

Electrical transport properties of black phosphorus based field-effect transistor with Au/Co/MgO tunneling contacts

Shiheng Liang, Huaiwen Yang, Abdelhak Djeffal, Bingshan Tao, Stefan Mc-Murtry, Stéphane Mangin, Yuan Lu

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Shiheng Liang, Huaiwen Yang, Abdelhak Djeffal, Bingshan Tao, Stefan Mc-Murtry, Stéphane Mangin, and Yuan Lu^{a)}

Institut Jean Lamour, UMR 7198, CNRS-Université de Lorraine, BP 239, 54506 Vandœuvre, France

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Black phosphorus (BP) has recently emerged as a promising two-dimensional direct bandgap semiconducting material. Here, we report the fabrication and the electrical transport measurements of the black phosphorus based field-effect transistor with the Au/Co/MgO as drain and source tunneling contacts. By modulating the back-gate voltage, the multilayer black phosphorus channel exhibits ambipolar characteristics (both *n*-type and *p*-type) and the conduction behavior can be switched from hole dominated to electron dominated transport region. In the hole dominated region, we have measured a minimum of Schottky barrier height of 37 meV for Au/Co/MgO contact on BP. Moreover, the transistor ON/OFF (I_{on}/I_{off}) ratio is obtained as large as 10⁷ at 20 K and 10⁵ at 300 K. A systematic study of the temperature and the back-gate voltage dependent conduction properties has been performed to understand the modulation of band structure and the ambipolar behavior. The demonstration of high ON/OFF ratio and low Schottky barrier height by using Au/Co/MgO tunneling contacts reveals a promising potential for spintronics applications with multilayer black phosphorus field-effect transistor. *Published by AIP Publishing*.

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20 I. INTRODUCTION

Two-dimensional (2D) materials with atomic thickness 21 have been recently unveiled as an important family of materi-22 als in physics and materials science.¹⁻⁹ Since the discovery of 23 graphene in 2004,¹ a fair amount of research has been dedi-24 cated to fabricate other thin layer 2D materials, for examples 25 of boron nitride¹⁰ and transition metal dichalcogenides 26 (TMDs) materials.^{3–9} The understanding of physics and mate-27 rial characteristics of 2D materials leads to the possibility of 28 many applications, such as transistors,^{7,9} optoelectronics,¹ 29 sensors,¹² photovoltaics,¹³ medicine,¹⁴ and energy storage.¹⁵ 30 In the 2D material family, graphene is known as a semicon-31 ductor with zero bandgap. Despite its high mobility, the gra-32 phene is not suitable to be used as field-effect transistors 33 (FETs)^{1,2} due to the zero bandgap. Another 2D material is 34 35 boron nitride, which is an insulator and can be used as a tunnel barrier in 2D-heterostructure device to improve the physi-36 cal properties.¹⁰ Besides the above two types of 2D materials, 37 TMDs such as MoS₂, WSe₂, and MoSe₂ have semiconducting 38 properties and can play the role of drain-source channel in 39 FETs, but their mobility is relatively low.^{3–9} 40

Recently, black phosphorus (BP) has attracted a large 41 amount of attention and emerged as an important 2D mate-42 rial due to its interesting physics properties.¹⁶⁻²⁴ The BP has 43 a layer stacked structure by van der Waals interactions. The 44 45 monolayer (ML) BP has a direct bandgap of about 2 eV. For multilayer BP, the band gap decreases with the increase of 46 number of layers, changing from 2 eV (ML) to about 0.3 eV 47 (bulk). This provides a wide range of tunability of bandgap 48 for the multilayer BP.¹⁶ In addition, BP has a larger carrier 49

mobility (highest values up to $\sim 1000 \text{ cm}^2 \text{ V}^{-1} \text{s}^{-1}$ at room 50 temperature)¹⁸ compared to TMDs, which is better to serve 51 as channel for FET applications. Moreover, by using BP as 52 channel, the FET with ambipolar modulated behavior (both 53 *n*-type and *p*-type) can be realized.^{17–21} Recently, spin trans-54 port experiments have also been demonstrated in ultrathin 55 multilayer BP based non-local spin valve structures.²² A 56 long spin diffusion length (>2.5 μ m) was measured owing to 57 the high mobility and low spin-orbit coupling properties of 58 BP. Therefore, great efforts have been carried out to push the 59 BP based devices towards application in nano-electron-60 ics,^{17,19} optoelectronics,^{20,21} FETs,¹⁸ and spintronics.²² 61

In this work, we have fabricated the BP based FETs 62 with Au/Co/MgO tunneling contacts and systematically stud-63 ied the transport properties as a function of back-gate voltage 64 and temperature. The ambipolar characteristics (both *n*-type 65 and *p*-type) in multilayer BP has been observed with a high 66 ON/OFF ratio as large as 10^7 . The Schottky barrier height is 67 measured as low as 37 meV for Au/Co/MgO contact on BP. 68 The high ON/OFF ratio and low Schottky barrier height 69 demonstrate that BP has a promising potential for future 70 FET and spintronics applications. 71

II. EXPERIMENT

Figure 1(a) shows the optical image of our BP based 73 FET device. First, a flake of multilayer BP was mechanically 74 exfoliated onto a $Si(n^{++})/SiO_2(280 \text{ nm})$ substrate as the FET 75 channel. The thickness of this flake was measured by an 76 atomic force microscopy (AFM) to be about 7 nm [inset of 77 Fig. 1(a)]. Considering 0.5 nm for one ML BP,¹⁸ the thick-78 ness of the flake corresponds to about 14 MLs. Second, 79 e-beam lithography (Raith-150) was performed to define five 80

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^{a)}Email: yuan.lu@univ-lorraine.fr

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electrodes with a width of 500 nm on the selected flake. The 81 distance between each electrode is about 450 nm. Then the 82 sample was introduced into a molecular beam epitaxy 83 84 (MBE) system to deposit the ferromagnetic (FM) electrodes as drain and source tunneling contacts, which consists of 85 Au(10 nm)/Co(10 nm)/MgO(2 nm). The 2 nm MgO is used 86 as a tunnel barrier between metals and BP to effectively 87 reduce the contact Schottky barrier height.²⁵ After deposition 88 and lift-off procedures, a second e-beam lithography was 89 performed to define the large pads for electrical connection. 90 Au(190 nm)/Ti(10 nm) was thermally evaporated in a 91 PLASSYS MEB400s system for the large pads. Finally, the 92 device was annealed at 120 °C for one hour in vacuum and 93 then followed by the coverage of 10 nm MgO protection 94 layer. Figure 1(b) shows the schematic of electric characteri-95 zation of BP based transistor. A drain-source bias (V_{ds}) was 96 applied between the two contacts to inject the current I_{ds} 97 through the BP channel. Meanwhile, a back-gate voltage 98 (V_{σ}) was applied between the substrate and one electrode to 99 modulate the carrier density in the BP channel. 100

101 III. RESULTS AND DISCUSSIONS

102 A. Drain-source current-voltage $(I_{ds} - V_{ds})$ 103 characteristics

The two-terminal drain-source current-voltage charac-104 teristics $(I_{ds}-V_{ds})$ were studied at 20 K between the electro-105 des E1 and E2 with negative and positive back-gate voltages 106 107 [Figs. 1(c) and 1(d), respectively]. From the measurement of $I_{\rm ds}-V_{\rm ds}$, the back-gate voltages show an efficient modulation 108 on the I_{ds} , which indicates the field-effect transistor behavior. 109 At $V_{\rm g} = 0$ V, the current density is rather low ($I_{\rm ds} < 1$ pA at 110 111 $V_{\rm ds} = \pm 1$ V). As soon as we applied a negative or positive back-gate voltage $V_{\rm g}$, the $I_{\rm ds}$ - $V_{\rm ds}$ characteristics dramatically 112 change. The quasi-symmetric nonlinearity of I_{ds} - V_{ds} is 113 attributed to the back-to-back Schottky diode structures of 114

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FIG. 1. (a) Optical image of black phosphorus flake exfoliated on $Si(n^{++})/$ 280 nm SiO₂ substrate with contacts of Au(10 nm)/Co(10 nm)/MgO(2 nm). Insert: the thickness of this BP flake was measured by AFM to be about 7 nm. (b) Schematics of BP based field effect transistor. A drain-source bias (V_{ds}) was applied to inject the current I_{ds} through the BP channel. Meanwhile, a back-gate voltage (Vg) was applied between the substrate and one contact to modulate the carrier density in the BP channel. (c) Output characteristics of drain-source current-voltage $(I_{ds}-V_{ds})$ measured with applying negative back-gate voltages . Insert: schematic of band profile in BP by applying V_{ds} under negative V_{g} . (d) Output characteristics of drainsource current-voltage $(I_{ds}-V_{ds})$ measured with applying positive back-gate voltages $V_{\rm s}$. Insert: schematic of band profile in BP by applying $V_{\rm ds}$ under positive Vg.

the device, which is induced by the Schottky contacts of Co/ 115 MgO on BP [inset of Figs. 1(c) and 1(d)]. It is found that 116 applying negative $V_{\rm g}$ can get much higher current density 117 than that with positive $V_{\rm g}$. Under a negative back-gate volt- 118 age of $V_g = -80$ V, I_{ds} can reach 80 μ A at $V_{ds} = \pm 1$ V, while 119 there is about 0.02 μ A at $V_{ds} = \pm 1$ V under a positive back- 120 gate voltage of $V_g = +80$ V. In fact, at different V_g , the transport mechanism is different since $V_{\rm g}$ can effectively modu- 122 late the Fermi level $(E_{\rm F})$ inside the bandgap of BP. Under the 123 negative back-gate voltage, the $E_{\rm F}$ is attracted to be close to 124 the energy of valence band maximum (E_V) of BP, resulting 125 in the hole conduction transport. However, under positive 126 back-gate voltage, the $E_{\rm F}$ is pushed close to the energy of 127 conduction band minimum ($E_{\rm C}$) of BP, resulting in the elec- 128 tron conduction transport. The larger conductivity for hole 129 transport region indicates a higher carrier density in BP for 130 hole transport, which means that the $E_{\rm F}$ in our BP covered 131 with MgO should be much closer to E_V than E_C at zero V_g . 132

B. Field-effect transistor $(I_{ds} - V_g)$ characteristics 133

The field-effect transistor characteristics were measured 134 from the I_{ds} vs. V_g curves at different temperature, as shown 135 in Fig. 2(a). The asymmetric ambipolar behavior can be 136 observed in all investigated temperature region. At large 137 negative back-gate voltage ($V_g = -80$ V) when hole transport is dominated, the temperature dependence is not evident 139 with $V_{ds} = -1$ V. However, at a large positive back-gate volt-140 age ($V_g = +80$ V) when electron transport is dominated, the 141 conductance with $V_{ds} = -1$ V can be changed more than one 142 order from 20 K to 300 K. Since the variation of mobility 143 with temperature is small with $V_{ds} = -1$ V (see below), the 144 different temperature dependent conductance mainly reflects 145 different carrier densities in the *p*-type and *n*-type transport 146 region. If assuming that the carrier density in BP follows the 147 thermal activation rule in the intrinsic semiconductor, the 148

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hole and electron densities can be expressed by $p = n_i e^{\frac{E_i - E_F}{k_B T}}$ 149 and $n = n_i e^{\frac{E_F - E_i}{k_B T}}$, respectively.²⁶ $n_i = 2.509 \times 10^{19} (\frac{m_n m_p}{m_n^2})^{3/4}$ 150 $\left(\frac{T}{300}\right)^{3/2} e^{-\frac{E_g}{2k_BT}}$ (cm⁻³) is the intrinsic carrier density, and E_i is 151 the intrinsic Fermi energy. m_n , m_p , and, m_0 are the electron 152 mass in $E_{\rm C}$, the hole mass in $E_{\rm V}$ and the free electron mass, 153 respectively. This can easily explain that the larger $|E_i - E_F|$ 154 results in higher carrier density when increasing V_{g} . In addi-155 tion, the ratio of carrier density between 300 and 20 K can 156 be expressed as $p(300K)/p(20K) = (\frac{300}{20})^{3/2} e^{\frac{E_i - E_F - 0.5E_g}{k_B}(\frac{1}{300} - \frac{1}{20})}$ 157 $\propto e^{\frac{0.5L_B - (E_i - E_F)}{k_B}} \text{ for hole transport region} \\ n(300K)/n(20K) = (\frac{300}{20})^{3/2} e^{\frac{E_F - E_i - 0.5E_B}{k_B}(\frac{1}{300} - \frac{1}{20})} \propto e^{\frac{0.5E_B - (E_F - E_i)}{k_B}}$ 158 and for 159 electron transport region. This explains that the carrier den-160 sity is more sensitive to the temperature variation when 161 $|E_i - E_F|$ is smaller under positive V_g in the *n*-type transport 162 163 region.

164 C. Temperature dependent channel mobility

The effective field-effect mobility can be extracted from the slope of dI_{ds}/dV_g from the $I_{ds}-V_g$ curves, as shown in Fig. 2(b)

$$\mu_{\rm eff} = \frac{dI_{ds}}{dV_g} \frac{L}{wC_i V_{ds}} \tag{1}$$

where *L* is the length of the channel (450 nm), *w* is the width of the channel (2.9 μ m), and *C*_i is the gate capacitance [1.3 × 10⁻⁴ Fm⁻² for Si/SiO₂(280 nm) substrate]. The effective field-effect mobility is found to increase under negative *V*_g [Fig. 2(c)]. At 20 K, with *V*_{ds} = -1 V and *V*_g = -80 V, we can obtain a mobility of $\mu_{eff} \sim 38 \text{ cm}^2 \text{ V}^{-1} \text{s}^{-1}$. This value is 173 lower than the previously reported values, which could be due 174 to the scattering related to the charged impurities at BP/sub- 175 strate interface at low temperature.²² The enhancement of 176 mobility with the increase of $V_{\rm g}$ as well as the carrier density 177 is due to the shielding effect of carrier to the Coulomb scatter- 178 ing from the charged impurities,²⁶ which has also been 179 observed in MoS₂ based FET system.⁹ Figure 2(c) displays 180 the variation of $\mu_{\rm eff}$ with temperature measured under different 181 $V_{\rm g}$. It is interesting to find that there exist two distinct temper- 182 ature dependences. $\mu_{\rm eff}$ decreases with the increasing T when 183 $V_{\rm g} < -50$ V, while it increases with T when $V_{\rm g} > -50$ V. For 184 $V_{\rm g} < -50$ V, $\mu_{\rm eff}$ decreases faster when T > 200 K, which is 185 due to the carrier-phonon scattering at higher temperature.²⁷ 186 This can be expressed as $\mu \sim T^{-\alpha}$, the exponent α is fitted to 187 be 1.27 and 1.21, and 0.91 for the data at $V_{\rm g} = -60 \,\text{V}, -70 \,\text{V}$ 188 and -80 V, respectively. For atomically thin 2D materials, the 189 exponent α is reported to be ~1.69 for MoS₂,²⁷ and between 1 190 and 6 for graphene.^{28–30} Below 200 K, the slower decrease of 191 μ suggests an impurity-dominated scattering mechanism.¹⁸ 192 For $V_{\rm g} > -50 \,\mathrm{V}$ when $E_{\rm F}$ moves far away from $E_{\rm V}$, μ 193 increases monotonically with the increase of T. This behavior 194 means that when the carrier density is very low, the mobility 195 is only limited by the scattering from the charged impurities.²⁶ 196

D. Temperature dependent transistor ON/OFF ratio 197

The transistor current ON/OFF ratio can be extracted 198 from I_{on} ($|V_g| = 80$ V)/ I_{off} ($V_g = 0$ V) from the I_{ds} - V_g curves. 199 At 20 K, a large ON/OFF ratio of 10⁷ is obtained for hole 200 transport and a ratio of 10⁴ is measured for electron trans- 201 port. The ON/OFF ratio for hole transport is found to be 202 much larger than the recent reported values: 10³ with Au/BP 203

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contacts,²¹ 10⁵ with Au/Pd/Ti/BP contacts,²⁰ and 10⁶ with 204 Co/TiO₂/BP contacts.²⁴ This high I_{on}/I_{off} ratio provides prom-205 ising device characteristics for future applications. Figure 2(d) 206 shows the temperature dependent I_{op}/I_{off} behavior. For the 207 holes dominated FET, the I_{on}/I_{off} increases with the decrease 208 of temperature. Since I_{on} has little change with temperature, 209 the improvement of I_{on}/I_{off} at low temperature is mainly 210 attributed to the reduction in I_{off} current. When T > 200 K, the 211 $I_{\rm off}$ current (at $V_{\rm g} \sim 0 \,\rm V$) is mainly dominated by the therm-212 ionic injection through Schottky barrier, which is proportional 213 to $\exp(-q\Phi_{\rm B}/k_{\rm B}T)$,³¹ where $k_{\rm B}$ is the Boltzmann constant and 214 $\Phi_{\rm B}$ is Schottky barrier height [see also below for Eq. (2)]. 215 Thus, the slope of $-q\Phi_{\rm B}/k_{\rm B}$ can be extracted from a linear fit-216 ting of $\ln(I_{on}/I_{off})$ versus 1/T, as shown in the insert of Fig. 217 2(d). The slope obtained from 300 K to 200 K leads to a 218 Schottky barrier height $\Phi_{\rm B}$ of 270 meV at $V_{\rm g} = 0$ V. 219 Moreover, both for hole and electron transport regions, the 220 $I_{\rm on}/I_{\rm off}$ do not improve too much when the temperature is 221 below 200 K. This could be due to the presence of tunneling 222 through defect states inside the MgO tunnel barrier.³² This 223 phenomenon has also been observed in both carbon nano-224 tube³³ and graphene nanoribbon transistors.³⁴ 225

226 E. Determination of Schottky barrier height

In order to extract the Schottky barrier height (Φ_B) of Au/Co/MgO contact on BP [inset of Fig. 3(a)] and understand the effect of V_g on Φ_B , we have measured the $I_{ds}-V_{ds}$ characteristics with different V_g from 140 K to 200 K [Fig. 3(a)]. In this temperature range, the thermionic emission transport mechanism through the Schottky barrier can be mainly considered. We have employed a two-dimensional



thermionic emission equation describing the electrical trans- 234 port through the Schottky barrier into the BP channel³⁵ 235

$$I_{\rm ds} = AA^*T^{1.5} \exp\left[-\frac{q}{k_{\rm B}T} \left(\Phi_{\rm B} - \frac{V_{\rm ds}}{n_0}\right)\right]$$
(2)

where *A* is the contact area, A^* is the Richardson constant, *q* is 236 the hole charge, and n_0 is the ideality factor. Figure 3(b) shows 237 the Arrhenius plot $[\ln(I_{ds}/T^{-3/2}) vs. 1000/T]$ for different V_{ds} . 238 The slopes $S(V_{ds})$ extracted from the Arrhenius plot follow a linear dependence with V_{ds} : $S(V_{ds}) = -(q/1000k_B)(\Phi_B - V_{ds}/n_0)$, as 240 displayed in Fig. 3(c). Then the Schottky barrier height can 241 be evaluated from the extrapolated value at zero V_{ds} [S_0 242 $= -(q\Phi_B/1000k_B)$]. A similar procedure has been used to 243 determine Φ_B with different V_g , as shown in Fig. 3(d). 244

As shown in the inset of Fig. 3(d), the back-gate mainly 245 plays two roles. One is to modulate the Fermi level inside 246 the BP bandgap yielding a change of the carrier density in 247 the channel. The second role is to modify the Schottky bar- 248 rier profile and depletion layer width. In Fig. 3(d), we can 249 identify two regions from the variation of $\Phi_{\rm B}$ vs. $V_{\rm g}$. For 250 $V_{\rm g} > -15$ V when the depletion layer is thick, the thermionic 251 emission dominates, and this results in a large linear increase 252 of $\Phi_{\rm B}$ at low $|V_{\rm g}|$. Note here, the $\Phi_{\rm B}$ obtained at $V_{\rm g} = 0$ V is 253 \sim 200 meV, which is in good agreement with the value of 254 270 meV estimated from $I_{\rm on}/I_{\rm off}$ ratio at $V_{\rm g} = 0$ V. For 255 $V_{\rm g}$ < -15 V, the tunneling current through the thin Schottky 256 barrier impinges on the linearity of Φ_B . The real value of Φ_B 257 for Co/MgO on BP is obtained at the point of the onset of the 258 deviation ($V_{\rm f} = -15$ V) equaling thus 37 meV, which is cor- 259 responding to the flat band condition. This $\Phi_{\rm B}$ value is much 260 smaller than the recent reports of Py contacts (110-200 meV),³⁶ 261 contacts (200 meV),¹⁸ and Co/TiO₂/contacts 262 Au/Ti/BP



FIG. 3. (a) $I_{ds} - V_{ds}$ characteristics for temperatures between 140 and 200 K under $V_g = -15$ V. Inset: Schematics of the Schottky barrier height for Co/ MgO contact on *p*-type BP. (b) $\ln(I_{ds}/$ T^{3} ²) versus 1000/T at different drainsource bias (V_{ds}) , in an Arrhenius plot with linear fits in the temperature range from 160 K to 200 K. (c) Bias dependence of the slope (S) from linear fits. The slope at zero V_{ds} (S₀) is used to extract the Schottky barrier height Φ_B . (d) Schottky barrier height Φ_B extracted at different back-gate voltages. The real Φ_B (37 meV) for Au/ Co/MgO on BP is obtained with the flat band condition $(V_{o} = V_{f} = -15 \text{ V}),$ which is defined at the cross point from the linear response of $\Phi_{\rm B}$ with $V_{\rm g}$ (blue solid lines). Insert: band diagram of Co/MgO/BP interfaces with different back-gate voltages.



FIG. 4. Characteristics of $I_{ds} - V_{ds}$ at 140 K, measured under (a) different negative back-gate voltages and (b) different positive back-gate voltages. (c)–(g) Band structure of Co/MgO/BP interface modulated under different back-gate voltages. (c) $V_g < -15$ V; (d) $V_g = -15$ V; (e) $V_g = 0$ V; (f) $V_g = +10$ V; (g) $V_g > +10$ V.

263 (50 meV).²⁴ The efficient lowing $\Phi_{\rm B}$ by inserting thin tunnel 264 barrier between the ferromagnetic metal and 2D materials 265 have also been reported in TMDs systems.^{25,37,38} This result 266 of low Schottky barrier by using Au/Co/MgO tunneling con-267 tact is important for future application of BP based FET and 268 spintronics.

269 F. Modulation of band structure by back-gate voltage

In the end, to have a global view of the band structure 270 modulation by the back-gate voltage, we have measured I_{ds} 271 vs. V_{ds} with applying different V_g at 140 K. Figures 4(a) and 4(b) show $I_{ds} - V_{ds}$ characteristics with negative and positive 273 $V_{\rm g}$, respectively. From the analysis of $\Phi_{\rm B}$ vs. $V_{\rm g}$, we have 274 identified that the flat band condition reaches at $V_{\rm g} = -15 \, {\rm V}$ 275 [Fig. 3(d)]. In addition, due to the hole transport feature, the 276 band structure can be schematically drawn as in Fig. 4(d) with 277 278 a situation of $E_{\rm C} - E_{\rm F} > E_{\rm F} - E_{\rm V}$. For $V_{\rm g} < -15$ V, the depletion layer tilts the band down due to the $E_{\rm F}$ pinning at 279 the interface [Fig. 4(c)]. With the increase of negative V_{g} , 280 more hole can be injected into BP by crossing the depletion 281 282 layer. For $V_g > -15$ V, the depletion layer tilts the band up at the interface. However, it is not the case that the larger $V_{\rm g}$ results 283 in larger I_{ds} . From Fig. 4(b), we can see that when we increase 284 $V_{\rm g}$ from 0 to +80 V, the $I_{\rm ds}$ firstly decreases to a minimum at 285 $V_{\rm g} = +10$ V and then increases with $V_{\rm g}$. This indicates that it is 286 hard to inject both holes and electrons at $V_g = +10 \text{ V}$, which 287 should correspond to the condition that $E_{\rm F}$ is located in the mid-288 289 dle of band $(E_{\rm C} - E_{\rm F} = E_{\rm F} - E_{\rm V})$, as shown in Fig. 4(f)). When continuing with the increasing $V_{\rm g}$, both the $E_{\rm F}$ moving closer to 290 $E_{\rm C}$ and the width of depletion region becoming thinner make 291 the conditions favorable for the electron injection into the BP 292

conduction band [Fig. 4(g)]. Finally, at zero back-gate voltage, 293 the BP shows a hole transport behavior ($E_{\rm C} - E_{\rm F} > E_{\rm F} - E_{\rm V}$), 294 while the depletion layer tilts up [Fig. 4(e)]. This could be 295 related to the defects in the contact regions, which effectively 296 pin the Fermi level at MgO/BP interface. 297

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IV. CONCLUSION

In summary, we have studied the electrical transport 299 properties in multilayer BP based FET device with Au/Co/ 300 MgO tunneling contacts. In the hole dominated transport 301 region, we have measured a minimum of Schottky barrier 302 height of 37 meV for Au/Co/MgO contact on BP. Moreover, 303 the transistor ON/OFF (I_{on}/I_{off}) ratio is obtained as large as 304 10^7 at 20 K and 10^5 at 300 K. A systematic study of the tem- 305 perature and back-gate voltage dependent conduction meas- 306 urements has been performed to understand the modulation 307 of the band structure and the ambipolar behavior. This dem- 308 onstration of high ON/OFF ratio and low Schottky barrier 309 height by using Au/Co/MgO tunneling contacts reveal a 310 great potential promising for spintronics applications with 311 multilayer black phosphorus field effect transistor. 312

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