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Active terahertz wave modulator based on molybdenum disulfide

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ABSTRACT

A high-efficiency active terahertz wave modulator based on a molybdenum disulfide (MoS_2)/germanium (Ge) structure was investigated. Spectrally broadband modulation of the THz transmission was obtained using optical control over the frequency range from 0.2 to 2.6 THz. The MoS_2 monolayer structure on germanium demonstrated enhancement of the terahertz modulation depth when compared with those of bare Ge and the graphene/Ge structures. The results show that the MoS_2-based modulator demonstrated even higher modulation efficiency than the graphene-based device. The modulation enhancement mechanism that originated from increased conductivity was analyzed. The optical modulation properties of the MoS_2/Ge device show tremendous promise for applications in terahertz modulation and switching.

1. Introduction

Terahertz (THz) waves, for which the frequency range is 0.1–10 THz, have attracted major research interest because of their unique properties for use in fields including spectrum measurement, public security, imaging and communications [1,2]. Considerable efforts have been devoted to the development of THz sources and detectors. However, the development of an active modulation device is also crucial to the realization of substantial progress in THz applications. Many active modulators have been reported in recent years, including those based on thermally controlled phase change in vanadium dioxide and simultaneous optically and electrically excited artificial negative index materials [3–41]. Some two-dimensional (2D) materials modulator was also been investigated, recently [27–33]. Q. Wen investigated a modulator based on graphene on Ge which has a modulation depth of 83% upon pumping by 1.55μm laser with a power of 400mw [6]. Y. Cao investigated a modulator based on MoS_2 on Si which has a modulation depth of 57.5% at a pump power of 1.5W [27]. However, these devices also have room for improvement in terms of their costs, fabrication processes, high pumped power, response speeds and modulation depths.

Monolayer molybdenum disulphide (MoS_2) has recently been realized using physical and chemical methods [27–29]. The available two-dimensional (2D) materials, i.e., monolayer MoS_2 and graphene, have familiar structures but have different energy band structures [20,30]. Monolayer MoS_2 has a direct band gap of 1.8 eV, while graphene has no energy band gap [33–36]. Ge is a typical kind of semiconductor and the pumped laser with 1.3–1.55μm is enough to exciting photon-generated carriers since Ge has a small bandgap of 0.66 eV. Another advantage of Ge compared to silicon is that Ge has higher bulk mobility for both electrons and holes, which should ideally correspond to an increase in surface mobility and ultimately an increase in the device performance such as modulation depth and speed [6].

In this work, a high-efficiency active THz wave modulator based on molybdenum disulfide has been investigated. Spectrally broadband modulation of the THz transmission was obtained by optical control of the device over the frequency range from 0.2 to 2.6 THz. The monolayer MoS_2 on Ge structure demonstrates a terahertz modulation depth and is compared with bare Ge and graphene/Ge based devices. The modulation enhancement mechanism, which originated from an increase in the conductivity, was analyzed.

2. Experimental details

The monolayer MoS_2 and graphene samples were grown on N-doping Ge substrates by chemical vapor deposition (CVD). The areas of both the MoS_2 and graphene films are approximately 1 cm^2 (i.e., 1 cm × 1 cm). The Raman spectra of the monolayer MoS_2 and

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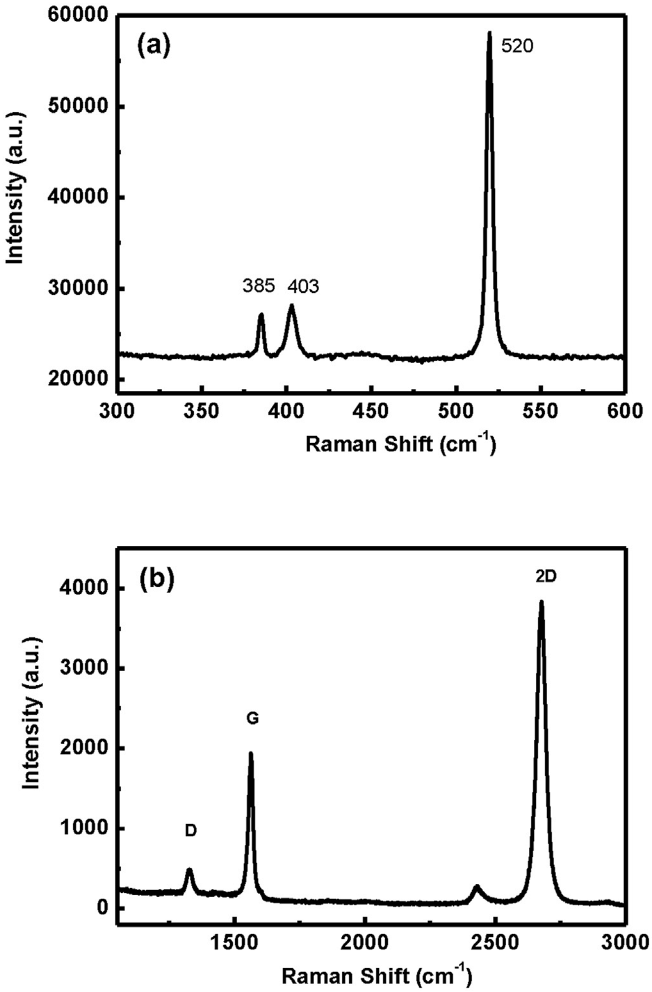

Fig. 1. Raman spectra of (a) monolayer MoS_2 and (b) monolayer graphene on SiO_2 substrates.

graphene samples on SiO_2 substrates when excited by 532 nm light are shown in Fig. 1(a) and (b), respectively. Fig. 1(a) shows that the monolayer MoS_2 film structure is confirmed by its Raman spectrum, in which the peaks are located at 385, 403 and 520 cm^{-1} [42]. Fig. 1(b) shows that the monolayer graphene structure is also confirmed by its Raman spectrum, in which the 2D peak is located at 2677 cm^{-1} and the G peak is located at 1564 cm^{-1} [43]. A conventional THz time domain spectroscopy (THz-TDS) system shows as Fig. 2(a) was used to measure the THz transmission characteristics through the MoS_2/Ge hybrid structure. The generated THz pulses had a normal angle of incidence relative to the hybrid structures, while the external continuous wave (CW) diode laser had an oblique angle of incidence. The external CW laser operated at a wavelength of 450 nm. The modulated THz waveform was detected using a ZnTe crystal in combination with an electro-optic sampling technique.

3. Results and discussions

Fig. 3(a) shows normalized power spectra for THz transmission through the Ge substrate, the graphene/Ge structure, and the MoS_2/Ge structure, with and without laser light irradiation. The spectra indicate that the THz transmission through the MoS_2/Ge structure dropped to less than 10% of its original value at an intensity of only 0.6 W/cm^2. Fig. 3(b) shows the dependence of the amplitude transmission of the MoS_2/Ge sample when averaged over a frequency window that ranges from 0.2 to 2.6 THz on the basis of the modulation beam power. The THz transmission decreased gradually with increasing laser intensity, and dropped to almost zero at an intensity of 1.7 W/cm^2. To evaluate the modulation performances of the samples, the modulation depth (*MD*), which is defined as the change in the integrated transmitted THz power that is caused by the photoexcitation intensity, is introduced as follows [44–48]:

$$MD = \frac{\int P_{laser-off}(\omega)d\omega - \int P_{laser-on}(\omega)d\omega}{\int P_{laser-off}(\omega)d\omega} \tag{1}$$

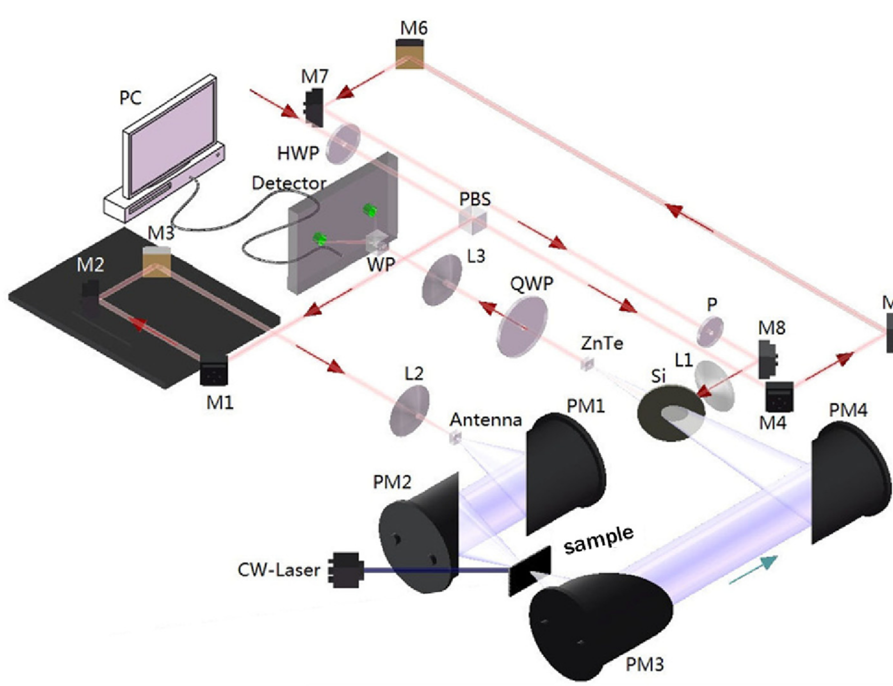

Fig. 2. Schematic diagram of the terahertz time domain spectroscopy (THz-TDS) system.