Break Voltage of the 1G₀ Contact of Noble Metals and Alloys

Daisuke Miura, Keiichi Iwata, Shu Kurokawa, and Akira Sakai*

Department of Materials Science and Engineering, Kyoto University, Sakyo-ku, Kyoto 606-8501, Japan

(Received 6 October 2009; Accepted 7 December 2009; Published 19 December 2009)

We have measured the break voltage of the 1G₀ contact of Au, Ag, Cu, and AuAg alloys at room temperature in ultrahigh vacuum. Exploiting the break junction technique, we produced a 1G₀ contact and broke it by applying a voltage ramp. The break voltage of each metal exhibits a broad distribution, and the average break voltage decreases as Au > Cu ≥ Ag, in consistent with the elemental dependence of the high-bias stability of the 1G₀ contact suggested in previous experimental studies. In AuAg alloys, the break-voltage distribution for some alloys exhibits a double-peak structure, each peak locating close to the break voltage of the 1G₀ contact of pure Au and Ag, respectively. This observation suggests that the break voltage of AuAg alloys is locally determined by the elemental species of the atom occupying the contact site. [DOI: 10.1380/ejssnt.2009.891]

Keywords: Break voltage; Single-atom contacts; Noble metals; AuAg Alloys

I. INTRODUCTION

Single-atom contacts (SACs) of metals are the smallest of metal contacts and exhibit a variety of unique mechanical and electronic properties that cannot be realized in bulk contacts [1]. Electron transport through metal SACs is of particular interest because SACs are smaller than the electron mean free path and exhibit a ballistic conduction where electrons can pass through a contact without suffering substantial scattering. In such a ballistic SAC, the contact conductance is determined by a quantum mechanical transmission of electrons, which primarily depends on the valence electronic state of the contact atom [1]. A contact atom of monovalent noble metals, Au, Ag, and Cu, for example, has an s-like valence state which constitutes a highly transparent state of ~100% transmission. As a result, the conductance of the noble-metal SAC is in good agreement with \( G₀ = 2e^2/h \), the quantum unit of conductance, in accordance with the Landauer formula for the ballistic conductance. Furthermore, the noble metal SACs, specifically the Au SAC, are capable of sustaining huge current density as high as \( 8 \times 10^{10} \) A/cm² [2]. These unique properties of noble metal SACs make them a potential candidate for interconnects in atomic and molecular devices.

In device applications, SACs should be sufficiently stable and long-lived in various working conditions, some of which may involve high biases and/or high currents. Thus, the stability of noble-metal SACs under high-bias/current conditions is of practical importance. For an SAC placed under a bias \( V \) and a tensile force \( F \), Todorov et al. [3] proposed the following thermal-activation-type formula for its lifetime \( \tau \):

\[
\tau = f^{-1} \exp \left[ \left( W₀ - \alpha V - \beta F \right) / k_B T^* \right]
\]  

where \( f \) is a frequency factor, \( W₀ \) is an activation energy of contact failure at \( V = 0 \) and \( F = 0 \), and \( \alpha \) and \( \beta \) are coefficients. The temperature \( T^* \) is an effective temperature which is a function of \( V \) [3]. Though Eq. (1) is based on a simple thermal activation model of the contact failure, it can account for various experimental observations [4–6] and is considered as a working formula for describing the SAC stability. Equation (1) clearly shows that an SAC becomes unstable when one applies it too high bias or too strong tensile force. The maximum bias and force allowable for obtaining measurable lifetime define the break voltage \( V_b \) and the tensile strength \( F_b \) of an SAC, respectively. For Au SACs, these parameters have been investigated in previous experiments [6–9] and determined as \( V_b \sim 1.2 \) V [6] and \( F_b \sim 1.5 \) nN [8], respectively. On the other hand, almost nothing has been understood on the stability of non-Au SACs, and no experimental data are available about \( V_b \) and \( F_b \), except for Pt SACs which show \( V_b \sim 0.4 \) V [6].

In our previous experiments [10], we measured the formation probability of noble-metal SACs as a function of bias and found that the formation probability of Au SACs vanishes at ~ 2.2 V, while this bias decreases to ~ 0.7 V for Cu and Ag. The same elemental dependence was also observed for the threshold voltage below which a contact failure occurs after it reduces to SAC. This threshold is ~ 1.2 V, ~ 0.3 V, and ~ 0.2 V for Au, Cu, and Ag, respectively [11]. These results naturally suggest that the high-bias stability of noble metal SAC varies as Au > Cu ≥ Ag. This relationship, however, remains unconfirmed because we inferred the high-bias stability not directly from \( V_b \) but indirectly from other properties such as the SAC formation probability and the break conductance. There is also a possibility that some previous measurements made under a constant bias condition might be affected by the current-induced instability which occurs in the course of SAC formation [12]. To properly address the genuine high-bias stability of SACs, it is necessary to directly determine their \( V_b \) and compare its magnitude.

To obtain more insight on the high-bias break of SAC of metals, we carried out in this work the direct measurement of \( V_b \) for noble metal SACs. We employed the same voltage-ramp technique as used in previous breakdown experiments [6, 7] but conducted all measurements at room temperature. Different from a cryogenic environment used in previous experiments, where SACs are quite long-lived, we cannot expect long SAC lifetime at room temperature, [13] unless under the condition of self-breaking [4]. We therefore have to complete the \( V_b \) measurement within a short lifetime. On the other hand, the
room-temperature experiment has an advantage that the results should be free from any ambiguities about the contact temperature \( T^* \). Usually, \( T^* \) is higher than the ambient temperature due to the local contact heating, and this has been a subject of extensive theoretical \([3, 14-17]\) and experimental studies \([5, 18-20]\). Results of previous work suggest that the contact overheating at 1 V is significant at 4 K \([19]\) but becomes negligible at 300 K \([5, 20]\). Also, the break voltage data at room temperature would be more valuable for practical device applications of SACs than those obtained at 4 K.

We also extended our break-voltage experiment to AuAg alloys. Previous conductance measurements on a couple of Au-based and Cu-based binary alloys \([21-23]\) indicate that the SAC conductance of an alloy is primarily determined by the species of the contact atom, i.e. the conductance becomes either \( G_A \) or \( G_B \) when A or B atom occupies the contact site. This “locality” of the alloy SAC conductance has been clearly demonstrated by Heemskerk et al. \([24]\) who showed that the Au-like conductance histogram of AuPt changes to the Pt-like one when a Pt atom migrates to the contact site. If a similar locality holds for the break voltage of AuAg SACs, it would be either \( V_{b,\text{Au}} \) or \( V_{b,\text{Ag}} \) depending on whether the contact atom is Au or Ag. Then, the break-voltage distribution would show a two-peak structure, with Au- and Ag-break-voltage peaks, unless these peaks are significantly broadened.

It should be noted here that our measurements of \( V_b \) were made on 1G\(_0\) contacts. For noble metals and AuAg alloys, the 1G\(_0\) contact is nearly synonymous with SAC but not completely identifiable because contacts larger than SAC can happen to exhibit the 1G\(_0\) conductance. \([25]\) Our \( V_b \) data were, however, obtained not on a few specific 1G\(_0\) contacts but on a large ensemble of them, in which the population of non-SACs would be around 10% \([25]\). Thus, we will not make rigorous distinction between SACs and the 1G\(_0\) contacts in the following sections, though we prefer to use “1G\(_0\) contact(s)” when referring to our contacts.

II. EXPERIMENT

We have developed an ultrahigh vacuum mechanically-controllable-break-junction (UHV-MCBJ) apparatus shown in Fig. 1 and used it for all measurements in this work. The bending beam is a 0.2 mm thick stainless steel substrate covered with a 25 \( \mu \)m thick polyimide film thermally bonded to the substrate (UBE UPISCEL-C). Metal wires are fixed onto the beam using a vacuum-compatible epoxy resin (varian TorrSoul). A micrometer-driven linear motion feedthrough (Huntington L-2241-2) and a piezo actuator (PI P-810.30) are used for making coarse and fine bending of the beam, respectively. Sample wires are 0.25 mm in diameter and of 99.99-99.999% purity. All measurements were made at room temperature in vacuum better than 2 \( \times 10^{-8} \) Pa.

Figure 2(a) depicts the block diagram of the experimental setup for measuring the break voltage. We connected a current-sensing resistor \( R_0 = 1 \) k\( \Omega \) in series with a break junction and monitored the voltage drop \( V_m \) across \( R_0 \) with a digital oscilloscope (Agilent DSO6032A, DSO in

![FIG. 1: Schematic view of the ultrahigh vacuum MCBJ used in this experiment.](image-url)
Au and Cu, we set $\Delta t = 40 \mu s$, while $\Delta t = 10 \mu s$ for Ag and AuAg alloys as will be explained below. The example shown in Fig. 2(b) is on a Au contact, and thus the bias ramp starts at point B in the lower panel in Fig. 2(b), that is 40 $\mu$s after the trigger point A. During the bias ramp, $V_a$ increases linearly from 100 mV to 4.1 V within 50 $\mu$s at a rate of 80 mV/$\mu$s. The contact current rises up with $V_a$ and at point C, suddenly drops to zero. At such a contact failure, the contact current falls down rapidly but still within a non-zero time interval. We therefore defined the break point by the peak position of each $I(t)$ curve and obtained the break voltage $V_b$ as $V_b = V_a - IR_0$ where $V_a$ and $I$ are their values at the current peak.

We first measured the $1G_0$ plateau length at $V_a = 100$ mV to examine whether typical $1G_0$ plateaus are longer than the specified $\Delta t$ and can be available for the break voltage measurement. We selected those plateaus that locate within the conductance range $(1 \pm 0.1)G_0$ and determined their duration. The average plateau length is $\tau_{Au} \sim 321 \mu s$, $\tau_{Ag} \sim 41 \mu s$, and $\tau_{Cu} \sim 169 \mu s$ for Au, Ag, and Cu $1G_0$ plateaus, respectively. If we estimate the typical plateau length based on log $\tau$ [4, 13], we obtain $\tau_{Au} \sim 130 \mu s$, $\tau_{Ag} \sim 15 \mu s$, and $\tau_{Cu} \sim 61 \mu s$. In either estimation, the condition $\tau > \Delta t = 40 \mu s$ is satisfied for Au and Cu $1G_0$ contacts but it is marginal for Ag. As a result, we shortened $\Delta t$ to 10 $\mu$s for Ag and AuAg alloys.

### III. RESULTS AND DISCUSSION

#### A. Break voltage

1. **Au and Cu**

We found that the chance of observing long $1G_0$ plateaus, suitable for the break voltage measurement, varies with the specimen. As a result, different specimens yielded different numbers of the break voltage data. To compensate the uneven statistical weight among break-voltage data, we first constructed a break voltage histogram for each specimen, normalized it by the number of data used for the histogram, and then added these normalized histograms to obtain the final break-voltage distribution. The results are shown in Fig. 3 for Au and Cu. The total number of data used to construct each histogram is 2,395 and 4,989 for Au and Cu, respectively.

The break voltage of the Au $1G_0$ contact shows a wide distribution that spans from $\gtrsim 0.1$ V to 2.2 V and takes a broad maximum around 1 V. The average break voltage is $(V_b,Au) = 0.93 \pm 0.62$ V. Smit et al. [6] reported similar broad distribution for the break voltage of Au single-atom chains at 4 K and showed that the average break voltage for the 0.5-nm atomic chain is 1.2 V. The effective temperature $T^*$ of their atomic chains at
1.2 V is not accurately known but can be estimated as $T^* \sim (50 - 60)$ K, based on the contact heating model [3] and the previous temperature measurements [19] on the Au atom-sized contacts at 4 K. On the other hand, $T^* \sim 300$ K in our experiment because the local overheating would be negligible at 300 K as mentioned in Sec. I. Thus, comparison of our $\langle V_b, A_1 \rangle$ with that of Smit et al. can yield the temperature sensitivity of $V_b$ as $dV_b/dT^* = -1.1$ mV/K. If we consider that the contact failure occurs when $W_0 - \alpha V_b - 3F \approx k_B T^*$ in eq. 1, we have $dV_b/dT^* = -k_B/\alpha$ that becomes $dV_b/dT^* \sim -0.9$ mV/K for $\alpha \sim 0.1$ eV/V [6, 18]. Thus, the observed weak temperature dependence of $\langle V_b, A_1 \rangle$ is consistent with the thermal activation model of the contact lifetime described by eq. 1. We note that Hansen [7] measured $V_b$ of the Au 1G0 contact for $T^* = (140 - 240)$K and found higher temperature sensitivity $dV_b/dT^* \sim -2$ mV/K. However, considering the limited temperature range of his experiment, our $dV_b/dT^*$ would not be in serious contradiction with his result.

The break voltage of the Cu 1G0 contact also exhibits a single-peak distribution as seen in Fig. 3. When compared with that of Au, the distribution shows a narrower width and more concentrated around the peak. The average break voltage is $\langle V_b, A_1 \rangle = 0.69 \pm 0.41$ V, which is lower than $\langle V_b, A_1 \rangle$. This result directly establishes the superior high-bias stability of the Au 1G0 contact compared to that of Cu, a conclusion which has been inferred from our previous experiments [10, 11] but remained unconfirmed due to ambiguities associated with the current-induced instability as mentioned in Sec. I.

In the framework of the thermal activation model, $W_0 - \alpha V_b - 3F \approx k_B T^*$ at $V_b$ so that lower $V_b$ for Cu indicates either lower $W_0 - 3F$ or higher $\alpha$ than for Au. From the measurement of the conductance two-level fluctuations at 77 K, Tsutsui et al. [18] estimated $\alpha$ and obtained nearly the same $\alpha \sim 0.1$ eV/V for Au, Ag, and Cu. Thus, the observed difference in the break voltage of the Au and Cu 1G0 contacts is likely to come from the difference in $W_0$ or $W_0 - 3F$. For the Au single-atom chains, Smit et al. [6] obtained $W_0 = 0.738$ eV and $\beta = 0.49$ eV/nN and also estimated $F = 0.95 \pm 0.15$ nN. However, no such quantitative data are available for the Cu 1G0 contact, and we cannot know at this time whether $W_0$ or $W_0 - 3F$ of Cu is actually smaller than that of Au.

We point out that two distributions of $V_b$ shown in Fig. 3 take a maximum at nearly the same voltage around 0.7 - 0.8 V. The observed higher $\langle V_b, A_1 \rangle$ comes from the extended high-bias tail of $V_b$ which results in enlarging the distribution width and pushing up the average break voltage above the position of distribution maximum. This high-bias tail in the distribution indicates that Au contacts yield high-$V_b$ 1G0 contacts more abundantly than Cu. The high production rate of such contacts should thus be an important factor for realizing a high-$V_b$ contact, along with the intrinsic contact stability. In fact, contacts of very high $V_b$ would be of no practical use if they can be rarely formed. In the case of Au, the easy formation of the 1G0 contact has been well documented. Smit et al. [26] pointed out the strong tendency of Au for forming an atomic chain and explained it by the specific electronic structure of 5d-metals. Also, Bahn and Jacobsen [27] theoretically showed that a single atom chain of Au has stronger break force than Ag and Cu. This capability of forming high-strength atomic chain, together with the intrinsic high ductility and low activation barrier for surface migration of Au all favorably act to produce those 1G0 contacts that has a lower built-in force $F$ in Eq. (1) and hence achieve higher $V_b$. The high-bias tail in the $V_b$ distribution of Au is probably due to such weakly strained 1G0 contacts.

### Ag

The break voltage distribution of the Ag 1G0 contact, constructed from 728 events over one specimen, is shown in Fig. 4. Because of the smaller number of the break voltage data and the shorter $\Delta t$ used in the $V_b$ measurement, the $V_b$ distribution for Ag is depicted separately from those of Au and Cu shown in Fig. 3. Although the Ag histogram has lower statistical significance, it is clear from the figure that the distribution of $V_b$ is similar to that of $V_b$ and exhibits a peak at a voltage which is slightly lower than that of $V_b$. The average break voltage is $\langle V_b, Ag \rangle = 0.65 \pm 0.26$ V. Thus, $\langle V \rangle$ of noble metals varies as $\langle V_b, Ag \rangle > \langle V_b, Cu \rangle \sim \langle V_b, Au \rangle$. This elemental dependence of $\langle V_b \rangle$ matches with and hence confirms the relative high-bias stability among the 1G0 contacts of noble metals, i.e. Cu > Ag inferred from our previous experiments [10, 11].

We note that the average $\langle V_b \rangle$ of Ag and Cu 1G0 contacts differs by 0.04 V, while the average lifetime of the Ag 1G0 contact, mentioned in Sec. II, is approximately one-fourth of that of Cu. Presumably, the Ag specimen used for the $V_b$ measurements happened to be of exceptionally good performance for producing stable 1G0 contacts more abundantly than typical Ag contacts used for the lifetime measurements. In fact, a small number of log $\tau$ data sampled prior to the $V_b$ measurements suggest that $\tau_{Ag} \sim 57 \mu$s for that specimen, which is longer than the typical $\tau_{Ag}$ and less but close to $\tau_{Cu}$. It is thus likely that the observed $\langle V_b, Ag \rangle$ would be above an average, and for typical Ag 1G0 contacts, the magnitude relationship would follow as $\langle V_b, Cu \rangle > \langle V_b, Ag \rangle$.

Although this and previous experiments indicate lower stability of the Ag 1G0 contact compared to that of Cu, there seems to exist no specific properties, electronic and/or mechanical, that clearly distinguish Ag and Cu.
1\(G_0\) contacts and account for their different stability. Possible sources might be a local overheating of Ag \(1G_0\) contacts [18] and/or lower \(W_0\) or \(W_0 - \beta F\) in Eq. (1). However, as is the case with the Cu \(1G_0\) contact, lack of experimental information on these issues makes it difficult to further discuss the origin of the lower stability of the Ag \(1G_0\) contact.

3. \(AuAg\) alloys

Figure 5 summarizes break-voltage distributions obtained on \(1G_0\) contacts of \(Au-17at\%Ag\), \(Au-31at\%Ag\), \(Au-55at\%Ag\), and \(Au-73at\%Ag\) alloys, respectively. As with distributions shown in figs. 3 and 4, each distribution is normalized by the number of the break voltage data which is 277, 972, 378, and 2535 for 17at\%, 31at\%, 55at\%, and 73at\% alloys, respectively. At 17at\%Ag, the break-voltage distribution exhibits a broad maximum around 1 V and is in overall agreement with that of pure Au shown in Fig. 3. This agreement suggests that majority of the \(1G_0\) contacts of \(Au-17at\%Ag\) alloy have a single Au atom at their contact site. On the other hand, when the Ag concentration increases to 31 and 55at\%, the distribution shows a double peak structure. Fitting these distributions by the two-peak Gaussian distribution yield the two peak positions as 0.49 V and 1.1 V for \(Au-31at\%Ag\), and 0.53 V and 1.2 V for \(Au-55at\%Ag\), respectively. At 73at\%Ag, the histogram seemingly exhibits a single-peak structure but displays an apparent shoulder around 1 V. The distribution can still be well approximated by the two-peak Gaussian distribution with peaks positioned at 0.72 V and 1.1 V, respectively. We also tried another fitting with two peaks being fixed at around 0.5 V and 1.1 V but obtained poor agreement with the experiment. Therefore, the observed distribution cannot be the result of broadening of the two-peak structure found for the 31 and 55at\%Ag alloys. It is not clear at this time why the low-voltage peak of the 73at\%Ag alloy appears at 0.7 V, not around 0.5 V as does the low-voltage peak of the 31 and 55at\%Ag alloys. As noted before, the 73at\%Ag alloy yielded a larger number of \(V_b\) data than other alloys, and this implies a possibility that the measured 73at\%Ag specimen accidentally had a high success rate of forming stable \(1G_0\) contacts. Then, a discussion similar to the one made in the previous section on the \(V_b\) of the Ag \(1G_0\) contact would suggest that the low-voltage peak might appear at a position above an average. This scenario, however, has no supporting evidences and remains at this time a mere assumption.

Through the break-voltage distributions shown in Fig. 5, the position of the high-voltage peak is nearly constant and close to \((V_{b,Ag}) = 0.93\) V. It is thus likely that this peak corresponds to the break voltage of the Ag-linked contacts. On the other hand, the assignment of the low-voltage peak is less clear because it does not appear at a fixed voltage as discussed above. Even for the 73at\%Ag alloy, however, the peak position stays within 25% from \((V_{b,Ag}) = 0.65\) V, and it may still be possible to interpret the low-voltage peak as representing the break voltage of the Ag-linked contacts. Despite this uncertainty in the low-voltage peak position, the experimental results show that the break voltage of the \(AuAg\) \(1G_0\) contact takes two preferred values which are not much different from \((V_{b,Ag})\) and \((V_{b,Ag})\). As mentioned in Sec. I, such a two-peak distribution is consistent with the “locality” of the break voltage and supports the idea that the break voltage of alloy SACs is primarily determined by the species of the contact atom, as is the case with the conductance.

If the break voltage is completely determined by the contact atom, the relative intensity of the Au- and Ag-peaks should scale with the relative abundance of Au and Ag atoms, i.e. the Ag/Au ratio. In fact, the \(1G_0\) peak in the conductance histogram of \(AuAg\) alloys decreases in height roughly linearly with the Au concentration [21]. However, no such systematic composition dependence can be observed for the two peaks shown in Fig. 5, even though the growth of the integrated intensity of the Ag peak (and the corresponding reduction of the Au peak) roughly scales with the concentration when the alloy composition changes from 31 to 55at\%Ag. It is also found that the relative intensity and the width of two peaks sensitively change with the sample and show a large variation among measurements. As mentioned before, the break voltage depends on such material parameters as \(W_0\) and \(F\) in Eq. (1). Even though these parameters are primarily determined by the contact atom, they must also contain

http://www.sssj.org/ejsnt (J-Stage: http://www.jstage.jst.go.jp/browse/ejsnt/)
non-negligible contributions from neighboring atoms and hence should be sensitive to their species and arrangement. This structural sensitivity would weaken the locality of the break voltage and obscures the compositional dependence of the Au- and Ag-peak heights. This is not the case with the conductance where the $1G_0$ peak is dominated by the Au-linked contacts and hence varies in height linearly with the Au concentration.

In our previous high-bias experiment on AuAg alloys [28], we found that the $1G_0$ conductance peak of the Au-31at%Ag alloy yields a higher $1G_0$ conductance peak than that of pure Au, and its $1G_0$ contacts are considered more stable. However, the break-voltage distribution of the Au-31at%Ag alloy shown in Fig. 5, when compared to that of pure Au in Fig. 3, exhibits no clear signs of stability enhancement. This apparent contradiction probably arises from the fact that the conductance and the break-voltage distributions characterize different groups of the $1G_0$ dominant contributions to the $1G_0$ conductance peak come from those contacts of low statistical significance that lie in the high-voltage tail of the break-voltage distribution. Considering this difference, no meaningful correlation can be expected between the break-voltage distributions shown in Fig. 5 and the $1G_0$ conductance peaks reported in Ref. 28.

B. Nonlinearity in the $I$-V characteristics

In our break-voltage measurement, we apply the $1G_0$ contact a linear bias ramp. The resulting increase in the contact current $I(t)$, like the one shown in Fig. 2(b), thus represents the $I$-V characteristic of the $1G_0$ contact. Since the bias rises up to the break voltage, the observed $I$-V curve extends to the high-bias regime where a nonlinearity in the $I$-V characteristics matters. In the past literatures, both linear and nonlinear $I$-V curves have been reported on the Au $1G_0$ contact. Cubic nonlinearity has been observed in experiments conducted in air or in low vacuum [29, 30], while measurements in ultrahigh vacuum yield straight $I$-V curves [31, 32]. To estimate the nonlinearity of each $I$-t curve, we obtained the conductance $G(V_b)$ at $V_b$ and calculated the conductance increment $\eta \equiv \frac{G(V_b) - G(V_0)}{G(V_0)}$, $V_0$ is the initial bias before applying the bias ramp. If the $I$-V characteristic is linear up to $V_b$, the conductance does not change with the bias, and $\eta = 0$. Figures 6(a) and 6(b) show the distribution of $\eta$ for Au and Cu $1G_0$ contacts, respectively.

As seen in the figure, $\eta$ exceeds 100% in some occasions. Except these minor events in the tail, however, the distribution is narrowly peaked around 0% for both Au and Cu $1G_0$ contacts. If the $I$-V characteristics of the Au $1G_0$ contact exhibit the reported cubic nonlinearity [29], $\eta$ would become $\sim 1,100\%$ at $V_b \approx 0.93$ V. On the contrary, the observed deviation of $\eta$ from 0 is 279% at the largest in Fig. 6(a). Thus, our results support the linearity of the $I$-V characteristic of the Au $1G_0$ contact: for the majority of the $1G_0$ contacts, the nonlinear contribution to the conductance amounts to less than $\sim 70\%$ of the low-bias conductance even when the bias increases to the break voltage. Similarly, $\eta$ of the Cu $1G_0$ contact shown in Fig. 6(b) shares the same distribution with that of Au and again indicates that most Cu $1G_0$ contacts reveal $\eta \sim 0$. Since no experimental data have been reported on the $I$-V curve of the Cu $1G_0$ contact, our result would be the first to prove its linearity up to $V_b$.

IV. SUMMARY

We have measured the break voltage of the $1G_0$ contacts of Au, Ag, Cu, and AuAg at room temperature. The observed break voltage exhibits a broad distribution with a single peak and yields an average break voltage $0.93 \pm 0.62$ V, $0.65 \pm 0.26$ V, and $0.69 \pm 0.41$ V for Au, Ag, and Cu $1G_0$ contacts, respectively. The break voltage distribution of the Au $1G_0$ shows weak temperature dependence, and our result at room temperature differs only slightly from the distribution obtained by Smit et al. [6] at 4 K. The higher break voltage of the Au $1G_0$ contact than that of the Ag and Cu $1G_0$ contacts arises from the abundance of the high-$V_b$ $1G_0$ contacts and confirms the previously suggested elemental dependence of the high-bias stability among noble-metal SACs. The break voltage of the $1G_0$ contact of some AuAg alloys exhibits a two-peak distribution with peaks locating close to the break voltage of the Au and Ag $1G_0$ contacts. This result suggests that the break voltage is locally determined by the elemental species of the contact atom. However, this locality of the break voltage is not a robust property, and the break voltage peaks do not scale with the alloy composition.
This work was supported by the Grant-in-Aid for Scientific Research (B) No.14340091 from Japan Society for the Promotion of Science.

[1] N. Agraït, A. Levy Yeyati, and J. M. van Ruitenbeek, Phys. Rep. 377, 81 (2003).
[2] A. I. Yanson, G. Rubio-Bollinger, H. E. van den Brom, N. Agraït, and J. M. van Ruitenbeek, Nature 395, 783 (1998).
[3] T. N. Todorov, J. Hoekstra, and A. P. Sutton, Phys. Rev. Lett. 86, 3606 (2001).
[4] M. Tsutsui, K. Shoji, M. Taniguchi, and T. Kawai, Nano Lett. 8, 345 (2008).
[5] M. Tsutsui, M. Taniguchi, and T. Kawai, Nano Lett. 8, 3293 (2008).
[6] R. H. M. Smit, C. Untiedt, and J. M. van Ruitenbeek, Nanotechnology 15, S472 (2004).
[7] K. Hansen, PhD Thesis (Aarhus University, 2000).
[8] G. Rubio-Bollinger, S. R. Bahn, N. Agraït, K. W. Jacobsen, and S. Vieira, Phys. Rev. Lett. 87, 026101 (2001).
[9] T. Kizuka, Phys. Rev. B 77, 155401 (2008).
[10] A. Fujii, A. Kusuda, J. Mizobata, T. Minowa, S. Kurokawa, and A. Sakai, Thin Solid Films 464-465, 251 (2004).
[11] A. Fujii, M. Tsutsui, S. Kurokawa, and A. Sakai, Phys. Rev. B 72, 045407 (2005).
[12] A. Fujii, S. Kurokawa, and A. Sakai, e-J. Surf. Sci. Nanotech. 2, 155 (2004).
[13] R. Suzuki, M. Tsutsui, D. Miura, S. Kurokawa, and A. Sakai, Jpn. J. Appl. Phys. 46 3604 (2007).
[14] T. N. Todorov, Philos. Mag. B 77, 965 (1998).
[15] Y. C. Chen, M. Zwolak, and M. Di Ventra, Nano Lett. 3, 1691 (2004).
[16] Z. Yang, M. Chshiev, M. Zwolak, Y. C. Chen, and M. Di Ventra, Phys. Rev. B 71, 041402 (2005).
[17] R. D’Agosta, N. Sai, and M. Di Ventra, Nano Lett. 6, 2395 (2006).
[18] M. Tsutsui, Y. Teramae, S. Kurokawa, and A. Sakai, Appl. Surf. Sci. 252, 8677 (2006).
[19] M. Tsutsui, S. Kurokawa, and A. Sakai, Nanotechnology 17, 5334 (2006).
[20] Z. Huang, B. Xu, Y. Chen, M. Di Ventra, and N. Tao, Nano Lett. 6, 1240 (2006).
[21] A. Enomoto, S. Kurokawa, and A. Sakai, Phys. Rev. B 65, 125410 (2002).
[22] D. J. Bakker, Y. Noat, A. I. Yanson, and J. M. van Ruitenbeek, Phys. Rev. B 65, 235416 (2002).
[23] A. Fujii, R. Ochi, S. Kurokawa, and A. Sakai, Appl. Surf. Sci. 225, 207 (2004).
[24] J. W. T. Heemskerk, Y. Noat, D. J. Bakker, J. M. van Ruitenbeek, B. J. Thijssse, and P. Klaver, Phys. Rev. B 67, 115416 (2003).
[25] M. Dreher, P. Pauly, J. Heurich, J. C. Cuevas, E. Scheer, and P. Nielaba, Phys. Rev. B 72, 075435 (2005).
[26] R. H. Smit, C. Untiedt, A. I. Yanson, and J. M. van Ruitenbeek, Phys. Rev. Lett. 87, 266102 (2001).
[27] S. R. Bahn and K. W. Jacobsen, Phys. Rev. Lett. 87, 266101 (2001).
[28] A. Enomoto, J. Mizobata, S. Kurokawa, and A. Sakai, Surf. Sci. 514, 182 (2002).
[29] J. L. Costa-Krämer, N. García, P. García-Mochales, P. A. Serena, M. I. Marqués, and A. Correa, Phys. Rev. B 55, 5416 (1997).
[30] J. Abellán, R. Chicón, and A. Arenas, Surf. Sci. 418, 493 (1998).
[31] K. Hansen, S. K. Nielsen, M. Brandbyge, L. Laegsgaard, I. Stensgaard, and F. Besenbacher, Phys. Rev. Lett. 77, 708 (2000).
[32] S. K. Nielsen, K. Hansen, M. Brandbyge, K. Stokbro, J. M. van Ruitenbeek, and F. Besenbacher, Phys. Rev. Lett. 89, 066804 (2002).