**Dual Top and Bottom Gated Black Phosphorus Field-Effect Transistors**

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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, bulk bP is a *bona fide* semiconductor with an intrinsic direct band gap of 0.3 eV which increases to ~2 eV in the atomic monolayer limit of *phosphorene*.

**Experimental**

We have fabricated both single and dual top and bottom gated bP transistors, with thicknesses ranging from 6±1nm to 47±1 nm. Using an Al2O3, Au, and a polymer encapsulant (Fig. 1a), we suppress bP oxidation without recourse to the multiple alignment of flakes exfoliated from different 2D materials [1].

**Results and Discussion**

 We observe field effect mobilities up to ~1000 cm2/Vs and on/off current ratios exceeding 105 [4]. The magnetoresistance shows Shubnikov-de Haas (SdH) oscillations in magnetic fields up to 35T and in the temperature range of 300mK-50K (Fig. 1b). These SdH oscillations reveal a 2D hole gas with Schroedinger fermion character (Berry phase $β≈0$) in an accumulation layer formed at the bP/oxide interface. The effective mass for holes m\*=0.36±0.03m0 extracted from the temperature dependence of the SdH oscillations is in excellent agreement with that reported by the Yuanbo Zhang group at Fudan University [5]. We also observe transconductance and mobilities that can be improved up to by 400% and 200%, respectively, as the top gate is set to negative voltages. This suggests that screening of charge impurities can be mitigated by forming a 2D hole gas at the bP/top gate interface (Fig. 1c).



**(a)**

**(b)**

**(c)**

Figure 1: **a**) A schematic of a dual gated bP FET structure. **b**) The oscillatory longitudinal resistance *ΔRXX* versus temperature T. c**)** Room temperature mobility versus hole density at different top gate voltages indicative of mobility enhancement.

**Conclusions**

Our work demonstrates that dual-gated bP field-effect devices can be fabricated and act as a canonical 2D semiconducting transistor. The effective mass extracted from the SdH oscillations is in excellent agreement with that reported elsewhere [5]. We also demonstrate a mobility and transconductance enhancement by applying a suitable gate voltage to both gates. This could prove useful in future high-performance electronic devices based on black phosphorus.

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