FINAL REPORT
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Quantum Electronic Matter in Two Dimensions

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Summary: This report summarizes the DOE-supported work we have done over the last three years. It is a final report; no renewal of the grant has been requested. In addition to comprehensive measurements of the thermopower of 2D electron systems in the fractional quantum Hall regime, this grant has supported our work on graphene including studies of transport in trilayer graphene and the effects of heavy adatoms on transport in single layer graphene. Also included is a brief description of our very recent work on the stripe phases of 2D electron systems at high Landau level occupancy.

I. Thermopower of Two Dimensional Electrons in the Fractional Quantum Hall Regime - (papers 1 and 3). Using a novel variation on a standard technique, we have performed the most detailed and accurate measurements of the longitudinal thermopower S_{xx} of 2D electrons in the regime of the fractional quantized Hall effect (FQHE). While our original motivation was the detection of predicted signatures of non-abelian quasiparticle statistics in the so-called 5/2 state (a goal which remains elusive), our experiments did yield the first-ever measurements of S_{xx} within the delicate states FQHE states at filling factors ν = 11/5, 7/3, 5/2, 8/3, and 14/5 in the first-excited (N=1) Landau level (LL). Perhaps most excitingly, we observed a very sharp collapse of the thermoelectric power at around 40 mK in the regime of the "re-entrant" integer quantum Hall effect (RIQHE) in the N=1 LL. This latter observation strongly suggests that these re-entrant phases form via a first-order phase transition.

II. Electronic Transport in ABA Trilayer Graphene – (paper 2). In recent years there has been an explosion of interest in the properties of graphene (a single atomic layer of carbon atoms). Unlike *graphite*, which is a semi-metal with finite populations of both electrons and holes at the Fermi surface, graphene is a gapless Dirac material: Ideally there are no holes or electrons present at the Fermi level (in the absence of doping). The question then arises: How many layers of carbon atoms are needed before semi-metallic behavior emerges? Years of experiments on Bernal stacked *bilayer* graphene have demonstrated that two layers is not enough. The energy spectrum of bilayers differs significantly from single layers but the conduction and valence bands still do not cross. Our recent experiments on *trilayer* graphene demonstrate convincingly that three layers is the minimum needed. We employed a dual-gated geometry whereby separate top and backside gate voltages could be applied. This is essential if the effects of increased total carrier density are to be separated from the effect of a symmetry-breaking electric field which maintains constant density but alters the bandstructure in a controlled fashion. Observations of distinct quantum Hall plateaus allowed us to unambiguously identify the

ABA stacking order in the trilayer. Additional low field transport measurements clearly reveal evidence that two distinct carrier populations are present even at the net charge neutrality point; this establishes ABA trilayer graphene as a true semi-metal.

III. Heavy Adatoms on Graphene - (manuscript 4) Using a home-built cryogenic ultra-high vacuum deposition system, we have explored the transport characteristics of graphene on which a dilute ($\sim 10^{12}$ cm^{-2}) population of indium (In) atoms have been deposited. This is an interesting system since there have been recent theoretical suggestions that the In adatoms would "loan" their strong spin-orbit coupling to the mobile carriers in graphene and thereby convert it into a 2D topological insulator. Our experiments have revealed that the In atoms donate electrons to the graphene, thereby shifting the chemical potential away from the Dirac point. Analysis of the conductivity and its dependence on In concentration has led us to the conclusion that In adatoms act as a simple charged scattering centers with, so far, no evidence for significant spin-orbit effects. In addition to shifting the chemical potential, the In reduces the mobility of the graphene carriers and increases the level of charge density inhomogeneity. The latter is especially important near the charge-neutrality point.

IV. Density Dependence of Quantum Hall Stripe Phases - At high Landau level (LL) occupancy ($N \geq 2$) 2D electrons in the GaAs/AlGaAs heterostructure system exhibit unusual collective phases which are distinct from the fractional quantum Hall states found at lower LL occupancy and the weakly disordered Fermi liquid at zero magnetic field. In particular, states with a strongly anisotropic resistivity are found near half-filling of several excited LLs (e.g. at $\nu = 9/2, 11/2$, etc.). Prior to our work these "stripe" states have only been examined in samples with a fixed electron density. Using a novel device architecture which includes an epitaxially-grown transparent heavily doped cap layer, we have begun to explore the stripe phases as functions of the carrier density, the latter being continuously controllable at low temperatures using the cap layer as an integrated top gate. Among our initial results is the observation that the "critical temperature" for stripe formation is significantly density dependent. While not surprising, this opens the prospect for quantitative comparison with theories of the stripe phase energetics.

Publications:

1. "Thermopower of Two Dimensional Electrons at $\nu = 3/2$ and $5/2$", W.E. Chickering, J.P. Eisenstein, L.N. Pfeiffer, and K.W. West, Physical Review B **81**, 245319 (2010).
2. "Quantum Hall Effect and Semimetallic Behavior of Dual-Gated ABA-Stacked Trilayer Graphene", E.A. Henriksen, D.Nandi, and J.P. Eisenstein, Physical Review X **2**, 011004 (2012).
3. "Thermoelectric response of fractional quantized Hall and re-entrant insulating states in the N=1 Landau level", W.E. Chickering, J.P. Eisenstein, L.N. Pfeiffer and K.W. West, Phys. Rev. B 87, 075302 (2013).
4. "Transport in indium-decorated graphene", Chandi U. E.A. Henriksen, and J.P. Eisenstein (in preparation).

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