Influence of Material Properties on Major Tribological Factors at a Nanoscale Sliding Electric Contact of Probe Devices*

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Abstract
Precise processes or devices utilizing scanning nanoprobes, e.g., probe-based nanolithography and probe-based data storage, are state-of-the-art technologies that can handle nm-sized tiny patterns. To transfer these technologies from the research and development stage to practical implementation, a significant improvement in the wear resistance of the probe tip is required for reliable and long-term operation of the system. On the other hand, to remove the unevenness of the size of drawn patterns or recorded bits, the electric contact resistance at the nanoscale sliding contact area of the probe tip must be stable even when the scanning speed of the probe increases to achieve higher throughput. To solve these dilemmatic problems, tribological investigation of the probe tip is very important.

In this study, the influence of the material properties on the relations among electric contact resistance, friction force, and wear durability of nanoprobe tips was examined in detail to clarify the tribological phenomena that occur at the nanoscale contact area of the probe tips. From the results, the authors discussed the key material properties that are dominant for the abovementioned three tribological factors. In conclusion, management of the surface oxide thickness of metal electrodes was the key among all the three factors.

Key words: Tribology, MEMS, Contact Problem, Friction and Wear, Nanomachining & Micromachining

1. Introduction
Recently, there has been ongoing research and development of the precise processes or devices that utilize scanning nanoprobes whose tip sizes are of nanometer size. In particular, ultra-high-density data storage devices using nanoprobes (1), (2), (3) are expected to be next-generation storage devices capable of surpassing the recording density limits of existing devices such as NAND flash memory and hard disk drive (HDD). The high-resolution lithography system using nanoprobes (4), (5), (6), (7) is also expected to be a precise and low-cost patterning technology for future, which does not require a short-wavelength light source. However, to transfer these technologies from the research and development stage to practical implementation, significant improvements in its
throughput are required by fabricating an array of multiple probes that are used simultaneously \((1), (6), (7)\).

A common problem for all devices utilizing multi-probe arrays (MPAs) is that the deviation of electric current flowing through each probe tip of the MPA may cause unevenness in the sizes of drawn patterns or recorded bits. Therefore, for actual commercialization of these devices, very stable and uniform electric contacts must be realized at all sliding contact areas between the probe tips and the substrates. On the other hand, wear and friction caused by sliding between the probe tips and the substrate must be suppressed as much as possible. In general, increasing the contact force of the probe is one way of improving the stability of the electric contact; however, it may worsen the wear and friction of the probes. To optimize the balance of these dilemmatic trade-off relations and achieve a practical system design, it is necessary to measure and understand the behavior of the tribological factors such as electric contact resistance, probe wear, and friction force that acts on a nanoscale contact area at the probe tip (Fig. 1).

Investigations on the electric contact between two materials have been ongoing for several decades \((8), (9)\); however, most of these traditional studies focused on macroscopic or mesoscopic sliding systems in which physical phenomena that occur locally in nanoscale true contact points were usually neglected or discussed under certain assumptions \((10)\). In particular, it was widely known that the contamination covering on the surface has a significant effect on electric contact behavior \((8)\); however, in traditional studies, the effects were only understood qualitatively and not quantitatively.

According to recent rapid improvements in the micro-electro-mechanical systems (MEMS) technology, the need for direct investigations on actual nanoscale contacts has increased, and several practical studies assuming real microdevices have been recently performed \((11)\). Owing to the significant increase in computer processing speeds, direct simulation of atom behaviors at the nanoscale contact using the molecular dynamics (MDs) method have been successfully executed \((12)\). However, even such state-of-the-art studies are conducted assuming very idealistic systems without any obstructive particles or topological disturbances, as in traditional studies, and none of these research groups have yet succeeded in building a practical and quantitative model of the nanoscale tribology that can be applied to optimize the design of actual MPA products.

As a first step to build such a practical tribology model, the authors have focused on the relations among three important tribological factors of actual nanoscale probe tips, namely, electric contact resistance, friction force, and wear durability. Moreover, we have attempted
to understand the trade-off relations among the three factors. In this study, we focused on
the materials that constitute a sliding system (nanoprobe and sliding substrate), which are
the most easily controlled parameters when designing a system. We prepared the probes and
the substrates that are coated with various materials, and measured their material properties
such as surface roughness, hardness, and thickness of their surface native oxide layer. By
performing the sliding tests with systems consisting of various material combinations, we
attempted to identify the key material properties that affect the abovementioned three
important tribological factors.

2. Measurement

2.1 Basic strategy and sample preparation

Measurements of tribological phenomena were performed using a scanning probe
microscope (SPM) for the electric contact resistance and friction force evaluation (Fig. 2),
and a scanning electron microscope (SEM) for the probe wear evaluation. To focus only on
investigations of the influence of material properties, sliding conditions such as sliding
speed, contact force, etc. were maintained constant as much as possible during the sliding
test with the SPM.

The probes mainly used in the SPM measurement were SI-DF20-R probes (SII
nanotechnology), which were coated with conductive Rh film, and their nominal tip radius
was about 30 nm. They were chosen because of their availability and good conductivity
suitable for electric resistance measurements as well as moderate hardness suitable for wear
evaluation. In addition, the probes coated with TiN, SiN, and W were also prepared
particularly for probe wear evaluation. They were fabricated by sputtering those materials
on the commercial silicon probes (SI-DF20, SII nanotechnology) and their tip radius was
also controlled to be 30 nm. Bare Si probes without any coatings were also used for probe
wear evaluation.

The substrates on which the probes slide were made by Si and covered with films of
various conductive materials. All films were deposited by sputtering, and their thicknesses
were about 100 nm. First, some noble metals (Pt, Au, Pd, Ru, and Rh) were selected as
covering film materials because of their good electric conductivity. In addition, WN, W, and
TiN were chosen as covering film materials because they are commonly used in
semiconductor devices as wiring metals, and are therefore suitable for practical
applications. For TiN in particular, four types of films with different properties were
prepared: two compositions of Ti and N (Ti:N = 1:1 and 4:1) with and without ashing
treatment by O₂ plasma (280 °C, 5 min., under a vacuum condition) (Table 1). The
compositions of the TiN films were measured by X-ray photoelectron spectroscopy (XPS).
Of all the films, only WN and W were polished on their surface by chemical mechanical polishing (CMP). W films before CMP and after CMP were measured for comparison purposes.

Table 1 Specifications of four TiN films

<table>
<thead>
<tr>
<th>Film name</th>
<th>TiN A</th>
<th>TiN B</th>
<th>TiN C</th>
<th>TiN D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti:N composition</td>
<td>1:1</td>
<td>4:1</td>
<td>1:1</td>
<td>4:1</td>
</tr>
<tr>
<td>Ashing</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

For almost all covering films, the measurements listed below were taken to understand their material properties:

I. Surface roughness (Ra): AFM measurement with tapping mode
II. Nanoindentation hardness: Nanoindentation using a Berkovich tip
III. Thickness of the native oxide layer on the film surface: Combination of field emission transmission electron microscopy (FE-TEM) observation and XPS measurement.

To avoid the influence of underlying Si substrates on the measured hardness of the films, indentation depth of the Berkovich tip were carefully controlled to be less than 10 nm, which is 10% of the film thickness. Cross-sectional direct FE-TEM observations (Fig. 3) of the native oxide thickness were primarily made for the wiring metal films with relatively thicker oxide layer. XPS measurements were done for the noble metal films with unnoticeable thin oxide layers. In this case, thickness was calculated from the ratio of the peak powers between the photoelectrons come from the oxide layer and the metal film.

![Fig. 3 FE-TEM observation of the oxide films](image)

2.2 Electric contact resistance

A specific optional function of the SPM system (E-Sweep, SII nanotechnology), called scanning spread resistance microscope (SSRM), was used for electric resistance measurements. The logarithmic current amplifier of the SSRM enables an extremely wide-range measurement ($10^3$–$10^9$ Ω) of the contact resistance between the probe tip and the substrate film while sliding the probe within a predetermined area on the film (Fig. 2).

As a result of performing the SSRM measurement, a map of the local contact resistance distribution within the sliding area (SSRM image) is obtained. We converted this two-dimensional SSRM image into a histogram of the contact resistance in the sliding area so as to discuss the deviation of the resistance together with its median value. Finally, the measurement results were plotted as box plots (Fig. 4).

All the measurements were performed in the open atmosphere. The substrates with conductive films were cleaned by acetone before the measurement. The sliding speed of the probe during the measurement was 0.4 μm/s. The size of the sliding area was 4 μm × 2 μm, and the total sliding distance per measurement was 260 μm. A bias voltage of −0.1 V was applied to the substrate holder to generate an electric current. For most of the measurements, the contact force of the probe against the substrate film was fixed at 500 nN, and only for the case of the comparison measurement of four different TiN films, the force...
was changed to 1400 nN. The probes were replaced after each measurement to remove the influence of sliding hysteresis.

To focus only on the difference of substrate film materials, all SSRM measurements were performed using Rh-coated probes. Only the substrate covered with Pt was measured as a representative of all noble materials.

<table>
<thead>
<tr>
<th>Resistance $[\Omega]$</th>
<th>Frequency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^3$</td>
<td>0</td>
</tr>
<tr>
<td>$10^6$</td>
<td>50</td>
</tr>
<tr>
<td>$10^9$</td>
<td>100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Displacement Y $[\mu m]$</th>
<th>Displacement X $[\mu m]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Contact Resistance $[\Omega]$  
Cumulative Frequency [%]  
0  50  100

Fig. 4 Data processing of the measured SSRM results: The measured two-dimensional SSRM image (a) was converted into a histogram (red curve in (b)) and a cumulative distribution (green) of the contact resistance in the sliding area. For brevity, the distribution was represented by a box plot (c) in the following graphs.

### 2.3 Friction force

The friction force was measured using the friction force microscope (FFM) function of the SPM system (SPA300-HV, SII nanotechnology). The friction force distribution can be plotted on a map (FFM image) by detecting the torsional angle of the cantilever caused by the friction force acting on the probe tip, while sliding the tip against the substrate film toward the orthogonal direction of the cantilever length (Fig. 2).

While scanning the predetermined 2 µm × 2 µm area that was divided into 32 scanning lines, the probe tip was made to slide on the substrate film 32 times with a trace and retrace tracking; as a result, 32 pairs of FFM signals (referred to as “frictional curve”) were obtained. From these data, the authors calculated the average kinetic friction force together with their standard deviation (Fig. 5). The total sliding distance per measurement was 160 µm and it included dummy scanning before data acquisition commencement.

![FFM image (trace)](image)

![FFM image (retrace)](image)

Fig. 5 Fictional curves and friction force

Similar to the SSRM measurement, each measurement was performed in the open atmosphere after the substrates were cleaned by acetone, and probes were replaced after each measurement. The sliding speed of the probe was 0.4 µm/s and the contact force was...
500 nN. A bias voltage of \(-0.1\) V was applied to the substrate holder even for the FFM measurement in order to maintain the electric status of the probe tips to exactly the same as that for the SSRM measurement.

For the same reason as with the SSRM, all FFM measurements were also performed using Rh-coated probes. The substrates covered with CMP-polished W and TiN-A were measured as representatives of each material.

2.4 Probe wear

The tips of all probes used in the measurements were observed by FE-SEM from the normal direction of the cantilever plane. From the FE-SEM images, their apparent probe tip areas were estimated by elliptic approximation (Fig. 6) such that the probe wear caused by the slide during the measurement could be evaluated.

In addition to SSRM or FFM measurements, additional experiments were performed only for evaluating the probe wear. In these additional experiments, probes coated with materials other than Rh were slid on the substrates covered with wiring metals (WN, WN–CMP, and TiN-A). The sliding conditions (speed, area, etc.) were exactly the same as those of the FFM measurement.

3. Results

3.1 Material properties

The measured material properties of the substrate films obtained using the measurements described in section 2.1 are shown in Table 2.

<table>
<thead>
<tr>
<th>Category</th>
<th>Wiring metals</th>
<th>Noble metals</th>
<th>Probes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WN</td>
<td>W</td>
<td>W(_{\text{CMP}})</td>
</tr>
<tr>
<td>Surface roughness (Ra) [nm]</td>
<td>0.28</td>
<td>1.13</td>
<td>0.28</td>
</tr>
<tr>
<td>Thickness of surface oxide layer [nm]</td>
<td>3.7</td>
<td>-</td>
<td>1.8</td>
</tr>
<tr>
<td>Nanoindenter hardness [GPa]</td>
<td>19.5</td>
<td>-</td>
<td>14.1</td>
</tr>
</tbody>
</table>

The oxide thickness and the hardness of the W film without CMP were not measured,
because it would be appropriate to consider that their values were about the same as W with CMP. Since the coatings of the probe tips couldn't be directly measured by nanoindentation, we fabricated extra samples with thicker films deposited on the flat Si substrates by the same deposition process condition.

In general, the metals on the substrate are easily oxidized in the open atmosphere and covered by native oxide layers. It is widely known that the native oxide thicknesses of wiring metals are thicker than those of noble metals. From a comparison of four TiN samples, we found that films having higher Ti content (TiN-B, TiN-D) had thicker oxide layers than other films (TiN-A, TiN-C). This is believed to be because N atoms occupy a dangling bond of Ti atoms at the substrate surface and prevent Ti from oxidization. The ashing process (TiN-C, TiN-D) was still more effective for increasing the oxide thickness.

3.2 Electric contact resistance

Figure 7 shows the measured contact resistance plotted in a box-plot style while the Rh-coated probe was sliding on the substrates coated with WN, W, TiN, and Pt. The roughness of the film surface (Ra) and the thickness of the native oxide layer are also shown in Fig. 7 for reference.

The deviation of the contact resistance is extremely wide (sometimes more than 2–3 orders of magnitude). Because the measurement range of the SSRM is $10^3–10^9 \Omega$, the result for the Pt-covered substrate means that its contact resistance may be widely distributed over a range of less than 1 kΩ.

![Fig. 7 Deviation of electric contact resistance (contact force: 500 nN)](image)

<table>
<thead>
<tr>
<th>Material</th>
<th>WN</th>
<th>W</th>
<th>W (CMP)</th>
<th>TiN A</th>
<th>Pt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughness</td>
<td>0.28 nm</td>
<td>1.13 nm</td>
<td>0.28 nm</td>
<td>0.96 nm</td>
<td>0.91 nm</td>
</tr>
<tr>
<td>Native oxide</td>
<td>3.7 nm (1.8 nm)</td>
<td>1.8 nm</td>
<td>1.0 nm</td>
<td>0.1 nm</td>
<td></td>
</tr>
</tbody>
</table>

A comparison of the electric contact resistance measured with four TiN samples is shown in Fig. 8. Because of the abovementioned measurement range saturation, the resistance deviations of TiN-C and TiN-D appeared to be very small, but would obviously vary widely over a range of more than $10^9 \Omega$. The fact that the result for TiN-A in Fig. 8 showed a smaller resistance than that in Fig. 7 implies that a larger probe contact force enables the electric contact resistance to be smaller and more stable.

From both the results, we deduce that the electric contact resistance showed strong dependence on the thickness of the oxide layer; the resistance is larger for thicker oxide, as reported in traditional theories. The effect of the oxide thickness will be discussed in a later section. A comparison of the results measured with two W-covered substrates revealed that the effect of the surface roughness was not significant.
3.3 Friction force

The results of the friction force measurement using FFM are shown in Fig. 9. In the figure, the kinetic friction force is plotted with its range of deviation. The properties of each substrate are also shown in the figure for reference.

When the probe slid on the substrate with a thick oxide film, the range of the deviation of the kinetic friction force was small and the effect of the film material was not so evident. However, once the Rh probe slid on the noble metal film, the friction force began to show a relatively larger range of deviations and clear material dependency. A detailed discussion will be presented in later sections.

3.4 Probe wear

The results of the probe tip area measurement using FE-SEM are shown in Fig. 10. In all the FE-SEM images, melting phenomena of the probe tips by Joule heat were not observed. It is difficult to find any tendency only from the results in Fig. 10. A detailed discussion will be presented in later sections.
4. Discussion

4.1 Effect of surface oxide thickness

As mentioned in previous sections, the existence of the native oxide layers on the substrate film appeared to be a key factor. To more accurately discuss the influence of the oxide layer, all the measurement results were re-plotted into the graphs against the thickness of the oxide layer.

The blue markers in Fig. 11(a) show the relation between the oxide layer thickness and the median of the electric contact resistance measured by the SSRM, whereas the red markers show the relation with the probe tip area after FFM measurement. The green markers in Fig. 11(b) show the relation with the average value of the kinetic friction force measured by FFM, whereas the purple markers show the relation with the standard deviation (σ) of the force. The coefficients of determination (R² values) between two parameters are also plotted in the figures to understand the strengths of their correlations. Because the probe contact force for the friction measurement was 500 nN, the kinetic friction coefficients were distributed within the range of 0.2–0.8. For better understanding, an extra vertical axis for "Kinetic Friction Coefficient" was added in Fig. 11(b) in addition to the axis for average kinetic friction force.

It has been repeatedly mentioned that the electric contact resistance showed a strong dependence on the thickness of the oxide layer. From Fig. 11(a), we observe that their relation is plotted almost as a straight line when the Y-axis has a logarithmic scale. This implies that the insulating metal oxide layer works as a potential barrier, and the electric current flowing from the probe tip to the substrate film is therefore affected by the tunneling current, which is generally inversely proportional to the exponential of the gap distance; in this case, the distance can be defined as the thickness of the oxide layer. Therefore, it would be physically possible for the electric currents measured by two W films to be almost the same, even though the two films had different surface roughness values, because the effect of reducing the true contact area caused by the increase in roughness may be of 1–2 orders of magnitude, which is much smaller than the exponential effect of the tunneling current.

On the other hand, the results in Fig. 11(b) imply that the oxide layer works positively for the friction force stabilization; increasing the thickness of the oxide layer reduces the deviation of the kinetic friction force. This means that two tribological requirements for
actual MPA products, namely low electric contact resistance and stable friction force, have a trade-off relation through the thickness of the oxide layer. Thicker oxide layers were also slightly effective for decreasing its average value; however, the $R^2$ value was not significantly large. This tendency appeared to be caused by the large variation in the friction forces acting on five noble metal films, all of which had very thin oxide layers.

![Fig. 11 Measured tribological factors vs oxide layer thickness](image)

The most obscure relation was that between the oxide thickness and the probe wear. As shown by the red markers in Fig. 11(a), there was almost no relation between the above two parameters. To determine whether the oxide layer thickness actually has an influence on the probe wear, we re-plotted the SSRM results measured with four TiN samples in Fig. 12. The blue markers show the relation between the oxide layer thickness and the median of the electric contact resistance measured by the SSRM, whereas the red markers show the relation with the probe tip area after the same SSRM measurement.

The only case in which a good electric contact was observed was the measurement of TiN-A, which has the thinnest oxide layer. However, in this case, the probe tip was extensively worn. This result implies that once materials constituting the system are fixed, the oxide layer works like a solid lubricant and prevents the probe tip from being worn. Moreover, this lubricating effect was gradually saturated when the oxide thickness increased above 3–4 nm. Hence, the optimum thickness of the oxide layer to balance two dilemmatic requirements (good electric contact and high probe wear durability) is...
considered to be about 1–2 nm.

Fig. 12 Summary of the SSRM measurement with four TiN samples

4.2 Effect of hardness on the probe wear

As explained in the previous section, when comparing the results of various materials, we cannot describe the probe wear phenomena only from the perspective of the thickness of the oxide layer. We must find another key material property that affects the probe wear. In general, the hardness would be the most probable candidate for this key property. To confirm this hypothesis, we focused on the relation between the hardness of the system (probe/substrate film) and the probe wear.

Figure 13 shows the tip area of the probes used in FFM measurements. As previously described, all probes used in the FFM measurements were covered with Rh coating (hardness: 13.0), and the hardness of the probes were therefore constant. Consequently, if the probe wear was affected by the hardness, harder substrate films would cause more intense probe wear, and as a result, the graph in Fig. 13 would have a positive slope.
However, the plot shown in the graph is almost horizontal, and the $R^2$ value is nearly zero. The results of the additional experiments explained in section 2.4 are shown in Fig. 14. In these experiments, probes coated with materials other than Rh were also slid on the substrates covered with wiring metals (WN, WN–CMP, and TiN-A). To compare the results obtained by the probes having different hardness values in a single figure, we assigned the ratio of the hardness between the probe and the substrate film to the X-axis. Consequently, if the probe wear was affected by the hardness, the graph in Fig. 14 would have a negative slope.

From observing the entire graph, the results don't exhibit a clear trend; however, when we focus on only the results obtained with each of the three substrate films, all the three lines exhibit a decreasing trend.

In conclusion, the hardness was not the material property that most affected the probe wear; however, in the case where the material of the substrate film is fixed into a wiring metal that has a relatively thicker oxide layer, an increase in the hardness of the probe is effective for reducing the probe wear.

4.3 Model of wear and friction without oxide layer

From previous discussions, we found that in a system that has a substrate film of wiring metals, the behaviors of tribological factors are relatively simpler, in that the native oxide layer on the film surface impedes good electric contact, but at the same time, it works like a solid lubricant that stabilizes the friction force and reduces the probe wear. In this instance, the use of a harder probe helps to reduce the probe wear.

It is necessary to discuss the remaining subject, that is, the material parameter that determines the friction force in a system that has no surface oxide layer (i.e., contact between two noble metal surfaces). Because two metals are in direct contact without any interference from the oxide layer, adhesion forces that originated in the atomic structure or crystal structure of two metals are supposed to affect the friction.

In previous studies, there were many possible candidates for the atomic parameters, which determine adhesional friction such as barrier height \(^{(14)}\) and d-valence bond characteristic \(^{(15)}\). Most importantly, one of the recent studies reported that the friction coefficient is affected by the crystalline interaction between the materials, and it therefore
increases as the difference in the interatomic distance between the materials decreases \(^{(16)}\).

Figure 15 shows the correlation between the friction forces measured with noble metal films and the difference in the atomic radii of two metals. Because the probes used in the FFM measurements were coated with Rh, the difference in the atomic radius became zero when the substrate film was the same material (Rh), and in that case, the measured friction force had a maximum value. The two parameters plotted in the graph show good linear correlation. Hence, we can say that an increasing difference in the interatomic distance between the materials is effective for friction force reduction.

\[ R^2 = 0.7952 \]

![Fig. 15 Effect of the difference in atomic radius](image)

In conclusion, we have to consider two different models of the probe wear and friction that are affected by the oxide layer (Fig. 16). If thickness of the oxide is negligibly thin, adhesion force caused by atomic interaction shows significant influence on the wear and friction behavior, hence the influence of hardness becomes relatively small. On the other hand, if there is thick oxide, it impedes the activity of adhesion force, hence the hardness plays dominant role on the wear.

![Fig. 16 Models of the wear and friction behavior](image)

**4.4 Effect of surface roughness**

As mentioned in the section 3.2, the results measured with two W-covered substrates imply the effect of the surface roughness has not significant effect on the electric resistance. Besides, the authors calculated the \( R^2 \) value between the surface roughness and the probe wear and found there was almost no correlation \( (R^2 = 0.0023) \).

The reason of less influence of the surface roughness is considered that both of the probe tip area and the roughness of the substrate film are small enough that the difference between real contact area and apparent contact area would be negligible.
5. Conclusion

To practically realize precise processes or devices utilizing scanning nanoprobes, e.g., probe-based nanolithography and probe-based data storage, we require a significant improvement in the wear resistance of the probe tip and a stable electric contact resistance at the nanoscale sliding contact area of the probe tip. To solve this dilemmatic trade-off problem, the influence of the material properties on the relations among the electric contact resistance, friction force, and wear at the nanoscale sliding contact area of the probe tips was investigated by measurements using SPM and SEM. Finally, we obtained the following observations:

- The native oxide layer on the metal surface plays the most significant role at the nanoscale sliding contact. The electric contact resistance has a trade-off relation with the other two factors (friction and wear) through the oxide layer thickness.
- A thick native oxide layer reduces the tunneling current and increases the apparent contact resistance. The effect of the surface roughness on the contact resistance is relatively negligible.
- The native oxide layer behaves like a solid lubricant and inhibits the adhesive friction and wear. In this case, the use of harder materials for the probe may help to reduce the probe wear.
- In case of a contact between two noble metals, the friction force increases as the difference in the atomic radius between the materials decreases.

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