Algorithms for determining resistances in quantum Hall annuli with $p-n$ junctions

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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 ($R_{2H} \approx 12906$ $\Omega$) 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 reflects 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

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

$$R = \frac{h}{2\pi e^2} R_K,$$

where $R_K = \frac{h}{e^2}$ is the von Klitzing constant, $n$ is an integer, $h$ is the Planck constant, and $e$ is the elementary charge. Conventional $p-n$ junction ($pnJ$) 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 quantum phenomena in other 2D materials [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 Material.

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
those 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 Notes]. 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 Notes] with graphite-
lining and heating and cooling rates of about 1.5 °C/s.

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 $T_c$ 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)$_3$ 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 $10^{10}$ 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 $4 \times 10^{11}$ cm$^{-2}$) upon exposure to an external ultraviolet lamp (254 nm) – see Supplementary Material [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 $10^{11}$ 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 Fig. 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 Fig. 1 (b), where the electron density has been successfully shifted from low values neighboring the Dirac point to around $10^{11}$ cm$^{-2}$. This electron density is sufficient to see the quantized plateau at $\nu = 2$, 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 $\nu = 2$ 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 second measurement is explained in more detail in the Supplementary Material. 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 Material.

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
of the form between points yields a quantized resistance of the form \( q_{N-1} \) and \( q_{N-1}^k \) are the coefficients of effective resistance (CER) for the cases with (Corbino device) and without (traditional Hall bar device) periodic boundary conditions, respectively, \( n_j \), 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 Fig. 2 (a) and (b), which represent the device in Fig. 1 (c) and are topologically identical (the actual schematic for LTspice is accurately reflected by (b)). The experimental device has \( M = 16 \). The \( pnJ \) circuit contains a total of 3 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 \( R_{AB} = q_{N-1}R_H \), where \( R_H \) is the Hall resistance at the \( v = 2 \) plateau \( (R_H \approx 12906 \, \Omega) \). The CER \( (q_{N-1}) \) can be represented as a either an integer or a fraction.

This work focused on varying the locations of the two \( (N=2) \) or three \( (N=3) \) current terminals, arbitrary in both position along the Corbino device and placement within the outer or inner circumference. The next step was to determine the best way of identifying \( n_1 \) (and \( n_2 \) for the \( N=3 \) 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 \( i_m \), are related by \( R_H = e_m - e_{m+1} \) for \( CW \) elements and \( R_H = e_m - e_{m-1} \) for \( CCW \) elements. The circuit’s behavior at \( A \) and \( B \) (Fig. 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 \( CCW \) (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 \( (q_1) \) 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 Fig. 3 (a).

![Fig. 2. (a) Schematic of the graphene Corbino \( pnJ \) device from Fig. 1 (c) is shown as part of a circuit intended to exhibit many quantized resistances. In this case, two positive current terminals were used (with each the outer and inner ring hosting one terminal) and one negative terminal was used (outer ring). (b) A topologically identical schematic of the device is shown and accurately reflects the configuration of the quantum Hall elements \( (n \)-type and \( p \)-type regions) in the LTspice simulation.](image-url)
Insight into how to interpret the observed alternating behavior. Consider the cases shown in Fig. 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 pnJs. 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 Fig. 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 $n_2$ to be the smaller spacing between the two terminals, leaving the larger one to be $n_x = M - n_1$. In the limit where $n_x \to \infty$, 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 $n_2$ (see Fig. 3 (c)), a logistic function known as the Hill-Langmuir equation may be used to fit the curves exactly:

$$q_1(n_x) = B + \frac{A - B}{1 + \left(\frac{n_x}{x_0}\right)^p} = \frac{Bn_x + Ax_0}{n_x + x_0}$$

(1)

The parameters in Eq. (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:

$$q_1(n_x \to n_1) = \frac{(n_1 + 1)(M - n_1) + q_1^{(0)}n_1}{M}$$

(2)

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

3.2 Comparing experimental data to corresponding simulations ($N = 2$)
Fig. 4. (a) Magnetoresistance measurements were performed for a variety of \( N = 2 \) configurations on the device shown in Fig. 1 (c). Two example magnetic flux density sweeps are shown in black and red for the harmonized and discordant case of \( \nu = 7 \), respectively. The thin gray and dark red lines are the simulated quantized values, and the shaded gold and green regions are the 1σ uncertainty regions of the respective experimental values. (b) The CERs were simulated (red X) and compared with experimental data (blue points) in harmonized cases as a function of junction number \( n_1 \). Error bars (same 1σ uncertainty as exemplified in (a)) are shown in light blue and fall within the size of the blue points in most cases. (c) CERs were simulated and compared with experimental data in discordant cases as a function of junction number \( n_1 \). The agreement between the experiment and calculated CERs supports the validity of Eq. (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 \( n_x = M - n_1 - n_2 \), where \( n_x \) 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 Fig. 5 (a), with both sets having \( n_1 = 1 \) and \( n_2 = 3 \). The number of regions \( M \) was modulated, allowing one to model \( q_2(n_x) \). Both the harmonized and discordant cases were modeled exactly to the Hill-Langmuir equation, and the limiting case of \( n_x \to \infty \) revealed again that \( q_2 \to q_2^0 \), which can be calculated [56]. In the case of Fig. 5 (a), \( q_2^0 = \frac{8}{5} \) and this value is marked by a dashed line. Additionally, \( q_2^{(0)} \) is marked for both cases. The two values at \( n_x = 12 \) are simulated values with corresponding experimental data shown in the first cases of Fig. 5 (b) and (c).

By rewriting Eq. (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:

\[
q_1(n_1) = \frac{q_1^1(M - n_1) + q_1^{(0)} n_1}{(M - n_1) + n_1}
\]

(3)

Here, the only term that changes for harmonized or discordant cases is \( q_1^{(0)} \). For all cases in \( N = 3 \), the parameter \( x_0 = \frac{n_2 + n_3}{n_1 + n_2 + 1} \), and the general CER formula becomes:

\[
q_2(n_1, n_2) = \frac{q_2^1(M - n_1 - n_2) + q_2^{(0)} x_0}{(M - n_1 - n_2) + x_0}
\]

(4)

And again, the difference between harmonized and discordant cases is embedded in the term \( q_2^{(0)} \), which takes on the values \( \frac{(n_1+1)(n_2+1)}{n_1+n_3} \) or \( \frac{n_1+n_2+n_3}{n_1+n_2} \), respectively (see Supplementary Material for more details on how these values were determined).

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

To verify Eq. (4), data were collected from several \( N = 3 \) cases. Six example harmonized and discordant cases are shown in Fig. 5 (b) and (c), respectively. Each experimental data point (light blue triangle) very nearly overlaps 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 error bars, in a darker shade of blue, indicate 1σ uncertainty and have a similar size as the experimental data points in most cases. The exact CERs for all presented experimental data are listed in the Supplementary Material. The agreement within uncertainty with simulations demonstrates promise that these large-scale devices can be fabricated with excellent functionality.

### 4. Conclusion

This work reports the successful fabrication of millimeter-scale graphene Corbino \( p+ \) devices and corresponding measurements of such devices in the quantum Hall regime to understand how the edge channel currents resulting from being in the \( \nu = 2 \) plateau, manifesting as quantized effective circuit resistances, are affected by periodic boundary conditions. Experimental data were compared with results.
from LTSpice current simulations. Furthermore, empirical formulae were derived for the case of using two or three current terminals of arbitrary configuration. Overall, these experiments have validated that these scalable pdf devices are versatile in how they are implemented in circuits and that using Corbino geometries to permit edge channel current flow between the outer and inner edges offers another adjustable parameter for quantum electrical circuits.

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