THz modulating property of vanadium oxide films

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We investigate the optical response of silicon-based V_xO_y film for terahertz (THz) transmission. We find that absorption of the THz wave by the film can be controlled by laser excitation. Using THz time-domain spectroscopy (THz-TDS), we observe that the amplitude of the THz pulse is modulated by the external optical beam. The linearity of the optical modulation is also analyzed. Weak modulation nonlinearity is found to be within tolerable range.

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A terahertz (THz) wave, previously called a submillimeter wave, is an electromagnetic wave with wavelengths between infrared light and microwave. It has promising applications in many fields, such as imaging, communications, radars, and so on[1−7]. With the development of high-power THz emission and effective detection techniques[8−11], these potential applications have become closer to reality. However, corresponding functional devices available in the THz range, i.e., modulator, filter and switch, are far from being sufficient.

Some THz modulating methods based on electrical or optical means have been reported in recent years[12−15]. However, problems have been found in these methods, such as the modulating efficiency or the strong modulation lagging. For this reason, fast modulation with high efficiency is still an open question to THz scientists. Vanadium oxide (i.e., VO_2, V_2O_3, and V_2O_5) is a transition metal oxide that could make phase transition (PT) from the insulator phase to the metal phase under excitation in thermal, electrical, and optical ways[16−20].

We have recently reported a study on the metallic property of silicon-based V_xO_y film before and after metal-insulator transitions (MITs) using THz time-domain spectroscopy (THz-TDS)[21]. The THz transmission change indicates that this kind of film can be a great THz modulating device. In this letter, we studied the transition property of vanadium oxide nanofilm based on high-resistivity silicon wafer and investigated the modulation performance for THz waves. The observed modulation is very efficient and shows tolerable nonlinearity.

A V_xO_y film was deposited by radio frequency (RF) magnetron sputtering from a pure metallic vanadium target onto a high-resistivity silicon substrate. This was followed by annealing in an oxygen environment with a pressure of 2 Pa. Gas mixture ratio of Ar:O_2 was 48:0.5 sccm, and the deposition lasted for 2 h. The valence of vanadium is diverse with mainly V^{5+}, V^{4+}, and V^{3+} existing inside the film; thus, the diversity of the component ratio highly influences the property of the film. In the current study, high-resistivity silicon (0.64 mm thick, <110> cut, resistivity $\rho > 1000\ \Omega$/cm) was chosen as the substrate because it had been proven to be a transparent material with little dispersion and low propagation loss in the THz range.

Measurement was done using standard THz-TDS. The complete experiment setup is shown in Fig. 1. The vanadium oxide film was placed at the THz focus with a size of about 1 mm. The exciting laser was continuous wave at 532 nm, which was the residue pump laser of the Ti:sapphire femtosecond (fs) laser. Lenses L_1 and L_2 were used to adjust the illuminating area on the surface of V_xO_y. In our experiment, the illuminating area was about 0.4 cm^2. The half wave plate (HWP) was used to change the existing laser power in combination with a polarizing beam splitter (PBS).

When samples with V_xO_y film were illuminated by the excitation laser, the V_xO_y film transfered from an insulator to a metal, with its conductivity dramatically increased. The metallic property was enhanced with the increase of laser power. The absorption of the THz wave propagating through also changed, indicating that the amplitude of the transmitted THz wave was modulated by the exciting laser. In the experiment, the transmitted THz signals were measured for different exciting laser

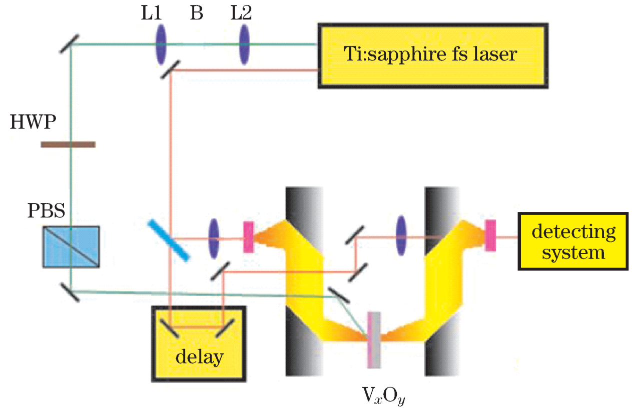

Fig. 1. Experiment setup based on THz-TDS.

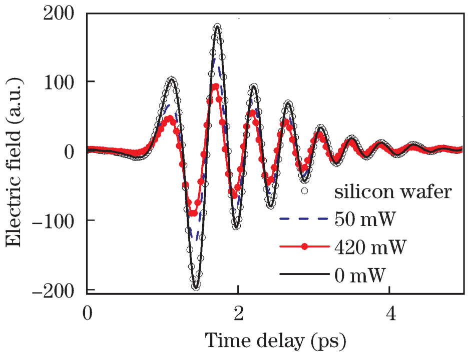

Fig. 2. Three respective signals measured in the experiment. The circle curve is the reference signal transmitted through the bare silicon substrate.

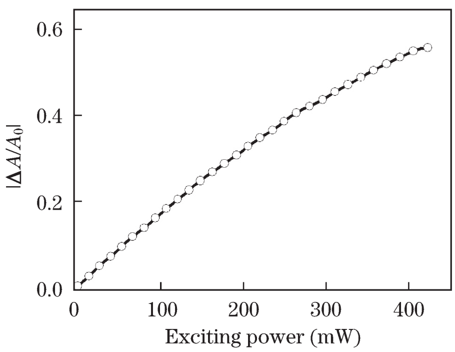

Fig. 3. Modulation degree variation versus exciting laser power.

powers ranging from 0 to 420 mW. Figure 2 shows waveforms for exciting powers at 0, 50, and 420 mW.

The results in Fig. 2 clearly show the optical modulation results of the silicon-based VO film. The amplitude of the THz pulse has been tuned by the laser excitation, and the sub-500 mW excitation is available for applications. We employed modulation degree to examine the modulation performance and compare it with other modulating methods. The modulation degree is defined as $|\Delta A/A_0| = |(A - A_0)/A_0|$, where A is the peak-peak amplitude and A_0 is that of the signal measured using a bare silicon substrate. The modulation degree variation with exciting power is shown in Fig. 3. The modulation degree could be as high as 0.6 in 420-mW excitation, which is more efficient than the published optical modulation results.

Figure 3 also demonstrates the modulation linearity of the PT film within 420 mW. The modulation degree shows high linearity below 200 mW. As the excitation power increases over 200 mW, linearity declines. This is due to the saturation of the photo-induced PT, which means nearly all the VO lattices in the illuminating area are transitioned to the metal phase and the increase of illuminating power does not result in the transition of more lattices.

The time of photo-induced PT of V_xO_y nanofilm generally ranges from tens of fs to hundreds of μs, due to different qualities of the film. The best sample is the VO_2 film of a single crystal, which exhibits the fastest and most sensitive PT response. By arranging with a 7-MΩ resistor and a 9-V direct current voltage source in

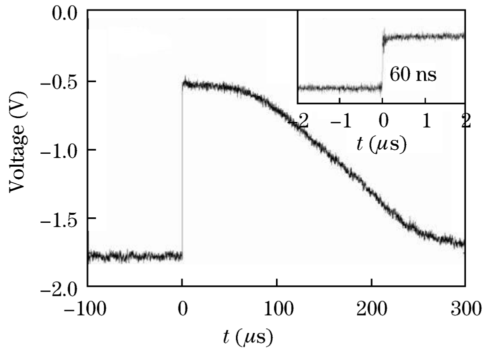

Fig. 4. Time response of the VO_x film during photo-induced transition.

series, the time response was measured (see Fig. 4). In our experiment, the valence of the vanadium was not a single value; the optical response time was measured as 60 ns with a relatively long recovery time of about 200 μs.

In conclusion, we have measured the transmitted THz signals propagating through a VO film under different excitation power levels using THz-TDS. The experimental results indicate that the amplitude of the THz wave could be modulated by external optical control. Although the modulation degree shows some nonlinearity under high excitation power, this could be improved by mathematical methods in many circumstances. VO film based on high-resistivity silicon is a promising material for THz research. In addition, by improving the preparation of the VO film, the modulation frequency could be as high as MHz, enabling VO film to be used as a promising candidate in low-speed communication applications.

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