Integrated Electronic Transport and Thermometry at milliKelvin Temperatures and in Strong Magnetic Fields

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We fabricated a He-3 immersion cell for transport measurements of semiconductor nanostructures at ultra low temperatures and in strong magnetic fields. We have a new scheme of field-independent thermometry based on quartz tuning fork Helium-3 viscometry which monitors the local temperature of the sample’s environment in real time. The operation and measurement circuitry of the quartz viscometer is described in detail. We provide evidence that the temperature of two-dimensional electron gas confined to a GaAs quantum well follows the temperature of the quartz viscometer down to 4mK.

I. INTRODUCTION

One of the most exciting subjects in contemporary condensed matter physics is the study of the emergent phenomena in correlated electron systems. In particular, the two-dimensional electron gas has a very rich physics and new phenomena are expected to occur as the temperature is lowered. In the absence of a magnetic field a transition to a ferromagnetic state is predicted with decreasing electron density. In strong magnetic fields recent theories predict that certain fractional quantum Hall states could have exotic excitations obeying non-Abelian statistics. Extending transport experiments to ultra low temperatures is expected therefore to lead to the discovery of new electronic ground states and offers the rare chance of finding a new class of non-Abelian particles.

A critical experimental capability for studying correlated ground states is the achievement of ultra low electronic temperatures in transport measurements of systems such as GaAs. While modern dilution refrigerators can routinely cool below 10mK, such low electronic temperatures in semiconductor nanostructures are often difficult to achieve. There are several mechanisms which limit cooling of the electrons. First, cooling of a semiconductor crystal is limited by the Kapitza thermal resistance due to the phonon mismatch of the semiconductor and its thermal environment. Second, electrons couple to the host lattice via the electron-phonon coupling which increases surface area and therefore reduce the Kapitza thermalization at milliKelvin temperatures.

Heatsinking of the leads in traditional setups of sample-in-vacuum is done by wrapping copper wires with a thin enamel insulation around copper posts attached to different stages of the refrigerator, including the mixing chamber. The limiting factor in cooling of the sample is therefore the Kapitza thermal resistance due to phonon mismatch between the copper post, wire insulation, epoxy used, and the wire itself. The Kapitza resistance is inversely proportional to the geometric area of overlap. Since wrapping of the wires permits a relatively modest overlap, one often finds a poor electron thermalization at milliKelvin temperatures.

The use of sintered metals is a known way to increase surface area and therefore reduce the Kapitza resistance. To cool our sample we use heatsinks made of 100-500nm silver powder sintered onto 0.7mm diameter silver wires. One such heatsink is shown in Fig.1e and the sample attached onto several heatsinks can be seen in Fig.1d. In order to take advantage of the increased surface area of the heatsinks we immerse them...
cap onto which the sample is soldered with indium (see Fig.1d). During soldering we use a copper alligator clip to prevent overheating of the heatsink sinters. The cell is attached to the mixing chamber via an annealed high purity copper tail and filled with liquid He-3 through a capillary which is silver brazed onto copper posts attached to each cooling stage of the refrigerator.

III. THERMOMETRY BASED ON QUARTZ TUNING FORK VISCOMETRY

At low milliKelvin temperatures the widely used Ruthenium Oxide (RuO) resistive thermometers are not suitable for temperature measurement because of the loss of thermal contact and a strong dependence on the magnetic field applied\(^\text{13}\). For thermometry down to the 5mK base temperature of our dilution refrigerator we choose to measure the strongly temperature dependent viscosity of the He-3 liquid that, together with our sample to be measured, is enclosed in the immersion cell. According to the Fermi liquid theory the viscosity of He-3 obeys the simple equation \(\eta \propto T^2\)\(^\text{14}\) in the strongly degenerate limit, i.e. below about 30mK\(^\text{14}\). It was found that a correction of the form \(\eta T^2 (1 - 2.92T)\)\(^\text{14}\) constant can be used for temperatures up to 125mK\(^\text{15}\).

We measure the viscosity of He-3 with an oscillating quartz tuning fork which is fastened to the main heat exchanger of our immersion cell. Quartz tuning fork thermometers have recently been used in studies of quantum liquids\(^\text{16–18}\) and have a number of advantages. In our setup the quartz viscometer is in close vicinity of the sample and measures the in-situ temperature of the He-3 bath in real time. We will show later that the electron temperature follows that of the He-3 bath to the lowest temperatures. Quartz viscometers are simpler to build than the previously used vibrating wire viscometers\(^\text{19}\). In addition, quartz viscometers are easier to use than He-3 melting curve thermometers, are immune to radiofrequency heating, and dissipate very little heat. Since in vacuum the resonance of the quartz changes insignificantly with an applied magnetic field\(^\text{17,19}\), the strongly damped motion in the viscous He-3 is expected to be independent of the magnetic field.

The motion of the quartz tuning fork in pure He-3 is described by the Stokes hydrodynamic model\(^\text{16–18}\) which has recently been verified to be valid in the 5-100mK range by a cross-calibration against He-3 melting curve thermometers\(^\text{16,18}\). According to this model the quality factor of the oscillator \(Q\) is inversely proportional to the square root of the viscosity. Using the expression of the viscosity of He-3 below 125mK\(^\text{15}\), we find \(Q \propto T \sqrt{1 - 2.92T}\). The proportionality constant is determined from a calibration against a commercial RuO thermometer at 40mK\(^\text{20}\).

Figure 2a shows our measuring circuit for the quartz tuning fork viscometer. As seen in the dotted box in Fig.2a, the equivalent circuit of the quartz consists of an
FIG. 2. The measuring circuit (panel a), the in-phase component of the resonant current $I_x$ as function of the frequency of the driving oscillator at various temperatures (panel b), photo of the quartz tuning fork (inset of panel b), and the amplitude of the current at the maximum of the resonance versus the quality factor $Q$ (panel c). We used 5mV excitation.

RLC series resonant circuit connected in parallel to a parasitic capacitance $C_2^{19}$. In order to measure the resonant part of the current we used a bridge configuration$^{21,22}$ with a transformer$^{23}$ which effectively cancels the current due to the parasitic capacitance $C_2$ of the quartz. This is achieved by tuning the capacitance $C_3$ of a short semirigid coax to be equal to $C_2$. The current is measured with a wide bandwidth preamplifier with a gain of $10^6$ $V/A$ which is fed into a PAR model 124A lockin amplifier. The electrical cables of quartz are shielded using thin wall stainless steel tubing which is heatsunk to each stage of our refrigerator.

The circuit shown has two operating modes. When driving the reference channel of the lockin with an external generator we measure an in-phase resonant current with a perfect Lorentzian shape at any value of the temperature. Results of the frequency scan are shown in Fig.2b. While this way of scanning the frequency through the resonance is a good way to measure $Q$, it is somewhat cumbersome and time consuming. Inspired by a circuit used to drive torsional oscillators in studies of superfluid films$^{25}$, we employed a second operating mode which avoids the frequency scan and which utilizes a self-locking technique instead. This is achieved by switching the lockin frequency reference to the signal monitor output of the lockin. Using this technique we ensure that the frequency of the lockin automatically tracks the resonance frequency of the quartz. The phase shifter$^{26}$ is necessary to keep the frequency locked to the maximum of the Lorentzian curves rather than a different frequency close to it. We find that the current $I$ measured with the feedback loop containing the phase shifter is equal to the maximum of the Lorentzian current versus frequency scans and therefore the two different modes of running the quartz yield the same current output and hence the same temperature. In order to convert current into temperature, we first relate the measured current $I$ to $Q$. As seen in Fig.2c, this functional dependence is measured to be linear and therefore the current at resonance is $I \propto Q \propto T \sqrt{1 - 2.927}$. This technique substantially simplifies the measurement procedure and makes continuous monitoring of the temperature possible. We note that we did not succeed in running our quartz in the self-locked mode using an SRS lockin.

IV. CHARACTERIZING THE ELECTROMAGNETIC ENVIRONMENT OF THE SAMPLE

As discussed in the introduction, microwave heating is often a source of saturation of the electronic temperature in the milliKelvin range. In order to filter these waves we use a commercial room temperature filter$^{27}$ mounted in an aluminum housing, equipped with a Fischer connector which is directly plugged in to its mating connector on top of the refrigerator. Electrical connection from the top of the refrigerator to the mixing chamber is via constantan wires and from the mixing chamber to the immersion cell using polyimide coated copper wires. A second cold radiofrequency filter is made by enclosing these copper wires in silver epoxy. The same epoxy fastens the wires onto the copper tail connecting the immersion cell to the mixing chamber.

To characterize radiofrequency and possible ground loop heating in our setup we use a resistive thermometer soldered onto the heatsinks which are immersed into He-3. This is useful since cooling electrons in resistive thermometers encounters the same problems as cooling electrons in nanostructures$^{13}$. We considered two thermometers: a carbon-based thermometer described in Ref.13 and a RuO thermometer$^{28}$. The carbon resistor was thinned down by removing its phenolic protection...
for short response times. As discussed in Ref.13, such a carbon thermometer has an excellent thermal contact to its environment. In order to compare the thermal contact of the carbon and RuO thermometers we measured their self-heating curves at a constant cell temperature of 8mK as indicated by the quartz thermometer. These self-heating curves, shown in Fig.3, are performed by applying increasingly larger excitation currents and converting the measured resistances to temperatures using the calibration done in the limit of no self-heating. Since the RuO thermometer starts self-heating at the power of 100aW, we conclude that it is more suitable to estimate the residual heating and that the above value is an upper bound for the spurious radiofrequency power in our setup.

V. TESTING OF THE IMMERSION CELL

In order to assess the effectiveness of our immersion cell we measured the resistance of the carbon thermometer mounted onto the heatsinks as a function of mixing chamber temperature in two different configurations. First, we measured the resistance when the cell was intentionally left empty. In this configuration the carbon resistor is cooled only through the copper electrical leads. This configuration mimicks a traditional setup of sample-in-vacuum. As shown in Fig.4, we found that the resistance of the carbon thermometer saturates at 3kΩ below about 30mK. We conclude that in this configuration we are unable to cool our thermometer below 30mK even though our mixing chamber was at 5mK.

In the second configuration we filled the immersion cell with liquid He-3. We observed a dramatic change in the resistance of the thermometer from 3kΩ to 30kΩ at 5mK mixing chamber temperature. We interpret this tenfold increase of the resistance as evidence for a much reduced electron temperature in the thermometer when the cell is filled with He-3.

For further testing we performed a similar set of measurements on a two-dimensional electron gas in a GaAs quantum well mounted on the heatsinks. The size of the sample is $4 \times 4 \times 0.5mm^3$, its electron density is $3.0 \times 10^{11}cm^{-2}$ and mobility $2 \times 10^6cm^2/Vs$. We compared the magnetoresistance $R_{xx}$ of this sample with the refrigerator cooled to 6.9mK but the immersion cell empty to that measured with the cell filled with He-3 held at various temperatures. As seen in Fig.5, the magnetoresistance trace with the cell filled is much improved as compared to the trace taken with the cell empty while keeping the fridge at 6.9mK. For example the width of the $R_{xx}$ minima for the reentrant integer quantum Hall states is wider and the depth of $R_{xx}$ of the fractional quantum Hall state at Landau level filling factor $\nu = 2 + 2/5$ and $2 + 6/13$ is enhanced when the cell is filled. Furthermore, the trace with the cell empty has a very good overlap with the trace with the cell filled with He-3 and held at 22mK. We conclude that when the sample is cooled only through the measurement wires, its effective electron temperature is 22mK even when the refrigerator is very cold and that filling the cell with He-3 results in a lower electron temperature.

In order to directly compare the temperature of the electrons to that of the He-3 bath as measured by the quartz viscometer, we measure the dependence of the magnetoresistance of the $\nu = 2 + 3/8$ developing fractional quantum Hall state as function of the tempera-
FIG. 6. The activated temperature dependence of the magnetoresistance at $\nu = 2 + 3/8$ (panel a) and the monotonic width of the $\nu = 2 + 1/2$ plateau as function of the temperature (panel b) provide evidence that the electron temperature follows that of the He-3 bath.

VI. CONCLUSIONS

We have built a He-3 immersion cell which allows cooling of the electrons in semiconductor nanodevices to temperatures of a few milliKelvin. Such a low bath temperature is measured using a quartz He-3 viscometer. We have tested the performance of the cell subjected to a magnetic field by measuring the fractional quantum Hall effect. The activation measurement of the $\nu = 2 + 3/8$ fractional quantum Hall state provides evidence that the temperature of the charge carriers follows that of the He-3 bath, as measured by the quartz viscometer.

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