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# Transmission of phase information between electrons and holes in graphene

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Phys. Rev. B **87**, 081401 — Published 4 February 2013

DOI: [10.1103/PhysRevB.87.081401](https://doi.org/10.1103/PhysRevB.87.081401)



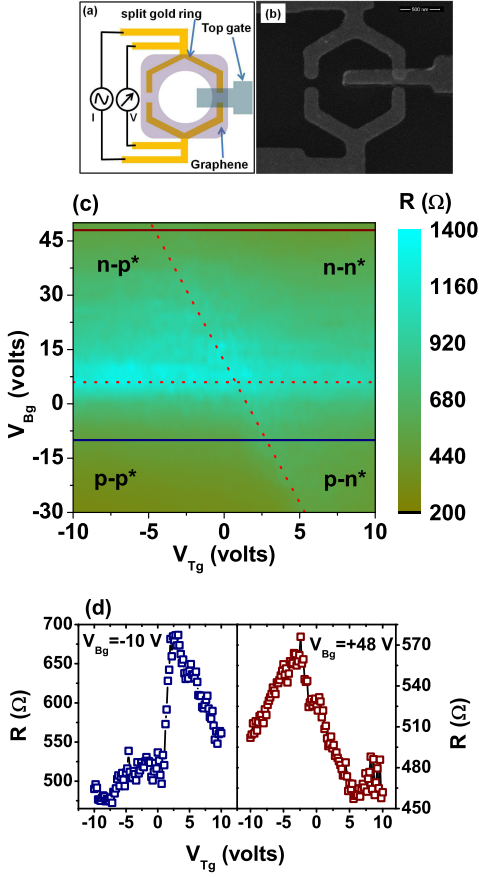


FIG. 1: (a) Device schematic and the measurement configuration. (b) Scanning electron microscope image of a device with a  $\sim 85$  nm wide graphene region completing the split gold ring. (c) Resistance as a function of back gate voltage and top gate voltage. All four regions (n-p\*, n-n\*, p-n\* and p-p\*) are clearly visible. Data corresponding to  $-10$  V and  $+48$  V back gate voltage (blue and red lines) are plotted separately in (d).

(where p and n denote the carrier type in the arm with no top gate, while p\* or n\* denote the carrier type in the top-gated arm with non-zero  $V_{Tg}$ ).

The resistance of the device as a function of top gate voltage is shown in Fig. 1(d) for two fixed values of back gate voltage ( $-10$  V and  $+48$  V).

To investigate the Aharonov-Bohm oscillations, we scanned the magnetic field at a ramp rate of 5 mT/min. The magnetoresistance at 250 mK shows a pronounced periodic oscillation on top of a slowly varying aperiodic background. The aperiodic background arises due to conductance fluctuations originating from the penetration of the magnetic field in the arms [24]. Using Fourier analysis, we filtered out the aperiodic conductance fluctuations and obtained the Aharonov-Bohm flux-dependent part of

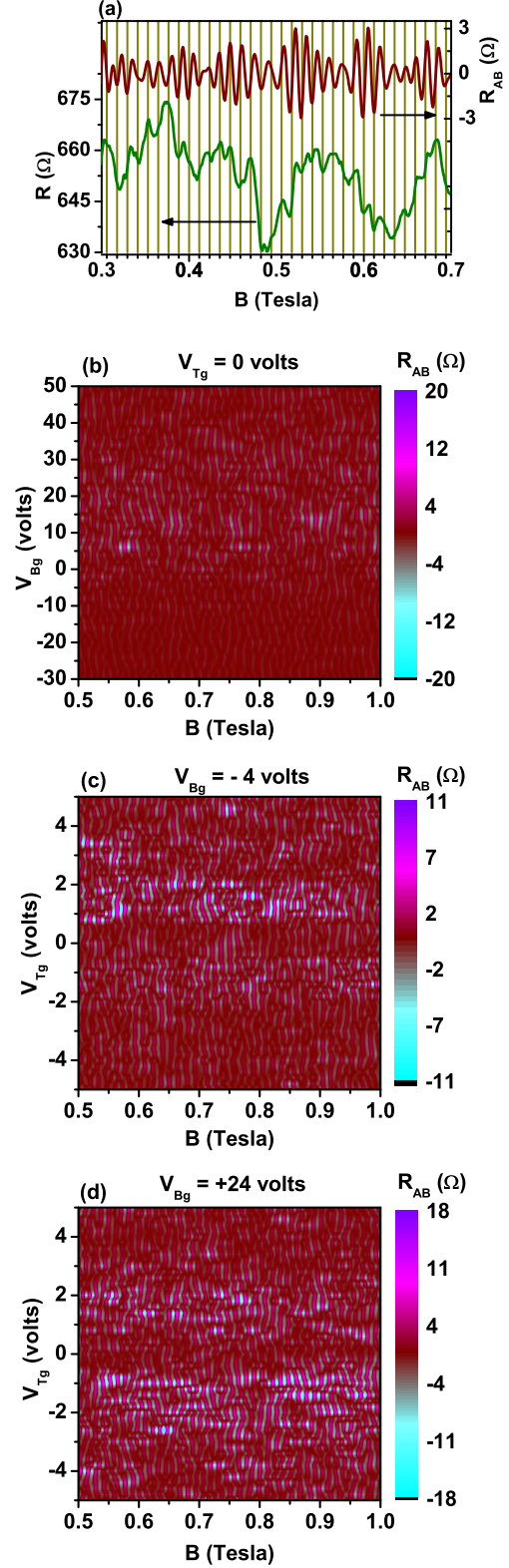


FIG. 2: (a) Resistance and the oscillating part of the resistance as a function of magnetic field for  $V_{Bg} = -4$  V and zero  $V_{Tg}$ . The average periodicity (marked by vertical lines) is  $\approx 12$  mT.  $R_{AB}$  as a function of magnetic field and (b) back gate voltage for  $V_{Tg} = 0$  V, and top gate voltage for (c)  $V_{Bg} = -4$  V and (d)  $V_{Bg} = +24$  V. Clear oscillations are visible for all combinations of back gate and top gate voltages.

the resistance ( $R_{AB}$ ). Fig. 2(a) shows magnetoresistance data for  $V_{Bg} = -4$  V with zero top gate voltage (the graphene sections in both arms of the interferometer are p-type in this case). A pronounced resistance oscillation is visible in the raw data. The oscillating part of the resistance shows that the period of  $R_{AB}$  is about 12 mT. For  $h/e$  Aharonov-Bohm oscillation, the observed period corresponds to a ring with a radius of 330 nm which is in reasonable agreement with the radius of our device. At a bias current of 10 nA, the peak-to-peak amplitude of  $R_{AB}$  is up to  $\sim 3\%$  of the total resistance.

In Fig. 2(b) we show the variation of  $R_{AB}$  as a function of magnetic field for various back gate voltages with zero top gate voltage. It is evident that oscillations are observed over the entire range of back gate voltage and magnetic field (also in supporting material, Fig. S3). For a fixed magnetic field,  $R_{AB}$  shows oscillatory behavior as a function of gate voltage. In Fig. 2(c) we show  $R_{AB}$  as a function of magnetic field for various top gate voltages and a fixed ( $-4$  V) back gate voltage. It is important to note that application of the top gate voltage does not destroy the Aharonov-Bohm oscillations: they are clearly visible even when the carrier types in the two arms of the ring are different. Observing the Aharonov-Bohm oscillations clearly demonstrates quantum interference between electron-type states in graphene in one arm and the hole-type states in the other arm. Similar results were obtained for a fixed positive back gate voltage as a function of top gate voltage (Fig. 2(d)). We find pronounced Aharonov-Bohm oscillations for all possible combinations of the carrier types in the two arms: p-p\*, n-n\*, p-n\* and n-p\*.

We do not observe any higher harmonics (those with periodicity  $\Phi_0/n$  where  $n$  is an integer) as a function of top gate voltage for any value of the back gate voltage. Also, the nature of the oscillations remains the same at relatively high magnetic field (up to 8 Tesla, the maximum field used in our measurements). This indicates that the main contribution to the Aharonov-Bohm oscillations comes from the direct paths through the arms of the ring [21, 23]. The overall resistance increases with increasing magnetic field and the oscillations survive even at high field, but no significant reduction or increase of the oscillation amplitude was observed as a function of the magnetic field (supporting material, Fig. S4), in contrast to previous observations [13–15]. An increase in the oscillation amplitude has been observed previously in graphene nanorings in the high field region [13], and was suggested to be due to orbital effects [13, 14] or scattering on magnetic impurities [14].

In contrast to the previous work on graphene rings [13–16], we find pronounced Aharonov-Bohm oscillations at the Dirac point (shown in Fig. 3(a), 3(b) and supporting material, Fig. S3). The r.m.s. value of the oscillation amplitude ( $\Delta R_{rms}$ ) increases as the back gate voltage approaches the Dirac point and becomes maximum at

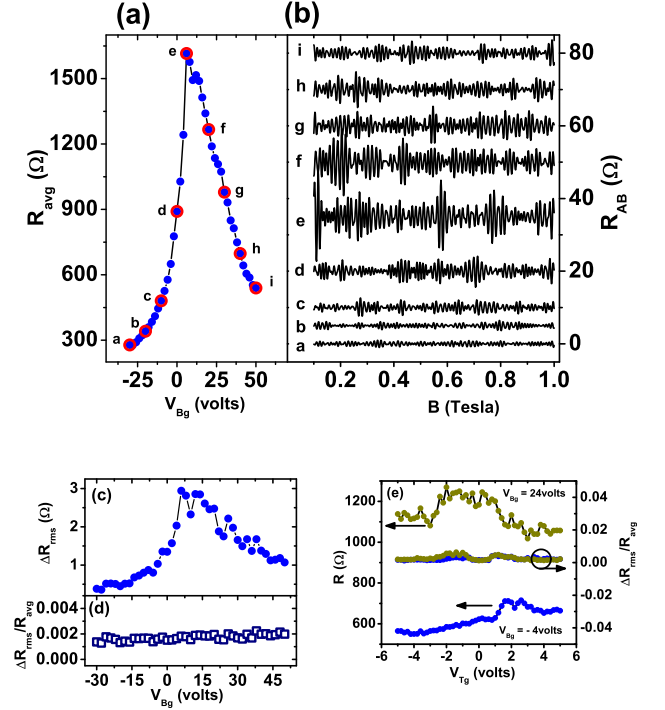


FIG. 3: (a) Average resistance (averaged over the entire magnetic field scan from 0 to 1.05 T) as a function of back gate voltage for zero top gate voltage. The  $R_{AB}$  values measured at different back gate voltages (indicated by solid circles in (a)) are shown in (b), offset for clarity. (c)  $\Delta R_{rms}$  as a function of back gate. It is clear that it follows the same trend as  $R_{avg}$  shown in (a). (d)  $\Delta R_{rms}/R_{avg}$  as a function of  $V_{Bg}$ . (e) Variation of  $R$  and  $\Delta R_{rms}/R_{avg}$  as a function of  $V_{Tg}$  for  $V_{Bg} = 24$  and  $-4$  V.

that point (as shown in Fig. 3(b) and (c)). Fig. 3(d) shows  $\Delta R_{rms}/R_{avg}$ , where  $R_{avg}$  is the resistance averaged over the entire magnetic field scan for fixed back and top gate voltages, as a function of back gate voltage for zero top gate voltage. It is clear from the data that the value of  $\Delta R_{rms}/R_{avg}$  is mostly independent of the back gate voltage. This indicates that the visibility of  $R_{AB}$  remains unaffected by the back gate voltage and  $\Delta R_{rms}$  shows a linear dependence on  $R_{avg}$  (supporting material, Fig. S5) [13, 20, 25]. Similar results are obtained as a function of top gate voltage for a fixed back gate voltage (Fig. 3(e)). For a fixed (positive or negative) back gate voltage  $\Delta R_{rms}/R_{avg}$  shows similar behavior, with similar amplitude for both positive and negative top gate voltages. We conclude that the nature and the visibility of the Aharonov-Bohm oscillation remain the same, regardless of whether the carrier types are the same (n-n\* or p-p\*) or different (n-p\* or p-n\*) in the two arms of the interferometer.

It has been demonstrated that electron-hole puddles are present at the charge neutrality point and that these puddles contribute to the observed non-zero conductivity

at the Dirac point [12, 26–29]. The typical size of the puddles is found to be on the order of 20nm, which is smaller than the gap between the gold electrodes in our samples. Our observation of pronounced Aharonov-Bohm oscillations at the Dirac point shows that the charge transport through these puddles preserves phase coherence. This is also consistent with our observation of phase coherence away from the Dirac point, in the case when the charge carriers are different in the two arms of the interferometer.

Furthermore, the edge of the top gate on some samples (such as the one pictured in Fig. 1.b.) was between the gold electrodes, allowing us to create a pn-junction in one of the arms of the interferometer. Clear AB oscillations were observed in that case as well. The amplitude of the oscillations was slightly asymmetric as a function of the top gate voltage, which might be expected for Klein tunneling in smooth pn junctions [30, 31].

The observation of phase coherence in the interferometer is further supported by the measurements of the temperature dependence of the oscillation amplitude for various back gate and top gate voltages. We found that, irrespective of all possible combinations of the back gate and top gate voltages,  $R_{AB}$  shows a  $T^{-1/2}$  dependence (shown in Fig. 4(a)) between 250 mK and 1.4 K. Such temperature dependence of Aharonov-Bohm oscillations has been observed before in various materials, including graphene [13, 14, 32], and has been attributed to the loss of phase coherence due to thermal averaging [32]. With increasing temperature, the sample resistance decreases (Fig. 4(b)) but this change is not significant ( $< 10\%$ ), whereas the decrease in  $R_{AB}$  is large ( $> 200\%$ ). The diminishing amplitude of the oscillations  $R_{AB}$  reflects the loss of phase coherence with increasing temperature. We found all the features of the samples to be robust and the data were reproducible even after several warm-up and cool-down cycles over months.

Our work represents a clear demonstration of quantum interference between electrons and holes and the efficient transmission of phase information between the electron-type and hole-type regions. These measurements can also give a direct estimate of the lower limit of the phase coherence length at the Dirac point.

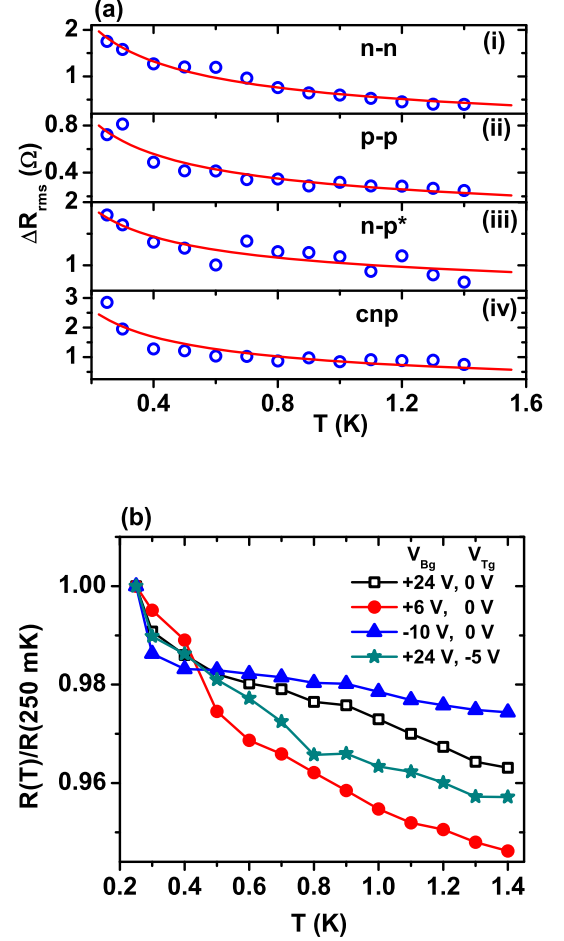


FIG. 4: (a) Temperature dependence of the  $\Delta R_{rms}$  for various back gate and top gate voltages. (i)  $V_{Bg} = 24 \text{ V}$ ,  $V_{Tg} = 0$ ; both the arms have n-type carriers (n-n\*). (ii)  $V_{Bg} = -10 \text{ V}$ ,  $V_{Tg} = 0$ ; both arms are p-type (p-p\*). (iii)  $V_{Bg} = 24 \text{ V}$ ,  $V_{Tg} = -5 \text{ V}$ ; one arm is n-type, and the other arm is p-type (n-p\*). (iv)  $V_{Bg} = 6 \text{ V}$ ,  $V_{Tg} = 0$ ; charge neutrality point (cnp). (b) Variation of resistance (normalized by the 250 mK values) as a function of temperature has been shown for the above combinations of  $V_{Bg}$  and  $V_{Tg}$ .

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