found for bulk SrTiO\(_3\). A linear temperature dependence is observed for the 20uc sample. The dephasing rate extrapolates to zero at zero temperature. This temperature dependence is expected from a Nyquist noise resulting from electron-electron interactions. For the 8uc sample a higher exponent is observed. Narozyński et al. calculated the dephasing rate for this case and found it to depend on the sheet resistance. This theory well describes the dephasing rate in semiconductors.

\[
\frac{1}{\tau_\phi} = \left\{ 1 + \frac{3(F_0^*)^2}{(1 + F_0^*)(2 + F_0^*)} \right\} \frac{k_BT}{\eta \hbar \ln[\eta(1 + F_0^*)]} + \frac{\pi}{4} \left\{ 1 + \frac{3(F_0^*)^2}{(1 + F_0^*)^2} \right\} \frac{(k_BT)^2}{\hbar E_F} \ln(E_F \tau / \hbar) \tag{6}
\]

where \( F_0^* \) is the interaction constant in the triplet channel, which depends on interaction strength, \( \eta = \frac{2\eta}{\sqrt{\eta_D}} \), \( k_B \) is the Boltzmann constant and \( E_F \) is the Fermi energy.
The solid lines in Fig. 1 are theoretical curves for the dephasing rate using the measured parameters for our samples. We used $F_0 = 0$ for both samples since the interaction parameter $r_s$ is expected to be small. The dephasing rate calculated from the 20 uc data fits the theoretical curve using $m^* = 5m_e^{28}$, we also show $\frac{1}{\tau_s}$ for $m^* = 3m_e$. Since the theoretical calculation is accurate within a factor of 2 one can safely state that both sets of $\tau_s$ agree with the theoretical curve. The dephasing rate for the 8 uc sample at 1.3 K $\tau_p \approx 2.1 \times 10^{10}$ sec$^{-1}$ which is indeed very close to $\frac{k_B T}{\phi^2} \approx 2.7 \times 10^{10}$ sec$^{-1}$ thus justifying the assumption of $L_0 \approx L_T$ use in the UCF analysis.

For the 20 uc sample the sheet resistance is high, therefore the first term in equation(6) dominates. This term gives the observed linear temperature dependence. For the 8 uc sample the sheet resistance is 3 times lower. Consequently the quadratic term has a significant contribution for the temperature range studied. The fact that data fit the theoretical curves put strong limitations on the product $N_v m^*$, which appears in the diffusion coefficient. Moreover, it can be seen in equation(6) that for low resistance samples the temperature dependence of the dephasing rate depends on the Fermi energy and hence on the the product $N_v m^*$ ($\alpha$ does not enter into the calculation of $\tau_s$). The importance of the quadratic term in our data (8uc) can therefore provide additional information on the effective mass. Hence we can conclude that $N_v m^*$ should be very close to $3m_e$. If we assume that $m^*$ is very large (say $m^* = 9$ and $N_v=1$) it will be difficult to explain the absence of a quadratic term in the dephasing rate for the 20uc sample. If $m^*$ is small the measured dephasing rate will go below the theoretical limit set by the Nyquist noise. We therefore conclude that $m^*$ is of the order of a few $m_e$. Similar results were obtained from infrared ellipsometry.$^{29}$

In summary, we measured universal conductance fluctuations in a mesoscopic sample of LaAlO${}_3$/SrTiO$_3$ interface. The phase coherence length obtained from these fluctuations equals (within the error) to that found from fitting the low field magnetoresistance curves. This suggests that the magnetoresistance at low fields is dominated by quantum corrections. We analyze the temperature dependence of the magnetoresistance in terms of the week localization theory. From the temperature dependence of the dephasing rate we conclude that it is dominated by electron-electron interactions. The dephasing time fits very well to the theoretical calculations of Narozhny et al.,$^{28}$ assuming an effective mass of $3m_e$. Since dephasing time is only limited by electron-electron interactions it seems that increasing the carrier concentration by gate voltage application will enhance the phase coherent length over the micrometer scale, meeting the requirements of quantum coherent electronic devices.

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