Analysing quantized resistance behaviour in graphene Corbino $p$-$n$ junction devices

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Abstract

Just a few of the promising applications of graphene Corbino $p$-$n$ devices include two-dimensional Dirac fermion microscopes, custom programmable quantized resistors, and mesoscopic valley filters. In some cases, device scalability is crucial, as seen in fields like resistance metrology, where graphene devices are required to accommodate currents of the order 100 $\mu$A to be compatible with existing infrastructure. However, fabrication of these devices still poses many difficulties. In this work, unusual quantized resistances are observed in epitaxial graphene Corbino $p$-$n$ junction devices held at the $\nu = 2$ plateau ($R_H \approx 12906 \ \Omega$) and agree with numerical simulations performed with the LTSpice circuit simulator. The formulae describing experimental and simulated data are empirically derived for generalized placement of up to three current terminals and accurately reflect observed partial edge channel cancellation. These results support the use of ultraviolet lithography as a way to scale up graphene-based devices with suitably narrow junctions that could be applied in a variety of subfields.

Keywords: quantum Hall effect, Corbino geometry, graphene $p$-$n$ junctions

(Some figures may appear in colour only in the online journal)

1. Introduction

Graphene and all devices fabricated from it have been studied extensively since its discovery [1–4]. Under strong magnetic flux densities leading to filled Landau levels, graphene exhibits fixed resistances that take the form $\frac{1}{2(n+1)} R_K$, where $R_K = \frac{h}{e^2}$ and is labelled as the von Klitzing constant, $n$ is an integer, $h$ is the Planck constant, and $e$ is the elementary charge. Conventional $p$-$n$ junction ($pn$) Hall devices may also exhibit a variety of ratios of the von Klitzing constant while in the quantum Hall regime [5–18]. Furthermore, similar phenomena have been observed in devices with a Corbino geometry [19–25]. When coupled with the commercial necessity of scaling graphene devices, applications involving millimeter-scale fabrication have the potential to provide solutions in a number...
of fields, notably those that focus on problems in photodetection [26–30], quantum Hall metrology [31–41], and electron optics [42–45].

The first question that may come to mind regards how such devices could be applied specifically to various problems. Applications of these Corbino pnJ devices include the possible construction of more sophisticated two-dimensional Dirac fermion microscopes that rely on large-scale junction interfaces [46], custom programmable quantized resistors [47], and mesoscopic valley filters [21]. The scalability is crucial for some of these applications. For instance, in resistance metrology, graphene devices are required to accommodate currents of the order 10 µA and above (modern-day usage may even exceed 100 µA) in order to ensure compatibility with existing infrastructure [31, 37, 40].

Two difficult steps in successfully fabricating millimeter-scale pnJ devices include the following: (1) uniformly doping large-area regions on epitaxial graphene (EG) such that it may exhibit both p-type and n-type behavior and (2) ensuring adequate junction narrowness to enable Landauer–Büttiker edge channel propagation and equilibration [5–9, 48–53]. For the first case, common nanodevice fabrication practices such as using a top-gate are unable to be used due to an increasing probability of current leakage through the gate with lateral size. Furthermore, such typical practices are time-consuming when scaled up beyond the micron level. Comparisons on other fabrication techniques are provided in the supplementary information (stacks.iop.org/JPhysD/53/275301/mmedia).

Other further specific applications of interest to those exploring quantum Hall transport may include the utilization of pnJ devices for accessing different quantized resistances or the repurposing of Corbino geometries for quantum Hall devices. In the latter case, not much has been reported regarding how a periodic boundary condition affects measured quantized resistances.

Recent studies show that the parameter space for quantized resistances opens up significantly when using several terminals as sources or drains [54–57]. In only one of these cases, Corbino pnJ devices were used, but mostly as a proof of principle for a more complex quantum dartboard device [57]. The empirical understanding of how these values are obtained is still lacking.

This work reports details on the millimeter-scale fabrication of EG Corbino pnJ devices and subsequent measurements of those devices in the quantum Hall regime to understand how periodic boundary conditions on edge channel currents affect quantized resistances. The data were compared with LTspice current simulations [58, 59], and both were then used as the basis for deriving empirical formulae for the generalized case of using two or three current terminals of either polarity with any arbitrary configuration.

Overall, these experiments further validate two endeavors: (1) fabrication of scalable of pnJ devices and their versatility in circuits (2) flexibility in device fabrication by transforming devices with Corbino geometries into ones that permit the flow of edge channel currents between the outer and inner edges [21, 52].

2. Experimental and numerical methods

2.1. Graphene growth and device fabrication

EG was grown on a 2.7 cm by 2.7 cm SiC square that was diced from a 4H-SiC(0001) wafer (CREE) (see Acknowledgments). The procedures for cleaning and treating the wafer before the growth are detailed in other works [32, 35, 54]. One crucial element to obtaining high-quality growth with limited SiC step formation was the AZ5214E solution, a polymer which has been shown to assist in homogenous sublimation [60]. The growth was performed at 1900 °C in an argon environment using a resistive-element furnace from Materials Research Furnaces Inc (see Acknowledgments) with graphite-lining and heating and cooling rates of about 1.5 °C s⁻¹.

Samples were inspected after growth with confocal laser scanning and optical microscopy to verify monolayer homogeneity [61]. For fabrication processes, it was important to protect the EG from photoresists and organic contamination, and this was achieved by depositing Pd and Au layers [32, 35]. For improved cryogenic contact resistances, EG was contacted with pads composed of NbTiN, a superconducting alloy with a Tc of about 12 K at 9 T [34, 41]. All EG Corbino pnJ devices underwent functionalization treatment with Cr(CO)₆, which sublimates in a furnace and decomposes into Cr(CO)₅ and bonds itself to the EG surface [62–65]. This treatment both provides uniformity along the millimeter-scale devices and reduces the electron density to a low value of the order 10¹⁰ cm⁻², thus enabling a greater control of the latter by annealing [66].

For both the control and experimental devices, intended n-type regions were protected by S1813 photoresist. Keeping control devices aside, ultraviolet photolithography was then used to remove S1813 from regions intended for p-type adjustment. PMMA/MMA was deposited as a mediation layer for ZEP520A, a polymer with photoactive properties. The latter enables graphene to become p-type (near 4 × 10¹¹ cm⁻²) upon exposure to an external ultraviolet lamp (254 nm)—see supplementary information [54, 67]. Regions still protected by S1813 did not undergo significant electron density shifting but still required an annealing process of approximately 25 min (at 350 K) to shift the electron density to about 10¹¹ cm⁻².

To verify that the devices are properly adjusted to the desired electron density, two types of measurements were required. For the control device in figure 1(a), a simple Hall measurement was performed after annealing using the green dots as the current terminals and the blue triangles as the voltage terminals. An example result is shown in figure 1(b), where the electron density has been successfully shifted from low values neighboring the Dirac point to around 10¹¹ cm⁻².

This electron density is sufficient to see the quantized plateau at ν = 2, which, for the case of using epitaxial graphene, exhibits a stable plateau for a large range of magnetic flux densities. This stability, labelled as a pinning of the 2 Landau level state and characterized by edge channels of opposite chirality, has been attributed to field-dependent charge transfer between the SiC surface and the graphene layer [33].
the ultraviolet lamp. The annealing does shift electron (or hole, in this case) density after the exposure to data in the intended

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corresponding Hall measurement shown in (b) Optical image of final bounds of the epitaxial graphene. Green dots and blue triangles indicate current and voltage terminals, respectively, for the Hall bar. The next step was to determine (c) Optical image of final device containing 16 distinct and alternating -type and -type regions. Purple dashed rings indicate the outer or inner circumference. The next step was to determine the large parameter space of quantized resistances subject to periodic boundary conditions, multiple current terminals must be used. One of the goals of this work is to develop an empirical framework for calculating the effective quantized resistance of the circuit shown in figure 2. Definitions for that framework include: (1) \( N \), the total number of terminals, (2) \( q_{N-1} \) and (3) \( q_{N-1}^J \) are the coefficients of effective resistance (CER) for the cases with (Corbino device) and without (traditional Hall bar device) periodic boundary conditions, respectively, (4) \( n_j \), where \( j \) can be either 1 or 2 and is used to label the number of junctions between two terminals, (5) \( M \), the number of distinct regions in the Corbino \( pnJ \) device (must be an even, positive integer), and (6) \( n_x \), where \( n_x = M - n_1 \) for two-terminal circuits and \( n_x = M - n_1 - n_2 \) for three-terminal circuits.

The second measurement is explained in more detail in the supplementary information. In essence, a traditional Hall bar with a \( pnJ \) was fabricated using identical steps. Simple Hall data in the intended \( p \)-type region was collected to show the electron (or hole, in this case) density after the exposure to the ultraviolet lamp. The annealing does shift \( p \)-type regions slightly closer to the Dirac point, but the density remains well within the order \( 10^{11} \) cm\(^{-2} \). Additional data from monitoring the carrier density during the photochemical gating process are also shown in the supplementary information.

Though these two measurements are direct ways of obtaining the electron density, an indirect way of validating device functionality is to assess the agreement between two- and three-terminal simulations and corresponding experimental data. These analyses are part of the core of this work and will be presented in the next section.

### 2.2. Definitions for empirical framework

Before continuing, one major assumption of the more specific framework below is that all regions are quantized at the \( \nu = 2 \) plateau. That said, this framework may be reformulated to accurately reflect the conditions of any quantum Hall \( pnJ \) system, including conditions whereby some regions exhibit other plateaus such as the \( \nu = 6 \) plateau. Now, to thoroughly investigate the large parameter space of quantized resistances subject to periodic boundary conditions, multiple current terminals must be used. One of the goals of this work is to develop an empirical framework for calculating the effective quantized resistance of the circuit shown in figure 2. Definitions for that framework include: (1) \( N \), the total number of terminals, (2) \( q_{N-1} \) and (3) \( q_{N-1}^J \) are the coefficients of effective resistance (CER) for the cases with (Corbino device) and without (traditional Hall bar device) periodic boundary conditions, respectively, (4) \( n_j \), where \( j \) can be either 1 or 2 and is used to label the number of junctions between two terminals, (5) \( M \), the number of distinct regions in the Corbino \( pnJ \) device (must be an even, positive integer), and (6) \( n_x \), where \( n_x = M - n_1 \) for two-terminal circuits and \( n_x = M - n_1 - n_2 \) for three-terminal circuits.

For greater clarity, refer to the schematics in figures 2(a) and (b), which represent the device in figure 1(c) and are topologically identical (the actual schematic for LTspice simulations is accurately reflected by (b)). The experimental device has \( M = 16 \). The \( pnJ \) circuit contains a total of three terminals (\( N = 3 \)), with the voltage always being measured between points \( A \) and \( B \) (green squares). This measurement yields a quantized resistance of the form \( R_{AB} = q_{N-1}^J R_H \), where \( R_H \) is the Hall resistance at the \( \nu = 2 \) plateau (\( R_H \approx 12906 \) Ω). The CER (\( q_{N-1} \)) can be represented as a \( 3 \) case). These determinations and corresponding simulations will be shown and discussed in the results section.

### 2.3. LTspice simulations

The electronic circuit simulator LTspice was used for predicting the electrical behavior of the graphene Corbino \( pnJ \) devices. The circuit comprised interconnected \( p \)-type and \( n \)-type quantized regions that were modeled either as ideal clockwise (CW) or counterclockwise (CCW) \( k \)-terminal
quantum Hall effect elements. The terminal voltages and currents, represented as \( e_m \) and \( j_m \), are related by \( R_{Hm} = e_m - e_{m-1} \) for CW elements and \( R_{Hm} = e_m - e_{m+1} \) for CCW elements. The circuit’s behavior at \( A \) and \( B \) (figure 2(b)) could only be modeled for one polarity of magnetic flux density per simulation. For a positive \( B \)-field, an \( n \)-doped (\( p \)-doped) graphene device was modeled by a CW (CCW) element, whereas, when \( B \) is negative, a CWW (CW) element was used.

3. Results

3.1. Interpreting simulation trends \((N = 2)\)

Simulations were first carried out for the \( N = 2 \) case (which, by default, is one positive and one negative current terminal). By keeping the positive terminal (source) fixed on an arbitrary terminal on the outer circumference of the device, and by moving the negative terminal (drain) along both the outer and inner circumference, the resulting CERs (labelled \( q_1 \)) were simulated as a function of junction number \( n_1 \) between the two terminals, for several devices containing different numbers of total regions \( M \). These results are summarized in figure 3(a).

In the case where a positive terminal is held on the outer circumference of the device and a negative terminal is moved along the outer circumference, a parabolic trend appears to form having an intuitive symmetry like the device itself. However, alternating behavior was observed along this parabolic trace. Similarly, when the negative terminal is instead simulated along the inner circumference, a parabolic trend is also seen with alternating behavior. The combination of both, seen in figure 3(a), suggests that two parabolic trends actually exist, with one of them taking on slightly lower values than the other.

There are two consistent physical pictures that arise from the periodic boundary conditions, and these may provide insight into how to interpret the observed alternating behavior. Consider the cases shown in figure 3(b). With the condition that current flows only if it eventually terminates on a positive terminal, then in one case, current is allowed to flow along the edges unimpeded by any other flow. Let us label this as a harmonized configuration. The second case involves current flow that impedes itself in several regions of the device. There are special cases (within the \( N = 3 \) configuration) where this impeding leads to outright cancellation, enabling the device to emulate a traditional Hall bar with several \( pnJ \)s. All instances of currents appearing to self-impede in this picture may be labelled as discordant.
Separating configurations as harmonized or discordant allows the data in figure 3(a) to be fit to a parabola exactly. In doing so, one may parameterize the problem for arbitrary devices and terminal placements. For this analysis, since $n_1$ is symmetric, one may choose $n_1$ to be the smaller spacing between the two terminals, leaving the larger one to be $n_2 = M - n_1$. In the limit where $n_2 \to \infty$, the periodic boundary condition is effectively lifted, giving us a CER of $q_1^2$, which may be calculated for the traditional Hall bar case \[56\]. By simulating the CERs ($q_1$) as a function of $n_1$ (see figure 3(c)), a logistic function known as the Hill–Langmuir equation may be used to fit the curves exactly:

$$q_1 (n_1) = B + \frac{A - B}{1 + \left( \frac{n_1}{n_0} \right)^p} = \frac{B n_1 + A x_0}{n_1 + x_0}.$$  \hspace{1cm} (1)

The parameters in equation (1) can be interpreted as meaningful quantities (with $p = 1$). With the limiting case described earlier, $B = q_1^2$, and as $n_x \to 0$, $q_1 = A \equiv q_1^{(0)}$. For all $N = 2$ configurations, $x_0 = n_1$. Furthermore, with the relation $q_1^2 = n_1 + 1$ \[56\], a function of $n_1$ can be expressed:

$$q_1 (n_1 \to 0) = \frac{(n_1 + 1) (M - n_1) + q_1^{(0)} n_1}{M}.$$  \hspace{1cm} (2)

In equation (2), $q_1^{(0)}$ can be interpreted as the initial condition for a fixed $n_1$ (and $n_2 = 0$). It takes on a single value for all harmonized and discordant (within $N = 2$)—either $\frac{n_1 + 1}{n_1}$ or $\frac{n_2}{n_1} = 1$, respectively. This distinction contributes to the observed separation of the two similar parabolas seen in figure 3(a) and expressed exactly in equation (2).

3.2. Comparing experimental data to corresponding simulations ($N = 2$)

To assess the validity of equation (2), measurements were performed at a temperature of 1.6 K, with a current of 1 µA, on the device shown in figure 1(c) ($M = 16$). The supplementary information also includes information about the mobility of the devices, which range from 3000 cm$^2$ V$^{-1}$ s$^{-1}$ and 5000 cm$^2$ V$^{-1}$ s$^{-1}$ for both region types. Recall that regarding edge channel dynamics in a bipolar graphene pnJ, the quantized states exhibited by the $v = 2$ plateau circulate in opposite directions and merge to form a parallel edge channel at the junction. These channels, as mentioned in \[50\], supply particles at the junction from both reservoirs. After particles jointly propagate across the interface and to the device boundary, they return to their respective regions. Resistance quantization was explained by mode-mixing at the junction, with the idea that regardless of reservoir, all incoming charges had the same probability of crossing the junction \[50\]. For information regarding quantum shot noise and Fano factor calculations, please see the supplementary information. Overall, these dynamics manifest themselves as a quantized resistance across the junction and can be treated as a circuit element in LTspice.

In figure 4(a), two example measurements taken between ±9 T are shown in black and red for the harmonized and discordant case of $n_1 = 7$, respectively. For Case 1 (black line), a thin gray line is used to mark the simulated CER of 5, and a shaded gold region marks the 1σ uncertainty of the experimental average, as calculated by the whole range excluding −5 T to 5 T. For Case 2 (red line), a dark red line is used to mark the simulated CER of $\frac{25}{16}$, with a corresponding experimental uncertainty range shaded in green. The simulated values fall within the error of the experimentally-obtained values. The CERs were calculated with equation (2) for the $M = 16$ device and are shown in figures 4(b) and (c). The calculations agreed exactly with the simulations, as expected. Both the calculations and simulations are represented by a red ‘X’ and
The thin gray and dark red lines are the simulated quantized values, for both harmonized and discordant cases. The error bars (same 1σ uncertainty as exemplified in (a)) are shown in light blue and fall within the size of the experimental data points. The same gray and red lines were compared with experimental data, represented by blue points, for both harmonized and discordant cases. The error bars are shown in light blue, with many falling within the size of the experimental data points. The same gray and red lines from figure 4(a) are shown, along with a box surrounding the relevant data points. These markers enhance the clarity of the difference between the harmonized and discordant cases. The agreement between the experiment and calculated CERs supports the validity of equation (2) for all $N = 2$ configurations.

### 3.3. Interpreting simulation trends ($N = 3$)

Simulations were next carried out for the $N = 3$ case (two terminals of a single polarity and one terminal of opposite polarity). The CERs (now labelled $q_2$) of numerous arbitrary configurations were again simulated as a function of junction number $n_k = M - n_1 - n_2$, where $n_k$ is defined between the two like-polar terminals. The other two numbers $n_1$ and $n_2$ describe the junction number between the two opposite-polarity pairs, with $n_1$ being the smaller number to be consistent with the traditional Hall bar case [56].

Two example simulation sets are shown in figure 5(a), with both sets having $n_1 = 1$ and $n_2 = 3$. The number of regions $M$ was modulated, allowing one to model $q_2(n_k)$. Both the harmonized and discordant cases were modeled exactly to the Hill-Langmuir equation, and the limiting case of $n_k \to \infty$ revealed again that $q_2 \to q_2^{(0)}$, which can be calculated [56].

In the case of figure 5(a), $q_2^{(0)} = \frac{8}{7}$, and this value is marked by a dashed line. Additionally, $q_2^{(0)}$ is marked for both cases. The two values at $n_k = 12$ are simulated values with corresponding experimental data shown in the first cases of figures 5(b) and (c).

By rewriting equations (1) and (2), one may more clearly see the iterative nature of the formula that will describe all $N = 3$ cases. Recall that for all $N = 2$ cases:

$$q_1(n_1) = \frac{q_1^{(0)}(M - n_1) + q_1^{(0)}n_1}{(M - n_1) + n_1}. \quad (3)$$

Here, the only term that changes for harmonized or discordant cases is $q_1^{(0)}$. For all cases in $N = 3$, the parameter $x_0 = \frac{n_1 + n_2}{n_1 + n_2 + 1}$, and the general CER formula becomes:

$$q_2(n_1, n_2) = \frac{q_2^{(0)}(M - n_1 - n_2) + q_2^{(0)}x_0}{(M - n_1 - n_2) + x_0}. \quad (4)$$

Again, the difference between harmonized and discordant cases is embedded in the term $q_2^{(0)}$, which takes on the values $\frac{(n_1+1)(n_2+1)}{n_1+n_2}$ or $\frac{n_1+n_2+n_1n_2}{n_1+n_2}$, respectively (see supplementary information for more details on how these values were determined).

### 3.4. Comparing experimental data to corresponding simulations ($N = 3$)

To verify equation (4), data were collected from several $N = 3$ cases. Six example harmonized and discordant cases are shown in figures 5(b) and (c), respectively. Each experimental data point (light blue triangle) very nearly overlays with its corresponding simulation (red ‘X’), and the simulations match the calculations exactly. Additionally, each point is accompanied by an illustration of each configuration. The
Figure 5. (a) Simulations for the two shown configurations were performed while varying \( n_x \). (b) Experimental data for a variety of harmonized and (c) discordant cases are compared with their simulated counterparts (and verified again with equation (4)). The exact configuration is depicted for each case, and error bars indicate 1\( \sigma \) uncertainty and are of similar size to the light blue triangles (experimental data points) in most cases.
[13] Gan X, Shiue R-J, Gao Y, Meric I, Heinz T F, Shepard K, Hone J, Assfalg S and Enghild D 2013 Nat. Photonics 7 883
[14] Rickhaus P, Liu M H, Makk P, Maurand R, Hess S, Zilhm P, Weiss M, Richter K and Schönenberger C 2015 Nano Lett. 15 5819
[15] Amet F, Williams J R, Watanabe K, Taniguchi T and Goldhaber-Gordon D 2014 Phys. Rev. Lett. 112 196601
[16] Kumada N, Parmentier F D, Hibino H, Glattli D C and Rouleau P 2015 Nat. Commun. 6 8096
[17] Taychatanapat T, Tan J Y, Yeo Y, Watanabe K, Taniguchi T and Özyilmaz B 2015 Nat. Commun. 6 6093
[18] Lee J et al 2016 Nat. Phys. 12 1032
[19] Peters E C, Giesbers A J M, Burghard M and Kern K 2014 Appl. Phys. Lett. 104 203109
[20] Ryerzeck A 2010 Phys. Rev. B 81 121404(R)
[21] Suszalski D, Rut G and Ryercez A 2020 J. Phys. Mater. 3 015006
[22] Kumar M, Laitinen A and Hakonen P 2018 Nat. Commun. 9 2776
[23] Zhao Y, Cadden-Zimiansky P, Ghahari F and Kim P 2012 Phys. Rev. Lett. 108 106804
[24] Zeng Y, Li J I A, Dietrich S A, Ghosh O M, Watanabe K, Taniguchi T, Hone J and Dean C R 2019 Phys. Rev. Lett. 122 137701
[25] Polshyn H, Zhou H, Spanton E M, Taniguchi T, Watanabe K and Young A F 2018 Phys. Rev. Lett. 121 226801
[26] Mueller T, Xia F and Avouris P 2010 Nat. Photonics 4 297
[27] Ghahari F et al 2017 Science 356 645
[28] Fang J, Wang D, Devault C T, Chung T F, Chen Y P, Boltasseva A, Shalaev V M and Kildishev A V 2017 Nano Lett. 17 57
[29] Xia F, Mueller T, Lin Y, Valdes-Garcia A and Avouris P 2009 Nano Technol. 4 839
[30] Schulter S, Schall D, Neumaier D, Dobusch L, Bethge O, Schwarz B, Krall M and Mueller T 2016 Nano Lett. 16 7107
[31] Tzalenchuk A, Lara-Avila S, Kalaboukhov A, Paoillo S, Syväjärvi M, Yakimova R, Kazakova O, Janssen T J B M, Fal’ko V and Kubatkin S 2010 Nano Technol. 5 186
[32] Rigosi A F et al 2017 Small 13 1700452
[33] Janssen T J B M, Tzalenchuk A, Yakimova R, Kubatkin S, Lara-Avila S, Kopylov S and Fal’ko V I 2011 Phys. Rev. B 83 233402
[34] Kruskopf M, Rigosi A F, Panna A R, Marzano M, Patel D K, Jin H, Newell D B and Elmquist R E 2019 Metrologia 56 065002
[35] Rigosi A F, Liu C I, Glavin N R, Yang Y, Hill H M, Hu J, Hight Walker A R, Richter C A, Elmquist R E and Newell D B 2017 ACS Omega 2 2326
[36] Ribeiro-Palau R et al 2015 Nat. Nanotechnol. 10 965
[37] Oe T, Rigosi A F, Kruskopf M, Wu B Y, Lee H Y, Yang Y, Elmquist R E, Kaneko N H and Jarrett D G 2019 IEEE Trans. Instrum. Meas. (https://doi.org/10.1109/TIM.2019.2930436)
[38] Rigosi A F et al 2019 IEEE Trans. Instrum. Meas. 68 1870
[39] Fukuyama Y, Elmquist R E, Huang L I, Yang Y, Liu F-H and Kaneko N H 2015 IEEE Trans. Instrum. Meas. 64 1451
[40] Rigosi A F and Elmquist R E 2019 Semicond. Sci. Technol. 34 093004
[41] Kruskopf M, Rigosi A F, Panna A R, Patel D K, Jin H, Marzano M, Berilla M, Newell D B and Elmquist R E 2019 IEEE Trans. Electron Dev. 66 3973
[42] Chen S et al 2016 Science 353 1522
[43] Cheianov V V, Fal’ko V and Altshuler B L 2007 Science 315 1252
[44] Zhao Y, Wyrick J, Natterer F D, Rodriguez-Nieva J F, Lewandowski C, Watanabe K, Taniguchi T, Levitov L S, Zhitenev N B and Stosso J A 2015 Science 348 672
[45] Elahi M M, Masum Habib K M, Wang K, Lee G-H, Kim P and Ghosh A W 2019 Appl. Phys. Lett. 114 013507
[46] Bosgild P, Caridad J M, Stumper F, Calogero G, Papir N R and Brandbyge M 2017 Nat. Commun. 8 15783
[47] Hu J et al 2018 Sci. Rep. 8 15018
[48] Woszczyyna M, Friedmann M, Dziomba T, Weimann T and Ahlers F J 2011 Appl. Phys. Lett. 99 022112
[49] Lohmann T, von Klitzing K and Smet J H 2009 Nano Lett. 9 1973
[50] Ahanin D A and Levitov L S 2007 Science 317 641
[51] Matsuo S, Takeshita S, Tanaka T, Nakaharai S, Tsukagoshi K, Moriyama T, Ono T and Kobayashi K 2015 Nat. Commun. 6 8066
[52] Hu J, Rigosi A F, Lee J U, Lee H Y, Yang Y, Liu C I, Elmquist R E and Newell D B 2018 Phys. Rev. B 98 045412
[53] Kumar C, Kuri M and Das A 2018 Solid State Commun. 270 38
[54] Rigosi A F et al 2019 Carbon 154 230
[55] Patel D K et al 2020 AIP Adv. 10 025112
[56] Rigosi A F, Patel D K, Marzano M, Kruskopf M, Hill H M, Jin H, Hu J, Elmquist R E and Newell D B 2020 Physica B 582 411971
[57] Liu C I, Patel D K, Marzano M, Kruskopf M, Hill H M and Rigosi A F 2020 AIP Adv. 10 035205
[58] Linear Technology 2018 LTspice XVII (www.linear.com/designtools/software/)
[59] Ortolano M and Callegaro L 2015 Meas. Sci. Technol. 26 085018
[60] Kruskopf M, Pakdeli D M, Pierz K, Wundrack S, Stosch R, Dziomba T, Götz M, Baringhaus J, Aprojanz J and Tegenkamp C 2016 2D Mater. 3 041002
[61] Panchal V et al 2018 Nat. Commun. Phys. 1 83
[62] Bekyarova E, Sarkar S, Niyogi S, Itkis M E and Haddon R C 2012 J. Phys. D: Appl. Phys. 45 154009
[63] Sarkar S, Zhang H, Huang J W, Wang F, Bekyarova E, Lau C N and Haddon R C 2013 Adv. Mater. 25 1131
[64] Dai J, Zhao Y, Wu X, Zeng X C and Yang J 2013 J. Phys. Chem. C 117 22156
[65] Che S, Sasu S, Behura S K, Nguyen P, Sreeprasad T S and Berry V 2017 Nano Lett. 17 4381
[66] Rigosi A F et al 2019 Carbon 142 468
[67] Lara-Avila S, Moth-Poulsen K, Yakimova R, Bjørnholm T, Fal’ko V, Tzalenchuk A and Kubatkin S 2011 Adv. Mater. 23 878