FINAL SCIENTIFIC/TECHNICAL REPORT

Project Title: Development of a Sub-millikelvin Demagnetization Refrigerator for Solid State Research and Education

Principal Investigator/Project Director: Rui-Rui Du, University of Utah

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Name and Address of Recipient Organization: University of Utah

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I. Executive Summary

This project was previously funded by DOE (DE-FG03-01ER45886) from 06/01/2001 to 01/31/2005; the current grant is a renewal grant for funding period 02/01/2005-01/31/2008. Since the PI Rui-Rui Du had accepted a faculty appointment at Rice University starting effectively January 1, 2005, the renewal was awarded to University of Utah for one year (02/01/2005-01/31/2006) for continuing operation of the project. The 2nd and 3rd year funding will be awarded to Rice following PI's move.

We are developing an instrument to cool electrons in semiconductors to extremely low temperatures (lower than 1 millikelvin), a unique capability that would allow studies of new states of matter formed by low-dimensional electrons. At such low temperatures (and with an intense magnetic field), electronic behavior differs completely from ordinary ones observed at room temperatures. Studies of electrons at such low temperatures would open the door for fundamental discoveries in condensed matter physics. Understanding low-temperature electron transport in low-dimensional and nano-scale devices is the foundation for developing next generation quantum information and quantum computation technologies. The primary material systems for such investigations will be ultra-high quality GaAs/AlGaAs quantum structures grown by molecular beam epitaxy, materials that are widely used in lasers and telecommunications.

Beyond the immense potential for the discovery of yet unforeseen new physics the development and application of such instrumentation offers a unique opportunity to train students in novel technologies at the cutting edge of present day capabilities. Just as many of today's openings in condensed matter research require knowledge of dilution refrigeration the next decade is bound to request familiarity with yet lower temperature techniques. Not only will the student receive training in ultra-low temperature methods, they will also acquire a solid understanding of lower-dimensional electron systems, which are building blocks of microelectronics and the workhorse of today's semiconductor industry.

II. Instrumentation

Achievement Supported by Previous DOE Grant

The main objective for this project is to develop a demagnetization refrigerator and related experimental techniques to cool electrons in semiconductors to submillikelvin temperatures, in order to pursue many-electron physics at the forefront of condensed matter science. This instrument is being developed using commercially available components. An Oxford model

FIG. 1 The superconducting high magnetic field system and dewar

FIG. 2 The Oxford model 1000 dilution refrigerator installed on the vibration isolation support inside the RF screened enclosure

FIG. 3 The instrument during the initial test experiments at low temperatures

FIG. 4 The instrument during the initial test experiments at low temperatures

1000 $^3\text{He}/^4\text{He}$ mixture dilution refrigerator and a superconducting double-magnet system consisting of a demagnetization coil (9 T) and a high magnetic field sample coil (16 T) are the two major components. We have successfully installed and tested the refrigerator (see FIG. 1 - 4). The doubled-magnet system has been manufactured and tested successfully.

Achievement Support by the Current Grant

Instrumentation work supported by the current grant has been centered around the designing and fabrication of Cu demagnetization stage, heat-switch, and Pt NMR thermometer. In addition, we have installed RF filters in the refrigerator and have performed the initial test of the refrigerator system. We have already observed fractional quantum Hall effect in very-high mobility GaAs/AlGaAs quantum wells at a temperature $T < 10$ mK.

A major component, the Cu demagnetization stage, has been constructed. This is a solid copper rod with slits cut into the high field section to avoid excessive eddy current heating. The material has been acquired from Hitachi Copper, it has a nominal purity of 99.99% and low content of magnetic impurities. The demagnetization stage is 530 mm long and 60 mm in diameter, a total of 180 moles of which about 120 moles are effectively in the magnetic field. The slits were cut by an electro-erosive spark cutter lengthwise through the section that is exposed to high magnetic field. This limits the eddy currents that are formed in a conducting material subjected to a changing magnetic field. After cutting, the copper stage will be annealed in a low oxygen environment at close to melting temperature. Annealing removes crystalline defects thus improving the thermal conductivity of the stage. Furthermore the low oxygen atmosphere neutralizes the remaining magnetic impurities by forming non-magnetic oxides. A residual resistivity ratio of around 2000 is easily achieved with this material and is high enough to guarantee that the whole stage will remain in good thermal equilibrium even at ultra-low temperatures below 1 millikelvin.

Both the demagnetization stage and heat-switch will be integrated into the refrigerator system. The stage will be mounted to the bottom of the dilution refrigerator through four Aluminium-oxide tubes, which provide a rigid but thermally very well isolated support structure. The thermal connection for the pre-cooling phase of the stage is a superconducting type heat-switch made out of Al-foils. Aluminium has the highest switching ratio, around 1600 T^{-2} (the ratio of thermal conductivity at normal state vs. conductivity at the superconducting stage) of materials suitable for use in a heat-switch. The technical difficulty in using Al is that it has a strong surface oxide layer, which can prevent from making a good thermal contact into the metal itself. This problem can be avoided by diffusion welding the Al-foils into copper pieces. The heat-switch is operated by a small superconducting coil surrounding the Al-foils. The critical field of Aluminium is only 10 mT, so a rather small external field is sufficient to drive the Al into the normal state thus opening the heat switch.

Thermometry for the demagnetization stage will be performed by NMR on Platinum nuclei. At the temperature range of the demagnetization stage, the magnetization of the Pt-nuclei follows the Curie law and hence the magnetization is inversely proportional to temperature. For measuring the magnetization we have purchased a commercial unit specifically designed for this purpose, a PLM-5. The PLM-5 makes the measurement convenient and reliable. The thermal probe itself is a small brush consisting of thin Platinum wires fixed to the top of the demagnetization stage. A superconducting solenoid around the probe polarizes the nuclei while

the excitation pulse and response signal will be transmitted through a smaller perpendicular coil wound around the Pt-brush. Pt-NMR is not a primary method of thermometry and thus the thermometer has to be calibrated before use. This is done by comparing it against the primary Co-60 thermometer fixed at the mixing chamber of the dilution unit. At zero external field the demagnetization stage has very low heat capacity and will be in good thermal equilibrium with the dilution unit and thus both thermometers will be at the same temperature.

The most challenging part of the project is transfer of the sub-millikelvin refrigerator temperature to the electron system and credible measurement of ensuing electron temperature. It requires the development of specialized instrumentation. The aim must be twofold: First, minimization of heating from external sources and from the actual measurement; Second, optimization of thermal coupling between the electron system and the refrigerator. All incoming wires are carefully filtered for RF radiation to prevent inadvertent heating of the samples. The system is enclosed in a double-shielded RF screened room manufactured and installed by Lindgren Inc.

III. Experimental Results

In the testing phase we have reached a base temperature of 7 mK in the absence of the demagnetization stage and have measured preliminary magnetotransport data in the fractional quantum Hall effect for temperatures < 10 mK. This test is crucial to assess the performance of the dilution refrigerator as well as for its optimization.

FIG. 5 The longitudinal and Hall resistances (vertical axis, in arbitrary units) versus magnetic field (horizontal axis, in T) from a high-mobility GaAs/AlGaAs quantum well at a temperature 10 mK.

From our preliminary experiments, it appears that a simple way to cool electrons to a few millikelvin would be to cool the electrical leads of the quantum well sample. In this approach the sample substrate is mounted on a Cu rod connecting to the mixing chamber of the refrigerator, and the Au leads are heat sinking to the Cu as well. It has been shown that

following this simple scheme an electron temperature of ~ 10 mK can be achieved in the presence of a few T of the magnetic field.

FIG 1 shows the magnetotransport data for a low electron density, very high-mobility GaAs/AlGaAs quantum well from Bell Labs, Lucent Technology. Using this high quality 2D electron sample, we are able to measure the electronic state at Landau level filling factor $\nu = 1/2$ at around 5 T. To our knowledge, this is the first time that a $\nu = 1/2$ state is measured at $T < 10$ mK. We have observed a sharp minimum in longitudinal resistance at $\nu = 1/2$. Clearly, with the demagnetization technique we will soon be able to achieve much lower temperatures, and study systematically the electronic state at $\nu = 1/2$ as well as other novel many-electron phases in the high-mobility semiconductor 2D electron systems.

IV. Lab Construction and Research Plan at Rice University

Lab Construction: The lab construction at Rice University has progressed well. The lab space (1200 SQF) is remodeled according to the plan of Utah lab, and has been completed.

Personnel: Our postdoctoral research associate, Dr. Tauno Knuuttila, who joined the project in September 2001, performed the instrumentation work and the actual low temperature experiments in the fractional quantum Hall effect. Dr. Knuuttila comes from the Low Temperature Physics Lab of the Technical University of Helsinki, where he participated in the original design and construction of a double stage demagnetization refrigerator. His experiments successfully reached the lowest temperature achieved in any laboratory in the world. Dr. Knuuttila will move to Rice following the project.

Research Plan: It is anticipated that shipping and assembling of the instrument, initial test and experiment will take place in Rice during 2006. Once the instrument is in place we will follow the proposed plan to pursue ultralow temperature research. The first set of experiments will be centered around the same type of samples (shown in FIG. 5), but with the lower temperatures provided by demagnetization technique, to study the physics at $\nu = 1/2$ and $5/2$. The experimental work will focus on the effective cooling of electrons in semiconductors.

We are in a good position to complete the integration of the instrument and to perform ultralow temperature experiments. The objective for the 2nd and 3rd year research is: 1) To integrate the demagnetization stage and the thermometry into the refrigerator system and to optimize the instrument performance; 2) To perform magnetotransport measurements below 5 mK on the quantum Hall states and other many-particle phases at higher Landau levels; 3) To explore novel approaches on the 2D electron physics such as lateral tunneling into the edge of the quantum Hall liquid and resistive detected nuclear magnetic resonance in quantum wells.

V. Information

Web page: <http://www.ruf.rice.edu/~dulab/index.html>