Phase-transition driven memristive system

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Memristors are passive circuit elements which behave as resistors with memory. The recent experimental realization of a memristor has triggered interest in this concept and its possible applications. Here, we demonstrate memristive response in a thin film of vanadium dioxide. This behavior is driven by the insulator-to-metal phase transition typical of this oxide. We discuss details of this form of phase-change memristance and potential applications of our device. Most importantly, our results demonstrate the potential for a realization of memristive systems based on phase-transition phenomena. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3187531]

The memristor was postulated as a missing fourth circuit element in 1971 based on an observed symmetry in integral-variations of ohm's law.[1] Although this device has remained purely theoretical for many decades, a recent experimental demonstration of a practical system which displays memristive behavior[2,3] has rekindled attention in memristors. Further interest has been fueled by predictions that such devices may play key roles in developing neuromorphic circuits,[4] spintronics,[5] ultradense information storage,[6] and other applications.[7] The key attribute of a memristor is that the resistance of a two-terminal device depends not on the instantaneous value of the applied voltage (as for an Ohmic device), rather on the entire dynamical history of the charge flowing in the system. Memristors act as "resistors with memory"—hence their name. They belong to a much more general class of memory devices, named memristive systems[8,9] where the resistance state may depend on other state variables, such as temperature, structural properties, etc. This memory resistance enables circuit functionalities not possible with any combination of the other three passive circuit elements (resistor, capacitor, and inductor), and therefore is of great practical utility.

In this letter, we demonstrate memristive behavior in a vanadium dioxide (VO_2) thin film. VO_2 has proven to be a versatile material, exhibiting many properties exploitable for devices.[10–12] What makes VO_2 both useful and interesting is its insulator-to-metal (IMT) phase transition occurring near room temperature,[13,14] and the ability to control this transition by applied current,[15] electric field,[16] and photoexcitation.[17,18] As VO_2 passes through the IMT, nanoscale metallic regions emerge from the insulating host, increasing in number and size to form a percolative transition.[19] The memristive behavior we observe in VO_2 stems directly from this IMT phase transition as will be discussed below. Our thin film of VO_2 is deposited by sol-gel technique on a sapphire substrate as described elsewhere.[20] This technique has been shown to produce VO_2 films with up to four orders of magnitude (10^4) change in conductivity across the IMT. Electrical leads are attached to the VO_2 film using Epotec silver epoxy and the device is mounted to a thermal stage. A schematic of our device is shown in Fig. 1(a).

To demonstrate memristive behavior in VO_2, we first set the operation temperature of our device near the onset of the phase transition (340 K). This puts the device into a regime where the resistivity is a highly hysteretic function of temperature [see Fig. 2(a)]. Applying a ramped voltage pulse we monitor the current through the device. Three such current-voltage (*I-V*) curves are shown in Fig. 1(b). The ramp used for each is 50 V 5 s. Arrows on the curves indicate the direction of time as voltage is ramped up and then ramped back down. Examining these *I-V* curves, we observe several hallmarks of memristive devices. First, the *I-V* curve is nonlinear for voltages above a certain threshold level (approximately 20 V in this device). This illustrates non-Ohmic behavior present by definition in any memristive system. All *I-V* traces in Fig. 1(b) are anchored at the origin [$I=0$, $V=0$] indicating that our device does not store capacitive or inductive energy. Thus *I-V* characteristics comply with a fundamental requirement for a memristive system. Second, the *I-V* curves are hysteretic—each curve makes a loop rather

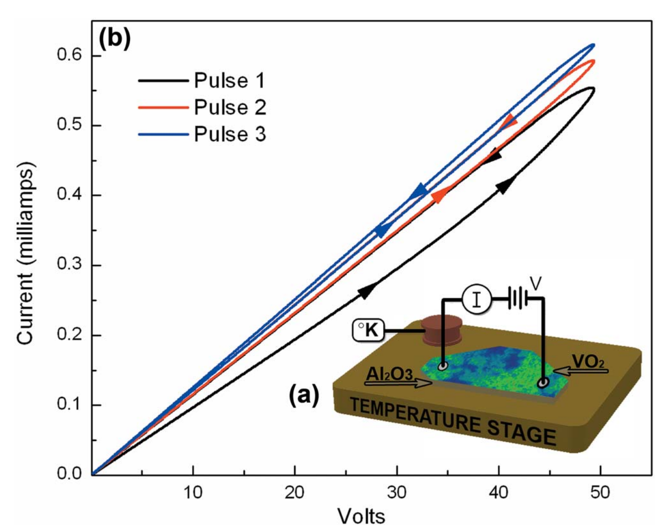

FIG. 1. (Color online) (a) Schematic of the device. The area of the VO_2 film is ~ 25 mm^2. (b) Three current-voltage (*I-V*) curves for our device exhibiting nonlinear hysteretic behavior which is indicative of a memristive system.

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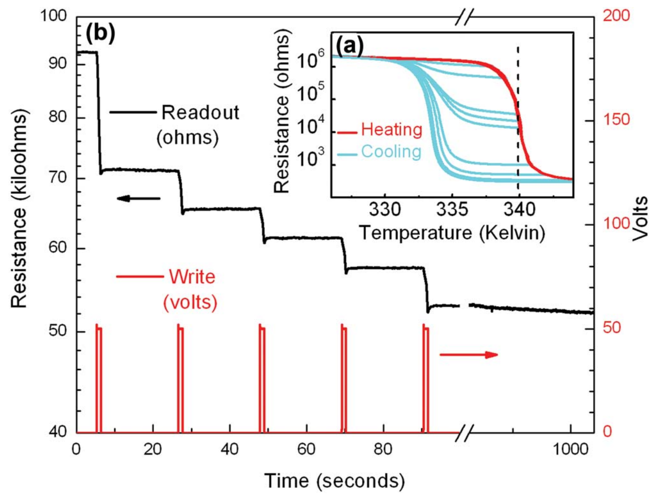

FIG. 2. (Color online) (a) Resistivity-temperature curves of our device illustrating the hysteretic nature of the IMT phase transition. The vertical dotted line shows the bias temperature for experiments of Figs. 1(b) and 2(b). (b) Demonstration of information storage in a memristive vanadium dioxide film. Each 50 V pulse triggers the transition to a new resistivity level.

than retracing its path for increasing and decreasing voltage. The hysteresis present in the VO_2 IMT contains the memory aspect of the memristor. This memory lasts between subsequent ramp pulses, even when the applied voltage has been set to zero for some time. This is illustrated in Fig. 1(b), as the *I-V* slope of each subsequent pulse picks up where the last pulse left off. In an ideal memristor this memory would last indefinitely, although all systems demonstrated so far exhibit finite storage times. Our device shows long memory durations, tested to be longer than several hours.

We observe experimentally that the $-I,-V$ and $+I,+V$ memristance behavior are identical for our device, which indicates memristance in VO_2 is an even function of the current. This differs substantially from the behavior of the TiO_2 crossbar device,[2] wherein reversed voltage polarity reverses the resistance rate of change $\dot{R}$. Although these two behaviors are quite different, they both fit within the definition of memristance phenomena, written as any system which follows the relations $V_M(t)=R(x,I,t)I(t)$, $\dot{x}=f(x,I,t)$ where V_M is the bias across the system and x is a set of state variables.[9] The form of the function $f(x,I,t)$ is not explicitly fixed. If it is an even function of the current, as in our device, $\dot{x}$ will always be positive and $\dot{R}$ will always have the same sign. In general, the function f describes the physics by which the state variable(s) x enable memory resistance. We observe the memristive effect only within a range of temperatures associated with the IMT, suggesting that the memristance is fundamentally related to power dissipated in the VO_2. These observations lead us to conclude that in our device $f(x,I,t) \propto I^2$. Our device is best described as an even-function current-controlled memristive system.

It is important to note that the energy input to the device is negligible compared with the volumetric heat-capacity of the total system. This means the overall temperature is unchanged; confirmed by temperature monitoring. Our VO_2 film is at the same temperature before and after each pulse, which distinguishes the operation from more common materials which change their resistance with temperature. The operation of our device is intimately connected with the percolative nature of the IMT phenomenon in VO_2. Applied voltage promotes the formation of new metallic puddles in the insulating VO_2 host due to transient local heating. When the voltage drops back to zero the film rapidly thermalizes back to its original temperature, yet the new lower resistance state persists: a consequence of the hysteretic transition. Figure 2(a) helps illustrate this, showing that $R(t)$ takes different paths for heating and cooling process. A temporary increase in VO_2 temperature results in a lasting change in resistance. Therefore the information stored in our phase transition memristor is contained in the internal configuration of the VO_2 film: a nanoscale spatial pattern of electronically (and structurally) dissimilar regions.[21]

To further illustrate memristive behavior in our VO_2 device, we apply a sequence of short voltage pulses while monitoring the resistance of the device. Figure 2(b) shows this for a spaced sequence of five 50 V 1 s pulses, with 20 s between pulses. We observe that each pulse triggers a latched change in the resistivity of the film. This latching is found to be extremely stable. The small shift over half an hour of hold time is accounted for by the thermal drift of our setup—which can be easily improved. The amplitude of the resistivity step can be varied by adjusting the amplitude and duration of applied pulses. Repeatable resistance steps of $(R_0\text{-}R_1)/R_0=0.5\%$ are achievable in our setup, where R_0 and R_1 are the pre- and postpulse resistances, respectively. These small steps combined with the very large range of accessible resistance values across the VO_2 IMT could yield more than 2^{10} possible selectable values of resistance in a typical film of VO_2.

We conclude by noting that different memristive systems are likely to retain information via different physical mechanisms.[22–25] For instance, the recent implementation of memristance in titanium dioxide[2] retains information by way of drifting oxygen vacancies and physical crystal expansion. However, alternative mechanisms may prove more suitable for some applications.[5] We have demonstrated memristive behavior in an IMT material, which suggests memristance may exist in many similar phase-transition systems. In particular, electronic phase separation phenomena in the vicinity of the phase transition have been observed in a variety of complex oxides[26] including colossal magneto-resistance manganites.[27] The VO_2 appeal for memristive applications stems both from the magnitude of the conductivity change and the near (or at) room temperature operation. Both the phase-transition threshold temperature and the width of the hysteretic region can be readily adjusted through the film growth and nanopatterning.[15,28] Furthermore, VO_2 is sensitive to a variety of nonthermal stimuli including static electric field[16] and photoexcitations[18]—thus offering yet another dimension of memristive optoelectronics. Finally, switching in VO_2 can occur in the subpicosecond regime.[17] Memristive applications such as learning circuits,[4] information storage[24,29–31] and adaptive networks[32] seem poised to open a paradigm in electronics, and this demonstration of phase-transition driven memristance broadens the scope of materials that may facilitate this revolution.

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