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# Electron Temperature and Thermal Conductance of GaAs 2D Electron Gas Samples Below 0.5 K

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The electron phase coherence length is used as a thermometer to measure the temperature of a 2DEG. We find that the electron temperature differs from the mixing chamber temperature of the refrigerator by as much as 100 mK at base temperature. We also measure the thermal resistance between the electron gas and the mixing chamber and find a resistance comparable to that predicted by the Wiedemann-Franz law for the electron gas alone. Our results indicate an extraneous power level of about 4 pW in our experimental configuration.

## 1. INTRODUCTION

For experiments designed to measure low temperature transport properties of an electron gas, the ultimate measure of performance of a dilution refrigerator system is the temperature reached by the electrons under typical conditions. This temperature will differ from the mixing chamber temperature, $T_{mc}$, because of power P dissipated in the sample, which must flow through some thermal resistance to reach the source of cooling power. By analogy with Ohm's law, for small temperature differences we have

$$\left(T_e - T_{mc}\right) = PR_{th} \qquad (1)$$

where $T_e$ is the effective temperature of the electron gas as inferred from measurement and $R_{th}$ is the thermal resistance of the path for the heat flow. (For large differences in temperature see below.)

The power P may come from the current used to measure the electrical resistance, or from extraneous sources such as electrical noise and thermal radiation from surfaces surrounding the sample. In this paper we present measurements of $T_e$ and $R_{th}$ for a GaAs/AlGaAs 2D electron gas. Our results indicate that $R_{th}$ is dominated by the electron gas itself, which is an important consideration in designing a system to achieve the minimum electron temperature.

## 2. RESULTS

Our 2DEG sample has a simple rectangular shape, 2 mm long and 100 μm wide, with current probes at either end and voltage leads along each side. The resistance per square at 4.2 K is 300 Ω with an electron density of about $1.6 \times 10^{15}$ $m^{-2}$. The sample is mounted in vacuum on the end of a Cu and epoxy rod which extends from the mixing chamber into the magnet. Each sample lead has a pi filter where it enters the cryostat and is capacitively coupled to electrical ground at the mixing chamber.

The low field magnetoresistance of the sample displays 2D weak localization. This can be fit to a well-established theory [1] to find the electron phase coherence length $L_\varphi$. A temperature dependence of $L_\varphi \propto T_e^{-1/2}$ is expected to hold down to millikelvin temperatures. Our results for $L_\varphi$ at mixing chamber temperatures from 500 to 40 mK are shown in Fig. 1 The straight line is a fit to $L_\varphi \propto T_{mc}^{-1/2}$ for the five points with $T_{mc} \geq 150$ mK. Below 130 mK, $L_\varphi$ is nearly independent of mixing chamber temperature. This indicates the electron gas did not reach temperatures below 130 mK. The current was kept small enough to avoid self-heating.

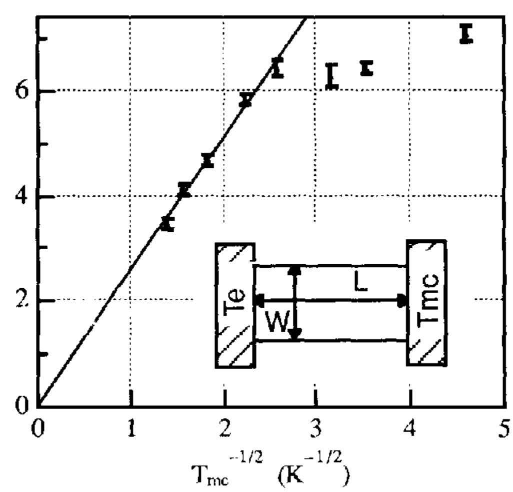


Fig. 1: Phase coherence length vs mixing chamber temperature (see text for inset).


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Heat conduction from the electron gas to the mixing chamber will occur predominantly through the ohmic contacts of the sample and the leads connected to them, since the electron-phonon coupling is very weak below 1 K. The thermal path consists of the Au wire bonds, the header pins and sockets, the Cu leads, the wrapping of the leads at various heat sinks at or near $T_{mc}$, and the thermal resistance of the electron gas itself. When estimates of these contributions are made using standard expressions and values from literature [2], the electron gas is seen to be the dominant thermal resistance in the problem. The Wiedemann-Franz law for $T_e \approx T_{mc} \equiv T$ (in S.I. units) gives

$$R_{th} = \frac{3}{\pi^2}\left(\frac{e}{k_B}\right)^2 \frac{R_{el}}{T} \approx 4\times10^7 \frac{R_{el}}{T} \tag{2}$$

where $R_{el}$ is the electrical resistance. Using $R_{el}$ for one square, we can define a thermal sheet resistance

$$\rho_{th} \approx \frac{10^{10}}{T} \equiv \frac{A}{T} \tag{3}$$

We model the thermal path between the 2DEG and the mixing chamber as a single lead of width W and length L as (see inset of Fig.1 ). The heat flow equation using (3) is

$$\frac{dT}{dx} = \left(\frac{P}{W}\right)\left(\frac{A}{T(x)}\right) \tag{4}$$

Considering the non-uniform temperature in our sample and the average distance heat must travel to reach the ohmic contacts, we estimate about two squares of resistance for the geometry of our sample (L = 2W). Integrating (4) along the lead gives

$$P = \frac{1}{2A}\int_{T_{mc}}^{T_e} T\,dT \tag{5}$$

To determine if the 2DEG limits $T_e$ we must measure the constant A for our sample. We do this by applying a known amount of extra power $\Delta P$ to the sample using the measuring current. We use the magnetoresistance to find $L_\varphi$ and infer the new $T_e$ assuming $T_e \propto L_\varphi^{-2}$. From (5) we have

$$A = \frac{1}{4\Delta P}\left(T_{e_f}^2 - T_{e_i}^2\right) \tag{6}$$

where $T_{ef}$ and $T_{ei}$ are the initial and final electron temperatures. Using (6) we obtain the results shown in Table 1. These show that A is roughly of the magnitude expected if the electron gas dominates the thermal path.

Table 1: Thermal resistance results.

| I (nA) | $\Delta P$ (pW) | $T_{ef}$ (mK) | $T_{ei}$ (mK) | A(from (6)) ($K^2/W$) |
|---|---|---|---|---|
| $\leq 10$ | — | | 130 | — |
| 14.6 | 1.3 | 140 | 130 | $0.52 \times 10^9$ |
| 22.6 | 3.2 | 200 | 130 | $1.8 \times 10^9$ |
| 51.1 | 16 | 280 | 130 | $0.96 \times 10^9$ |

## 3. DISCUSSION

According to (3), the constant A should be about $10^{10}$, which is about an order of magnitude larger than observed. However, this difference may not be so significant since the temperature profile along the sample is not uniform and the magnetoresistance is an average over the sample which reflects an effective temperature. With proper modeling of the temperature profile and the resulting magnetoresistance, better agreement is likely to be found, although the presence of some other thermal path cannot be ruled out at this stage.

From (5) and using $A=10^9$, we estimate the extraneous power heating the electron gas to 130 mK, with the mixing chamber at 40 mK, to be about 4 pW. We also estimate an upper bound for the black body radiation from the walls of the vacuum can surrounding the refrigerator (T = 4.2 K) to be 3.5 pW. Hence an obvious next step is to build around the sample a second enclosure which has $T \approx T_{mc}$ and produces negligible blackbody radiation. Such an enclosure may also provide better shielding of electrical noise. Shorter contacts would also be desirable to minimize the intrinsic thermal resistance of the 2DEG.

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