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Heat transfer at van der Waals interface between graphene and NbSe₂

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Abstract. Graphene has been widely used to construct low-resistance van der Waals (vdW) contacts to other two-dimensional (2D) materials. However, a rise of graphene's electron temperature under a current flow has not been seriously considered in many applications. Owing to its small electronic heat capacity and electron-phonon coupling, graphene's electron temperature can be increased easily by the application of current. The heat generated within the graphene is transferred to the contacted 2D materials through the vdW interface and potentially influences their properties. Here, we compare the superconducting critical currents of an NbSe₂ flake for two different methods of current application: with a Au/Ti electrode fabricated by thermal evaporation and with a graphene electrode contacted to the NbSe₂ flake through a vdW interface. The influence of the heat transfer from the graphene to NbSe₂ is detected through the change of the superconductivity of NbSe₂. We found that the critical current of NbSe₂ significantly reduces when the current is applied with the graphene electrode compared to that from the conventional Au/Ti electrode. Further, since the electron heating in graphene exhibits ambipolar back-gate modulation, we demonstrate the electric field modulation of the critical current in NbSe₂ when the current is applied with graphene electrode. These results are attributed to the significant heat transfer from the graphene electrode to NbSe₂ through vdW interface.

1. Introduction

Graphene has been widely studied as a high-quality electrode material for van der Waals (vdW) heterostructures. Exfoliated graphene exhibits an inert surface owing to its non-bonding nature and can be transferred easily onto other two-dimensional (2D) materials to construct highly transparent vdW contact. Various high-quality 2D material heterostructures have been achieved with the help of graphene vdW contact; for example, high mobility MoS₂ transistors [1,2], air-stable black phosphorus [3,4], light-emitting diodes based on vdW heterostructures [5], and vertical field-effect transistors based on graphene/transition metal dichalcogenide (TMD) vdW heterostructures [6,7]. More recently, owing to its small electronic heat capacity and small electron–phonon coupling, graphene has received considerable attention for studying hot carrier dynamics such as photodetection [8], thermal emission [9], bolometric effects [10], multiple hot carrier generation [11], and heat transfer at vdW interface [12,13]. In these experiments, heat dissipation pathways of hot electrons within graphene are important because they are used to determine the performance of the above-mentioned devices. In particular, recent publications revealed that out-of-plane electronic heat transfer in the vdW interface is a dominant pathway of heat dissipation in vdW heterostructures [12,14]. Such an out-of-plane electron heat transfer might overcome intrinsically weak phonon heat transfer at the vdW interface and could be useful to control the local heat flow and thermoelectric property in vdW heterostructures between graphene and other 2D materials [15,16]. Thus far, vertical heat transport in vdW heterostructure was detected using optical method [12-14]. However, another detection scheme such as electrical detection is required for device applications. Since superconductivity is very sensitive to temperature, a change in the superconductivity can be used as a tool to detect heat transfer between a superconductor and an adjacent material [17-19]. In this study, we investigate heat transfer in a vdW interface by using a graphene/superconductor junction. NbSe₂ is selected as a superconductor material because this material demonstrated the ability to construct high-quality vdW heterostructures with other 2D materials [4,20-22].

2. Method

An optical micrograph of the fabricated mono-layer graphene/23-nm-thick NbSe₂ device is shown in Fig. 1(a). NbSe₂ devices with two different types of contacts are fabricated: a conventional thermally evaporated contact of Au/Ti metal stack electrode and the vdW contact of the graphene electrode. To fabricate this device, we adopted a mechanical exfoliation and dry transfer technique. First, **mono- to few-layer** graphene was fabricated onto the 300-nm-thick SiO₂/highly-doped-Si substrate. Separately, a flake of NbSe₂ **with the thickness range 23–51 nm were** fabricated onto a polymer sheet (Gel-Pak, PF-X4). By using a dry transfer method, the NbSe₂ flake was transferred on graphene to construct the graphene/NbSe₂ vdW junction between freshly cleaved surfaces [21,23]. Subsequently, electron beam (EB) lithography and EB evaporation was used to form Au (30 nm)/Ti (50 nm) electrodes numbered from 1 to 6 in Fig. 1(a) on both graphene and NbSe₂ flakes. The Au/Ti electrode number 5 was broken during metal lift-off process, thus did not use for the measurement. The fabrication was carried out without introducing any heat treatment to avoid degrading the NbSe₂ flake [21,24]; **using same fabrication procedure, high quality NbSe₂-based vdW junction without any oxidation at interface has been previously demonstrated** [21]. To measure the current–voltage (I – V) characteristics of the NbSe₂, the current I was applied between the contacts, and then, the voltage difference was measured using a voltmeter with four-terminal geometry when there was a voltage drop within the NbSe₂. For the dV/dI measurement, ac-current $I_{AC} = 10$ nA with a frequency of 18 Hz was applied, and then ac-voltage was measured using a lock-in amplifier. The back-gate voltage (V_{BG}) was applied to the highly doped-Si substrate to change the carrier density of graphene. The transport properties were measured using the variable temperature cryostat.

3. Results

First, we compared current–voltage (I – V) characteristics between two different geometries as illustrated in Figs. 1(b) and 1(c); here we illustrated the direction of current flow in NbSe₂ and the

position of electrical contacts to detect the voltage drop within NbSe₂ layer. These geometries are current application with the graphene electrode (Fig. 1(b)) and with the metal (Au/Ti) electrode (Fig. 1(c)). For current application with the graphene electrode (Fig. 1(b)), current is applied between the graphene and Au/Ti contacts (between terminals 3 and 1 in Fig. 1(a)). The electron temperature of the graphene increases significantly during the current application due to its small heat capacity and electron-phonon coupling [8,10]. The heat flow illustrated in Fig. 1(d) includes heat conduction through electron diffusion at the graphene/NbSe₂ vdW interface G_e^{vdW} , heat conduction from electron to phonon in graphene G_{ep}^{Gr} , heat conduction through phonons at the graphene/NbSe₂ vdW interface G_p^{vdW} , heat conduction between electron to phonon in NbSe₂ G_{ep}^{NS} , and heat conduction from graphene or NbSe₂ to heat the bath (SiO₂/Si substrate) via phonon. Here, we assume that electron-phonon coupling in NbSe₂ is strong enough such that they are quickly thermalized with each other. Part of the heat generated in graphene is transferred to the NbSe₂ layer through the vdW interface between graphene and NbSe₂. As can be seen from the figure, there are two possible cooling paths for the electron temperature of the graphene: electron heat transfer G_e^{vdW} and electron-phonon coupling G_{ep}^{Gr} . Through one or both of these cooling paths, the heat transferred to NbSe₂ subsequently influences the superconducting property of NbSe₂ and detected through the resistance change of NbSe₂. For current application with the metal electrode (Fig. 1(c)), the current is applied between two Au/Ti contacts (between terminals 3 and 6 in Fig. 1(c)) and the voltage difference between terminals 2 and 1 is measured. Here, temperature rise in Au/Ti during current application is negligibly small due to the large heat capacity of the Au and Ti metals. In this case, the dominant contribution of the applied current to the superconductivity of the NbSe₂ is only the conventional Oersted field effect, such that magnetic field generated by the current breaks the superconductivity when its value exceeds the critical field. By comparing the two geometries, the influence of the heat transfer at vdW interface could be determined. Note that the contact resistances between the Au/Ti and the NbSe₂ in the device shown in Fig. 1(a) are

ranged between 40–90 Ω measured by applying voltage to each of the Au/Ti contacts while other contacts are connected to electrical ground. From the quantum Hall effect measurement, the contact resistance of NbSe₂/graphene contacts is determined smaller than $\sim 50 \Omega$ (see Appendix A).

The I - V curves measured in different geometries obtained from mono-layer graphene/NbSe₂ device are shown in Fig. 2(a). In the figure, the measurement results at 2.0 K and 7.8 K are plotted as solid and dashed black lines, respectively. Here, 2.0 K and 7.8 K are below and above the critical temperature $T_c \sim 6.8$ K of NbSe₂, respectively. We set $V_{BG} = -50$ V to ensure highly hole-doped graphene. In both geometries, when increasing current at 2.0 K, measured voltage (or resistance of the NbSe₂) deviates from zero to finite value above their critical current I_c ; suggesting breakdown of the superconductivity. With further increase of the current, NbSe₂ turns into the normal-metal state and the I - V curve follows a linear relationship. We note that the I - V curves for the normal states are identical to that measured at 7.8 K, which is a higher temperature than the critical temperature T_c of NbSe₂. Noticeably, we obtained significantly different critical current (I_c) values between the two geometries such that $I_c \sim 400 \mu\text{A}$ for current application with the graphene electrode and $I_c \sim 0.95 \text{ mA}$ for current application with the metal electrode. Further, the I_c values measured with different voltage probe configurations are compared and the results are presented in Figs. 2(b) and 2(c) for current application with graphene and metal contacts, respectively (I - V curves measured using different voltage probe configurations are presented in the Appendix B). The I_c values are nearly the same under the same current application geometry irrespective to the voltage probe configurations. We identified that I_c is smaller for current application with the graphene electrode than that with the metal electrode. These results suggest that the graphene vdW contact strongly influences the superconducting property of the NbSe₂. The critical current density is calculated as $8 \times 10^5 \text{ A/cm}^2$ for the current application with the metal electrode. The critical current density measured with this contact geometry is in good agreement with that typically observed in NbSe₂ due to the Oersted field effect of the current [25].

The resistance of graphene electrode can be significantly tuned by V_{BG} . The I - V curves measured at 2.0 K with different V_{BG} values are compared in both contact geometries and the results are shown in Fig. 3(a) and 3(b). In Fig. 3(a), I - V curves measured at different V_{BG} values are plotted for current application with the graphene electrode. We observed a significant change of I - V curves with varying V_{BG} . I_c is larger at $V_{\text{BG}} \pm 50$ V and it exhibits a significant drop when $V_{\text{BG}} \approx 0$ V. In contrast, we did not observe a noticeable difference between the I - V curves measured at different V_{BG} values for the current application with the metal electrode as shown in Fig. 3(b). The change of I_c with V_{BG} for current application with the graphene electrode can be more clearly seen in Fig. 3(c), where I_c vs. V_{BG} is plotted at 2.0 K. We demonstrated the lowest I_c of ~ 100 μA at $V_{\text{BG}} = 0$ V, which is nearly an order of magnitude reduction for I_c compared to the current application with the metal electrode (Fig. 3(c)). For comparison, the V_{BG} dependence of the two-terminal resistance of graphene is determined by applying a current between terminals 3 and 1, and measuring the voltage between terminals 2 and 1 and the result is shown in Fig. 3(d) (measurement geometry is also depicted in the inset of the figure). It shows the ambipolar modulation of the graphene's resistance with charge neutrality point at $V_{\text{BG}} \sim 0$ V. We found that Figs. 3(c) and 3(d) indicate good agreement with each other. This suggests that the modulation of I_c with V_{BG} for current application with the graphene electrode is originated from the change of the resistance of graphene electrode. These results contrast with the relation between I_c and V_{BG} for the case of current application with the metal contact as shown in Fig. 3(e). The result shows an $I_c \sim \pm 0.95$ mA irrespective of V_{BG} ; therefore, we think there is no apparent electric field effect in this case. This seems to be in good coincidence with the fact that the electric field effect on the Au/Ti is negligibly small in the V_{BG} range we applied.

From these results, we infer that the resistance of the graphene contact plays a significant role for the reduction and the V_{BG} modulation of the I_c . Different resistances of the graphene contact result in different amounts of Joule heating under the application of current. Therefore, we estimated the total power P injected into the graphene with the measurement geometry shown

in Fig. 4(a) (note that this is same geometry as Fig. 3(d)). In this geometry, contact resistances of Au/Ti/graphene, NbSe₂/graphene contacts, and resistance of graphene are measured in series. However, since these contact resistances are much smaller than the resistance of graphene, most of the injected power is dissipated in the graphene region (see Appendix A). The I - V curves measured in different V_{BG} values are shown in Fig. 4(b). The curves are offset for clarity with the dashed lines denoting the $V = 0$ V levels for each curve. From these I - V curves, current I dependence of the injected power $P = I \times V$ for different V_{BG} values are determined and plotted in Fig. 4(c); P quadratically increases with increasing I . When V_{BG} is changed from ± 50 V to 0 V, P increases more rapidly with I . On each curve, we marked the point for $P = 50$ μ W with solid circles for clarity. Since the resistance of graphene increases as it approaches its charge neutrality point, the current value I for the same injected power P becomes lower towards $V_{\text{BG}} = 0$ V and higher towards $V_{\text{BG}} = \pm 50$ V. The current values I for the same injected powers of $P = 25, 50,$ and 75 μ W are plotted for different V_{BG} in Fig. 4(d). For comparison, the change of I_c of the NbSe₂ layer with respect to V_{BG} for current application with the graphene electrode at 2.0 K (data presented in Fig. 3(c)) was plotted together. The I_c vs. V_{BG} data shows good agreement with the current value for the constant power of $P = 50$ μ W. Therefore, it is suggested that the breakdown of superconductivity in NbSe₂ with current application with the graphene electrode is determined by the injected power. This is in contrast from conventional current-induced breakdown of superconductivity, where breakdown is determined by the critical current density. These results suggest that the breakdown of superconductivity in NbSe₂ with current application with the graphene electrode is due to the heating of the graphene electrode.

By changing the measurement temperature, the phonon temperature of both graphene and NbSe₂ is controlled. Thus, the temperature dependence of I - V curve provides us with information on the **contribution of phonon temperature**. In Figs. 5(a)-5(c), the temperature dependence of I - V curves measured with V_{BG} values of $-50, -15,$ and 0 V are shown. Irrespective of the V_{BG} value, I_c

decreases as the measurement temperature approaches the critical temperature T_c of NbSe₂ (~ 6.8 K). Similarly to the previous section, we extracted power injected in the graphene, P , as a function of injected current I at each V_{BG} and temperature. Then, the $I-V$ curves in Figs. 5(a)-5(c) are replotted as $P-V$ as shown in Figs. 5(d)-5(f). In the figure, $+P$ denotes the injected power for current flow from NbSe₂ to graphene and $-P$ denotes the injected power for current from graphene to NbSe₂. The overall changes of the $P-V$ curve in Figs. 5(d)-5(f) are nearly identical irrespective of the V_{BG} values. This suggests that the current-induced breakdown of the NbSe₂ in this case is solely determined by the electron heating of graphene within the measurement temperature range for both doped graphene (V_{BG} is away from 0 V) and charge-neutral graphene ($V_{BG} = 0$ V) case. From Figs. 5(d)-5(f), critical power P_c is defined such that above this power value, the measured voltage (or resistance of the NbSe₂) deviates from zero to a finite value (e.g. P_c values for the case of positive P is indicated by the arrows in the figure). Then, the P_c as a function of temperature T is plotted for different V_{BG} values of -50 , -15 , and 0 V in Fig. 5(g). For all the V_{BG} values, the P_c decreases with increasing temperature and shows similar temperature dependence.

Finally, we present the data obtained from the bilayer-graphene/NbSe₂ and the 8-graphene/NbSe₂ devices in Figs. 6. The device photographs of each devices are shown in Figs. 6(a) and 6(e), respectively. The $I-V$ curves shown in Figs. 6(b) and 6(f) measured at different V_{BG} values demonstrate gate modulation of I_c for bilayer graphene/NbSe₂ and 8-layer graphene/NbSe₂ device, respectively. The V_{BG} dependences of I_c for each device are summarized in Figs. 6(c) and 6(g), respectively. These change of I_c are showing good coincidence with the V_{BG} dependence of the resistance of bilayer graphene or 8-layer graphene electrode shown in Figs. 6(d) and 6(h), respectively. The smallest critical current density demonstrated in bilayer-graphene/NbSe₂ and the 8-graphene/NbSe₂ devices are calculated to be 1.7×10^4 and 3.3×10^4 A/cm², respectively. These results demonstrate that not only the mono-layer graphene electrode, but also bilayer or few-layer graphene electrode exhibits significant heat transfer effect across the vdW interface.

We think this is a consequence of the small electron-phonon coupling of both monolayer graphene and few-layer graphene [26]; thus their electron temperature can be easily increase under the application of current [27] and influence the superconductivity of adjacent NbSe₂ layer. In total, we have measured three monolayer graphene/NbSe₂ devices, one bilayer graphene/NbSe₂ device, and one 8-layer graphene/NbSe₂ device. In all the devices, we observed significant reduction of I_c in NbSe₂ flake compared to its bulk value as well as the gate modulations of I_c when current is applied from graphene electrode; therefore, these results demonstrate the robustness of the heat transfer effect at graphene/NbSe₂ vdW interface.

4. Conclusion

We performed systematic comparisons of the superconducting critical current of an NbSe₂ flake when current is applied with a Au/Ti contact and with a graphene vdW contact. We found that the superconducting critical current is significantly reduced when the current is applied with the graphene vdW contact compared with that applied with the Au/Ti contact. Moreover, we demonstrated that the critical current of NbSe₂ is significantly altered by the gate voltage when the current is applied with the graphene vdW contact. These results are attributed to the significant heat transfer from the graphene electrode under the application of current. When using graphene as an electrode, it is necessary to consider the potential change of the superconducting property of NbSe₂ caused by the increase in the electron temperature of the graphene.

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Appendix A: Estimation of contact resistances at Ti/graphene and NbSe₂/graphene junctions

To estimate the contact resistance contribution of the Au/Ti/graphene and the NbSe₂/graphene junctions, the following procedure has been used. The two-terminal resistance of graphene R_{2T} vs. V_{BG} are measured under the magnetic field of 8.5 T applied perpendicular to the plane and data is shown in Fig. 7(a). (Measurement configuration is same as shown in Fig. 3(d) of the main text). Well-defined quantum Hall plateaus are visible at the V_{BG} values of -4, 7, 17, and 27 V. These corresponds to a filling factor $\nu = 2, 6, \text{ and } 10$, respectively. Other plateaus were not clearly visible and thus did not used for the analysis. Within the quantum Hall plateau, R_{2T} can be described as $R_{2T}=(R_K/\nu)+R_c$, where $R_K= 25812.807 \ \Omega$ denotes the von Klitzing constant, ν the filling factor, R_c the total resistances contribution of graphene/NbSe₂ contact, Au/Ti/graphene contact, and lead resistance of Au/Ti. The deviation from R_K/ν at each of quantum Hall plateau gives us the estimation of R_c and it is plotted in Fig. 7(b). The determined R_c value does not significantly change with the V_{BG} .

Appendix B: I - V curves of NbSe₂ flake obtained from different voltage probe configurations

I - V curves measured on NbSe₂ flakes are presented in Fig. 8. The contact electrode numbers are shown in Fig. 1(a). In Fig. 8(a), I - V curves are displayed for the current applied with graphene electrode (dc current is applied between contacts 3 and 1 in Fig. 1(a)). Different pairs of contacts are used for measuring voltage. In Fig. 8(b), I - V curves are displayed for current applied with the metal electrode (dc current is applied between contacts 3 and 6 in Fig. 1(a)). Similar to Fig. 1(b), voltage measured with different pairs of contacts are displayed. Both Figs. 8(a) and 8(b) show that the critical current I_c for the breakdown of superconductivity does not depend on the measurement voltage configuration.

References

- [1] X. Cui, G.-H. Lee, Y. D. Kim, G. Arefe, P. Y. Huang, C.-H. Lee, D. A. Chenet, X. Zhang, L. Wang, F. Ye, F. Pizzocchero, B. S. Jessen, K. Watanabe, T. Taniguchi, D. A. Muller, T. Low, P. Kim, and J. Hone, *Nat. Nanotechnol.* **10**, 534 (2015).
- [2] Y. Liu, H. Wu, H.-C. Cheng, S. Yang, E. Zhu, Q. He, M. Ding, D. Li, J. Guo, N. O. Weiss, Y. Huang, and X. Duan, *Nano Lett.* **15**, 3030 (2015).
- [3] R. A. Doganov, E. C. T. O'Farrell, S. P. Koenig, Y. Yeo, A. Ziletti, A. Carvalho, D. K. Campbell, D. F. Coker, K. Watanabe, T. Taniguchi, A. H. C. Neto, and B. Ozyilmaz, *Nature Commun.* **6**, (2015).
- [4] Y. Cao, A. Mishchenko, G. L. Yu, E. Khestanova, A. P. Rooney, E. Prestat, A. V. Kretinin, P. Blake, M. B. Shalom, C. Woods, J. Chapman, G. Balakrishnan, I. V. Grigorieva, K. S. Novoselov, B. A. Piot, M. Potemski, K. Watanabe, T. Taniguchi, S. J. Haigh, A. K. Geim, and R. V. Gorbachev, *Nano Lett.* **15**, 4914 (2015).
- [5] F. Withers, O. Del Pozo-Zamudio, A. Mishchenko, A. P. Rooney, A. Gholinia, K. Watanabe, T. Taniguchi, S. J. Haigh, A. K. Geim, A. I. Tartakovskii, and K. S. Novoselov, *Nature Mater.* **14**, 301 (2015).
- [6] W. J. Yu, Z. Li, H. Zhou, Y. Chen, Y. Wang, Y. Huang, and X. Duan, *Nat. Mater.* **12**, 246 (2013).
- [7] R. Moriya, T. Yamaguchi, Y. Inoue, S. Morikawa, Y. Sata, S. Masubuchi, and T. Machida, *Appl. Phys. Lett.* **105**, 083119 (2014).
- [8] F. H. L. Koppens, T. Mueller, P. Avouris, A. C. Ferrari, M. S. Vitiello, and M. Polini, *Nat. Nanotechnol.* **9**, 780 (2014).
- [9] Y. D. Kim, H. Kim, Y. Cho, J. H. Ryoo, C.-H. Park, P. Kim, Y. S. Kim, S. Lee, Y. Li, S.-N. Park, Y. Shim Yoo, D. Yoon, V. E. Dorgan, E. Pop, T. F. Heinz, J. Hone, S.-H. Chun, H. Cheong, S. W. Lee, M.-H. Bae, and Y. D. Park, *Nat. Nanotechnol.* **10**, 676 (2015).
- [10] K. C. Fong, E. E. Wollman, H. Ravi, W. Chen, A. A. Clerk, M. D. Shaw, H. G. Leduc, and K. C. Schwab, *Phys. Rev. X* **3**, 041008 (2013).
- [11] K. J. Tielrooij, J. C. W. Song, S. A. Jensen, A. Centeno, A. Pesquera, A. Zurutuza Elorza, M. Bonn, L. S. Levitov, and F. H. L. Koppens, *Nat. Phys.* **9**, 248 (2013).
- [12] Q. Ma, T. I. Andersen, N. L. Nair, N. M. Gabor, M. Massicotte, C. H. Lui, A. F. Young, W. Fang, K. Watanabe, T. Taniguchi, J. Kong, N. Gedik, F. H. L. Koppens, and P. Jarillo-Herrero, *Nat. Phys.* **12**, 455 (2016).
- [13] R. Yu, A. Manjavacas, and F. J. García de Abajo, *Nat. Commun.* **8**, 2 (2017).
- [14] M. Massicotte, P. Schmidt, F. Violla, K. Watanabe, T. Taniguchi, K. J. Tielrooij, and F. H. L. Koppens, *Nat. Commun.* **7**, 12174 (2016).
- [15] S.-J. Liang, B. Liu, W. Hu, K. Zhou, and L. K. Ang, *Sci. Rep.* **7**, 46211 (2017).
- [16] H. Sadeghi, S. Sangtarash, and C. J. Lambert, *2D Mater.* **4**, 015012 (2017).
- [17] H. Vora, P. Kumaravadivel, B. Nielsen, and X. Du, *Appl. Phys. Lett.* **100**, 153507 (2012).
- [18] I. V. Borzenets, U. C. Coskun, H. T. Mebrahtu, Y. V. Bomze, A. I. Smirnov, and G. Finkelstein, *Phys. Rev. Lett.* **111**, 027001 (2013).
- [19] J.-H. Choi, H.-J. Lee, and Y.-J. Doh, *J. Korean Phys. Soc.* **57**, 149 (2010).
- [20] D. K. Efetov, L. Wang, C. Handschin, K. B. Efetov, J. Shuang, R. Cava, T. Taniguchi, K. Watanabe, J. Hone, C. R. Dean, and P. Kim, *Nat. Phys.* **12**, 328 (2016).

- [21] N. Yabuki, R. Moriya, M. Arai, Y. Sata, S. Morikawa, S. Masubuchi, and T. Machida, *Nat. Commun.* **7**, 10616 (2016).
- [22] Y. Sata, R. Moriya, S. Masubuchi, K. Watanabe, T. Taniguchi, and T. Machida, *Jpn. J. Appl. Phys.* **56**, 04CK09 (2017).
- [23] A. Castellanos-Gomez, M. Buscema, R. Molenaar, V. Singh, L. Janssen, H. S. J. van der Zant, and G. A. Steele, *2D Mater.* **1**, 011002 (2014).
- [24] Y. Yamasaki, R. Moriya, M. Arai, S. Masubuchi, S. Pyon, T. Tamegai, K. Ueno, and T. Machida, *2D Mater.* **4**, 041007 (2017).
- [25] Z. Zhou, R. Jin, G. Eres, D. Mandrus, V. Barzykin, P. Schlottmann, Y.-S. Hor, Z. Xiao, and J. F. Mitchell, *Phys. Rev. B* **76**, 104511 (2007).
- [26] C.-H. Park, F. Giustino, M. L. Cohen, and S. G. Louie, *Nano Lett.* **8**, 4229 (2008).
- [27] D. Brunel, S. Berthou, R. Parret, F. Vialla, P. Morfin, Q. Wilmart, G. Fève, J. M. Berroir, P. Roussignol, C. Voisin, and B. Plaçais, *J. Phys.: Condens. Matter* **27**, 164208 (2015).

Figure captions

Figure 1 (a) Optical micrograph of the fabricated device. (b,c) Schematic illustration of the graphene/NbSe₂ device structure with different current application geometries. Arrows indicate the flow of current. (b) Current application with graphene electrode. (c) Current application with Au/Ti metal electrode. (d) Diagram of heat flow in the device. p denotes the injected power density to the electrons of the graphene due to Joule heating, G_e^{vdW} the heat conduction through electron at graphene/NbSe₂ vdW interface, $G_{\text{ep}}^{\text{Gr}}$ the heat conduction from electrons to phonons in graphene, G_p^{vdW} the heat conduction through phonons at graphene/NbSe₂ vdW interface, $G_{\text{ep}}^{\text{NS}}$ the heat conduction between electrons to phonons in NbSe₂, and the heat conduction from graphene or NbSe₂ to SiO₂/Si substrate heat bath via phonons. (e) Schematic illustration of graphene/NbSe₂ vdW interface.

Figure 2 (a) Current–voltage (I – V) curves for different measurement configurations; current application with the graphene electrode or application with the metal electrode at $V_G = -50$ V. Data obtained from temperatures $T = 2.0$ and 7.8 K are presented. Measurements are performed under zero magnetic fields. (b) Critical current I_c values for the current application with the graphene electrode at 2 K with different voltage probe configuration. (c) Critical current I_c values for the current application with the metal electrode at 2 K and $V_{\text{BG}} = -50$ V with different voltage probe configurations.

Figure 3 (a) I – V curves at 2 K at various back-gate voltages V_{BG} measured with current application with the graphene (Gr.) electrode. The curves are offset for clarity and dashed lines indicate offset values. (b) I – V curves at 2 K at various V_{BG} measured with current application with the metal electrode. The curves are offset for clarity and dashed lines indicate offset values. (c) V_{BG} dependence of critical current I_c for current application with the graphene contact. (d) V_{BG} dependence of the two-terminal resistance of the graphene measured at 2.0 K. Inset: illustration of the measurement configuration. (e) V_{BG} dependence of critical current I_c for current application with the metal contact.

Figure 4 (a) The measurement geometry of the voltage probes. (b) I – V curves at 2 K at various back-gate voltages V_{BG} measured with current application with the graphene electrode. The curves are offset for clarity and dashed lines indicate offset values. (c) Current I dependence of the power P injected to the device measured at different V_{BG} . The curves are offset for clarity and

dashed lines indicate offset values. (d) Plot of I values for constant injected powers of $P = 25, 50,$ and $75 \mu\text{W}$. In comparison, V_{BG} dependence of I_c is plotted with circles.

Figure 5 (a-c) I - V curves obtained at different temperatures of 2.0 K, 4.8 K, 5.8 K, and 7.8 K for current application with the graphene electrode at different V_{BG} values of (a) -50 V, (b) -15 V, and (c) 0 V. (d-f) P - V curves obtained at different temperatures of 2.0 K, 4.8 K, 5.8 K, and 7.8 K for current application with the graphene electrode at different V_{BG} values of (d) -50 V, (e) -15 V, and (f) 0 V. Critical power P_c values for positive P are indicated by arrows. (g) Critical power P_c with respect to the temperature T obtained for different values of V_{BG} .

Figure 6 (a-d) Data obtained from bilayer graphene(BLG)/51-nm-thick NbSe₂ device. (a) Optical micrograph. (b) I - V curves at 2 K at various back-gate voltages V_{BG} measured with current application with the bilayer graphene electrode. (c) V_{BG} dependence of critical current I_c for current application with the bilayer graphene contact at 2.0 K. (d) V_{BG} dependence of the resistance of the bilayer graphene measured at 2.0 K. (e-h) Data obtained from 8-layer graphene(8LG)/40-nm-thick NbSe₂ device. (e) Optical micrograph. (f) I - V curves at 2 K at various back-gate voltages V_{BG} measured with current application with the 8-layer graphene electrode. (g) V_{BG} dependence of critical current I_c for current application with the 8-layer graphene contact at 2.0 K. (h) V_{BG} dependence of the resistance of the 8-layer graphene measured at 2.0 K.

Figure 7 (a) Two-terminal differential resistance dV/dI of a graphene as a function of V_{BG} measured with the geometry shown in Fig. 3(d). Measurement temperature was 2 K and magnetic field of 8.5 T was applied perpendicular to the sample plane. (b,c) Closeup of the Fig. 7(a). (d) Total contact resistance contribution R_c of the Au/Ti/graphene and the NbSe₂/graphene junctions determined for different V_{BG} values.

Figure 8 (a) Current-voltage (I - V) curves for different voltage measurement configurations for current application with the graphene electrode at $V_G = -50$ V at 2.0 K. (b) Current-voltage (I - V) curves for different voltage measurement configurations for current application with the metal electrode at $V_{\text{BG}} = -50$ V at 2.0 K. Arrows indicate sweep direction of current I .

Figure 1

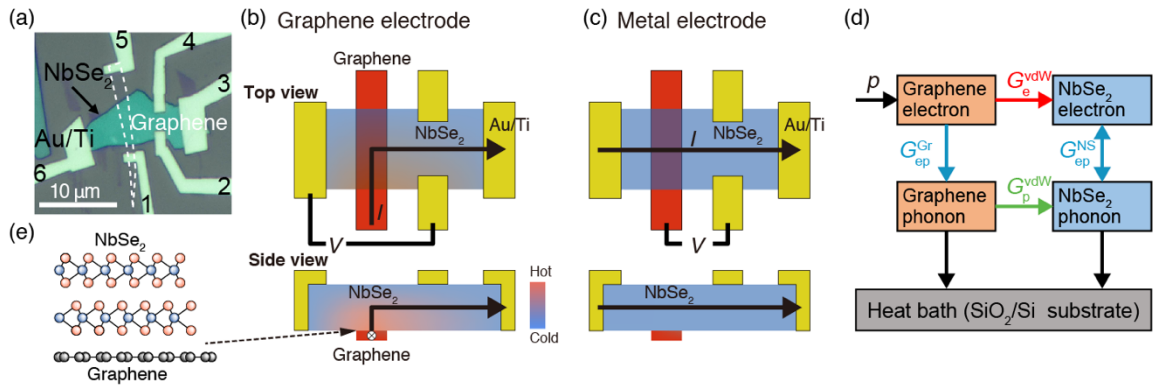


Figure 2

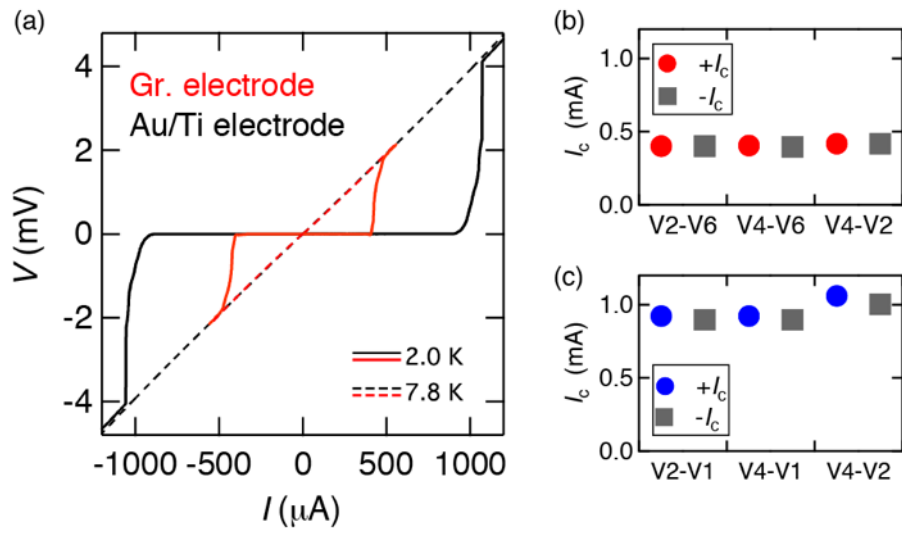


Figure 3

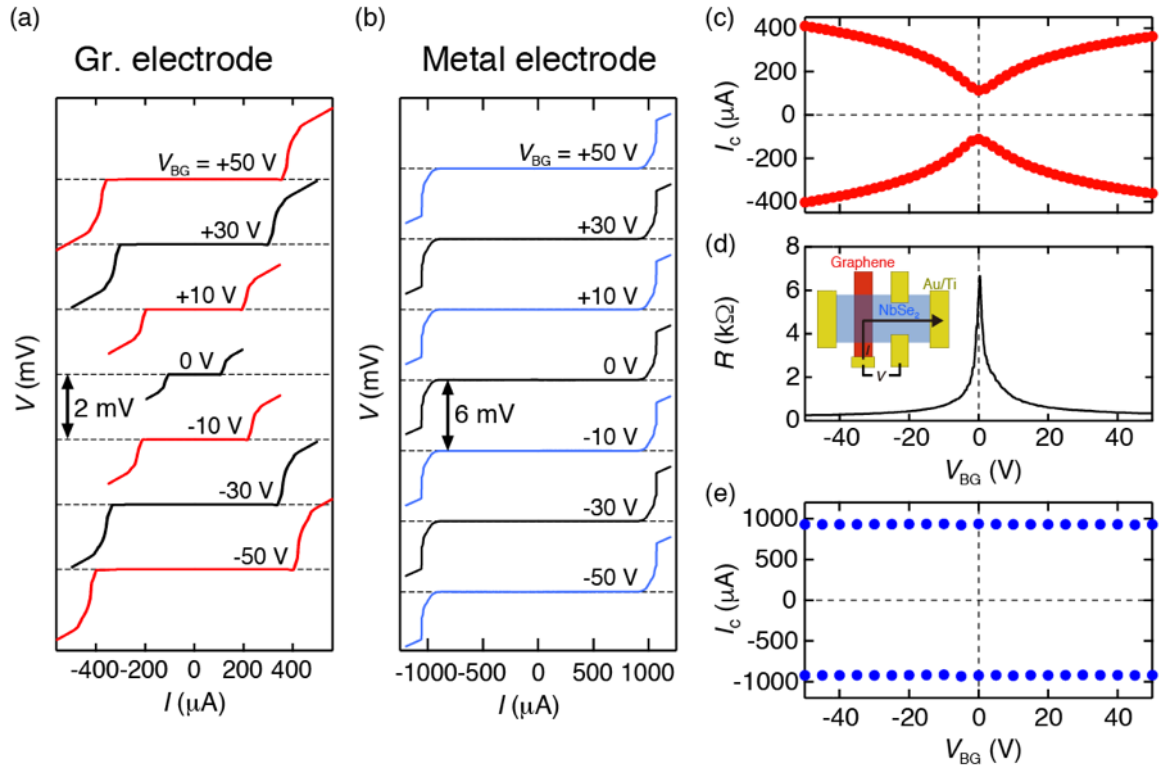


Figure 4

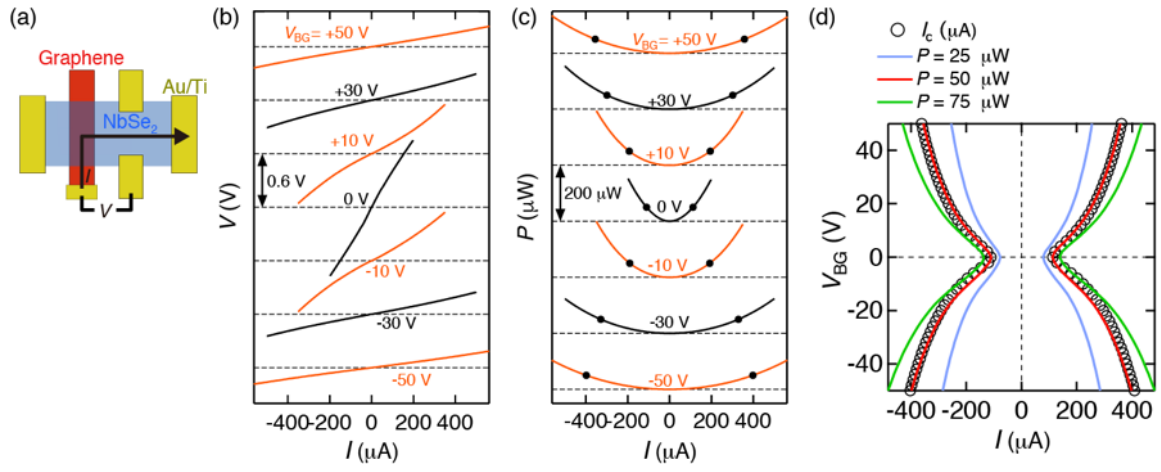


Figure 5

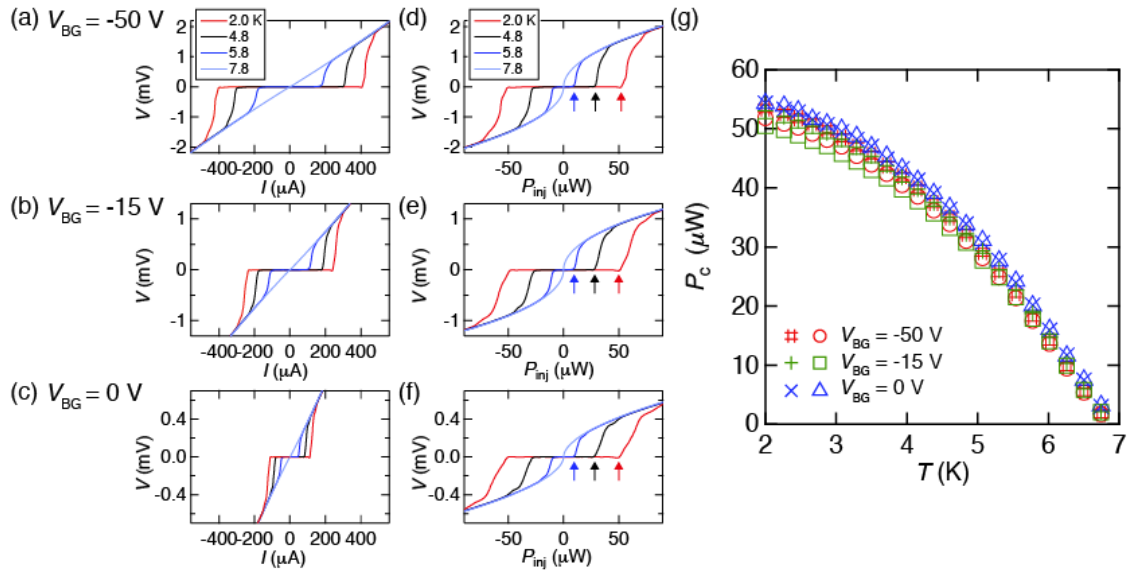


Figure 6

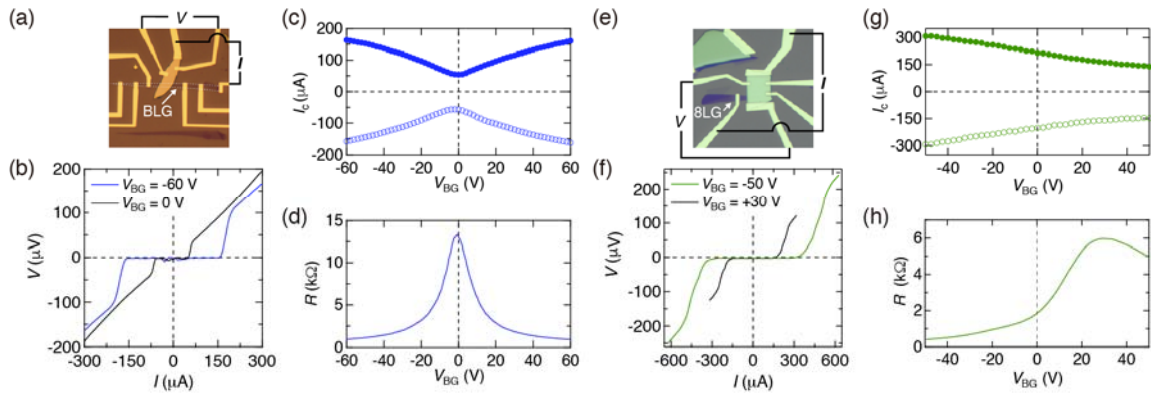


Figure 7

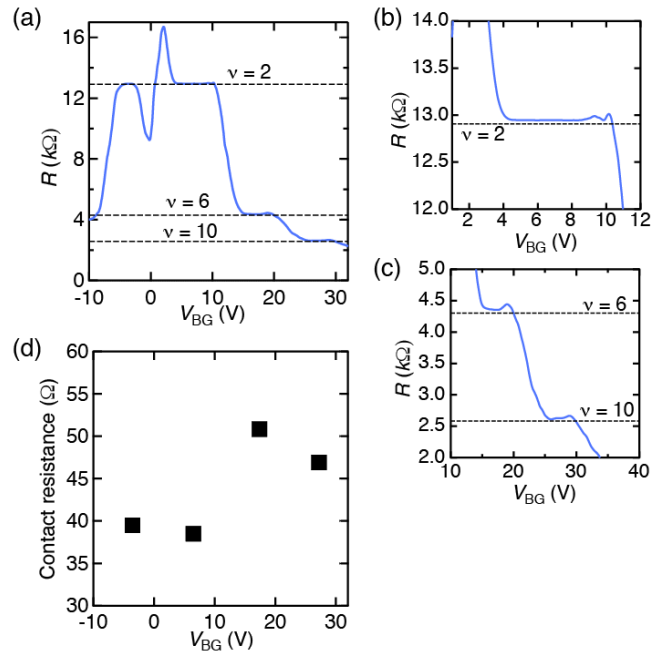


Figure 8

