Superballistic electron flow through a point contact in a Ga[Al]As heterostructures

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We measure electronic transport through point contacts in the high-mobility electron gas in a Ga[Al]As heterostructure at different temperatures and bulk electron densities. The conductance through all point contacts increases with increasing temperature in a temperature window around \( T \sim 10 \text{ K} \) for all investigated electron densities and point contact widths. For high electron densities this conductance exceeds the fundamental ballistic limit (Sharvin limit). These observations are in agreement with a viscous electron transport model and previous experiments in graphene.

I. INTRODUCTION

Various electron transport regimes can be observed by changing the temperature and carrier density of a two-dimensional electron gas (2DEG). Two widely used models of electron transport imply either ballistic or diffusive electron flow. The ballistic transport model describes the situation where electron-electron interactions are irrelevant, and the electron mean free path related to momentum relaxation is much larger than the characteristic sample size. In turn, the diffusive model represents the non-interacting case, where momentum relaxation occurs mostly inside the system rather than at the boundaries. Beyond that, in some materials electron-electron scattering can be the dominant process within a certain range of temperatures. In this case the electron-electron scattering length is much shorter than both the transport mean free path and the characteristic sample size. This transport regime is known as the regime of viscous electron flow [1].

The viscous regime has been widely investigated in graphene [2, 3], where it is most pronounced at temperatures around 150 K. It was also shown in Ga[Al]As heterostructures using the Gurzhi effect [4] or Stockes flow [5], or based on a geometry which enables the measurement of the vicinity resistance [6]. In these experiments the temperature window was around 10 K. One hallmark of viscous flow that has been shown in graphene [7] but not yet in Ga[Al]As is the so-called superballistic flow through a point contact (PC) [8]. In this case, the conductance through the PC can be increased above the fundamental ballistic limit (Sharvin conductance). Here we demonstrate this characteristic increase of the conductance through a PC in a Ga[Al]As heterostructure in a temperature window around 10 K. These results add support to the fact that viscous flow can be observed in Ga[Al]As heterostructures.

II. SAMPLE

The sample is a Ga[Al]As heterostructure with a 2DEG buried 200 nm below the surface. The global patterned back-gate, roughly 1 \( \mu \)m below the 2DEG, allows us to change the electron density from \( 1.5 \times 10^{11} \text{ cm}^{-2} \) to \( 2.7 \times 10^{11} \text{ cm}^{-2} \) [9]. The sample has several top-gate defined PCs in series, with a lithographic width \( d \) ranging from 0.75 \( \mu \)m to 2.5 \( \mu \)m. The electronic width may differ from \( d \) depending on the details of the geometry and the applied gate voltages, but it remains much larger than the Fermi-wavelength in all measurements shown in this paper. For any given experiment discussed here, only a single PC was used at a time, and the remaining, unused, top-gates were grounded.

III. MEASUREMENTS AND DISCUSSION

All linear conductance measurements were performed in \(^4\text{He}\) systems at temperatures between 1.9 K and 16 K using standard lock-in techniques at 27 Hz. The carrier densities measured using the classical Hall effect were found to be independent of temperature in the investigated range. Figure 1(a) shows the bulk mobility \( \mu \) of the 2DEG resulting from a four-terminal measurement for various carrier densities tuned by the back-gate. The mobility decreases with increasing temperature as a result of acoustic phonon scattering [10].

Next, we describe the temperature dependence of the two-terminal conductance \( G \) through a single PC with lithographic size \( d \) for the same bulk electron densities \( n \) as in (a). Figures 1(b, c) show the results for the narrowest \( \left( d = 0.75 \mu \text{m} \right) \) and widest \( \left( d = 2.5 \mu \text{m} \right) \) PCs in our sample. Below a density- and width-dependent threshold temperature, the conductance \( G \) increases with temperature \( T \) for every set of \( n \) and \( d \), above it decreases. In general, the increase of the conductance with temperature is more pronounced and occurs over a larger range of temperatures for high electron density \( n \) and small PC width \( d \). This increase of \( G \) with increasing temperature is in contrast to the decrease of the bulk conductance of the 2DEG, which is proportional to the 2DEG mobility \( \mu \) (Figures 1(a)).

We discuss this behavior based on the geometry of the sample and the scattering lengths of electrons. At low temperatures, electron transport is ballistic and electron-electron interactions are irrelevant. The PC conductance \( G \) will always be smaller than or equal to the Sharvin
conductance \[ G_{\text{Sh}} = \frac{2e^2}{h} \sqrt{\frac{2nd^2}{\pi}} \] 
shown by the horizontal lines in Figures 1(b,c) for the highest \((n = 2.7 \times 10^{11} \text{ cm}^{-2})\) and lowest \((n = 1.5 \times 10^{11} \text{ cm}^{-2})\) displayed electron densities. The dashed lines show \(G_{\text{Sh}}\) calculated for the lithographic width of the PC. In reality, the PC width and the electron density in the PC will be slightly smaller because of the side depletion and stray field effects of the gates. Therefore, we numerically calculated the effective electronic width of the PC with the software package COMSOL within the Thomas-Fermi approximation \[12\]. For the gate voltages applied in our sample, we found values which are about 250 nm smaller than the lithographic width. The dotted horizontal lines in Figures 1(b,c) show \(G_{\text{Sh}}\) for this effective width. Our observation that \(G\) increases with temperature, eventually exceeding the Sharvin limit, agrees with observations in graphene \[7\]. Theoretical calculations \[8\] relate this behavior to electron–electron interaction effects, which result in a hydrodynamic behavior of the electron fluid. Within this interpretation we can say that our data exhibit superballistic flow in a GaAlAs PC.

The decrease of the conductance with temperature above the threshold temperature can be explained in the following way. The measured two-terminal resistance comprises not only the PC resistance discussed above, but also the resistance of the 2DEG between the PC and the source/drain contacts, which is in series to the PC resistance and therefore increases it. The resistance of the bulk 2DEG can be neglected at low temperatures, but electron-phonon interaction increases the bulk resistance at higher temperatures so that the measured conductance \(G\) increases more slowly with temperature or even starts decreasing (Figures 1(b,c)). This effect is expected to be more pronounced for wider PCs \[7\], which is consistent with the experimental data in Figures 1(b,c).

The PC conductance in turn can be approximated as a sum of ballistic \(G_{\text{Sh}}\) and viscous \(G_{\text{vis}}\) contributions \[8\]. Therefore, the total measured conductance \(G\) can be expressed as

\[
\frac{1}{G} = \frac{1}{G_{\text{Sh}}} + \frac{1}{G_{\text{vis}}} + \frac{1}{G_{2\text{DEG}}}. \tag{2}
\]

Here \(G_{2\text{DEG}}\) is the conductance of the bulk 2DEG between the PC and the source/drain contacts. As discussed above, \(G_{\text{Sh}}\) is independent of temperature and \(G_{\text{vis}}\) increases with temperature. The 2DEG conductance is diffusive and has the same temperature dependence as the bulk electron mobility \(\mu\) (Figure 1(a)). We did numerical calculations of \(G_{2\text{DEG}}\) with the COMSOL software package for known geometry and measured electron mobility and density, which gave us values of \(G_{2\text{DEG}}\) down to 0.01 \(\Omega^{-1}\) at temperatures above 10 K. The contribution \(G_{\text{vis}}\) was calculated from experimental data and numerical simulations; unfortunately the result depends significantly on the exact parameters for the simulations. Thus we were not able to validate the theoretically predicted \[8\] types of dependencies of \(G_{\text{vis}}\) on temperature, electron density or width of the PC. Nevertheless, we observe the increase of \(G_{\text{vis}}\) with increasing temperature and we can make an order of magnitude estimate for the kinetic viscosity \(\nu\) and the corresponding electron-electron scattering length \(l_{ee}\) based on the measured \(G\) and calculated \(G_{\text{Sh}}\) and \(G_{2\text{DEG}}\). At temperature \(T = 10\) K and electron density \(n = 2.7 \times 10^{11} \text{ cm}^{-2}\) we estimate \(\nu \sim 0.05 \text{ m}^2/\text{s}\) and \(l_{ee} \sim 1 \mu\text{m}\), which is comparable to theoretical estimates of these quantities \[13\].

![FIG. 1. (a) Bulk mobility of the 2DEG (all top-gates are grounded) as a function of temperature for electron densities from 1.5 \times 10^{11} \text{ cm}^{-2} \) to 2.7 \times 10^{11} \text{ cm}^{-2} \) changed in steps of 0.3 \times 10^{11} \text{ cm}^{-2}. (b) Conductance \(G\) of the narrowest PC \((d = 0.75 \mu\text{m})\) and (c) conductance of the widest PC \((d = 2.5 \mu\text{m})\) as a function of temperature; horizontal lines show the calculated Sharvin limit of PC conductance for the lithographic (dashed lines) and effective electronic (dotted lines) widths at the highest and lowest displayed charge densities.
IV. CONCLUSIONS

We performed measurements of the conductance through point contacts in a Ga[Al]As 2DEG for different temperatures, bulk electron densities and point contact widths. We consistently observe an increase of the conductance with increasing temperature within a certain temperature interval around $T \sim 10$ K for all available values of the electron density and the point contact width. For high electron densities the point contact conductance exceeds the fundamental ballistic (Sharvin) limit. We interpret these observations within the viscous electron transport model as superballistic flow through the point contact.

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