Effect of surface contact potential in atomic-size contacts

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Abstract

We present a study of the effect of surface contact potential in a mechanical break junction experiment. Using amplitude-modulated Kelvin probe microscopy (KPM), we show that the surface potential of a real metal is highly non-uniform and is strongly distance-dependent. Based on our KMP results, we propose a model in which a current is induced from the capacitive coupling of the surface potential and accounts for much of the observed shifts of the conductance peaks from integer multiples. The significance of our results in other areas of physics is also discussed.

I. INTRODUCTION

The creation of atomic-size contacts via the mechanical break junction (MBJ) technique provides a simple experimental platform in which fundamental properties of nano-scale electron transport can be probed. According to the Landauer formula¹, the electrical conductance is quantized in units of $G_0 = 2e^2/h \sim 1/(12.9 \text{ k}\Omega)$ (with e and h being the magnitude of electric charge and Planck’s constant, respectively), as the size of atomic constrictions becomes comparable to the Fermi wavelength of electrons. The physics of quantized conductance has received growing interest since the landmark demonstration of finite electrical conductances in two-dimensional electron gas (2DEG) in 1988². There, electrons were successfully confined on a lithographically defined quantum dot with precisely controlled dimensions. Later, J. L. Costa-Krämer *et al.*³ demonstrated quantized conductance from a pair of bulk metallic wires as a table-top experiment at room temperature. Other experimental works include studies of quantized conductance using scanning tunneling microscopy (STM)⁴⁻⁶, commercial electromechanical relays⁷, and low temperature MBJ’s^{8,9}.

In most MBJ experiments, gold is a popular choice for creating atomic contacts because it is considered to be “clean” and is more immune to oxidation and corrosion than other common metals, such as silver and copper. Additionally, the interpretation of the conductance quantization in gold is rather straightforward since it has only one electron in its spherically symmetric valence shell (i.e., monovalent). Recent shot noise measurements on gold contacts suggest that the first peak of a conductance histogram originates from an almost fully-transparent single conductance channel, confirming that the step-like feature in the conductance data is likely to be the direct consequence of conductance quantization, rather than repeated creations of a preferred atomic configuration¹⁰⁻¹³.

Common to many of the previous experiments involving atomic-sized point contacts is the apparent shift of conductance peaks in histograms below quantized values nG_0 , (where $n = 1, 2, 3, \dots$). To account for the observed shift, a “residual” resistance R_r is commonly introduced to position the observed conductance peaks at integer values. Although there is no definite theoretical justification for adding this *ad-hoc* resistance in series with an atomic contact, the resistance model serves a useful purpose by quantifying a degree of possible disorder arising from surface defects and imperfections at the banks of atomic-scale contacts leading to electron backscattering¹⁴⁻¹⁹. Typical values of the added resistance to

account for the apparent shift range from $100\ \Omega$ to $1500\ \Omega$ ^{6–8,20}. To investigate the effect of disorder experimentally, Bakker *et al.*²⁰ demonstrated the shift of the conductance peaks in histograms upon addition of nickel impurities to pure copper. They found that the increase in nickel concentration directly led to the increase in series resistance needed to align the observed peaks at integer values, with the amount of resistance differing among different peaks. In the case of the $n = 3$ conductance peak, the applied “correction” was as large as $1.6\ \text{k}\Omega$.

In this report, we suggest a realistic scenario in which electron conduction is modified due to strong capacitive coupling arising from the surface contact potential effect. Unlike a perfect conductor, the surface of a real metal is not equipotential, and its surface potential spatially fluctuates around the so-called contact potential difference (CPD), as routinely measured by Kelvin probe microscopy (KPM)²¹. As a consequence, when two imperfectly-conducting tips are brought into contact, surface charges are no longer free to move so as to keep the electrochemical potential constant on the surface^{22,23}. Microscopically, the inherent process of repeated, physical indentations in an MBJ experiment—the making of atomic-sized contacts—causes the crystalline orientation of the surface atoms to change, thereby modifying the local electrical properties upon the formation of each atomic junction. We show that the induced current effected by the surface potential variation could account for the observed shift in the conductance peaks without having to add a large series resistance.

II. EXPERIMENTAL SETUP AND RESULTS

Shown in Fig. 1 is a schematic of our mechanical break junction apparatus (left) and a typical conductance trace captured on an oscilloscope (right). Two gold wires are repeatedly brought in and out of contact by a piezoelectric transducer (PZT) connected to a function generator (FG). Typical modulation frequencies of the PZT translation range from $100\ \text{mHz}$ to $10\ \text{Hz}$. Inside a home-built electric control box are a bias voltage source V_b , which is tunable from $-1\ \text{V}$ to $+1\ \text{V}$ in $10\ \mu\text{V}$ -step resolution, and a current-to-voltage (I-V) converter with variable gain settings. Repeated contacts are made at room temperature in ambient pressure, with the entire apparatus sitting on a vibration-isolation table. The resulting conductance data are recorded in MATLAB installed on a PC. Most of our data acquisition took place overnight to minimize the noise associated with nearby human activity during

FIG. 1. Schematic of a mechanical break junction experiment (left) and a typical conductance trace (right). The piezoelectric transducer (PZT), driven by a function generator (FG), moves one of the gold tips in and out of contact with the other tip. The conductance is measured by an I-V converter inside the control box. All of the data collections, along with the PZT modulation, are automated in a MATLAB script.

the daytime.

In Fig. 2, we present a calibration result of our I-V converter, which enables us to convert the measured current to the actual conductance in units of G_0 . For this, a number of precision resistors with known resistances (better than 1% tolerance) were employed to plot the current, measured in terms of the voltage output of the I-V converter V_m , against the known resistance R . The linear relationship between $1/V_m$ and R is evident from the calibration result shown in Fig. 2 and is given by

$$\frac{1}{V_m} = \frac{R + R_0}{V_b R_{\text{gain}}}, \quad (1)$$

where R_{gain} is the gain factor ($10^3 \Omega$), and R_0 is the constant resistance mostly attributed to an internal resistor (470Ω), which is connected in series with the gold junction. A bias voltage of $V_b = 500 \text{ mV}$ was applied throughout the calibration and during the conductance measurements. The calibration data are fit to Eq. 1, with the slope defined as $a \equiv 1/(V_b R_{\text{gain}})$ and the y -intercept by $b \equiv R_0/(V_b R_{\text{gain}})$. The obtained fit, indicated by the solid line in Fig. 2, gives excellent agreement with our calibration data. All of our subsequent conductance data are then directly obtained from the relation: $G = aV_m/(1 - bV_m)$, with $G \equiv 1/R$.

Next, we collected over 200 conductance traces and created a histogram, as shown in Fig. 3. The horizontal axis of the histogram represents the normalized conductance in units of

FIG. 2. Calibration of the I-V converter inside our electric control box: A linear fit (red, solid) is applied to calibration data (black, circle) and yields $R_0 = 470.4 \pm 0.5 \, \Omega$ and $R_{\text{gain}} = 1002 \pm 2 \, \Omega$, as expected.

G_0 . The first three peaks are well resolved, with the peak positions falling slightly below the integer indices: 0.93, 1.82, and 2.64 for $n = 1, 2$, and 3, respectively. In terms of the residual resistance R_r needed to position the peaks at integers, we obtain 903 Ω , 638 Ω , 586 Ω for $n = 1, 2$, and 3, respectively. Our result is consistent with the previous findings in which the experimental shifts were corrected by the extra resistance, with typical values being 400 Ω for a 2DEG² and 100 Ω -1500 Ω for STM and MBJ-style experiments^{6-8,20}. Note that although our experimental results were obtained at room temperature under an ambient condition, the extra resistance needed to correct the downshift of the peaks in our histogram is of similar order of magnitude as those applied to the results obtained at low temperature (UHV at 4.2 K)⁶. This implies that the origin of disorder, manifested by an extra resistance, might be due in large part to the intrinsic, local nature of atomic contacts themselves, rather than the extrinsic conditions of an experiment, such as pressure and temperature.

In a typical MBJ experiment, when a contact is created, the tip of a wire is mechanically ‘pressed’ into the tip of another wire and then pulled apart. Repeated contacts through this macroscopic “pressing” effectively translate into continuous modifications of crystallo-

FIG. 3. A histogram of measured conductances representing over 200 traces of conductance steps similarly shown on the right of Fig. 1. Based on Gaussian fits, the first three peaks (widths) are 0.93 ± 0.08 , 1.82 ± 0.15 , and 2.64 ± 0.20 for $n=1$, 2, and 3, respectively.

graphic orientation of the surface atoms at the microscopic level, leading to a change in the surface potential. Even in the absence of externally driven physical contacts, it is well-known that the surface potential distribution is non-uniform due to the random nature of crystallographic orientations and shows a significant variation over the surface of a metal. The magnitude of the surface potential variation, as recently performed by precision force measurements using the KPM technique, ranges from 50 mV to 500 mV between a pair of Au samples in a sphere-plane geometry^{28–31}. As such, the surface of a real metal is far from perfect, and it is more appropriate to perceive the surface of a real metal as a *dielectric* layer with which an approaching (or retracting) tip is capacitively coupled. In a recent study of ion trapping^{22–24}, the surface of gold is indeed modeled as a dielectric layer whereby dipoles are randomly oriented as a source of non-equilibrium noise.

III. SURFACE POTENTIAL MEASUREMENTS VIA KPM

Before discussing how the surface potential effect influences break junction experiments, let us first discuss the basic principle of the KPM technique. Originally devised by Lord

Kelvin, the technique seeks to minimize electrostatic interactions between two objects by applying a contact potential difference (CPD)²¹. This is the voltage necessary to minimize the electrostatic interaction and represents the primary signal of KPM. The electric force between two metallic objects separated by a distance z is given by

$$F(V) = -\frac{1}{2} \frac{\partial C}{\partial z} (V - V_c)^2, \quad (2)$$

where C is the capacitance between the objects. The minus sign indicates an attractive nature of the electric force. Note that applying zero voltage (i.e., $V = 0$) does not achieve an electrically-minimized configuration; only when the applied voltage coincides with the contact potential difference (i.e., $V = V_c$) does the system experience zero net force. In an amplitude-modulated KPM, an alternating voltage combined with a dc voltage, $V = V_{dc} + V_{ac} \sin(\omega t)$, is applied to a tip, and the total force between the tip and another electrode (i.e., sample) is expressed as

$$F(V) = -\frac{1}{2} \frac{\partial C}{\partial z} \left(\left[(V_{dc} - V_c)^2 + \frac{V_{ac}^2}{2} \right] + 2(V_{dc} - V_c)V_{ac} \sin \omega t + \frac{V_{ac}^2}{2} \cos 2\omega t \right). \quad (3)$$

Using a lock-in technique, the term containing $\sin \omega t$ is monitored at the modulation frequency ω and is minimized when a feedback-controlled, dc voltage coincides with the CPD (i.e., $V_{dc} = V_c$). While the term inside the bracket could be also used to find the contact potential via dc signals (i.e., static deflection), the lock-in detection usually provides much greater stability. To characterize the capacitance gradient $C' \equiv \partial C / \partial z$, one can modulate the term containing $\cos 2\omega t$ using a second lock-in amplifier at 2ω . Then, the force detected ($F_{2\omega}$) is directly proportional to the capacitance gradient C' , as applied to a precision electric force calibration³². For more technical details about the KPM techniques, see^{21,24,33–36}.

To examine the connection between the surface potential variation, as measured by KPM, and the peak shifts in the conductance histograms in atomic-sized contacts, we have performed amplitude-modulated KPM measurements on one of the actual gold wires used for our conductance measurements. Our KPM signals are essentially the CPDs that are obtained by nullifying the $\sin \omega t$ term in Eq. (3) with the ω modulation. Below we discuss four main observations based on our KPM studies.

Non-uniform surface potential distribution– Presented in Fig. 4 are two KPM scans acquired at the heights of 4.8 nm and 27.3 nm, respectively. Clearly, the surface potential landscape of our gold sample is *not* uniform. In obtaining these images, we moved the

FIG. 4. Kelvin probe microscopy (KPM) scans of one of the Au wires used in our MBJ experiment at heights of 4.8 nm (left) and 27.3 nm (right), respectively. Each pixel in KPM corresponds to a value of local contact potential difference that minimizes the tip-sample electrostatic interaction, as shown in Eq. (3). The surface potential distribution is changing both *laterally* (i.e. over the scanned area) and *vertically* (i.e. z -distance-dependent). To acquire these scans, we have used a commercial atomic force microscope equipped with KPM features (CYPHER-ES, Asylum Research), with a typical cantilever frequency of 70 kHz and the spring constant of 2 N/m.

KPM tip over the *horizontal* surface of our gold sample (i.e., lengthwise), not over the frontal surface where actual atomic point contacts had been made. Yet the obtained scans clearly reveal the non-uniformity of contact potential on the surface of a real metal, with the magnitude of the potential fluctuation, as measured by the maximum and minimum values of CPD, exceeding 30 mV in both scans. Notice that while the fluctuation is roughly the same for both scans, the average CPDs (or the “middle” values in the contrast bar) differ considerably at two different heights: 10 mV and 96 mV for 4.8 nm and 27.3 nm, respectively. This leads to our next point.

Strong distance-dependency of CPD– The contrast of the surface potential variation in Fig. 4 is significantly diminished as we move out from $z = 4.8$ nm (left) to $z = 27.3$ nm (right). As the KPM tip is moved away from the sample, the potential contrast almost completely disappears, with the CPD eventually reaching a fixed average value without showing any variation. In Fig. 5, we plot the average CPD’s against the tip-sample separations. There, the magnitude of the contact potential decays *exponentially* as the tip-sample separation is progressively reduced. Our finding is consistent with a recent KPM study in which an exponential dependence of the CPD variation with distance has been observed and subsequently

FIG. 5. CPDs as a function of z at a given lateral position: A strong distance-dependent CPD demonstrated here is consistent with similar results reported in the literature^{22,28–30,37,39,40}. An exponential fit $V_c(d) = V_\infty - \alpha e^{-d/\lambda}$ (blue, solid) gives good agreement with experimental data (red, circle), with the characteristic strength and decaying factors $\alpha = 164$ mV and $\lambda = 23$ nm, respectively. The large-distance limit (i.e., dc offset), represented by V_∞ , is 138 mV. For convenience, the vertical axis indicates the change in CPD defined as $V_c(d) - V_\infty$.

attributed to the averaging effect of the local potential patches³³. The variation of the surface potential, in our case, is as large as 120 mV as z is adjusted from 100 nm to 5 nm. Given the decaying factor $\lambda \sim 23$ nm, an atomic-size contact created well below sub-nanometer separation experiences strong capacitive coupling through the distance-dependent CPD. For example, at the point of nominal contact at $z = 0$, the value of CPD reaches an asymptotic value of -24 mV corresponding to the total variation in CPD of -150 mV at “zero” distance. Incidentally, the CPD variation with distance has been observed in a number of recent precision experiments and has posed a great challenge in many physical situations whereby a metal surface is in close vicinity of a sample^{22,28–30,37,39,40}.

Modification of CPD upon repeated contacts— In making atomic contacts, two metal tips are repeatedly squeezed and pressed. These repeated macroscopic contacts dramatically

FIG. 6. Repeated KPM measurements at two different lateral positions: Each potential measurement is performed at $z = 5$ nm and is followed by a topographic scan in which a gentle contact is made with the surface. In both runs, the potential measurement experiences drifts at the onset of an experiment but settles in after about 50 contacts. These scans, taken at a relatively large tip-sample separation, mimics the physical situation of an actual break junction experiment in which the effective tip-to-tip separation is much closer, on the sub-nm level.

modify the local arrangements of atoms at the microscopic level, leading to the continuous evolution of crystallographic orientations responsible for the surface potential variation. It has been shown that the CPD is not only *passively* modified by a mere change in external conditions, such as temperature, pressure, and humidity^{41,42}, but also it is *actively* modified by repeated indentations, leading to an intrinsic change in the surface state. To quantitatively understand the situation, we have measured the surface potential at a single location over 500 times at 5 nm of height, with each measurement preceded by a gentle contact with the surface. The result is shown in Fig. 6. Even though the KPM scanner is stationary, the obtained CPD significantly changes as repeated contacts are exerted on the same location. Essentially, by performing KPM followed by a surface contact, we mimic the physical situation of an actual MBJ experiment in which mechanical contacts repeatedly occur.

A potential variation as large as 100 mV is evident over the course of the measurements, coupled with short-term drifts of 20–30 mV.

Relative change versus absolute value of CPD—In the context of understanding the surface potential effect in an MBJ experiment, what matters most is the *relative* value of the KPM measurement, not its *absolute* measured value. In general, the actual value of a CPD taken from a separate KPM measurement is meaningless unless KPM is simultaneously applied to another experiment of interest (e.g., a mechanical break junction experiment). While a CPD value between two materials depends upon a variety of microscopic parameters, such as the work function difference, adsorption and oxide layers, and other defects, it also depends on those of macroscopic origins including device operating conditions^{41–44} and even the electrical wiring implemented for a given experiment. Hence, unless KPM is simultaneously performed with conductance measurements in an atomic contact experiment with the same wiring condition, much of the measured CPD value may reflect the physical arrangement of an independent Kelvin probe setup, with no relation to the atomic contact experiment itself.

IV. INDUCED CURRENT DUE TO A SURFACE POTENTIAL VARIATION

The underlying message of our results presented in Figs. 4–6 is quite revealing: (i) The surface potential distribution on a real metal is highly non-uniform (Fig. 4); (ii) the average contact potential difference (CPD) is strongly distance-dependent (Fig. 5); and (iii) the CPD is significantly modified due to repeated, physical contacts (Fig. 6), all of which is consistent with the fact that the surface of a real metal is *far* from perfect. This allows us to model the surface of a real metal as a thin dielectric layer throughout which dipoles of different patch potentials are randomly oriented as a source of non-equilibrium noise^{22,23}. We express the total charge accumulated between the two surfaces as $Q(t) = C(t)V(t)$, where C is the capacitance between the two tip surfaces and is time-dependent through $d(t)$ (i.e., the tips are continuously brought in and out of contact over time). The electric current induced by the capacitive coupling is then

$$I_c = d' \left[C \frac{\partial V_{\text{CPD}}}{\partial d} + V_{\text{CPD}} \frac{\partial C}{\partial d} \right], \quad (4)$$

where $d' \equiv \partial d / \partial t$. Below we consider three different cases that are relevant in an experiment involving atomic-size contacts.

Case I: Static coupling– During an I-V characterization, the relative separation between the MBJ tips is fixed ($d' = 0$), and hence $I_c = 0$. No induced current would be observed as long as the tip is stationary.

Case II: Dynamic coupling on a perfect conductor– This case corresponds to producing atomic-size contacts over time to construct a conductance histogram such as shown in Fig. 3. For a perfect conductor, the potential distribution on its surface is uniform and no CPD variation is expected. Hence, $V_{\text{CPD}}=0$ and $\partial V_{\text{CPD}}/\partial d = 0$. Furthermore, when two perfectly conducting surfaces are brought into contact, surface charges move freely until the position of the Fermi level become identical. With an externally applied voltage V_b , the electric gradient is established and a non-equilibrium charge distribution immediately leads to a conduction current, driven only by V_b . Thus, no induced current is expected as long as the employed materials are ideal conductors.

Case III: Dynamic coupling on a real conductor– This case corresponds to producing atomic-size contacts involving a real metallic conductor, as considered in the present study. As demonstrated in Figs. 4-5, the surface potential distribution on a real conductor is highly non-uniform and the average CPD is strongly distance-dependent. In this case, it is more appropriate to regard the surface of a real conductor as a dielectric layer. Even in the contact regime, the two tips are effectively forming a capacitor with a layer of randomly oriented electric dipoles in between. Therefore, the induced current is produced through dynamic coupling on an imperfect conductor.

To give a realistic estimate on the magnitude of the capacitively-induced current on a real conductor, we consider repeated contacts at an atomic separation of $d=10$ Å, driven by a PZT at a modulation speed of $d'=1.0$ nm/ms. This is a typical speed used in our present study and elsewhere⁴⁵. The capacitance is directly measured to be $C \approx 100$ pF using a precision capacitance meter⁴⁶ and its derivative is approximated as $\partial C/\partial d \approx C/d = 10$ nF/nm. With $\partial V_{\text{CPD}}/\partial d \approx \alpha/\lambda = 7.1$ mV/nm and $V_{\text{CPD}} \approx 180$ mV based upon our KPM measurements, the induced current predicted by Eq. 4 is as large as $2 \mu\text{A}$. This is already over 5% of the total current expected from the first conductance peak at $V_b=500$ mV in our experiment and accounts for much of the reported shift in the first conductance peak.

Some remarks are in order with regard to our estimate. First, the actual capacitance

near the contact regime ($d \approx 10 \text{ \AA}$) is not precisely known. Because a typical capacitance measurement at the closest distance is performed at a few- μm separation^{38,46}, the capacitance value 100 pF is a conservative estimate. Note that the measured value also reflects the parasitic capacitance near and around the tip-sample contact, which is only specific to a particular experimental setup. Second, the modulation speed could be much faster in some experiments; a faster modulation speed $d' = 100 \text{ nm/ms}$ could immediately increase I_c by two orders of magnitude. Most important is the estimate of the surface potential variation. In our case, $V_{\text{CPD}} \approx 180 \text{ mV}$ is the average value taken from separate KPM measurements and might not represent the actual surface potential present in our MBJ contact itself; a direct, simultaneous application of the two experiments, namely MBJ and KPM, could provide a more reliable measure of V_{CPD} for an accurate quantification of the induced current.

Presented in Fig. 7 is the residual resistance model (left) routinely adopted in the literature in which the effect of surface disorder associated with atomic contacts is characterized by an ad-hoc residual resistance R_r . On the right of the same figure is the imperfect conductor model in which the current induced by the capacitive coupling through the contact potential variation replaces the extra resistance. Our results provide a realistic model to understand the observed anomaly in the conductance histogram in terms of the capacitively-induced current due to the surface potential effect, instead of the ad-hoc model using a very large extra resistance that has no physical origin. Although the surface potential effect might not be solely responsible for the overall shift, it is clear that the imperfect conductor model does account for a significant portion of the observed conductance shift, providing a direct physical link to the surface potential effect in a real conductor.

One may argue that the surface potential variation measured through KPM is essentially irrelevant in electron transport because the position of the two Fermi levels becomes identical when two metal tips are in contact; hence, the surface potential should produce no effect. This interpretation is incorrect if the metal under consideration is a *real* conductor. In any experiment involving the surface of a real metal, one must carefully assess the actual potential distribution on the surface of a real metal, as conducted in our present study.

FIG. 7. The residual resistance model (left) routinely adopted in the literature and the imperfect conductor (right) proposed in this report. The current source I_c can be regarded as induced current through capacitive coupling arising from the surface potential effect, as shown in Eq. (4). The atomic junction is denoted by QPC (i.e., quantum point contact). The polarity of the current source is depicted in such a way that the overall measured current is diminished from that expected from the external potential V_b alone. Another way to understand the opposite polarity is to imagine electrons having to overcome an added electrostatic force ($F \propto \partial C / \partial d$) owing to the surface potential effect and the reduction of the potential difference causing downshifts of the conductance peaks.

V. CONCLUSION

We have proposed the surface contact potential effect as a possible source of surface disorder found in conductance experiments involving atomic-size contacts. Our KPM results have clearly demonstrated that the surface of a metal is not equipotential and displays non-uniform local contact potential variation, all of which is consistent with the fact that a real metal is far from a perfect conductor. Based on our experimental evidence, we have provided an alternative model to understand the surface defects in atomic-size contacts due to the induced current arising from the contact potential variation. Using our imperfect conductor model, the conductance shift can be well-described by the capacitively-induced current I_c without introducing a large extra resistance R_r .

Our model is not only more realistic than the ad-hoc resistance model, but also fits well with the current status of many modern precision measurements in which the surface potential effect is ubiquitously encountered. The most significant source of systematic error in the recently completed GP-B project (for testing the predictions of General Relativity) turned out to be the surface potential effect^{47,48}. In a number of precision Casimir force

measurements, the surface potential effect is a primary suspect in the unexpectedly large signal observed in the sub- μm separation^{28,29,31,49,50}. In atomic physics, supposedly-stable ions trapped between a pair of metallic electrodes quickly dissipate away due to a stray electric effect on the electrode surface^{23,51}. The affected examples are numerous^{24,52–54}.

Because quantized conductance experiments always involve direct, physical contacts with two metallic tips, the surface electric effect could play a much more significant role than in the aforementioned experiments. One way to mitigate the effect of the induced current is to reduce the contact speed d' well below 1 nm/ms. Given the nature of MBJ experiments, one has to compromise between the stability of the formation of atomic chains and the speed at which those atomic chains (e.g., conductance steps) are created. As a future experiment, we suggest undertaking simultaneous measurements of conductance and KPM, similar to the way that simultaneous measurements of force and conductance have been attempted in atomic-sized contacts using an atomic force microscope⁵⁵. Detailed information on the local electrical properties of a metal surface not only opens up a new opportunity to understand scattering processes of electrons in atomic-sized contact experiments, but also provides critical clues to many of the puzzles remaining in other areas of modern physics such as nano/micro-electro-mechanical systems (NEMS/MEMS) involving a pair of metallic surfaces in close proximity.

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