Final Technical Report

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Thermal Conductivity and Thermopower Near the 2D Metal-Insulator Transition

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The goal of the research during this grant period was to measure the thermoelectric power of a dilute high-mobility (i.e., low-disorder) strongly interacting two-dimensional electron system in a silicon MOSFET (Metal Oxide Semiconductor Field Effect Transistor). These are samples in which unexpected metallic-like behavior and an apparent metal-insulator transition at a finite critical electron density n_c had been reported, based largely on transport measurements (resistivity, Hall resistance, magnetoresistance). Whether the behavior observed in these materials is indeed evidence for a true quantum phase transition, or whether it is crossover behavior, has been the subject of a great deal of debate and many publications during the past 20 years or so.

The thermoelectric power is a different property that had not been probed in the region of interest near the transition. This turned out to be an exceptionally difficult experiment that required the reliable measurement of exceedingly small voltages. The work entailed finding the right conditions (for example, immersion of the samples in He-3 liquid, or in thermal contact with the He-3 through exchange gas, or immersion in the liquid or out of the liquid in a He-3/He-4 dilution refrigerator fridge). Noise suppression was a major challenge that required painstaking rf filtering and sophisticated electronic techniques. The proper amplifier had to be identified. The time required to obtain a single data point increased as the temperature was decreased, reaching many hours at the lowest temperatures. And other issues as well. Measurements were attempted in several different laboratories using different instrumentation and methods.

The goal was ultimately achieved. The results are definitive, and are published in the last paper listed below. In brief, we found that the thermopower *diverges* at a finite electron density n_t that is the same or very close to the density n_c deduced from the transport measurements. Such a divergence is generally the hallmark of a genuine quantum phase transition. Moreover, detailed examination of the results allowed us to conclude that the transition was driven by the interaction between the electrons rather than by disorder – a circumstance that is of great interest in the field. Thus, metallic behavior obtains at densities above the critical density, while insulating behavior is found below. The nature of the insulating phase is not currently known, and is the subject of on-going investigations.

SUMMARY:

Measurements of the thermoelectric power of the dilute, strongly-interacting two-dimensional electron system in high-mobility, low-disorder silicon MOSFETs were obtained at low temperatures down to 0.2 K. With decreasing density n_s, the thermopower was found to exhibit a sharp increase by more than an order of magnitude, tending to a divergence at a finite, disorder-independent density n_t. The critical behavior of the thermopower observed in our experiments provides clear evidence for an interaction-induced quantum phase transition to a new phase at low density in a strongly interacting 2D electron system, thereby settling a 20-year debate.

PUBLICATIONS:

“Scaling of the Thermoelectric Voltage induced by Microwave Radiation at the Boundary between 2D Electron Systems,” Ivan A. Larkin, N. Romero Kalmanovitz, I. Hoxha, Y. Jin, S. A. Vitkalov, M. P. Sarachik, and T. M. Klapwijk, AIP Conf. Proc. **119**, 215 (2010)

"Metal-Insulator Transition in 2D: Established facts and open questions," S. V. Kravchenko and M. P. Sarachik, in *50 Years of Anderson Localization,* edited by Elihu Abrahams (World Scientific, 2010); International Jour. of Mod. Phys. B, **24**, 1640-1663 (2010).

“Critical Behavior of a Strongly-interacting 2D Electron System,” A. Mokashi, Shiqi Li, Bo Wen, S. V. Kravchenko, A. A, Shashkin, V. T. Dolgopolov, and M. P. Sarachik, Phys. Rev Lett. **109**, 096405 (2012).