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Electrical switching and oscillations in vanadium dioxide

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ABSTRACT

We have studied electrical switching with S-shaped *I-V* characteristics in two-terminal MOM devices based on vanadium dioxide thin films. The switching effect is associated with the metal-insulator phase transition. Relaxation oscillations are observed in circuits with VO_2-based switches. Dependences of the oscillator critical frequency F_{max}, threshold power and voltage, as well as the time of current rise, on the switching structure size are obtained by numerical simulation. The empirical dependence of the threshold voltage on the switching region dimensions and film thickness is found. It is shown that, for the VO_2 channel sizes of 10 × 10 nm, F_{max} can reach the value of 300 MHz at a film thickness of ~20 nm. Next, it is shown that oscillatory neural networks can be implemented on the basis of coupled VO_2 oscillators. For the weak capacitive coupling, we revealed the dependence of the phase difference upon synchronization on the coupling capacitance value. When the switches are scaled down, the limiting time of synchronization is reduced to T_s ~13 μs, and the number of oscillation periods for the entering to the synchronization mode remains constant, N_s ~ 17. In the case of weak thermal coupling in the synchronization mode, we observe in-phase behavior of oscillators, and there is a certain range of parameters of the supply current, in which the synchronization effect becomes possible. With a decrease in dimensions, a decrease in the thermal coupling action radius is observed, which can vary in the range from 0.5 to 50 μm for structures with characteristic dimensions of 0.1–5 μm, respectively. Thermal coupling may have a promising effect for realization of a 3D integrated oscillatory neural network.

1. Introduction

Vanadium dioxide is an archetypal strongly correlated system that undergoes a Mott metal-insulator transition (MIT) due to the electron interactions accompanied by a structural Peierls transition [1–3]. The switching effect in vanadium dioxide is associated with the MIT, and oscillations are observed in circuits with metal/VO_2/metal switching structures [1]. In the present paper, we report on the numerical simulation and experimental study of the electrical switching effect when scaling the channel region, as well as on the switching dynamics of coupled VO_2-based oscillators with a capacitive and thermal coupling, and explore the capability of their application in an oscillatory neural network (ONN).

An artificial neural network is one of the most promising approaches for development of the next generation computing architectures realizing the brain-inspired massively parallel computing paradigm [3]. Hardware implementations of ONNs are based both on current CMOS devices (e.g., phase-locked loop circuits [4] or Van der Pol oscillators [5]) and on emerging new devices, such as, spin-torque nano-oscillators [6], switches based on materials with metal-to-insulator transitions [1,3,7] or charge-density-wave transitions [8], and oxide RRAM [9].

Vanadium dioxide is currently considered as one of the key materials for neuromorphic oxide electronics [3]. Two-terminal thin-film metal/oxide/metal devices based on VO_2 exhibit S-type switching, and in an electrical circuit containing such a switching device, relaxation oscillations are observed under certain conditions, namely, when the load line intersects the *I-V* curve at a unique point in the negative differential resistance (NDR) region [1]. The switching effect in vanadium dioxide is caused by the MIT occurring in this material at T_t = 340 K [2,10–12]. This thermally driven MIT between the insulating monoclinic and the metallic rutile phases of VO_2 most likely belongs to the class of electronic Mott transitions [10], since the energy gap in the insulating phase arises due to Mott-Hubbard type Coulomb correlations [11]. Nevertheless, the switching effect in relatively low electric fields (namely, if the threshold switching field does not reach a value at which the development of high-field effects becomes feasible [12,13]) is purely thermal. Basically, switching is governed by the current-induced Joule heating, up to the transition temperature T_t, of the oxide film between two metal electrodes.

In an ONN, an elementary cell comprises an oscillator circuit, and the cells are locally coupled by resistors or capacitors [7–9]. Also, in the work [5], the variable resistive coupling via a memristive device has been proposed. Factually, such a type of coupling might be controllable,

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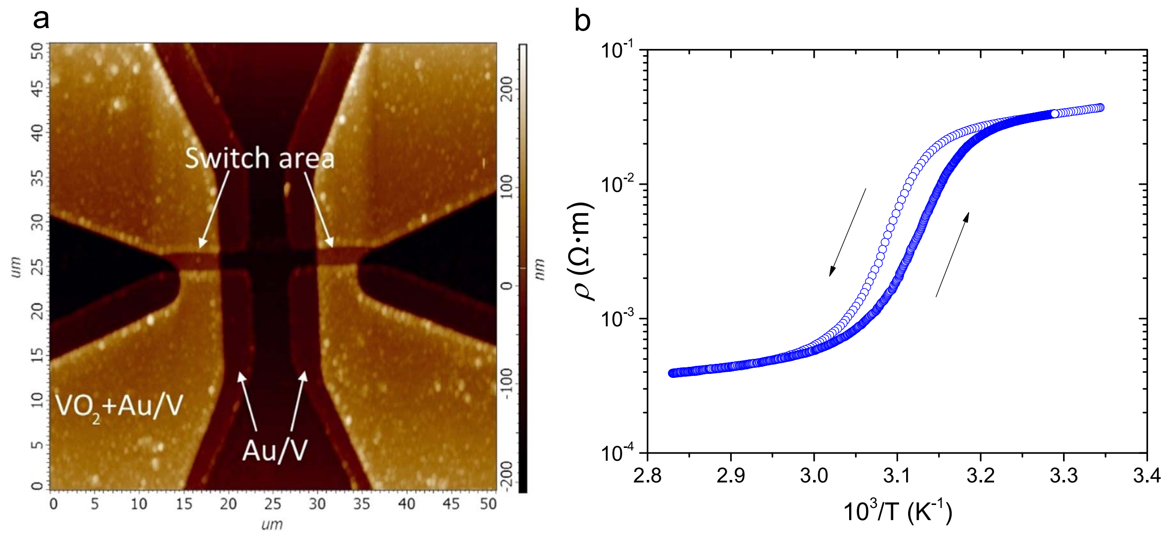

Fig. 1. (a) AFM image of the structure under study and (b) the temperature dependence of the film resistivity.

since the transition of the memristor between the ON and OFF states would bring about the coupling strength hopping between the strong-coupling and weak-coupling modes. Note, that the VO_2-based oscillators can be linked to each other by a thermal coupling owing to a heat-induced switching mechanism. In this case, the coupling strength could also be made controllable via the variation of the heating intensity.

Capacitive and thermal couplings allow obtaining DC decoupling of two oscillators. DC decoupling does not shift operating points of oscillator circuits and is a basic requirement for oscillators' stable operation under variation of the coupling strength. Nevertheless, the question of which one of these coupling modes is more promising for ONN realization and how switch scaling affects the oscillator's main parameters remains unclear.

Thus, the objective of this work is to study the switching dynamics as a function of oscillator size and explore the capability of their application in ONNs.

2. Experimental techniques and numerical calculation methods

Vanadium dioxide films were deposited by DC magnetron sputtering onto *R*-cut sapphire substrates using an AJA Orion 5 sputtering system. The film deposition process has been described in more detail elsewhere [7]. The oxide film thickness was measured by a NTEGRA Prima atomic force microscope (AFM), and it was typically in the range of 200–250 nm.

Planar devices were formed by the optical lithography (a Heidelberg Instruments µPG 101 laser lithograph) and lift-off processes. The electrodes were two-layer V-Au metal contacts with the overall thickness of about 50 nm (30 nm of vanadium and 20 nm of gold). After lithography, the structures were annealed in air at a temperature of 380 °C for 10 min. To study the effect of thermal coupling, electrically isolated planar microstructures were formed at a distance of d = 21 µm from each other, with the shape of the contacts shown in Fig. 1a. The length l and gap h of the switch interelectrode space were ~ 3–4 µm and 2.5 µm, respectively.

The X-ray structural analysis showed that annealing was accompanied by partial oxidation and crystallization of the vanadium oxide films with formation of V_2O_5, V_2O_3 and, predominantly, VO_2 phases. This was also confirmed by the temperature dependence of the film resistivity (Fig. 2b) measured by the four-probe method, which demonstrated a resistivity jump of ~10^2 at the transition temperature, T_t ~320 K. The temperature coefficient of resistance (TCR) at room temperature, calculated from the graph of Fig. 1b, was ~2.1%/K.

Note, that the obtained value of T_t is lower than 340 K, which is typical for thin films as compared to perfect single crystals [13,14].

The study of oscillation dynamics was performed with a four-channel oscilloscope Picoscope 5442B with the maximum sampling rate of 125 MS/s in 14-bit mode. A two-channel sourcemeter Keythley 2636A was used for the DC *I-V* characteristic measurements (the sweeping rate was 1 V/s), and also as an oscillatory circuit voltage and current source.

The simulation was performed using the COMSOL Multiphysics software platform. The calculation area consisted of a 100 × 100 × 100 µm sapphire substrate element with a switch on the lateral side, which in turn consisted of a VO_2 film strip and gold film electrodes, while the other faces were maintained at room temperature T_0 = 300 K. The structure image with the indicated switch width l and interelectrode gap h, as well as the size of the gold contacts, is shown in Fig. 2. In the case when the dimensions were the same, we applied the definition $h = l = a$. The dimensions of contacts a and film thicknesses d are given in Table 1. A sawtooth voltage with the sweeping rate of 1 V/s was applied to the Au contacts, and the amplitude was selected experimentally, depending on the switch threshold voltage. The

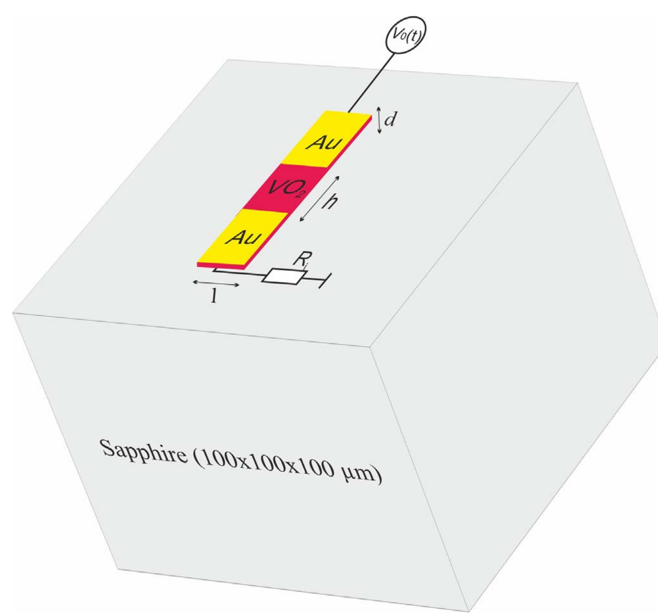

Fig. 2. Model structure image with the parameters $h = l = 1$ µm, and d = 100 nm.