AIP | Review of Scientific Instruments

In situ biaxial rotation at low-temperatures in high magnetic fields

N. S. Selby, M. Crawford, L. Tracey, J. L. Reno, and W. Pan

Citation: Review of Scientific Instruments **85**, 095116 (2014); doi: 10.1063/1.4896100
View online: http://dx.doi.org/10.1063/1.4896100
View Table of Contents: http://scitation.aip.org/content/aip/journal/rsi/85/9?ver=pdfcov
Published by the AIP Publishing

REVIEW OF SCIENTIFIC INSTRUMENTS **85**, 095116 (2014)

In situ biaxial rotation at low-temperatures in high magnetic fields

N. S. Selby,[1,2,a)] M. Crawford,[1,3] L. Tracey,[1] J. L. Reno,[1] and W. Pan[1]
[1]*Sandia National Labs, Albuquerque, New Mexico 87185, USA*
[2]*Georgia Institute of Technology, Atlanta, Georgia 30332, USA*
[3]*Department of Mechanical Engineering, University of New Mexico, Albuquerque, New Mexico 87131, USA*

(Received 2 July 2014; accepted 8 September 2014; published online 24 September 2014)

We report the design, construction, and characterization of a biaxial sample rotation stage for use in a cryogenic system for orientation-dependent studies of anisotropic electronic transport phenomena at low temperatures and high magnetic fields. Our apparatus allows for continuous rotation of a sample about two axes, both independently and simultaneously. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4896100]

I. INTRODUCTION

Even in an isotropic two-dimensional electron system (2DES), due to strong electron-electron interactions, elections can form anisotropic phases. One of the most famous examples, for instance, is the stripe phase at half-filled high Landau levels in high mobility 2DES.[1,2] As a result, the electronic transport properties depend on the relative direction of the magnetic field with respect to the stripe orientations. To study these anisotropic transport properties (e.g., diagonal magnetoresistance R_{xx} and Hall resistance R_{xy}), rotating the magnetic field about a desired orientation in these anisotropic phases becomes necessary.[3,4] Often, an *in situ* sample rotator capable of operating at low temperatures and high magnetic fields has been exploited.

A common method to construct a low temperature (T) rotator involves using worm-gears. However, due to the friction between the gears in this approach, the heat generated by rotation is significant. In fact, one often has to wait for a long time for the cryogenic system to cool down to the base temperature. In 1999, invention of an ingeniously designed and extremely efficient low T string rotator was reported.[5] There, rotation was accomplished by pulling a string using a room-temperature mechanic feed-through and by using jewel bearings to reduce the friction heating. It can rotate 360° about one axis at temperatures as low as ∼20 mK and at magnetic fields up to 45 T with a power dissipation of less than 50 μW at slow rotation speeds.

Since its invention, this type of rotator has been copied and installed in many cryogenic systems. In particular, it has gained worldwide popularity in the so-called top-loading dilution refrigerators. However, this type of rotator can only rotate about one axis. On the other hand, in some experiments, it is desirable for the sample to be rotated about two axes. For example, in studying the in-plane magnetic field dependence of the stripe phase, it was observed that the rotation about two perpendicular crystalline directions [110] and [1-10] shows drastically different transport behaviors. In the two original experiments,[3,4] in order to achieve this biaxial rotation, one first measured the tilt field dependence for the in-plane magnetic field parallel to one crystalline direction. Then one warmed the sample up to room temperature, physically re-orientated the sample, and re-cooled it down to base temperature to study the transport properties for the in-plane field parallel to the other crystalline direction. Not only is this procedure lengthy, but the sample state in a high quality semiconductor device can be changed from one cool-down to another due to disorder configurations. As a result, some of the subtle electronic physics may become difficult to study.

Considering this, it becomes clear that it is highly desirable to rotate the sample about two axes *in situ* without warming up the sample. A search of literature shows that two-axial rotators have been designed and constructed, but most of them use worm-gear method.[6] Therefore, the drawback of large heat generation still exists. In addition to this severe heating issue, construction of a biaxial rotator is delicate and complicated. Furthermore, this kind of rotators are often bulky and could not even fit into the sample space.[7] Recently, two-axial rotators using piezoelectric materials have become available.[8] This kind of rotators were found to work extremely well in certain situations. However, cost of this kind of rotators is high and the high voltage needed to tune the rotating stage can interfere with some of delicate electronic transport property measurements.

In this article, we report the design, construction, and characterization of a simple to construct, easy to adapt and operate biaxial rotation stage. We show that this type of rotators can achieve independent two-axial rotation at low temperatures and high magnetic fields.

II. DESIGN AND CONSTRUCTION

The design constraints required to conduct our orientation-dependent experiments in cryogenic refrigerators are as follows:

- The ability to saddle a 16 pin dual in-line package (DIP) socket with standard chip to hold the sample.
- Maximum cross-sectional area less than 38 mm in diameter for the sample saddle to fit into the sample space.
- Maximum cross-sectional area less than 51 mm in diameter for the probe to fit into the refrigerator.

[a)]Email: nselby3@gatech.edu

- Components in the cryostat need to be made of nonmagnetic materials to ensure accurate operation in high magnetic fields.
- Achieve an angular resolution better than 0.1° to accurately and completely characterize orientation-dependent properties of semiconductors.
- Minimize power dissipation to be no greater than $100\ \mu W$ to allow for low temperature operation.
- The ability to operate in a vacuum or submerged in liquid or gaseous helium.

With these constraints, we design and construct a dome-shaped biaxial rotator. The details of constructing a cryogenic probe with this dome-shaped rotator are given as follows:

(1) Top assembly
As shown in Figure 1, outside the dilution refrigerator, a 3D printed holster secures two linear motion feedthroughs that are capable of .0025 in. linear resolution, which translates to a rotating angle resolution of 0.1°. The feedthroughs used in this design were Michael del Costello (MDC) BLM-133-1's (Bellows Linear Motion). They are then attached to two-stainless steel rod of diameter 0.01 in., as discussed below. In order to fit the two feedthroughs to a 1 in. Kwik-Flange (KF) flange, a 3/8 in. diameter stainless steel pipe is bent and brazed to both the Kwik-Flange and a KF to Del Seal ConFlat adapter which is bolted to the feedthrough. On the opposite side of the KF top, an Edwards Speedivalve is sealed to allow for the pumping of gas into and out of the sample space. In the center of the KF top is brazed a 3/8 in. diameter stainless steel pipe which is welded to a vacuum-sealed fisher connector for electrical measurements and temperature sensor readouts.

(2) Shaft assembly
The rotator is attached to a 1750 mm stainless steel shaft running from the top of the tank to the sample space. In order to reduce the heat load from room temperature to sample, seven 1.5 in. diameter $\times$ 0.1 in. thick brass discs spaced 2.4 in. apart run down the shaft starting 11.4 in. from the top. Three more 1 in. diameter $\times$ 0.1 in. thick brass discs spaced 3 in. apart run up the shaft starting two inches from the top of the brass coldhead. These discs are brazed to the shaft and, in addition, serve to stabilize two, 1/16th inch diameter stainless steel rotation-manipulation rods running parallel to the shaft from the top of the tank to the coldhead. The linear motion feedthroughs are attached to these manipulation rods via strings. On the opposite side of the shaft runs a 1/8th inch stainless steel pipe from the top of the shaft to the bottom used to pump gas from the chamber.

(3) Rotator assembly
At the bottom of the shaft, two strings are fastened to the stainless steel rods. The strings are 2 in. long twisted nylon fishing wire. This ensures that the strings will not become too brittle at low temperatures. Both strings are fed through slots cut in a coldhead. Also from the coldhead hang two quarter-inch strings of the same material which, together with the strings from the stainless steel rods, hang a dome. The dome's inertia holds it at rest until the one of the two stainless steel rods is adjusted. When this happens, one side of the dome is hoisted upward or allowed to drop slightly, effectively reorienting it with respect to the magnetic field. The coldhead and dome are machined from C360-grade brass on a computer numerical control (CNC) lathe and CNC mill. The dome saddles a 16-pin dual in-line package integrated circuit (IC) socket which, in turn, holds the sample. Brass was used because it is easily machinable and nonmagnetic.

(4) Wiring
Ribbon cable wiring bought from Oxford CryoSpare[9] is soldered to the 16-pin DIP IC socket. The wire runs up through the dome and coldhead before exiting the tube through a hole in the shaft (Figure 2). The wiring is coiled around the shaft in 5 in. intervals, except between 5 and 8 in. from the coldhead where the wiring is tightly wound around a length of 1/4 in. diameter copper rod for thermal anchoring. Upon reaching the top of the shaft, the wiring is fed through another drilled hole into the KF top and is soldered to pins of the Fisher connector.

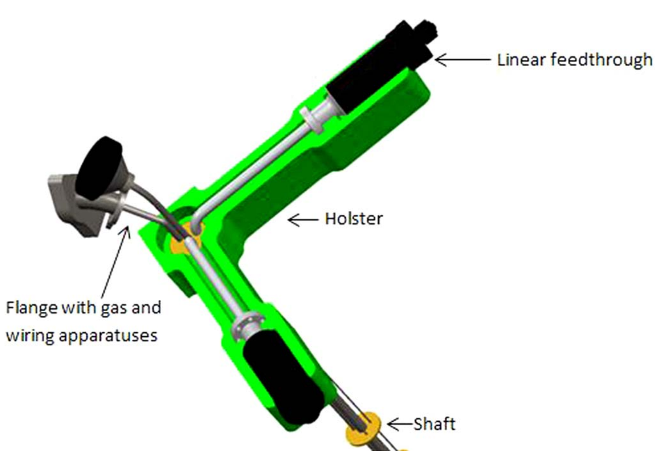

FIG. 1. CAD of top.

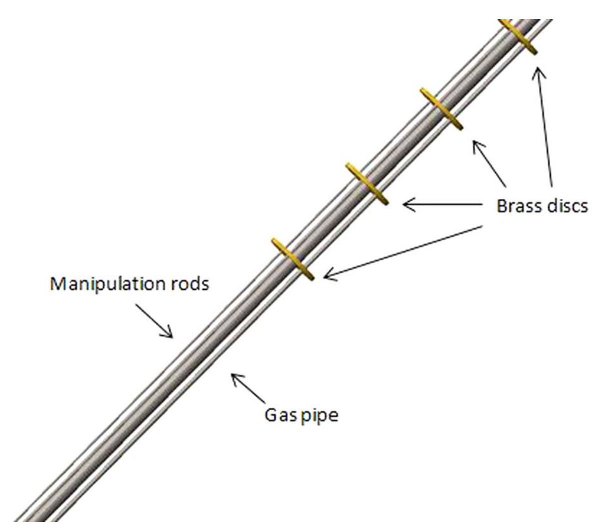

FIG. 2. CAD of shaft.

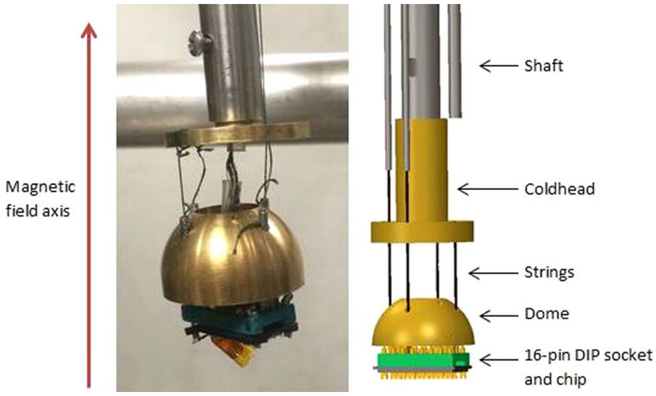

FIG. 3. Picture (left) and CAD (right) of rotator.

III. RESULTS

The rotator's performance was tested with a two-dimensional hole gas realized in a carbon doped GaAs/AlGaAs heterostructure grown on a {001} GaAs substrate.[10] The rotator was lowered into a variable temperature inset and cooled to 1.2 K. Once it was confirmed that the sample had reached the desired temperature, R_{xx} and R_{xy} (not shown) were measured. We used the R_{xx} minimum of a particular Landau level filling to calibrate the tilt angle. To find the zero tilt angle, we tuned the both feedthrough so that the B field position, for example, at Landau level filling $\nu = 2$, is at its lowest value of 2.250 T. This ensures that the tilt angle is zero and the sample normal is parallel to the magnetic field. To characterize our biaxial rotator, we first rotated the sample using one feedthrough to an angle of 16.5° (Figure 3). As a result, the R_{xx} minimum at $\nu = 2$ moved to a total magnetic field (B_{total}) of 2.347 T. After this, we rotated the sample again by 7.8° by using the second feedthrough. Now, the R_{xx} minimum at $\nu = 2$ moves to 2.367 T, giving an effective total rotating angle of 18.0°. In Figure 4, we plot R_{xx} traces at these tilt angles. The x-axis is the perpendicular magnetic field (B_{perp}), which is given by $B_{perp} = B_{total}$ x $\cos(\theta)$. It is clear that all the traces perfectly overlap with each other, implying that the rotator successfully rotated the sample about both axes independently and precisely.

IV. DISCUSSIONS

First, we note that, due to geometric constraints, the largest rotation values are 45° in either rotation direction. Beyond 45°, the strings begin to interfere with the dome's rotation. This limited rotating range is inherent in our current design. As a consequence, our biaxial rotator will not be suitable for high tilt angle measurements. On the other hand, we notice that in many experiments often a perfect orientation of magnetic field direction with a preferable sample crystal direction is necessary. For example, in studying the anisotropic fractional quantum Hall effect,[11] a perfect alignment of the sample normal to the external magnetic field direction is crucial. Our biaxial rotator is ideal for this purpose.

Second, we want to point out that the rotation mechanism in our biaxial rotation stage is the same as in the string rotator described in Ref. 5. In this regard, it is expected that

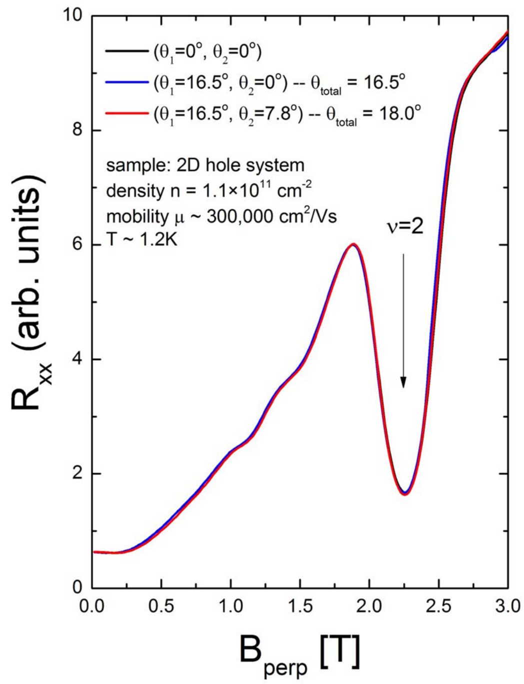

FIG. 4. R_{xx} versus perpendicular magnetic field B_{perp} for two-axis rotation.

the biaxial rotator showed above should be operable at lower temperatures down to dilution refrigerator temperatures. Of course, the second rotation rod will inevitably introduce extra heat load. We believe that this extra heat load can be alleviated by using thin wall stainless tubing in the future design for dilfridge applications.

Solid brass was used in our dome construction. This material was chosen because (1) it is non-magnetic; (2) it has a high mass density to ensure that the dome's inertia holds it at rest until one of the two stainless steel rods is adjusted. Indeed, the solid brass dome is prone to eddy current heating when sweeping magnetic field. To address this issue, we are working on our second generation design by introducing thin slots in solid brass. This technique has widely been used in ultra-low temperature dilfridge applications and is known to significantly reduce eddy current heating. Moreover, new materials, such as non-conducting, high mass density plastic, will also be examined as a replacement of solid brass.

In summary, we have reported in this article the design, construction, and characterization of a biaxial sample rotation stage for use in a cryogenic system for orientation-dependent studies of anisotropic electronic transport phenomena at low temperatures and high magnetic fields. Our apparatus allows for continuous rotation of a sample about two axes, both independently and simultaneously. We expect that this experimental capability will be found widely applications in studying spin transitions and ferromagnetic ordering in quantum Hall systems, critical magnetic field anisotropy in superconductors, bistability in hybrid semiconductor/ferromagnet systems, polarization reversal in multiferroics, etc.

ACKNOWLEDGMENTS

This work was supported by the Department of Energy, the Office of Basic Energy Science, Division of Material

Science and Technology. N.S.S. was supported by Sandia Student Internship Program. The authors would like to thank D. Barton, D. Huang, B. Vaandrager, X. Shi, and T. Coley for their help. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under Contract No. DE-AC04-94AL85000.

[1]M. P. Lilly, K. B. Cooper, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **82**, 394 (1999).
[2]R. R. Du, D. C. Tsui, H. L. Stormer, L. N. Pfeiffer, K. W. Baldwin, and K. W. West, Solid State Commun. **109**, 389 (1999).
[3]W. Pan, R. R. Du, H. L. Stormer, D. C. Tsui, L. N. Pfeiffer, K. W. Baldwin, and K. W. West, Phys. Rev. Lett. **83**, 820 (1999).
[4]M. P. Lilly, K. B. Cooper, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **83**, 824 (1999).
[5]E. C. Palm and T. P. Murphy, Rev. Sci. Instrum. **70**, 237 (1999)
[6]S. Takahashi and S. Hill, Rev. Sci. Instrum. **76**, 023114 (2005).
[7]R. Settai, M. Chida, S. Yanagida, and T. Goto, Jpn. J. Appl. Phys. **31**, 3736 (1992).
[8]L. A. Yeoh, A. Srinivasan, T. P. Martin, O. Klochan, A. P. Micolich, and A. R. Hamilton, Rev. Sci. Instrum. **81**, 113905 (2010).
[9]See www.cryospares.com for information about the wiring ribbon cable used.
[10]M. J. Manfra, L. N. Pfeiffer, K. W. West, R. de Picciotto, and K. W. Baldwin, Appl. Phys. Lett. **86**, 162106 (2005).
[11]J. Xia, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Nat. Phys. **7**, 845 (2011).