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Wide-Range Control of Tunnel Resistance on Metallic Nanogaps Using Migration

S Kayashima, K Takahashi, M Motoyama and J Shirakashi

Department of Electrical and Electronic Engineering, Tokyo University of Agriculture and Technology, Koganei, Tokyo 184-8588, Japan

E-mail: shrakash@cc.tuat.ac.jp

Abstract. A simple technique, based on electromigration induced by field emission current, is developed in order to control a tunnel resistance on nanogap electrodes. In this paper, we study a controllability of the resistance on nanogap electrodes by only adjusting the applied current. First, initial planar nanogaps of Ni with below 50 nm separation were defined on SiO₂/Si substrate. Then, the voltage was applied to the nanogaps while monitoring the current passing through the gaps at room temperature. The applied voltage was slowly ramped up until the current reached a preset value. With increasing the preset value from about 1 nA to 30 μ A, the resistance of the nanogaps decreased ranging from the order of 100 T Ω to 10 M Ω . These results suggest that this technique can contribute to simplifying a fabrication process of tunneling devices.

1. Introduction

Nanometer-scale tunnel junction devices such as planar-type single-electron transistors (SETs) are proposed to be one of the promising alternatives to the silicon-based technology when it reaches its miniaturization limits in the future. For the fabrication of these devices, sophisticated nanolithography techniques are required due to the nanometer-scale dimension of the devices. In order to simplify the fabrication process of planar-type tunnel junction devices, we propose a new approach to fabricate the tunnel devices using a nanogap electrode as a vacuum tunnel junction. The nanogap electrode, which is a pair of electrodes with nanometer separation, is frequently used to measure the transport properties of nanoparticles in the field of molecular electronics [1-3]. Various approaches for fabricating the nanogap electrodes have been reported, including shadow evaporation [1], electroplating [4], electron-beam overlapping and overexposure techniques [5], mechanical break junction [6], and electromigration [7]. The electromigration method is particularly simple, but the nanogap electrodes fabricated by this method tend to exhibit high tunnel resistance [7]. In this paper, a simple method for the fabrication of nanogap electrodes with well-controlled tunnel resistance is presented. This method is based on electromigration induced by Fowler-Nordheim (F-N) field emission current. The fundamental process of this method, in which we call it "activation", is as follows. By applying a voltage to the nanogap electrode, a field emission current flows through the gap. Then, the field emission current induces electromigration of metal atoms at the tip of the electrode, resulting in a decrease of the separation of the nanogap electrodes. Consequently, the tunnel resistance of the nanogaps is decreased. Here, we investigate a controllability of the tunnel resistance on the nanogap electrodes by adjusting the applied current.

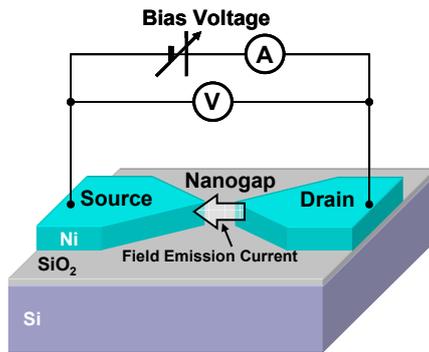


Figure 1. The activation procedure of nanogap electrodes. The current passes through the nanogap by applying the voltage. Sharpened nanogap electrodes of Ni are defined on SiO₂/Si substrates.

2. Fabrication and activation procedure of nanogap electrodes

A conventional electron-beam lithography and lift-off process were utilized to fabricate the nanogap electrodes. First, the initial planar nanogap electrodes with less than 50 nm separation were patterned on resist-coated SiO₂/Si substrates using electron-beam lithography. Then, electron-beam evaporation of 10 nm Ni was carried out using developed pattern as a template. Finally, the metal electrodes were fabricated by lift-off technique. As shown in figure 1, source and drain nanogap electrodes placed in plane were sharpened in order to generate field emission current caused by electric field concentration at the tip of the electrode. Figure 2 (a) shows an atomic force microscope (AFM) image of a typical initial nanogap electrode. The separation of the gap is approximately 44 nm. All the samples were fabricated under the same lithographic conditions, but the separation of the gap spontaneously fluctuated between 22 and 44 nm. Before performing the activation, the nanogaps in the samples exhibited high tunnel resistance over 100 TΩ due to large separation of the gaps.

Following these fabrication processes, the activation was performed, and the controllability of the tunnel resistance of the nanogaps was investigated. Initial nanogap electrodes were mounted on a stage with manual probes in a vacuum chamber. The activation and the measurements of the electrical properties of the samples were carried out using a semiconductor parameter analyzer. The detailed experimental steps are as follows. First, we applied the voltage V to the initial nanogap electrodes while monitoring the current I passing through the gaps. Then we stopped applying the voltage when

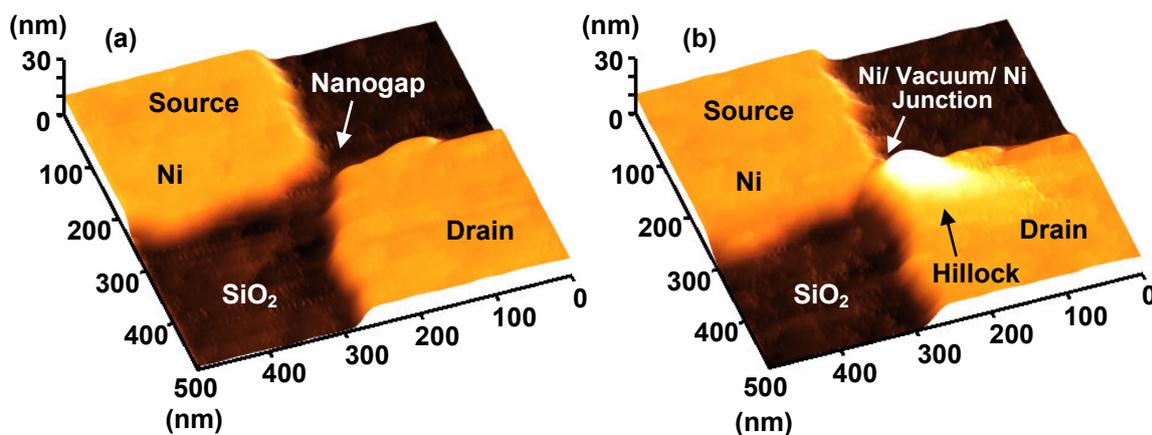


Figure 2. AFM images of typical nanogap electrodes (a) before and (b) after activation with the preset current I_s of 0.83 nA.

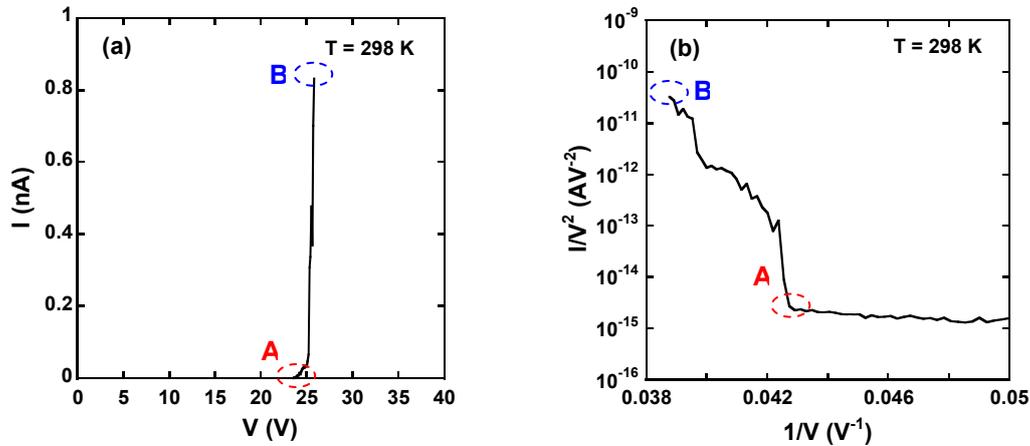


Figure 3. (a) I - V curve and (b) F-N plot (I/V^2 versus $1/V$) of the sample during the activation procedure. Electromigration is induced by field emission current at point A. Applying the voltage was stopped at point B.

the current I reached a preset current I_s . We defined the voltage V_s as the value of the voltage V at which the current I has the value of the preset current I_s . Finally, the tunnel resistance of the nanogaps was measured.

3. Results and discussion

The AFM image of the nanogap electrode after performing the activation with the preset current I_s of 0.83 nA is shown in figure 2 (b). This observation clearly indicates that the separation of the gap becomes narrower from 44 nm before the activation to less than 10 nm. Additionally, the formation of the hillock, which is an accumulation of metal atoms caused by electromigration, is observed at the tip of the drain electrode. As shown in figure 3 (a), a typical I - V curve during the activation exhibits an abrupt increase in the current I at a threshold voltage V_{th} of 23 V (point A). Applying the voltage was stopped at point B. The F-N plot representing the same data is shown in figure 3 (b). The sudden change of the slope in the F-N plot also corresponds to the point A shown in figure 3 (a). This behavior implies that the electromigration is induced by the field emission current with applying a voltage of 23 V. Typically, the voltage application time between point A and point B varies from about 0.3 sec to 5 sec, depending on the preset current I_s . The mechanism of the activation process can be understood on the basis of the electrical breakdown in planar contacts [8, 9].

Furthermore, the controllability of the tunnel resistance on a preset current I_s was investigated. We defined the tunnel resistance R as the resistance measured in low voltage regime after the activation. Figure 4 shows the dependence of the resistances on the preset current I_s . In this experiment, the tunnel resistance R decreased from the order of 100 T Ω to 10 M Ω with increasing the preset current I_s from 1 nA to 30 μ A. It should be noted that the dependence of the tunnel resistance R on the preset current I_s from different samples exhibits a similar tendency in spite of the initial separation of the nanogaps. This result suggests that the tunnel resistance R of the nanogap electrodes can be controlled by adjusting the preset current I_s . A resistance R_s given by V_s/I_s and a differential resistance given by dV_s/dI_s are also plotted in figure 4. R_s - I_s and dV_s/dI_s - I_s exhibited a linear relation with a slope of -1. This result implies that the tunnel resistance R after the activation can be estimated by a relation between R and R_s or R and dV_s/dI_s . In addition, a drastic decrease of the tunnel resistance R is clearly seen in the range of 100 nA $< I_s < 1$ μ A. It can be considered as a transition of the electrical properties of the nanogaps from insulating regime to tunneling regime.

The measurements of the electrical properties of the nanogap electrodes were carried out under a two-terminal configuration in a shield room at room temperature. Figure 5 shows the current-voltage

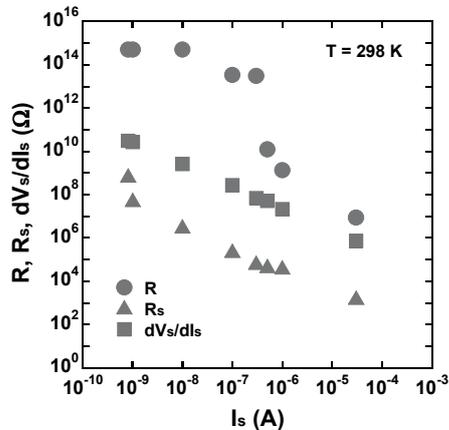


Figure 4. Dependence of resistances of the nanogap electrodes on preset current I_s . The tunnel resistance R measured in low voltage regime after the activation, the resistance R_s ($= V_s/I_s$) and the differential resistance dV_s/dI_s are plotted as a function of the preset current I_s .

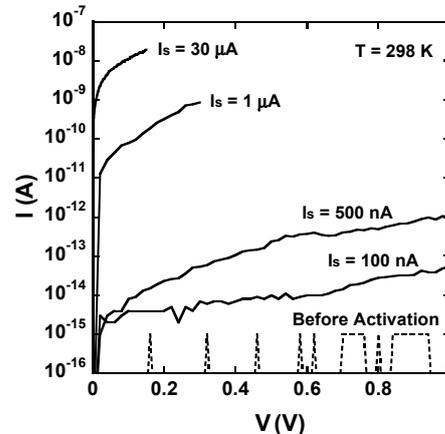


Figure 5. I - V characteristics of the nanogap electrodes measured before (dashed line) and after (solid line) performing the activation with the preset current $I_s = 100$ nA, 500 nA, 1 μ A, and 30 μ A. The data are plotted on semi-log scale.

(I - V) characteristics of the nanogaps measured before and after performing the activation. The current increased from the order of 10 fA to 10 nA with increasing the preset current I_s from 100 nA to 30 μ A. These results suggest that wide-range control of the electrical properties on the nanogaps is achieved by performing the activation.

4. Conclusion

In conclusion, a simple technique for the fabrication of nanogap electrodes with well-controlled tunnel resistance, based on electromigration induced by F-N field emission current, has been developed. The tunnel resistance on nanogap electrodes was well controlled ranging from the order of 100 T Ω to 10 M Ω by adjusting the preset current I_s from 1 nA to 30 μ A. Moreover, I - V characteristics of the nanogap electrodes after performing the activation imply that the electrical properties of the nanogaps can be controlled from insulating regime to tunneling regime. These results suggest that this technique can contribute to simplifying a fabrication process of tunneling devices.

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