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Investigation on I-V characteristics of current induced metal insulator transition in VO_2 device

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The I-V characteristics of two terminal planar VO_2 film devices are investigated as the devices undergo the current induced metal insulator transition (I-MIT). The I-MIT occured when the device resistivity reached ~7 Ωcm, where metallic grains formed initial conductive current path within insulating matrix. The transition time needed for the I-MIT increased with increasing external resistance, R_{EXT}, connected to the device in series, i.e. ~390 μs (R_{EXT} = 5 kΩ) to ~1400 μs (R_{EXT} = 20 kΩ). The transition time is closely related to the RC time delay from capacitance discharge of the VO_2 device. During the I-MIT, the amount of discharge current was estimated as large as ~100 mA, which was larger than the current just before the I-MIT. After the I-MIT, the current density decreased from 1.1 × 10^6 A/cm^2 to 6.5 × 10^5 A/cm^2, suggesting a large temperature changes up to ~300 °C.

1. Introduction

Vanadium dioxide (VO_2) exhibits various dramatic physical phenomena, such as metal insulator transitions (MIT), optical reflectivity change, structural phase transition, and super elasticity, owing to the abrupt collapes of the subtle metastable insulating state among the competing interactions of lattice, spin, charge, and orbital degrees of freedom caused by diverse external stimuli such as changes in temperature, pressure, current, voltage, and light [1–5]. These unique physical properties of VO_2 make it one of the appealing candidates for future advanced materials in countless applications, including ultrafast sensors, Mott transistors, optical switching devices, and future memory devices [6–9].

Among the diverse stimuli that induce MIT in VO_2, changes in electric current and voltage are considered to be the most promising method for use in future VO_2 applications [10,11]. Temperature-induced MIT occurs in over the entire VO_2 area owing to the uniform temperature change of the sample, while the electrically-induced MIT occurs only in local conductive areas like conduction channels placed inside of the insulating phase of VO_2 samples [12]. There are two competing models explaining the mechanism of the electrically induced MIT: Joule heating model and electric-field-induced breakdown model [7,13]. In the Joule heating model, the MIT occurs when the sample temperature is raised to the transition temperature by Joule heat. On the other hand, in the electric-field-induced breakdown model, the MIT occurs when the intense electric field above critical field 50 V/μm frees its bound electrons in vanadium dimers. Although over forty years have been passed since the first report of electrically induced MIT [3], the primary origin of electrically induced MIT is still not well understood and many debates still continue. While numerous studies have been conducted on voltage-induced MIT [14,15], there are only a few studies on current-induced MIT (I-MIT) [16] despite the fact that both voltage and current are of almost equal importance in determining the nature of electrically-induced MIT.

In this study, a systematic investigation on the I-V characteristics of I-MIT in VO_2 thin film planar-type devices was conducted. Based on the current percolation model, we conclude that the I-MIT occurs when metallic phase grains are connected to form first conductive channel. The transition time for I-MIT was also found to be positively correlated with external resistance R_{EXT}, going from ~390 μs at R_{EXT} = 5 kΩ to ~1400 μs at R_{EXT} = 20 kΩ. Conduction

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channel temperature was shown to have varied as much as 300 °C by adjusting conduction channel width.

2. Experiment

A 200-nm-thick VO_2 thin films were prepared on Al_2O_3 (0001) substrates by the annealing of sputter deposited vanadium metal films at 540 °C for two hours at oxygen annealing pressure of 160 mtorr, followed by cooling procedure at 120 mtorr. The preparation details of VO_2 thin films were reported elsewhere [17]. Upon the fabrication of VO_2 film, the VO_2 film strips in dimension 1 mm × 100 μm were fabricated with the standard optical lithography process, followed by lift-off processes. For electrical contacts, Au(50 nm)/Cr(10 nm) electrodes were prepared on the VO_2 film stripe using dc magnetron sputtering and conventional photolithography methods. The device length (L) was either 10 μm or 20 μm with a fixed width (W) of 100 μm. The temperature dependence of the resistivity of the VO_2 device was measured with custom-built heating stage in the temperature range from 30 °C to 100 °C. During the temperature-dependent resistivity measurements, a constant current of 10 μA was flowed in the VO_2 device. During the measurements, the temperature of the VO_2 device was controlled with the accuracy better than ± 0.5 °C. During current versus voltage measurements (I-V) and high speed voltage versus time (t) measurements, the external resistors, R_{EXT} = 5, 7.5, 10, 15, or 20 kΩ, were connected in series with the VO_2 device to protect the device and the measuring instruments. The high-speed V-t measurement of VO_2 devices were performed using a source meter (Keithley 2635A) with data collection rate up to 20,000 data per second. Current ramping rate during I-V measurements was set to 0.01 mA/s for all I-V measurement and this ensured the nearly steady state within the film devices. Optical microscopy with reflection geometry mode was applied to monitor the metallic and insulating phases of VO_2 before and after the I-MIT measurements. The microstructure and morphology of VO_2 devices were characterized by scanning electron microscopy (SEM; JSM7800F, JEOL).

3. Results and discussion

Fig. 1 shows the temperature dependence of the resistivity of VO_2 devices with length (L) of 10 μm and 20 μm. The VO_2 devices exhibit typical MIT behavior from a low temperature insulating state to a high temperature metallic state with a hysteresis loop occurred during heating and cooling cycles. The transition temperatures during heating and cooling, determined from the positions of maximum slope in the temperature dependence of the device resistivity, were ~69 °C and ~58 °C, respectively, indicated with dotted line in Fig. 1. The insulating resistivity at 30 °C, ρ(30 °C), of VO_2 devices with L = 10 μm and 20 μm were the same magnitude of ~21 Ωcm, while the metallic resistivity at 100 °C, ρ(100 °C), of the devices were ~16 mΩcm for 10 μm long device and ~11 mΩcm for 20 μm long device, respectively. The slope of insulating resistivity showed exponential temperature dependence, i.e. a linear slope in log(ρ) vs. T plot in Fig. 1. On the other hand, the resistivity begun to drop significantly when the temperature reached at 61 °C, e.g. the resistivity reached ~6.5 Ωcm, indicated by the dotted circle in Fig. 1. This temperature is ~8 °C lower than the transition temperature during heating up (69 °C). The discussion on this observation will be followed later.

Fig. 2(a) illustrates a schematic circuit diagram constructed for the current controlled I-V and high speed V-t measurements of the planar VO_2 device with Au/Cr electrodes. The single-loop circuit was composed of a VO_2 device (L of either 10 or 20 μm at fixed width W = 100 μm), a R_{EXT}, and a current source. Fig. 2(b) shows SEM micrograph of VO_2 film in the device, which display the closely packed grains with the average grain size of ~180 nm. Fig. 2(c) shows the scanning electron microscope (SEM) micrographs of a VO_2 films device with L = 20 μm and the enlarged view of the interface between VO_2 device and electrodes is shown in Fig. 2(d), showing a sharp interface formed between VO_2 device and electrodes. The VO_2 device was consisted of a wide strip on top of a Al_2O_3 substrate with Au/Cr contact electrodes.

We measured I-V characteristics of VO_2 devices at room temperature (not shown) and however the VO_2 devices often suffered permanent damages after the repeated measurements because of the high voltage appeared on the device during the measurement. Thus all the data is taken at 40 °C to ensure the device reliability during repeated measurements. Fig. 3. (a) shows current controlled

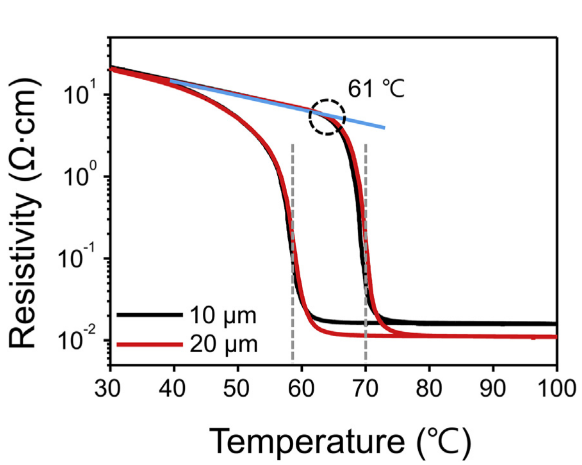

Fig. 1. (a) Temperature dependence of the resistivity of VO_2 film devices with the lengths of 10 μm (black line) and 20 μm (red line). Vertical lines on the graph represent the transition temperature during heating ($T_{C\uparrow}$) and cooling ($T_{C\downarrow}$), determined from the maximum slope of the graph. The resistivity begins to drop rapidly at ~61 °C. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

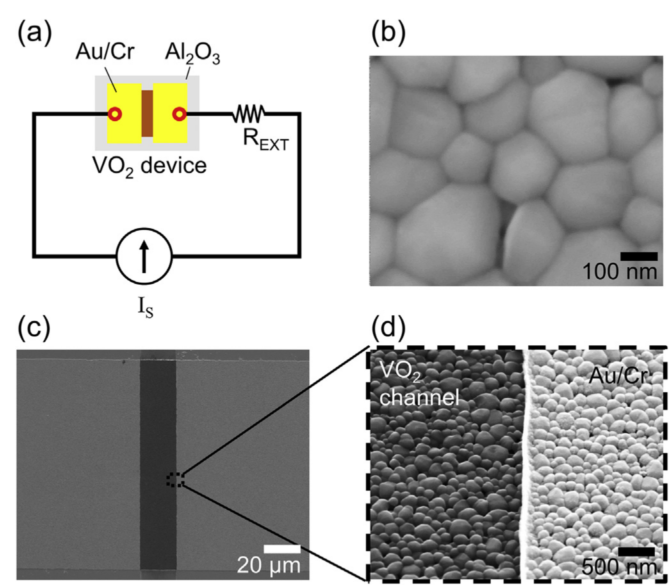

Fig. 2. (a) Schematic circuit drawing for the current induced MIT and high-speed measurements of the VO_2 film devices (device length = 20 μm) with Au (50 nm)/Cr(10 nm) contact electrodes. I_S: current source and R_{EXT}: external resistance. (b) Scanning electron micrograph of a VO_2 film in the VO_2 device (c) Scanning electron micrograph of a VO_2 device (L = 20 μm). (d) Scanning electron micrograph of the VO_2 device near the Au/Cr electrode (enlarged view of (c) near the contact electrode).