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Solid-State Operation of Mott Transistors with Ultra-Thin VO_2 Channels

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Abstract
A Mott transistor is one of the promising device platforms for realizing low-voltage switching, where the gate voltage induces a Mott transition in the transistor channel to abruptly change the electrical conductivity. However, the operation of Mott transistors often require a sheet carrier modulation more than 10^{14} /cm^2, which is hard to access by conventional high-*k* dielectrics. Here, we achieved ~10^{14} /cm^2 carrier modulation by an extremely high-*k* gate dielectric of TiO_2, and demonstrated a clear operation of a Mott transistor in a solid-state device for the first time. A transition was induced by the electrostatic carrier modulation in the ultra-thin VO_2 channel, which opens the door for the low-voltage device using electronic phases and their transitions.

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 Mott transistors with VO_2 channels have been studied for more than 10 years, it has been difficult to electrostatically induce the transition even by using the high-*k* dielectrics [1,2].

2. Device design

In this study, we focused on the TiO_2 gate dielectric (Fig. 1a) which has an extremely high relative dielectric permittivity more than 100. Although TiO_2 was not applicable to conventional semiconductor channel due to the lack of band offset, it is applicable to the VO_2 channel due to the band offset of ~0.9 eV at the interface. Besides, TiO_2 has the same crystalline structure (rutile) and a small lattice mismatch (~1 %) with VO_2, which forms an epitaxial interface. Here, the TiO_2 gate dielectric was used in an "inverse-Schottky" geometry (Fig. 1b,c), where the N-type doped TiO_2 substrate (Nb:TiO_2) was used both as the gate insulator and the gate electrode. Because this geometry uses

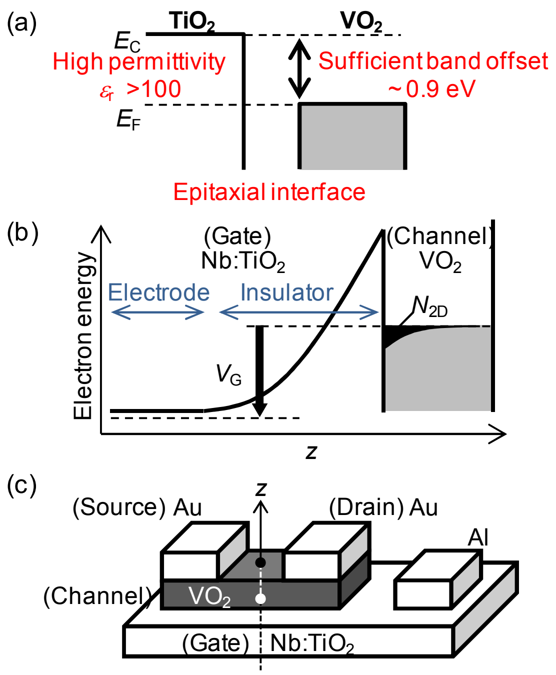

Fig. 1 Schematic illustrations of the VO_2-channel Mott transistors. (a) The band alignment of the VO_2/TiO_2 gate stack, (b) the inverse Schottky gate, and (c) the device structure.

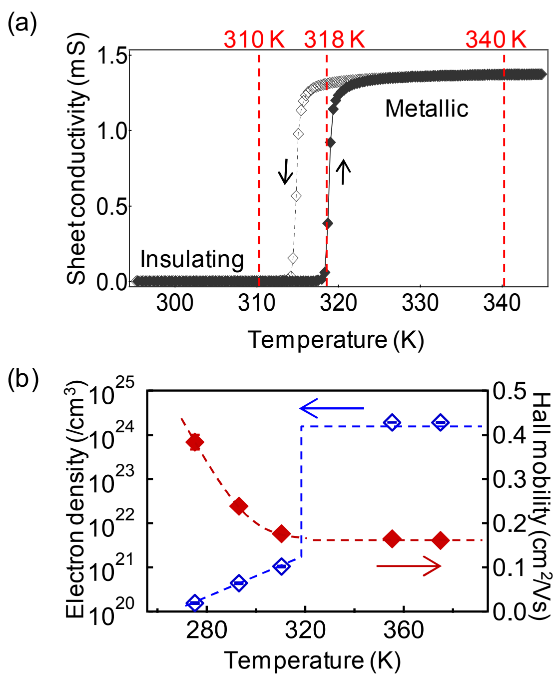

Fig. 2 Electrical characteristics of a VO_2 thin film on the TiO_2 (101) substrate. (a) The metal-insulator transition with temperature for the 8 nm film, (b) and the corresponding results of the Hall measurement.

the high-quality single-crystal substrate for the gate stack, a reliable gate modulation can be achieved even under the high electric field.

3. Experiments

VO_2 thin films were grown by pulsed laser deposition onto the single-crystal rutile Nb[0.05 wt%]:TiO_2 (101) substrate at the temperature of 350 °C and the oxygen pressure of 1 Pa. The VO_2 thin film was patterned by diluted aquilegia, and the source and drain electrodes were fabricated by evaporating Au to form a channel with the 131 μm length and the 100 μm width.

4. Results

Characterization of VO_2 channels. VO_2 thin films on the TiO_2 (101) substrate had an atomically flat surface and was tensile-strained by the substrate. In this study, an ultra-thin 6 nm film was adopted as the transistor channel to avoid lattice relaxation, which showed a sharp transition around room temperature (Fig. 2a). This transition involved the three-order change of the electron concentration and the negligible change of Hall mobility ~0.2 cm^2/Vs (Fig. 2b).

TiO_2 inverse Schottky gate. The VO_2/Nb:TiO_2 showed a typical rectifying property (Fig. 3a), where the breakdown voltage (V_{BD}) more than 10 V ensures the large gate modulation in the inverse Schottky gate geometry. The capacitance was well fit by the Mott-Schottky plot (Fig. 3b), whose slope gives the relative permittivity of 111. This large permittivity enables a small equivalent oxide thickness (EOT), and hence, a large accumulated charges > 10^{14} /cm^2 at V_G = 10 V (Fig. 3c).

Transistor operation. The transfer characteristics in Fig. 4 were measured at three different temperatures as indicated by red lines in Fig. 2a. A large gate modulation was obtained in the vicinity of the transition temperature ~318 K. The obtained ON current was two orders of magnitude larger than the value predicted by the gate capacitance (Fig. 3b) and the electron mobility in the channel (Fig. 2b), as shown by open diamonds in Fig. 4a and b. This large discrepancy clearly captures the characteristics of Mott transistor operation which involves the transition in the VO_2 channel.

5. Conclusion

A solid-state operation of Mott transistors was first demonstrated, by using an ultra-thin VO_2 channel and a TiO_2 gate dielectric. Reflecting the characteristics of Mott transistors, the obtained ON current was two orders of magnitude larger than predicted by the accumulated charge density. Although the operation voltage is still high, this first clear demonstration will lay the basis for the development of Mott transistors.

Acknowledgements

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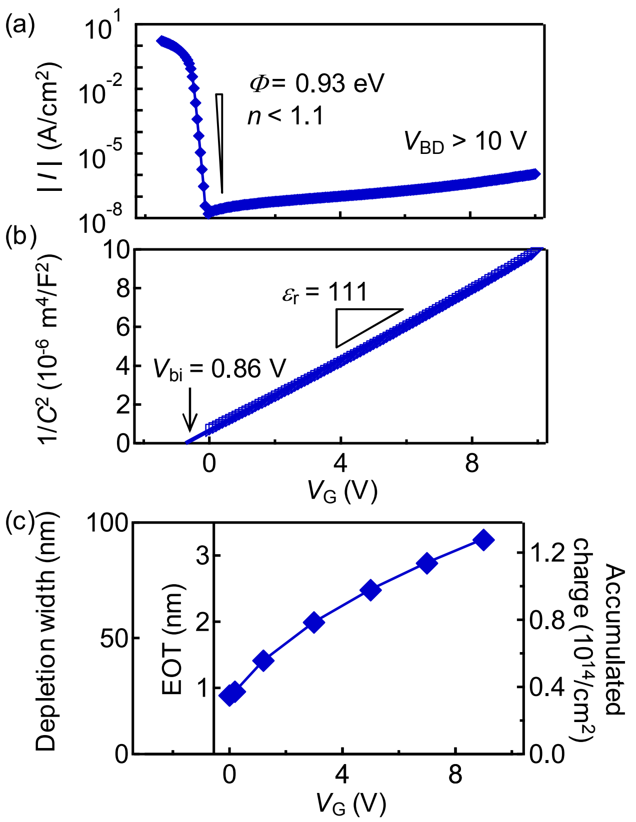

Fig. 3 Electrical characteristics of the TiO_2 inverse Schottky gate with the VO_2 channel. (a) The I_G *vs.* V_G, (b) $1/C^2$ *vs.* V_G, and (c) several basic parameters.

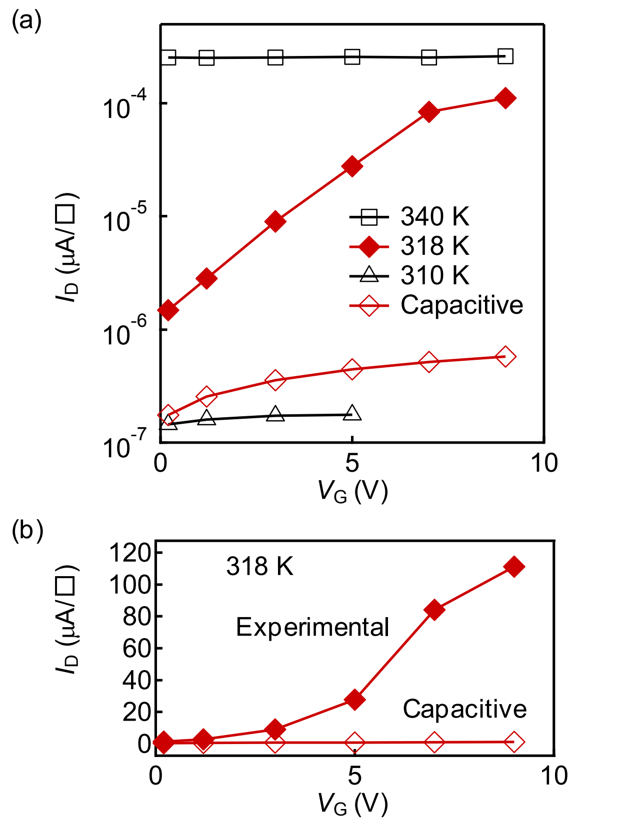

Fig. 4 The transfer characteristics of the VO_2-channel transistors (a) in a logarithmic scale and (b) in a linear scale.