Imaging electron flow from collimating contacts in graphene

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Abstract

The ballistic motion of electrons in graphene opens exciting opportunities for electron-optic devices based on collimated electron beams. We form a collimating contact in a hBN-encapsulated graphene hall bar by adding zigzag contacts on either side of an electron emitter that absorb stray electrons; collimation can be turned off by floating the zig-zag contacts. The electron beam is imaged using a liquid-He cooled scanning gate microscope (SGM). The tip deflects electrons as they pass from the collimating contact to a receiving contact on the opposite side of the channel, and an image of electron flow can be made by displaying the change in transmission as the tip is raster scanned across the sample. The angular half width $\Delta \theta$ of the electron beam is found by applying a perpendicular magnetic field $B$ that bends electron paths into cyclotron orbits. The images reveal that the electron flow from the collimating contact drops quickly at $B = 0.05$ T when the electron orbits miss the receiving contact. The flow for the non-collimating case persists longer, up to $B = 0.19$ T, due to the broader range of entry angles. Ray-tracing simulations agree well with the experimental images. By fitting the fields $B$ at which the magnitude of electron flow drops in the experimental SGM images, we find $\Delta \theta = 9^\circ$ for electron flow from the collimating contact, compared with $\Delta \theta = 54^\circ$ for the non-collimating case.

1. Introduction

Ballistic graphene devices open pathways for new electronic and photonic applications [1–6]. Electrons move through graphene at a constant speed $\sim 10^6 \text{ m s}^{-1}$ as if they were photons, and they easily pass through potential barriers via Klein tunneling, as electrons change into holes, due to the gapless bandstructure [7–12]. The differences between the two-dimensional electron gas (2DEG) in graphene and GaAs/AlGaAs heterostructures present challenges to understanding the device physics, and offer new types of devices that make use of graphene’s virtues. The ballistic motion of electrons through a device can be controlled by using magnetic focusing—in a perpendicular magnetic field $B$ electrons emitted from a point contact refocus at a second point contact located a cyclotron diameter away [13, 14]. Magnetic focusing has been demonstrated in ballistic GaAs 2DEGs [15, 16] and in graphene [17, 18]. The angular distribution of the lowest quantum mode of a quantum point contact (QPC) provides a degree of collimation in a GaAs 2DEG [19–21], but a more tightly directed electron beam is desirable. A collimated beam has been formed in GaAs in flow between two separated QPCs [22], and by using an electrostatic lens [23]. Graphene has the ability to create a negative index of refraction [24, 25] for electron waves, allowing a lateral $p$-$n$ junction to act as a lens that focuses electron waves [11, 26, 27]. For ballistic electronics, a narrow, collimated electron beam with the electrons pointed in the same direction would be ideal. Recently a collimating contact for electrons in graphene has been demonstrated via transport measurements [28].

In this paper, we demonstrate that a collimating contact can produce a narrow electron beam in graphene by imaging the pattern of electron flow using a cooled scanning gate microscope (SGM). We have adapted a technique previously used to image electron flow through a GaAs 2DEG [16, 19–21] and graphene [18, 29], and we now use this technique to image the pattern of electron flow from a collimating contact in graphene. The collimating contact is formed by a rectangular end contact with zigzag side contacts on either side that form a collimated beam of electrons inside the sample. Images of electron flow confirm that...
the collimating contact substantially narrows the electron beam. A quantitative measure of angular width of the electron beam is obtained by applying a perpendicular magnetic field $B$ to bend the electron trajectories into cyclotron orbits, so they miss the collecting contact, reducing the intensity of electron beam image. A fit to ray tracing simulations gives a (HWHM) angular width $\Delta \theta = 9^\circ$ for the collimating contact and much wider width $\Delta \theta = 54^\circ$ when collimation is turned off.

2. Methods

2.1. Collimating contact device

The geometry of the collimating contact is shown in figure 1(a), an SEM image of the Hall-bar graphene sample; the white square indicates the imaged region. The Hall bar (blue region) is patterned from a hBN/graphene/hBN sandwich. It has dimensions $1.6 \times 5.0 \, \mu m^2$, with two collimating contacts (yellow) along each side, separated by $1.6 \, \mu m$, and large source and drain contacts (width $1.6 \, \mu m$) at either end. The four collimating contacts have an end contact that emits electrons and two zigzag side contacts that collimate the electron beam by absorbing electrons. The device sits on a heavily doped Si substrate which acts as a back-gate, covered by a 285 nm thick insulating layer of silicon oxide ($SiO_2$). The top and bottom hBN flakes along with the graphene are mechanically cleaved. Using a dry transfer technique, the flakes are stacked onto the $SiO_2$ substrate. To achieve highly transparent metallic contacts to the graphene, we expose the freshly etched graphene edge with reactive ion etching and evaporate chromium and gold layers immediately afterwards.

Figure 1(b) shows ray-tracing simulation of electron trajectories passing through a collimating contact, which consists of an end contact (yellow) that emits electrons into the graphene and zigzag side contacts on either side (yellow) that form a series of constrictions. Electrons emitted from top narrow contact enter at all angles. Collimation is turned on by grounding the zigzag side contacts—stray electrons entering at wide angles hit the zigzags and are absorbed—only electrons that pass through the gap get through, producing a narrow electron beam. The collimating contact can be turned off by simply connecting the top contact to the two zigzag side contacts. In this case, the combined contact behaves as a single source of electrons with a wider width and no collimation.

2.2. Cooled SGM

We have developed a technique that uses a cooled SGM to image the flow of electrons through a 2DEG that we used for GaAs/AlGaAs heterostructures [16, 19–21] and graphene samples [18, 29, 31]. The charged tip creates an image charge in the 2DEG below (figure 1(c)) that deflects electrons away from their original paths, changing the transmission $T$ between two contacts of a ballistic device. An image of the electron flow is obtained by displaying the change in transmission $\Delta T$ as the tip is raster scanned across the device.

In this paper, we used this approach to image electron flow from a collimating emitter contact at the top of the graphene sample in the area indicated by a white square in figure 1(a) to a non-collimating collector contact at the bottom of the sample. With the tip absent, electrons pass ballistically through the channel between the emitter and the collector contacts. The shape of the electron beam is imaged by displaying the change in transmission $\Delta T$ versus tip location as the SGM tip scatters electrons away from their original paths, as the tip is raster scanned across the sample. We measure voltage difference $\Delta V$ between contacts 3, 5, and 6 tied together, and contact 4. One can determine $\Delta T$ from the change in voltage $\Delta V$ at the ungrounded collecting contact for a current $I$ into the emitting contact. As electrons accumulate, raising the electron density, the chemical potential increases, creating an opposing current that maintains zero net current flow. By measuring the voltage change $\Delta V$ or the transresistance change $\Delta R = \Delta V/I$.

\[ \Delta R = \frac{\Delta V}{I} \]
at the receiving contact, the transmission change \( \Delta T \) induced by the tip can be obtained \([18, 31]\). For a collimated electron beam, the current is emitted from contact 1 to contact 2 in figure 1(a), while contacts 7 and 8 are grounded to collect sideways moving electrons. To turn collimation off, contacts 1, 7 and 8 are connected together as a single current emitter while contact 2 is grounded. The collecting contact always has collimation turned off with contacts 3, 5 and 6 connected together.

The width of the emitted electron beam is substantially reduced when collimation is turned on for the top contact. To obtain a quantitative measure of the angular width of the emitted electron beam, we apply a perpendicular magnetic field \( B \) that bends electron paths into cyclotron orbits. The curvature causes electrons to miss the collecting contact and reduces the intensity of the imaged flow.

2.3. Electron path simulations
Bending electron trajectories with a perpendicular magnetic field \( B \) is used to measure the angular width \( \theta \) of the emitted electron beam in the experiments below. We use a ray-tracing model of electron motion and tip perturbation to simulate the electron flow through graphene in this case \([18, 31]\). Our model computes the transmission of electrons between two contacts in graphene for each tip position. The electrons trajectories from the emitter contact are traced by considering two forces: (1) the force from the tip induced charge density profile, and (2) the Lorentz force from \( B \).

![Figure 2. (a) SGM image of electron flow from the non-collimating top contact to the non-collimating bottom contact (figure 1(a)). (b) SGM image of the electron flow when the collimation is turned on in the top contact (see text) (figure 1(b)). (c) Simulated image of electron flow from the non-collimating top contact to the non-collimating bottom contact. (d) Simulated image of electron flow when collimation is turned on in the top contact. All images at zero magnetic field \( B = 0 \) T and electron density \( n = 1.08 \times 10^{12} \) cm\(^{-2}\). The orange bars on the top and bottom of each image show the contact locations.](image-url)
be constant in space. Taking a spatial derivative yields the force $F(a) = -\vec{\nabla} U(a) = \vec{\nabla} E_F(a)$ on electrons in graphene passing nearby the tip position. The resulting acceleration of an electron due to the tip at position $\vec{r}$ using the electron dynamical mass $m^* = \frac{\hbar}{(\pi n)^{1/2}}/v_F$ is:

$$\frac{d^2 \vec{r}}{dt^2} = \frac{1}{2} \left( \frac{e^2}{n} \right) \nabla n(\vec{r}). \tag{2}$$

The tip-induced charge density profile creates a force that pushes an electron away from region with low electron density beneath the tip. The Lorentz force $\vec{F}$ that acts on an electron with velocity $\vec{v}$ under a magnetic field $\vec{B}$ is:

$$\vec{F} = e \vec{v} \times \vec{B}. \tag{3}$$

In our simulations, we pass $N = 10,000$ electrons at the Fermi energy into the graphene from the emitting contact. The number of electrons passed from the contact follow a cosine distribution where maximum number of electrons pass perpendicular to the contact. The distribution is cosine within the angular width $\pm \Delta \theta$ on either side of the contact while outside of the angular width $\Delta \theta$ no electrons are emitted. The value of $\Delta \theta$ is determined by fitting the image data in figure 5, below. The electron paths are computed by numerically integrating the equation of motion from equations (2) and (3). The transmission $T$ between the top and bottom contacts is then computed by counting the fraction of electrons that reach the non-collimating collecting contact, which has contacts 3, 5 and 6 tied together. An image of electron flow is obtained from the simulations, by displaying the transmission changed $\Delta T = T_{\text{tip}} - T_{\text{notip}}$ versus tip position. The angular width $\Delta \theta$ of the experimental electron beam is determined by using the simulations to fit the image intensity data versus $B$.

The dip in electron density $\Delta n_{\text{tip}}$ produced by the SGM tip scatters electrons away from their original trajectories. For an electron originally headed toward the receiving contact, scattering by the tip reduces the transmission, so that a display of $\Delta T$ versus tip position shows the original electron paths (red regions in figures 2–4). The half-width of the density dip $\Delta n_{\text{tip}}$ from equation (1) is the height $h$ of the tip above the graphene sheet, determined by the thickness of the top hBN layer. The depth of the dip is determined by the difference in work functions between the tip and sample materials. The fixed dip in density produces proportionally greater scattering at low densities and lower scattering at high densities. The density dip below the SGM tip can also increase the transmission $T$.

\[\text{Figure 3. A magnetic field}\ \vec{B}\ \text{was used to measure the angular width of the electron beam emitted into the graphene—the field bends their trajectories and causes them to miss the collecting contact. Tiled experimental SGM images versus $B$ and electron density of (a) electron flow from the non-collimating top contact to the non-collimating bottom contact and (b) electron flow from the collimation top contact. The fields are}\ \vec{B} = 0 \ \text{T, 0.025 T, 0.050 T, 0.075 T, 0.100 T, 0.125 T, 0.150 T, and 0.175 T.}\]

\[\text{Figure 4. Simulated images, tiled versus $B$ and $n$ of (a) electron flow from the non-collimating top contact to the non-collimating bottom contact and (b) electron flow when collimation is turned on in the top contact. The fields are}\ \vec{B} = 0 \ \text{T, 0.025 T, 0.050 T, 0.075 T, 0.100 T, 0.125 T, 0.150 T, and 0.175 T.}\]
by bumping electrons into the receiving contact from orbits that did not originally go there (blue regions in figures 2–4).

3. Results and discussion

3.1. Images of collimated electron flow

The SGM images of electron flow (figures 2(a) and (b)) and simulated images (figures 2(c) and (d)) clearly demonstrate that the collimating contact significantly narrows the width of the emitted electron beam. Collimation in the top contact is turned off in figures 2(a) and (c) and turned on in figures 2(b) and (d). The experimental images agree quite well with the simulations. In each image, the red regions ($\Delta T < 0$) image the electron flow between the top and bottom contacts by showing where the tip reduces the transmission $T$ by scattering electrons away from their original paths into the receiving contact. As the tip is moved to the side of the electron flow, the blue regions ($\Delta T > 0$) show where the tip increases transmission by knocking electrons that enter at large angles $\theta$ toward the receiving contact. The images are stronger at low densities in figure 2(a), where the tip creates a proportionally larger dip in electron density. When collimation is turned on (figure 2(b)), blue regions go away, confirming that the emitted electron beam has been collimated with fewer electrons entering at wider angles. All these images were obtained at electron density $n = 1.08 \times 10^{12} \text{ cm}^{-2}$ and $B = 0 \text{ T}$.

3.2. Angular distribution of the electron beam

To measure the angular distribution $\Delta \theta$ of the electron beam emitted into the graphene from the collimating contact, we bent electron paths away from their original directions with a perpendicular magnetic field, so that some miss the receiving contact. Figures 3(a) and (b) show SGM images of electron flow for the non-collimating and collimating cases respectively, tiled against the magnetic field $B$ and the electron density $n$. The direct electron flow (red region), is strong at $B = 0$ and decreases as the magnetic field is increased. With collimation turned off (figure 3(a)), the electron flow persists to much higher fields $B = 0.15 \text{ T}$ than for or the collimated case $B = 0.05 \text{ T}$ (figure 3(b)), because the electron paths enter the graphene over a wider range of angles $\theta$. In addition, large blue regions are seen for the non-collimating case (figure 3(a)) on either side of the electron flow (red region) between contacts, because the tip knocks electrons entering at relatively large angles $\theta$ toward the receiving contact. The images are stronger at low densities in figure 3(a), where the tip creates a proportionally larger dip in electron density. When collimation is turned on (figure 3(b)), at $B = 0 \text{ T}$, blue regions go away, because fewer electrons enter the graphene at large angles. The images in figure 3 show that the angular width $\Delta \theta$ of the electron beam emitted by the collimating contact is much sharper than for the non-collimating case. A quantitative analysis of the experimental images to determine $\Delta \theta$ is given below.

Figure 4 shows simulated images, tiled against the magnetic field $B$ and the electron density $n$, that correspond to the experimental images in figure 3, showing the non-collimating (figure 4(a)) and the collimating
cases. For the collimating case (figure 5(a)),
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images agree very well, confirming that the collimat-
Figures 5(a) and (c) show the total magnitude of elec-
ing case (figure 4(b)), and the intensity persists to
simulated cases by plotting in
the non-collimating case were obtained by fitting the
Δ
angular width
experimental data shown in figures 5(a) and (c). Our meas-
summing
measurements show that the collimating contact dramati-
Figure 6. Experimental magnetic field \( B \) required to drop
the total magnitude of electron flow to half the zero-field
value for the collimating top contact (red) (figure 3(a)) and
for the non-collimating top contact (blue) (figure 3(c)).
Simulated HWHM for collimating case (green) and non-
collimating case (yellow). The width for the collimating top
contact is approximately four times smaller than for the
non-collimating contact, showing that the angular width of
the electron beam is narrower.

\[ \Delta \theta = \frac{\pi}{2} \left[ \frac{1}{n} \right]^{1/2} \text{[18, 31]} \]

Therefore, we fit the density dependence of the HWHM field by
HWHM = \( a \ n^{1/2} + b \). For the collimating case, the
fit gives \( a = 5.4 \times 10^{-8} \text{ cm} \), and \( b = 2.7 \times 10^{-2} \text{ T} \),
shown by the red dotted line in figure 6. For the non-
collimating case, we have \( a = 1.3 \times 10^{-7} \text{ cm} \), and \( b = 2.6 \times 10^{-2} \text{ T} \)
shown as the blue dotted line in figure 6.

To determine the angular width \( \Delta \theta \) for the col-
limiting contact, we compare measurements of
HWHM versus \( B \) from in figures 5(a) and (c) with
simulations. The procedure is the following: A series
of angular widths \( \Delta \theta \) are input into simulated images
of electron flow, such as figures 4(a) and (b). The total
magnitude \( \sum \Delta T_m \) of electron flow is computed by
summing \( \Delta T_m \) for all of the pixels in the red region of
the simulated image. The resulting values of \( \sum \Delta T_m \)
are plotted versus magnetic field \( B \) and electron den-
sity \( n \), as shown for the non-collimating (figure 5(b))
and collimating (figure 5(d)) cases. For each value of
\( \Delta \theta \) input into the simulations, we plot HWHM of the
simulations versus \( B \), similar to the experimental ver-
sions in figure 6. By matching experiments with simu-
lations in this way, we obtain the best values for \( \Delta \theta \) for
the collimating and non-collimating cases.

Carrying out this comparison of experimental
SPM images with simulations, we find that the exper-
imental angular width of the electron beam exiting
the collimating contact is \( \Delta \theta = 9^\circ \) (on either side)
and that the angular width with collimation turned
off is \( \Delta \theta = 54^\circ \); these values were used for the simu-
lations in figures 4(a) and (b). The simulations of the
total magnitude \( \sum \Delta T_m \) of electron flow based on
these angular widths are shown in for the collimating
case in figure 5(b) and for the non-collimating case
in figure 5(d), which agree quite well with the exper-
imental data shown in figures 5(a) and (c). Our mea-
surements show that the collimating contact dramati-
cally sharpens the electron beam. The angular width
\( \Delta \theta \) for the collimating contact is more than five times
smaller than the non-collimating case. Previous trans-
port measurements in graphene that used two con-
strictions to collimate electron flow show an angular
width \( \Delta \theta = 9^\circ \) similar to our results [28].

4. Conclusion
By imaging the electron flow with a cooled SGM we
have shown that a collimating contact design based on
zigzag side contacts considerably narrows the angular
width of the electron beam emitted into the graphene
sample. We observe a spatially narrow beam of electron
flow with angular width \( \Delta \theta = 9^\circ \) (either side) for the
collimating contact which is more than five times

\[ (\text{figure 4(b)}) \]

The simulated and experimental images agree very well, confirming that the collimating contact reduces the angular width \( \Delta \theta \) of the emitted electron beam. For these simulations, we input the angular width \( \Delta \theta = 9^\circ \) for the collimating case, and \( \Delta \theta = 54^\circ \) for the uncollimating case that were deter-
mind by fits of simulations to the experimental data,
described below. The simulations have the same char-
acteristics as the SGM images: the electron flow (red
regions) between the top and bottom contacts is wider
for non-uncollimating case (figure 4(a)) that for collini-
mated case (figure 4(b)), and the intensity persists to
much higher magnetic fields \( B = 0.15 \text{ T} \) for the non-
collimating then for the collimating case \( B = 0.05 \text{ T} \).
Blue regions occur in the images to the left of the elec-
tron flow (red regions) between the top and bottom
contacts, where the tip knocks electron orbits into the
receiving contact that would have missed on the left.

The angular width \( \Delta \theta \) of the electron beam emit-
ted into the graphene for the collimating contact and
the non-collimating case were obtained by fitting the
experimental data (figure 3) with simulated images.
Figures 5(a) and (c) show the total magnitude of elec-
tron flow for the collimated (figure 5(b)) and non-
collimated (figure 5(c)) cases, respectively, obtained by
taking sum of the imaged electron flow (\( \sum \Delta R_m \))
over the red region of the panel at each magnetic field
\( B \), shown on the horizontal axis, and electron density
\( n \), shown by the colors blue (\( n = 0.72 \times 10^{12} \text{ cm}^{-2} \)),
red (\( n = 1.08 \times 10^{12} \text{ cm}^{-2} \)), yellow (\( n = 1.44 \times 10^{12} \text{ cm}^{-2} \)), and purple (\( n = 1.80 \times 10^{12} \text{ cm}^{-2} \)). The mag-
nitude of electron flow \( \sum \Delta R_m \) dies off with \( B \) in all
cases. For the collimating case (figure 5(a)), \( \sum \Delta R_m \)
shows a rapid decrease as \( B \) increases. For the non-collimi-
nated case (figure 5(c)), \( \sum \Delta R_m \) shows a much slower
decline in flow with \( B \) due to the wider angular distribu-
tion of electrons emitted into the graphene.

The angular width \( \Delta \theta \) of the electron beam can be
obtained from the experimental images for the
collimating and non-collimating cases by plotting in

\[ \sum \Delta \theta = \sum \theta \]

\[ \sum \Delta \theta = \sum \theta \]
narrower than the angular width $\Delta\theta = 54^\circ$ for the non-collimating contact. The ability of a collimating contact to create a narrow electron beam is promising for future experiments on ballistic devices in graphene as well as other atomic layer materials.

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**References**

[1] Zhang Y, Tan Y W, Stormer H L and Kim P 2005 Nature **438** 201–4  
[2] Novoselov K S, Geim A K, Morozov S V, Jiang D, Zhang Y, Dubonos S V, Grigorieva I V and Firsov A A 2004 Science **306** 666–9  
[3] Geim A and Novoselov K 2007 Nat. Mater. **6** 183–91  
[4] Geim A and Kim P 2008 Sci. Am. **298** 90–7  
[5] Castro N, Guinea F, Peres N M R, Novoselov K S and Geim A K 2009 Rev. Mod. Phys. **81** 109–62  
[6] Dean C R et al 2010 Nat. Nanotechnol. **5** 722–6  
[7] Lui C H et al 2009 Nature **462** 339  
[8] Katsnelson M I, Novoselov K S and Geim A K 2006 Nat. Phys. **2** 620–5  
[9] Stander N, Huard B and Goldhaber-Gordon D 2009 Phys. Rev. Lett. **102** 026807  
[10] Young A F and Kim P 2009 Nat. Phys. **5** 222–6  
[11] Lee G H, Park G H and Lee H J 2015 Nat. Phys. **11** 925–9  
[12] Shytov A V, Rudner M S and Levitov L S 2008 Phys. Rev. Lett. **101** 156804  
[13] Sharvin Y V and Fisher L M 1965 JETP Lett. **1** 152  
[14] Tsio V S 1974 JETP Lett. **19** 70–1  
[15] Houten H V, Beenakker C W J, Williamson J G, Broekhart M E I, Loosdrecht P H M V, Wees B J V, Mooij J E, Foxon C T and Harris J J 1989 Phys. Rev. B **39** 8556  
[16] Aidala K E, Parrott R E, Kramer T, Heller E J, Westervelt R M, Hanson M P and Gossard A C 2007 Nat. Phys. **3** 464  
[17] Taychatanapat T, Watanabe K, Taniguchi T and Jarillo-Herrero P 2013 Nat. Phys. **9** 225–9  
[18] Bhandari S, Lee G H, Taniguchi T, Watanabe K, Kim P and Westervelt R M 2016 Nano Lett. **21** 1–10  
[19] Topinka M A, LeRoy B J, Shaw S E J, Heller E J, Westervelt R M, Maranowski K D and Gossard A C 2000 Science **289** 5468  
[20] Topinka M A, LeRoy B J, Westervelt R M, Shaw S E J, Fleischmann R, Heller E J, Maranowski K D and Gossard A C 2000 Nature **410** 6825  
[21] Topinka M A 2001 PhD Thesis Harvard University  
[22] Molenkamp L W, Staring A A M, Beenakker C W J, Eppenga R, Timmering C E, Williamson J G, Harman M J P M and Foxon C T 1999 Phys. Rev. B **60** 1274  
[23] Sivan U, Heiblum M, Umibach C P and Shtrikman H 1990 Phys. Rev. B **41** 7937  
[24] Veselago V G 1968 Sov. Phys.—Usp. **10** 509  
[25] Pendry J B 2003 Nature **423** 22  
[26] Cheianov V, Fal’ko V and Atulshower B L 2007 Science **315** 1252–5  
[27] Moghaddam A G and Zareyan M 2010 Phys. Rev. Lett. **105** 146803  
[28] Barnard A W, Hughes A, Sharpe A L, Watanabe K, Taniguchi T and Goldhaber-Gordon D 2017 Nat. Commun. **8** 15418  
[29] Berezovsky J and Westervelt R M 2010 Nanotechnology **21** 27  
[30] Lee G H, Huang K F, Efetov D K, Weig S, Hart S, Taniguchi T, Watanabe K, Yacoby A and Kim P 2017 Nat. Phys. **13** 693–8  
[31] Bhandari S, Lee G H, Kim P and Westervelt R M 2017 J. Electron. Mater. **46** 3837–41  
[32] Kim K K, Hsu A, Jia X, Kim S M, Shi Y, Dresselhaus M, Palacios T and Kong J 2012 ACS Nano **6** 8583–90