Lattice temperature dependence of electromigration process at Ni nanojunctions

Ni ナノ接合におけるエレクトロマイグレーションの格子温度依存性

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The use of ferromagnetic electrodes has been attracting considerable attention to add novel functions to molecular devices and investigate electron transport at the single molecule level. However, it has been difficult to reproducibly fabricate ferromagnetic (FM) nanogap electrodes by the electrical break junction (EBJ) method [1] and form single molecule transistors with FM electrodes, mainly because of high melting temperatures, T_m, of FM metal species. Therefore, it is necessary to clarify the elementary processes of electromigration (EM) process for FM nanojunctions.

We applied the feedback controlled EBJ process to Au and Ni nanojunctions in vacuum at ~4.2K. For Au nanojunctions, EM process is divided into two parts; *i.e.*, the diffusive region and the ballistic region. We found that, in the diffusive region, the atoms are removed by Joule heating, while in ballistic region, EM proceeds by kinetic energy transfer from one electron to one atom; *i.e.*, when the applied voltage V is equal to the surface diffusion potential of metal atoms, E_b, the atom is removed [2]. In contrast, we observed the kinetic energy transfer mechanism even in the diffusive region for Ni EM. We think this difference between Au and Ni comes from the difference in T_m. We proposed "the lucky electron model" to explain the EM in metals of high T_m, as is shown in Fig. 1(a). In this mechanism, most of the electrons travel diffusively from the cathode to the anode. However, the generated Joule heat is not enough to melt the metal. In this diffusive transport, a small fraction of atoms can travel ballistically from the cathode to the anode and transfer its kinetic energy to remove one atom.

To prove the validity of our lucky electron model, we have studied EM process of Ni at 4.2 K, 77K, and 300 K. When the EM takes place at low temperatures, we need a large Joule heat to reach T_m and the applied V exceeds E_b/e and the kinetic energy transfer sets in. When the temperature is high, however, the necessary Joule heat to reach T_m becomes less and we may be able to see the Joule heating behavior. We plot the critical voltage at which EM is observed, V_C, as a function of the junction resistance R_J, as shown in Fig. 1(b). R_J is normalized in in the unit of the quantum resistance $R_0 \equiv h/2e^2$. At 300 K, Joule heating region appears in a range of 0.003 – 0.03R_0, as shown by a green dashed line. We have made histograms for V_C. There are two broad peaks; 0.2 V is very close to E_b/e for the (111) orientation of Ni [3]. Higher voltage peak appears at 0.37 V, which is very close to E_b/e for the (311) orientation of Ni [4]. However, the Joule heating behavior disappears at 77K and 4.2 K in the V_C-R_J curves and the step-like feature becomes more dominant. The observed results strongly support the validity of the luck electron mechanism.

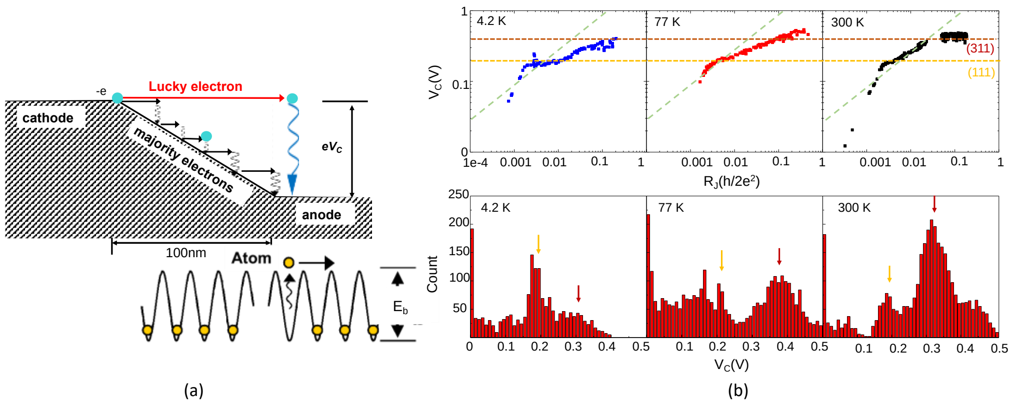

Fig.1(a) The 'lucky electron' model, (b) V_C-R_J relationship the histogram of V_C at 4.2 K, 77 K, and 300 K.

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