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Shiheng Liang, Huaiwen Yang, Abdelhak Djeflal, Bingshan Tao, Stefan Mc-Murtry, et al.. Electrical transport properties of black phosphorus based field-effect transistor with Au/Co/MgO tunneling contacts. *Journal of Applied Physics*, 2017, 122 (16), pp.164301. 10.1063/1.5000524 . hal-02011640v1

**HAL Id: hal-02011640**


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Submitted on 8 Feb 2019 (v1), last revised 8 Feb 2019 (v2)

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# 1 Electrical transport properties of black phosphorus based field-effect 2 transistor with Au/Co/MgO tunneling contacts

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6 (Received 16 August 2017; accepted 10 October 2017; published online xx xx xxxx)

7 Black phosphorus (BP) has recently emerged as a promising two-dimensional direct bandgap semi-  
8 conducting material. Here, we report the fabrication and the electrical transport measurements of  
9 the black phosphorus based field-effect transistor with the Au/Co/MgO as drain and source tunnel-  
10 ing contacts. By modulating the back-gate voltage, the multilayer black phosphorus channel exhib-  
11 its ambipolar characteristics (both *n*-type and *p*-type) and the conduction behavior can be switched  
12 from hole dominated to electron dominated transport region. In the hole dominated region, we have  
13 measured a minimum of Schottky barrier height of 37 meV for Au/Co/MgO contact on BP.  
14 Moreover, the transistor ON/OFF ( $I_{on}/I_{off}$ ) ratio is obtained as large as  $10^7$  at 20 K and  $10^5$   
15 at 300 K. A systematic study of the temperature and the back-gate voltage dependent conduction  
16 properties has been performed to understand the modulation of band structure and the ambipolar  
17 behavior. The demonstration of high ON/OFF ratio and low Schottky barrier height by using  
18 Au/Co/MgO tunneling contacts reveals a promising potential for spintronics applications with mul-  
19 tilayer black phosphorus field-effect transistor. *Published by AIP Publishing.*

<https://doi.org/10.1063/1.5000524>

## 20 I. INTRODUCTION

21 Two-dimensional (2D) materials with atomic thickness  
22 have been recently unveiled as an important family of materi-  
23 als in physics and materials science.<sup>1-9</sup> Since the discovery of  
24 graphene in 2004,<sup>1</sup> a fair amount of research has been dedi-  
25 cated to fabricate other thin layer 2D materials, for examples  
26 of boron nitride<sup>10</sup> and transition metal dichalcogenides  
27 (TMDs) materials.<sup>3-9</sup> The understanding of physics and mater-  
28 ial characteristics of 2D materials leads to the possibility of  
29 many applications, such as transistors,<sup>7,9</sup> optoelectronics,<sup>11</sup>  
30 sensors,<sup>12</sup> photovoltaics,<sup>13</sup> medicine,<sup>14</sup> and energy storage.<sup>15</sup>  
31 In the 2D material family, graphene is known as a semicon-  
32 ductor with zero bandgap. Despite its high mobility, the gra-  
33 phene is not suitable to be used as field-effect transistors  
34 (FETs)<sup>1,2</sup> due to the zero bandgap. Another 2D material is  
35 boron nitride, which is an insulator and can be used as a tun-  
36 nel barrier in 2D-heterostructure device to improve the phys-  
37 ical properties.<sup>10</sup> Besides the above two types of 2D materials,  
38 TMDs such as MoS<sub>2</sub>, WSe<sub>2</sub>, and MoSe<sub>2</sub> have semiconducting  
39 properties and can play the role of drain-source channel in  
40 FETs, but their mobility is relatively low.<sup>3-9</sup>

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

mobility (highest values up to  $\sim 1000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  at room 50  
temperature)<sup>18</sup> 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.<sup>17-21</sup> Recently, spin trans- 54  
port experiments have also been demonstrated in ultrathin 55  
multilayer BP based non-local spin valve structures.<sup>22</sup> A 56  
long spin diffusion length ( $> 2.5 \mu\text{m}$ ) 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,<sup>17,19</sup> optoelectronics,<sup>20,21</sup> FETs,<sup>18</sup> and spintronics.<sup>22</sup> 61

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

## 72 II. EXPERIMENT

73 Figure 1(a) shows the optical image of our BP based  
74 FET device. First, a flake of multilayer BP was mechanically  
75 exfoliated onto a Si( $n^{++}$ )/SiO<sub>2</sub>(280 nm) substrate as the FET  
76 channel. The thickness of this flake was measured by an  
77 atomic force microscopy (AFM) to be about 7 nm [inset of  
78 Fig. 1(a)]. Considering 0.5 nm for one ML BP,<sup>18</sup> the thick-  
79 ness of the flake corresponds to about 14 MLs. Second,  
80 e-beam lithography (Raith-150) was performed to define five

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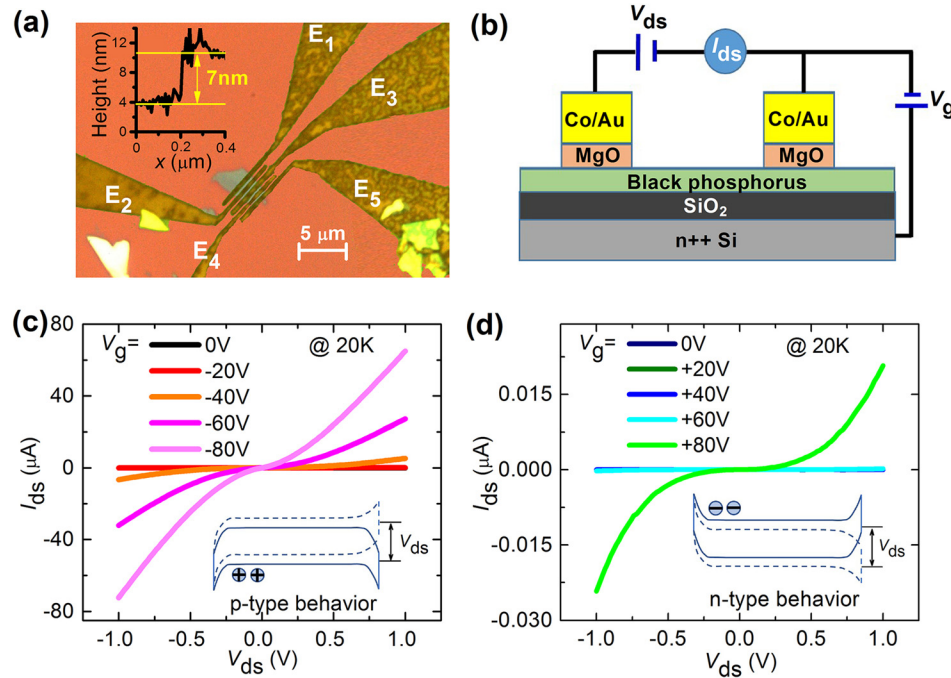


FIG. 1. (a) Optical image of black phosphorus flake exfoliated on  $\text{Si}(n^{++})/280 \text{ nm SiO}_2$  substrate with contacts of  $\text{Au}(10 \text{ nm})/\text{Co}(10 \text{ nm})/\text{MgO}(2 \text{ nm})$ . Inset: the thickness of this BP flake was measured by AFM to be about 7 nm. (b) Schematics 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 ( $V_g$ ) 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  $V_g$ . Inset: schematic of band profile in BP by applying  $V_{ds}$  under negative  $V_g$ . (d) Output characteristics of drain-source current-voltage ( $I_{ds}-V_{ds}$ ) measured with applying positive back-gate voltages  $V_g$ . Inset: schematic of band profile in BP by applying  $V_{ds}$  under positive  $V_g$ .

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

### 101 III. RESULTS AND DISCUSSIONS

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

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

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

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

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



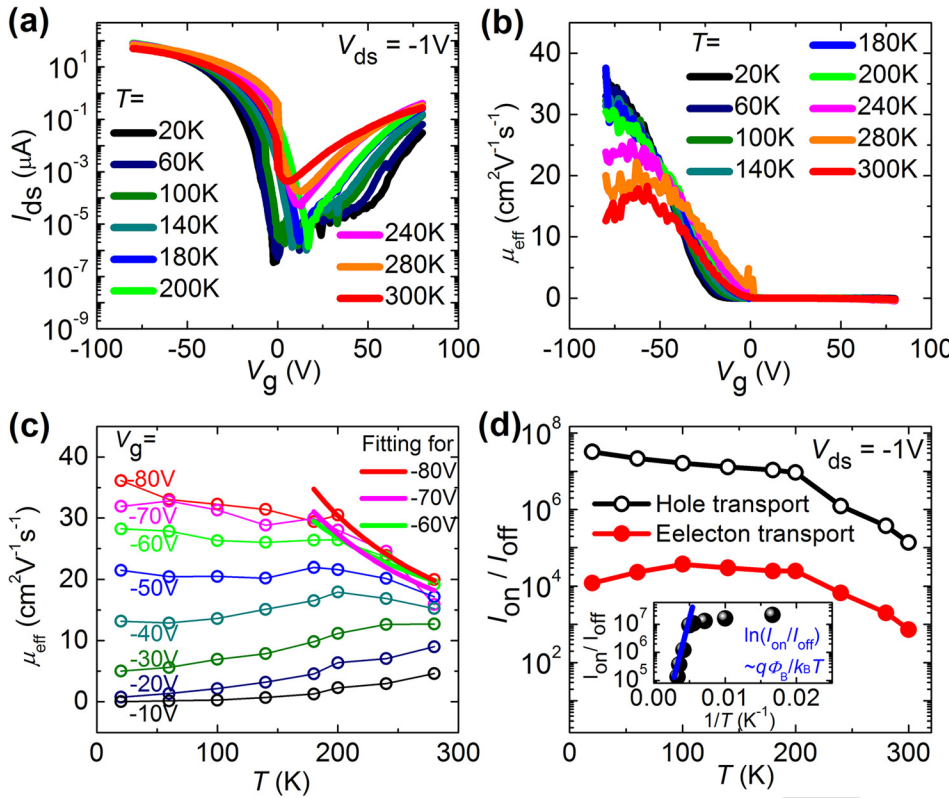


FIG. 2. (a) Transfer characteristics of  $I_{ds} - V_g$  in logarithmic scale measured with  $V_{ds} = -1$  V at different temperatures. (b) Extracted effective mobility  $\mu_{\text{eff}}$  versus  $V_g$  at different temperatures with  $V_{ds} = -1$  V. (c) Temperature dependent mobility  $\mu_{\text{eff}}$  measured under different back-gate voltages  $V_g$ . (d) Temperature dependent  $I_{\text{on}}/I_{\text{off}}$  ratio measured for hole transport (black open) and electron transport (red solid) situations, respectively. Inset:  $I_{\text{on}}/I_{\text{off}}$  ratio under hole transport in logarithmic scale plotted with  $1/T$ . The blue line is a linear fitting for  $\ln(I_{\text{on}}/I_{\text{off}})$  vs.  $1/T$ .

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

### 164 C. Temperature dependent channel mobility

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

$$\mu_{\text{eff}} = \frac{dI_{ds}}{dV_g} \frac{L}{wC_i V_{ds}} \quad (1)$$

168 where  $L$  is the length of the channel (450 nm),  $w$  is the width  
 169 of the channel (2.9  $\mu\text{m}$ ), and  $C_i$  is the gate capacitance  
 170 [ $1.3 \times 10^{-4}$   $\text{Fm}^{-2}$  for  $\text{Si/SiO}_2$  (280 nm) substrate]. The effec-  
 171 tive field-effect mobility is found to increase under negative  
 172  $V_g$  [Fig. 2(c)]. At 20 K, with  $V_{ds} = -1$  V and  $V_g = -80$  V, we

can obtain a mobility of  $\mu_{\text{eff}} \sim 38 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ . This value is  
 lower than the previously reported values, which could be due  
 to the scattering related to the charged impurities at BP/sub-  
 strate interface at low temperature.<sup>22</sup> The enhancement of  
 mobility with the increase of  $V_g$  as well as the carrier den-  
 sity is due to the shielding effect of carrier to the Coulomb scatter-  
 ing from the charged impurities,<sup>26</sup> which has also been  
 observed in  $\text{MoS}_2$  based FET system.<sup>9</sup> Figure 2(c) displays  
 the variation of  $\mu_{\text{eff}}$  with temperature measured under different  
 $V_g$ . It is interesting to find that there exist two distinct tempera-  
 ture dependences.  $\mu_{\text{eff}}$  decreases with the increasing  $T$  when  
 $V_g < -50$  V, while it increases with  $T$  when  $V_g > -50$  V. For  
 $V_g < -50$  V,  $\mu_{\text{eff}}$  decreases faster when  $T > 200$  K, which is  
 due to the carrier-phonon scattering at higher temperature.<sup>27</sup>  
 This can be expressed as  $\mu \sim T^{-\alpha}$ , the exponent  $\alpha$  is fitted to  
 be 1.27 and 1.21, and 0.91 for the data at  $V_g = -60$  V,  $-70$  V  
 and  $-80$  V, respectively. For atomically thin 2D materials, the  
 exponent  $\alpha$  is reported to be  $\sim 1.69$  for  $\text{MoS}_2$ ,<sup>27</sup> and between 1  
 and 6 for graphene.<sup>28-30</sup> Below 200 K, the slower decrease of  
 $\mu$  suggests an impurity-dominated scattering mechanism.<sup>18</sup>  
 For  $V_g > -50$  V when  $E_F$  moves far away from  $E_V$ ,  $\mu$   
 increases monotonically with the increase of  $T$ . This behavior  
 means that when the carrier density is very low, the mobility  
 is only limited by the scattering from the charged impurities.<sup>26</sup>

### D. Temperature dependent transistor ON/OFF ratio

The transistor current ON/OFF ratio can be extracted  
 from  $I_{\text{on}} (|V_g| = 80 \text{ V})/I_{\text{off}} (V_g = 0 \text{ V})$  from the  $I_{ds} - V_g$  curves.  
 At 20 K, a large ON/OFF ratio of  $10^7$  is obtained for hole  
 transport and a ratio of  $10^4$  is measured for electron trans-  
 port. The ON/OFF ratio for hole transport is found to be  
 much larger than the recent reported values:  $10^3$  with Au/BP

204 contacts,<sup>21</sup>  $10^5$  with Au/Pd/Ti/BP contacts,<sup>20</sup> and  $10^6$  with  
 205 Co/TiO<sub>2</sub>/BP contacts.<sup>24</sup> This high  $I_{on}/I_{off}$  ratio provides prom-  
 206 ising device characteristics for future applications. Figure 2(d)  
 207 shows the temperature dependent  $I_{on}/I_{off}$  behavior. For the  
 208 holes dominated FET, the  $I_{on}/I_{off}$  increases with the decrease  
 209 of temperature. Since  $I_{on}$  has little change with temperature,  
 210 the improvement of  $I_{on}/I_{off}$  at low temperature is mainly  
 211 attributed to the reduction in  $I_{off}$  current. When  $T > 200$  K, the  
 212  $I_{off}$  current (at  $V_g \sim 0$  V) is mainly dominated by the therm-  
 213 ionic injection through Schottky barrier, which is proportional  
 214 to  $\exp(-q\Phi_B/k_B T)$ ,<sup>31</sup> where  $k_B$  is the Boltzmann constant and  
 215  $\Phi_B$  is Schottky barrier height [see also below for Eq. (2)].  
 216 Thus, the slope of  $-q\Phi_B/k_B$  can be extracted from a linear fit-  
 217 ting of  $\ln(I_{on}/I_{off})$  versus  $1/T$ , as shown in the insert of Fig.  
 218 2(d). The slope obtained from 300 K to 200 K leads to a  
 219 Schottky barrier height  $\Phi_B$  of 270 meV at  $V_g = 0$  V.  
 220 Moreover, both for hole and electron transport regions, the  
 221  $I_{on}/I_{off}$  do not improve too much when the temperature is  
 222 below 200 K. This could be due to the presence of tunneling  
 223 through defect states inside the MgO tunnel barrier.<sup>32</sup> This  
 224 phenomenon has also been observed in both carbon nano-  
 225 tube<sup>33</sup> and graphene nanoribbon transistors.<sup>34</sup>

226 **E. Determination of Schottky barrier height**

227 In order to extract the Schottky barrier height ( $\Phi_B$ ) of  
 228 Au/Co/MgO contact on BP [inset of Fig. 3(a)] and under-  
 229 stand the effect of  $V_g$  on  $\Phi_B$ , we have measured the  $I_{ds}-V_{ds}$   
 230 characteristics with different  $V_g$  from 140 K to 200 K [Fig.  
 231 3(a)]. In this temperature range, the thermionic emission  
 232 transport mechanism through the Schottky barrier can be  
 233 mainly considered. We have employed a two-dimensional

thermionic emission equation describing the electrical trans- 234  
 port through the Schottky barrier into the BP channel<sup>35</sup> 235

$$I_{ds} = AA^*T^{1.5} \exp \left[ -\frac{q}{k_B T} \left( \Phi_B - \frac{V_{ds}}{n_0} \right) \right] \quad (2)$$

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 239  
 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  $\Phi_B$  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 barrier 248  
 profile and depletion layer width. In Fig. 3(d), we can 249  
 identify two regions from the variation of  $\Phi_B$  vs.  $V_g$ . For 250  
 $V_g > -15$  V when the depletion layer is thick, the thermionic 251  
 emission dominates, and this results in a large linear increase 252  
 of  $\Phi_B$  at low  $|V_g|$ . Note here, the  $\Phi_B$  obtained at  $V_g = 0$  V is 253  
 $\sim 200$  meV, which is in good agreement with the value of 254  
 $270$  meV estimated from  $I_{on}/I_{off}$  ratio at  $V_g = 0$  V. For 255  
 $V_g < -15$  V, the tunneling current through the thin Schottky 256  
 barrier impinges on the linearity of  $\Phi_B$ . The real value of  $\Phi_B$  257  
 for Co/MgO on BP is obtained at the point of the onset of the 258  
 deviation ( $V_f = -15$  V) equaling thus 37 meV, which is cor- 259  
 responding to the flat band condition. This  $\Phi_B$  value is much 260  
 smaller than the recent reports of Py contacts (110–200 meV),<sup>36</sup> 261  
 Au/Ti/BP contacts (200 meV),<sup>18</sup> and Co/TiO<sub>2</sub>/contacts 262

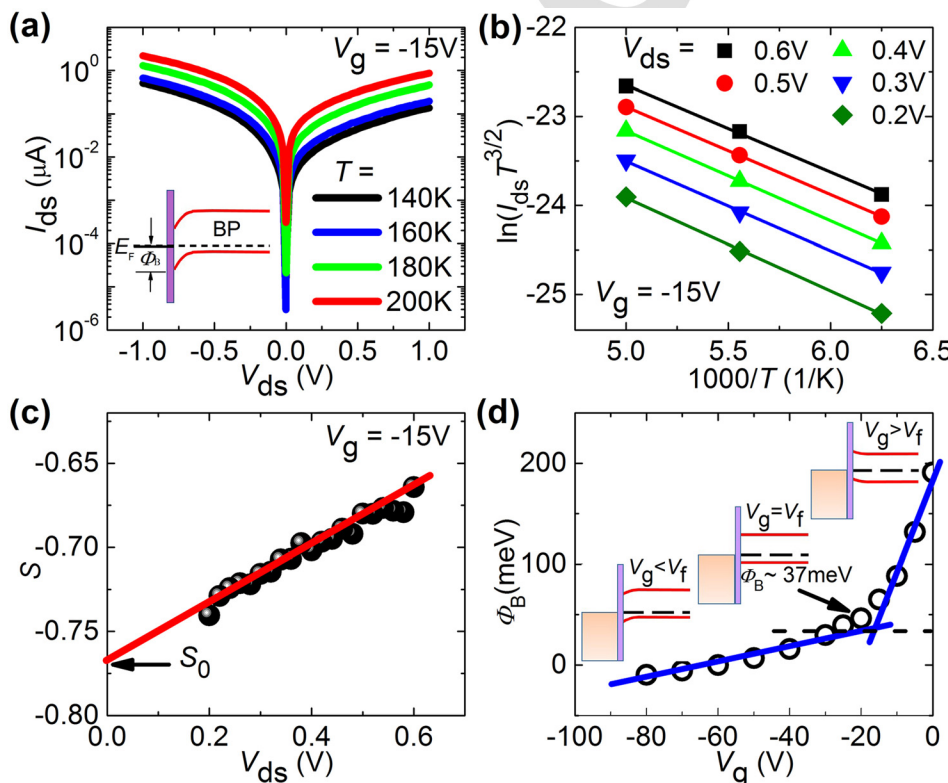


FIG. 3. (a)  $I_{ds} - V_{ds}$  characteristics for temperatures between 140 and 200 K under  $V_g = -15$  V. Inset: Schematics of the Schottky barrier height for Co/MgO contact on *p*-type BP. (b)  $\ln(I_{ds}/T^{3/2})$  versus  $1000/T$  at different drain-source bias ( $V_{ds}$ ), in an Arrhenius 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  $V_{ds}$  ( $S_0$ ) is used to extract the Schottky barrier height  $\Phi_B$ . (d) Schottky barrier height  $\Phi_B$  extracted at different back-gate voltages. The real  $\Phi_B$  (37 meV) for Au/Co/MgO on BP is obtained with the flat band condition ( $V_g = V_f = -15$  V), which is defined at the cross point from the linear response of  $\Phi_B$  with  $V_g$  (blue solid lines). Inset: band diagram of Co/MgO/BP interfaces with different back-gate voltages.

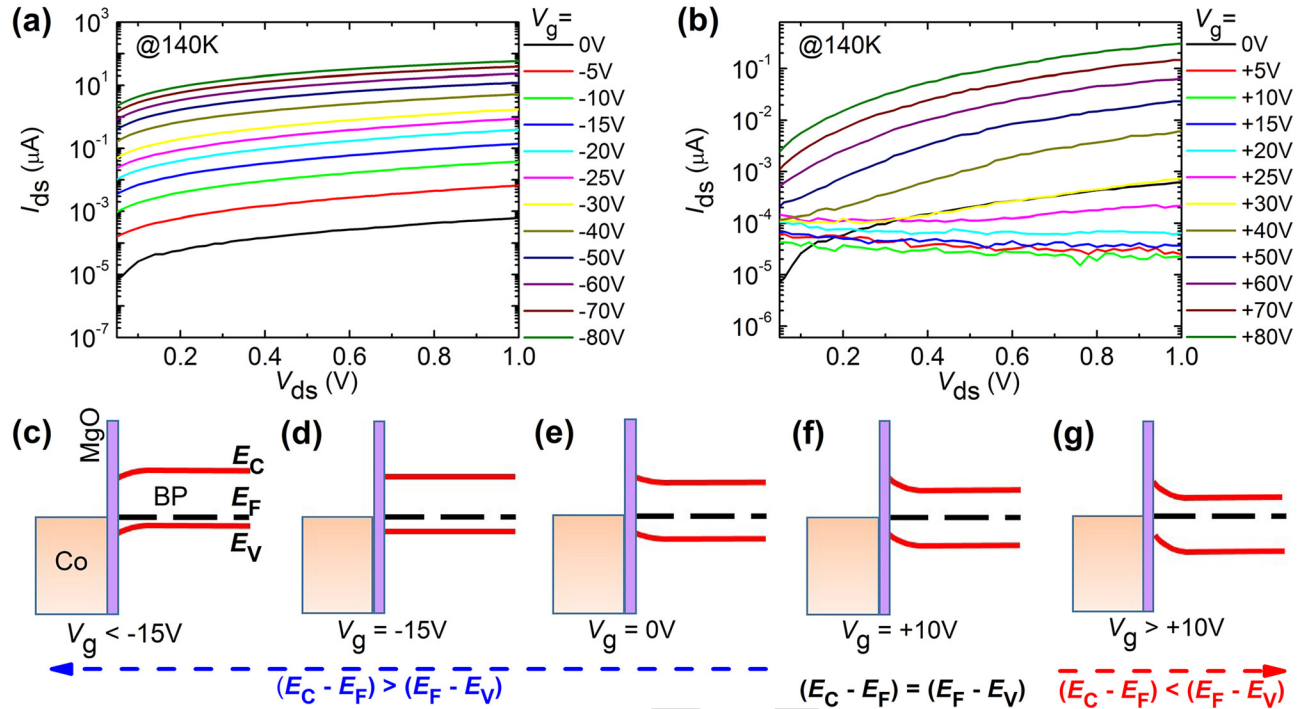


FIG. 4. Characteristics of  $I_{ds} - V_{ds}$  at 140 K, measured under (a) different negative back-gate voltages and (b) different positive back-gate voltages. (c)–(g) Band structure of Co/MgO/BP interface modulated under different back-gate voltages. (c)  $V_g < -15$  V; (d)  $V_g = -15$  V; (e)  $V_g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

(50 meV).<sup>24</sup> The efficient lowering  $\Phi_B$  by inserting thin tunnel barrier between the ferromagnetic metal and 2D materials have also been reported in TMDs systems.<sup>25,37,38</sup> This result of low Schottky barrier by using Au/Co/MgO tunneling contact is important for future application of BP based FET and spintronics.

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

In the end, to have a global view of the band structure modulation by the back-gate voltage, we have measured  $I_{ds}$  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  $V_g$ , respectively. From the analysis of  $\Phi_B$  vs.  $V_g$ , we have identified that the flat band condition reaches at  $V_g = -15$  V [Fig. 3(d)]. In addition, due to the hole transport feature, the band structure can be schematically drawn as in Fig. 4(d) with a situation of  $E_C - E_F > E_F - E_V$ . For  $V_g < -15$  V, the depletion layer tilts the band down due to the  $E_F$  pinning at the interface [Fig. 4(c)]. With the increase of negative  $V_g$ , more hole can be injected into BP by crossing the depletion 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  $V_g$  results in larger  $I_{ds}$ . From Fig. 4(b), we can see that when we increase  $V_g$  from 0 to +80 V, the  $I_{ds}$  firstly decreases to a minimum at  $V_g = +10$  V and then increases with  $V_g$ . This indicates that it is hard to inject both holes and electrons at  $V_g = +10$  V, which should correspond to the condition that  $E_F$  is located in the middle of band ( $E_C - E_F = E_F - E_V$ ), as shown in Fig. 4(f). When continuing with the increasing  $V_g$ , both the  $E_F$  moving closer to  $E_C$  and the width of depletion region becoming thinner make the conditions favorable for the electron injection into the BP

conduction band [Fig. 4(g)]. Finally, at zero back-gate voltage, the BP shows a hole transport behavior ( $E_C - E_F > E_F - E_V$ ), while the depletion layer tilts up [Fig. 4(e)]. This could be related to the defects in the contact regions, which effectively pin the Fermi level at MgO/BP interface.

#### IV. CONCLUSION

In summary, we have studied the electrical transport properties in multilayer BP based FET device with Au/Co/MgO tunneling contacts. In the hole dominated transport 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  $10^7$  at 20 K and  $10^5$  at 300 K. A systematic study of the temperature and back-gate voltage dependent conduction measurements has been performed to understand the modulation of the band structure and the ambipolar behavior. This demonstration of high ON/OFF ratio and low Schottky barrier height by using Au/Co/MgO tunneling contacts reveal a great potential promising for spintronics applications with multilayer black phosphorus field effect transistor.

#### ACKNOWLEDGMENTS

This work was supported by the French National Research Agency (ANR) MoS2ValleyControl project (Grant No. ANR-14-CE26-0017-04) and the joint ANR-National Natural Science Foundation of China (NNSFC) ENSEMBLE project (Grant Nos. ANR-14-CE26-0028-01 and NNSFC 61411136001). The experiments were performed using the equipment from the platform TUBE-Davm funded by FEDER (EU), ANR, the Region Lorraine, and Grand Nancy.



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