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New Operation Mode of VO_2-Channel Mott Transistors for Ultra-Sharp ON/OFF Switching

Takeaki Yajima, Tomonori Nishimura, and Akira Toriumi

Department of Materials Engineering, The Univ. of Tokyo
7-3-1 Hongo, Bunkyo, Tokyo 113-8656, Japan
Phone: +81-3-5841-7161 E-mail: yajima@adam.t.u-tokyo.ac.jp

Abstract

The characteristics of the VO_2-channel Mott transistor is systematically studied. The transfer characteristics shows a complete phase transition of the VO_2 channel from the insulating state to the metallic state as a function of the gate voltage. Interestingly, the transfer characteristics has a universal point at a critical gate voltage, where the channel current is almost independent of the applied drain voltage. When the gate voltage is swept across this universal point, the channel current discontinuously jumps showing an exceptionally low sub-threshold swing < 0.5 mV/dec, although accompanied by a hysteresis. The observed discontinuity in the channel current can be well understood by the negative resistance instability of the phase-coexisting VO_2 channel, which can be utilized for designing a ultra-low-voltage switch in the Mott transistor.

1. Introduction

Various types of low-voltage transistors have been studied for decreasing the power consumption in integrated circuits. Although the tunneling field effect transistor is one of such representatives, it has an intrinsic problem of small tunneling current in its ON state. A different approach which enables a large ON current is the Mott transistor, and VO_2 is a promising material for the channel because its electric conductivity changes by three orders of magnitude by a metal-insulator transition as a function of temperature or carrier concentration. Although it has been difficult to electrostatically induce the transition by solid-state gating, we have recently succeeded in solid-state gating the VO_2 metal-insulator transition with an extremely high-*k* epitaxial TiO_2 gate [1], and elucidated the basic operation mechanism of this device [2]. In this study, we achieve a large improvement in the device performance due to the process improvement, and clearly observe the discontinuous switching in the channel current, which indicates an alternative pathway toward an ultra-low-voltage transistor using a phase transition material.

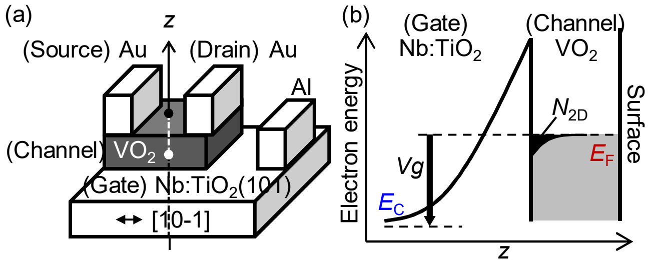

Fig. 1: The schematic illustrations of (a) the VO_2 channel transistor and (b) the band diagram.

2. Device fabrication

In the fabricated device, the TiO_2 gate dielectric is used in an "inverse-Schottky" geometry (Fig. 1a,b), where the N-type doped TiO_2 substrate ($Nb:TiO_2$) is used as the gate electrode and the depletion layer at the interface is used as the gate insulator. Because this geometry uses the high-quality single-crystal substrate for the gate stack, the gate leakage current can be minimized under the high electric field with ~1×10^{14} cm^{-3} electron carrier accumulation [3]. The VO_2 channel with 7.3 nm thickness is formed by pulsed laser deposition on a single-crystal rutile Nb[0.05 wt%]:TiO_2 (101) substrate at the temperature of 300 °C and the oxygen pressure of 1 Pa. The VO_2 channel is patterned

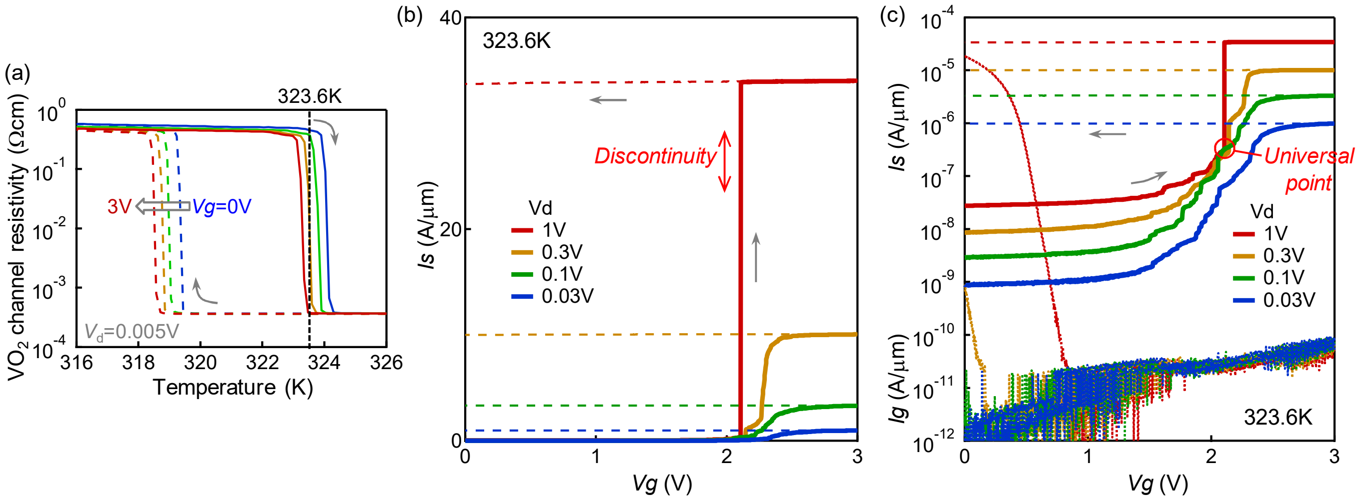

Fig. 2: (a) The VO_2 channel resistivity as a function of temperature and *Vg*. (b,c) The linear plot and the logarithmic plot of the transfer characteristics of the VO_2 channel transistor.

with $NaIO_4$ (0.4 $molL^{-1}$) wet etching with the 50 μm length and the 35 μm width. The source and drain electrodes are formed by Au evaporation, and the contact to the $Nb:TiO_2$ substrate is formed by Al wire bonding. The fabricated VO_2 channel shows an abrupt metal-insulator transition with temperature (Fig. 2a), and the transition temperature is modulated by the gate voltage (*Vg*). All the following experiments are performed at 323.6 K as indicated by the dashed line in Fig. 1c.

3. Results and analysis

Transfer characteristics. The source current (*Is*) is measured as a function of *Vg*, showing a clear switching behavior due to the VO_2 metal-insulator transition (Fig. 2b). The switching is accompanied by a hysteresis as indicated by the dashed lines. Most interestingly, the switching becomes sharper for the larger drain voltage (*Vd*), leading to a completely discontinuous switching at *Vd* = 1 V (red). The logarithmic plot of this transfer characteristics (Fif. 2c) indicates the discontinuous switching initiates from the universal point, where *Is* is independent of *Vd* (analogous to the pinch-off behavior in the normal FET).

Output characteristics. The discontinuous switching by the gate voltage is further confirmed by measuring *Is vs. Vd* at various constant *Vg* (Fig. 3a). By increasing the constant *Vg*, *Is* increases due to the transition to the metallic state in the VO_2 channel. However, as *Vg* approaches the critical value ~2 V, *Is* becomes more and more independent of *Vd*, finally leading to the critical *Is*, which corresponds to the universal point in Fig. 2c. When *Vg* is further increased, the *Is vs. Vd* curve suddenly jumps and *Is* reaches the value for the metallic VO_2 channel.

Device operation diagram. The transfer and output characteristics are summarized as a *Vd vs. Vg* diagram in Fig. 3b. The diagram is separated by the ON/OFF boundary at the critical *Vg* ~2 V (red line), which corresponds to the universal point in Fig. 2c. *Is* discontinuously changes when *Vg* is swept across this ON/OFF boundary. On the left side of this boundary, *Is* is independent of *Vd* as observed in Fig. 3a. On the right side of this boundary, the VO_2 channel becomes almost metallic with large *Is*. For the low *Vd*, the ON/OFF boundary disappears at the critical point around *Vd* ~0.1 V. It is interesting to note that this behavior is analogous to the first-order phase transition, which becomes second order and disappears at the critical temperature in the higher temperature.

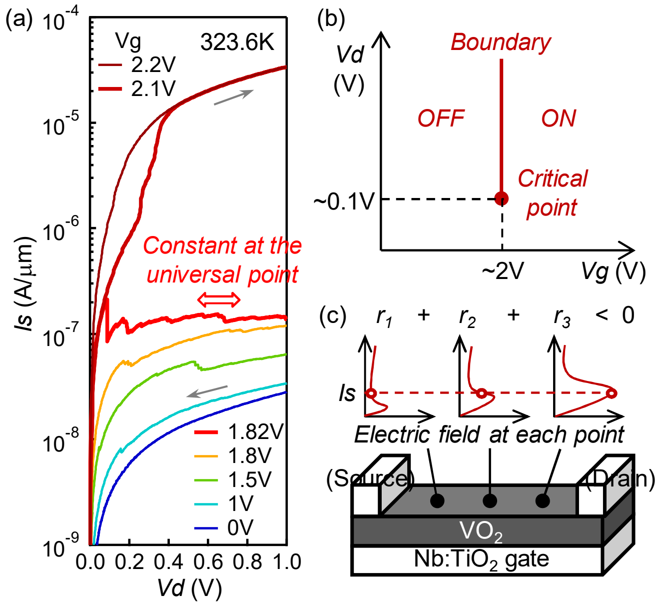

Fig. 3: (a) The output characteristics and (b) the operation diagram of the VO_2-channel transistor. (c) A schematic illustration of the negative resistance instability in the VO_2 channel.

Mechanism. All the discontinuous or critical behaviors in the device can be well understood by the negative resistance instability in the VO_2 channel. Generally, the current-voltage characteristics of VO_2 shows a negative-resistance region in the current-sweep measurement (red curve in Fig. 3c). Therefore, when both *Vg* and *Vd* are increased, the total differential resistance in the VO_2 channel becomes negative, and shows a discontinuous jump in *Is*, corresponding to the ON/OFF boundary in Fig. 3b.

When we look inside the VO_2 channel, the local characteristics of VO_2 gradually changes from the drain to the source due to the applied *Vd* with respect to *Vg*, and the negative-resistance region at each position becomes smaller toward the source (Fig. 3c). Then, *Is* is calculated as:

$$Is = \frac{1}{x_c}\int_0^{xc}\frac{1}{r(x)}\frac{dv(x)}{dx}dx$$
$$= \frac{1}{x_0}\int_0^{Vc}\frac{1}{r(x)}dv$$

Here, we denote the position by x (0 at the source), the local differential resistance by $r(x)$, the local electrical potential as $v(x)$, the critical position by x_c where $r(x_c) = 0$, and the critical *Vg* by *Vc* where the total differential resistance in the channel becomes zero. Therefore, *Is* becomes independent of *Vd* as long as x_0 is almost at the source and becomes constant, just in the same way as the pinch-off phenomenon in FET.

4. Conclusion

The VO_2-channel Mott transistor shows a novel critical behavior at a certain gate voltage, which is accompanied by a discontinuous increase in the channel current. This discontinuity can be understood by the negative resistance instability of the phase-coexisting VO_2 channel, which can be utilized for designing a ultra-low-voltage switch in the Mott transistor. While a similar switch was simulated by externally connecting a "two-terminal" VO_2 device to the source of a Si FET [3], our VO_2 device is intrinsically "three-terminal" with two control variables for the VO_2 channel (*Vg* and *Vd*), and its novel critical behavior enables larger ON/OFF ratio and much smaller sub-threshold swing < 0.5 mV/dec.

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References

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