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Cyclotron Resonance-induced Thermionic Emission in Graphene/MoS_2 van del Waals Schottky Junctions

We study detection of infrared light utilizing vertical field effect transistor (FET) with a new mechanism. The detector is based on a vertical FET composed of graphene and MoS_2. We achieved a very high infrared light sensitivity. This detector has the following advantages: (i) Structure is very simple. Owing to its simplicity, we can assemble the detector structure into other 2D material devices. (ii) The detection mechanism is very simple. (iii) This detector uses interface conduction. All the previous graphene detector uses in-plane detection with bolometric, photovoltaic, and photo-thermoelectric effects. Thus we can improve sensitivity by increasing junction area. Here we demonstrate the infrared light detection of cyclotron resonance by using this device.

A schematic of device structure and optical micrograph are presented in Figs. 1(a) and 1(b), respectively. Monolayer graphene (MLG)/few-layer MoS_2/few layer graphene (FLG) heterostructure is fabricated on a 290-nm SiO_2 /p-doped Si substrate by dry transfer method [1,2]. Layer number of MoS_2 and FLG is 9 and 3, respectively. Since the top FLG has high light transparency, we have light absorption in both MLG and FLG. By applying back-gate voltage V_G to the p-doped Si gate, the Fermi level of MLG can be modulated. Measurements were performed at 4 K. A magnetic field was applied perpendicular to the 2D plane. A wavelength-tunable CO_2 laser (λ = 9.28-10.61 μm) was used to irradiate the device through a light pipe. The laser light has the power density of 2.71E-2 Wcm^{-2} with spot size of approximately 30 mm^2.

By using the device, we demonstrate a detection of cyclotron resonance of monolayer graphene. Under a high magnetic field, the energy state of graphene is Landau-quantized and forms a discrete energy levels [Fig. 1(c)]. The inter-Landau level transition (called cyclotron resonance) is induced by light absorption in far-infrared region. In particular, the energy separation between N = 0 and N = 1 at the magnetic field of ~11 T corresponds to ~130 meV. Noticeably, this energy is comparable to the band offset between the bottom of a conduction band of MoS_2 and N = 0 of the graphene as illustrated in Fig. 1(c). The interface between graphene and MoS_2 forms a Schottky junction. Fig. 1(d) shows conductance -V_G plot. Conductance rapidly increases above V_G = 20 V, thus there is no potential barrier above this V_G. Electrons excited from N = 0 to N = 1 under light irradiation of infrared light can overcome the Schottky barrier to flow into the adjacent MoS_2 layer by a thermionic emission process; that subsequently detects through photovoltage.

The photo-induced voltage (V_{ind}) measured under the sweep of both V_G and B is presented in Fig. 2(a). Fig. 2(b) shows a V_{ind}-V_{BG} curve at B = 11 T. There is a remarkable dip at V_{BG} = 10 V and B = 11 T between N = 0 and N = 1. The sensitivity obtained in this device is determined as 2.0E+7 V/W using the power density of the irradiation laser and the area of the junction area. With changing the wavelength of light, the resonance magnetic field changes as shown in Fig. 2(c). We plot this result in a photon energy v.s. magnetic field plane. The experimental results matched well with the calculated Landau level of N = 1 with the Fermi velocity of 1.1E+6 m/s [Fig. 2(d)]. From these results, we conclued that cyclotron resonance was successfully detected in the graphene/MoS_2/few-layer graphene vertical field transfer. Our study shows a high sensitivity detection using the simple heterojunction with graphene. The important finding in the present work is that we have achieved high sensitivity with a simple structure and a simple mechanism without detailed optimization. Therefore, this detection mechanism has a big potential for further developments.

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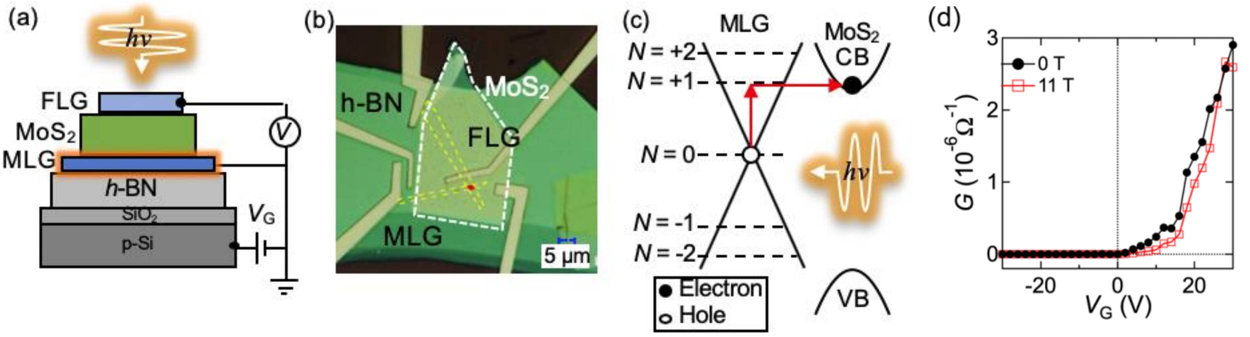

Figure 1: (a) A schematic of the fabricated device. (b) Optical micrograph of the device. (c) The band structure of graphene/MoS_2 junction. (d) Change of the conductance G as a function of back-gate voltage V_G.

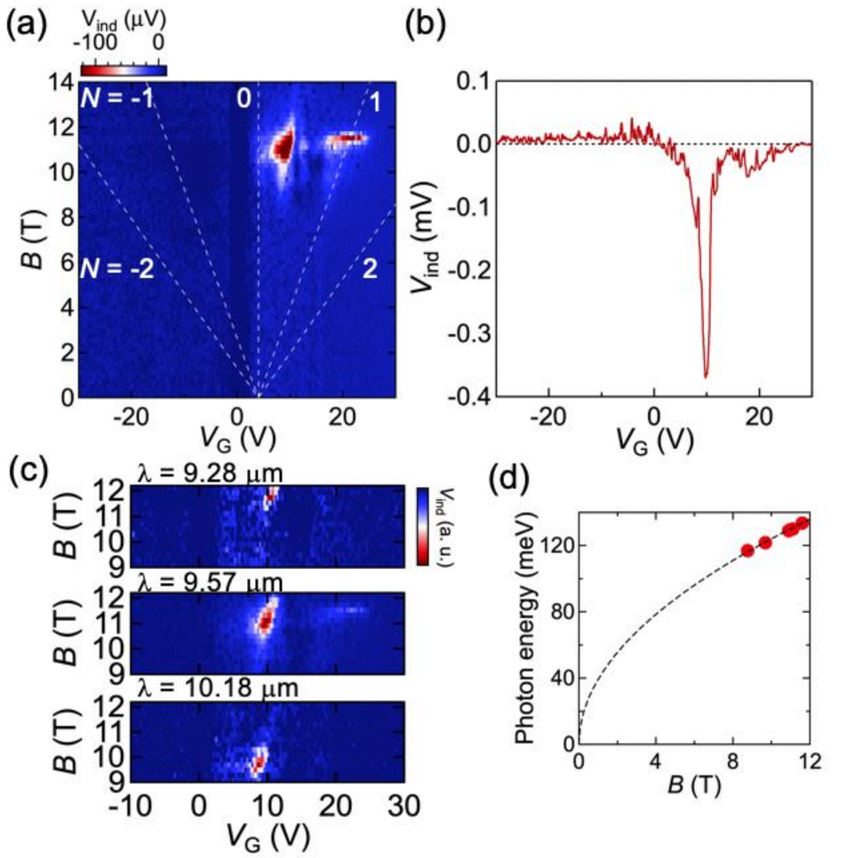

Figure 2: (a) Color plot of the photo-induced voltage. A vertical axis is magnetic field B, a horizontal axis is back-gate voltage V_G. (b) Photo-induced voltage v.s. back-gate voltage V_G at B = 10 T. (c) Color plots of photo-induced voltage obtained by irradiating mid-infrared light of λ = 9.28 μm, 9.57 μm, 10.18 μm. (d) Red dots show the infrared light energy and the cyclotron resonance magnetic field. Calculated energy of Landau level of N = 1 (dashed line)