Toward Topologically Manipulation of Terahertz Photoresponse in Layered Materials

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ABSTRACT

Recently, different layered two-dimensional (2D) materials have been employed as active channels in FET-based THz photodetectors. However, due to the presence of Dirac fermions in the detector topological protection surface states, Topological Insulators (TIs) are considered as promising candidates for long wavelength photon detection. TIs are semiconductors in the bulk, whereas they exhibit well-defined topological surface states (TSS) ,representing ideal systems for devising FETs for THz photodetection. The joint presence of narrow bandgap and a 2D electron gas (2DEG) arising from TSS enables the realization of excellent Ohmic contacts. Here, we selected several different layered materials to construct a terahertz detector, such as Bi_2Se_3 and $TaSe_2$. The achieved photoresponse stems from the asymmetric scattering of TSS driven by the localized surface plasmon-induced terahertz field, which ultimately produces direct photocarrier generation beyond the interband limit. The device enables high responsivity in the self-powered mode and the bias mode even at room temperature. The achieved responsivity is over 75A/W, with response time shorter than 60μs in the self-powered mode, which demonstrating the RT effectiveness of the detector.
Keywords: Topologically Manipulation, photodetector, Terahertz Waves

1.1 INTRODUCATION

Nowadays, terahertz (THz) radiation represents one of the most promising technologicalchallenges[1], in consideration of its wide application capabilities, including non-invasive imaging[2-4], remote sensing[5], and communication[6]. However, the large-scale diffusion of new disruptive technologies based on THz waves requires progressive development of (i) coherent THz sources and (ii) sensitive, portable photodetectors. These crucial priorities have encouraged research activities on a wealth of novel materials, whose physicochemical and electronic properties are suitable to fulfil detection requirements. Therefore, a new detection scheme concurrently providing fast response time, operation at RT, good sensitivity and ease of fabrication is highly desired. Among the various RT detection technologies recently developed, THz photodetection with field-effect transistors (FETs) based on III-V semiconductors[7] is particularly promising for their high efficiency in both speed response and responsivity. Moreover, FETs can be easily integrated in chips. In FETs, the plasma-wave photodetection mechanism is activated whenever an electromagnetic wave in the THz range irradiate the source and/or the gate electrodes of the FET. The excitation of plasma waves induces a modulation of both the carrier density and the velocity in the active channel of the FET and, subsequently, a direct photovoltage signal is originated between the source and drain[8].

Recently, Topological Insulators (TIs) have attracted considerable attention. TIs are semiconductors in the bulk, whereas they exhibit well-defined topological surface states (TSS) forming a Dirac cone around the Γ point. So we propose an innovative strategy for the direct detection of millimeter and THz photons at RT, based on a subwavelength metal-TI-metal (MTM) heterostructure. A subwavelength metal contact is used to convert the incident long-wavelength photons into localized surface-plasmon field at the metal-TI interface, which drives back and forth the TSS.

2. DATA AND RESULTS

Figure 1a illustrates the devised MTM heterostructure, with a Bi_2Se_3 flake serving as an active material in the channel. One should consider that the point-group symmetry of the Bi_2Se_3 bulk crystal is D_{3v}, which includes the center of inversion, whereas the surface lacks the space inversion and its point group is C_{3v}. This implies an anisotropic scattering of TSS under the action of an electric field, resulting into a direct photocurrent in response to the ac electric field. Therefore, when the device is irradiated with millimeter and THz radiation, a direct photocurrent is generated in response to the ac electric field, due to the interplay of the TSS and the incident radiation. When a bias electric field along the photovoltaic potential is applied on the structure, the additional photocarrier injection driven by the photogalvanic effect, the resistance of MTM device changes under a fixed voltage, leading to the variation of output current. Under a finite electric field, a photocarrier will be accelerated from one side of metallic contact toward other side. According to the principle of charge conservation, when the photocarrier reaches the contact another charged carrier will be replenished from the contact to the channel. The same process reiterates several times, until the THz light is blocked and carriers are annihilated with lifetime Γ_{life}~60 μs, leading to the large photoconductive gain. Figure 1c displays the dependence of the responsivity (R) at 0.12 THz electrical bias. Photoresponse shows a nearly linear dependence on the bias voltage, with an evident photovoltaic effect around the zero-bias voltage. Additionally, the responsivity (R) can be increased from 75 up to 475 A/W by applying a bias voltage of only 50 mV. The responsivity exhibits no obvious reduction even with a power density changed by two orders of magnitude. This is essentially different from photon detection via quantum transition and can be attributed to TSS.

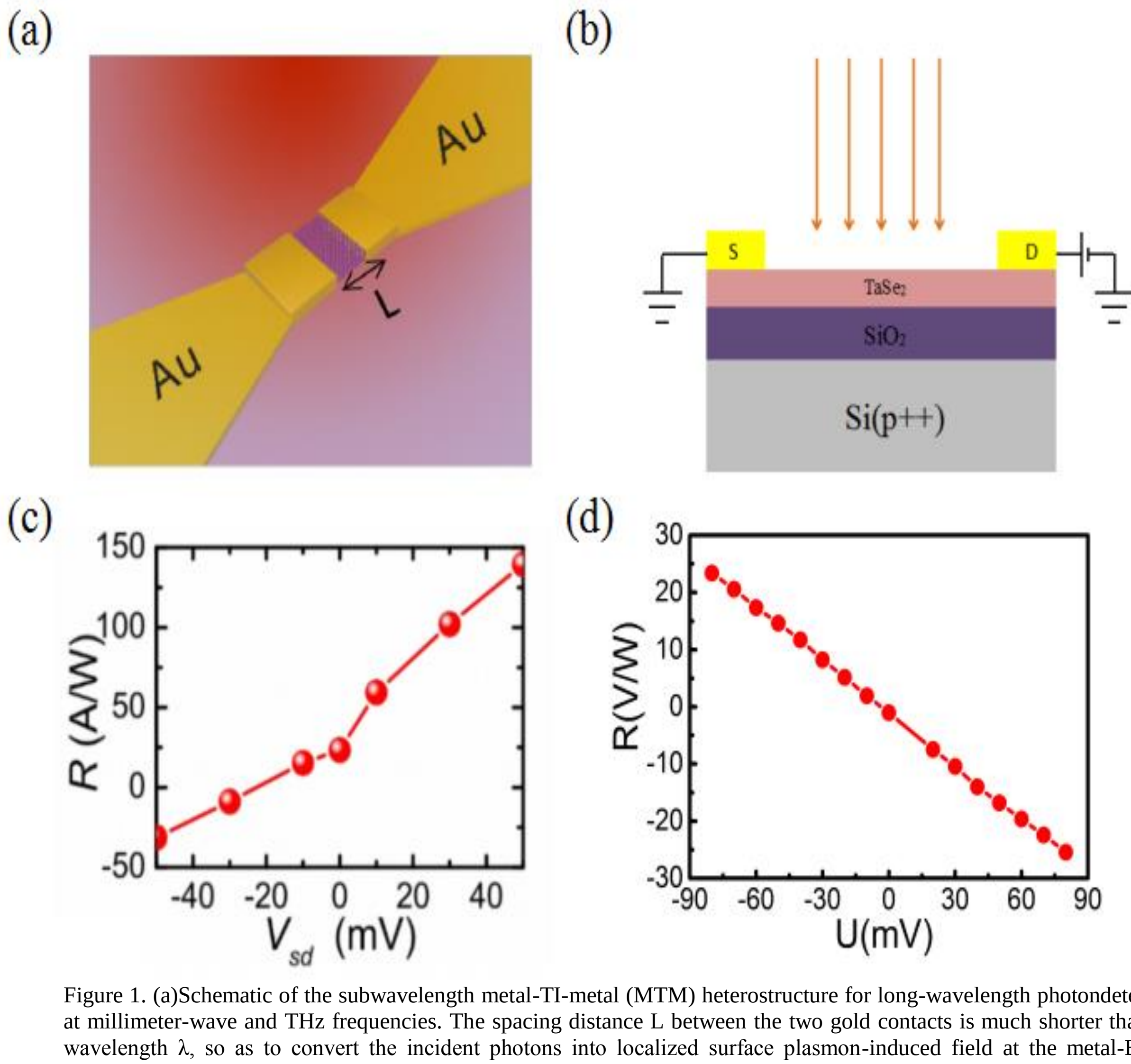

Figure 1. (a)Schematic of the subwavelength metal-TI-metal (MTM) heterostructure for long-wavelength photondetection at millimeter-wave and THz frequencies. The spacing distance L between the two gold contacts is much shorter than the wavelength λ, so as to convert the incident photons into localized surface plasmon-induced field at the metal-Bi_2Se_3 heterointerface. (b)Schematic cross section and equivalent circuit of the detector. (c)The responsivity dependence(Bi_2Se_3) on bias voltage under irradiation with 0.12 THz radiation. (d)The responsivity of the device($TaSe_2$) under 120GHz radiation.

In addition, we also fabricated the $TaSe_2$ device. $TaSe_{2,}$ the charge density wave materials that also belong to the topological range, using the ultraviolet (UV) lithography, followed by metal evaporation techniques to make drain and source contact electrodes. The schematic cross section of the detector are shown in Fig1b. Adding a bias voltage of 80mV at room temperature, the device's responsivity has reached 25.5V/W. Here, the responsivity ($R=I_{ph}/PS$) is defined as the ratio of the generated photocurrent (I_{ph}) to the optical power (P) impinging onto the detector (S: illuminated area). It can also be seen from Figure 1d that the device responsivity and the bias voltage change linearly. When no bias is applied to the device, the responsivity is 1.5V/W. Relatively speaking, an improvement by orders of magnitude can be achieved by exploiting the photoconductive gain, by imposing a small bias voltage.

3.CONCLUTION

In summary, we have explored and experimentally validated the topologically manipulation of terahertz photoresponse in layered materials. Our experiments demonstrate RT effectiveness of the detector, showing both high sensitivity and fast response for the self-powered mode and the bias mode. Our work opens up a way to activate, probe and exploit the TSS for devising novel THz devices, such as alternative structures integrated with metamaterials, so as to properly engineering photonic and electronic behaviors. These results are crucial to bring to fruition TIs in the field of THz optoelectronics, specifically enabling large-area, fast imaging applications.

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