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High-Performance Optical Gating in Junction Device based on Vanadium Dioxide Thin Film Grown by Sol-Gel Method

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Abstract – In this paper, a high-performance optical gating in a junction device based on a vanadium dioxide dioxide (VO_2) thin grown by a sol-gel method was experimentally demonstrated by directly illuminating the VO_2 film of the device with an infrared light at ~1554.6 nm. The threshold voltage of the fabricated device could be tuned by ~76.8 % at an illumination power of ~39.8 mW resulting in a tuning efficiency of ~1.930 %/mW, which was ~4.9 times as large as that obtained in the previous device fabricated using the VO_2 thin film deposited by a pulsed laser deposition method. The rising and falling times of the optical gating operation were measured as ~50 ms and ~200 ms, respectively, which were ~20 times as rapid as those obtained in the previous device.

Keywords: Vanadium dioxide, Thin film, Junction device, Phase transition, Laser-induced breakdown

1. Introduction

To date, a phase transition (PT) between insulating and metallic states in a vanadium dioxide (VO_2) thin film, known to be induced by temperature [1], pressure [2], light [3], electric field [4], etc., has attracted intensive interest due to some potential applications like ultrafast optical switches [5], bistable optoelectronic devices [6], microbolometers [7, 8], and programmable critical temperature sensors [9]. This PT of the VO_2 thin film can be employed to embody a two-terminal junction device with a negative-differential-resistance (NDR) property resulting in an abrupt current jump at a specific threshold voltage [4, 10]. In order to control the threshold voltage of the VO_2 junction device, the photo-assisted electrical gating (optical gating) was recently proposed by utilizing an infrared light illumination that played a role of a gate terminal of a three-terminal device [11]. At an illumination power of 100 mW, however, the tuning displacement of the threshold voltage of the previous device, which was fabricated by using VO_2 thin film deposited by a pulsed laser deposition method, was only ~38.9 % with respect to the initial threshold voltage without the illumination, resulting in a tuning efficiency of ~0.389 %/mW [11]. Moreover, the rising and falling times of the optical gating operation were limited as ~1.0 ms and ~1.2 ms, respectively.

In this paper, a high-performance optical gating in a two-terminal junction device based on a VO_2 thin film grown by a sol-gel method was experimentally demonstrated by using an infrared light with a wavelength of ~1554.6 nm as the gate terminal of the three-terminal device. At an illumination power of ~39.8 mW, the threshold voltage of the fabricated VO_2 junction device could be tuned by ~76.8 % resulting in the tuning efficiency of ~1.930 %/mW, which was ~4.9 times as large as that obtained in the previous device. In particular, the rising and falling times of the optical gating operation were improved up to ~50 μs and ~200 μs, respectively, which were ~20 times as rapid as those obtained in the previous device.

2. Experimental Setup

Fig. 1 shows a plane-view and cross-section of the two-terminal VO_2 junction device with Ni/Au electrodes. A plane-view optical microscope image and a zoomed snapshot of the VO_2 film area of the fabricated device are also shown in Fig. 1. VO_2 thin films with a thickness of ~100 nm were grown onto Al_2O_3 substrates by the sol-gel method [12]. The fabricated VO_2 film was proven to be highly oriented by using an X-ray diffraction analysis, and the electrical resistance of the film was observed to be changed by more than four orders of magnitude [12]. For the device fabrication, the VO_2 film was selectively etched by an RF ion milling technique in order to isolate the VO_2 film to be used as a current channel, and Ni and Au electrodes were formed on the etched VO_2 film using a lift-off method and an RF magnetron sputter deposition technique. The dimension of the fabricated VO_2 junction device (L × W) was 10 × 5 μm^2 where L and W are the length and width of the exposed film, respectively.

A schematic diagram of the experimental setup, in which the infrared light with a wavelength of ~1554.6 nm illuminates the film for the optical gating in the fabricated

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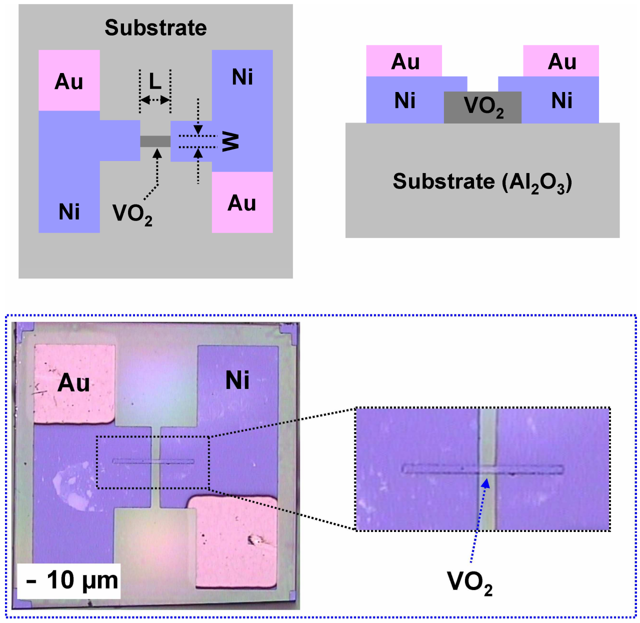


Fig. 1. Plane-view and cross-sectional view of VO_2 device and plane-view optical microscope image of fabricated VO_2 device

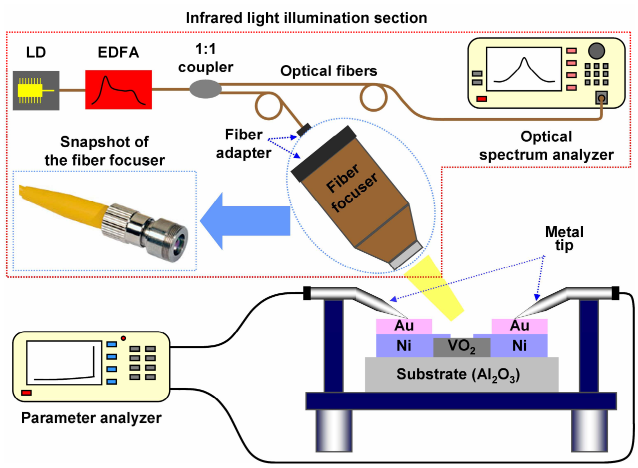


Fig. 2. Schematic diagram of experimental setup for implementing high-performance optical gating in fabricated VO_2 devices

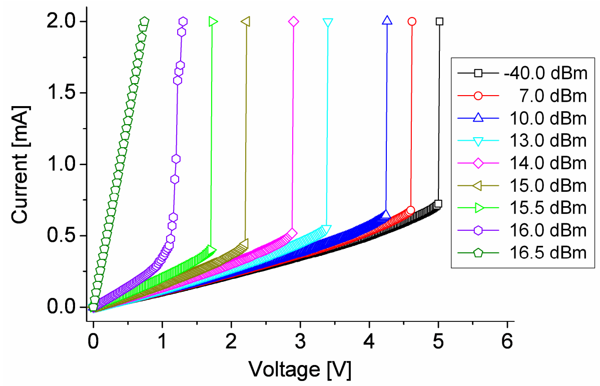
devices, is composed of the infrared light illumination and the electrical measurement sections, as shown in Fig. 2. In the optical part, an optical output of a distributed feedback laser diode (LD) goes into an erbium-doped fiber amplifier (EDFA) to increase its optical power. Through a 1:1 optical fiber coupler, the amplified output of the EDFA is routed into two output arms of the fiber coupler, and each light component at each output arm has an equal power. One component enters the fiber focuser for illuminating the VO_2 film, and the other component an optical spectrum analyzer (Yokogawa AQ6370) for monitoring the optical power and spectrum of the fiber focuser input. For the investigation of the gating speed, an optical chopper will be inserted between the EDFA and the fiber coupler. The fiber focuser output is launched into the film at 30° incidence. The location of the focuser, whose spot diameter at beam waist and working distance to beam waist were designed as ~18 μm and ~10 mm, respectively, was adjusted for the beam spot diameter to be ~450 μm by using an *xyz* translation stage. For electrical measurements of the VO_2 devices, a parameter analyzer (HP 4156C) and a microprobe-station were employed. For fine position control of the metal tip brought into contact with the electrodes of the junction devices, the microprobe-station contained micromanipulators and an optical microscope.

3. Experimental Results and Discussions

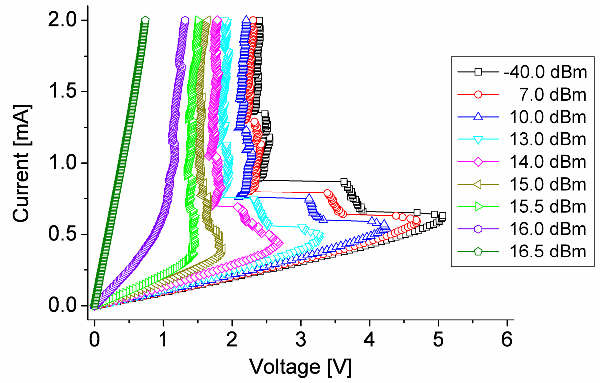
For the fabricated VO_2 junction devices, optical gating operations were experimentally investigated in a voltage-controlled mode (*V* mode) and a current-controlled mode (*I* mode) as shown in Figs. 3(a) and 3(b), respectively. The central wavelength of the amplified light from the EDFA was measured as ~1554.6 nm, and the optical intensity of the light beam projected onto the film was ~25.2 W/cm^2 at an illumination power of 40 mW. Figs. 3(a) and 3(b) show the change of current-voltage (*I*-*V*) properties of the junction device with respect to various illumination powers, which are measured with a parameter analyzer in *V* mode and *I* mode, respectively. In order to prevent the high current from flowing through the device, the device current was restricted to 2 mA, that is to say, the compliance current was set as 2 mA.

As can be seen from Fig. 3(a), the threshold voltage of the fabricated VO_2 device is fixed as ~5.0 V without the light illumination, but it decreases, i.e., is shifted toward 0 V, with the increase of the illumination power. The tuning displacement of the threshold voltage is evaluated as ~3.9 V with respect to the illumination power variation of ~39.8 mW (16.0 dBm). Fig. 3(b) shows the NDR characteristics of the fabricated VO_2 device resulting in abrupt current jumps measured in *V* mode. With the increase of the illumination power, these NDR curves also shrink toward 0 V, and the NDR features gradually disappear. At an illumination power of ~44.7 mW (16.5 dBm), the current jump cannot be found in both measurement mode, just showing an *I*-*V* behavior of a standard resistor, which implies that metallic VO_2 grains dominate within the VO_2 film compared with insulating VO_2 grains [13].

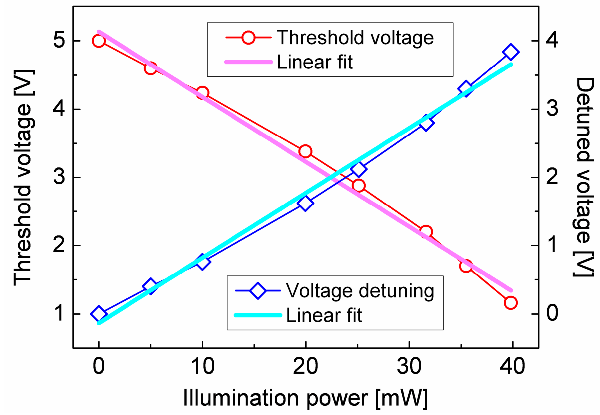
Fig. 3(c) shows the tuning linearity of the measured threshold voltage and detuned voltage with respect to illumination power, which are indicated in red circular and blue diamond symbols, respectively. On the basis of the threshold voltages obtained at various illumination powers in Fig. 3(a), detuned voltages were calculated by setting the threshold voltage at zero illumination power as the reference. Both measured threshold voltages and detuned voltages calculated from them were linearly fitted with the



(a)



(b)

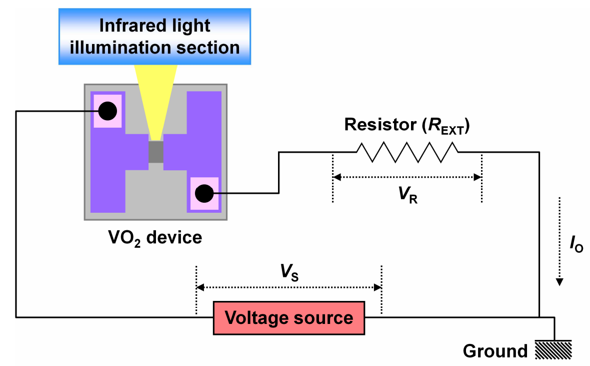


(c)

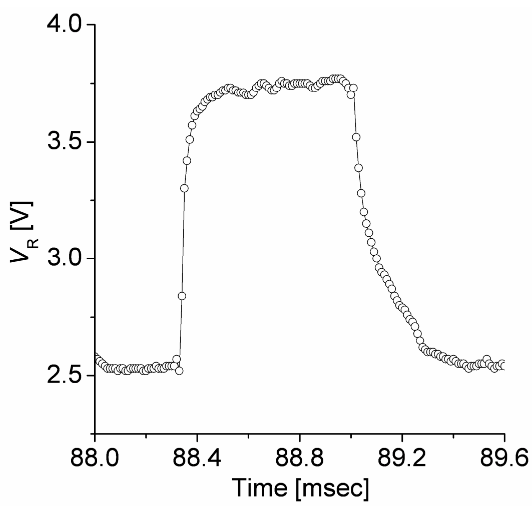
Fig. 3. Optical gating operations in (a) *V* mode; (b) *I* mode; (c) Tuning linearity of threshold voltage and detuned voltage of VO_2 device

adjusted R-square value of the linear fit evaluated as 0.99092, and the tuning sensitivity of the threshold voltage with respect to the illumination power was obtained as ~96.5 V/W. Especially, the threshold voltage could be tuned by ~76.8 % (from ~5.0 V to ~1.1 V) at an illumination power of ~39.8 mW resulting in a tuning efficiency of ~1.930 %/mW, which was ~4.9 times as large as that obtained in the previous device [11].

In order to examine the enhancement of the gating speed, additional experiments on the gating speed were performed by employing an optical chopper that was inserted between the EDFA and the fiber coupler in the infrared light illumination section of Fig. 2. A test electrical circuit used in the previous study, composed of a standard resistor (R_{EXT}) connected in series with the VO_2 device and a DC voltage source (V_S), as shown in Fig. 4(a), was utilized again. When V_S is set at a fixed value that is slightly less than the threshold voltage of the VO_2 device, the device remains in its high resistance state. If the device is illuminated by the infrared light, however, its threshold voltage becomes less than V_S; then, it changes into its low resistance state. In the test circuit, the voltage across the standard resistance (V_R) is defined as V_S minus the device voltage, and V_R has a complementary relationship with the device voltage. For the investigation of the gating speed, the transient electrical responses of V_R were observed with V_S and R_S fixed as 4 V and 2 kΩ, respectively, when the optical chopper was rotated at a fixed operating frequency



(a)



(b)

Fig. 4. (a) Test electrical circuit for investigation of gating speed in VO_2 devices; (b) Transient electrical response of V_R with optical chopper rotated at 700 Hz

with the LD continuously operated. The wavelength and optical power of the light coming out of the optical chopper were ~1554.6 nm and 25 mW, respectively.

Fig. 4(b) shows the transient electrical response of V_R when the optical chopper is rotated with its operating frequency of 700 Hz. The rising and falling times were measured as ~50 μs and ~200 μs, respectively, which were ~20 times as rapid as those obtained in the previous study. Longer falling time is considered to be caused from the thermal diffusion due to the subsequent system thermalization. Although this thermalization cannot be completely avoided, the area of the heat sink is expected to be somewhat diminished by reducing the spot diameter of the illuminated beam so that the beam should not be illuminated onto the surrounding materials (electrodes and substrates) adjacent to the VO_2 thin film.

4. Conclusion

In this paper, a high-performance optical gating operation was experimentally investigated with respect to the junction devices based on VO_2 thin films grown by the sol-gel method by direct infrared illumination of the film of the device. The tuning efficiency and gating speed were highly enhanced compared with the previous study employing the VO_2 film grown by the pulsed laser deposition technique. The demonstrated high-performance optical gating is expected to be usefully applied to light triggered thyristors recently being adopted for many power stations, substations, and power utilities.

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