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Ultrahigh speed graphene diode with reversible polarity

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ABSTRACT

The ability to tune the carrier-type concentration ratio with applied field along with a mean-free path length approaching 1 μ m in graphene enables a new diode in which the diode polarity can be reversed. The diode consists of a thin graphene film with a geometric asymmetry that determines a preferred direction for charge-carrier transport, independent of whether the carriers are electrons or holes. We fabricated submicron geometric diodes by patterning and etching exfoliated graphene. Applying field-effect voltages to the substrate, we reversed the carrier type and demonstrated reversal of the diode polarity. The graphene geometric diodes exhibited rectification at 28 THz, opening the way to ultrahigh speed applications for these versatile devices.

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1. Introduction

Along with its promising physical and optoelectronic properties, graphene has the potential to form terahertz diodes [1,2]. Optical response [3] and near-DC diode operation have been demonstrated in graphene p–n [4,5] and Schottky junctions [6,7]. Because its mean-free path length approaches 1 μ m [8] and its conical bandstructure allows the dominant carrier-type to be tuned with applied field [8,9], a new graphene diode is possible in which the diode polarity can be reversed.

In conventional semiconductor diodes formed from p–n junctions or metal contacts, the direction of asymmetry in the current–voltage [I(V)] characteristics is fixed. Several reversible polarity devices have been reported recently in other materials, including a reversible-polarity ratchet device for magnetic flux vortices in superconductors [10], and a device composed of a ferroelectric material in which the electrical polarity is reversible [11]. With a field-effect configuration excess charge is induced in a current-carrying layer by applying a voltage to an electrode that is electrically isolated from it. In a conventional diode such induced charge cannot affect the diode polarity, but in carbon nanotubes it can affect the dominant carrier type (electrons or holes). A carbon nanotube that bridged two dissimilar metals produced a reversible polarity with gate field due to interaction of the metals with the dominant carrier [12].

Similarly, applying a gate voltage in graphene induces charge that causes the Fermi level to shift continuously from the valence band to the conduction band, changing the dominant carrier type from holes to electrons [8,9]. Conversion of this change of carrier type into a reversal of diode polarity is a function provided by a new type of geometric diode. Device geometry was used previously in semiconductors to form a four terminal, fixed polarity rectifier that exhibited rectification up to 50 GHz [13]. We describe an ultra-fast graphene geometric diode having the usual two terminals plus a gate electrode used to tune the I(V)characteristics and reverse the polarity with applied voltage.

2. Device concept

The operation of geometric diodes can be visualized using the Drude model for charge conduction [14], depicted in Fig. 1(a), where charge carriers are shown moving through an asymmetric planar structure. Charges undergo ballistic transport until they suffer a collision or are reflected off an edge. In the simplest case we assume that the reflections are specular. After each collision the carriers are launched again, moving at the Fermi velocity in a random direction modified slightly by applied electric fields. Leftward-moving carriers in the right-hand region are likely to encounter a vertical edge that causes them to reverse direction. On the other hand, rightward moving carriers in the left-hand region are likely to encounter a diagonal edge that funnels them towards the aperture. In this way carriers move more easily from left to right. Forward bias corresponds to an applied field that drives carriers in their preferred direction, and reverse bias is of the opposite polarity. Thus, a structural asymmetry gives rise to an electrical asymmetry [15].

The geometric effect is independent of carrier charge type so that the diode polarity depends upon the sign of the dominant carrier. For holes, forward bias corresponds to a field that drives

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Fig. 1. Depictions of a geometric diode. (a) Schematic top view of a geometric diode. In the region to the right of the aperture charges moving leftwards are deflected to the right due to the vertical edge, while charges in the left region moving rightwards collide with the slanting edge, and funnel through the aperture. Inelastic scattering resets the trajectory to a random direction modified by the applied electric field. A charge carrier near the aperture senses the geometric diode made from graphene having a neck width of 75 nm and shoulder width of 400 nm. Rounding at the neck due to e-beam resist resolution reduces the effectiveness of the geometric asymmetry. The height is shown by the color scale on the right hand side. The observed surface texture of the graphene appears to be a consequence of substrate roughness.

them rightward, while for electrons the forward bias field that drives them rightward is of the opposite sign.

For the asymmetric geometry to be effective in controlling the carrier flow the carrier mean-free path length (MFPL) must be on the order of or greater than the neck width. For smaller MFPLs scattering resets the trajectory of the charge before it encounters the boundaries. Because the MFPL can be relatively large in graphene, on the order of several hundred nanometers even at room temperature, it is feasible to fabricate devices with the required dimensions.

3. Device fabrication and measurement

We fabricated the geometric diodes using exfoliated graphene [8] applied to an oxidized silicon wafer (90-nm thick SiO₂). Ti/Au (10/40 nm thickness) electrodes and antennas were deposited by evaporation and patterned using lift-off with PMMA electron-beam resist. The graphene was patterned using electron-beam lithography (JEOL JBX-9300FS) with maN negative resist followed by a low-power oxygen-plasma etch. The atomic force microscope (AFM) image of the device was obtained using a Veeco Dimension 3100 AFM in tapping mode with a Tap300-G silicon AFM tip, made by BudgetSensors. As shown in Fig. 1(b), structures with a 75 nm neck and 400 nm shoulder were obtained. The surface texture of the

graphene is typical of what we observe and appears to be a consequence of substrate roughness. After exfoliation and patterning, the graphene had a MFPL of 50 nm, as determined from the conductivity versus gate voltage (V_G) [16] measured in a region adjacent to the diode. Thus it marginally met the criterion that the neck width be on the order of or smaller than the MFPL. Improved processing is expected to result in a higher MFPL.

The configuration used to measure the electrical characteristics, including a gate formed by the silicon substrate, is shown in Fig. 2. A four-point electrode configuration was used, in which the drain-source voltage (V_{DS}) was measured between the inner top electrodes using a high-impedance voltmeter and the current was measured through the outer top electrodes for a range of applied voltages. Because the current between the inner electrodes was negligible virtually no voltage was developed between the contacts and the graphene, even if Schottky barriers were present. Because no voltage was applied between the inner electrodes the formation of voltage-induced p-n junctions in the vicinity of the electrodes [17] was avoided. To reduce the hysteresis due to charging of graphene [18] and to prevent overheating, channel B of a Keithley SourceMeter 2612 provided a pulsed drain-source current. Channel A was used to apply a constant gate field. The gate voltage (V_G) was applied to a contact on the back of the silicon substrate to induce a change in the graphene charge concentration. Measurements were carried out in a probe station in air at room temperature under computer control.

The V_{DS} pulse was generated in the following order: first a positive voltage V_i for 23 µs, then a reset to 0 V for 5 s, and then a negative voltage $-V_i$ for 23 µs. The sequence was repeated for each voltage. The magnitude of V_i was increased from 0 V to 1.5 V in steps of 0.1 V. The V_G corresponding to the minimum conductivity shifted from 24 V for the measurements of Fig. 4 to 30 V for the measurements of Fig. 3, carried out a day later. The shift was likely caused by water absorption due to exposure of the graphene to moisture in the air [8].

Measured I(V) characteristics matched simulated characteristics, found by evaluating the current in a Monte Carlo simulation of Drude charge carriers over a range of voltages [19]. We also modeled similar diode configurations quantum mechanically using the non-equilibrium Green's function method, and obtained consistent I(V) asymmetry [20].

4. Results

A reversal of the diode polarity occurs as the dominant carrier type is reversed with gate voltage. Current–voltage characteristics providing evidence for the geometric effect and the reversible polarity of the diode given in Fig. 3(a). Room temperature I(V)



Fig. 2. DC current-voltage measurement configuration using four-point probe top electrodes and a back gate contact. Current is supplied between the outer electrodes, and voltage V_{DS} is measured between the inner drain-source electrodes, circumventing contact resistance effects and the formation of voltage-induced p-n junctions in the vicinity of the inner electrodes [17]. For field-effect measurements voltage V_G is applied to the silicon substrate, which forms the gate electrode.



Fig. 3. Measured transport characteristics as a function of drain-source voltage for two gate voltages. (a) Current, (b) differential resistance, and (c) responsivity are plotted as a function of drain-source voltage (V_{DS}) at room temperature. Due to a reversal of majority carrier type, the diode reverses its polarity about the conductivity minimum, which occurs at high gate voltages. With holes as the majority carriers for V_G =20 V, the higher-current direction is left-to-right in Fig. 1, leading to a higher current at positive bias. The behavior reverses for electrons, which dominate for V_G =40 V.

curves for one value of $V_{\rm G}$ on either side of the conductivity minimum are shown in Fig. 3(a). For $V_{\rm G}$ =20 V p-type carriers dominate, causing larger current for $V_{\rm DS}$ > 0. For $V_{\rm G}$ =40 V n-type carriers dominate and the larger current occurred at $V_{\rm DS}$ < 0. This asymmetry is more evident in the differential resistance, as shown in Fig. 3(b). Although the nonlinearity of these devices is small, the responsivity shown in Fig. 3(c), a measure of rectified DC current as a function of the applied AC power [21], is already substantial. The devices are expected to show greater asymmetry and curvature by decreasing the neck width, reducing the neck rounding, and using graphene with larger MFPLs. Clearer evidence for the diode polarity reversal is given in Fig. 4. As shown in Fig. 4(a), a minimum in the conductivity versus V_G occurred at $V_G = 24$ V, which corresponded to the gate voltage that shifted the Fermi level to the Dirac point, the energy level between the conduction and valence bands [22]. For V_G below 24 V holes dominated while electrons dominated for higher V_G . This reversal is more evident in Fig. 4(b), where the ratio of the forward-to-reverse current asymmetry is plotted as a function of V_G . To verify that these effects were due to the geometrical asymmetry, we carried out these measurements on a symmetric-junction device having similar dimensions and neck width and found no electrical asymmetry (see Supplementary data).

For high frequency applications, a key advantage of the geometric diode over other configurations is its ultra-low capacitance, which we have calculated to be only several attofarads for ideal graphene. This is because the device is planar, as opposed to most other diodes that have a parallel plate configuration, which gives rise to much larger capacitances. Even devices in which the intrinsic response time is on the order of femtoseconds, such as metalinsulator-metal tunnel diodes, are limited to lower frequency operation because of their resistance-capacitance (RC) time [24].



Fig. 4. Measured transport characteristics as a function of gate voltage for the diode of Fig. 3. (a) Measured drain-source current (I_{DS}) is plotted versus gate voltage (V_G) for fixed values of drain-source voltage (V_{DS}) for the geometric diode at room temperature. (b) Forward-to-reverse diode asymmetry (A) given by the current-ratio ($A = |I_{DS} (+V_{DS})|I_{DS} (-V_{DS})|$) is shown versus V_G . The A is greater than 1 for V_G below 24 V (p-type) and is less than 1 for V_G above 24 V (n-type). The $I_{DS} (V_G)$ plot reveals the change in carrier concentration and type with V_G . At the conductivity minimum, equal contributions from electrons and holes leads to A = 1. This shows that the diode does not just have a reversibly polarity but can also be tuned to have a linear I(V). At high positive and negative V_G the A approaches 1 due to current saturation [23].

To measure the high-speed response of geometric diodes at a frequency well above that of available electronics we used an optical source. Geometric diodes were coupled to metal bow-tie antennas, forming rectennas [21], and illuminated with CO_2 laser infrared radiation having a wavelength of 10.6 μ m. The radiation produced a 28 THz current that was rectified by the diode without any applied bias voltage. This DC response was measured as a function of angle between the polarization of the illumination and the antenna, and exhibited a maximum when the optical field and the antenna were aligned. This showed that the current was indeed produced by the radiation coupled through the antenna [20,25].

5. Discussion and conclusions

The geometric diode has several applications in the near term and potentially more in the future, as electronics catches up to the diode's frequency capabilities. It can be used in high-frequency mixing applications and, coupled to an antenna to form a rectenna [21], it can be used in infrared detectors for imaging arrays, e.g., for night vision, for optical communications, and if the response extends to the visible, for rectenna solar cells. The ability to tune the diode I(V) characteristics with gate voltage allows the resistance of the diode to be matched to the antenna for optimal power transfer.

The ability to reverse the diode polarity opens a range of ultrahigh frequency digital applications. The device can operate as a floating gate digital storage element [26], where a binary voltage applied to the gate determines the polarity of the diode. The state of the memory can be sensed at high speed by applying an AC probe signal to the source-drain electrodes and sensing the polarity of the rectified signal. An ultra-high frequency bistable digital storage element (flip-flop [27]) can be formed in which the DC voltage produced by the diode due to the rectification of an applied AC signal can be used as feedback to maintain the binary state (i.e., polarity) of the diode. The state can be changed by overriding the feedback with an applied voltage corresponding to the new state that is to be recorded.

In summary, we have demonstrated a new planar, asymmetric graphene diode in which the polarity can be tuned and which can operate at ultra-high frequencies.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.ssc.2012.06.013.

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