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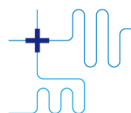
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Zuyu Xu,^{1,2} Wei Chen,¹ Junwei Huang,³ Wanghao Tian,¹ Shixian Chen,¹ Wencheng Yue,¹ Tianyuan Chi,¹ Yang-Yang Lyu,¹ Hancong Sun,² Yong-Lei Wang,¹ Guozhu Sun,¹ Jian Chen,¹ Biaobing Jin,¹ Song-Lin Li,¹ Hongtao Yuan,³ Jun Li,^{4,a)} Dieter Koelle,⁵ Reinhold Kleiner,^{5,a)} Huabing Wang,^{1,2,a)} and Peiheng Wu¹

AFFILIATIONS

¹Research Institute of Superconductor Electronics & School of Electronic Science and Engineering, Nanjing University, Nanjing 210023, China

²Purple Mountain Laboratories, Nanjing 211111, China

³National Laboratory of Solid State Microstructures and College of Engineering and Applied Sciences, Nanjing University, Nanjing 210023, China

⁴School of Physical Science and Technology & ShanghaiTech Laboratory for Topological Physics, ShanghaiTech University, Shanghai 200031, China

⁵Physikalisches Institut, Center for Quantum Science and LISA⁺, Universität Tübingen, D-72076 Tübingen, Germany

^{a)}Authors to whom correspondence should be addressed: lijun3@shanghaitech.edu.cn; kleiner@uni-tuebingen.de; and hbwang@nju.edu.cn

ABSTRACT

The gate-tunable Josephson junction, generally achieved in planar Josephson field-effect transistors (JoFETs), is a key element for the applications of superconducting devices. At present, the performance of these systems with planar JoFETs is often impeded by the large channel length, which, at best, lies in the range of tens of nanometers. In contrast, the channel length in vertical junctions can be easily scaled down to nano-scale to realize the strong Josephson coupling. However, the vertical junctions are believed to be insensitive to the field-effect due to the atomic screening of electric fields in metals. Here, we report on a novel realization of few-layer black phosphorus (BP)-based vertical JoFETs using an electric-double-layer configuration. In transport experiments, using junctions of different shape, superconducting quantum interference device-like magnetic diffraction patterns of the junction critical current and anomalous Shapiro steps on current voltage characteristics are observed, strongly indicating that the critical current density in the junctions is highly inhomogeneous and peaked at the edges or even near the junction corners. The electric-field tunability of the Josephson coupling could be attributed to the edge- or corner-dominated supercurrent density profile combining with the carrier diffusivity in the few-layer BP. The ability to control the vertical Josephson coupling provides us with new opportunities to study high-performance and high-temperature superconducting Josephson field-effect transistors operating on an atomic-scale channel length.

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Field-effect superconducting devices utilize an applied electric field to control the coupling between the superconducting electrodes.^{1–8} These systems, typically made of a two-dimensional electron gas (2DEG) as the Josephson barrier, have considerable potential for low-loss, fast digital elements as well as for tunable superconducting qubits (i.e., gatemon).^{9–12} Two-dimensional (2D) materials, due to their rich physical properties,^{13,14} provide a versatile platform to study the electric field-effect and field-induced phenomena in hybrid Josephson junctions. Josephson junctions combined with different 2D materials have attracted many studies experimentally and theoretically in recent

years.^{2,15–20} Heersche and co-workers developed a gate-tunable Josephson supercurrent through two closely spaced superconducting electrodes coupled by monolayer graphene.² Subsequently, graphene-based Josephson junctions with one-dimensional edge contacts of superconducting electrodes have enabled demonstrations of Josephson effects in the long ballistic regime.^{15,21} Moreover, Josephson junctions with the newly discovered 2D topological materials as barriers opened up new ways to explore Majorana fermionic excitation states.^{16,22} However, most of these in-plane junctions, typically formed by using electron beam lithography (EBL), show relatively weak Josephson coupling and

low operation temperature due to the short coherence length (ξ) compared with the channel length (L). The resolution of the EBL fabrication method, being in the range of tens of nanometers, fundamentally limits the channel length and, thereby, the device performance.^{1,2,8} One possible solution to enable an electric field-effect in more strongly coupled Josephson junctions is to change the direction of current flow from parallel to perpendicular to the substrate surface, in which case the channel length L can be reduced to the atomic scale.^{18,23,24} In this geometry, to realize vertical Josephson field-effect transistors (vJoFET), the major obstacle is electrostatic screening by the junction electrodes. This limitation can be overcome using the recently discovered 2D material black phosphorus (BP) as the barrier of Josephson junctions.

Due to its fascinating physical and semiconducting properties,^{25,26} BP is an intriguing candidate for exploiting JoFETs. In this paper, we investigate the vJoFET in Nb/BP/Nb sandwiched Josephson junctions (BPJJs) with an atomic-scale channel length. The ambient degradation of BP is minimized by *in situ* fabrication steps.²⁷ In magnetic fields, the junction critical currents exhibit a magnetic diffraction pattern that is similar to the case of a direct current (dc) superconducting quantum interference device (SQUID), indicating that the critical supercurrent density j_c is dominated by contributions from the edges or even the corners.^{17,28,29} This view is also confirmed by the disappearance of low-index Shapiro steps in microwave fields point to Joule overheating caused by high- j_c regions in the junction.^{30,31} Making use of this strongly inhomogeneous critical current density profile, an electric double-layer transistor (EDLT) structure with an ionic liquid gate is applied to the BPJJs. We find a strong electric-field dependence of the junction critical current and resistance. The observed gate-tunability of the Josephson supercurrent is highly desired for vertical Josephson junctions integrated into superconducting classical and quantum computation circuits.^{32,33}

An optical image of the structure we use is shown in Fig. 1(a). Two BPJJs, labeled JJ1 and JJ2, are formed between the Nb electrodes. The structure also contains all electrodes to perform four-probe transport measurements on the junctions and on the BP flake. The four leads on the left sides are used to perform four-point measurements on the BP flakes, and the leads on, respectively, the top side and the right side are used to measure the junctions. The side-gate electrode is also indicated. To form the BPJJ, we encapsulate a few-layer BP between two superconducting Nb films (about 100 nm thick) using a dry-transfer method and an *in situ* fabrication system. For a detailed description of the device fabrication, see the [supplementary material](#) Sec. 1. A droplet of ionic liquid covers both the region between the junctions and the gate pad. Figure 1(b) shows a cross-sectional schematic of the device with EDLT. The ionic liquid [(N,N-diethyl-N-(2-methoxyethyl)-N-methylammonium bis(trifluoromethylsulfonate) imide (DEME-TFSI)] was chosen as the gate insulator. The electric double layer formed at the liquid/solid interface allows us to accumulate or deplete charge carriers of the bare BP.

Figures 1(c) and 1(d) show transfer curves of the BP EDLT, as measured at 230 K. Figure 1(c) displays the source-drain current I_{ds} as a function of the gate voltage V_g between -3 and 3 V with a sweep speed of 10 mV/s. Figure 1(d) shows the four-probe resistance R_{ds} with a fixed source-drain voltage V_{ds} of 10 mV as a function of V_g . The curves show the typical ambipolar behavior of BP, which is in the ON-state with p-type behavior.^{34–37} Therefore, a positive gating

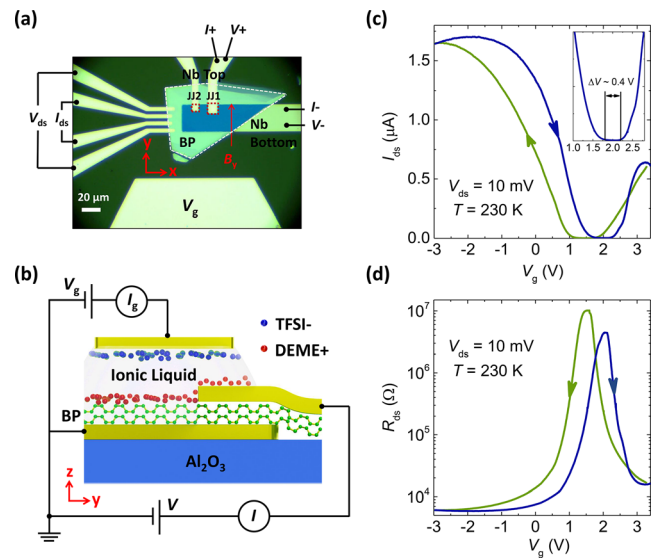


FIG. 1. (a) Optical image of the overall structure. The area enclosed by the white dashed line is the BP flake, and two areas indicated by the red dot lines are the sandwiched BP Josephson junctions (BPJJs: JJ1: $10 \times 10 \mu m^2$ and JJ2: $7 \times 7 \mu m^2$). The isolated niobium pad is the side-gate electrode, and four extra electrodes on the BP are used to measure the transport characteristics of the BP. A magnetic field B_z can be applied as indicated. A four-probe setup is used for all the measurements. (b) Schematic y - z plane cross section and measurement configuration of the BPJJ field-effect transistor. (c) Source-drain current (I_{ds}) as a function of the gate voltage (V_g) at $V_{ds} = 10$ mV, $T = 230$ K, showing an ambipolar behavior. The inset shows a magnified image of the threshold voltage. (d) Four-probe resistance R_{ds} as a function of V_g .

accumulates electrons while depleting holes and vice versa. A charge neutrality point (CNP) is reached at about $V_g = 1.5$ – 2.0 V forming a sharp R_{ds} peak. The ON-OFF ratio is $\sim 2 \times 10^3$, which is comparable to previous reports.^{34,35} As shown in the inset of Fig. 1(c), the bandgap is approximately obtained to be 0.4 eV due to the high geometrical capacitance of EDLT. From this value, we can estimate that the thickness of the BP flake is about 10 nm.^{26,38} We note that since the device is covered by the ionic liquid immediately to prevent degradation, its actual thickness cannot be confirmed by atomic force microscopy. These ambipolar transfer curves, plus the Raman spectroscopy characterization of the few-layer BP ([supplementary material](#) Fig. S1), demonstrate that the influence of chemical reactions and ambient degradation of the BP flakes is minimal.

We have performed low-temperature experiments to characterize the transport properties of the BPJJ. In the following analysis, we will focus on the properties of JJ1. The temperature dependence of the junction resistance, shown in Fig. 2(a), is metallic, pointing to an Ohmic interface contact between BP and the niobium electrodes. We see such metallic behavior in our *in situ* fabrication system. In contrast, devices fabricated in *ex situ* conditions behaved strongly insulating ([supplementary material](#) Fig. S2). At low temperature, a series of superconducting transitions are observed, of which the first transition $T_{c1} \sim 8.2$ K is for the bottom electrode, $T_{c2} \sim 7.8$ K for the top electrode, and $T_c \sim 4.5$ K for the Josephson junction, i.e., when phase coherence is established across the BP layer. Figure 2(b) displays an current-voltage characteristic (IVC) of the junction at 2.8 K.

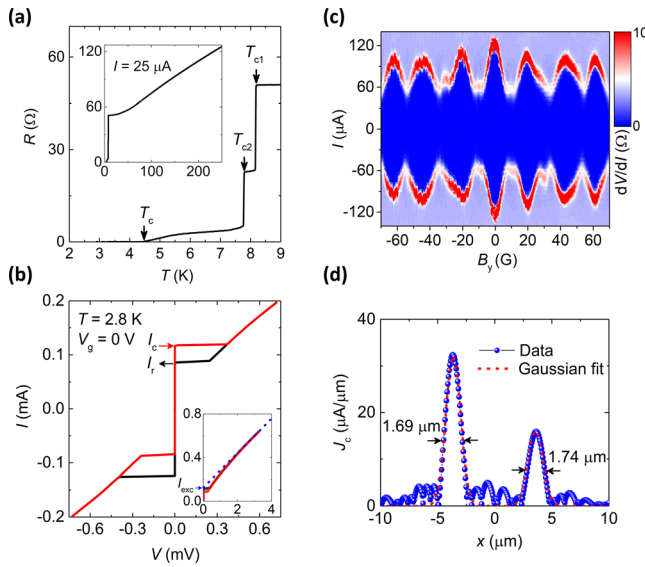


FIG. 2. (a) R - T characteristic measured at a bias current of $25 \mu\text{A}$, $V_g = 0 \text{ V}$. The inset shows the R - T curve over a wide temperature range. (b) IVC measured at $T = 2.8 \text{ K}$, $V_g = 0 \text{ V}$, with a current sweep from negative to positive (red line) and vice versa (black line). The inset shows a part of the IVC on expanded current and voltage scales. An excess current is indicated in the inset by the blue dashed line. (c) Differential resistance map of the junction as a function of the applied magnetic field B_y and the bias current I , showing a SQUID-like periodic oscillation of I_c . (d) Critical current distribution (blue dotted line) integrated along the x -direction as obtained by FFT of the $I_c(B_y)$ pattern. The width of the edge currents is extracted from Gaussian fits and is estimated to be about $1.7 \mu\text{m}$ (red dashed line).

The junction carries a supercurrent up to the critical current $I_c = 118 \mu\text{A}$, above which the junction switches to the resistive state. When lowering the bias current, the reverse switching to the zero-voltage state occurs at the retrapping current $I_r = 86 \mu\text{A}$. Often hysteresis arises from capacitive effects as, e.g., described by the resistively and capacitively shunted junction (RCSJ) model. By contrast, in our case, the hysteresis is very likely of thermal origin and arises from Joule heating. We will analyze this below in the context of microwave field data. An asymptote that does not go through the origin (blue dashed line) appears in the IVC for the voltages larger than 2.6 mV , shown in the inset of Fig. 2(b). The slope represents the normal state resistance R_n ($R_n = 6.3 \Omega$) of the BPJJ, whereas the intercept is the excess current I_{exc} . The large positive excess current $I_{\text{exc}} = 125 \mu\text{A}$ is likely to stem from multiple Andreev reflections and indicates the high transparency of the Nb/BP interface.³⁹

We investigate the profile of the Josephson critical current density by applying a magnetic field B_y in the y -direction, cf. Fig. 1(a). The total critical current $I_c(B_y)$ can be written as follows:²⁸

$$I_c(B_y) = \left| \int_{-\infty}^{\infty} dx j_c(x) e^{\frac{i2\pi t_{\text{eff}} B_y x}{\Phi_0}} \right|, \quad (1)$$

where $t_{\text{eff}} = d_{\text{BP}} + 2\lambda_{\text{Nb}} \tanh(d_{\text{Nb}}/2\lambda_{\text{Nb}}) \sim 105 \text{ nm}$ is the effective junction thickness,⁴⁰ $\lambda_{\text{Nb}} \sim 110 \text{ nm}$ is the London penetration depth of the $d_{\text{Nb}} = 100 \text{ nm}$ thick Nb film,⁴¹ d_{BP} is the thickness of BP, and Φ_0 is the flux quantum. $j_c(x)$ is the Josephson critical current density integrated along x . Note that once t_{eff} is fixed, the coordinate x in $j_c(x)$ can be calculated without further assumptions, and below we find very good

agreement with the actual size of our junction. Also note that Eq. (1) assumes a sinusoidal Josephson current phase relation. As we will see below, this assumption is presumably not completely fulfilled for our junctions. From Eq. (1), for a uniform critical current density, one would obtain the standard Fraunhofer pattern for $I_c(B_y)$. By contrast, our BPJJs exhibit a “SQUID-like” interference pattern, as shown in Fig. 2(c). Here, the differential resistance is plotted color-coded as a function of the magnetic field and bias current, and $I_c(B_y)$ appears as the boundary between zero and finite resistance. For quantitative analysis of the critical current density, we invert Eq. (1) by a Fourier transform yielding $J_c(x)$, as shown in Fig. 2(d). The accuracy is limited by the finite range of magnetic fields in which the interference pattern was measured.

Evidently, the projection $J_c(x)$ peaks at the junction edges. The (resolution limited) widths of the peaks, estimated via Gaussian fits, are 1.69 and $1.74 \mu\text{m}$ for the two edges. The behavior observed in this device is reproduced in all other BPJJs of either square or rectangular cross section we measured. However, from a single I_c vs B measurement, because of the limited number of oscillation periods recorded, we cannot clearly deduce whether the edges carry the supercurrent homogeneously or if only some parts contribute. In the [supplementary material](#) Sec. 6, we present additional data for another square-shaped junction and an equilateral triangle. For both junctions, we have applied the in-plane magnetic field in different directions. From these measurements, we conclude that the supercurrent is dominantly, although probably not completely, carried by regions near the corners of the junctions, i.e., we basically may have a set of weak links near the corners. The origin of corner-dominated critical current distribution is not certain but may be attributed to corrugations in the BP at the niobium edges or corners.^{42–44}

To gain more insight into the dynamics of the BPJJs, we investigated the ac Josephson effect by applying a microwave field to the samples. In the presence of a microwave excitation, the IVCs exhibit a series of quantized voltage plateaus (i.e., Shapiro steps) at voltage intervals $\Delta V = \Phi_0 f$, where f is the microwave frequency. Figure 3(a) shows IVCs at $f = 35 \text{ GHz}$ for different values of the microwave amplitude. We find a voltage interval $\Delta V \sim 70 \mu\text{V}$, consistent with the Josephson relation. At low values of the microwave amplitude, the third Shapiro step appears on the return branch of the hysteretic IVC, while the first and second steps are not observed. When the microwave amplitude is increased, the first and the second steps appear, but the hysteresis becomes even more pronounced. A color map of the differential resistance (dV/dI) as a function of microwave amplitude $P^{1/2}$ and bias current I is shown in Fig. 3(b). This is in contrast to the behavior of traditional Josephson junctions where hysteresis is caused by capacitance effects. In this case, the hysteresis is suppressed before stable Shapiro steps appear. Similar behaviors as for our BPJJs have been reported for high critical-current-density superconductor-normal metal-superconductor (SNS) junctions and Dayem bridge Josephson weak links.^{30,31} Here, the hysteresis is thermal in origin and caused by a local temperature increase due to Joule heating.

The thermal hysteresis typically occurs when the supercurrent density J_c is well above 10^5 A/cm^2 .³⁰ This, in turn, says that much less than 1% of the actual area of JJ1 carries a significant Josephson current, pointing to weak links or nano-bridges either near the edges or corners, or somewhere inside the junction area. Thus, also taking the $I_c(B_y)$ data into account, we basically may have a set of weak links along the junction edges or corners that heat up strongly. We also find

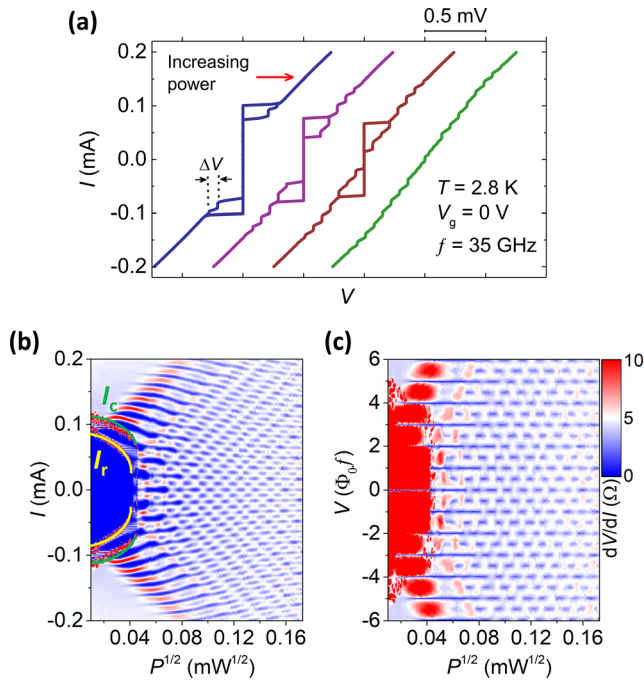


FIG. 3. (a) Selected IVCs of BPJJ with microwave frequency $f = 35$ GHz. The curves are horizontally offset for clarity. (b) Differential-resistance (dV/dI) color map as a function of current (I) and power amplitude ($P^{1/2}$). The blue regions indicate the Shapiro steps; the power dependence of I_c and I_n is marked by the green and yellow solid lines, respectively. (c) Differential-resistance (dV/dI) color map as a function of normalized voltage ($V/\Phi_0 f$) and microwave power ($P^{1/2}$). Integer and half-integer Shapiro steps can be seen.

a series of half-integer Shapiro steps, as can be seen in the color map of the differential resistance (dV/dI) as a function of microwave amplitude $P^{1/2}$ and normalized voltage $V/\Phi_0 f$, cf. Fig. 3(c). These subharmonic steps may arise from a non-sinusoidal current-phase relation of the junctions containing a substantial second harmonic.^{45,46}

Having demonstrated the existence of an edge- or corner-dominated Josephson supercurrent distribution in BPJJ, we now analyze the gate voltage dependence of the junction properties. To our best knowledge, due to the atomic-scale Thomas-Fermi screening length of metals, the effective gating region of our junctions is on the naked BP around the edge of niobium electrodes, as shown in Fig. 4(a). In the presence of a static electric field, a charge-carrier concentration gradient occurs in the BP between the inside and outside of the junction. In turn, charge carriers diffuse from higher concentration areas to lower concentration areas of the BP, with diffusion length L_d ,

$$L_d = \sqrt{D\tau}, \quad (2)$$

where D is the diffusion coefficient and τ is the charge carrier lifetime. It has been reported that the value of L_d is about 450 nm for a 2 nm BP thin flake²⁵ and 1 or 4 μm for the case of 16 nm thick flakes.⁴⁷ In our device, we estimate a diffusion length of about 0.9 μm . This diffusion process will influence the BP at the edges of the junction, leading to a modification of the Josephson coupling.

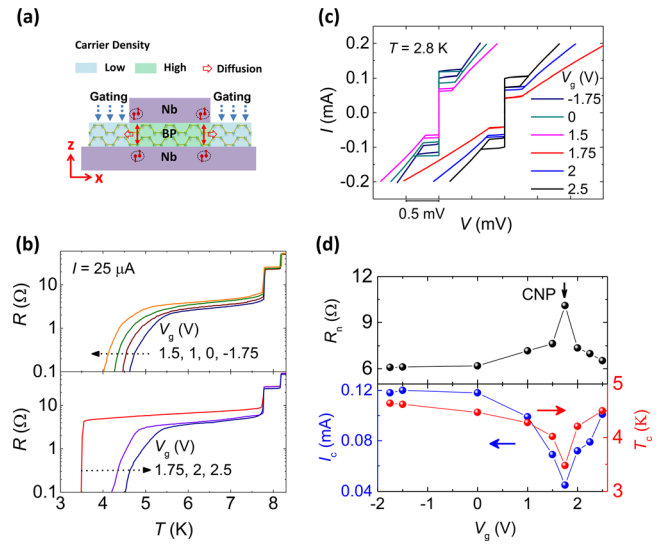


FIG. 4. (a) Schematic x-z plane cross section of the device with gate voltage; the supercurrent mainly passes through the edges. Gating results in a gradient of the carrier density along the edges of BPJJ. (b) R - T curves at different V_g , the measurement current is set to 25 μA . (c) IVCs at 2.8 K measured at different V_g . The curves are horizontally offset for clarity. (d) Extracted normal resistance (R_n), critical current (I_c), and critical temperature (T_c) vs gate voltage (V_g).

After applying electric fields at 230 K with different gate voltages V_g , we measured R - T curves across the junction when the device was further cooled down to 2.8 K, cf. Fig. 4(b). The gate voltages were applied in the sequence 0, 1, 1.5, 1.75, 2, 2.25, 2.5, 0, -1.5 , and -1.75 V. The reproducible characteristics at 0 V indicate that the modulation of our device does not stem from a chemical reaction in the BP. The diffusion effect under gating can be clearly seen. The junction transition temperature T_c is reduced as the gate voltage increases and reaches a minimum at 1.75 V. By contrast, the transition temperatures of the Nb electrodes are not affected by the different gate voltages. Simultaneously, the constant transition temperatures of Nb electrodes allow us to exclude field-effect-driven weakening of superconductivity in the Nb electrodes.

In the superconducting state, we observe that also the critical current (I_c) and the normal resistance (R_n) can be modulated by the gate voltages. Figure 4(c) shows IVCs taken at different gate voltages at 2.8 K. In Fig. 4(d), we have extracted the values of T_c , I_c , and R_n for the various applied gate voltages. Note that the dependence of these quantities on V_g is found to be consistent with the ambipolar transfer characteristics of BP, indicating that the carrier diffusion in BP plays an important role. A positive V_g results in a reduction of the charge carrier concentration in the naked area of the BP. Near the junction edges, the carriers will diffuse due to the large gradients, giving rise to a higher R_n and, hence, a lower I_c .^{1,9} As it can be seen in the [supplementary material Fig. S5](#), the magnetic field modulation of I_c remains SQUID like, i.e., the supercurrent density remains edge- or corner-dominated also under gating. Furthermore, the gate-induced change in I_c and in R_n also affects the junction dynamics and, thus, the microwave response. This is shown in the [supplementary material Fig. S6](#). Overall, it is the semiconducting nature of BP in combination with the

edge- or corner-dominated supercurrent density, which allows the strong electric-field tunability of the properties of our vertical Josephson junctions.

In conclusion, we have fabricated vertical Josephson transistors made with BP barriers using our *in situ* fabrication system. The electric-field tunability of the BPJJs could be attributed to the edge- or corner-dominated supercurrent density profile in combination with the carrier diffusivity in the few-layer BP. Although the origin of the edge- or corner-dominated current in BPJJs is unclear, we think it is quite promising to conduct more in-depth research on it. We emphasize that Josephson supercurrent field-effect transistors in the vertical structure are superior to those in planar geometry. The atomic-scale channel length in BPJJ enables the strong Josephson coupling even in a short ballistic regime,^{18,23} leading to an operating temperature of the field-effect vertical junctions, which is much higher than that of the planar geometry. These observations would be desirable in search for high-performance or even high-temperature superconductor (HTS) JoFETs. We anticipate that this work will inspire a comprehensive investigation of vertical superconducting field-effect devices ranging from tunable superconducting qubits to HTS Josephson devices, which would benefit from the field-effect control to enhance their device functionality.

AUTHORS' CONTRIBUTIONS

Z.X. and W.C. contributed equally to this work.

See the [supplementary material](#) for the sample fabrications of BPJJs, characterization of few-layer BP (Raman spectroscopy and estimation of the diffusion length), properties of *ex situ* fabricated BPJJ, transport properties of JJ1 and JJ2 with different ionic liquid gate voltages, and magnetic interference and critical current density distribution of a square-shaped and a triangle-shaped junction.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

REFERENCES

- Y. J. Doh, J. A. van Dam, A. L. Roest, E. Bakkers, L. P. Kouwenhoven, and S. De Franceschi, "Tunable supercurrent through semiconductor nanowires," *Science* **309**, 272 (2005).
- H. B. Heersche, P. Jarillo-Herrero, J. B. Oostinga, L. M. K. Vandersypen, and A. F. Morpurgo, "Bipolar supercurrent in graphene," *Nature* **446**, 56 (2007).
- A. Chrestin, T. Matsuyama, and U. Merkt, "Critical currents and supercurrent oscillations in Josephson field-effect transistors," *Phys. Rev. B* **49**, 498 (1994).
- O. Zheliuk, J. M. Lu, Q. H. Chen, A. A. El Yumin, S. Golightly, and J. T. Ye, "Josephson coupled Ising pairing induced in suspended MoS₂ bilayers by double-side ionic gating," *Nat. Nanotechnol.* **14**, 1123 (2019).
- G. D. Simoni, F. Paolucci, P. Solinas, E. Strambini, and F. Giazotto, "Metallic supercurrent field-effect transistor," *Nat. Nanotechnol.* **13**, 802 (2018).
- F. Barati, J. P. Thompson, M. C. Dartailh, K. Sardashti, W. Mayer, J. Yuan, K. Wickramasinghe, K. Watanabe, T. Taniguchi, H. Churchill, and J. Shabani, "Tuning supercurrent in Josephson field-effect transistors using h-BN dielectric," *Nano Lett.* **21**, 1915 (2021).
- A. W. Kleinsasser, T. N. Jackson, D. McInturff, F. Rammo, G. D. Pettit, and J. M. Woodall, "Superconducting InGaAs junction field-effect transistors with Nb electrodes," *Appl. Phys. Lett.* **55**, 1909 (1989).
- J. Xiang, A. Vidan, M. Tinkham, R. M. Westervelt, and C. M. Lieber, "Ge/Si nanowire mesoscopic Josephson junctions," *Nat. Nanotechnol.* **1**, 208 (2006).
- T. D. Clark, R. J. Prance, and A. D. C. Grassie, "Feasibility of hybrid Josephson field effect transistors," *J. Appl. Phys.* **51**, 2736 (1980).
- T. Akazaki, H. Takayanagi, J. Nitta, and T. Enoki, "A Josephson field effect transistor using an InAs-inserted-channel In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As inverted modulation-doped structure," *Appl. Phys. Lett.* **68**, 418 (1996).
- H. Takayanagi and T. Kawakami, "Superconducting proximity effect in the native inversion layer on InAs," *Phys. Rev. Lett.* **54**, 2449 (1985).
- L. Casparis, M. R. Connolly, M. Kjaergaard, N. J. Pearson, A. Kringhøj, T. W. Larsen, F. Kuemmeth, T. Wang, C. Thomas, S. Gronin, G. C. Gardner, M. J. Manfra, C. M. Marcus, and K. D. Petersson, "Superconducting gatemon qubit based on a proximitized two-dimensional electron gas," *Nat. Nanotechnol.* **13**, 915 (2018).
- A. H. Castro Neto, F. Guinea, N. M. R. Peres, K. S. Novoselov, and A. K. Geim, "The electronic properties of graphene," *Rev. Mod. Phys.* **81**, 109 (2009).
- A. K. Geim and K. S. Novoselov, "The rise of graphene," *Nat. Mater.* **6**, 183 (2007).
- V. E. Calado, S. Goswami, G. Nanda, M. Diez, A. R. Akhmerov, K. Watanabe, T. Taniguchi, T. M. Klapwijk, and L. M. K. Vandersypen, "Ballistic Josephson junctions in edge-contacted graphene," *Nat. Nanotechnol.* **10**, 761 (2015).
- M. Veldhorst, M. Snelder, M. Hoek, T. Gang, V. K. Guduru, X. L. Wang, U. Zeitler, W. G. van der Wiel, A. A. Golubov, H. Hilgenkamp, and A. Brinkman, "Josephson supercurrent through a topological insulator surface state," *Nat. Mater.* **11**, 417 (2012).
- M. T. Allen, O. Shtanko, I. C. Fulga, A. R. Akhmerov, K. Watanabe, T. Taniguchi, P. Jarillo-Herrero, L. S. Levitov, and A. Yacoby, "Spatially resolved edge currents and guided-wave electronic states in graphene," *Nat. Phys.* **12**, 128 (2016).
- G.-H. Lee, S. Kim, S.-H. Jhi, and H.-J. Lee, "Ultimately short ballistic vertical graphene Josephson junctions," *Nat. Commun.* **6**, 6181 (2015).
- J. H. Choi, G. H. Lee, S. Park, D. Jeong, J. O. Lee, H. S. Sim, Y. J. Doh, and H. J. Lee, "Complete gate control of supercurrent in graphene p-n junctions," *Nat. Commun.* **4**, 2525 (2013).
- G.-H. Lee, D. Jeong, J.-H. Choi, Y.-J. Doh, and H.-J. Lee, "Electrically tunable macroscopic quantum tunneling in a graphene-based Josephson junction," *Phys. Rev. Lett.* **107**, 146605 (2011).
- I. V. Borzenets, F. Amet, C. T. Ke, A. W. Draelos, M. T. Wei, A. Seredinski, K. Watanabe, T. Taniguchi, Y. Bomze, M. Yamamoto, S. Tarucha, and G. Finkelstein, "Ballistic graphene Josephson junctions from the short to the long junction regimes," *Phys. Rev. Lett.* **117**, 237002 (2016).
- L. Fu and C. L. Kane, "Superconducting proximity effect and Majorana fermions at the surface of a topological insulator," *Phys. Rev. Lett.* **100**, 096407 (2008).
- M. Kim, G. H. Park, J. Lee, J. H. Lee, J. Park, H. Lee, G. H. Lee, and H. J. Lee, "Strong proximity Josephson coupling in vertically stacked NbSe₂-graphene-NbSe₂ van der Waals junctions," *Nano Lett.* **17**, 6125 (2017).
- J. O. Island, G. A. Steele, H. S. J. van der Zant, and A. Castellanos-Gomez, "Thickness dependent interlayer transport in vertical MoS₂ Josephson junctions," *2D Mater.* **3**, 031002 (2016).
- M. Z. Bellus, Z. Yang, J. Hao, S. Ping Lau, and H. Zhao, "Amorphous two-dimensional black phosphorus with exceptional photocarrier transport properties," *2D Mater.* **4**, 025063 (2017).
- T. Vy, R. Soklaski, Y. Liang, and L. Yang, "Layer-controlled band gap and anisotropic excitons in few-layer black phosphorus," *Phys. Rev. B* **89**, 235319 (2014).

- ²⁷W. Chen, Z. Xu, W. Tian, Y. Lv, M. Yu, X. Zhou, X. Tu, J. Wu, J. Li, S. Li, B. Jin, W. Xu, D. Koelle, R. Kleiner, H. Wang, and P. Wu, "High-quality in situ fabricated Nb Josephson junctions with black phosphorus barriers," *Supercond. Sci. Technol.* **32**, 115005 (2019).
- ²⁸R. C. Dynes and T. A. Fulton, "Supercurrent density distribution in Josephson junctions," *Phys. Rev. B* **3**, 3015 (1971).
- ²⁹M. J. Zhu, A. V. Kretinin, M. D. Thompson, D. A. Bandurin, S. Hu, G. L. Yu, J. Birkbeck, A. Mishchenko, I. J. Vera-Marun, K. Watanabe, T. Taniguchi, M. Polini, J. R. Prance, K. S. Novoselov, A. K. Geim, and M. B. Shalom, "Edge currents shunt the insulating bulk in gapped graphene," *Nat. Commun.* **8**, 14552 (2017).
- ³⁰A. De Cecco, K. L. Calvez, B. Sacépé, C. B. Winkelmann, and H. Courtois, "Interplay between electron overheating and ac Josephson effect," *Phys. Rev. B* **93**, 180505 (2016).
- ³¹C. D. Shelly, P. See, I. Rungger, and J. M. Williams, "Existence of Shapiro steps in the dissipative regime in superconducting weak links," *Phys. Rev. Appl.* **13**, 024070 (2020).
- ³²J. I. J. Wang, D. Rodan-Legrain, L. Bretheau, D. L. Campbell, B. Kannan, D. Kim, M. Kjaergaard, P. Krantz, G. O. Samach, F. Yan, J. L. Yoders, K. Watanabe, T. Taniguchi, T. P. Orlando, S. Gustavsson, P. Jarillo-Herrero, and W. D. Oliver, "Coherent control of a hybrid superconducting circuit made with graphene-based van der Waals heterostructures," *Nat. Nanotechnol.* **14**, 120 (2019).
- ³³J. G. Kroll, W. Uilhoorn, K. L. van der Enden, D. de Jong, K. Watanabe, T. Taniguchi, S. Goswami, M. C. Cassidy, and L. P. Kouwenhoven, "Magnetic field compatible circuit quantum electrodynamics with graphene Josephson junctions," *Nat. Commun.* **9**, 4615 (2018).
- ³⁴L. Li, Y. Yu, G. J. Ye, Q. Ge, X. Ou, H. Wu, D. Feng, X. H. Chen, and Y. Zhang, "Black phosphorus field-effect transistors," *Nat. Nanotechnol.* **9**, 372 (2014).
- ³⁵Y. Saito and Y. Iwasa, "Ambipolar insulator-to-metal transition in black phosphorus by ionic-liquid gating," *ACS Nano* **9**, 3192 (2015).
- ³⁶A. Castellanos-Gomez, L. Vicarelli, E. Prada, J. O. Island, K. L. Narasimha-Acharya, S. I. Blanter, D. J. Groenendijk, M. Buscema, G. A. Steele, J. V. Alvarez, H. W. Zandbergen, J. J. Palacios, and H. S. J. van der Zant, "Isolation and characterization of few-layer black phosphorus," *2D Mater.* **1**, 025001 (2014).
- ³⁷H. Yuan, X. Liu, F. Afshinmanesh, W. Li, G. Xu, J. Sun, B. Lian, A. G. Curto, G. Ye, Y. Hikita, Z. Shen, S. C. Zhang, X. Chen, M. Brongersma, H. Y. Hwang, and Y. Cui, "Polarization-sensitive broadband photodetector using a black phosphorus vertical p-n junction," *Nat. Nanotechnol.* **10**, 707 (2015).
- ³⁸A. Carvalho, M. Wang, X. Zhu, A. S. Rodin, H. B. Su, and A. H. C. Neto, "Phosphorene: From theory to applications," *Nat. Rev. Mater.* **1**, 16061 (2016).
- ³⁹G. E. Blonder, M. Tinkham, and T. M. Klapwijk, "Transition from metallic to tunneling regimes in superconducting microconstrictions: Excess current, charge imbalance, and supercurrent conversion," *Phys. Rev. B* **25**, 4515 (1982).
- ⁴⁰M. Wehnacht, "Influence of film thickness on dc Josephson current," *Phys. Status Solidi* **32**, K169 (1969).
- ⁴¹A. I. Gubin, K. S. Il'in, S. A. Vitusevich, M. Siegel, and N. Klein, "Dependence of magnetic penetration depth on the thickness of superconducting Nb thin films," *Phys. Rev. B* **72**, 064503 (2005).
- ⁴²M. B. Lundeberg and J. A. Folk, "Rippled graphene in an in-plane magnetic field: Effects of a random vector potential," *Phys. Rev. Lett.* **105**, 146804 (2010).
- ⁴³V. Geringer, M. Liebmann, T. Echtermeyer, S. Runte, M. Schmidt, R. Ruckamp, M. C. Lemme, and M. Morgenstern, "Intrinsic and extrinsic corrugation of monolayer graphene deposited on SiO₂," *Phys. Rev. Lett.* **102**, 076102 (2009).
- ⁴⁴A. Fasolino, J. H. Los, and M. I. Katsnelson, "Intrinsic ripples in graphene," *Nat. Mater.* **6**, 858 (2007).
- ⁴⁵B. Raes, N. Tubssrinuan, R. Sreedhar, D. S. Guala, R. Panghotra, H. Dausy, C. C. de Souza Silva, and J. Van de Vondel, "Fractional Shapiro steps in resistively shunted Josephson junctions as a fingerprint of a skewed current-phase relationship," *Phys. Rev. B* **102**, 054057 (2020).
- ⁴⁶J. Wiedenmann, E. Bocquillon, R. S. Deacon, S. Hartinger, O. Herrmann, T. M. Klapwijk, L. Maier, C. Ames, C. Brune, C. Gould, A. Oiwa, K. Ishibashi, S. Tarucha, H. Buhmann, and L. W. Molenkamp, "4π-periodic Josephson supercurrent in HgTe-based topological Josephson junctions," *Nat. Commun.* **7**, 10303 (2016).
- ⁴⁷J. Q. He, D. W. He, Y. S. Wang, Q. N. Cui, M. Z. Bellus, H. Y. Chiu, and H. Zhao, "Exceptional and anisotropic transport properties of photocarriers in black phosphorus," *ACS Nano* **9**, 6436 (2015).