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Investigation of Switching Behavior of 2-terminal Devices on VO_2

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1. Introduction

Vanadium dioxide VO_2 undergoes a metal to insulator transition (MIT) at about 70°C with the resistivity of the material changing by approximately 4 orders of magnitude (see Fig. 1). This transition has been initially ascribed to a Mott purely electronic effect [1]. However, at the same temperature a structural change from a monoclinic to a rutile crystal lattice takes place. This points to a mixed electronic and phononic mechanism of the MIT [2]. Independent of the mechanism, there is considerable interest to employ the MIT in switching devices and explore novel device concepts [3]. The interest has been generated by the large change in resistivity and the speed of the transition. The MIT can happen on femtosecond time scales [4].

In the framework of resistive RAM we are investigating switching behavior in 2-terminal VO_2 devices for memory and selector applications [5]. We find that the material shows very good endurance over more than 10^{10} cycles while the ON-OFF resistance ratio is ~1000.

2. Results and discussion

Material and device fabrication

Thin films of VO_2 are produced by low pressure oxidation of vanadium metal. Vanadium films 50nm thick are dc sputtered onto Si wafers on which an insulating oxide (either 20nm Al_2O_3 from ALD or 20nm thermal SiO_2) has been deposited. The metal is oxidized at pressures of about 1Torr O_2 and temperatures of around 500°C. The resulting VO_2 films are approximately 100nm thick with an RMS surface roughness of ~5nm. By varying the oxygen pressure during oxidation or the underlying insulator, thin films of VO_2 with different resistivity can be obtained [6].

Two terminal devices are fabricated onto the VO_2 thin films using electron beam lithography and metal (5nm Ti/50nm Au) lift-off. Devices with electrode separation ranging between 100nm and 10μm and electrode width of 2 or 10μm and are thus patterned. A scanning electron micrograph of such a device is shown in Fig. 1 inset.

DC electrical characterization

A typical current vs. voltage behavior is shown in Fig. 2. The current increases abruptly at a voltage which varies with electrode separation and VO_2 resistivity. The I-V characteristic is symmetric about zero and displays volatile switching. The current decreases abruptly and the VO_2 changes from metallic to insulating at a lower voltage than the turn-on voltage. Fig. 2 inset presents an I-V characteristic showing that the switching takes place in several cascading steps as different sections of the device turn on.

The electric fields at which the devices turn on (E_{ON}) and off (E_{OFF}) are approximately constant as shown in Fig. 3. This would seem to suggest that the electric field induces the MIT. However, Joule heating increasing the temperature of the device beyond the MIT can also explain this phenomenon. Constant Joule power density (per volume of VO_2) needed to turn on a device, in the given geometry, translates into constant E_{ON} for devices with the same VO_2 resistivity. E_{ON} also is expected to be proportional to the square root of the resistivity. Similar considerations apply to E_{OFF}. Deviations from constant value are present at small electrode separation. They could be explained by device dimension being comparable to the contact length or an increasingly larger role played by device area compared to device volume. Heat flow out of the device depends on the area rather than the volume of the device.

To discriminate between the two possible switching mechanisms two experiments are performed. In the first experiment, devices are patterned on VO_2 with resistivity ~10 times lower (Fig. 2 inset) than of those presented in Fig. 3. E_{ON} was found to be ~3 times smaller in these devices consistent with Joule heating inducing the MIT.

In the second experiment, I-V characterization is performed at different temperatures (see Fig. 4). The ON and OFF voltages decrease with increasing temperature and the switching disappears above the MIT temperature. The power dissipated at the device turn-on (Fig. 5) is found to decrease approximately linearly with increasing temperature as expected for a Joule heating mechanism.

AC electrical characterization

When a high enough voltage pulse is applied, the devices turn on in less than 40ns (see Fig. 6 inset). The device returns to the high resistance state after hundreds of ns from the end of the pulse. This is consistent with the time needed for the heat to dissipate out of the device. AC cycling over 10^{10} cycles is performed on a random device (Fig. 6). The device resistance changes by a factor of ~1000 with very good window stability over the tested cycles. The endurance test was stopped because of time constraints.

3. Conclusions

We have investigated switching behavior in 2-terminal VO_2 devices and found that the turn on voltage scales with electrode separation and decreases with increasing temperature. The mechanism inducing the MIT in these devices is likely Joule heating. Upon cycling, the devices showed good endurance over 10^{10} cycles with the resistance changing by a factor of approximately 1000.

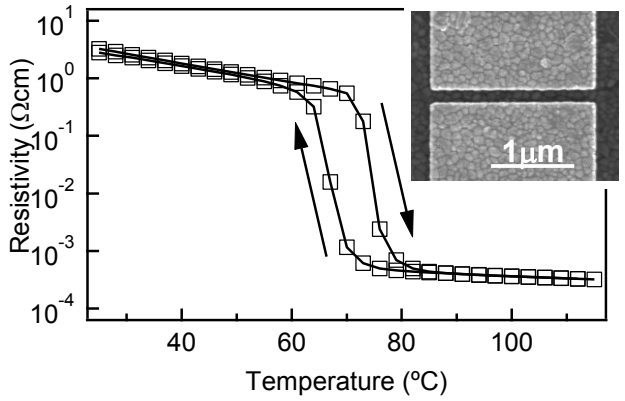

Fig. 1: Dependence of resistivity on temperature for a typical VO_2 thin film showing an abrupt change in resistivity by almost 4 orders of magnitude at ~70°C. Inset: SEM of a 2-terminal device patterned on VO_2. Device dimensions: 0.2x2 μm.

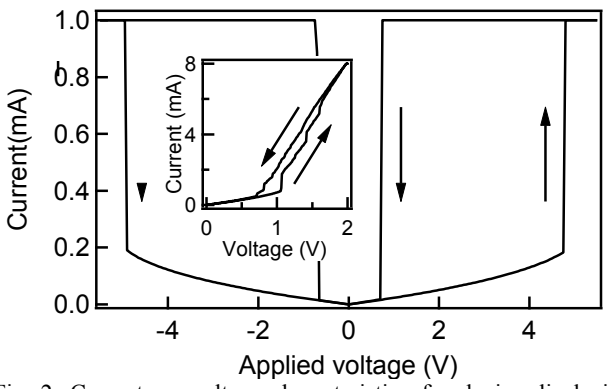

Fig. 2: Current vs. voltage characteristic of a device displaying symmetric volatile switching. A current compliance of 1mA was used. Device size: 0.2x10μm. Inset: current vs. voltage characteristic of a device of 0.2x10μm patterned on VO_2 with ~10 times lower resistivity than in the main figure.

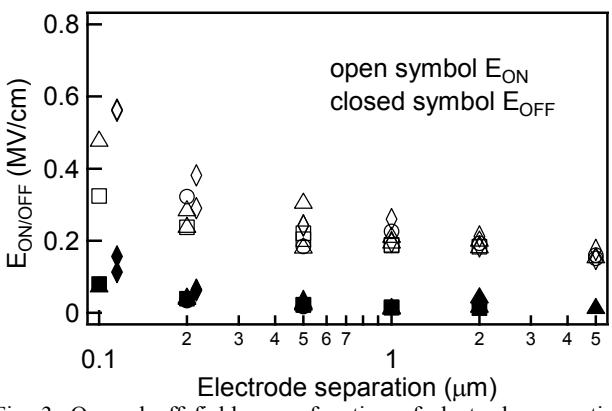

Fig. 3: On and off fields as a function of electrode separation. Open symbols are E_{ON} while closed symbols are E_{OFF}. Different symbols represent different samples.

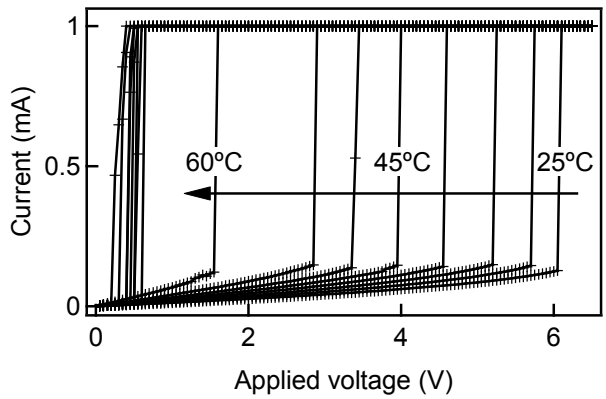

Fig. 4: Current vs. voltage characteristic at different temperatures. The temperature increases between 25 and 60°C in steps of 5°C. The ON and OFF voltages decrease with increasing temperature. Device dimensions: 0.2x2 μm.

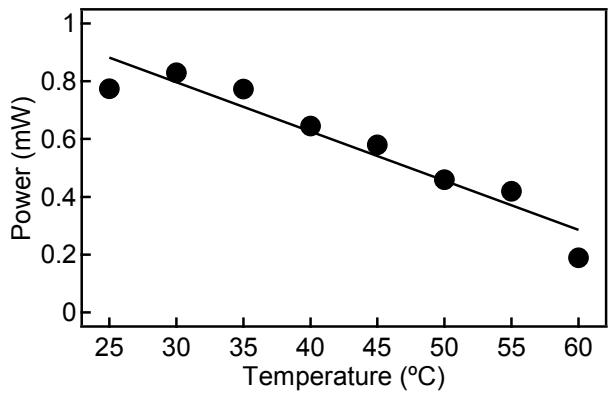

Fig. 5: Power needed to turn on the device. Data extracted from Fig. 4. Solid line is best fit to the data.

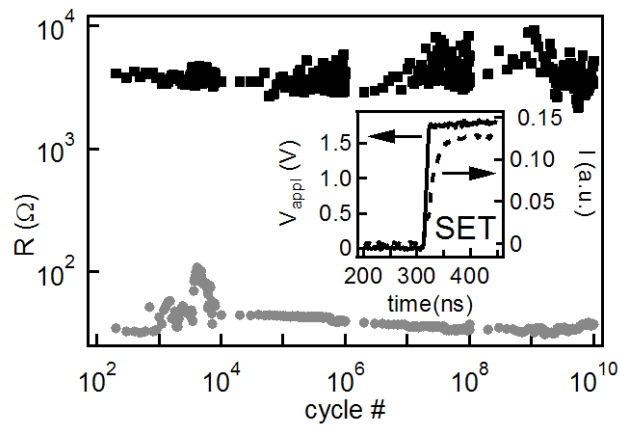

Fig. 6: Cycling of a 0.2x10μm device. A constant resistance of 77Ω has been subtracted from the measured resistances. The value was determined experimentally from short-circuit structures with the same size as the device investigated. The device was still functional when the testing was stopped. Inset: oscilloscope response of the voltage and current through the device during SET.

References

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