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Electrical contact formation in micro four-point probe measurements

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Keywords: mirco four-point probe, finFET, electrical contact

Abstract – This paper describes the electrical contact formation between the electrodes of the micro four-point technique and a semiconducting sample. It is shown that the contact is formed in two stages: a voltage-induced electrical contact formation, followed by a current-induced decrease in contact resistance. Moreover, a method is proposed allowing for precise control of the final contact resistance. Finally, it is demonstrated that the contacting process is similar on one-dimensional fin structures, where the demonstrated control of the electrical contact is needed when measuring on nanometer-wide fins in arrays with a pitch smaller than the electrode contact size.

1. Introduction

Ever since the transition from planar to three-dimensional transistor architectures such as the fin field-effect transistor (finFET)[1] there has been a rising need for metrology solutions able

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to measure the electrical properties of nanometer-wide conducting features.[2] Recently, it has been shown that the micro four-point probe (μ4pp) technique is able to measure the resistance in nanometer-wide fins.[3,4] In order to perform such measurements with a high precision, all four electrodes are required to form low resistance contacts with the sample under investigation.[5] When landing the electrodes on a semiconducting sample, however, the native oxides present on both the sample surface and the Ni-coated Si electrodes act as highly resistive barriers and prevent good electrical contact.[6] Thus, every time the electrodes are landed on the sample surface, a lowly resistive electrical contact has to be created first. Generally, the electrical contacting is done by inducing an electrical bias to the sample with a current source, which results in the formation of an electrical contact under the electrodes. At present however, the understanding of this process is limited and the transients in induced voltage and injected current make the electrical contact formation hard to control.

In this paper, we show experimentally that the electrical contact between the μ4pp electrodes and a blanket Si sample is formed in two separate phases; (1) a voltage-induced electrical contact formation and (2) a current-induced contact improvement (i.e. a further reduction of the contact resistance). Moreover, for phase 2, we propose a new method allowing for excellent control of the contact resistance of the created electrical contacts. Finally, we show that the electrical contact formation is similar on more confined structures such as fins, where the precise control of the electrical contact is needed for measuring single fins in dense arrays.[4]

2. The electrical contacting process

As mentioned in the introduction, the formation of an electrical contact can be separated into two distinct phases. First, we show that a voltage-induced dielectric breakdown of the native oxide between the μ4pp electrodes and the sample forms the initial electrical contact. Then,

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we demonstrate that a current can be used to further lower the contact resistances, such that an ohmic contact is created. Here, we start from the more general case of a Si blanket layer with a B implant (3×10^{15} cm^{-2}, 5 keV with a 1150 ˚C laser anneal) and a deep lowly n-doped well as a sample. The description in this paper as well as **Figure 1a** is only focused on two of the four electrodes needed for a micro four-point probe measurement. Needless to say, the extra two electrodes will have to undergo a similar contact formation process before an actual four-point measurement can be performed.

2.1. Voltage induced contact formation

In the first phase of the contacting process, the system attempts to inject a sinusoidal current I_{in} through electrodes 1 and 2 landed on the Si sample surface, which has a native oxide layer (i.e. SiO_2) of 1-2 nm (as illustrated in **Figure 1a)**, grown by exposing the Si surface to air ($t >$ month).[6] In this paper, we use I_{in} = 10 µA with a 7 Hz frequency. When injecting the current I_{in}, a high load resistance (i.e. $R_{load} >> R_{sample}$ in **Figure 1a**) is present between the sample and the current source. While I_{in} is being applied, we can measure both the output voltage over the electrodes, i.e. $V_{out} = I_{in} * R_{series}$ (with $R_{series} = R_1 + R_{sample} + R_2$) and the contact resistances R_1 and R_2, i.e. the resistances under electrodes 1 and 2 respectively (**Figure 1b**).

Note that the measurement of R_1 and R_2 is done using the extra two electrodes 3 and 4 (not shown in **Figure 1a**) of our micro-probes after forming the corrrespoding electrical contacts R_3 and R_4 with a high current (>500 µA, see **Figure 2b** in the next section) to ensure a low contact resistance (i.e. $R_3, R_4 << R_1, R_2$). Here, since the Si sample is highly doped, R_{sample} is much lower than the contact resistances (i.e. $R_{sample} << R_1, R_2, R_3, R_4$)[3][4] and can thus be neglected, making that all contact resistances can be ontained using a series of independent two-point measurements. For example, R_1 is extracted using $R_1 = 0.5 * (R_{1-3} + R_{1-4} - R_{3-4})$,

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where $R_{1\text{-}3}$ is the two-point measurements between electrode 1 and 3 etc. R_2 is extracted in a similar fashion. Furthermore, to make sure R_1 and R_2 can be measured during the short time frame in **Figure 1b**, the applied current signal is stopped at a specific time. For instance, to measure R_1 and R_2 at t = 2.5 ms, the applied current is stopped at t = 2.5 ms, after which R_1 and R_2 are measured as described above. This process is then repeated for each of the data points in **Figure 1b**. The contact resistances reported in this paper represent the median values of a set of 50 measurements done in subsequent electrode landings, since several large outliers are generally present. The corresponding error bars represenent the 25th and 75th percentile.

As can be seen in **Figure 1b**, V_{out} goes through a series of two spikes when trying to apply I_{in}. These two voltage spikes correspond quite precisely to the moment that respectively R_1 (blue triangles) and R_2 (red circles) drop from ~10 MΩ to ~10-100 kΩ. During the first spike, i.e. the first 2.5 ms in **Figure 1b**, V_{out} increases as the tool tries to apply I_{in}. In this time frame both R_1 and R_2 are still very high, indicating that the oxide under both electrodes 1 and 2 is intact. However, after V_{out} reaches ~4.5V (i.e. at time ~2.5 ms), there is a sudden drop in R_1 to ~10^5 Ω, while R_2 remains very high. As a consequence, there is a corresponding rapid drop in V_{out}. We understand this first peak as indicative of the dielectric breakdown of the oxide under electrode 1, creating a conductive path between the electrode and the sample, while the oxide under electrode 2 is still intact.[6,7,8] Quantitatively, since now $R_1 << R_2$, the total series resistance drops by a factor ~2, thus resulting in V_{out} dropping by a factor ~2 as well.

Next, after contact 1 is created (i.e. at time >2.5 ms), V_{out} increases again as the system tries to supply I_{in} while R_2 is still very high. Then, when the voltage reaches ~4.5 V (i.e. at time ~4.5 ms), R_2 suddenly drops to ~10^5 Ω at its turn, expectedly corresponding to a drop in V_{out}. This indicates the dielectric breakdown of the oxide under electrode 2. The exact breakdown voltage required will depend on the local oxide thickness[9] and electrode geometry and might

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vary for the different electrodes, as can be seen by the slightly different breakdown voltages in **Figure 1b**. After the second peak, the electrical contacts under electrodes 1 and 2 are formed.

It is important to mention that the exact mechanism leading to the creation of these electrical contacts is not fully understood as yet. However, a possible explanation is the formation of conductive filaments in the oxide between the electrodes and the sample. Indeed, filament-based switching behaviour has been observed in similar material stacks, i.e. Ni – SiO_2 – Si. [10,11,12] Such a process could also explain why R_1 breaks down first, as the filament formation is favoured when a positive field is applied from the metal towards the semiconductor. The electric field is indeed not symmetric for both electrodes as it points into the sample under electrode 1 and out of the sample under electrode 2 (red arrows in **Figure 1a**).[13] Further support for the filament formation process in our case is the fact that the resistance of such filaments also depends strongly on the current during their formation.[14,15] As we show in the next section, the contact resistances R_1 and R_2 can be reduced by ~1-2 orders of magnitude by applying a current into the newly created electrical contacts.

2.2. Current induced contact improvement

As mentioned above, we now demonstrate that by applying a current through the electrical contacts after the voltage-induced contact formation, R_1 and R_2 can be further reduced. One of the main reasons why we need a low contact resistance is that an otherwise high contact resistance is observed as a non-linear contact, which in turn leads to inaccurate measurements. Typically, after both contacts have been formed (i.e. at 4.5 ms in **Figure 1b**), the load for the current source (i.e $R_{load} + R_1 + R_{sample} + R_2$) drops from ~10 MΩ , as both R_1 and R_2 become much smaller (~10-100 kΩ). As the system cannot respond fast enough, this leads to a short (~µs) current spike running through the electrodes, until V_{out} is adapted to the

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new output resistance. Unfortunately, the magnitude of the current spike cannot be measured directly and moreover depends on R_1 and R_2 during the voltage transient (i.e. at t =4.5 ms in **Figure 1b**), making the current spike hard to predict. However the result of this current transient can be seen and is that the contact resistances decrease further (in line with the behaviour seen for filamentary devices[13,14]), as is observed by the further reduction of R_1 after the second voltage peak (i.e. at 4.5 ms in **Figure 1b**).

To demonstrate this in more detail and to highlight the role of the current on the contact resistance more clearly, we measure R_1 and R_2 as a function of an extra applied current *after* the initial voltage-induced contact formation of R_1 and R_2 (see **Figure 2a**). Here, we can vary the magnitude of the current spike during the voltage-induced contact formation by varying the load resistance on the electrodes, i.e. R_{load}. Indeed, it is expected that a low current spike is generated when a high load resistance $R_{load} >> R_{sample}$ is used (as was done for the data in **Figure 1b**) whereas a much larger current spike is expected when using a low load resistance $R_{load} \sim R_{sample}$. It is now instructive to see that for the case of a low current spike, both R_1 and R_2 (i.e. red circles and blue triangles in **Figure 2a**) are initially much higher (~100 kΩ) than for the case of a high current spike (~1 kΩ, dashed lines in **Figure 2a**). Moreover, both R_1 and R_2 can be lowered (~1-2 orders of magnitude) to the value obtained with a high current spike by applying an additional current. Vice versa, when applying similar currents for the case of a high current spike, no further change in resistance is observed.

It is also interesting to evaluate the quality of the contacts after these procedures. Indeed, in a four-point measurement, where a sinusoidal current is injected between two electrodes and the voltage drop is measured by the other two electrodes, a non-zero phase shift (~0˚) between these two signals is indicative of a high resistive, non-linear contact under one or more of the electrodes, which can be observed when measuring V_{out} as a function of time (not shown).[5] To evaluate whether the formed contacts are indeed resistive, the phase shift can

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be measured while applying the current ramp through the electrodes. Here, the phase shift is measured in the regular four-point setup using all four electrodes, requiring the contacting process used for electrodes 1 and 2 to be repeated on electrodes 3 and 4. As expected for the case of a low current spike (i.e. $R_{load} >> R_{sample}$), the phase shift decreases with increasing current (see circles **Figure 2b**), corresponding to the decreasing contact resistances R_1 and R_2 (and thus R_3 and R_4) in **Figure 2a**. Moreover, the phase shift approaches zero (i.e. the contacts are resistive) after applying a high enough current (i.e. ~400 μA). Subsequently, as expected for the case of a high current spike (i.e $R_{load} \sim R_{sample}$), the phase shift remains ~0˚ since R_1 and R_2 (and thus R_3 and R_4) are already low (see triangles **Figure 2b**).

These results clearly indicate that the final contact resistance is controlled by the maximum current either during or after the voltage-induced contact formation process and that ohmic contact can be achieved. As the current spike is nevertheless hard to predict or control, our observations suggest a simple approach for a finer control of the final contact resistances. Indeed, in the case of using a high load resistance ($R_{load} >> R_{sample}$) to suppress the current spike during the voltage-induced contact formation and a subsequent injection of a current with a desired magnitude, the contact resistances can be reduced in a controlled fashion.

3. Electrical contact on fin structures

Finally, the same electrical contacting process can also be used on confined structures such as fins. **Figure 3a** shows the contact resistance under electrodes 1 (R_1, red circles) and 2 (R_2, blue triangles) when measuring on an 80 nm wide Si fin with a B implant (3×10^{15} cm^{-2}, 5 keV) and a 1150 ˚C laser anneal. Here, we used a high load resistance ($R_{load} >> R_{sample}$) during the voltage-induced contact formation. Similar to the blanket Si case discussed before, R_1 and R_2 decrease as a function of current from initially ~2 $\times 10^5$ Ω to ~2–5 kΩ. Correspondingly, the phase shift during regular four-point measurement is also observed to decrease with increasing current (**Figure 3b**). Note that here the current needed to create an

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ohmic contact (i.e. phase shift ~ 0˚ at ~40 µA) is much lower compared to the current needed when measuring on a blanket layer (i.e. ~ 400 µA). At present the physical mechanism for this difference is not yet understood and needs further exploration as a function of fin width. Interestingly, with our proposed method of using a controlled current to lower the contact resistances, an excellent control of the electrical contact formation and the current during this process is achieved, which is required when trying to contact single fins in fin arrays with a pitch smaller than the electrode contact size. Indeed, it was shown that the maximum current during the electrical contact formation has to be carefully controlled in order to make sure a the electrical contacting remains isolated to a single fin.[4]

4. Conclusions

In this paper, we discussed the electrical contact formation between the µ4pp electrodes and the sample. First, we showed an initial electrical contact is created by inducing the dielectric breakdown of the native oxide of the sample under the µ4pp electrodes. Secondly, we demonstrated that the contact resistance under the electrodes can be further improved (i.e. decreased) by running a current through the electrodes. Moreover, we proposed a method which allows for excellent control of the contact resistance, which is essential when trying to contact on single fins in dense arrays. Additionally, this method could also be used to investigate the electrical contacting procedure on other materials such as Ge, where the difference in native oxide properties might change the electrical contacting process.[16]

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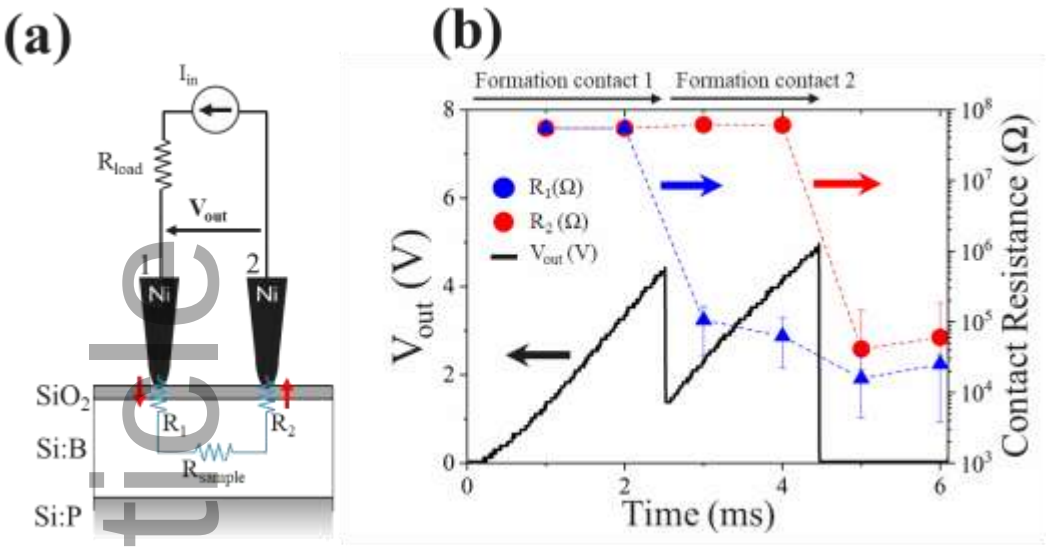

Figure 1: (a) Schematic of two of the four µ4pp electrodes, consisting of Ni coated Si cantilevers, landed on the surface of a Si sample, with a native oxide layer of 1-2 nm. A current I_{in} is applied between the two electrodes in order to create an electrical contact with the sample. R_1 and R_2 represent the contact resistances between the sample and electrodes 1 and 2, respectively, while R_{sample} is the sample resistance and R_{load} is an external series resistance. The red arrows show the direction of the electric field at the contact as the system tries to inject a current from electrode 1 to electrode 2. (b): Output voltage of the current source during the electrical contact formation process, as the tool tries to apply I_{in}. The contact resistances for each of the electrodes, R_1 and R_2, during the contact formation process are also shown. The two spikes in V_{out} while I_{in} is being applied, correspond to the moment when contact resistances R_1 and R_2 drop from ~10 MΩ to ~10-100 kΩ, respectively. Arrows indicate the corresponding axes of the data points.

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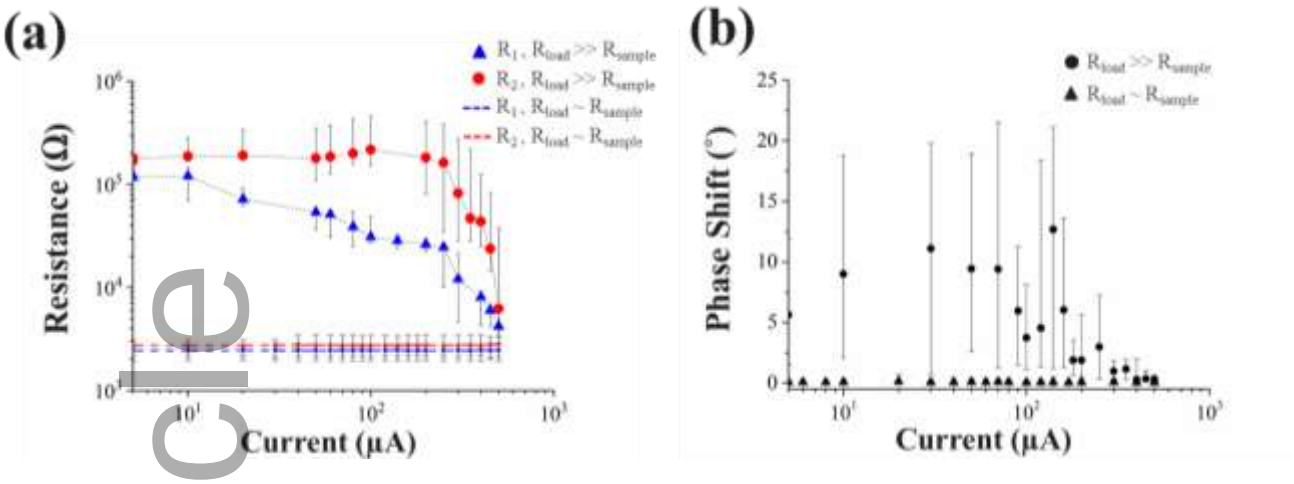

Figure 2: (a) Contact resistances under electrodes 1 and 2, i.e. R_1 and R_2, as a function of applied current after the voltage-induced contact formation. The data is shown for both the case of using R_{load} >> R_{sample} (red circles and blue triangles) or R_{load} ~ R_{sample} (red and blue dashed lines) during the voltage-induced contact forming. (b) Phase shift between injected current and measured voltage signal using the electrodes in regular four-point setup using all four electrodes (after also forming electrical contacts under the extra two electrodes), both for the case of R_{load} >> R_{sample} and R_{load} ~ R_{sample}. The phase shift is ~0˚ (i.e. the system is resistive) only when R1 and R2 are low (~kΩ).

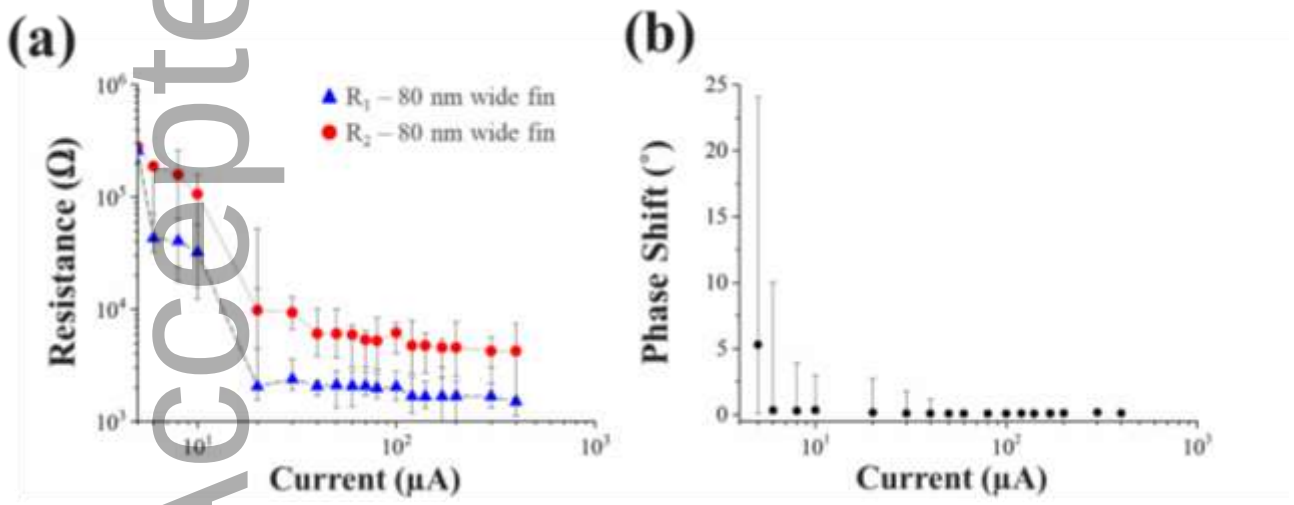

Figure 3: (a) Contact resistances under electrodes 1 and 2, i.e. R_1 and R_2, as a function of applied current when using 80 nm wide Si fins with a B (3×10^{15} cm^{-2} with a 1150 ˚C laser anneal) implant as a sample. Similar to a Si blanket layer, R_1 and R_2 decrease as a higher current is applied through the contacts. (b) Phase shift between the injected current and measured voltage signal using the electrodes in regular four-point setup.

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This paper presents a detailed study on the electrical contact formation between the electrodes of the micro four-point technique and a semiconducting sample. Additionally, we propose an electrical contact formation method which allows for precise control of the final contact resistance, which is essential when trying to measure on nanometer-wide fins dense arrays.

Keyword: micro four-point probe

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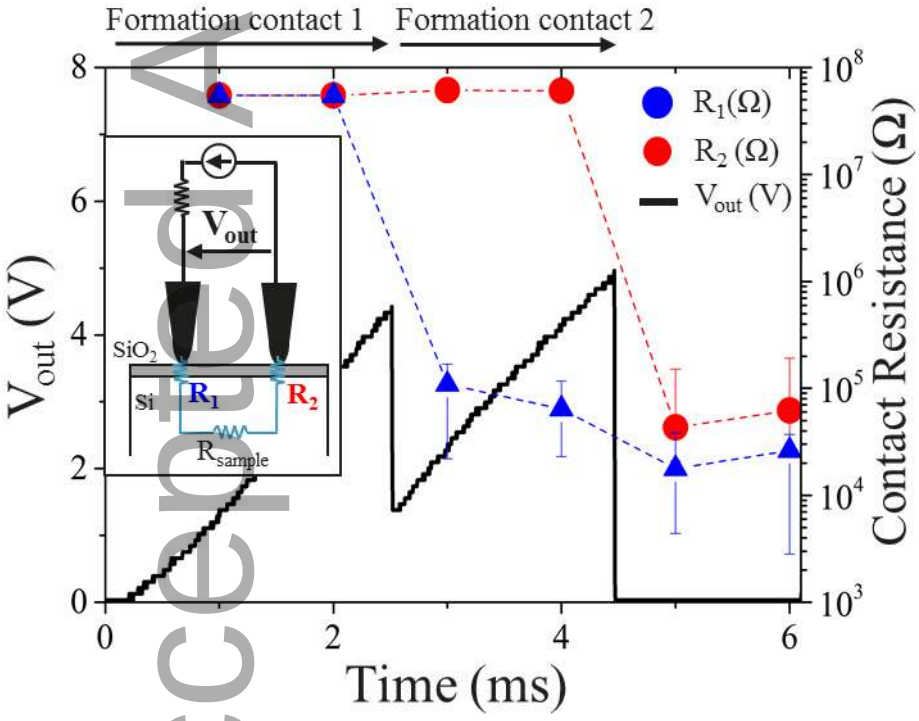

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