Field-Induced Phase Transition in the Weyl Semimetal TaAs

Ramshaw, B.J. (NHMFL-PFF, Cornell University); Modic, K.A. (NHMFL-PFF, MPI-CPFS); Moll, P.J.W. (MPI-CPFS); N.J. Ghimire (LANL, ANL); Bauer, E.D. (LANL); Ronning, F. (LANL); McDonald, R.D. (NHMFL-PFF)

Introduction

Electrons in a metal can be confined to a single, highly-degenerate, quantum level by application of extreme magnetic fields—a regime known as the quantum limit. The fractional quantum Hall effect appears in this limit in 2D electron systems, providing rich emergent physics. In three dimensions, on the other hand, it is rare that sufficient fields can be reached to enter the quantum limit, with graphite providing a notable exception. We used magnetic fields up to 82 Tesla to put the Weyl semimetal TaAs far into its quantum limit, and discovered a field-induced phase transition. As the bandstructure of TaAs is topologically non-trivial, this represents a unique opportunity to study a correlated state entwined with a topological bandstructure.

Experimental

We used focused ion beam lithography at Los Alamos National Labs to structure single-crystal TaAs for an optimal transport geometry (Fig. 1). This allows for a well-defined current path—important for accurate measurements given the extremely anisotropic magnetoresistance of TaAs. We measured resistivity using a digital-lockin method at 300 kHz with a 100 µA excitation current. Fig. 2 shows field pulses up to 82 Tesla for a range of temperatures.

Results and Discussion

The Fermi surface of TaAs contains both electron-pockets, which have linear dispersions and each contain a single Weyl-node, and hole pockets, which have trivial parabolic bandstructure [1]. The largest Weyl pockets have a quantum limit of 8 T, at which point all electrons are confined to the field-independent 0th Landau level; the hole pocket has a quantum limit of 18 T, and is ultimately depopulated at twice this value. Above 36 T the only quasiparticles at the Fermi surface are in the 0th Weyl Landau levels. Near 65 T the resistance for B||J||c increases rapidly with magnetic field. Above 65 T the conductivity can be fit to an activated-in-temperature form, yielding a gap that opens at a rate of approximately 1 Kelvin/Tesla. This is between 10 and 100 times smaller than the cyclotron gaps in the system, indicating that this gap does not represent the thermal population of empty Landau levels, but rather is the result of a correlated electronic state.

Conclusions

We have induced a phase transition in TaAs by application of magnetic fields well beyond the quantum limit threshold. Opening up a gap in a 3D Dirac or Weyl bandstructure cannot be done by perturbing the single-particle spectrum alone (as opposed to 2D), but rather requires the presence of electron-electron correlations [2]. Our discovery of a field-induced state in TaAs significantly advances our understanding of how electrons in 3D can behave in the quantum limit; it remains to be discovered what the exact nature of this state is, and what is the role the topologically non-trivial bandstructure.

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References