Technology Offer

A graphene diode with bias-induced barrier modulation

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Background

Metal-insulator-metal (MIM) diodes are very promising for application as rectennas for solar energy harvesting, photo-detectors and high frequency mixers. Good MIM diode performance requires a high asymmetry, a strong nonlinearity, a large responsively, as well as a low resistance or a high on-current. These figures of merit are mainly determined by the work function difference of the electrodes, and the barrier height between the insulator and the electrode materials. In the design of MIM diodes, a trade-off between these parameters is needed. A high asymmetry requires both, a large work function difference between the two electrodes and a large barrier height, but a too high barrier decreases the on-current or increases the resistance of the device. Moreover, the metal surface of the MIM diodes exhibits a high roughness that results in a non-uniform electric field and a non-uniform tunneling current. Therefore, a diode that overcomes the above-mentioned disadvantages is highly required.

Technology

We offer a new graphene-TiO_x-Ti (Gr-TiO_x-Ti) diode that fulfills the requirements mentioned above. Our Gr-TiO_x-Ti diode features a high asymmetry, a large nonlinearity and a high on-current density. In contrast to MIM diodes, graphene-insulator-metal (GrIM) diodes allow the modulation of the graphene work function and correspondingly the transport barrier height by the bias applied between the graphene and a metal electrode that are separated by an ultrathin layer. The comparison of the proposed operation principle of the GrIM diode with that of a conventional MIM diode is shown in Fig. 1.

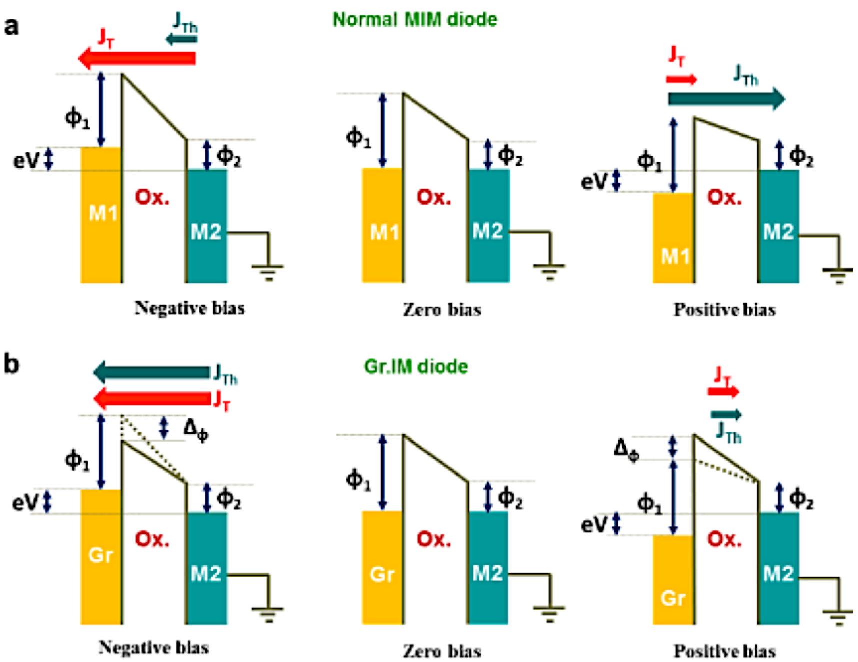

Fig. 1: Operation principle of (a) a conventional MIM and (b) a GrIM diode. Φ_1 and Φ_2 corresponding to the difference between the work function of metal electrodes and the electron affinity of the oxide insulator. J_{Th} (blue-green arrow) and J_T (red arrow) denote the thermionic emission and tunneling current, respectively.

A key feature that allows exploiting the internal barrier height modulation is the TiO_x insulating barrier, which implements a large barrier for holes combined with a low barrier for electron transport. The diode consists of the first electrically conductive graphene monolayer that allows the extensive modulation of the corresponding work function.

The I-V characteristics of our Gr-TiO_x-Ti diode acquired between the four layer-thick graphene sheet and the Ti electrode as well as the effect of temperature on the diode behavior are shown in Fig. 2.

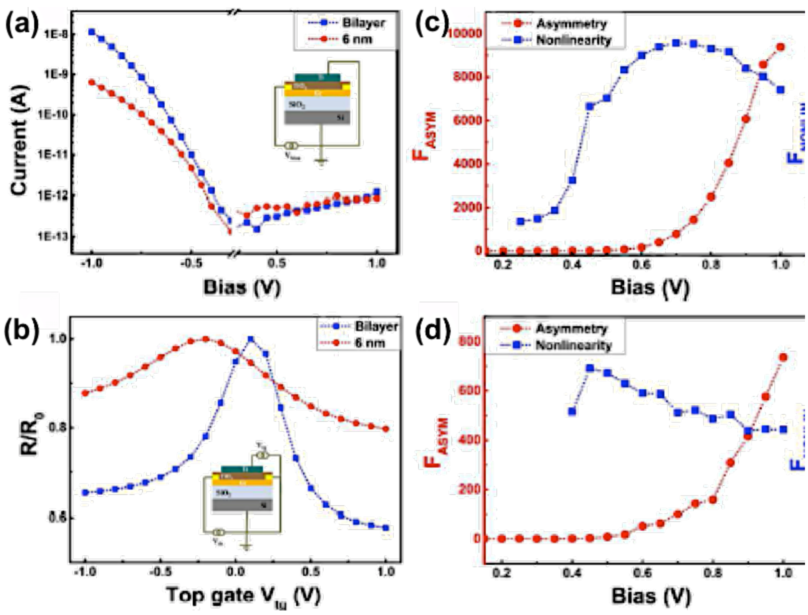

Fig. 2: (a-d) Electrical characteristics of the Gr-TiO_x-Ti diodes in dependence of the graphene thickness. All data were acquired at room temperature. (a) I-V characteristics of two different diodes comprising a graphene bilayer (blue points) and a 6 nm thick graphene sheet (red points), respectively. (b) Normalized resistance of the graphene channel as a function Ti top gate voltage. Plot of asymmetry and nonlinearity vs. bias voltage for (c) a bilayer graphene diode and (d) a Gr-TiO_x-Ti diode comprising the 6 nm thick graphene layer. (e-f) Effect of temperature on the Gr-TiO_x-Ti diode performance. (e) I-V characteristics at different temperatures. (f) Temperature dependence of asymmetry.

The I-V characteristics display a diode-like behavior with a high current under negative bias and a low current under positive bias. The asymmetry reaches up to 9000 (at 1 V) and a corresponding nonlinearity of 8. The performance of the GrIM diode increases with the modulation rate of the barrier potential as a function of applied bias. Accordingly, the diode performance should increase when the thickness of the graphene electrode and TiO_2 layer decreases. For both the positive and the negative bias regime, the current decreases notably with decreasing temperature as shown in Fig. 2e. Likewise, the temperature dependence of the diode asymmetry exhibits a fast decrease upon cooling (Fig. 2f).

Advantages

- Internal modulation of the transport barrier height as a new device operation concept
- High asymmetry (up to 9000 at 1 V), large nonlinearity (up to 8 at 1 V) and high on-current density (0.1 A/cm^2 at 1 V) of the diode
- Balancing of the thermionic and tunneling current
- Usability as a component of high frequency rectenna devices

Literature

Urcuyo R., Duong D. L., Jeong H. Y., Burghard M., Kern K. (2016). *"High Performance Graphene–Oxide–Metal Diode through Bias-Induced Barrier Height Modulation."* Adv. Electron. Mater., 2: 1600223. doi: 10.1002/aelm.201600223

Patent Information

PCT patent application filed in April 2016.