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Impact of Scaling the VO_2-Channel Mott Transistor below Material Correlation Length

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Abstract
The sharp ON/OFF switching in Mott transistors, originating from the metal-insulator transition in the channel, is often hindered by the inherent material inhomogeneity. Yet, the sharp switching is expected to be recovered by scaling down the transistor channel to the length scale of inhomogeneity. In this study, an ultra-sharp switching in the VO_2-channel Mott transistor is experimentally demonstrated by scaling down the VO_2 channel to several hundred nm. The sharpness of the switching is independent of the applied drain voltage (V_d), indicating it is originated from collective nature of the phase transition, rather than the V_d-induced non-equilibrium effect as previously reported. It is concluded the ultra-sharp switching is feasible by scaling down the Mott transistor below the material correlation length, implying the great potential for its low-voltage application.

1. Introduction

Various types of low-voltage transistors have been studied for decreasing the power consumption in integrated circuits. One of the candidates for such low-voltage transistors is the Mott transistor, where an exceptionally sharp ON/OFF switching by the metal-insulator transition is expected. For the metal-insulator transition materials, VO_2 is a promising candidate because its electric conductivity changes by three orders of magnitude as a function of temperature or carrier concentration around room temperature. Indeed, we have fabricated the VO_2-channel Mott transistor, and demonstrated the solid-state operation by electrostatically accumulating electron carriers in VO_2 via an extremely high-*k* epitaxial TiO_2 gate [1].

On the other hand, the exceptionally sharp switching, which is initially expected for the Mott transistor, has been hindered by the inherent material inhomogeneity in VO_2 thin films [2]. Such inhomogeneity is considered to originate from the extrinsic effect of various defects or the intrinsic effect of transition stress [3], which limits the correlation length of the VO_2 metal-insulator transition [4] and degrades the sharpness of ON/OFF switching. On the other hand, there is a possibility that a sharp switching could be recovered by scaling down the VO_2 channel to the correlation length of inhomogeneity. In this study, an ultra-sharp switching is experimentally demonstrated in the VO_2-channel Mott transistor by scaling down the VO_2 channel to several hundred nm. The sharpness of the switching is independent of the applied drain voltage, indicating it is originated from collective nature of the phase transition, rather than the V_d-induced non-equilibrium effect as previously reported [5].

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 $\sim 1\times10^{14}$ cm^{-3} electron carrier accumulation [1]. The VO_2 channel with 6 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 thin film is patterned with $NaIO_4$ (0.4 $molL^{-1}$) wet etching, and the source and drain electrodes are formed by Au evaporation and photo- or electron beam-lithography. The fabricated VO_2 channel shows an abrupt metal-insulator transition with temperature, and the transfer characteristics are measured just below the transition temperature.

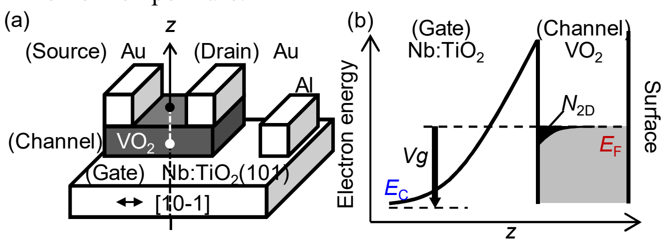

Fig. 1: The schematic illustrations of (a) the VO_2 channel transistor and (b) the band diagram.

3. Results and analysis

Figs. 2 and 3 show the transfer characteristics of the long-channel (L/W = 50/35 μm) and short-channel devices (L/W = 0.24/0.59 μm), respectively. In both devices, the gate leakage (I_g) is sufficiently small, and the increase in the gate voltage (V_g) induces the transition of the VO_2 channel. On the other hand, there is a clear difference between the two devices about the influence of V_d. The long-channel device in **Fig. 2a** shows a gradual switching under the small V_d (0.1 or 0.03 V), reflecting the VO_2-channel inhomogeneity, and a sharp switching for the larger V_d owing to the positive feedback of the constant V_d application [5]. These behaviors are summarized in the operation phase diagram in **Fig. 2b**, where the clear

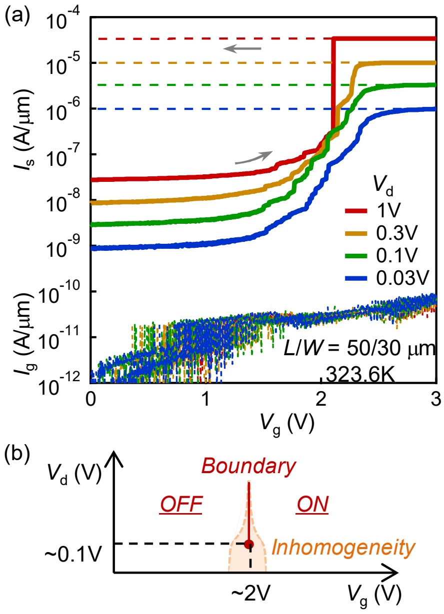

Fig. 2: (a) The transfer characteristics and (b) the operation phase diagram of the long-channel device with various V_d values.

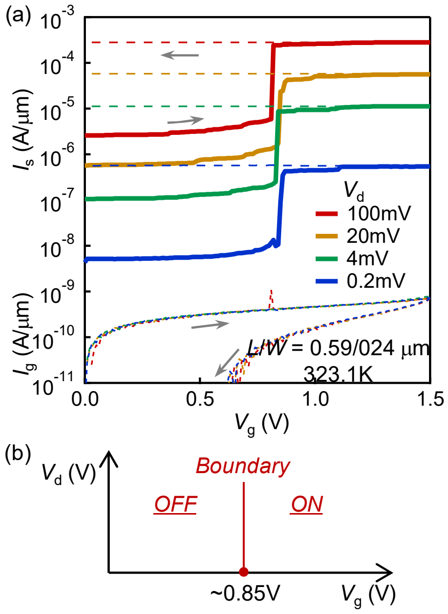

Fig. 3: (a) The transfer characteristics and (b) the operation phase diagram of the short-channel device with various V_d values.

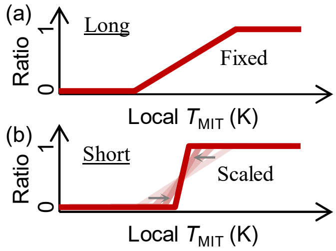

Fig. 4: The cumulative distribution of the local transition temperature (T_{MIT}) for the (a) long- and (b) short-channel devices.

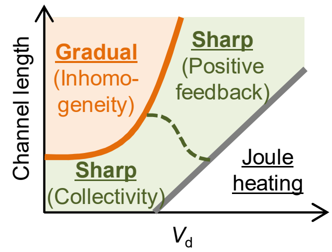

Fig. 5: The switching property of the VO_2 Mott transistors as a function of V_d and channel length.

ON/OFF phase boundary disappears for the smaller V_d because the inhomogeneity becomes dominant. For the short-channel device, on the other hand, the sharp switching is maintained even for the small V_d (**Fig. 3a**), where the inhomogeneity effect seems to be absent. This difference between the long channel and the short channel still remains even if we normalize the drain voltage by the channel length, showing the inhomogeneity effect is suppressed by scaling down the VO_2 channel.

It should be noted what the inhomogeneity specifically means from the perspective of the device operation. The inhomogeneity of the metal-insulator transition can be schematically understood by the distribution of the local transition temperature (T_{MIT}), as shown for the long channel (**Fig. 4a**) and the short channel (**Fig. 4b**), respectively. The important point is that the local T_{MIT} has a certain correlation length in space due to the collective nature of the metal-insulator transition [4]. Therefore, as long as the correlation length is negligible with respect to the channel length, the distribution is independent of the channel length (the long-channel regime, **Fig. 4a**). On the other hand, the distribution can be decreased by channel scaling when the correlation length is comparable to the channel length (short-channel regime, **Fig. 4b**). Then, this T_{MIT} distribution directly influences the Mott transistor operation, especially the sharpness of the ON/OFF switching as demonstrated in **Figs. 2 and 3**.

Finally, the switching property of the VO_2-channel Mott transistor is summarized as a function of the channel length and V_d in **Fig. 5**. The right-bottom region (white color) corresponds to the short channel with large V_d, which leads to the severe Joule heating and the VO_2 transition irrespective of V_g. The left-top region (orange color) corresponds to the long channel with small V_d, which results in the gradual switching due to the VO_2-channel inhomogeneity. The other two regions (right-top and left-bottom, green color) both show the sharp switching, but its dominant origins are different. In the right-top region, the sharp switching is mainly caused by the positive feedback of the constant V_d, where the pinch-off effect on the drain side plays an essential role [5]. In the left-bottom region, the sharp switching is mainly attributed to the collective nature of the VO_2 metal-insulator transition, where V_d is too small to activate the pinch-off effect.

4. Conclusion

An ultra-sharp switching is experimentally demonstrated in the VO_2-channel Mott transistor by scaling down the VO_2 channel to several hundred nm. This ultra-sharp switching is almost independent of the applied drain voltage, indicating its physical mechanism originating from collective nature of the phase transition. Thus, the ultra-sharp switching is obtained simply by scaling down the VO_2 channel, implying the great potential of the Mott transistor for low-voltage application.

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References

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