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RAPID COMMUNICATION

Gate-controlled magnetic transitions in Fe_3GeTe_2 with lithium ion conducting glass substrate*

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Since the discovery of magnetism in two dimensions, effective manipulation of magnetism in van der Waals magnets has always been a crucial goal. Ionic gating is a promising method for such manipulation, yet devices gated with conventional ionic liquid may have some restrictions in applications due to the liquid nature of the gate dielectric. Lithium-ion conducting glass-ceramics (LICGC), a solid Li^+ electrolyte, could be used as a substrate while simultaneously acts as a promising substitute for ionic liquid. Here we demonstrate that the ferromagnetism of Fe_3GeTe_2 (FGT) could be modulated via LICGC. By applying a voltage between FGT and the back side of LICGC substrate, Li^+ doping occurs and causes the decrease of the coercive field (H_c) and ferromagnetic transition temperature (T_c) in FGT nanoflakes. A modulation efficiency for H_c of up to $\sim 24.6\%$ under $V_g = 3.5$ V at $T = 100$ K is achieved. Our results provide another method to construct electrically-controlled magnetoelectronics, with potential applications in future information technology.

Keywords: two-dimensional magnetism, two-dimensional material, ionic gating

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1. Introduction

In recent years, van der Waals (vdW) two-dimensional (2D) materials[1–3] have attracted a lot of attention, with numerous research focusing on the physical properties and potential applications in such systems with strong confinement. So far, a large number of 2D materials have been investigated, with properties including insulators, semiconductors, semimetals, and even correlated electronic materials. Among these compounds, vdW magnets are of great interest. According to the Mermin–Wagner theorem, long-range magnetic order in 2D systems would be strongly suppressed by thermal fluctuations. Recently, it is realized that magnetic anisotropy could counteract such fluctuations,[4] resulting in ferromagnetic order in $Cr_2Ge_2Te_6$[5,6] and CrI_3[7–9] atomic layers. Such findings inspire people to further study the intrinsic magnetism in 2D vdw magnets. Fe_3GeTe_2 (FGT) is considered as a promising vdW ferromagnet.[10–14] Due to strong spin–orbit coupling-induced magneto crystalline anisotropy along the c axis, bulk FGT crystals exhibit a relatively high ferromagnetic transition temperature (T_c) of about 220 K, and long-range magnetic order exists down to the monolayer limit. FGT with such intrinsic ferromagnetic property and its metallic nature in the 2D limit gives us with a good material platform: we could study its magnetic properties through electrical transport measurement, and the interplay of spin and charge degrees of freedom provides more possibilities in device concepts based on magnetic vdW heterostructures.[15–17]

The magnetic properties of magnetic materials can be modulated with different methods, such as strain[18–21] and electrical-gating.[12,22] Gate-controlled magnetism is an attractive way to realize magnetoelectronic devices. vdW crystals have the advantage to be prepared into thin layers and could be readily tuned by various kinds of gating modulation. Typically, gating could cause changes in the ferromagnetic transition temperature T_c and the coercive field H_c, which are driven by magnetoelectric effect. Ionic gating provides a much larger gating effect compared with conventional solid dielectric and is a promising method to modulate magnetism in 2D materials.[12] However, ionic liquid gating could be less convenient in practical application due to its liquid nature. Thus solid electrolytes could provide the benefits of a solid substrate and at the same time deliver similar doping capacity as liquid electrolytes. Previously, such a technique has been applied to modulate the carrier density in FeSe using solid electrolyte ($Li_{1+x+y}Al_x(Ti_{2y}Ge_y)P_{3-z}Si_zO_{12}$)[23,24] and to induce superconductivity in $SnSe_2$ using solid electrolyte $Li_2Al_2SiP_2TiO_{13}$.[23–25] Solid electrolytes are also used

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in a number of experiments to construct special field effect devices,[26–34] yet there is no report so far on tuning magnetism in vdW magnets via solid electrolyte. In this work, we investigate the modulation of FGT's ferromagnetism by Li^+doping via lithium-ion conducting glass-ceramics (LICGC) substrate. H_c and T_c are both found to decrease with the increasing gating voltages, and such variation is attributed to Li^+ intercalation effect. We believe that the tunability of FGT provides more possibilities for electrically controlled magnetoelectronic devices.

2. Method

The bulk FGT crystals are grown by the chemical vapor transport method, and thin FGT samples measured in this work are mechanically exfoliated from bulk crystals and deposited on LICGC substrates. As shown in Fig. 1(a), we use four-terminal measurement method to measure our samples. Standard electron-beam lithography technique is used to pattern electrodes with 5-nm Ti/50-nm Au. The bottom gate electrodes are evaporated on the back of the LICGC substrate. In addition, to prevent FGT from oxidizing when exposed to ambient conditions, the samples were kept in inert atmosphere or with a PMMA capping layer during the preparation and measurement process. In order to improve the contact quality, Ar^+ plasma cleaning is carried out for 20 minutes during the electrodes fabrication process. The transport measurements were performed in a Quantum Design PPMS-9, with 80-nA AC current at 18.88 Hz provided by a lock-in amplifier (Stanford Research SR830). The back-gate voltage is applied from 0 V to 3.5 V using a Keithley 2400 multimeter.

3. Results and discussion

In this letter, we study the magnetic properties of FGT thin flakes by measuring the Hall resistance R_{xy} with the external magnetic field applied perpendicular to the sample plane. As a ferromagnetic material, the Hall resistance R_{xy} is composed of a normal Hall resistance and an anomalous Hall resistance, which could be described as[35]

$$R_{xy} = R_0\mu_0 H + R_S M, \tag{1}$$

where $R_0\mu_0 H$ is the normal Hall resistance, $R_S M$ is the anomalous Hall resistance, where R_0 is the ordinary Hall coefficient and R_S is the anomalous Hall coefficient, H is the applied magnetic field and M represents the magnetic moment of the sample. For a metallic ferromagnetic material, the anomalous Hall resistance is the main part of the R_{xy}. The characteristics of M could then be extracted from the Hall resistance. The Hall resistance as a function of the applied magnetic field H at various temperatures is shown in Fig. 1(b). The magnetic field is applied perpendicular to the sample plane, which is swept between -2 T and 2 T. At low temperature, the R_{xy}–H curve of FGT thin flakes shows standard ferromagnetic hysteresis behavior, with a coercive field of ~ 2200 Oe (1 Oe = 79.5775 A·m^{-1}) at 10 K. The remanent Hall resistance $R_{xy|H=0}$ is directly proportional to the zero-field spontaneous magnetization according to Eq. (1). At higher temperature, *e.g.*, $T = 250$ K, the hysteresis loop disappears, which indicates that thermal fluctuations severely suppressed ferromagnetism. The coercive magnetic field H_c is defined as the magnitude of the magnetic field at which $R_{xy} = 0$ in the R_{xy}–H hysteresis loop. Generally, H_c is the same for the positive and negative magnetic field since there is no exchange bias effect in our devices. To get the information of the temperature-dependent $R_{xy|H=0}$, we first polarized our sample with $H = -2$ T at 10 K, then measured $R_{xy|H=0}$ at $H = 0$ T from 10 K to 300 K, with a ramp rate of 5 K/min. Figure 1(c) plots $R_{xy|H=0}$ *versus* T from 150 K to 240 K. It can be seen that $R_{xy|H=0}$ decreases sharply at about 200 K, indicating the transition of the FGT thin flake from ferromagnetic state to paramagnetic state. Such a rapid decrease is observed in 4 different samples, with thickness ranging from 42.7 nm to 84.5 nm. We define T_c as the temperature at the middle point of such sharp transition in the $R_{xy|H=0}$ *versus* T curves. Figure 1(d) shows H_c *versus* T in which H_c is found to decrease monotonically with increasing T, and become too small to measure before reaching 200 K.

Next, we focus on modulating the magnetism of FGT thin flakes by Li^+ doping using solid electrolyte LICGC substrates. Just like the charging process that occurs in lithium-ion batteries, when a positive voltage V_g is applied on the bottom gate, the Li^+ in LICGC are expected to move towards the other surface of the LICGC, and get close to the FGT crystals. As we examine the effect of gating on FGT with LICGC, a remarkable change in the ferromagnetism of FGT thin flakes with gating could be observed with increasing gating voltage. As shown in Fig. 2(a), H_c of the FGT thin flake decreases with an increasing V_g at different temperatures from 10 K to 100 K. When none zero V_g is applied, H_c changes from 654.9 Oe ($V_g = 0$ V) to 493.6 Oe ($V_g = 3.5$ V). We can see that the temperature would also influence the gating effect. At lower temperature, variation in H_c seems to increase as a function of the gate voltage. We also measure the percentage change of H_c as a function of V_g, namely, $|\Delta H_c(V_g)|/H_c(V_g = 0)$ *versus* V_g, as shown in Fig. 2(b). Here $\Delta H_c(V_g) = H_c(V_g) - H_c(V_g = 0\ \text{V})$ is the difference of gate voltage induced changes in H_c at a particular temperature as compares to the zero gate value. It can be seen that the modulation of H_c by V_g is not linear when applying V_g from zero to 3.5 V at 100 K: an abrupt change is observed at around $V_g = 2.75$ V. The total $\Delta H_c/H_c(0)$ modulation efficiency is found to be up to $\sim 24.6\%$ for V_g from 0 to 3.5 V at $T = 100$ K.

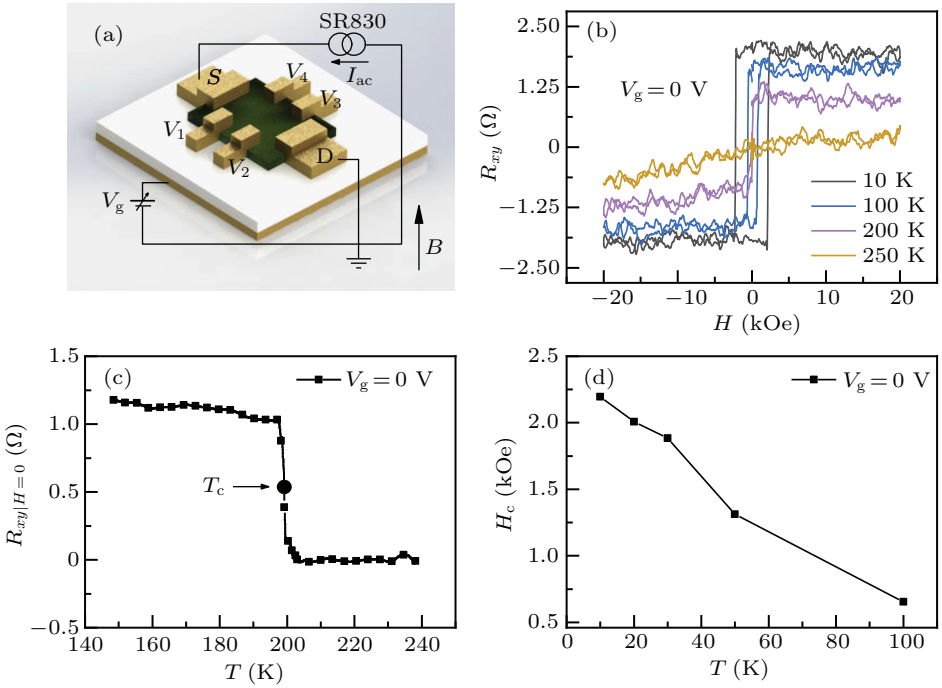


Fig. 1. Anomalous Hall effect in thin FGT flake. (a) Schematic diagram of few-layered FGT on LICGC substrate with Ti/Au electrodes. (b) R_{xy} *versus* H loops measured at T from 10 K to 250 K. The hysteresis behavior of the R_{xy} *versus* H loop is evident. (c) $R_{xy|H=0}$ *versus* T curve at $V_g = 0$ V and T from 150 K to 240 K, the circle point marks the T_c. (d) Temperature dependence of H_c from 10 K to 100 K, which decreases monotonically with increasing temperature.

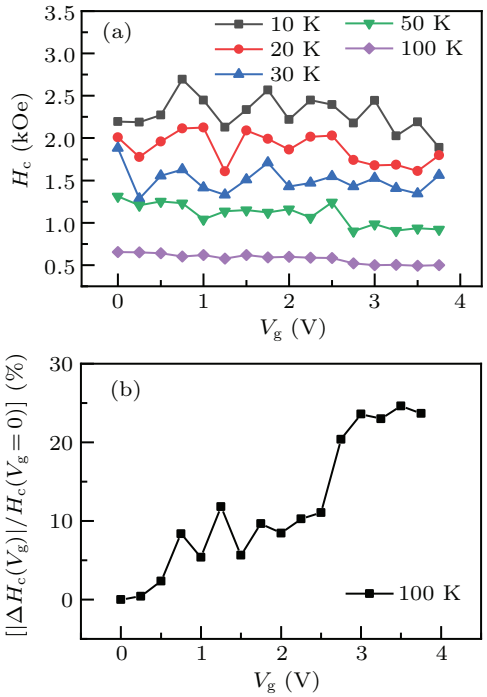


Fig. 2. The modulation of H_c in the thin FGT flake by ionic gating with LICGC. (a) H_c *versus* V_g from 0 V to 3.5 V at different temperature T. (b) The percentage change of H_c as a function of V_g, *e.g.*, $|\Delta H_c(V_g)|/H_c(V_g = 0\text{ V})$ as a function of V_g from 0 V to 3.5 V at $T = 100$ K. Here $\Delta H_c = H_c(V_g) - H_c(V_g = 0\text{ V})$.

To fully illustrate such modulation effect on the ferromagnetism of our sample, we further investigated the influence of Li^+ doping on T_c. Figure 3(a) shows the temperature dependence of the normalized $R_{xy|H=0}$, *e.g.*, $R_{xy|H=0}(T)/R_{xy|H=0}$ ($T = 150$ K), with different V_g, measured from low temperature to high temperature. Here the $R_{xy|H=0}$ data are normalized by their values at $T = 150$ K and plotted at the range of 150 K to 250 K, in order to illustrate the small but finite tunability in T_c at around 200 K. It is worth pointing out that for larger applied V_g, the temperature at which $R_{xy|H=0}$ reaches zero does not change much, while the onset temperature for the sharp transition from finite to zero $R_{xy|H=0}$ is tuned. Thus, in addition to defining T_c as the middle temperature point of such finite to zero $R_{xy|H=0}$ transition, we could also use the width of such transition W_T as a characterization of the transition process. It could be seen that at larger V_g, T_c shifts to lower temperatures. Specifically, in the T_c *versus* V_g curve, we could see that T_c drops sharply at $V_g = 2.5$ V while it is almost invariant at smaller V_g, as shown in Fig. 3(b). A decrease in T_c could mean a shift of the transition step, a change in the slope of the step, or a combination of both. Using W_T, we could see that it is mainly a change in the slope of the transition step that is modified by V_g, as W_T is significantly widened when $V_g > 2$ V. This effect may be caused by the increase in inhomogeneity in FGT due to Li^+ intercalations during gating.

The observed gate dependence of H_c and T_c of FGT thin flakes on LICGC substrates may involve the following effects: i) pure electrostatic gating effect, including conventional electric field effect as well as the accumulation of Li^+ at the bottom surface of FGT; ii) intercalation of Li^+ in the FGT atomic layers; iii) irreversible electrochemical reactions. It is unlikely that pure electrostatic gating effect would induce such substantial change of H_c (up to 24.6%) and T_c (up to 2.5%), since FGT is a metal with high carrier concentration and our samples thickness of 52.1 nm. Thus, pure electrostatic gating

would not provide enough change in carrier concentration to significantly affect H_c and T_c. Besides, electrostatic gating of only the bottom surface of FGT would not significantly influence H_c and T_c of the whole crystal of FGT containing ~65 atomic layers. Thus, such effects are unlikely to come from pure electrostatic gating. Furthermore, we found that when we set V_g back to zero after previously setting it at a finite value, H_c recovers partially overtime. For example, when we set $V_g = 3.5$ V first and then back to 0 V, H_c could recover from 493.6 Oe to 528 Oe at 100 K. As a matter of fact, in order to protect the sample from air, our gate modulation and measurements are done in high vacuum environment or in helium atmosphere. Thus irreversible electrochemical reactions are unlikely to be the cause of such gate modulation. With the above information, we came to the conclusion that our experimental observation is in line with the scenario that Li^+ intercalations might occur during the gating process of FGT on LICGC substrate. The diffusion of Li^+ between FGT layers would influence the interlayer exchange coupling and the magnetic anisotropy, which results in the decrease of H_c and T_c. Such the mechanism is shown in Fig. 4, and it is consistent with previous experiment on FGT gating with ionic liquid, in the regime that $V_g < 1.4$ V.[12] The enhancement of T_c observed in Ref. [12], for $V_g > 1.4$ V is not observed in our experiment, possibly due to the difference in the stages and homogeneity of Li^+ intercalations between ionic liquid gating and gating through solid electrolyte substrates. The details of such differences warrant further investigations.

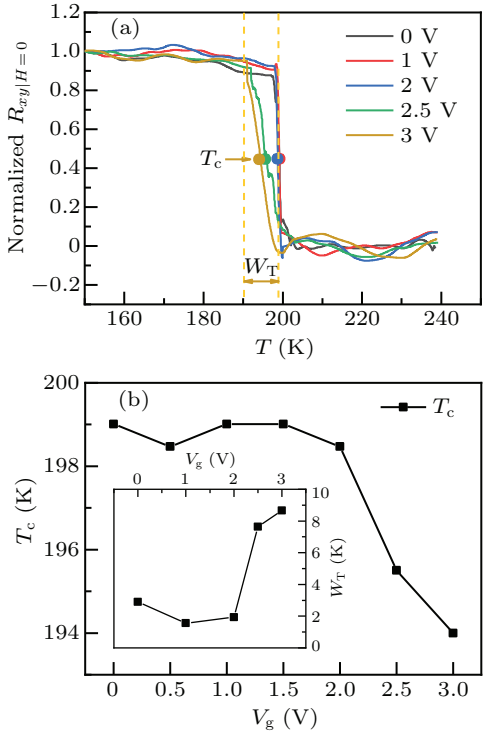


Fig. 3. The modulation of T_c in the thin FGT flake by ionic gating with LICGC. (a) The remanent Hall voltage $R_{xy|H=0}$ *versus* T at various V_g, where the $R_{xy|H=0}$ data are normalized by their values at $T = 150$ K. T_c is marked as circle points. (b) The V_g dependence of T_c, the inset shows the width of the transition step W_T *versus* V_g.

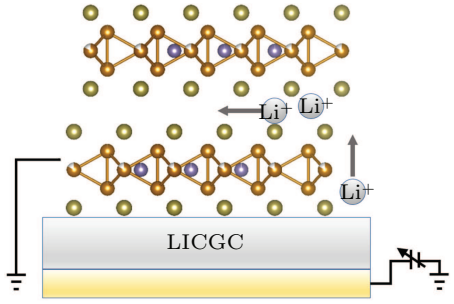


Fig. 4. The schematic diagram of gate-controlled Li^+ doping in the FGT flake with LICGC substrate.

4. Conclusion

In summary, we have fabricated FGT thin flake devices on solid Li^+ electrolyte LICGC substrates. Ferromagnetism in FGT thin flakes is found to be modulated with the help of LICGC. Specifically, the coercive field H_c and the Curie temperature T_c are strongly determined by the ionic gating voltage. We attribute such variation of H_c and T_c to the ionic doping and possibly intercalations of Li^+ between the atomic layers of FGT. Our results shows that solid electrolytes provide a new way to manipulate ferromagnetism in van der Waals magnets, and open new possibilities in future magnetoelectronic devices.

References

[1] Geim A K and Novoselov K S 2007 *Nat. Mater.* **6** 183
[2] Mak K F, McGill K L, Park J and McEuen P L 2014 *Science* **344** 1489
[3] Xia F, Mueller T, Lin Y M, Valdes-Garcia A and Avouris P 2009 *Nat. Nanotechnol.* **4** 839
[4] Mermin N D and Wagner H 1966 *Phys. Rev. Lett.* **17** 1133
[5] Wang Z, Zhang T, Ding M, *et al.* 2018 *Nat. Nanotechnol.* **13** 554
[6] Gong C, Li L, Li Z, Ji H, Stern A, Xia Y, Cao T, Bao W, Wang C, Wang Y, Qiu Z Q, Cava R J, Louie S G, Xia J and Zhang X 2017 *Nature* **546** 265
[7] Huang B, Clark G, Klein D R, MacNeill D, Navarro-Moratalla E, Seyler K L, Wilson N, McGuire M A, Cobden D H, Xiao D, Yao W, Jarillo-Herrero P and Xu X 2018 *Nat. Nanotechnol.* **13** 544
[8] Jiang S, Li L, Wang Z, Mak K F and Shan J 2018 *Nat. Nanotechnol.* **13** 549
[9] Wang Z, Gutierrez-Lezama I, Ubrig N, Kroner M, Gibertini M, Taniguchi T, Watanabe K, Imamoglu A, Giannini E and Morpurgo A F 2018 *Nat. Commun.* **9** 2516
[10] Tan C, Lee J, Jung S G, Park T, Albarakati S, Partridge J, Field M R, McCulloch D G, Wang L and Lee C 2018 *Nat. Commun.* **9** 1554
[11] Zhuang H L L, Kent P R C and Hennig R G 2016 *Phys. Rev. B* **93** 134407
[12] Deng Y, Yu Y, Song Y, Zhang J, Wang N Z, Sun Z, Yi Y, Wu Y Z, Wu S, Zhu J, Wang J, Chen X H and Zhang Y 2018 *Nature* **563** 94
[13] Fei Z, Huang B, Malinowski P, Wang W, Song T, Sanchez J, Yao W, Xiao D, Zhu X, May A F, Wu W, Cobden D H, Chu J H and Xu X 2018 *Nat. Mater.* **17** 778
[14] Chen B, Yang J H, Wang H D, Imai M, Ohta H, Michioka C, Yoshimura K and Fang M H 2013 *J. Phys. Soc. Jpn.* **82** 124711
[15] Zhao C, Norden T, Zhang P, Zhao P, Cheng Y, Sun F, Parry J P, Taheri P, Wang J, Yang Y, Scrace T, Kang K, Yang S, Miao G X, Sabirianov R, Kioseoglou G, Huang W, Petrou A and Zeng H 2017 *Nat. Nanotechnol.* **12** 757
[16] Benedikt S, Xu G F, Alex M A and Igor Ž 2017 *Phys. Rev. Lett.* **119** 127403
[17] Zhong D, Seyler K L, Linpeng X, Cheng R, Sivadas N, Huang B, Schmidgall E, Taniguchi T, Watanabe K, McGuire M A, Yao W, Xiao D, Fu K C and Xu X 2017 *Sci. Adv.* **3** e1603113

[18] Bai Y H, Wang X, Mu L P and Xu X H 2016 *Chin. Phys. Lett.* **33** 087501
[19] Wei W G, Wang H, Zhang K, Liu H, Kou Y F, Chen J J, Du K, Zhu Y Y, Hou D L, Wu R Q, Yin L F and Shen J 2015 *Chin. Phys. Lett.* **32** 087504
[20] Ling Z B, Zhang Q Y, Yang C P, Li X T, Liang W S, Wang Y Q, Yang H W and Sun J R 2020 *Chin. Phys. B* **29** 096802
[21] Liu L W, Hu C C, Xu Y C, Huang H B, Cao J W, Liang L and Rao W F 2018 *Chin. Phys. B* **27** 077503
[22] Gong Y, Guo J, Li J, *et al*. 2019 *Chin. Phys. Lett.* **36** 076801
[23] Lei B, Wang N Z, Shang C, Meng F B, Ma L K, Luo X G, Wu T, Sun Z, Wang Y, Jiang Z, Mao B H, Liu Z, Yu Y J, Zhang Y B and Chen X H 2017 *Phys. Rev. B* **95** 020503
[24] Ying T P, Wang M X, Wu X X, Zhao Z Y, Zhang Z Z, Song B Q, Li Y C, Lei B, Li Q, Yu Y, Cheng E J, An Z H, Zhang Y, Jia X Y, Yang W, Chen X H and Li S Y 2018 *Phys. Rev. Lett.* **121** 207003
[25] Song Y, Liang X, Guo J, Deng J, Gao G and Chen X 2019 *Phys. Rev. B* **3** 054804
[26] Philippi M, Gutierrez-Lezama I, Ubrig N and Morpurgo A F 2018 *Appl. Phys. Lett.* **113** 033502
[27] Alam M H, Xu Z, Chowdhury S, Jiang Z, Taneja D, Banerjee S K, Lai K, Braga M H and Akinwande D 2020 *Nat. Commun.* **11** 3203
[28] Arihori K, Ogawa M, Souma S, Sato-Iwanaga J and Suzuki M A 2020 *IEEE International Conference on Simulation of Semiconductor Processes and Devices,* September 23–October 06, 2020, Hyogo, Japan, p. 367
[29] Wang H S, Liu Q Y, Feng X M, Zhang Z, Wang K, Liu Z J and Dai J F 2020 *Mater. Res. Express* **7** 076302
[30] Zhou Z, Wu L M, Chen J C, Ma J J, Huang Y, Shen C M, Bao L H and Gao H J 2020 *Chin. Phys. B* **29** 118501
[31] Kühne M, Zhao D, Zschieschang U, Buck R, Müller M, Klauk H and Smet J H 2020 *Adv. Mater. Interfaces* **8** 2001453
[32] Alam M H, Chowdhury S, Roy A, Braga M H, Banerjee S K and Akinwande D 2021 *Phys. Rev. B* **5** 054003
[33] Zhang X Y, Hen B, Palevski A and Kapitulnik A 2021 *npj Quantum Mater.* **6** 30
[34] Pravarthana D, Wang B M, Mustafa Z, Agarwal S, Pei K, Yang H L and Li R W 2019 *Phys. Rev. Appl.* **12** 054065
[35] Ohno H, Munekata H, Penney T, von Molnar S and Chang L L 1992 *Phys. Rev. Lett.* **68** 2664