Conductive oxide cantilever for cryogenic nano-potentiometry

Tsutomu Hiroya [a,1], Katsuhiko Inagaki [a], Satoshi Tanda [a], Taku Tsuneta [a], Kazuhiko Yamaya [a]

[a] *Department of Applied Physics, Hokkaido University, Sapporo 060-8628 Japan*

Abstract

Nanoscale electrical transport properties have been attracted because of new phenomena such as ballistic transport, quantized resistance, and Coulomb blockade. For measurement of nanoscale resistance, we have been developing a cryogenic atomic force microscope that can operate at 1.8 K. To use it as an electrode, we coated the cantilever with conductive oxides of TiO and indium tin oxide (ITO) . We verified that TiO and ITO thin films remain conductive even at 4.2 K. Also we measured *I-V* characteristic of the tip-sample contact with a standard sample of $NbSe_2$ single crystal, and found that the conductive coats were not lost under large stresses due to the tip-sample contact. Moreover, we succeeded to obtain a room temperature nano-potentiometry of a gold thin film with the ITO coated cantilever. In conclusion, the TiO and ITO coated cantilevers are applicable to cryogenic nano-potentiometry.

Key words: cryogenic AFM; nano-potentiometry

Nanoscale electrical transport properties have been attracted because of new phenomena such as ballistic transport, quantized resistance, Coulomb blockade, and interference effects of electron wavefunctions. Intrinsic properties can, however, be made clear only at low temperatures since ground states are smeared out by thermal fluctuations. Combination of nanoscale transport measurement with low temperature technique will reveal new quantum effect.

The tip of the atomic force microscope (AFM) [1] is treated as a controllable electrode with nanoscale resolution since it is free from the force-controlled feedback loop, contrast to the scanning tunneling microscope (STM) in which the tip-sample distance is maintained by the tunneling current through the tip. Early experiments of nanoscale resistance measurement with AFM have been performed for a thin tungsten film [2] and for a carbon nanotube [3], both of which were measured at room temperature.

We have been developing a cryogenic AFM that can operate at 1.8 K. Selection of material for the conductive tip is important for our goal since it should be mechanically hard, chemically stable, in particular, against oxidation, and conductive down to low temperatures. To satisfy these requirements, we used the AFM tips coated with conductive oxides. In this study, we report the electrical properties of TiO and indium tin oxide (ITO) coated tips, and preliminary results of nano-potentiometry with the ITO tip.

The TiO-coated tip was a commercial product [4] and the ITO-coated tip was made by RF-sputter evaporation onto a silicon cantilever. We verified that TiO and ITO thin films remain conductive. Resistances of borh films were almost constant from room temperature to 4.2 K.

We measured *I-V* characteristic of the tip-sample contact with a standard sample of $NbSe_2$ single crystal. Fresh surface was prepared by cleaving just before experiment. A resistance of 47 kΩ was inserted in the circuit to limit the current. Sensitivity was 10^{-13} A. All the experiments were performed in ambient condition.

Figure 1 shows *I-V* characteristic for the TiO tip. Ohmic behavior was clearly shown, and the resistance was calculated as 3.36 kΩ. Since the bulk resistance of

[1] E-mail:hiroya@eng.hokudai.ac.jp

the TiO film and the $NbSe_2$ sample were 315 Ω and 0.1 Ω, respectively, the major contribution to the observed I-V characteristic is the contact resistance. The contact resistance consists of two elements: the interface resistance and the spreading resistance. Since the I-V characteristic is Ohmic, the interface resistance becomes negligible, On the other hand, the spreading resistance is expected to be Ohmic. The spreading resistance R between two metals is given by the following formula:

$$R = \frac{1}{4a\lambda_1} + \frac{1}{4a\lambda_2},$$

where a is the radius of real contact area, λ_1, λ_2 are conductivities for the metals. We applied the Hertzian contact theory to calculate the radius a as

$$a = \left(\frac{4Wr_0}{3E}\right)^{\frac{1}{3}},$$

where W is the applied load, r_0 the radius of the sphere, and E the reduced Young's modulus. In this experiment, $W = 4.5$ nN, $r_0 = 35$ nm, and $E = 180$ GPa, leading to $a = 1$ nm. By considering anisotropy of $NbSe_2$ conductivity, we finally calculated the contact resistance as $R = 700\ \Omega \sim 10$ kΩ. This is consistent with the experimental result of 3.36 kΩ.

Figure 2 shows I-V characteristic for the ITO tip. Even though the non-Ohmic behavior was observed, this does not directly mean the tip was worn nor Schottky barrier was generated at the interface. Symmetry of the I-V characteristic implies the interface resistance was caused by metal-insulator-metal contact, probably because a contaminant was accidentally sandwiched between the tip and the sample.

These results imply that both of the tips were electrically conductive under large stresses due to the tip-sample contact. Concerning with temperature dependence of resistance, we conclude the TiO and ITO coated tips are applicable to cryogenic nano-potentiometry.

Room temperature nano-potentiometry was performed to test the tips as preliminary study. One example is shown in Fig. 3. Topography (left) and nano-potentiometry (right) for a gold thin film evaporated onto a glass substrate were taken with the ITO tip. Bias voltage was 1.0 V. The gold film was clearly resolved from the glass substrate in both images. We attempt to apply our results to the cryogenic AFM.

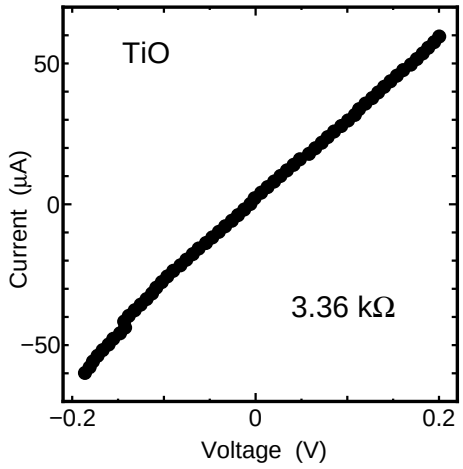

Fig. 1. current-voltage characteristic of TiO-$NbSe_2$.

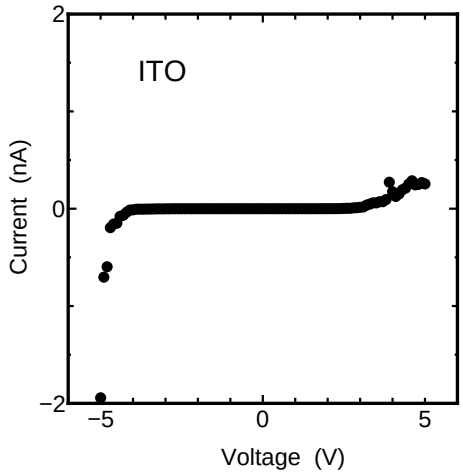

Fig. 2. current-voltage characteristic of ITO-$NbSe_2$.

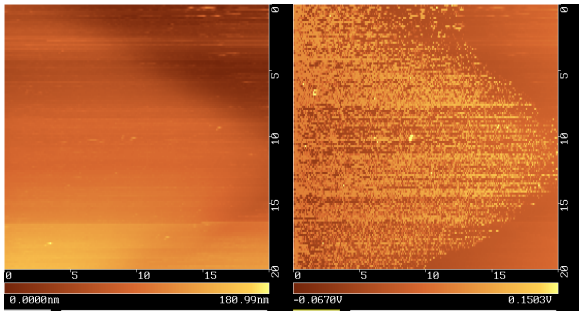

Fig. 3. Topography (left) and potentiometry (right) at room temperature. Scan area was 20 × 20 μm^2.

References

[1] G. Binnig, C. F. Quate and Ch. Gerber, Phys. Rev. Lett. 56, 930 (1986).

[2] F. Houze, R. Meyer, O. Schneegans, and L. Boyer, Appl. Phys. Lett. 69, 1975 (1996).

[3] P. J. de Pablo, C. Gomez-Navarro, J. Colchero, P. A. Serena, J. Gomez-Herrero, and A. M. Baro, Phys. Rev. Lett. 88, 036804 (2002).

[4] V. Shevyakov, S. Lemeshko, and V. Roschin, Nanotechnology 9, 352 (1998).