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Highly-Efficient Optical Gating in Vanadium Dioxide Junction Device

Yong Wook Lee+

Abstract

In this paper, highly-efficient optical gating in a junction device based on vanadium dioxide(VO_2) thin film grown by a sol-gel method was investigated as a gate terminal of a three-terminal device using infrared light with a wavelength of ~1554.6 nm. Due to the photo-induced phase transition, the threshold voltage of the VO_2 junction device, at which the device current abruptly jumps, could be tuned with a sensitivity of ~96.5 V/W by adjusting the optical power of the infrared light directly illuminating the device. Compared with the tuning efficiency of the previous device fabricated using VO_2 thin film deposited by a pulsed laser deposition method, the threshold voltage of this 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 is ~4.9 times larger than the previous device.

Keywords : Vanadium Dioxide, Thin Film, Junction Device, Photo-Induced Phase Transition

1. INTRODUCTION

Over the past decade, much attention has been paid to vanadium dioxide(VO_2) thin film due to its phase transition(PT) property that leads to the possibility of its use in some fascinating applications like ultrafast optical switches, microbolometers, and programmable critical temperature sensors[1-3]. The PT between insulating and metallic states in VO_2 thin film can be used to implement a junction device with strongly nonlinear current-voltage(*I-V*) behavior showing an abrupt current jump at a specific threshold voltage[4, 5]. Recently, photo-assisted electrical gating(optical gating) was proposed to control the threshold voltage of VO_2 junction devices for its practical application as a three-terminal device[6]. However, the tuning displacement of the threshold voltage of the previous device, fabricated using VO_2 thin film deposited by a pulsed laser deposition method, was only~38.9 % with respect to the initial threshold voltage at an illumination power of 100 mW, resulting in a tuning efficiency of ~0.389 %/mW[6].

In this paper, highly-efficient optical gating in a junction device based on VO_2 thin film grown by a sol-gel method was investigated as a gate terminal of a three-terminal device using infrared light with a wavelength of ~1554.6 nm. Due to the photo-induced PT, the threshold voltage of the VO_2 junction device could be tuned with a tuning sensitivity of ~96.5 V/W by adjusting the optical power of the infrared light that directly illuminated the device. 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 larger than the previous device.

2. EXPERIMENTAL PREPARATION

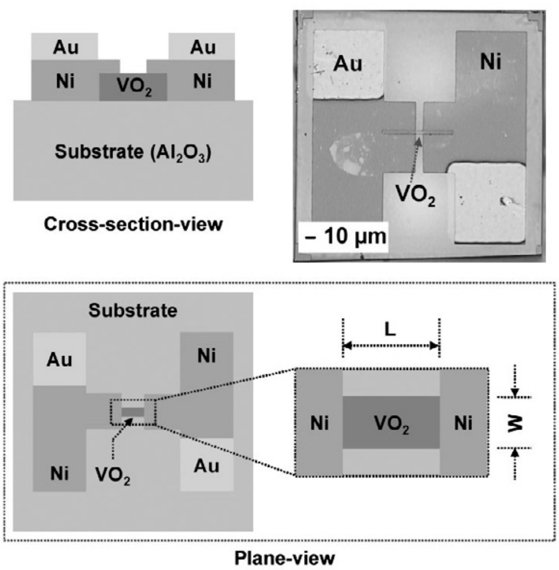

Fig. 1. Cross-section and plane-views of the fabricated VO_2 device and its plane-view optical microscope image(upper right corner).

School of Electrical Engineering, Pukyong National Unversity Gaon Bldg. 305, Pukyong National University, 45 Yongso-ro, Nam-gu, Busan 608-737, Korea
+Corresponding author : yongwook@pknu.ac.kr
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Fig. 1 shows a cross-section and plane-views of the VO_2 junction device with Ni/Au electrodes. A plane-view optical microscope image of the fabricated device is also shown in upper right corner of Fig. 1. VO_2 thin films were grown onto Al_2O_3 substrates by the sol-gel method[7]. The thickness of the VO_2 film was ~100 nm. The fabricated VO_2 film was proven to be highly oriented by an X-ray diffraction(XRD) analysis as shown in Fig. 2. Fig. 2 shows XRD patterns of VO_2 films grown on Al_2O_3(10-10) substrates. The films were annealed at various temperatures(400 °C, 450 °C, and 500 °C) in an oxygen atmosphere of 32 mTorr. In the film growth, the annealing process was carried out under only an oxygen atmosphere without using reducing gases such as H_2 and CO, which was regarded to be the origin of the highly oriented crystal showing no intermediate phases at various annealing temperatures.

For the fabrication of the junction device, the VO_2 film was selectively etched by a RF ion milling technique in order to isolate the current channel. Using the lift-off method and the RF magnetron sputter deposition technique, Ni and Au electrodes were formed on the etched VO_2 film. The dimension of the fabricated device(L × W) was 5 × 5 μm^2, where L and W were the length and width of the exposed film, respectively.

A schematic diagram of the experimental setup, in which the infrared light illuminates the film for the optical gating in the fabricated devices, is shown in Fig. 3. In this setup, a laser diode(LD) output enters an erbium-doped fiber amplifier(EDFA) to increase its intensity. Through a 1:1 optical fiber coupler, the amplified output from the EDFA is separated into two light components. One component is introduced into the fiber focuser for shedding light onto the VO_2 film, and the other component into an optical spectrum analyzer(Yokogawa AQ6370) for monitoring its output power and spectrum.

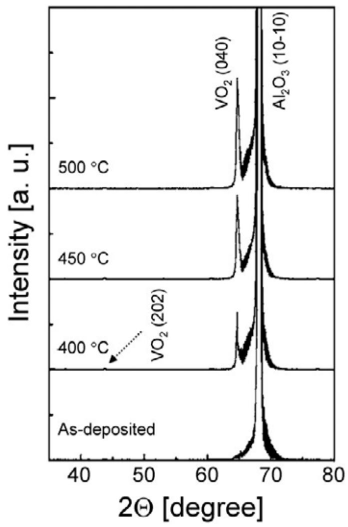

Fig. 2. XRD patterns of VO_2 films grown on Al_2O_3(10-10) substrates. The films were annealed at various temperatures in an oxygen atmosphere of 32 mTorr.

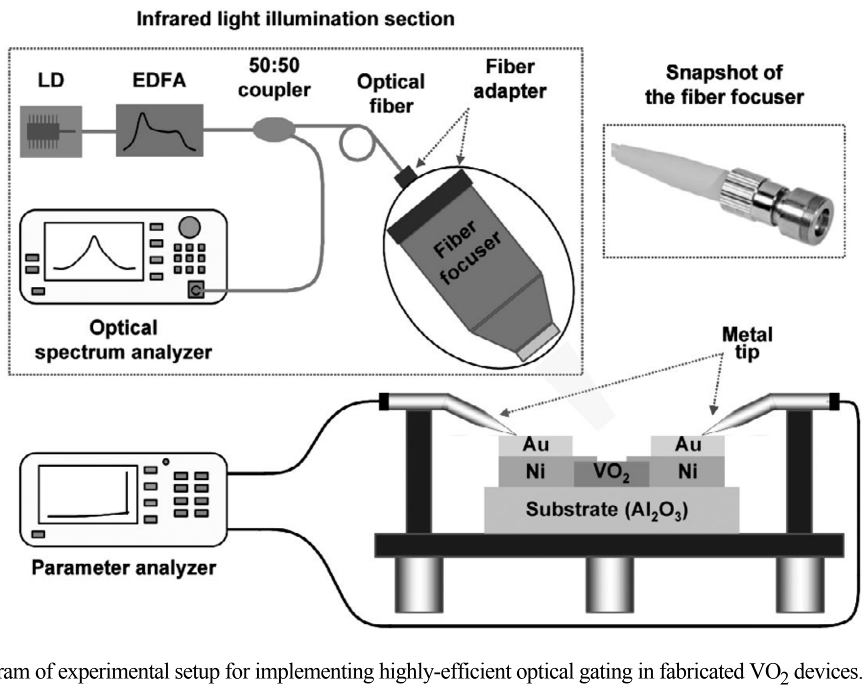

Fig. 3. Schematic diagram of experimental setup for implementing highly-efficient optical gating in fabricated VO_2 devices.

The fiber focuser output is incident on the film at 30 °. 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 so that the beam spot diameter became ~450 μm by using an xyz translation stage. For electrical measurements of the VO_2 devices, a parameter analyzer(HP 4156C) and two micromanipulators were employed.

Fig. 4 shows the optical power spectra of the EDFA output with respect to various powers(0.001 mW~50 mW) as measured by an optical spectrum analyzer with a resolution bandwidth of 0.1 nm. The center wavelength and signal-to-amplified spontaneous emission ratio of the EDFA output were measured as ~1554.6 nm and at least more than 25 dB, respectively. The optical intensity of the light beam projected onto the film was ~25.2 W/cm^2 at an input optical power of 40 mW.

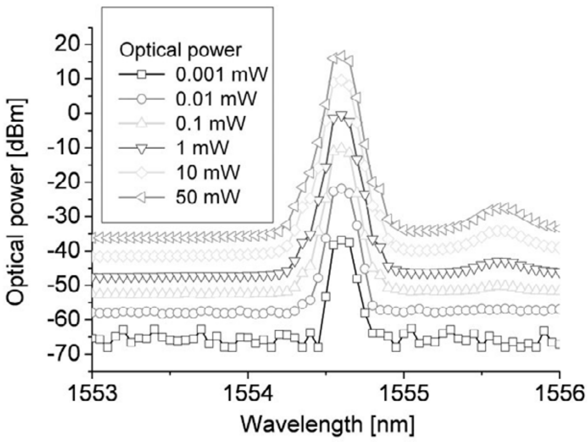

Fig. 4. Measured optical power spectra of EDFA output.

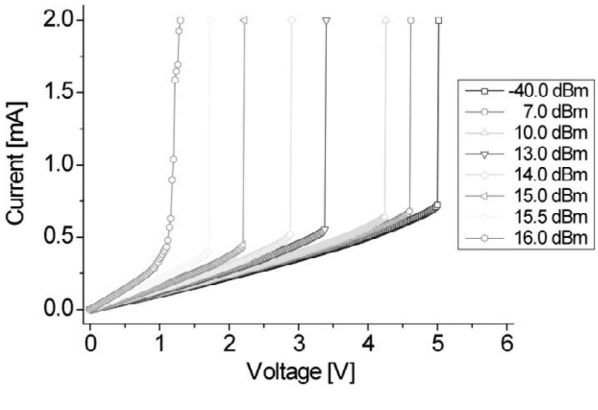

Fig. 5. Optical gating operation of the fabricated VO_2 junction device.

3. RESULTS AND DISCUSSIONS

For the fabricated VO_2 junction devices, the optical gating operation was experimentally investigated in a voltage-controlled mode, as shown in Fig. 5. Fig. 5 shows the change of the *I-V* property of the junction device with respect to various illumination powers as measured with a parameter analyzer. In order to protect the device from high current flow, the device current was limited to a current compliance of 2 mA. In Fig. 5, the threshold voltage of the device was observed as ~5.0 V without the illumination. As the illumination power increases, the threshold voltage of the device decreases, i.e., is tuned toward 0 V, as shown in the figure. The tuning displacement was measured as ~3.9 V with respect to an illumination power variation of ~39.8 mW.

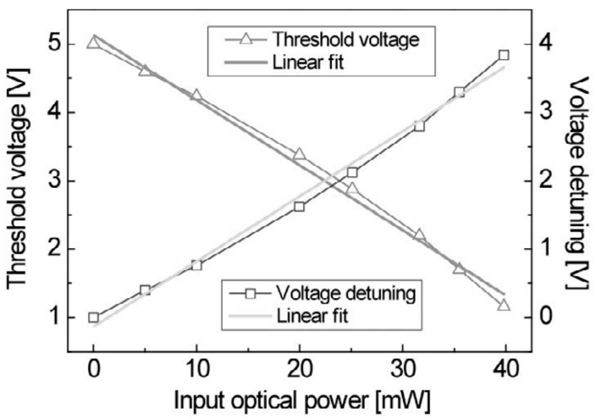

Fig. 6. Tuning linearity of the threshold voltage and voltage detuning of the VO_2 device.

Fig. 6 shows the tuning linearity of the measured threshold voltage and voltage detuning with respect to the illumination power in red triangle and blue square symbols, respectively. Based on the information about threshold voltages in Fig. 5, the voltage detuning was evaluated with the threshold voltage at zero illumination power as the reference voltage. The tuning sensitivity of the threshold voltage with respect to the illumination power was measured as ~96.5 V/W. The adjusted R-square value and rms deviation of the linear fit were evaluated as ~0.991 and ~0.134 V, respectively. From analysis of the linear fit, it was confirmed that the threshold voltage had a nearly linear relationship with the illumination power. This linearity of the threshold voltage of the VO_2 thin film device with respect to external illumination may come from a breakdown of an energy gap by energy excitation[8]. In particular, 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 is ~4.9 times larger than the previous device.

4. CONCLUSIONS

In this paper, highly-efficient optical gating operation was experimentally investigated with respect to junction devices based on VO_2 thin films grown by a sol-gel method with direct illumination of infrared light onto the film of the device. The threshold voltage of the VO_2 junction device could be tuned with a tuning sensitivity of ~96.5 V/W by adjusting the illumination power. Especially, a tuning efficiency of up to ~1.930 %/mW was achieved, and this is ~4.9 times larger than the previous device.

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Yong Wook Lee received his B.S., M.S., and Ph.D. degrees in Electrical Engineering in 1998, 2000, and 2004, respectively, from Seoul National University, Seoul, Korea. He worked as a senior researcher in Electronics and Telecommunications Research Institute (ETRI), Daejeon, Korea, from 2004 to 2008. Currently, he is an assistant professor in School of Electrical Engineering, Pukyong National University. His research areas include optical devices for optical sensors and communications such as optical fiber gratings, optical filters, and optical amplifiers as well as optical gating in semiconductor thin films based on photo-induced phase transition.