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Electrical gating and rectification in graphene three-terminal junctions

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ABSTRACT

Graphene was grown on semiinsulating silicon carbide at 1800 °C and atmospheric argon pressure. The all carbon T- and Y-shape three terminal junction devices were fabricated using electron beam lithography. All devices featured the negative rectification effect. The exact properties of the devices like the curvature of the output voltage response can be tuned by changing the branch width in the T- and Y-shape devices. Beside the rectification a switching behavior is demonstrated with the same three terminal junctions.

1. Introduction

Graphene is a fascinating new material, whose properties are very promising for electronic applications [1–4]. Especially the mobility [5,6], the electrostatic control of the carrier type and their concentration [7] and the aggressive scalability of graphene devices [8] offer advantages for deep scaled and high frequency devices. Nevertheless, the unique band structure of large area graphene with no band gap and linear dispersion around the Dirac point [9,10] ask for new concepts to explore graphene's unique capabilities in electronics [11–20]. One promising concept in this respect is the three-terminal junction devices (TTJ) [21]. These T- or Y-shaped devices of sub-micrometer dimensions capitalize on certain characteristics of the nonlinear response regime of charge carrier transport appearing in two dimensional charge carrier gases confined laterally in channels [22,23]. In this devices geometrically [24,25] or electrically [26] controlled charge transport as well as a rectification [22,27] can be used for information processing and was demonstrated on III–V heterostructures. Recently, the rectification effect was also demonstrated on graphene [28–33]. As a first application the frequency doubling was realized using graphene TTJ devices [30]. In contrast to III–V heterostructures where only on carrier type is available, the graphene TTJ allows the electrical tuning of the rectification effect from negative to positive rectification in dependence on the carrier type in the device, negative rectification in case of electron conduction and positive rectification if the holes are responsible for the charge transport [28,32]. Many attempts have been made to explain this effect based on the propagation of electromagnetic waves [34], ballistic [35,36] or diffuse–ballistic [37] transport. Here we show a dependence of the rectifying effect on the geometry of graphene TTJ which supports the theory set forth by Sadi et al. [37].

Yet actually the original idea behind the TTJ design was to obtain a new electronic switch [24] or an in-plane gated field effect transistor [38]. With TTJs made of carbon nanotubes a switching behavior [39] and differential current amplification [40] was actually observed. Here we report the observation of such behavior in TTJs made of graphene.

2. Experimental

Epitaxial graphene was grown on Si-face semiinsulating silicon carbide. Before the growth process the SiC underwent a direct capping procedure during which it was annealed with a graphite cover

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at 1800 °C for 3 min. Thereby a stepped surface morphology was obtained [41].

Consecutively graphitization was realized by heating the SiC at a rate of 10 K/min up to 1800 °C in a graphite furnace in an argon atmosphere at normal pressure. Raman spectroscopy revealed the formation of 1–4 layers of graphene sheets with sizes up to several micrometers on the SiC surfaces [41]. Hall measurements of the grown graphene layers were carried out with an Accent Hall measurement system in van der Pauw geometry. A Hall mobility μ of 1000 $\text{cm}^2/\text{V/s}$ and a sheet carrier concentration n_s between 3 and $5 \times 10^{12}\ \text{cm}^{-2}$ was obtained. Using a semiclassical model the electron mean free path l_e can be calculated as $l_e = (h/2e)\,\mu\,(n_s/\pi)^{1/2}$, where h is the Planck constant and e is the elementary charge [42]. The estimated mean free path of the electrons is between 20 and 26 nm.

These graphene sheets were structured into T- and Y-shaped structures with graphene contact pads at the end of each terminal with an electron beam lithography system Raith 150 using negative tone electron beam resist HSQ. Next the graphene was etched with oxygen plasma in an electron cyclotron resonance plasma etching apparatus. Afterwards the HSQ was removed by 10 min exposure to HF-vapor.

The graphene contact pads, included in the design, had a size of $90 \times 90\ \mu\text{m}$ and were situated at the end of each of the three terminals giving the ability for electric measurements. This solution is minimizing problems of contact resistance due to the metal graphene interface. Graphite tips were lowered onto these contact pads to allow for electronic measurements with a Keithley SCS 4200. The pads were framed by gold frames to ease finding them during measurement.

The electrical measurements were conducted in two different modes. The rectifying behavior of the three terminal junctions was probed with so called push–pull-measurements. All three branches are contacted. A voltage V_L is applied to one branch and another voltage V_R to another. At the third branch the resulting voltage V_C was measured with a high impedance voltmeter. Push–pull hereby implies that $V_L = -V_R$ while V_L was varied from 0 to 4 V. This setup is shown in Fig. 1.

The switching ability of the TTJ was tested by connecting one branch to mass. At the other a voltage was varied from 0 to 8 V each for a different voltage applied to the third branch. In essence this third branch was hereby considered a gate and the other two branches of the channel as source and gate.

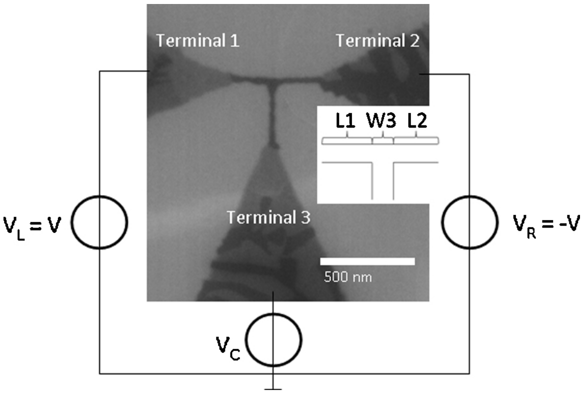

Fig. 1. A typical T-shape TTJ structure made of graphene is shown. The three branches end in larger graphene pads whose beginning can be discerned in this image. These endings are called terminal 1, 2 and 3. The setup of the measurement is sketched around the image of the T-structure. The small inset defines the definition of the device geometry.

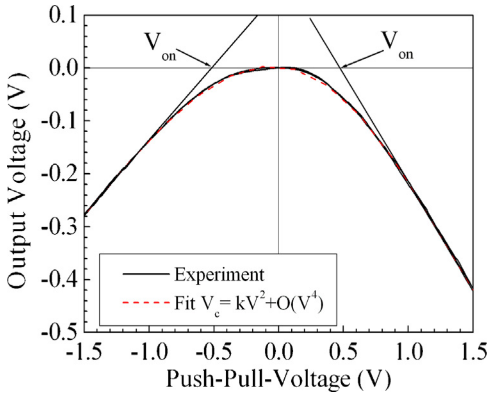

Fig. 2. The output voltage at the centre terminal V_C in dependence on the push–pull-voltage for a T-shape device with a horizontal bar and a vertical bar width of 15 nm for both bars. The experimental output voltage is shown together with the fitted curve. The intersection of the dotted line gives the onset voltage V_{on}.

3. Geometrical dependence of rectifying behavior

A typical device used is shown in Fig. 1. It consists of a T-shape conductor with three ohmic contacts at the end of each branch. The fabricated T-shape devices have horizontal terminals bar widths H of 15 to 150 nm and a length from one terminal end to the other L of approximately 400 nm. The vertical terminal bar width W varied between 13 and 30 nm with respect to the horizontal terminal bar width. L_1 is the length of the left terminal; L_2 is the length of the right terminal and W is the width of the vertical terminal. The overall length of the horizontal bar L is $L = L_1 + L_2 + W$. The Y-shape devices had a symmetrical structure with an angel between the bars of 120°. The bar width varied between 15 and 100 nm and was equal in width for all bars within the limitations of electron beam lithography.

Push–pull-measurements with the circuit setup shown in Fig. 1 of the T- and Y-shaped TTJ structures revealed the characteristic dependence of the electrical response V_C at the central terminal in dependence on the applied push–pull voltage V_{PP}. Even if the third branch is situated exactly half way from the other two branches, the observed potential is negative and not zero as expected from classical transport theory. This behavior has been observed and identified as rectification regardless of whether the horizontal channel is in the diffusive or linear-ballistic regime [22]. A typical dependence of the output voltage V_C at the central branch is shown in Fig. 2 for a T-shape TTJ structure.

The voltage response at the central contact consists of two parts. At low push–pull voltages V_{PP} the voltage response follows the equation [22]:

$$V_C = kV_{PP}^2 + O(V^4), \tag{1}$$

where k is a fitting parameter representing the curvature of the voltage response at $V_{PP} = 0$ V. The constant k is negative if the two dimensional electron gas consists of electrons and positive if the charge carriers are holes. This was recently demonstrated for grapheme TTJs [29–33]. For all fabricated structures regardless of the shape and the geometrical dimensions a down bending of the voltage response V_C was observed which indicates electron transport.

Different attempts have been made to explain the occurrence of this phenomenon [22,37,43]. The most plausible seems to be the one from Sadi et al. as, contrary to others it is not solely based on the assumption of ballistic transport alone [37]. Sadi et al. argue that the electrons in the three terminal junctions undergo a “quasi” ballistic transport. “Quasi” ballistic transport is hereby understood as instances where scattering on boundaries tends toward dominating