Pulse-controlled electromigration

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1. Introduction
To fabricate single molecular transistor devices, electromigration (EM) is a useful technique to make nanogap electrodes from a gold nanowire (NW) [1]. Since electric currents induce EM, large current densities are needed to give rise to gap formation in the NW. Associated Joule heating (JH) increases the local temperature $T_{\text{local}}$ of the NW and promotes EM. At a critical point for EM, JH at the gap abruptly increases due to the rapid increase in its resistance, ending up with bigger gaps and gold island formation [2]. Therefore it is important to control JH during EM.

We propose a new way to control JH as well as EM. Voltage pulses $V_p$ combined with a DC voltage $V_{dc}$ are introduced to the NW. The total source-drain voltage $V_{sd}(t)$ changes in time, as shown in Fig. 1(a). Here $T_p$ and $t_p$ stand for the pulse period and pulse length of the pulse train, respectively. The power $P(t)$ applied to the NW follows $V_{sd}(t)^2$, as shown in Fig. 1(b). This power is converted to JH through the electron-phonon interactions. When the voltage pulse is high, $T_{\text{local}}$ increases exponentially in time with a thermal relaxation time $\tau$, as shown by a dotted line in Fig. 1(c). If $\tau$ is much larger than $t_p$, the voltage pulse becomes low before the NW reaches the thermal equilibrium (Fig. 1(c)). Therefore, in this case, $T_{\text{local}}$ can be kept low all the while, the current density becomes enough large when the voltage pulse is high. In other words, the driving force for EM and $T_{\text{local}}$ can be separately controlled by the combination of $V_{dc}$ and $V_p$. On the other hand, if $t_p$ is much smaller than $\tau_p$, $T_{\text{local}}$ follows $V_{sd}(t)$ (Fig. 1(d)). In this case, the separate control can not be obtained. For both cases, however, EM can be induced only when the voltage pulse is high, and there is a possibility to control the speed of the gap formation.

2. Experiment
Gold NWs defined by electron beam lithography are deposited on a SiO$_2$ insulating layer on a GaAs substrate. The width, height and length of the NWs are fixed at 60 nm, 20 nm and 200 nm, respectively. All the measurements were done at 1.6 K. The total resistance $R_{\text{total}} (= V_{sd}/I_{sd})$ is the sum of the NW resistance $R_n$ and lead resistance $R_L$. Since JH increases $T_{\text{local}}$, $R_n$ increases as increasing $V_{sd}$ [3]. To estimate the thermal relaxation time $\tau$ of the NWs, we studied this thermal change in $R_n$ by applying a voltage pulse $V_p (= 400$ mV). Before the voltage pulse, $R_n$ is 6.7 $\Omega$ and the electric potential $V_D$ at the position marked $D$ in Fig. 2(a) is 55 mV. When the voltage pulse becomes high, $R_n$ and $V_D$ increase to 8.2 $\Omega$ and 63 mV, respectively, with the relaxation time $\tau$. Fig. 2(b) shows the time-evolution of $V_D$. At the beginning ($< 1$ $\mu$s), an oscillation of $V_D$ was observed. It is attributed to an electric interference in our circuit, which sets the low limit of the measurement. After the oscillation, $V_D$ was stabilized at 63 mV. Therefore, we conclude that $\tau$ should be smaller than 1 $\mu$s. Thus, it is not possible to control JH and EM separately in our current setup, but it is possible to switch on and off both of them by a short voltage pulse.

The voltage pulse technique can be a useful tool for the study of voltage-induced rearrangement of atoms in a short time scale (10 $\mu$s). An example sequence of $V_{sd}$ is depicted in Fig. 2(c). When the voltage pulse is high, atoms are thermally activated and EM can occur. On the other hand, when the voltage pulse is low, they do not move from their equilibrium positions. Following a single voltage pulse, $R_{\text{total}}$ is measured from a slope of the $I$-$V$ curve at a low voltage region. In this way, we can study the changes in $R_{\text{total}}$ induced by single voltage pulses. Without pulse, $R_{\text{total}}$ is almost constant at the initial value ($R_0 \sim 26$ $\Omega$). The drift $\Delta R/R_0$ is smaller than 0.4 %. When $V_p$ is still much smaller than the critical $V_p$ (~845 mV), $R_{\text{total}}$ fluctuates around $R_0$, but there is no decrease in the mean $R_{\text{total}}$. The fluctuation comes from the thermal rearrangement of the atoms. As increasing $V_p$, the $R_{\text{total}}$ deviation is getting larger. Finally, near the critical $V_p$, $\Delta R/R_0$ becomes 4 % and the mean $R_{\text{total}}$ gradually increases due to EM, as shown in Fig. 2(d).

3. Summary
In summary, we propose a new electromigration technique in which a voltage pulse supplies an additional knob to control both electromigration and Joule heating simultaneously. Since the usage of pulse voltage lowers the speed of the gap formation, we have observed atomic rearrangements by single pulse measurements.

References
Fig. 1: Scheme for electromigration with voltage pulse. (a) Time-evolution of a source-drain bias voltage $V_{sd}(t)$. A voltage pulse train with pulse voltage $V_p$, pulse length $t_p$, and pulse period $T_p$ is added to a DC voltage $V_{dc}$. (b) Time-evolution of the applied power $P(t)$. $\langle P \rangle$ is the time-averaged power. (c, d) Time evolution of the local temperature of the nanowire for (c) $\tau >> t_p$ and (d) $\tau << t_p$. $\tau$ is a thermal relaxation time of the nanowire.

Fig. 2: (a) Schematic setup for thermal relaxation measurements. (b) Time-evolution of the electric potential marked at D in (a). (c) A sequence of the applied source-drain voltage. An I-V curve is taken at low voltage region. A single voltage pulse with 10 ms pulse length is applied to induce atomic rearrangements in the nanowire. (d) Total resistance $R_{total}$ changing under single voltage pulses $V_p (=830 \text{ mV})$. 

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