I-5-03 Extended Abstracts of the 2020 International Conference on Solid State Devices and Materials, VIRTUAL conference, 2020, pp631-632

Operation Principle of VO_2 Mott Transistor: Local Electrostatic Modulation and Global Avalanche Effect

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Abstract

Controlling material phases by applying gate voltage has been a long standing challenge in a three-terminal device. Recently, such electrostatic control of metal-insulator transition has successfully been demonstrated using an ultra-thin VO_2 channel and a TiO_2 inverse-Schottky gate. However, an operation principle of this so-called Mott transistor has yet to be known. In this paper, the experiments are compared with model calculation of the VO_2 Mott transistor which incorporates local electrostatic modulation of the VO_2 phases and global avalanche effect throughout the VO_2 channel. The calculation reproduces the transfer and output characteristics, and elucidates the origins of the ultra-sharp switching therein. These results provide a basis not only for abrupt switching functions in electronics but also for high-precision control of material phases in fundamental science.

1. Introduction

Electrical control of phase transitions is essential for non-volatile memories, novel switches, sensors, batteries, neuromorphic devices, to name but a few. Among various control methods, an electrostatic control in a three-terminal geometry is considered the most energy efficient with the highest resolution. Therefore, a field-effect transistor with a phase transition material in the channel (Mott transistor) has been fabricated for more than several decades. In practice, however, the impact of the gate voltage is too small to induce the phase transition, and its electrostatic control was not straightforward. Recently, such electrostatic control of metal-insulator transition has been demonstrated using the ultra-thin VO_2 channel and the TiO_2 gate dielectrics, exploiting an extremely high relative permittivity of TiO_2 beyond 100 [1,2]. Although the device works only in the vicinity of the transition temperature, the VO_2 channel conductance is successfully modulated electrostatically by three orders for the first time. Interestingly, the device shows an ultra-sharp switching as a function of the gate voltage (V_G) when the drain voltage (V_D) is relatively large. However, the physical origin of this unique property in Mott transistors has yet to be elucidated.

In this paper, a compact model for the VO_2 Mott transistor is constructed which incorporates the local electrostatic modulation of the VO_2 phases and the global avalanche effect throughout the VO_2 channel. The model calculation successfully reproduces the experimentally obtained characteristics, and provides a theoretical platform

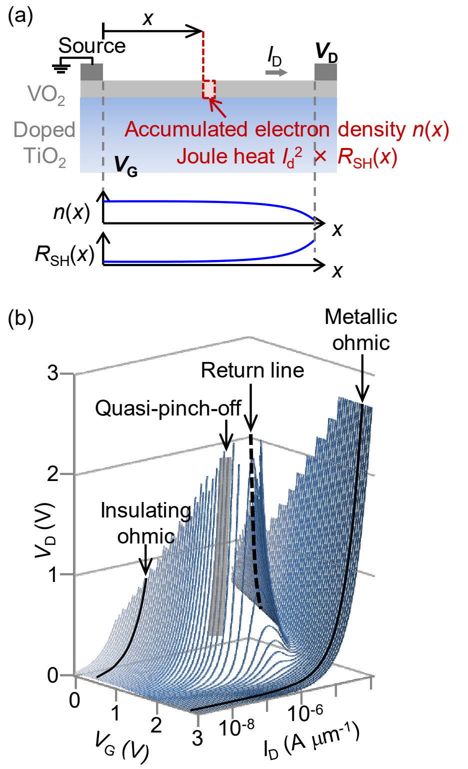

Fig. 1 (a) Schematic illustration of the VO_2-channel transistor, and its model based on the accumulated electron density $n(x)$ and the sheet channel resistance $R_{SH}(x)$. (b) Calculated I_D-V_G-V_D characteristics.

for Mott transistor operation for the first time.

2. Experiments and simulations

In the TiO_2 inverse-Schottky gate (**Fig. 1a**), the N-type doped TiO_2 substrate (doped TiO_2) is used as the gate electrode and the depletion layer at the interface is used as the gate insulator [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 channel and the source and drain electrodes (Au) are formed by photolithography.

For the small V_D, the VO_2 channel can be regarded as a homogeneous resistor, and its resistance is simply determined by the temperature and the V_G. The V_G accumulates electrons in the VO_2 channel with the areal density proportional to $(V_G + V_b)^{1/2}$ - $V_b^{1/2}$ according to the Mott-Schottky model [3], and decreases the transition temperature (T_{MIT}) by $a\{(V_G + V_b)^{1/2} - V_b^{1/2}\}$ where V_b (= 0.7 V) is the equilibrium built-in potential and a (= 0.73 $KV^{-1/2}$) is a linear co-

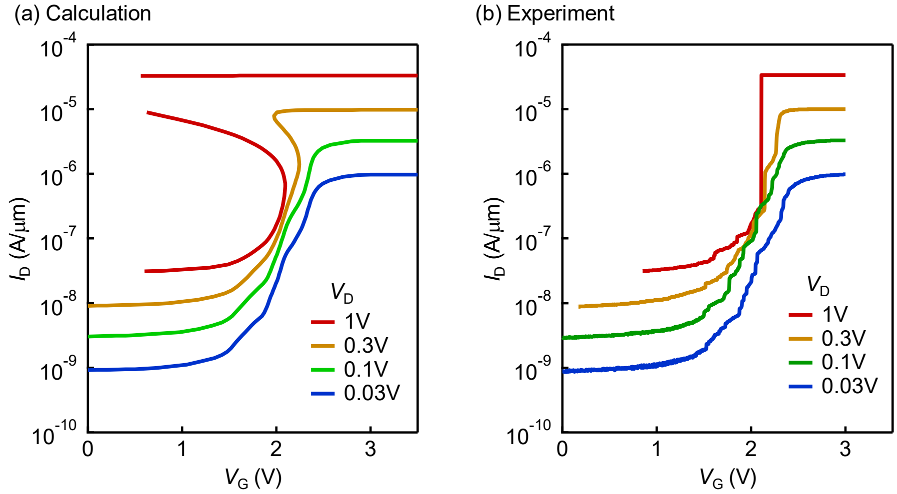

Fig. 2 (a,b) Calculated and experimental I_D-V_G characteristics of the VO_2-channel transistor.

efficient [1]. Because the Joule heating is negligible in the small-V_D condition, the transition of the VO_2 channel is simply induced by $T + a\{(V_G + V_b)^{1/2} - V_b^{1/2}\}$ where T is the temperature. Here, an electrostatic temperature is defined by $T_{ES} = T + a\{(V_G + V_b)^{1/2} - V_b^{1/2}\}$, and this T_{ES} can evaluate the temperature effect and the electrostatic effect simultaneously.

For the large V_D, the local gate voltage and the local temperature varies as functions of the distance from the source. The local sheet resistance of the VO_2 channel R_{SH}(x) is determined by the local electrostatic temperature by $R_{SH}(x) = f(T_{ES})$, where the function $f(\ )$ is obtained from the experiment. The local temperature $T(x)$ including the Joule heating effect is approximated by $T(x) = T_0 + I_D^2 R_{SH}(x)/D$. The first term T_0 is the environmental temperature (323.5 K), and the second term $I_D^2 R_{SH}(x)/K$ is the approximate increase in the local temperature induced by Joule heating, where I_D is the sheet current, and K is the effective thermal conductance to the surroundings (3×10^5 $WK^{-1}m^{-2}$). Therefore, $T_{ES}(x) = T_0 + I_D^2 R_{SH}(x)/K + a\{(-V_{CG}(x) + V_b)^{1/2} - V_b^{1/2}\}$, where $-V_{CG}(x)$ is the local gate voltage, namely, $-V_{CG}(0) = V_G$, and $-V_{CG}(L) = V_G - V_D$. The $V_{CG}(x)$ follows the local Ohm's law: $dV_{CG}(x)/dx = I_D R_{SH}$(x). By solving these equations for fixed I_D values and the boundary condition of $V_{CG}(0) = -V_G$, $V_{CG}(x)$ and the $R_{SH}(x)$ can be calculated. Accordingly, V_D is obtained by $V_{CG}(L) = -(V_G - V_D)$. By iterating this calculation for various I_D and V_G values, the three-dimensional map (I_D–V_G–V_D) of the steady state is obtained as shown in **Fig. 1b**.

3. Results and analysis

The model calculation in **Fig. 2a**, which is a cross section of **Fig. 1b**, well reproduces the experimental transfer characteristics in **Fig. 2b**. The comparison shows the discontinuous jump for V_D = 1 V in the experiments originates from the negative differential transconductance in calculation. To understand the discontinuous jump, the stability problem against the thermal fluctuation is considered. When the temperature slightly increased by $\delta T(x)$ owing to the fluctuation in the channel, the channel resistance slightly decreased by $-\delta R_{SH}(x)$ owing to the evolution of the metallic transition. The decreased resistance increases Joule heating at a constant V_D condition. If this increased Joule heating is not sufficient to maintain the initial $\delta T(x)$, the fluctuation decays with time indicating the initial steady state is stable. If the fluctuation diverges with time, the system is unstable leading to the thermal runaway and the discontinuous transition.

The stability against fluctuation can be controlled as a function of V_G and V_D. In **Fig. 1b**, all the steady states with a negative I_D–V_D differential conductance or a negative I_D–V_G transconductance are unstable. Conversely, all the steady states with the positive differential conductance (the regions labeled with “metallic ohmic” or “insulating ohmic” for example) are stable. Therefore, when the steady state crosses the “return line” with the increase in V_G, the system becomes unstable and the I_D shows a discontinuous jump due to the thermal runaway. It should be noted simply increasing V_D cannot induce thermal runaway within the measurement voltage range as shown in **Fig. 1b**. For the discontinuous jump, the increase in V_G is necded which can increase the fluctuation gain and flips the system stability.

4. Conclusion

An ultra-sharp switching in the VO_2-channel Mott transistor is successfully reproduced by a compact model calculation based on the local electrostatic modulation and the global avalanche effect. According to the model, a relatively large V_D makes the channel nonequilibrium, and its stability against fluctuation is decreased by V_G leading to the ultra-sharp switching at the threshold. These results provide the device physics of the Mott transistor for the first time enabling the systematic design of this novel device platform.

Acknowledgements. This research was supported by JST-CREST JPMJCR14F2, and was partially supported by JSPS KAKENHI 15K17466.

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