Two-Dimensional Magnetotransport in a Black Phosphorus Naked Quantum Well

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Introduction

Black phosphorus (bP) is the second known elemental allotrope with a layered crystal structure that can be mechanically exfoliated down to atomic layer thickness [1-3]. In contrast to graphene, bP has an intrinsic direct band gap of 0.3 eV bandgap, which approaches 2 eV in the atomic monolayer limit [1], ideal for applications in electronics and optoelectronics.

Experimental

We have fabricated bP naked quantum wells of varying thickness in a back-gated field effect transistor geometry. Using an encapsulating polymer superstrate (Fig. 1a), we have protected bP from oxidation, allowing a variety of experiments to be conducted from 300 K to 300 mK. Further, using a resistive magnet with a 300 mK He^3 cryostat at the NHMFL, we have measured magnetoresistance up to 35 T.

Results and Discussion

We have observed field effect mobilities up to 600 cm^2/Vs and on/off current ratios exceeding 10^5, indicative of the high electronic quality of naked bP [3]. Shubnikov-de Haas (SdH) oscillations observed in magnetotransport measurements (Fig. 1b) reveal the presence of a 2D hole gas with Schrödinger fermion character (Berry phase $\beta \approx 0$) in an accumulation layer at the bP/oxide interface (see Fig. 1c). The Schrödinger fermion character is expected with the band extremum located at the time invariant momentum Z in the Brillouin zone.

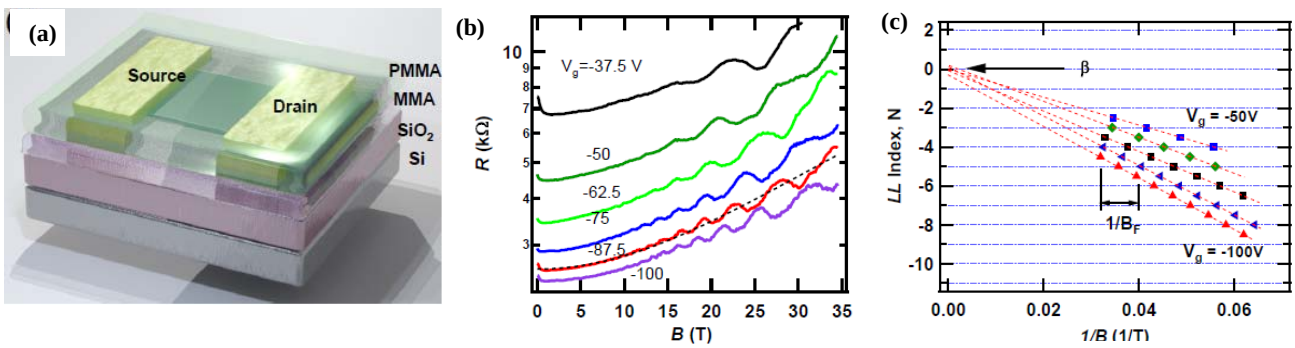

Figure 1: **a**, A schematic of a bP FET structure used in our work. b, The measured 2 point resistance *R* as a function of applied magnetic field B at different gate voltages at *T*=300 mK. **c**, The Landau fan diagram of LL index N versus *1/B* at different gate voltages. The SdH frequency, B_F, and Berry phase, β, are extracted from the slope and intercept of the diagram. Quantitative analysis reveals the holes to be confined to a single 2D sub-band.

Conclusions

Our work demonstrates that 2-D electronic structure and 2-D atomic structure are independent. 2-D carrier confinement can be achieved in layered semiconducting materials without necessarily approaching atomic layer thickness, advantageous for materials that become increasingly reactive in the few-layer limit such as bP. Since the completion of our work, we have learned of similar and consistent results reported by the Yuanbo Zhang group [5].

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