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# Integrate-and-Fire of Input Spike Signals with High Scalability and Low Energy Consumption Using $VO_2$ Metal-Insulator Transition

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**Abstract**

**Integrate-and-fire of the input spike signals is the basic signal processing in brain-inspired computing, such as deep learning, reservoir computing etc. In such processes, analog technology is essential for low energy consumption. However, analog technology often faces problems in miniaturization due to deteriorated noise tolerance by scaling and intrinsically large analog elements such as capacitors. Here, we propose to exploit a thermal degree of freedom in $VO_2$ metal-insulator transition for scalable and noise-tolerant analog spike processing. We focus on a two-terminal $VO_2$ device, where quasi-adiabatic Joule heating enables efficient spike integration, and metal-insulator transition implements firing. This $VO_2$ device is highly scalable, consuming only ~1fJ/spike (smallest so far) according to the simulation, promising a scalable and energy-efficient integrate-and-fire function for a wide range of brain-inspired computing.**

## 1. Introduction

Low-power brain-inspired computing often uses spike signals. In such systems, the basic signal processing consists of integrate-and-fire of the input spike signals [**Fig. 1a**], which are then interconnected on the network such as cross-bar arrays. Analog implementation of these processes has often used capacitors [1], which have hindered scaling due to their low noise tolerance and large-area occupation [**Fig. 1b**]. Instead of charge integration in capacitors, we propose to integrate input Joule heat in the metal-insulator transition material $VO_2$ for a scalable and noise-tolerant alternative [**Fig. 1b**]. Within the time scale of heat dissipation, the input Joule heat is quasi-adiabatically integrated in the insulating state of $VO_2$, and induces its transition to the metallic state above the transition temperature (~320K). Since the transition decreases the $VO_2$ resistivity by three orders of magnitude, it can easily be detected by a CMOS inverter to drive the following circuits. It should also be noted the hysteresis of this transition mitigates input noise and stabilizes the analog operation [2].

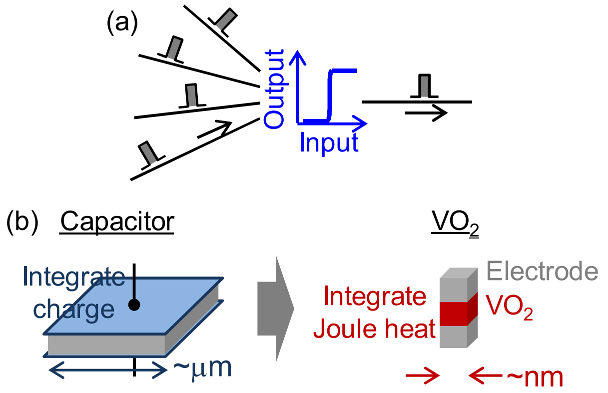



Fig. 1: (a) A schematic illustration of the integrate and fire function and (b) the two different ways of its implementation using capacitors and $VO_2$ metal-insulator transition devices.

## 2. Experimental Demonstration

The two-terminal $VO_2$ device consists of an epitaxial $VO_2$ thin film, which are fabricated at 300°C on a single-crystalline $TiO_2$ (101) substrate [**Fig. 2a**]. Voltage application induces $VO_2$ transition from the initial insulating

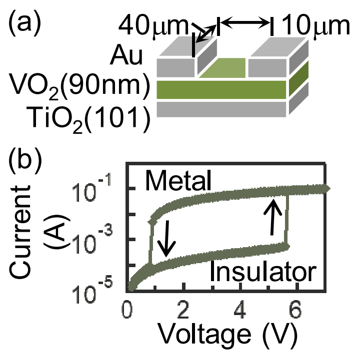



Fig. 2: (a) The fabricated $VO_2$ device. (b) The current-voltage characteristics, which shows the metal-insulator transition.

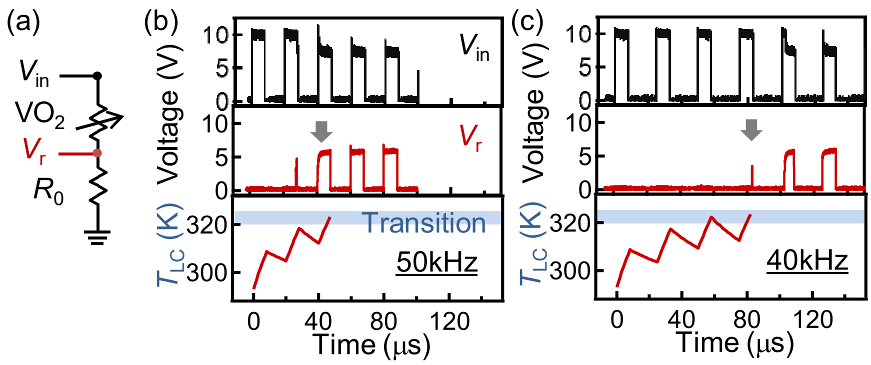
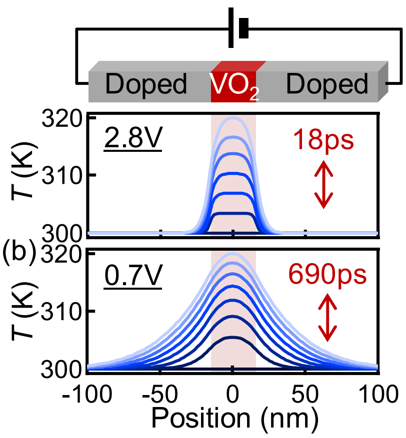



Fig. 3: (a) The experimental setting ($R_0$= 106Ω) and (b,c) the experimental demonstrations of integrate and fire function with two different input spike frequencies: (b) 50kHz and (c) 40kHz. The $VO_2$ temperature ($T_{LC}$) is also estimated with $\tau$ = 43µs and $C_T$ = 47µJ/K.

state to the high-temperature metallic state [**Fig. 2b**]. When the voltage is reset, the $VO_2$ recovers the insulating state, demonstrating the threshold-switching property under the DC voltage [2]. On the other hand, the dynamic property of this device under fast input spikes is defined by the time-dependent local temperature according to Joule heat accumulation and dissipation. The $VO_2$ local temperature, $T_{LC}(t) = C_T \int_0^t e^{-(t-p)/\tau} V(p)^2/R\, dp$ ($C_T$: effective heat capacity, $V(p)$: applied voltage at time $p$, $R$: insulating $VO_2$ resistance), indicats Joule heat integration within the heat dissipation time scale $\tau$. By using these dynamic properties of $VO_2$, the spike integration and threshold processing is experimentally demonstrated, by applying spike voltages on $VO_2$ in a setup shown in **Fig. 3a**. The $VO_2$ transition, which is indicated by the sudden increase in $V_r$, is induced only after a couple of spikes [arrows in **Fig. 3b,c**]. The estimated $T_{LC}$ (bottom panels) confirms the input spike integration by Joule heating.

(a)




(b)

| | V | t | E | $L^2$ | ref |
|---|---|---|---|---|---|
| C | 0.2V | ~100ms | 4fJ | $23mm^2$ | [a] |
| FG | 0.5V | ~10ms | ~300fJ | $\sim 0.07mm^2$ | [b] |
| PRAM | 5.5V | ~ms | 60pJ | $\sim 0.1mm^2$ | [c] |
| $VO_2$(sim) | 0.7V | ~ns | ~1fJ | $\sim 100nm^2$ | – |
| Neuron | 0.1V | ~100ms | ~0.1pJ | $\sim 1000mm^2$ | [d] |

[a] I. Sourikopoulos *et al.*, Front. Neuro. **11**, 123 (2017). [b] V. Kornijcuk *et al.*, Front. Neuro. **10**, 212 (2016). [c] T. Tuma *et al.*, Nature Nano. **11**, 693 (2016). [d] L. J. Gentet *et al.*, Biophys. J. **79**, 314 (2000).

Fig. 4: Simulation of Joule heating in the W-doped $VO_2$ / $VO_2$(32nm) / W-doped $VO_2$ stack for two different applied voltages. Heat capacitance: $3.5J/Kcm^3$ [4], thermal conductivity: 0.06W/Kcm [3] for both $VO_2$ and doped $VO_2$. (b) Benchmarks of spike integration devices such as capacitor ("*C*"), floating gate FET ("FG"), PRAM, $VO_2$, and biological neuron. *V*: typical operation voltage, *t*: typical spike period, *E*: energy per spike, $L^2$: area of the integration device (not circuit).

## 3. Simulation

In order to investigate the potential of the scaled $VO_2$ device, Joule heating inside the 10×10nm out-of-plane two-terminal structure is simulated based on the thermal diffusion equation [**Fig. 4a,b**]. In the structure, the $VO_2$ layer is sandwiched with two metallic W-doped $VO_2$ electrodes, which can minimize the contact resistance with $VO_2$ as well as enable Joule heat confinement by their exceptionally low thermal conductivity [3]. The simulation shows the lower energy consumption for the larger applied voltage. This is because the shorter transition delay enhances the Joule heat confinement as indicated in **Fig. 4a** (quasi-adiabatic heating). In this quasi-adiabatic regime, however, the time scales for the transition and the recovery (cooling) become too short (~ps). Therefore, the transition delay and the energy consumption are compromised at 0.7V, leading to the sub-ns operation time scale and 1fJ energy consumption. This scaled $VO_2$ device is benchmarked with the previous reports including biological neurons [**Fig. 4b**], showing the large potential of this device due to the exploitation of the thermal degree of freedom.

## 4. Conclusion

The two-terminal $VO_2$ device showing the metal-insulator transition is utilized in order to integrate and fire the input spike signals. The quasi-adiabatic Joule heating of $VO_2$ by the input spike signal enables efficient spike integration, and the $VO_2$ metal-insulator transition implements firing. This integrate-and-fire function with the thermal degree of freedom is highly scalable compared an alternative implementation by integrating electronic charge in capacitors, and only consumes ~1fJ/spike (smallest so far) according to the simulation, promising a scalable and energy-efficient integrate-and-fire function for a wide range of brain-inspired computing

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