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Application of VO_2 metal-insulator transition to capacitor-less neuron circuits

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Abstract

The VO_2 metal-insulator transition exhibits a function averaging the voltage pulses with a specific time constant, similar to the function of biological neurons. In this study, this time averaging function of VO_2 is exploited in neuromorphic circuits, resulting in a capacitor-less neuron circuit which overcomes the fundamental challenges of downscaling capacitors. The time averaging function can be understood by the slow Joule heat dissipation in VO_2, which enables heat integral in analogy with charge integral in capacitors. Thus, the phase transition materials with time averaging function, including VO_2, can replace capacitors and help integrate the neuromorphic circuits.

1. Introduction

Silicon integrated circuits are encountered with the fundamental problem of power consumption and heat dissipation. An effective solution for this problem is parallelizing the circuit structures, highlighting the potential of such frameworks as GPU and FPGA. Furthermore, the neuromorphic circuit mimicking the neuronal circuits is thought to be one of the extreme solutions for this problem because the neuronal circuit is one of the most parallelized structures among all the existing systems.

Just like neuronal circuits, the neuromorphic circuit consists of local neuron circuits, which average the input voltage pulses, and if the average exceeds the threshold, generate an output voltage pulse. This averaging function is usually obtained by integrating and leaking the input pulses simultaneously, and the timescale of averaging is determined by the time constant of leakage. The conventional neuron circuits have implemented this time constant by the time constant of charging and discharging capacitors ("*RC* time constant") [1]. However, using capacitors inevitably leads to an extremely short time constant ~ps when each capacitor is scaled down in the integrated circuits. Such a short time constant poses challenge when the neuromorphic circuit tries to directly interact with the humans and their surroundings, just like the operation of neuronal circuits in our body. Therefore, it is highly desired for the future neuromorphic circuit to achieve a slow neuron operation by replacing capacitors.

One of the ways for this replacement is to use the phase transition materials. Phase transition materials can average the input signal with a specific time constant, and in addition, the change in their physical properties can simply be utilized for the threshold switching of neuron circuits. One of the

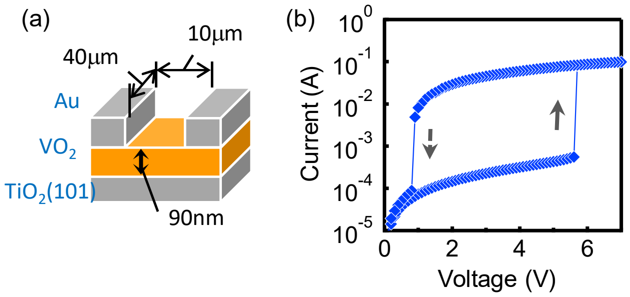

Fig. 1 (a) A schematic illustration and (b) the current-voltage characteristics of the fabricated VO_2 device.

archetypical materials showing phase transitions is VO_2, which is insulating at room temperature and transits to the metallic state by applying electric voltage [2,3]. In this study, we tried to utilize the VO_2 metal-insulator transition for demonstrating the averaging function of neuron circuits. The averaging function in a relatively long timescale of several tens μs was clearly observed in the VO_2 metal-insulator transition under voltage pulses. Then, this time averaging function was exploited for successfully demonstrating the slow operation of the neuron circuits without capacitors. Furthermore, such a relatively long time constant of the VO_2 metal-insulator transition was attributed to the slow dissipation of Joule heat generated by the applied voltage, which indeed well explained the property of the fabricated neuron circuit. These results indicate the phase transition materials may help integrate the neuromorphic circuits by implementing time averaging function without using capacitors.

2. Experiments

A 90 nm VO_2 thin film was fabricated on the (101)-oriented TiO_2 substrate by pulsed laser deposition. During the deposition, the substrate temperature and the oxygen pressure were maintained at 300 °C and 1 Pa, respectively. The VO_2 thin film was further patterned into the 40 μm width by photolithography, and the gold electrodes were fabricated with the 10 μm distance as shown in **Fig. 1a**. All the following measurements using AC or pulse voltage were performed by combining a pulse generator and a digital oscilloscope.

3. Results and discussions

The fabricated VO_2 was insulating at room temperature, but transited to the metallic state under the threshold voltage of ~6 V (**Fig. 1b**) because of the Joule heating of VO_2 up to the transition temperature ~320 K. When the voltage was reset to zero, on the other hand, the heat dissipation de-

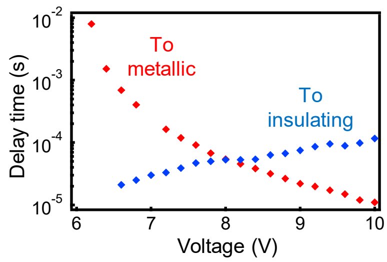

Fig. 2 The time constants of VO_2 metal-insulator transitions under various voltages. The red and blue diamonds correspond to the transition to the metallic state and the transition to the insulating state, respectively.

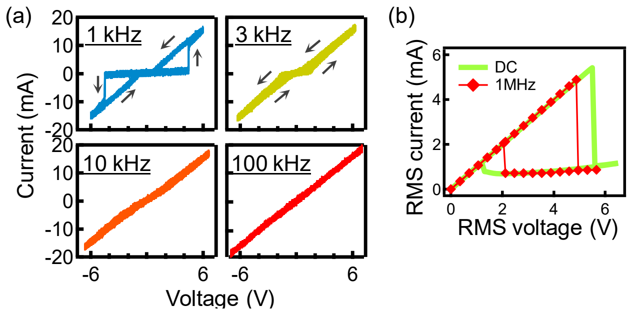

Fig. 3 (a) Instantaneous current vs. instantaneous voltage of VO_2 under AC voltages with various frequencies. (b) The root mean square (RSM) current vs. RSM voltage of VO_2 under DC voltage and the 1 MHz AC voltage.

creased the VO_2 temperature below the transition temperature, and induced the transition to the insulating state (**Fig. 1b**). The time constants of these transitions were in the order of 10-100 µs for the voltage values of 7-10 V as shown in **Fig. 2**.

In order to investigate the time averaging function of the VO_2 metal-insulator transition, AC voltage was applied on VO_2 with the period shorter than this time scale. **Fig. 3a** plotted the VO_2 current as a function of the instantaneous voltage under various frequencies of AC voltage. They showed a clear crossover from the transition by the instantaneous voltage (1 kHz) to the transition by the averaged voltage (100 kHz). The current-voltage characteristics in the root mean square values actually showed coincidence between the DC voltage and the high frequency AC voltage in **Fig. 3b**. This coincidence indicates the averaging function of VO_2 is actually the averaging of square voltage, corroborating the underlying mechanism of Joule heat.

Then, this averaging function of VO_2 was utilized to implement the slow operation of the neuron circuit. The inset of **Fig. 4a** showed the core structure of the neuron circuit using VO_2, and **Fig. 4a** showed the VO_2 metal-insulator transition when voltage pulses with the 8 µs width were applied on this structure. The transition took place at the third pulse for the 50 Hz pulse frequency, reflecting its time averaging function over several tens µs. The number of pulses before transition increased for 40 and 30 kHz due to the decrease in the averaged voltage for the lower frequency. Assuming the transition originated from the Joule heat in VO_2, the VO_2 temperature was simulated in **Fig. 4b** based on the

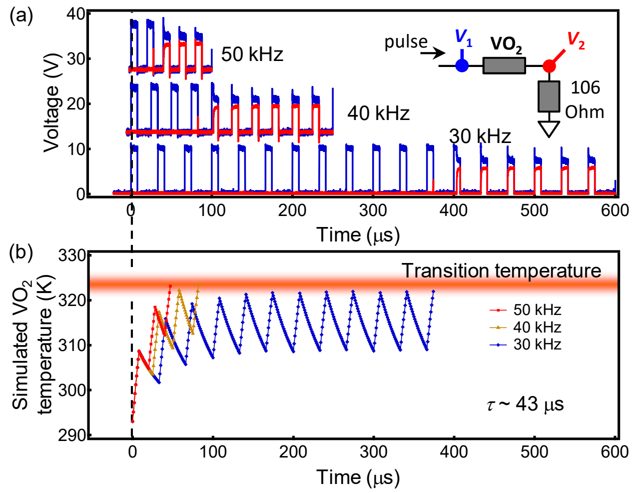

Fig. 4 (a) VO_2 metal-insulator transition under voltage pulses at various frequencies. The blue and red curves correspond to V_1 and V_2 in the inset. (b) The simulated temperature of VO_2 based on the heat dissipation equation with a time constant $\tau \sim 43$ µs.

equation of heat dissipation: $dT/dt = (T - T_{eq})/\tau$, where T is the VO_2 temperature, T_{eq} is the equilibrium temperature under the instantaneous voltage, t is the time, and τ is the time constant of heat dissipation from VO_2. By setting the parameter $\tau = 43$ µs, the transition tool place when the simulated temperature of VO_2 reached the transition temperature.

3. Conclusions

The VO_2 metal-insulator transition, which averages the input voltage pulses over the time constant of heat dissipation, was utilized to implement the neuron function without capacitors. This strategy can also be applied to the combination of other phase transition materials and neuron circuits with various time constants. The capacitor-less neuron circuits will enable the slow operation in the downscaled circuits, providing a fundamental advantage for interacting with the humans and their surroundings in the future.

Acknowledgements

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