NbO$_2$-based frequency storable coupled oscillators for associative memory application

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Abstract—Oscillatory neural networks with nano-oscillators and synapse devices are a promising alternative to implement neuromorphic systems owing to its fast recognition speed and low power consumption. In this work, we demonstrate a compact frequency storable oscillator using nanoscale two-terminal NbO$_2$ insulator-metal-transition (IMT) devices along with TaO$_x$-based resistive switching memory (RRAM) devices. By controlling RRAM resistance, we realized a wide range of analog oscillation frequencies. The synchronization window of two coupled oscillators, which is a key parameter for determining pattern recognition, increases with the increasing coupling capacitance and decreasing RRAM resistance of the reference oscillator. The simple device structure (Metal-NbO$_2$-Metal-TaO$_x$-Metal), small device area (4F$^2$), and frequency storable of NbO$_2$-based coupled oscillator device show a strong potential for future integrated neuromorphic device application.

Index Terms—insulator-metal-transition, neuromorphic system, oscillatory neuron, coupled oscillators

I. INTRODUCTION

Synchronization phenomena of oscillators have been the focus of considerable interest in the field of mathematics, physics, and neurobiology. Specifically, many studies have reported that periodic firing and synchronization of neurons play an important role during the information processing in brain systems [1]. An oscillator-based neuromorphic system that simulates these biological characteristics in hardware has been reported to have advantages in terms of parallel processing and energy consumption [2].

In oscillator-based neuromorphic systems, the input information is stored as oscillator parameters such as phase or frequency. If the patterns stored in the oscillation parameters are similar to each other, synchronization between the oscillators occurs, and this is considered to be pattern recognition [3], [4]. Recently, associative memory characteristics of various coupled oscillator devices such as nanoscale spin-torque oscillator [5], VO$_2$ insulator-metal-transition (IMT) device [6] - [8], NbO$_2$ IMT device [9], [10] and TaO$_x$-based volatile filamentary switching device [11] were reported. However, implementing associative memory hardware using coupled oscillators is complex since it requires additional circuitry to memorize the information of the oscillator [3], [4]. In addition to this, VO$_2$ is not a practical candidate material for oscillator neuron because of its intrinsic low transition temperature (~340K). Also, the threshold switching mechanism of the TaO$_x$-based device has not yet been clearly understood, it needs additional research to guarantee device reliability and uniformity.

In this paper, we demonstrate the nanoscale frequency storable oscillator using NbO$_2$ with TaO$_x$ resistive switching memory (RRAM) device having multi-level linear conductance to store information as an oscillation frequency [12]. NbO$_2$ has a relatively high transition temperature (~1080K), and lower leakage current due to its large band gap (1.0eV) compared to that of VO$_2$ (0.67eV) [13]. Owing to the above reason, NbO$_2$ has the following benefits in IMT based oscillator: 1) wide range temperature operation; 2) reduced power consumption [14]; and 3) increased oscillation frequency due to the reduced charging time [15]. Through the combination of IMT and RRAM devices, we presented a compact and frequency storable oscillator device with a wide range of frequency modulation as a potential candidate for associative memory application. Furthermore, we evaluated the synchronization window of two coupled oscillators for associative memory application.

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II. RESULTS AND DISCUSSION

Fig. 1(a) shows a schematic of the oscillation neuron circuit consisting of two frequency storable oscillators and a capacitor for capacitive coupling. Each oscillator consists of an IMT device and a RRAM device with multi-level conductance states to store analog input values. To configure the circuit as shown in Fig. 1(a), we developed an IMT and a RRAM device with a TiN/NbO$_2$/W [16] and TiN/TaO$_x$/Pt [17] structure, respectively. Both IMT and RRAM devices were fabricated using simple metal-insulator-metal (MIM) structure with an effective device diameter of a 100 nm. Fig 1(b) shows the current-voltage characteristics of the NbO$_2$ IMT device measured by a triangular voltage pulse. Through the AC measurement, we extracted important parameters needed to evaluate the oscillation characteristics of the NbO$_2$ IMT device such as the threshold voltage ($V_{th}$), hold voltage ($V_{hold}$), resistance in the insulating state ($R_{off}$), and resistance in the metallic state ($R_{on}$). The $V_{th}$ and $V_{hold}$ parameters determine the voltage window of oscillation. The $R_{off}$ and $R_{on}$ parameters, on the other hand, represent the allowable range of the external resistor for oscillation. The NbO$_2$ IMT device transforms from the insulating state to the metallic state when the applied voltage exceeds $V_{th}$. In contrast, if the applied voltage is smaller than $V_{hold}$, the NbO$_2$ IMT device goes back to the initial insulating state. Considering the thickness of the NbO$_2$ layer (~30 nm), it was confirmed that an electric field of 0.4 MV/cm is required for the insulator-metal-transition at room temperature. Fig 1(c) shows the current-voltage characteristics of TaO$_x$-based RRAM device. By adjusting the compliance current during SET operation (from high resistance state to low resistance state), we confirmed the multi-level resistance characteristics of the RRAM device. The RRAM device also exhibited linear resistance regardless of the compliance current. After evaluation of the electrical characteristics of the IMT and RRAM devices, we investigated the DC I–V characteristics of the proposed frequency storable oscillator by connecting the IMT device and RRAM device as shown in Fig. 1(d). The oscillator shows the same SET and RESET switching as RRAM, and the current suppressed region at low voltage. By controlling the compliance current during SET or the voltage amplitude during RESET, we confirmed the modulation of the resistance states of the RRAM in the oscillator.

The oscillation characteristics of the frequency storable oscillator device were evaluated through experiments and SPICE simulations, as shown in Fig 2(a). For the SPICE simulation, we used experimentally obtained IMT parameters and a parasitic capacitance value ($C_{12}$ in Fig. 1) of 50 pF. The result of the oscillation obtained from the electrical measurement was in a good agreement with the SPICE simulation result. In addition, the linear conductance of the RRAM was helpful in predicting the oscillation characteristics depending on the voltage. The oscillation behavior is the consequence of a repetitive change in the voltage drop between the IMT and RRAM device. When supply voltage $V_{DD}$ ($> V_{th}$) is applied to the oscillator, most of the voltage is dropped on the IMT device, taking into consideration the relative resistance difference ($R_{off}$ of the IMT device > Resistance of RRAM), and the IMT device begins to change from an insulating state to a metallic state while charging a capacitor connected in parallel. When the transition of the IMT device is completed, most of the voltage will dropped on the RRAM device because $R_{on}$ of the IMT device is smaller than the resistance of RRAM. Following this, the IMT device quickly changes from a metallic state to an insulating state while discharging the capacitor. Through this process, the voltage applied to the oscillator can oscillate with a constant period, and the oscillation frequency is determined by the charging and discharging time [15]. Fig. 2(b) shows the oscillation frequency dependency on the resistance of RRAM device and the supply voltage. As shown in the figure, the oscillator frequency increases as the RRAM resistance decreases and supply voltage increases. Small RRAM resistance and high supply voltage reduce charging time [15], which in turn increases oscillation frequency. Compared to 1T-1IMT based oscillators [7], [8], in which the oscillation frequency is tuned by controlling the gate voltage, our proposed frequency storable oscillator has advantages due to nonvolatility and tunability of RRAM resistance. The oscillator can store the desired oscillation frequency just by controlling the resistance of the RRAM.

Stable oscillation characteristics are realized only in a specific resistance and voltage ranges as shown in Fig. 1(b) and Fig. 1(d), respectively. The available supply voltage of the oscillator with a stable frequency is determined in the following manner. When supply voltage to the oscillator is smaller than the threshold voltage of the IMT device, the oscillation behavior does not occur owing to the absence of a repetitive change of voltage drop of the IMT and the RRAM device. Further, when the supply voltage to the oscillator is larger than the SET voltage, oscillator does not show a stable oscillation behavior owing to the change of the resistance state of RRAM in the oscillator.
Using the SPICE simulation, it was confirmed that the oscillator frequency can be modulated up to 30 times with varying RRAM resistance as shown in Fig. 2(b).

Finally, we evaluated the synchronization characteristics of a coupled oscillator consisting of two oscillators and a capacitor by SPICE simulation. Fig. 3(a) shows the process of synchronizing two oscillators with different RRAM resistance. We observed that the synchronization of the coupled oscillators occurs within a few cycles of locking the phase and frequency simultaneously. Comparing the voltage across the two ends of the coupled capacitor, we can confirm that the two oscillators synchronized as shown in Fig. 3(b). If the two oscillators fully synchronized, the periodic orbit of both voltages shows a constant trace regardless of time. Otherwise, the periodic orbit of the two voltages shows random orbit over time. We identified the parameters that affect synchronization in the coupled oscillator. Fig. 3(c) shows the synchronization window of the coupled oscillator with varying the coupling capacitance and the RRAM resistances in two oscillators. For example, when the coupling capacitance is 10 pF and the resistance of the reference RRAM is 2 kΩ, the synchronization of the two oscillators is realized when the resistance of the other RRAM is within 100% of the resistance difference (ΔRRAM < 4 kΩ). Therefore, the synchronization window of the coupled oscillator increases with increasing coupling capacitance and decreasing RRAM resistance of the reference oscillator.

Synchronization phenomenon in the coupled oscillator can be used for associative memory application by using ‘degree of match’ in the voltage periodic orbits or common coupling node [4] - [8]. In case of pattern recognition application using associative memory, template patterns need to be stored for evaluating ‘degree of match’ between template patterns and input pattern. According to associative memory researches using coupled oscillator, it is necessary to have an additional memory to store the template pattern [3], [4]. Due to the nonvolatility and tunability of RRAM resistance, template patterns can be memorized in our proposed frequency storable oscillator for associative memory application.

III. CONCLUSION

In summary, we have demonstrated a compact frequency storable oscillator device comprising a two-terminal NbO₂-based IMT and TaOₓ-based RRAM device. The proposed device showed nonvolatile frequency storing function and analog oscillation behavior with wide frequency tuning range by controlling the resistance state of RRAM. In addition, the synchronization phenomenon of the coupled oscillator system was analyzed. The synchronization window of the coupled oscillator was evaluated by coupling the capacitance and resistance of RRAM in the oscillator. Considering various advantages such as compact device structure, frequency storable, analog oscillatory behavior, and synchronization characteristics, the NbO₂-based frequency storable oscillator has a strong potential for neuromorphic pattern recognition applications.

REFERENCES


