ADVANCED ELECTRONIC MATERIALS

Supporting Information

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Observation of the Pinch-Off Effect during Electrostatically Gating the Metal-Insulator Transition

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Supporting Information

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Negligible Joule heating by the gate voltage

In the fabricated VO_2-channel three-terminal device, the application of V_G induces the metallic transition as shown in Figure 2A. As for the small V_D below 0.1 V, this gate-induced phase transition is purely electrostatic and not caused by Joule heating for the following three reasons:

1. In Figure 2A, the transfer curves are parallel to each other for V_D = 0.03 V and 0.1 V. This means the I_D linearly scales with V_D, in other words, the Joule heat of $I_D \times V_D$ is negligible for the transition up to V_D = 0.1 V. The V_G-induced Joule heat of $I_G \times V_G$ is orders of magnitude smaller than this V_D-induced Joule heat as shown in Figure S1. Therefore, $I_G \times V_G$ is also be negligible for the transition.

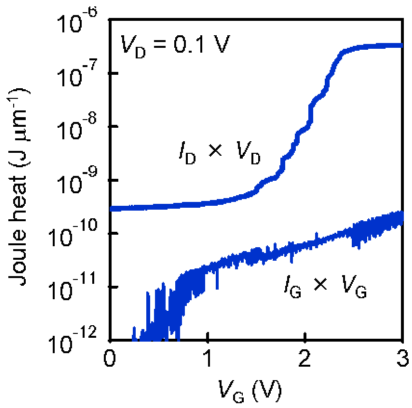

Figure S1. Joule heat comparison. The comparison of the V_G-induced Joule heat ($I_G \times V_G$) and the V_D-induced Joule heat ($I_D \times V_D$) in the transfer characteristics at V_D = 0.1 V in Figure 2A.

2. To the first approximation, the Joule heat linearly increases the local temperature according to the steady state heat equation: $E = D\ \Delta T$, where E is the Joule heat, D is the heat conductance to the heat sink, and ΔT is the temperature increase with respect to the heat sink. If the shift of the transition temperature by V_G (Figure 4B) is due to Joule heating, the

magnitude of the shift ΔT should linearly scales with $E = I_G \times V_G$ because of the abovementioned equation. As shown in Figure S2A, however, the shift does not linearly scales with $I_G \times V_G$ but rather scales with the accumulated electron density as shown in Fig. S2B. The similar scaling with the accumulated electron density is also reported in ref. 18, indicating the shift of the transition temperature is not caused by Joule heating but rather originated from electrostatic gating.

3. In the vicinity of the transition point, the I_D does not increase with V_D but rather saturates as shown in Figure 2A (V_D = 0.1, 0.3, and 1 V) and Figure 2B (V_G = 1.8 V). This I_D saturation is characteristic of the electrostatic gating as shown in **Analysis of I_D saturation** in this Supporting Information, and also well known as a pinch-off effect in the standard field-effect transistor in silicon electronics. Therefore, the observation of the I_D saturation corroborates the V_G-induced transition is mainly driven by electrostatic gating. On the other hand, there is no physical explanation about the I_D saturation based on the Joule heating.

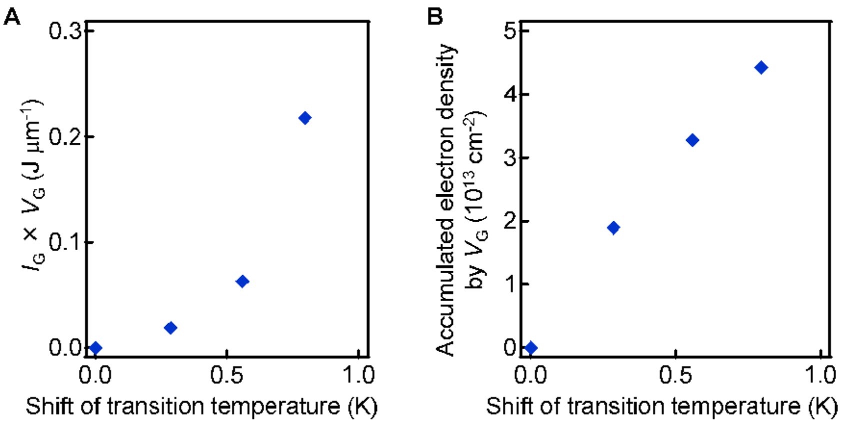

Figure S2. Origin of the shift of the transition temperature by V_G. A) $I_G \times V_G$ *vs*. the shift of the transition temperature. B) The accumulated electron density *vs*. the shift of the transition temperature.

Analysis of I_D saturation (pinch-off effect).

The I_D saturation in the VO_2-channel three-terminal device can be understood analytically in the following way. For simplicity, we ignore the Joule heating effect in this analysis of I_D saturation. Then, we can assume the local sheet conductance in the channel can be defined by the local gate voltage as $G_{SH}(-V_{CG}(x))$. The Ohm's law at x leads to $I_D = G_{SH}(-V_{CG}(x))$ $(dV_{CG}(x) / dx)$. By integrating this equation from $x = 0$ to L (channel length) and dividing by L, $I_D = \int_{V_G - V_D}^{V_G} G_{SH}(-V_{CG})\,d(-V_{CG})/L$. Therefore, when the source-region conductance $G_{SH}(V_G)$

is much larger than the drain-region conductance $G_{SH}(V_G - V_D)$, the I_D is dominated by the integral in the vicinity of $-V_{CG} = V_G$ and becomes insensitive to V_D: $I_D \approx \int_0^{V_G} G_{SH}(-V_{CG})\mathrm{d}(-V_{CG})/\mathrm{L}$, resulting in the I_D saturation. Thus, the condition for the I_D saturation is $G_{SH}(V_G) >> G_{SH}(V_G - V_D)$. This condition is met only around the transition point and also when the V_D is comparable or larger with respect to the sub-threshold swing (SS) of the V_G-induced transition that is evaluated in the quasi-equilibrium regime ($V_D \leq 0.1$ V). Indeed, the SS is approximately 0.2 V per decade around the transition point (Figure 2A), roughly consistent with the I_D saturation at $V_D \geq 0.1$ V. The discussion here is based on the similar discussion on the pinch-off effect in silicon transistors.[23] It should be noted that this analysis of the I_D saturation does not include Joule heating, and hence, cannot describe the discontinuous transition.

Understanding the V_D effect based on the stability analysis

While the transition itself is caused by the electrostatic gating, the discontinuity originates from the V_D-induced Joule heating. To precisely understand the origin of discontinuity, the stability problem against the fluctuation is considered. The stability of the steady state is defined against the infinitesimal fluctuation such as $\delta T(x)$, $\delta R_{SH}(x)$, $\delta V_{CG}(x)$, and $\mathrm{d}I_D$. Because the fluctuated state is slightly different from the steady state, any fluctuation cannot be stable and converges or diverges with time exponentially. When the fluctuation converges, the steady state is called stable. When the fluctuation diverges, the steady state is called unstable. Without calculation, this stability can be analyzed geometrically for any steady state on the I_D-V_G-V_D three-dimensional plot in Figure 5A (or on the I_D-V_G plot in Figure S3A and on the I_D-V_D plot in Figure S3B). By definition, any steady state in Figures 5A or S3B has no time evolution: $\mathrm{d}I_D / \mathrm{d}t = 0$. Then, obviously, any unsteady state on the larger V_D side shows $\mathrm{d}I_D / \mathrm{d}t > 0$, where the large V_D generates excessive Joule heat, induces the metallic transition of VO_2, and increases I_D. Since the sign of $\mathrm{d}I_D / \mathrm{d}t$ does not change unless it goes across the steady state, any unsteady state on the larger V_G side in Figure 5A or S3A also has $\mathrm{d}I_D / \mathrm{d}t > 0$. Thus, the sign of $\mathrm{d}I_D / \mathrm{d}t$ can be determined on either side of the steady state plot as shown in Figures S3A and S3B. Then, the solid curves in Figures S3A and S3B, which correspond to the positive differential conductance, are the head-to-head boundary with respect to the sign of $\mathrm{d}I_D / \mathrm{d}t$. Therefore, they are stable against fluctuation. In the same way, the dashed curves, which corresponds to the negative differential conductance, are the tail-to-tail boundary and unstable. The physical origin of this instability is thermal runaway, the positive feedback between the metallic transition and the Joule heating under the constant V_D.

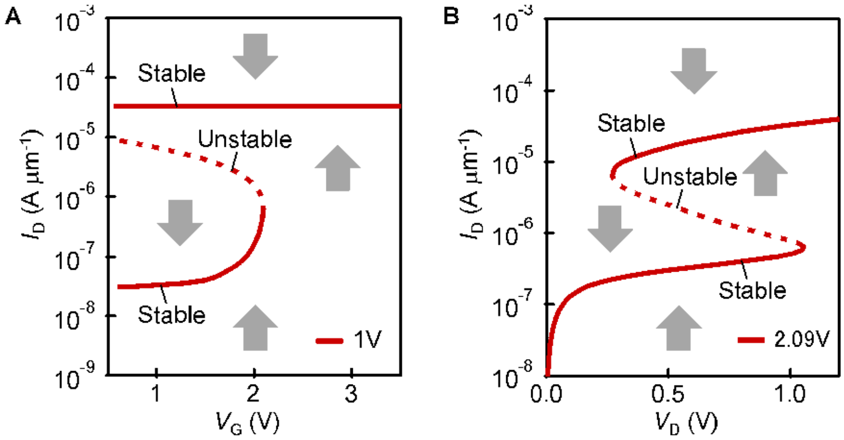

Figure S3. Time evolution. The time evolution of I_D (arrows) in A) the I_D-V_G plane (V_D = 1 V) and B) the I_D-V_D plane (V_G = 2.09 V). There is no time evolution on the plotted curves because they correspond to the steady states.

Based on this stability analysis, the origin of the V_D effect can be visually understood in the three-dimensional plot in Figure 5A. In the plot, the "return line" appears at $V_D \geq 0.2$ V. Because of this return line, the steady state suddenly disappears while increasing V_G at the constant V_D value, and results in the discontinuous transition (saddle-node bifurcation). Thus, the V_D effect can be understood as to form a return line in the steady state diagram by inducing instability of thermal runaway in the non-equilibrium regime.

It should be noted that it is hard to cross the return line by increasing V_D within the voltage used in this measurement while it is much easier to cross the return line by increasing V_G. At V_G = 1 V for example, the Joule heat is negligible irrespective of V_D owing to the high VO_2 resistivity ("Insulating ohmic" in Figure 5A), and therefore, the steady state remains stable and cannot reach the return line by increasing V_D. The difficulty of inducing instability only by V_D is also consistent with the fact that the V_D does not largely influence the critical V_G value for the transition (Figures 2A and 5B). This insensitivity to V_D is in a stark contrast to the two-terminal VO_2 devices where the transition can be induced only by V_D at a much larger voltage (several tens volts for a 50 µm channel length[28]).

In theory, the V_D effect should be observed for any non-zero V_D value. However, in practice, it is smeared out when the V_D is too small owing to the inhomogeneity in the VO_2 channel, which is represented by the 0.1 K distribution of transition temperature in Figure 4D. The minimum V_D value necessary for the V_D effect is determined based on the condition in which the Joule heating effect by V_D is larger than the channel inhomogeneity. Then, the Joule heating by 0.1 K for the fully metallic VO_2 channel corresponds to the application of V_D ~ 0.2 V, which sets the condition for the V_D effect to appear. This is consistent with the V_D value necessary for the discontinuous jump in the experiments (Figure 2A) and the simulation (Figure 5B). It is worth noting that the V_D effect may be applicable to all the other types of the gate-induced metal-insulator transitions because metal-insulator transitions are inherently affected by temperature, and hence by Joule heating.