Extended Abstracts of the 2007 International Conference on Solid State Devices and Materials, Tsukuba, 2007, pp. 612-613

P-9-8

Programmable VO_2 temperature sensor controlled by a constant voltage

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1. Introduction

The first-order Mott discontinuous metal-insulator transition (MIT) has been studied as a function of temperature in numerous materials such as Ti_2O_3, V_2O_3, and VO_2 etc [1]. Almost all have a low transition temperature, T_{MIT}, below room temperature except VO_2 with $T_{MIT} \approx 68^oC$. In particular, VO_2 thin films were used for fabrication of two- and three-terminal devices controlled by an electric field [2].

An interesting aspect in VO_2 is that the T_{MIT} can be modified by doping [3,4] and stress [5]. VO_2 thin films deposited on (001) and (110) TiO_2 substrates showed a modified T_{MIT} of 27 and 96^{o}C, respectively, where the c-axis length was stressed by a lattice mismatch between the film and the substrate [5]. The modification of the T_{MIT} by doping and stress is restricted to within a fixed temperature, whereas the T_{MIT} induced by an electric field linearly depends on the electric field intensity.

In this work, for applications of the MIT over wide temperature ranges, we observe a modification of the T_{MIT} in a VO_2 thin film device by applying voltages. Actually, the modification of the T_{MIT} is appreciable for a critical temperature sensor working at any set temperature below 68^{o}C. The relation between the MIT and the SPT is investigated by micro-Raman spectroscopy. By analysis of the micro-scale current localization with optical microscopy, we confirm a uniform current flow that is not explained by dielectric breakdown. Moreover, we perform a switching experiment with a triangle wave to observe generation of Joule heat in a device.

2. Results and discussions

VO_2 films on $(10\bar{1}0)$ Al_2O_3 substrates have been prepared by the sol-gel method described in detail elsewhere [6]. In order to observe the temperature dependence of the MIT, VO_2-based two-terminal devices were fabricated in which VO_2 films were patterned with an Ar^+ milling process. The thickness of the VO_2 films is about 100 nm. Nickel was used as an electrode metal for the Ohmic contacts. The temperature dependence of the current was measured from room temperature to 450 K in a cryostat.

Figure 1(a) shows the temperature dependence of conductivity,σ, at various constant applied voltages for a VO_2 device with $V_{MIT} \approx 21$ V (Device-I). The conductivities were obtained from the curves using the relation $I=V/R \propto \sigma$, as shown in Fig. 1(b), and are plotted on a log scale. Device-I has a dimension with a channel width of W=50 μm and a channel length between electrodes of L=20 μm (see inset in Fig. 1(b)). As the applied voltage increases from 1 to 22 V, an abrupt conductivity jump clearly appears above 5 V. As shown in Fig. 1(b), the transition temperatures gradually shift from 68^{o}C at $V_{applied}$ = 1 V to room temperature at $V_{applied}$ = 21 V. A new region containing linear behavior of conductivity is also clearly observed. This region corresponds to an intermediate regime between abrupt conductivity jumps and the SPT which is indicated by the red-dotted lines. The SPT is confirmed by micro-Raman measurements discussed in a next section. Thus we divided the σ-T curves into three phases, the semiconductor-monoclinic transient **t**riclinic T phase, the intermediate phase and the tetragonal **r**utile R metal phase. The SPT temperatures decrease slightly with increasing voltage due to an increase in Joule heat; the SPT line is newly observed.

The linear conductivity strongly suggests that VO_2 is in a monoclinic metallic state which is different from the tetragonal metallic state because the temperature is still lower than 68^{o}C. At the SPT, the conductivity has a maximum value, as indicated by A in Fig. 1(a). The

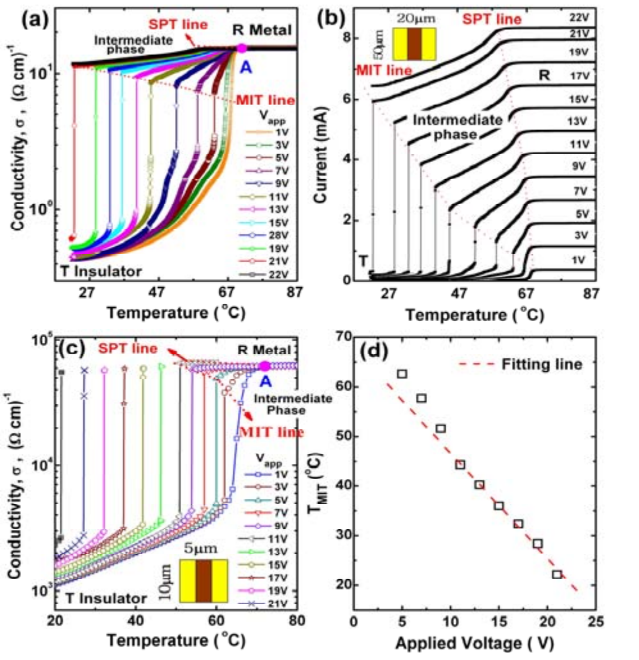

Fig. 1 Temperature dependences of the conductivity (a) and the current (b) for Device-I, and the conductivity (c) for Device-II for the MIT (Jump) at constant applied voltages. The plot in (d) shows the applied voltage dependence of T_{MIT} determined from Fig. 1(a). The dotted line is a linear fit. The slope of this line is -2.13 ^{o}C/Volt ($|dV/dt| \approx 0.47$ V/^{o}C).

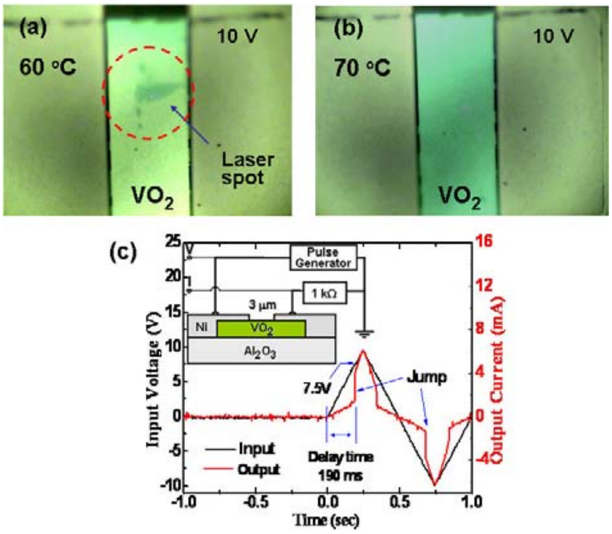

Fig. 2 (a) Enlarged images of Device-I taken by optical microscopy. At a high laser power a local laser spot is visible at 60°C and 10 V. (b) At 70°C and 10 V, the laser spot is no longer visible. The VO_2 films are then in the metal phase. (c) For Device-III with L=3 μm, W=10 μm, the MIT is switched repeatedly at 7.5 V (red solid line). The output current (red right axis) is measured for an input triangle voltage (black solid line) of 1 Hz (left axis). The delay time τ took 190 ms. V_{MIT}=7.5 V and I_{MIT}=4 mA were obtained. The inset shows the measurement circuit.

conductivity of the metallic phase above 67°C is much smaller than that of a good metal. This is because the film contains not only the VO_2 phase but also different phases; that is, the film is very inhomogeneous. For Device-II with W=5μm and L=10μm fabricated using a film with a higher conductivity than Device-I (see inset of Fig. 1c), the temperature dependence of conductivities as shown in Fig. 1(c) shows the same behavior as that in Fig. 1(a). The intermediate region becomes much narrower due to Joule heat caused by a higher current induced by the MIT of Device-II. This indicates that the SPT occurs by heat. The intermediate region widens with the increase of inhomogeneity, as compared with Fig. 1(a) and Fig. 1(c). This is because, for a more inhomogeneous system with a larger resistance in a measurement region, a lower MIT current causing a less Joule heating makes the SPT delay.

Figure 1(d) shows the applied voltage dependence of T_{MIT} obtained from Fig. 1(a) and is described by the linear fit; T_{MIT} = -2.13$V_{applied}$ + 68. Temperature sensitivity is $dV/dT \approx 0.47$ V/°C. This linear fit is denoted by a dashed line. At $V_{applied}$ = 0, T_{MIT} = 68°C, which is the SPT temperature. Except for a deviation near 68°C, T_{MIT} is linear. This indicates that the device can be used as a programmable critical temperature sensor.

Figure 2(a) shows an optical image of the VO_2 device taken at 10 V and 60°C. A ND filter used to decrease the laser power was not used. The dark trace of the laser spot, highlighted by the dashed circle appears on the VO_2 film. The temperature of the film illuminated by the laser spot is greater than 68°C and the difference in reflectance with other parts of the film becomes visible. At 10 V and 70°C, the laser beam spot is no longer visible, as shown in Fig. 2(b). The surface contrast of the VO_2 film is affected only by the temperature. Thus these optical images show that the current flows uniformly across the surface of the VO_2 film at a particular applied voltage.

From optical measurements, the transition time of the MIT in VO_2 has been measured to be in the subpicosecond regime [7], and in the order of nanoseconds for an electronic device [8]. The heating model predicts that a delay time of about 1 μs is required for a device with L=3 μm and W=50 μm for the device temperature, T_d, to become T_{SPT} as stated in previous report [8]. In order to check whether the SPT is produced by Joule heating or not ($Q=\int_0^{\tau} IV\, dt$, where τ≈190 ms which is a long delay time compared to 1 μs; Q increases with an increase in τ.), one triangle wave with a period of 1 sec is applied to Device-III with a width of L=3 μm and a length of W=10 μm, which has V_{MIT} = 7.5 V (Fig. 2(c)). The MIT is shown as a jump at $V_{MIT} \approx 7.5$ V and $I_{MIT} \approx 4$ mA. This indicates that T_d produced by Joule heating is less than T_{SPT}. When $T_d > T_{SPT}$, the current jump should not be observed because the MIT as observed in the I-V curves is continuous without an observed jump above T_{SPT} (Fig. 1(a)). Thus, Joule heat does not increase T_d up to T_{SPT}, which indicates that Joule heating is not responsible for the observed MIT.

3. Summary

For VO_2-based devices, (1) the MIT was controlled by external variables such as temperature and voltage (or electric field), (2) a conducting filament was not formed and (3) a large Joule heat causing the SPT was not produced even in the high currents induced by the MIT. In future, this device can be utilized as a programmable critical temperature sensor.

Acknowledgements

This work was supported by High Risk and High Return project of Electronics and Telecommunications Research Institute.

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