Voltage-Triggered Ultrafast Phase Transition in Vanadium Dioxide Switches

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Abstract—Electrically driven metal–insulator transition (MIT) in vanadium dioxide (VO₂) is of interest in emerging memory devices, neural computation, and high-speed electronics. We report on the fabrication of out-of-plane VO₂ metal–insulator–metal structures and reproducible high-speed switching measurements in these two-terminal devices. We have observed a clear correlation between the electrically driven ON/OFF current ratio and the thermally induced resistance change during MIT. It is also found that sharp MIT could be triggered by the external voltage pulses within 2 ns at room temperature and the achieved ON/OFF ratio is greater than two orders of magnitude with good endurance.

Index Terms—Correlated electrons, memory, metal–insulator transition (MIT), ultrafast switch, vanadium dioxide.

I. INTRODUCTION

Vanadium dioxide (VO₂) is a strongly correlated electron system that undergoes a metal–insulator transition (MIT) in the vicinity of room temperature. Electrically triggered phase transition (E-MIT) in vanadium dioxide is of particular interest in novel devices for information storage, memory resistance, and neural circuits [1]–[3]. In a broader context, ultrafast MIT's have relevance to a variety of optoelectronics and communications technologies. An important parameter for such two-terminal switches is the switching speed between the insulating and metallic states, which could provide information on both the application potential and the transition mechanism. Recently, subnanosecond switching has been demonstrated in NbO₂, which is a material showing the thermally triggered MIT (T-MIT) at ∼1080 K [4], whereas the reported switching speed of VO₂ devices is limited to several nanoseconds either due to the test structure or measurement setup limitations [5]–[8]. The demonstrated fastest switching speed (from electrical measurements) is ∼5 ns for planar devices [5] and ∼170 ns for out-of-plane devices [6]. Although the out-of-plane metal–VO₂–metal structures are desirable for memory devices, direct growth on semiconducting substrates, such as silicon, limits the switching speed measurements due to the additional series resistance.

In this letter, we report on the growth and fabrication of metal/VO₂/metal structures by careful process control and study of the switching properties of VO₂. A direct correlation between the transition magnitudes of E-MITs and those of T-MITs is observed and presented for the first time. We find that E-MITs triggered by a voltage pulse occur within less than 2 ns. The demonstrated ON/OFF resistance ratio is ∼100, which is among the largest for pulse measurements to the best of our knowledge, for this material system.

II. EXPERIMENTS

VO₂ thin films were grown on various substrates under different conditions by RF-magnetron sputtering at 550 °C in an Ar/O₂ gas mixture from a V₂O₅ target (as summarized in Table I). Au/c-sapphire structures for pulsed measurements were prepared by depositing Ti (20 nm)/Au (200 nm) layers onto c-sapphire using electron-beam evaporation. Different oxygen partial pressures were used during sample growth to tune the oxygen to vanadium ratio, and the film stoichiometry was studied by the X-ray photoelectron spectroscopy with Al Kα radiation (summarized in Table I). For electrical characterization of samples A to E, 300 μm × 300 μm Ti/Au square electrodes deposited by electron-beam evaporation were used as top electrodes, whereas the conducting substrates were the bottom electrodes as in Fig. 1(a). For sample F, a tungsten probe (tungsten, with a tip radius ∼15 μm) was used to contact the Ti/Au layer that was used as the bottom electrode, whereas a superthin/soft probe needle (tungsten, tip radius from 0.1 to 0.5 μm) contacted the VO₂ film as a top electrode, as shown in Fig. 1(b). The Keithley 2635A and HP 4156C were used for dc measurements. For pulse measurement, a pulse generator Agilent 81110A was used as the source and an HP Infinium oscilloscope 54832B measured the voltage on the sensing resistance Rₛ, as shown in Fig. 1(c). The current passing through the device is given by Vᵣ divided by Rₛ. The voltage was applied on the bottom electrode, so that lower parasitic capacitance and less voltage variation from the top electrode can benefit the bandwidth of the sensing circuit.
TABLE I

<table>
<thead>
<tr>
<th>Sample</th>
<th>Substrate</th>
<th>O₂/Ar partial pressure (mTorr/mTorr)</th>
<th>O/V ratio</th>
<th>Film Stoichiometry</th>
<th>Thickness (nm)</th>
<th>Device Size</th>
<th>Mₜ (Ω/Ω)</th>
<th>Mₑ (Ω/Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Al (100)</td>
<td>0/20</td>
<td>-2.1</td>
<td>Stoichiometric</td>
<td>~ 370</td>
<td>300 μm x 300 μm</td>
<td>~ 2855</td>
<td>146 ± 10</td>
</tr>
<tr>
<td>B</td>
<td>n⁺-Si (100)</td>
<td>0/20</td>
<td>-2.2</td>
<td>Stoichiometric</td>
<td>~ 370</td>
<td>300 μm x 300 μm</td>
<td>~ 2784</td>
<td>129 ± 47</td>
</tr>
<tr>
<td>C</td>
<td>n⁺-Si (100)</td>
<td>0.03/9.96</td>
<td>-2.1</td>
<td>Stoichiometric</td>
<td>~ 300</td>
<td>300 μm x 300 μm</td>
<td>~ 670</td>
<td>82 ± 9</td>
</tr>
<tr>
<td>D</td>
<td>n⁺-Si (100)</td>
<td>0/10</td>
<td>-1.9</td>
<td>O₂ deficient</td>
<td>~ 300</td>
<td>300 μm x 300 μm</td>
<td>~ 50</td>
<td>55 ± 20</td>
</tr>
<tr>
<td>E</td>
<td>n⁻-Si (100)</td>
<td>0.14/9.87</td>
<td>-2.3</td>
<td>O₂ rich</td>
<td>~ 200</td>
<td>300 μm x 300 μm</td>
<td>~ 15</td>
<td>11 ± 7</td>
</tr>
<tr>
<td>F</td>
<td>Au/Al₂O₃ (001)</td>
<td>0.03/9.96</td>
<td>-2.1</td>
<td>Stoichiometric</td>
<td>~ 400</td>
<td>0.1 to 0.5 um radius</td>
<td>~ 500</td>
<td>~ 150</td>
</tr>
</tbody>
</table>

III. RESULTS AND DISCUSSION

Fig. 2(a) shows the representative X-ray photoelectron spectra taken from samples C, D, and E to study the sample stoichiometry. (b) Normalized resistance versus temperature curves from the various samples listed in Table I. (c) Representative threshold switching phenomena in all samples. (d) ON- and OFF-state resistance values as a function of the device size on sample F.

Fig. 3(a) shows the voltage pulse source Vᴾ and the device current Iᴰ as a function of time taken from a device (0.1 μm tip radius) on sample F. At a threshold voltage of ~2.25 V, the device is switched ON sharply with a very short switching time. Vᴹᴹ in pulse measurement is almost the same with the value in dc measurements. The ON-state resistance is 1.1 × 10⁴ Ω. In the OFF-state, the current is too small to be detected by an oscilloscope, but we can estimate it to be ~2.4 × 10⁴ Ω from dc measurements. Therefore, the transition magnitude is roughly 2 × 10⁵Ω, which is among the largest reported (~10 times in [5], [6], [12]). Note that the voltage-pulse-triggered transition has a similar ON/OFF ratio with the T-MIT magnitude, which is consistent with the observations in Fig. 2(d). Fig. 3(b) shows the magnified rising edge of E-MIT. The current first abruptly increases at the threshold and starts to oscillate due to series resistance and capacitance. Within 2 ns, the device resistance changes from ~2.4 × 10⁴ to 150 Ω. Here, we define
the switching time $\tau$ as the time needed for the device resistance to change from $R_{OFF}$ to $R_{OFF}(R_{ON}/R_{OFF})^{0.9}$ (i.e., resistance change by 90% in log scale). The switching time $\tau$ of the device in Fig. 3(b) is $\sim$1.9 ns, which is much shorter than the reported out-of-plane devices on n$^+$-Si. Recent simulations based on a thermal circuit model suggest that the switching time of a VO$_2$ out-of-plane device (100 nm $\times$ 100 nm wide 100-nm-thick VO$_2$ device on Si) would be larger than 6 ns if the homogeneous current-induced Joule heating is the primary mechanism [13]. The switching time should be larger than 10 ns for the 400-nm-thick films studied here, as it would correspondingly scale. Therefore, simply the Joule heating model cannot explain the ultrafast E-MIT. Recently, it has been demonstrated that E-MIT could be triggered by an electric field without passing current, which is attributed to electronic correlation effects [14]. In this letter, the carrier injection, which happens at a faster timescale than thermal heating, could lead to an insulator-to-metal transition and explain the dynamics. Once the device is switched ON, the current conduction increases, which could help to stabilize the bulk MIT. Further modeling should therefore include coupled dynamical effects from both the electronic triggering and current-driven thermal effects. Fig. 3(c) shows the switching behavior of a specific device after multiple pulsed cycles. There is negligible change in the ON-state resistance as evidenced by the shape of the current pulse. The switching time $\tau$ of all the E-MITs shown is within $\sim$2 ns. We note there that the transition timescale to recover the original state is also an important parameter and could be comparable in nanoscale devices owing in part to the increased thermal conductivity in the metallic state [13].

IV. CONCLUSION

We have shown a clear correlation between the E-MIT magnitude and the sample stoichiometry in VO$_2$. We have shown that E-MITs happen close to a bulk form, being different from other CF-based resistive switching phenomena. The growth and fabrication of high-quality VO$_2$ metal–insulator–metal (MIM) two-terminal devices enabled us to obtain sharp E-MITs with a large ON/OFF ratio and probe the intrinsic switching in VO$_2$. The fast switching coupled with room temperature compatibility could lead to further interest in the use of correlated oxide phase transition devices for future electronics and high-frequency communications.

REFERENCES


