Abrupt metal-insulator transition observed in VO$_2$ thin films induced by a switching voltage pulse

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An abrupt metal-insulator transition (MIT) was observed in VO$_2$ thin films during the application of a switching voltage pulse to two-terminal devices. Any switching pulse over a threshold voltage for the MIT of 7.1 V enabled the device material to transform efficiently from an insulator to a metal. The characteristics of the transformation were analyzed by considering both the delay time and rise time of the measured current response. The extrapolated switching time of the MIT decreased down to 9 ns as the external load resistance decreased to zero. Observation of the intrinsic switching time of the MIT in the correlated oxide films is impossible because of the inhomogeneity of the material; both the metallic state and an insulating state co-exist in the measurement volume. This indicates that the intrinsic switching time is in the order of less than a nanosecond. The high switching speed might arise from a strong correlation effect (Coulomb repulsion) between the electrons in the material.

Vanadium dioxide, VO$_2$, possesses a first-order metal-insulator transition (MIT) making it an attractive material for switching devices.$^{1-3}$ The MIT occurs near 68 °C and is accompanied by a structural phase transition. Various transition properties have been studied such as crystal structure and other physical quantities. In particular, aspects of the transition have been examined during thermal and optical inducements.$^{3-7}$ It is also known that a negative differential resistance (NDR) is observed when the current-voltage characteristic of this material is controlled by a static current.$^8,9$ Such an experiment allows the measurement of the MIT with respect to temperature. The current-controlled NDR has been widely investigated for the various compounds of vanadium oxide.$^8-10$ The resistance of the systems abruptly changes at the transition point in contrast to the NDR properties of a conventional semiconductor system. The MIT behavior controlled by a static current is extremely stable and reversible.$^{9,10}$ Up until now, controversy over the mechanism of this transition has existed. It is not known whether the transition is due to thermal or electronic effects.

Recent research favors the electronic model. Observations of the sample stability and the current injected to initiate the MIT support this view.$^{9,10}$ We have reported a stable MIT induced by a constant applied electric field in highly oriented VO$_2$ films and revealed the mechanism of the MIT to be based upon electron-electron correlation using a Raman study of the planar devices.$^{11}$ The transition speed of the MIT in VO$_2$ films has been reported to be below a picosecond through the use of ultrafast optical techniques.$^{12}$ If the field-induced MIT occurs quickly enough to apply to high speed devices and shows a reproducible behavior, there are various applications for VO$_2$ in switching devices such as electrical switches, modulators, and electro-optical devices. Therefore, it is very important to observe the time dependence of the field-induced MIT and also to study the transient properties of the MIT.

In this letter, we investigate the transient current in the material during an abrupt MIT induced by applying switching voltage pulses to VO$_2$-based devices. VO$_2$ thin films with a preferential orientation of (100) are used in these switching experiments. The transient properties of the MIT are analyzed through the observation of the current response profiles.

(100) oriented VO$_2$ thin films were grown on α-Al$_2$O$_3$ (1012) by laser ablation. The partial pressure of oxygen during the deposition process plays an important role in obtaining the pure VO$_2$ phase. The VO$_2$ films were deposited in a working pressure of 60 mTorr with the argon gas atmosphere containing 10% oxygen. The substrate temperature and the deposition rate of the films were 450 °C and approximately 0.39 Å/sec, respectively. A detailed description of the conditions for the deposition of the films were given in previous papers.$^{13,14}$

VO$_2$-based two-terminal devices were fabricated using well-established semiconductor techniques, as shown in the device diagram of Fig. 1. The VO$_2$ films were isolated using selective etching and Au/Cr electrodes were patterned on the films using the lift-off method. The channel length and width between two electrodes were 3 μm and 30 μm, respectively.

A schematic of the apparatus used to observe the transient current profiles is provided in Fig. 1. The system is similar to the Sawyer-Tower circuit used for measuring the displacement current in dielectrics. Switching voltage pulses are generated by a function generator (HP 33120A) and pulse profiles are detected by a digital oscilloscope (HP 54810A). The transient current profiles passing through the device were observed via an external load resistance. The current is calculated using the voltage traces measured over the terminals of the load resistance and Ohm’s Law.
Figure 2 shows an abrupt MIT induced by a static electric field applied to the VO$_2$ films. The film had an abrupt resistivity change of an order of $3 \times 10^8$ at a critical temperature of $T_c \approx 338$ K.$^{11,13}$ A resistor of 1 kΩ was connected to the device in series to prevent an excessive current flow through the film, and the source-drain current between two electrodes was measured, as shown in the inset to Fig. 2. When a static electric field is applied to the device, the current slowly increases with increasing applied voltage and finally jumps up to 5.4 mA at the transition voltage, $V_{MIT}$, of 7.1 V. This behavior was described in detail in previous papers.$^{11,13}$

Figure 3 shows the transient current profiles measured while applying an external switching voltage pulse to the two-terminal device. The switching experiment was conducted at room temperature and used a load resistance of 1 kΩ. A single pulse with a width of 1 μs was applied to the device. We observed that the peak value in the measured current profiles abruptly increase when the applied pulse exceeds the MIT threshold voltage of 7.1 V. For an applied pulse of 7 V, which is below $V_{MIT}$, the height of current profile remains at approximately 300 μA, as shown in the inset to Fig. 3. This behavior is similar to that obtained using a static applied voltage as shown in the current vs. voltage measurement displayed in Fig. 2. At a peak voltage of 10 V, the current reaches a value of 7.5 mA. This corresponds to a current density of $2.5 \times 10^8$ A/cm$^2$, which is of the order of that in a dirty metal. This is a MIT induced by a switching voltage pulse.

In order to explore the switching speed of the MIT for a VO$_2$ film, the current profiles were measured by varying the external load resistances in the circuit. Figure 4 displays the current profiles as a function of the load resistance for measurements employing an applied voltage pulse of 10 V. The lower load resistance leads to the larger current flow through a film after the transition.

Figure 5(a) displays the current profiles observed using a 3 kΩ load resistance. The inset to the figure is a magnified view of the curves in the vicinity of the transition region. There is a time delay just before the current increases. We find that the time delay arises during the increasing portion of the applied switching voltage pulse. That is, although the applied pulse increases steeply, there is a finite time before it reaches the maximum voltage. As shown in the inset of Fig. 5(b), when the applied pulse exceeds $V_{MIT}$ and approaches the maximum value, the current profile begins to increase as indicated by an arrow. A pulse voltage above $V_{MIT}$ induces the MIT. In contrast, a delay is not observed at the falling edge of the current profiles, as shown in the inset to Fig. 3. This is explained by the fact that the applied pulse drops promptly through the value of $V_{MIT}$ in the falling edge. We define the delay time, $\Delta \tau$, as the interval between the onset of the applied switching pulse and the corresponding onset of the current signal. The linear extrapolation technique is used to determine the starting point of the transition. Both the voltage and the current signals are extrapolated to the lines where the current and the voltage are zero. The delay time is estimated to be approximately 20 ns and has no clear dependence on the load resistance, as shown in Fig. 5(b). Here, we did not consider the current profiles observed using less than a 1 kΩ load resistance since the resulting large current of approximately 10 mA can deform the profiles. The rise time of an applied pulse can be reduced by altering the experimental situation because it is related to the capacitance of the pulse generator. If we can make an applied pulse without a rise time, the delay time will approach zero.

We find that the switching speed of the MIT corresponds to the rise time of the current profile. Here, the rise time, $\tau_R$, is defined as the necessary for the current increase to 90% of its maximum value. A plot of $\tau_R$ versus load resistance is presented in Fig. 5(b). The plot is fitted with a straight line. When a $RC$ component is included in the sample, $\tau_R$ can be expressed as $\tau_R = \tau_0 + RC$, where $\tau_0$ is the intrinsic rise time when the resistance component is zero and $C$ is the capacitance of the film. The rise time on the straight line when $R = 0$ is the intrinsic rise time of the MIT, which is estimated to be 9 ns. It is known that the MIT in a VO$_2$ film occurs with inhomogeneity during the transition process.$^{15,16}$ An intrinsic resistance component inevitably exists in the films due to the spatially inhomogeneous system which contains both the metallic state and an insulating state co-existing in the measurement volume. Therefore, it is impossible to observe the intrinsic switching time of the MIT because of the remnant component of resistance. This indicates that the intrinsic switching speed of the MIT in VO$_2$ films can be lower than order of a nanosecond.

The switching time for the MIT can be estimated from a simple thermal model using the heat balance equation.$^9$ Here the heat power is assumed to be conserved in the device volume during the transition process. The estimated value of the switching time is of the order of a microsecond for a device of our scale. The thermal model does not account for a transition time for the MIT of order of a nanosecond. As one of the possible explanations, it may be suggested that conducting paths are formed in the device volume. The formation of conducting paths over repeated switching cycles could lead to the MIT that is unstable and irreversible. However, our experiments demonstrated that the transition was repeatable and reversible. We suggest that the high speed switching is attributable to a strong electron correlation effect as proposed in Mott’s construction of the metal-insulator transition.$^{17}$

In conclusion, the abrupt MIT for VO$_2$-based two-terminal devices was observed during the application of a switching voltage pulse. Current profiles resulted from the MIT were measured using switching pulses with a peak value above the MIT threshold voltage. The delay time and the rise time were compared and the intrinsic switching time was estimated to be about 9 ns. These planar devices are thus identified as being highly applica-
ble to various switching systems because of their excellent switching behavior and stability.

1 F. Morin, Phys. Rev. Lett. 3, 34 (1959).
2 A. Zylbersztejn and N. F. Mott, Phys. Rev. B 11, 4383 (1975).
3 S. Shin, S. Suga, M. Taniguchi, M. Fujisawa, H. Kanzaki, A. Fujimori, H. Daimon, Y. Ueda, K. Kosuge, and S. Kachi, Phys. Rev. B 41, 4993 (1990).
4 G. I. Petrov, V. V. Yakovlev, and J. Squier, Appl. Phys. Lett. 81, 1023 (2002).
5 Mark Borek, F. Qian, V. Nagabushnam, and R. K. Singh, Appl. Phys. Lett. 63, 3288 (1993).
6 D. P. Partlow, S. R. Gurkovich, K. C. Radford, and L. J. Denes, J. Appl. Phys. 70, 443 (1991).
7 Y. Muraoka and Z. Hiroi, Appl. Phys. Lett. 80, 583 (2002).
8 A. Mansingh and R. Singh, J. Phys. C: Solid St. Phys. 13, 5725 (1980).
9 G. Stefanovich, A. Pergament, and D. Stefanovich, J. Phys.: Condens. Matter, 12, 8837 (2000).
10 F. A. Chudnovskii, A. L. Pergament, G. B. Stefanovich, P. A. Metcalf, and J. M. Honig, J. Appl. Phys. 84, 2643 (1998).
11 H. T. Kim, B. G. Chae, D. H. Youn, S. L. Maeng, G. Kim, K. Y. Kang, and Y. S. Lim, New J. Phys. 6, 1 (2004), (www.njp.org).
12 M. F. Becker, A. B. Buckman, R. M. Walser, T. Lepine, P. Georges, and A. Brun, J. Appl. Phys. 79, 2404 (1996).
13 B. G. Chae, D. H. Youn, H. T. Kim, S. L. Maeng, and K. Y. Kang, J. Kor. Phys. Soc. 44, 884 (2004).
14 D.H. Youn, J. W. Lee, B. G. Chae, H. T. Kim, S. L. Maeng, and K. Y. Kang, J. Appl. Phys. 95, 1407 (2004).
15 H. T. Kim, *New Trends in Superconductivity*, NATO Science Series vol II/67, 137 (2002), (http://xxx.lanl.gov/abs/cond-mat/0110112).
16 H. S. Choi, J. S. Ahn, J. H. Jung, and T. W. Noh, D. H. Kim, Phys. Rev. B 54, 4621 (1996).
17 N. F. Mott, *Metal – Insulator Transition* (London, Taylor and Francis, 1990).
FIG. 2. Abrupt metal-insulator transition induced by a static electric field in a VO$_2$ thin film. The inset displays the circuit used for experiments. $I_{DS}$ is the drain-source current and $J_{DS}$ is the corresponding current density.

FIG. 3. Peak current as a function of the peak voltage of the switching pulse. The inset to the figure illustrates the pulse profiles measured using applied switching pulses of (a) 7 V and (b) 10 V.
FIG. 4. Current profiles from VO$_2$ devices with varying load resistance.

FIG. 5. (a) Current profiles measured with a 3 kΩ load resistance. The inset to the figure gives a magnified view of profiles. (b) Rise time and delay time as a function of load resistance.