JPL OSMA PROJECT PROPOSAL FACT SHEET POP 96-1

Project Title Quantum Hall Effect-Based Resistance Standard(Quantum Hall Res)

OSMA Program Manager and Division: Joseph T. Siedlecki, Code QW

New Start or Augmentation New Start

Proposed Start Date May 1996 **Proposed End Date** June 2000

JPL Technical POC Miguel Cerezo **Mail Code** 125-18

Phone Number (818) 354-3033

Technical Summary

Objective:

The present technology for observing the quantum Hall effect requires that a quantum Hall resistor (QHR) be maintained at temperatures below 1.4 K, and in magnetic fields between 5 T and 15 T. Furthermore, in contrast with wire-wound standard resistors that can pass milli-amperes of current, present quantum Hall resistors are limited to currents between 25 μA and 60 μA. This means that expensive cryogenic systems and super conducting solenoids are required to produce the conditions for the QHE to be observed. The very limited current-carrying capacity of present QHRs requires highly specialized and complex measurement systems that can compare the low voltages developed across them to the voltages developed across the resistors being calibrated. The primary objective of this project is to develop QHRs that can operate at lower magnetic fields, higher temperatures, and higher currents, in order to reduce the costs and complexity of the cryogenic system and the measurement system. A secondary objective is to develop and improve simple measurement techniques that can calibrate wire-wound resistors using QHRs with combined relative uncertainties less than 0.1 ppm, even with the present limitations on the current that can be passed through the devices.

Background:

The U.S. Legal unit of resistance is presently disseminated using wire-wound resistors. The values of these resistors vary with time, and also with ambient conditions, such as temperature, pressure, and humidity. As a consequence, the resistors must be returned to a central laboratory to be calibrated. The higher the final accuracy required, the more frequently the resistors must be calibrated, which increases logistical costs. The quantum Hall effect (QHE) provides an invariant standard of resistance of exceptionally high accuracy that is independent of ambient laboratory conditions. The resistance of quantum Hall devices attains specific, well-defined values (equal to a ratio of fundamental constants) at certain values of magnetic field, producing resistance steps quite analogous to the voltage steps in Josephson arrays. This makes QHE devices ideal for maintaining standards of resistance with extremely high accuracy.

Technical Approach:

Quantum Hall Resistors (QHRs) are made by alloying metal contacts to long, narrow bars cut from specially grown heterostructures consisting of alternating layers of GaAs and $Al_xGa_{1-x}As$. Standards-quality QHR devices require both the highest quality heterostructure material and particularly low resistance ohmic (non-rectifying) contacts. The preparation of the contacts requires great care: the geometries of the QHR devices must be defined accurately using photolithographic techniques, but the contacts are particularly sensitive to many kinds of contamination, from organic photoresist residues to metallic impurities. Part of our work this year will continue our efforts to understand and control the chemical reactions occurring at the metal semi-conductor interface during contact formation to increase the yield of high-quality contacts and reduce their resistance.

The first goal of this project, viz., increasing the operating current, can be met by adjusting the geometry of the QHR. The exact relationship between the width of the device and the maximum current that can be used with it is not well understood at present: a number of experiments have been done by many workers, and some theoretical work has been published, but the work done to date is contradictory, with some workers suggesting that the critical current increases linearly with the width of the sample, and others suggesting that it varies logarithmically. Since an increase in the width of the sample must be accompanied by an increase in length, and since the probability that the sample will contain defects or inhomogeneities increases with its area, some research will have to be done to determine the current limits of QHR devices. Beginning this year, and continuing into next, we will prepare sample designs and make QHRs with different widths and lengths, and perform accurate QHR measurements to ascertain the maximum currents at which they can be used.

The second goal of this project, reducing the magnetic field at which the QHR devices operate, can be met by altering the design of the heterostructure from which the QHRs are made. By adjusting the relative thickness of the layers in the heterostructure and the density of donor impurities in it, one can reduce the free electron concentration in the two-dimensional electron gas (2 DEG) that is responsible for the QHE, and thus reduce the magnetic field at which the resistance plateaus are observed. Reducing the electron concentration is made difficult by the increased influence of defects in the heterostructure that can trap electrons, significantly altering the local concentration of electrons and resulting in large non-uniformities in the 2 DEG, particularly at the low electron densities required. While the concentration of defects can be reduced by lowering the aluminum concentration in the AlGaAs layer, this will reduce the depth of the potential well in which the 2 DEG resides, and can result in "parallel conduction" in the top layer of the heterostructure, which will cause the device resistance to be offset from the proper values. Work this year will build on experience that we have had in making QHRs over the last 5 years. New heterostructures with lower aluminum fractions and lower donor concentrations will be designed so that they have reduced defect densities and the proper electron concentrations. Heterostructures will be grown, devices prepared from them, and initial tests made to verify that they are of standards quality.

Deliverables, incremental and final

Quantized Hall resistance (QHR) devices that perform to the highest present standards will be provided. As QHRs that operate at lower magnetic fields, higher temperatures, and higher currents are developed, they will be made available to NASA. Reports describing the various cryogenic, magnet, and measurement systems that can be used to calibrate wire-wound resistors to the required levels of accuracy using QHRs will be prepared. Reports describing sample design considerations and fabrication techniques will be prepared.

Benefits for NASA's Strategic Enterprise

This project emphasizes metrology and calibration (Met/Cal) improvements in resistance measurement capability and accuracy by supplying NASA calibration laboratories with an intrinsic, high accuracy resistance standard. Funding of this project would result in improved mission reliability and a reduction in the costs associated with NIST intercomparison measurements.

Achieving Benefits

A fully automated quantum Hall effect-based resistance standard would provide NASA with an absolute, drift-free standard of resistance that could be installed in primary and secondary standards laboratories, and would permit those laboratories to perform resistance calibrations with uncertainties below 0.1 ppm. Such accuracies will enhance NASA's ability to calibrate end-use test equipment, such as 8 1/2 digit multi-meters, and calibrators that deliver uncertainties in the ppm range. The development of QHRs that operate at lower magnetic fields and higher temperatures will reduce the costs in acquiring and maintaining QHE-based resistance standards, and devices that operate at higher currents will make the QHR system more productive by reducing measurement times and increasing the calibration volume. This will be an intrinsic quantum standard for resistance analogous to the Josephson effect for voltage.

Milestone/Schedule

Design heterostructure that will exhibit i = 2 plateau at magnetic fields between 5 T and 6 T. ***June 1997***

Design QHR device with critical current above 300 μA, that can be used for precision measurements at currents between 80 μA and 100 μA.
June 1997

Build and test QHR devices to verify critical current and sample quality at currents between 80 μA and 100 μA. ***June 1998***

Provide at least one standards-quality QHR device that exhibits i = 4 plateau(6453.20175 Ω) between 5 T and 6 T to NASA. ***June 1998***

Deliver report describing the cryogenic, magnet, and measurement systems that can be used to calibrate wire-wound resistors using quantized Hall resistors.
June 1999

Provide at least one standards-quality QHR device that exhibits i = 2 plateau(12906.4035 Ω) between 5 T and 6 T to NASA. ***June 1999***

Deliver a report describing the results of experiments to increase the operating temperature of QHE devices; after successful demonstrations, QHR devices will be made available. ***June 2000***

Deliver reports describing the work done, and transfer the technology developed in this project to interested industrial concerns. ***June 2000***

Funding

	FY97	FY98	FY99	FY00
Baseline	120,000	130,000	140,000	140,000
Requested Delta	None			
Total Requested	120,000	130,000	140,000	140,000

Proposed Staffing

(FTE's)	FY97	FY98	FY99	FY00
NIST	1	1	1	1
Contractor:	None			

Collateral Funding

[Amt.,(Prob.)]	FY97	FY98	FY99	FY00
NIST:	350k$(100%)	375 k$(100%)	400 k$(100%)	400 k$(100%)
CCG:	50 k$ (20%)			
NASA:	120 k$	130 k$	140 k$	140 k$
Total:				

Potential for Transfer to Industry

The primary product developed in this project will be standards-quality QHR devices. There has already been some interest from a few companies in developing commercial products using these devices, but the small size of the present market for high-accuracy resistance standards has discouraged the pursuit of these interests. There are several factors that have been driving the need for higher-accuracy resistance standards, and the interest in acquiring QHRs has been rapidly increasing over the last few years. At the present time, it is difficult to assess the market demand for these systems at the conclusion of this project, but based on the present rate of growth of interest, it seems likely that at least one commercial partner can be found, to which NIST can transfer the technology developed in this project.

JPL Approvals:

W J Marner

W. J. Marner
Manager
Measurement, Test, and Engineering Support Section

for M. C. Lou
Deputy Manager
Science and Technology Development Section

for

B. C. McGlinchey
Manager
Mechanical Systems Engineering and Research Division

Quantum Hall Effect-Based Resistance Standard

NASA Metrology Project: New Proposal

Project Leaders: Kevin C Lee
Marvin E Cage

Uses of Resistance Measurements

> Voltage Measurements

Resistors are used in Voltage Dividers & as gain-defining elements in linear amplifiers for Analog-to-Digital Converters

> Current Measurements

Resistors are used as Current Shunts and in Current Dividers

> Temperature Measurements

Resistance measurements form the basis of Pt resistance thermometry & are used with many forms of thermo-resistive temperature sensors

> Other sensors (pressure, humidity, etc.)

V1

Factors Driving Increased Accuracy Requirements:

> Reduced Cost:

Higher Accuracy & Stability ⇒ Longer Calibration Intervals

> Longer Space Missions

Higher stability, increased accuracy permits instruments to be used for the longer times required by many modern and future missions

> Requirements of more sophisticated science

Higher accuracy measurements are required to ensure that the results of more sophisticated experiments are "real" and not instrumental artifacts

> Increased need for international traceability

As international participation in the space program is increasing, there is an increasing need to ensure that components manufactured in different countries function smoothly together

V2

Metrological developments driven by need for higher accuracy

> Measuring instruments now incorporate:
- Embedded Standards
- Programmed Self-Calibration

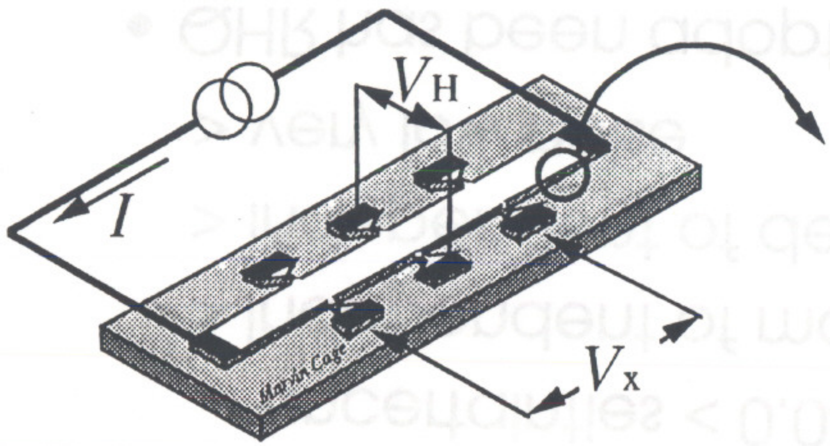
> Uncertainties of working instruments reduced to 1-2 ppm level *(e.g., HP3458A & Datron 1281);*

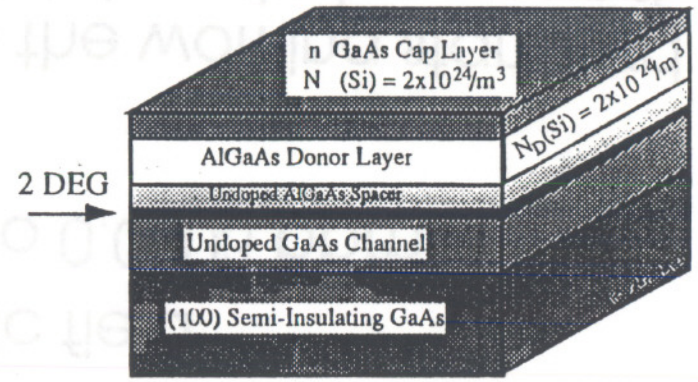
> Primary labs must be capable of 0.1-0.5 ppm or less

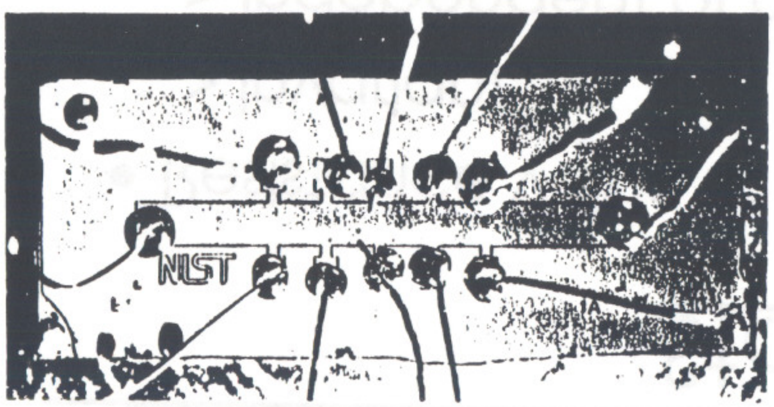
> These uncertainties can be achieved with:
- MAPs: *(0.02-0.1 ppm)*
- QHR standard: *(< 0.05 ppm)*

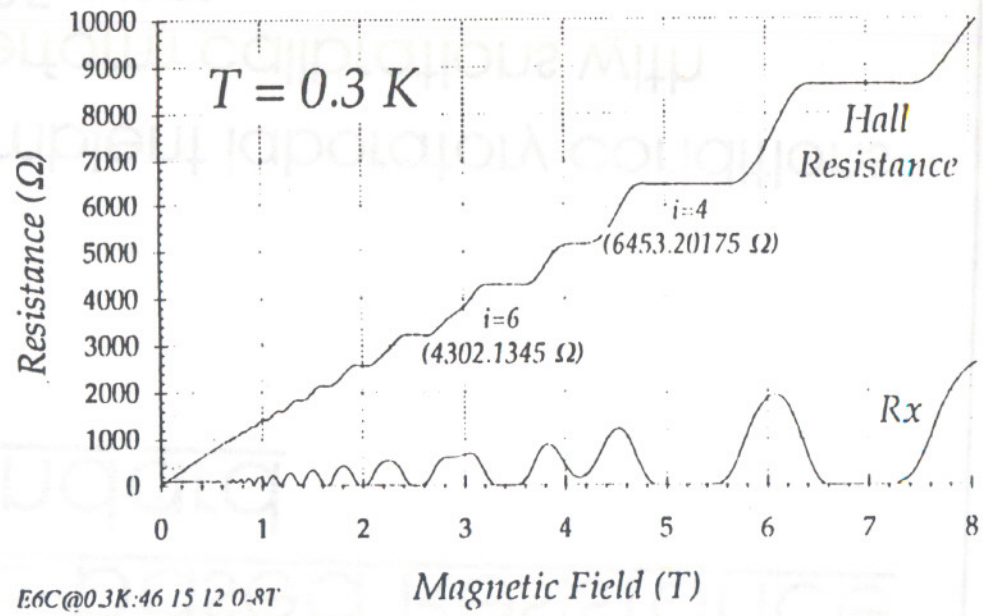
V3

Quantum Hall Effect-based Resistance Standard:









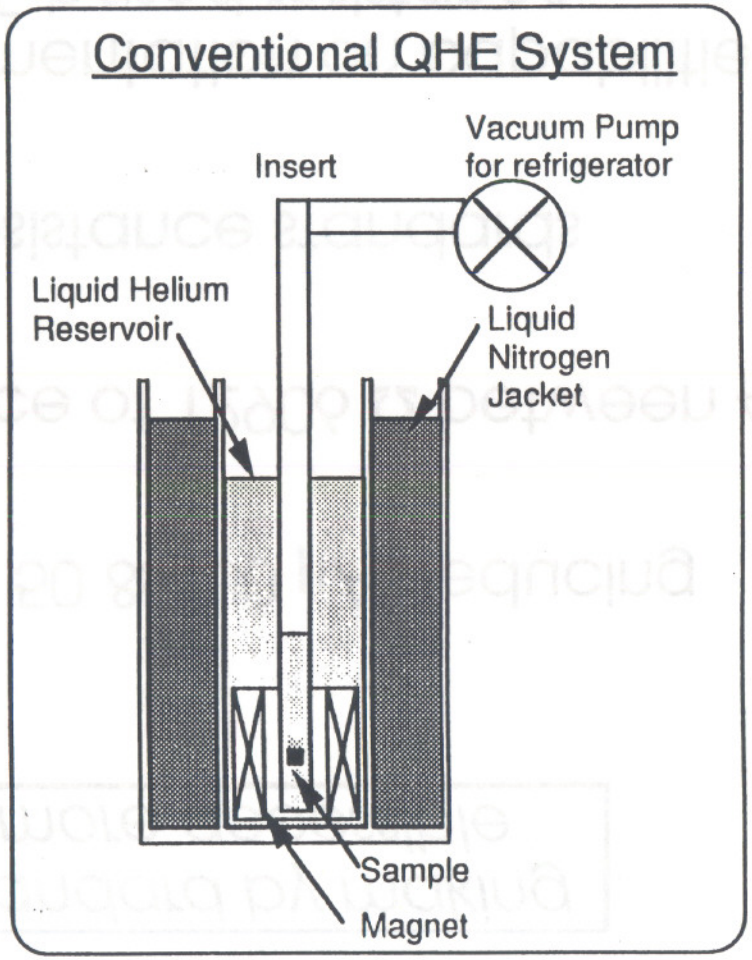
Benefits of a QHE-based Resistance Standard

- Resistance value is:
  - > invariant
  - > independent of ambient laboratory conditions
  - > can be used to perform calibrations with uncertainties < 0.05 ppm
  - > independent of magnetic field
  - > independent of device to 0.0003 ppm
  - > very low noise
- QHR has been adopted as the working standard by most national standards laboratories around the world

V5

QHE System Components:

- Cryogenic System
  (T ≤ 4.2 K)
  (Presently, ≤ 1.4 K required)
- Magnet
  (4 < B < 12 T)
- Sample *(I ≤ 30 μA)*
- Measurement System



589

Project Objectives:

Reduce costs of QHR standard by making operating conditions more accessible

- Prepare QHE Devices:
  - > that operate between 50 & 100 μA, reducing measurement time;
  - > that provide a resistance of 12906 Ω between 4 and 8 tesla;
  - > that can be used as resistance standards between 1 & 2 K
- Provide NASA with documentation on capabilities and requirements of QHE-based resistance standards.

V7

Benefits of achieving these goals:

- Intrinsic resistance standard providing lower uncertainty than present systems.
- High Current Devices:
  Permit use of automated measurement systems that deliver lower uncertainties than present systems in comparable measurement times.
- Lower Magnetic Field:
  Permits use of smaller & less expensive superconducting magnet systems.
- Higher Temperatures:
  Potentially permits attachment of small magnet to a probe that can be inserted directly into a storage dewar, greatly lowering costs of acquisition & simplifying operation

V8

Challenges in achieving objectives

> Increasing Current:

> *Determine dependence of current on width & geometry; improve quality of ohmic contacts;*

- *Models of width dependence have been developed, but not verified yet.*

> Decreasing Magnetic Field:

> *Design new heterostructures with lower electron densities; improve quality (uniformity, freedom from defects) of grown heterostructures*

- *New heterostructures have been designed, but not tested*

> Increase Operating Temperature:

-- *Causes of Temperature Dependence are not understood;*

> *Investigate effects of cooling rate, geometry, heterostructure design and quality.*

- *New cryogenic system to permit accurate temperature effect measurements is being installed presently.*

V9

Expected products to be delivered to NASA:

> QHE Devices:

- that can be operated with measurement currents between 50 and 100 μA;
- that give the $i = 4$ (6453 Ω) plateau between 4 and 8 T;
- that give the $i = 2$ (12906 Ω) plateau between 4 and 8 T;

> Full documentation on the design of a quantum Hall effect-based resistance standards system;

> Full documentation on sample design and preparation techniques;

> Technology transfer to NASA and interested companies.

V10

Funding Requirements

Source	FY 97	FY98	FY99	FY00
	Funding (Probability)			
NIST	$350k *(100%)*	$375k *(100%)*	$400k *(100%)*	$400k *(100%)*
CCG	$ 50k *(20%)*			
NASA *(requested)*	$120k	$130k	$140k	$140k

V11