RE-EXAMINATION OF QUANTUM HALL PLATEAUS

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Abstract

Even though the practical unit of electrical resistance was tied to the quantum Hall effect in 1990, our understanding of the fundamental physics of current flow, contacting, and impurity effects in quantum Hall systems remains incomplete. This paper examines some recently discovered effects which may affect quantum Hall resistance determinations.

Introduction

In contrast to the Josephson voltage steps which have no observed material-dependent corrections, the quantum Hall plateaus are not only temperature and current dependent [1], but also are not necessarily flat even when no significant longitudinal resistance is measured[2-3]. Furthermore, imperfections in the contacts can lead to contact-dependent corrections to the Hall resistance [4].

Recently, Hartland *et al.* [5] made a comparison of the quantized resistances of Si-MOSFET and GaAs heterostructure devices and found no discrepancies at the 0.0003 ppm (parts per million) level for a particular set of samples. This result, however, must not discourage investigations of physical phenomena which might lead to deviations from the quantized values. As the attainable precision and accuracy of quantum Hall resistance measurements improves beyond the 0.01 ppm level, it is necessary to re-examine, both experimentally and theoretically, questions related to the material- and parameter-independence of the effect. No conclusions tested at the 0.01 ppm level can be relied upon at the 0.001 ppm level.

Delahaye and Dominguez [6] carried out an extensive intercomparison of high-quality heterostructure devices, finding that the plateaus were device-independent at the 0.004 ppm level. Nevertheless, anomalies seen even in apparently "imperfect" devices, including Si-MOSFETs, must be understood since these effects may be present in "well-behaved" devices at a level more difficult to discern.

Plateau Flatness

We recently observed [3] irregularities in the i=4 plateau of a Si-MOSFET (grown by Sony Corp. and configured at Gakushuin University) which otherwise appeared to be an excellent candidate for use as a resistance standard. It had an exceedingly small ρ_{xx} (less than 0.002 ppm of R_{H}) for nearly 3% of its gate voltage at the i=4 plateau. Yet, its plateau undulated (with changing gate voltage) about the quantized value by up to ±0.04 ppm. Measurements on a similar device at the Electrotechnical Laboratory also revealed a comparable lack of flatness.

Heinonen [7] has offered a possible theoretical explanation for irregularities of the plateaus in Si-MOSFETs. He shows how scattering between discrete degenerate states at the edges can lead to Hall resistance anomalies without introducing dissipation.

Offset Plateaus

During the few years immediately following the discovery of the quantum Hall effect, there was much activity centered on testing the universality of the effect in different samples, for different filling factors, and for different semiconductor systems. The result was that the quantum Hall effect was established to be universal to within a few tenths of a part per million.

In 1988, however, Kawaji *et al.* [2] reported measurements of flat plateaus in Si-MOSFETs that were offset from the GaAs heterostructure value by 0.16 ppm. These samples satisfied all known criteria for standards quality devices including having ρ_{xx} values smaller than 0.015 ppm of the Hall resistance, a value not expected to shift the plateau by more than 0.003 ppm On the other hand, Delahaye and Bournaud [8] reported no anomalies in their examination of a similar Sony sample.

Measurements at NIST on our Sony sample and at ETL on two other Sony samples all revealed similar offsets [3] to those seen by Kawaji. At NIST, however, the offset plateaus were less stable, being induced by thunderstorm activity and cleared by warming to room temperature.

Contacts and Edges

In 1988, Büttiker [9] published a remarkable paper which emphasized the importance of edge currents and presented a model for their interaction with device contacts. Although his model actually applies only to currents less than those normally used for precision resistance measurements, it points to effects which can cause significant corrections to plateau resistance values. Komiyama and Hirai[4] have used his model to calculate corrections to measured plateau values which are dependent upon the resistance and arrangement of the sample contacts. Their corrections assume that all current flows in edge states, and consequently will overestimate contact effects present at the higher currents used for high precision measurements.

During the last few years, there has been a flood of experimental and theoretical work focused on clarifying the exact role of edge currents and contacts in quantum Hall systems.

Future Work

The quantum Hall effect in existing 2-D systems is a very complex phenomena that is only partially understood. Not only are the effects mentioned above not understood, but other basic questions regarding the current distribution, exact effect of impurities, the effect of edge-currents at medium current levels, and the breakdown of quantization at the highest currents all remain unresolved. These questions need to be *fully* understood in order to confidently rely on the quantum Hall effect at the parts in 10^9 level.

We have reduced our system noise by a factor of two and will present a comparison between the GaAs heterostructure used to maintain the ohm at NIST and a Si-MOSFET sample similar to that studied by Hartland at NPL.

References

[1] "Quantized Hall and Transverse Resistivities in Silicon MOS *n*-Inversion Layers," K. Yoshihiro, J. Kinoshita, K. Inagaki, C. Yamanouchi, J. Moriyama, and S. Kawaji, Physica B-C **117-118**, 706-8 (1983); "Temperature Dependence of the Quantum Hall Resistance," M.E. Cage, B.F. Field, R.F. Dziuba, S.M. Girvin, A.C. Gossard, and D.C. Tsui, Phys. Rev. B **30**, 2285-8 (1984).

[2] "Quantized Hall Resistance Measurements," S. Kawaji, N. Nagashima, N. Kikuchi, J. Wakabayashi, B.W. Ricketts, K. Yoshihiro, J. Kinoshita, K. Inagaki, and C. Yamanouchi, IEEE Trans. Instrum. Meas. **IM-38** 270-5 (1989); S. Kawaji, Physica B **164**, 50-8 (1990).

[3] C.T. Van Degrift, K. Yoshihiro, M.E. Cage, and D. Yu, K. Segawa, J. Kinoshita, and T. Endo, Proc. 9th Intern. Conf. Electronic Properties of 2-D Systems, Surface Science, in press; K. Yoshihiro, C.T. Van Degrift, M.E. Cage, and D. Yu, to be published.

[4] "Theory of contacts in a two-dimensional electron gas at high magnetic fields," S. Komiyama and H. Hirai, Phys. Rev. B **40**, 7767-75 (1989); "A contact limited precision of the quantized Hall resistance," H. Hirai and S. Komiyama, J. Appl. Phys. **68**, 655-62 (1990).

[5] "Direct Comparison of the Quantized Hall Resistance in Gallium Arsenide and Silicon," A. Hartland, K. Jones, J.M. Williams, B.L. Gallagher, and T. Galloway, Phys. Rev. Lett. **66**, 969-73 (1991).

[6] "Precise Comparisons of Quantized Resistances," F. Delahaye and D. Dominguez, IEEE Trans. Instrum. Meas. **IM-36**, 226-9 (1987).

[7] "Deviations from perfect integer quantum Hall effect," O. Heinonen, submitted for publication.

[8] "Low-Noise Measurements of the Quantized Hall Resistance using an Improved Cryogenic Current Comparator Bridge," F. Delahaye and D. Bournaud, IEEE Trans. Instrum. Meas. **IM-40**, 237-40 (1991).

[9] "Absence of backscattering in the quantum Hall effect in multiprobe conductors," M. Büttiker, Phys. Rev. B **38**, 9375-89 (1988).