Impact of Impurities on the Electrical Conduction of Anisotropic 2D Materials

Sun, Jianbo; Passacantando, Maurizio; Palummo, Maurizia; Nardone, Michele; Kaasbjerg, Kristen; Grillo, Alessandro; Di Bartolomeo, Antonio; Caridad, Jose; Camilli, Luca

Published in:
Physical Review Applied

Publication date:
2020

Document Version
Early version, also known as pre-print

Link back to DTU Orbit

Citation (APA):

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.
Impact of Impurities on the Electrical Conduction of Anisotropic 2D Materials

Jianbo Sun,1 Maurizio Passacantando,2 Maurizia Palummo,3,4 Michele Nardone,2 Kristen Kaasbjerg,1 Alessandro Grillo,5 Antonio Di Bartolomeo,5 José M. Caridad1,† and Luca Camilli1,4,*

1Department of Physics, Technical University of Denmark, Ørsteds Plads, 2800, Kgs. Lyngby, Denmark
2Dipartimento di Scienze Fisiche e Chimiche, Università di L’Aquila, via Vetoio, Coppito, 67100 L’Aquila, Italy
3INFN, Section at Roma “Tor Vergata”, Via della Ricerca Scientifica 1, 00133 Roma, Italy
4Dipartimento di Fisica, Università degli studi di Roma “Tor Vergata”, Via della Ricerca Scientifica 1, 00133 Roma, Italy
5Physics Department “E. R. Caianiello”, University of Salerno, Via Giovanni Paolo II n. 132, Fisciano 84084, Italy and CNR-SPIN Salerno, Via Giovanni Paolo II n. 132, Fisciano 84084, Italy
†: jcar@dtu.dk; *: lcam@dtu.dk

Abstract

Anisotropic two-dimensional materials possess intrinsic angle-dependent physical properties that originate from their low crystal symmetry. Yet, how these properties are affected by external impurities or structural defects in the material is still wholly unclear. Here, we address this question by investigating the electrical transport in the anisotropic layered model system germanium arsenide. First, we show that the ratio of conductivities along the armchair and zigzag crystallographic directions exhibits an intriguing dependence with respect to both temperature and
carrier density. Then, by using a conceptually-simple model, we demonstrate that this unexpected behavior is directly related to the presence of impurity-induced localized states in the bandgap that introduce isotropic hopping conduction. The presence of this conduction mechanism in addition to the intrinsic band conduction significantly influences the anisotropic electrical properties of the material, especially at room temperature, i.e. at application-relevant conditions.

I. INTRODUCTION

Anisotropic two-dimensional (2D) materials represent a unique class of materials with low crystal symmetry and strong anisotropic physical properties. [1] They have recently attracted a great deal of interest as they hold promises for the realization of conceptually-novel angle-dependent devices, such as digital inverters, [2,3] polarization-sensitive photodetectors [4,5] and thermoelectric devices. [1] In addition to the largely studied black phosphorus, [6] a vast number of anisotropic 2D materials have been explored recently, including for instance group IV monochalcogenide (e.g., GeS [7]), low-symmetry transition metal dichalcogenides (e.g., ReS$_2$ [8]), low-symmetry metal chalcogenide(s) (e.g., GaTe [9]) and the most recently discovered group IV-V compounds (e.g., GeAs [10,11], GeP [12]). Due to their ultrathin nature, the physical properties of anisotropic 2D materials are expected to be highly sensitive to inevitable structural defects and extrinsic charged impurities [13] as well as to many other factors, e.g., substrates, environment and surface roughness. [14] In particular, it is reasonable to believe that these extrinsic elements will significantly alter the intrinsic electrical anisotropic conduction in these materials. Such information is of course crucial for exploiting anisotropic 2D materials in practical applications, and yet our understanding of this topic is currently inadequate. [6,15–17] Filling this knowledge gap is the objective of this work. To this aim, we fabricate field-effect devices made from the model anisotropic layered system GeAs. GeAs exhibits a high anisotropy ratio [10,11] (more than 3 times
larger than black phosphorous) and a band gap relevant for optoelectronic applications (~0.5 eV for bulk and ~2 eV for monolayer). [18–21] We show that below 180 K the electron transport is mainly due to variable range hopping (VRH) via localized states in the bandgap created by impurities, while band conduction in the material plays a dominant role only at higher temperatures due to the thermal activation of free carriers (holes) into the valence band. Interestingly, the conductivity ratio along the two main crystallographic directions of the material, key parameter defining the anisotropy of the system, varies non-trivially with respect to both temperature and carrier density. By using a simple model, we demonstrate that this behavior is due to the coexistence of VRH and band conduction in the system.

II. EXPERIMENT METHOD

Layered GeAs crystalizes in the monoclinic structure in the space group C/2m (C2h) as shown in Fig. 1(a). [22] In order to measure the resistivity along the main crystallographic armchair and zigzag directions (\( \rho_{ac} \) and \( \rho_{zz} \)), we fabricated field-effect transistor (FET) devices that are deliberately oriented by an angle \( \theta \) relative to the crystallographic axes. The optical image of a typical device with a rotation angle of 51° is shown in Fig. 1(b). In this configuration, the non-zero off-diagonal component in the rotated resistivity tensor [23]

\[
\begin{pmatrix}
\rho_{xx} & \rho_{xy} \\
\rho_{yx} & \rho_{yy}
\end{pmatrix}
= \begin{pmatrix}
(\rho_{ac} \cos^2(\theta) + \rho_{zz} \sin^2(\theta)) & (\rho_{ac} - \rho_{zz}) \cos(\theta) \sin(\theta) \\
(\rho_{ac} - \rho_{zz}) \cos(\theta) \sin(\theta) & \rho_{zz} \cos^2(\theta) + \rho_{ac} \sin^2(\theta)
\end{pmatrix}
\]

(1)

would give rise to a transverse voltage \( V_{xy} \) when a source-drain current \( I_{sd} \) (or source drain voltage \( V_{sd} \)) is applied along the \( x \)-direction. Thus, measuring this voltage and the longitudinal one \( V_{xx} \), the longitudinal and transverse resistivity (\( \rho_{xx} \) and \( \rho_{xy} \)) can be determined. Consequently, \( \rho_{ac} \) and \( \rho_{zz} \) can be simultaneously extracted by using the rotated resistivity tensor. This method has been applied to measure the anisotropic electrical resistivity in other 2D systems where anisotropy is given by charge density wave (CDW) ordering [23] or superimposed periodic potential

3
modulation. [24, 25] The devices were fabricated using GeAs flakes of ~12nm thickness that were exfoliated on degenerately p-doped silicon wafers with a 300 nm oxide layer on top. The rotation angles of the devices were determined using angle-resolved polarized Raman spectroscopy. More details about device fabrication and determination of the rotation angle can be found in Appendix A and the Supplemental Material [26, 27].

FIG. 1. (a) The in-plane crystal structure of GeAs (Ge, green spheres; As, purple spheres). (b) The optical image of a device with rotation angle of 51° and the electrical connection for measuring $V_{xx}$ and $V_{xy}$. 
III. RESULTS AND DISCUSSION

The extracted conductivity along the armchair and zigzag directions ($\sigma_{ac}$ and $\sigma_{zz}$) are plotted as a function of the applied gate voltage ($V_g$) in Fig. 2(a) and 2(b), respectively. Three initial observations can be made. Firstly, the conductivity along the zigzag direction is higher than that along the armchair direction. Secondly, the sample shows typical p-type semiconductor behavior along both directions. Both of these observations are consistent with previous reports on FET devices made of this material. [10, 11] Lastly, the modulation of the conductivity by $V_g$ is very weak (less than one order of magnitude) and the channel cannot be turned off within the applied gate voltage range (-60 V to +60 V). Moreover, from the data in Fig. 2(a) and 2(b), we notice that the conductivity is not linear with respect to $V_g$ in the range from -60 V to +60 V; rather, the conductivity follows a power dependence on the carrier density $n$:

$$\sigma \propto n^\alpha$$  \hspace{1cm} (2)

According to theory [28,29], $\alpha$ is expected to be (i) < 1 if short-range potential dominates the scattering of the carrier transport, and (ii) $\geq 1$ if Coulomb scattering dominates. In our case, by fitting the conductivity plots in Fig. 2(a) and 2(b) at all the measured temperatures with Eq. (2), we extract $1.2 \leq \alpha \leq 2$. These values indicate that carrier transport in our devices is dominated by Coulomb scattering introduced by the charged impurities in the system. A similar observation was reported in a previous experimental study on MoS$_2$ [30]. Furthermore, we notice that $\alpha$ shows a strong dependence on temperature, in agreement with theoretical predictions that in 2D systems the screening of the Coulomb scattering is temperature-dependent in a nontrivial way. [29, 31]
FIG. 2. The conductivity along the (a) armchair and (b) zigzag directions at different temperatures as a function of the gate voltage. The conductivity along both crystallographic directions as a function of (c) $T^{1/3}$ and (d) $T^{-1}$. (e) Schematic illustration of the VRH via localized states in the bandgap and the thermal activation of the free carriers (holes) into the valence band in disordered systems.

The temperature-dependence of the conductivity at a constant gate voltage further emphasizes the cause for the observed gate-dependence of the conductivity. As shown in Fig. 2(c) for $V_g = 0$ V, at low temperatures ($T < 180$ K), $\sigma_{ac}$ and $\sigma_{zz}$ follow a linear dependence on $T^{1/3}$. This is a clear signature of variable range hopping (VRH) transport via localized states as described by the 2D Mott’s formalism [28]

$$\sigma \sim \exp \left[ -\left( \frac{T_0}{T} \right)^{1/3} \right]$$  \hspace{1cm} (3)
in which $T_0$ corresponds to the correlation energy scale. [32] The fact that the data can be well fitted with the 2D Mott’s formalism is a further proof that our materials effectively behaves as a 2D conductor. VRH transport normally occurs in polycrystalline crystals [32] and organic materials, [33] but has also been observed in many other 2D materials with a notable density of defects, such as MoS$_2$, [30,34] black phosphorus [35] and other group IV-V compound 2D materials. [22] The observation of VRH confirms the presence of impurities in the studied system, which is nonetheless expected for 2D materials which, like GeAs, are not very stable in air. [10] Nevertheless, other effects, for instance vacancies or presence of trapped states at the interface with substrate, could also play a role.

At higher temperature ($T > 180$ K), $\sigma_{ac}$ and $\sigma_{zz}$ instead show an exponential decrease proportional to $T^{-1}$ as shown in Fig. 2(d). This indicates the thermal activation of carriers (holes) from localized states in the bandgap to the valence band in our devices, leading to a band conduction regime described by the expression [36]

$$\sigma = \sigma_0 \exp \left(-\frac{E_a}{k_B T} \right)$$

where $E_a$ is the activation energy, $k_B$ is the Boltzmann constant and $\sigma_0$ is a fitting parameter. Fig. 2(e) illustrates schematically both conduction mechanisms observed in these samples, namely VRH via localized states and band conduction due to the thermal activation of the free carriers to the valence band.

Next, we focus our attention on the ratio ($\sigma_{zz}/\sigma_{ac}$) of conductivities along zigzag and armchair directions. This ratio is the key performance indicator of the electrical conduction in anisotropic materials. It provides information on the effective anisotropic transport achieved in real devices, accounting for both the intrinsic anisotropy conduction expected due to the crystal structure, and the conduction due to the presence of impurities. To a first approximation, electrical transport in semiconductors with band edge conduction will take place exclusively around the conduction band.
minimum (CBM for n-type semiconductors) or valence band maximum (VBM for p-type semiconductors). Thus, according to the Drude’s model [37]

\[ \sigma = \frac{e^2 \tau}{m^*} \]

(5)

and assuming a relaxation time of free carriers \( \tau \) and the carrier density in band conduction \( n_{band} \) independent of the lattice direction, the conductivity ratio in intrinsic anisotropic materials should be constant and given by the ratio of the effective masses \( m^* \) along the two crystallographic directions (here the effective masses of holes along the armchair and zigzag directions, \( m_{ac}^h \) and \( m_{zz}^h \), respectively). We estimate this anisotropic conductivity ratio in GeAs by means of first-principles density functional theory (DFT) simulations. First, we calculate the band structure of bulk GeAs along the zigzag and armchair directions of the monoclinic structure. In Fig. 3(a) we show a 3D contour-plot of the dispersion relation \( E(k) \) around the valence band maximum (VBM). Here, a larger dispersion is clearly visible along the zigzag with respect to the armchair direction. The calculated effective mass of holes at the VBM is 1.5\( m_o \) (\( m_o \) being the electron rest mass) and 0.24\( m_o \) along the armchair and zigzag directions, respectively, which gives a theoretical estimation of the conductivity ratio \( \sigma_{zz}/\sigma_{ac} \) of 6.25. We note that this value is close to the one found in previous calculations [11]. Details about the atomic structure, band structure and effective masses calculation are given in the Supplemental Material [38–43].

Interestingly, our experimentally measured \( \sigma_{zz}/\sigma_{ac} \) ratio is, however, not constant and exhibits an intriguing dependence on both temperature and gate voltage. As shown in Fig. 3(b), at the highest temperature (290 K), \( \sigma_{zz}/\sigma_{ac} \) is found to be around 6, but as temperature decreases, so does \( \sigma_{zz}/\sigma_{ac} \) and tends to unity when temperature approaches 0 K.

The small \( \sigma_{zz}/\sigma_{ac} \) ratio measured at low temperature is consistent with our previous observation of isotropic VRH being the dominant transport mechanism at low temperatures, as shown in Fig. 2(c). Indeed, considering a random distribution of the impurities, it is reasonable that isotropic VRH
occurs in our devices. As temperature increases, band conduction in the material progressively becomes more dominant in comparison with VRH, which explains the measured increment of the conductivity ratio (towards the intrinsic value). Nevertheless, we emphasize that even at room temperature, i.e., at application-relevant conditions, the measured \( \sigma_{zz}/\sigma_{ac} \) is still smaller than the theoretically predicted effective mass ratio (6.25), suggesting that VRH still plays a role in the carrier transport. Moreover, the observed modulation of \( \sigma_{zz}/\sigma_{ac} \) with respect to the gate-voltage at different temperatures (Fig. 3(c)) is also consistent with VRH and band conduction transport mechanisms coexisting simultaneously in the system; at lower \( V_g \), more free carriers are injected into the valence band which eventually leads to a higher band conduction and subsequently higher conductivity ratio.

We underpin all these observations by developing a logically simple model which, accounting for the interplay between both band conduction and VRH transport mechanisms, is able to qualitatively explain the measured evolution of the conductivity ratio as a function of \( T \) and \( V_g \). In general terms, the conductivity can be described as the sum [44] of the hopping conductivity (\( \sigma^{\text{vrh}} \)) and the band conductivity [45] (\( \sigma^{\text{band}} \)) as given by the expression:

\[
\sigma(V_g) = \sigma^{\text{band}} + \sigma^{\text{vrh}} = \mu C_g |V_g - V_{th}| + \sigma^{\text{vrh}}
\]

where, \( V_{th} \) is the voltage needed to compensate the doping introduced by impurities with the gate, \( \mu \) is the mobility of the carriers and \( C_g \) is the gate capacitance per unit area. Due to the assumed random distribution of impurities in our system, we impose \( \sigma^{\text{vrh}} \) to be constant along zigzag and armchair directions, whereas \( \mu \) is different (\( \mu_{zz} \) and \( \mu_{ac} \) being the carrier mobility along the zigzag and armchair directions, respectively). Thus, the overall conductivity ratio (\( \sigma_{zz}/\sigma_{ac} \)) in the system can be written as

\[
\frac{\sigma_{zz}}{\sigma_{ac}} = \frac{e n^{\text{band}} \mu_{zz} \sigma^{\text{band}} + \sigma^{\text{vrh}}}{e n^{\text{band}} \mu_{ac} \sigma^{\text{band}} + \sigma^{\text{vrh}}}
\]
As we can see, this model (Eq. (7)) reflects well the two aforementioned limit scenarios. Assuming $\sigma^{vrh} >> \sigma^{band}$, carrier transport is dominated by VRH and $\sigma_{zz}/\sigma_{ac}$ is 1, independent of the gate-voltage (dotted lines in Fig. 3(d)). On the other hand, assuming $\sigma^{vrh} << \sigma^{band}$, $\frac{\sigma_{zz}}{\sigma_{ac}} \approx \frac{\mu_{zz}}{\mu_{ac}} = 6.25$ at any gate voltage (dashed lines in Fig. 3(d)), i.e., the electrical conduction is anisotropic as a result of the intrinsic crystal structure of the material, with $\sigma_{zz}/\sigma_{ac}$ given by the ratio of effective masses along zigzag and armchair directions. When $\sigma^{vrh}$ is comparable to $\sigma^{band}_{ac}$ and $\sigma^{band}_{zz}$, an intermediate behavior in which $\sigma_{zz}/\sigma_{ac}$ depends on the gate voltage is expected. This is indeed shown in Fig. 3(d), where we calculate without fitting parameters the conductivity ratio as a function of $V_g$. The overall calculation is in remarkable qualitative agreement with the experimentally observed $V_g$-dependence of the conductivity ratio (Fig. 3(c)). Specifically, as $V_g$ decreases towards -60 V, more free carriers are injected into the valence band which makes the contribution of $\sigma^{band}$ larger than $\sigma^{vrh}$, which leads to an increasing of the conductivity ratio. Moreover, our model can well account for the temperature-dependence of the conductivity ratio and its modulation by the gate voltage. Firstly, as shown in Fig. 3(b) and 3(c), a decrease in conductivity ratio is observed for lower temperatures, which is due to the fact that at lower temperature $\sigma^{band}$ will contribute less than $\sigma^{vrh}$ to the overall conductance, hence the conductivity ratio will tend towards unity (the case of pure VRH). At low temperatures (e.g., 10 K and 20 K), the conductivity ratio exhibits much weaker modulation by $V_g$ than those at intermediate temperatures (140 ~ 220 K). This is clearly reflected by our model, that is, at lower temperature, VRH makes a larger contribution to the overall conductivity than band conduction; as a result, the conductivity ratio exhibits much weaker modulation by $V_g$ since one conduction mechanism clearly dominates over the other. Secondly, around 200 K, the variation of the conductivity ratio for the measured $V_g$ range is the strongest. This is because here VRH and band conduction have a
comparable contribution to the overall conductivity. Finally, as temperature increases further, the modulation of the conductivity ratio decreases, because band conduction dominates the overall conductivity in this range. In Table I, we listed the contributions of VRH and band conduction to the overall conductivity at three critical temperatures (10 K, 180 K and 290 K), which correspond to the changes of the conductivity ratio as shown in Fig. 3(b). Additionally, we note that the maximum conductivity ratio measured in our devices (~6 at $T = 290$ K and $V_g = -60$ V) approaches the theoretically predicted effective mass ratio (6.25), which is also in agreement with our simple model. Details regarding the model and further comparison with experimental values are reported in Appendix B.

TABLE I. The contributions of VRH and band conduction to the overall conductivity at three critical temperatures (10 K, 180 K and 290 K) at $V_g = -60$ V.

<table>
<thead>
<tr>
<th>$T$</th>
<th>$\Delta(\sigma_{zz}/\sigma_{ac})^*$</th>
<th>zigzag VRH</th>
<th>zigzag Band conduction</th>
<th>armchair VRH</th>
<th>armchair Band conduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 K</td>
<td>0</td>
<td>40%</td>
<td>60%</td>
<td>81%</td>
<td>19%</td>
</tr>
<tr>
<td>200 K</td>
<td>0.84</td>
<td>7%</td>
<td>93%</td>
<td>30%</td>
<td>70%</td>
</tr>
<tr>
<td>290 K</td>
<td>0.57</td>
<td>1%</td>
<td>99%</td>
<td>5%</td>
<td>95%</td>
</tr>
</tbody>
</table>

* represents the difference between the conductivity ratio measured at $V_g = -60$ V and that one measured $V_g = 60$ V.
FIG. 3. (a) The 3D-plot of the energy dispersion at VBM along the armchair and zigzag directions. The conductivity ratio as a function of (b) temperature and (c) $V_g$. (d) Simulation of the conductivity ratio as a function of $V_g$.

IV. CONCLUSION

In summary, we have experimentally studied the electronic transport in transistor devices made from the anisotropic layered model system GeAs. Notably, we have first measured the conductivity along the two relevant crystallographic directions by means of the transverse voltage method in the temperature range from room temperature down to 10 K. Then, we have shown that the extracted conductivity ratio is close to the theoretically predicted value (6.25) at room temperature and high carrier densities ($V_g = -60$ V). However, rather than being constant, it exhibits a peculiar dependence with gate and temperature. This dependence has been explained by considering the coexistence of
both the intrinsic anisotropic band conduction and the isotropic VRH induced by random-distributed impurities in the material. As impurities, such as structural defects or surface contamination, are in general extremely hard to avoid in devices made of 2D materials, we expect that our results will be beneficial for the exploitation of these materials in practical applications.

ACKNOWLEDGMENT

This research is supported by the Villum Fonden through the Young Investigator Program (project No. 19130). J.M.C acknowledges financial support from the Danish National Research Foundation Center for Nanostructured Graphene project DNRF103. M.P. is grateful to INFN for financial support through the National project Nemesys and ISCRA-B initiative for granting access to computational resources on Marconi at CINECA, Italy. L.C. acknowledges support from the Italian Ministry of Education, University and Research (MIUR) via “Programma per Giovani Ricercatori - Rita Levi Montalcini 2017”.

APPENDIX A

Devices were fabricated using GeAs thin flakes (2D Semiconductors) that were mechanically exfoliated onto Si wafer with 300 nm oxide layer. The FET structures were shaped using electron beam lithography using a LEO scanning electron microscope (SEM) integrated with a Raith Elphy System, followed by dry etching with sulfur hexafluoride (SF$_6$) using a STS inductively coupled plasma system. The electrodes were fabricated using a standard lift-off process with nickel (20 nm) and gold (50 nm) that were deposited by electron beam evaporation using a Temescal E-beam evaporator. The electrical measurements were performed in an Oxford Instrument Teslatron PT cryostat. After the electrical measurement, the crystal orientation of the material was determined based on the angle-resolved polarized Raman spectrum measured using a Labram Micro Raman
apparatus by Jobin Yvon with ~ 0.3 mW, $\lambda_0 = 632$ nm excitation in backscattering geometry through a 100x long working distance objective.

APPENDIX B

In our model, we keep $\frac{\mu_{\text{band}}^{\text{band}}}{\mu_{\text{ac}}^{\text{band}}}$ constant as the theoretically value of the effective mass ratio, 6.25. $\mu_{\text{ac}}^{\text{band}}$ is taken from the experimental value at $V_g = -60$ V, which is considered to be the best approximation to the mobility of the free carriers (in band conduction) at the different temperatures. We take the residual carrier density of the material at null gate voltage (i.e., doping induced by impurities) $n_0 = C_g V_{th}$, with $V_{th}$ being the voltage needed to compensate the doping introduced by impurities. In our devices, $V_{th} \sim 140$ V is extracted by extrapolating the $\sigma$ vs $V_g$ curve at 290 K based on the quadratic fitting. Finally, $\sigma^{\text{vrh}}$ is taken as the conductivity at the VRH to band conduction transition temperature (180 K) at $V_g = 60$ V, experimental conditions with a minimal amount of free carriers induced by gate voltage and temperature.

As shown in Fig. 3(c) and 3(d), despite the simple model used, the simulation results are qualitatively in good agreement with the experimental results. At 290 K, the simulation is in quantitative agreement with experimental data. However, the calculated conductivity ratios show values higher than the experimentally measured ones at lower temperature (for instance at $T = 200$ K, the calculated $\frac{\sigma_{xx}}{\sigma_{ac}}$ at $V_g = -60$ V is $\sim 5.7$; whereas the measured value is $\sim 4.5$). This disagreement, however, can be easily explained by the fact that the band conduction parameters used for the simulations are taken from the overall experimental conductivity, which however consists of contributions from both VRH and band conduction (i.e., it is not exclusively due to band conduction). Thus, the contribution of band conduction included in our model is overestimated at
those low temperature (200 K ~ 280 K). Nevertheless, we emphasize that in its simplicity our model is still able to capture qualitatively the observed behaviour.

References

[1] L. Li, W. Han, L. Pi, P. Niu, J. Han, C. Wang, B. Su, H. Li, J. Xiong, Y. Bando, and T. Zhai, Emerging in-plane anisotropic two-dimensional materials, InfoMat 1, 54 (2019).


[26] See Supplemental Material at [URL will be inserted by publisher] for details about the determination of the crystal orientation.


[38] See Supplemental Material at [URL will be inserted by publisher] for details about calculation of the effective mass ratio.


