Mutual Inductance of Small Solenoid Coil Equipped with Scanning Tunneling Electron Microscope

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A small solenoid coil was equipped with a scanning tunneling electron microscope (STM) which has an iron needle core tip as the probe. Mutual inductance of the coil with a thin gold film on a mica plate was investigated in order to profile electrical conductivity. It is important to maintain a small gap between the tip apex and the sample surface. The gap is related to the distribution of electron scattering by induced current. The conductivity mapping was carried out on a large terrace. If the tip is over the step edge, the output signal from the probe coil becomes unstable. Atomically smooth surface of the specimen was in need for the electrical conductivity mapping. The electrical conductivity on the terrace was almost constant. The mutual inductance values with the gold film at various temperatures were investigated by cooling it below 250 K. The mutual inductance is inversely proportional to the temperature to the one-third power, $T^{1/3}$. The relationship between the mutual inductance and the temperature was explained by the electromagnetic theory.

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1. Introduction

The invention of the scanning probe microscope has enabled the profiling of various specimens such as metal surfaces, semiconductor surfaces, and magnetic materials.^{1,2)} A scanning tunneling electron microscope (STM) was combined with the eddy current method by using a small solenoid coil to profile electrical conductivity for thin metal films of nanoscale thickness. The mutual inductance between the coil and the thin metal film provides information about the scattering of conduction electrons over a Fermi surface. In order to apply a magnetic field localized in the center of the probe, an iron needle tip was used as the tip of the STM. The localized magnetic field induces circular currents in small radii, which are related to the resolution of conductivity mapping. Induced circular current is scattered by phonon vibration, defects and dislocation of the specimen.

Constant distance between the tip apex and the metal film surface is maintained by means of tunneling current feedback control. Thin gold films were selected because they do not oxidize in ambient air. The electrical conductivity mapping measurements were carried out in ambient air. The iron tip oxidation problem exists. After the iron tip had been produced, the tips could be used as the probe tips for about twenty minutes, usually. After that, feedback height control worked intermittently. The tips are considered to crash and clean the tip and the sample surfaces. The experimental measurements had been carried out within twenty minutes.

The mutual inductance values with the gold film at various temperatures were investigated by cooling it using a Peltier element in the range from room temperature to 50 K below room temperature.

2. Experimental Procedure

Polycrystalline iron needles of 0.2 mm in diameter were mechanically sharpened. The maximum length of them was about 14 mm. The distance from the edge of the coil to the tip apex was within 1 mm. The iron needle tip apex was rounded in order to be coaxial to the coil and in order to avoid the mechanical vibration.³⁾ If it were used as the STM tip, atomic resolution would be impossible.⁴⁾

Copper wire of 32 μm in diameter was tightly wound on a thin Teflon tube 0.26 mm in diameter with four layers consisting of 200 turns. The length of the coil was 4 mm. Figure 1 shows a schematic illustration of the scanning head, the probe coil and the cold base. Double tube scanners accomplish simple X-, Y- and Z-axis movements. The inner piezoelectric tube has four electrodes outside of it in order to move in the X and the Y directions. The outer tube was used only for the Z-axis movement. The aluminum base can be cooled by the Peltier element to below 250 K in order to control the sample temperature. Three screws were adjusted in order to approach the tip to the sample surface using the tunneling current.

The thin gold film was produced through physical vapor deposition with annealing at 670 K under a vacuum of 10^{-4} Pa on freshly cleaved mica. The surface features of the gold film are shown in the STM image using a platinum iridium tip in Fig. 2. The tunneling current was 1.0 nA, and the bias voltage was 191.3 mV. Large terraces and steps are observed. The step height is about 0.2 nm.

The conductivity mapping was carried out on a large terrace, because the output signal becomes unstable at the step edge. A sinusoidal wave at the frequency of 1 kHz was applied with an electric current of 1 mA. The magnetic field was calculated to be 50 A/m from the finite-length solenoid coil theory. The magnetic flux at the apex of the iron tip was estimated to be about 0.063 T, which is insufficient to saturate the iron needle.⁵⁾ The direction of the magnetic flux at the tip

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Fig. 1 Schematic illustration of double tube piezoelectric scanner.

Fig. 2 STM image of gold film 10 nm thick on mica, obtained by platinum iridium tip.

apex is changed instantaneously by the Barkhausen effect. The amplitude of the change of the magnetic flux at the tip apex is also large due to the effects of the coaxial coil and the anisotropy of the iron needle.

Figure 3 shows an electric circuit to detect the small change by the mutual inductance. A similar system is used in the superconducting quantum interface device (SQUID) technique.⁶⁾ The iron cores are used for both the probe coil and the control coil. A variable capacitor and a resistor were adjusted in order to maintain the balance of the output signals from them. A potentiometer was used as a tap in order to reduce the common mode noise from them. The output signal cable from the probe coil was connected to a positive input

Fig. 3 Measurement circuit for electrical conductivity mapping. R_p is the total resistance of the probe coil and the protective resistor in the probe coil circuit. L_p and L_c are the inductances in the probe coil and in the control coil circuits. C_c and R_c are the capacitance and resistance in the control circuit. V_{sp} and V_{sc} are the voltages of the probe coil signal and of the control coil signal.

terminal of a digital lock-in amplifier and one from the control coil was connected to a negative input terminal of it. A code in front of the control coil was connected to a preamplifier, and the output signal was used as a reference signal of the digital lock-in amplifier.

3. Results

Figure 4 shows an electrical conductivity map on a terrace of a thin gold film 10 nm in thickness, where tunneling current was 10 nA and bias voltage was 0.206 V. The gap from the iron needle tip to the surface is approximated to 0.9 nm.⁷⁾ The tunneling current is considered to be a little high, but when it is 1 nA, the electric current inside the iron tip is influenced by the probe coil. The place of the maximum induced voltage at the gold film surface is estimated, using the electromagnetic theory, to be a circle of 2.5 nm in diameter under the tip.⁸⁾ The grid lines show measurement points at intervals of 21.5 nm on the X-axis and the Y-axis. The map represents the electrical conductivity change by using the gray scale. Areas of conductivity are represented black and areas of poor conductivity are represented white. The output voltage of the measurement circuit in Fig. 3, $R = V_{sp} - V_{sc}$ ranged from 100.00 μ V to 100.37 μ V. On the grid (279.5, 63), the iron tip came into light contact with the gold surface through thermal expansion of the tip, and applied thermal vibration and dynamic force to the surface. The conductivity became poorer in this area. Before the contact of the tip, the conductivity on the terrace had been constant. The electrical conductivity recovered quickly, and permanent defects (sets) were not introduced.

Figure 5 shows the mutual inductance characteristics of the probe coil versus temperature, T . The measurement had been carried out without coating the sample surface with frost. The aluminum base in Fig. 1 was firstly heated by inverse electric current into Peltier element in order to vapor humid and then cooled, soon. The mutual inductance values are divided by the inductance of the control coil, L_c . The inductance of the control coil is estimated to be 1.46×10^{-3} H. The mutual inductance is related to the vibration of phonons, since the relationship between the mutual inductance and the temperature is inversely proportional to temperature to the one-third power, $T^{1/3}$, and since the change of electrical resistance of

Fig. 4 Electrical conductivity map for gold film/mica.

Fig. 5 Mutual inductance characteristics of probe coil versus temperature.

the gold film with respect to temperature yields to the vibration of phonons.

4. Discussions

The electrical resistivity function, ρ , of temperature, T , under a constant pressure is expressed in the Bloch-Grüneisen's empirical equation,

$$\rho_P(T) = RT^5 \int_0^{\Theta/T} \frac{x^5}{(1 - e^{-x})(e^x - 1)} dx, \quad (1)$$

where Θ is the Debye temperature. At the elevated temperature, the equation is approximated to the following form.⁹⁾

$$\rho \approx \frac{RT}{\Theta} \quad (2)$$

The magnetic flux density in the axial direction, B_z , at the sample surface, $z = 0$ is written as

$$B_z = \frac{p_m(2z_1^2 - \beta^2)}{4\pi(\beta^2 + z_1^2)^{5/2}}, \quad (3)$$

Fig. 6 Schematic illustration of the electromagnetic induction current model.

where p_m is the magnetic dipole moment at the apex of the iron needle core, z_1 is the distance from the tip apex to the sample surface, and β is radial length on the horizontal plane at the origin. The schematic illustration of the electromagnetic induction current model is shown in Fig. 6. The magnetic flux through the area, $2\pi\beta d\beta$, is written as

$$\Delta\Phi = B_z \times 2\pi\beta d\beta, \quad (4)$$

so the electromagnetic induction voltage, V_e , is expressed as¹⁰⁾

$$\begin{aligned} V_e &= \frac{\Delta\Phi}{dt} \\ &= \dot{p}_m \times \frac{(2z_1^2 - \beta^2)\beta d\beta}{2(\beta^2 + z_1^2)^{5/2}} \end{aligned} \quad (5)$$

By Ohm's law, the limited electric current, $i_{\max}$, in unit electric conductive cross-sectional area at the surface $d\beta \times 1$, and

V_e are also written as

$$V_e = \rho \times 2\pi\beta \times i_{\max} \times d\beta \times 1. \quad (6)$$

The definite integrals of the function V_e of β with limits 0 and a for eqs. (5) and (6) were carried out.

$$\dot{p}_m \times \frac{a^2}{2(a^2 + z_1^2)^{3/2}} = \frac{\pi RT i_{\max} a^2}{\Theta} \quad (7)$$

As a result, the following relationship between the radius, a , of the eddy current and the temperature, T , is introduced:

$$\sqrt{a^2 + z_1^2} = \left(\frac{\dot{p}_m \Theta}{2\pi RT i_{\max}} \right)^{1/3}. \quad (8)$$

The mutual inductance, M , of the two circular current circuits, C_1 and C_2 , is expressed by Neumann's equation,

$$M = \frac{\mu_0}{4\pi} \int_{C_1} \int_{C_2} \frac{d\vec{s}_1 \cdot d\vec{s}_2}{r}, \quad (9)$$

where $d\vec{s}_1$, and $d\vec{s}_2$ are the unit vectors on C_1 , and C_2 , respectively, and r is the distance between $d\vec{s}_1$ and $d\vec{s}_2$. The point P is on C_1 and the point Q is on C_2 .¹¹⁾ Figure 7 shows a schematic illustration of the two circular current circuits, C_1 and C_2 , where z_1' represents the distance from the sample surface to the edge of the coil and c and a are the radii of C_1 and C_2 , respectively. These points and vectors are represented in the Cartesian coordinates as

$$\begin{aligned} \vec{r}_P &= (c, 0, z_1') \\ d\vec{s}_1 &= (0, c\Delta\theta', 0) \\ \vec{r}_Q &= (a\cos\theta, a\sin\theta, 0) \\ d\vec{s}_2 &= (-a\Delta\theta\sin\theta, a\Delta\theta\cos\theta, 0). \end{aligned}$$

The distance, r , is represented in the following equation.

$$|\vec{r}_P - \vec{r}_Q| = r = \sqrt{c^2 + a^2 + z_1'^2 - 2ca\cos\theta} \quad (10)$$

Fig. 7 Schematic illustration of two circular current circuits.

$$M = \frac{\mu_0}{4\pi} \int_{C_1} \int_{C_2} \frac{ca\Delta\theta'\Delta\theta\cos\theta}{\sqrt{c^2 + a^2 + z_1'^2 - 2ca\cos\theta}} \quad (11)$$

The denominator of eq. (11) is translated to Maclaurin's series by

$$l^2 = c^2 + a^2 + z_1'^2 \gg 2ca\cos\theta.$$

$$M = \frac{\mu_0 ca}{4\pi l} \int_{C_1} \int_{C_2} \left(1 + \frac{ca\cos\theta}{l^2} + \dots \right) d\theta' \cos\theta d\theta \quad (12)$$

In eq. (12), l can be considered to be almost constant, because the summation of c^2 and $z_1'^2$ is much greater than a^2 . The double net outflow integral of the first term in eq. (12) becomes zero, but a in the numerator in eq. (11) is important.

$$M = \frac{\mu_0 ca}{4\pi l} \left(\frac{2\pi^2 ca}{l^2} \right) \quad (13)$$

Ignoring the change of the minute term within the parentheses, M is in direct proportion to a , as seen in eq. (13). In eq. (8), z_1 is smaller than a and is constant. According to eqs. (8) and (13), M is considered to be inversely proportional to $T^{1/3}$.

5. Conclusions

The electrical conductivity for gold film about 10 nm thick was investigated using STM combined with a small solenoid coil for the eddy current method. The conductivity at the terrace of the gold film is almost constant. When the STM tip was in light contact with the gold film surface, an area of poor conductivity 20 nm in radius was detected. Through contact with the tip, phonon vibration and lattice strain were induced in the gold film.

The mutual inductance is investigated at various temperatures for the gold film. It is inversely proportional to $T^{1/3}$.

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- 3) With scanning movement of the piezoelectric tube, mechanical vibration occurs. The eigen frequencies of the tip edges yield to the shape of them. In the case of normal STM tip shape, the eigen frequency is low, because of small moment of inertia of area. In the case of the round tip, the eigen frequency is high. The round tip is not easy to vibrate mechanically.
- 4) The polycrystalline iron tip magnetostriction, Δl is roughly estimated to be 0.4 nm from the next equation, $\Delta l = \lambda_s l$, where l is the length of the solenoid coil and $\lambda_s = 2\lambda_{100}/5 + 3\lambda_{111}/5$ is the coefficient of the magnetostriction of polycrystalline. The anisotropic coefficients of the magnetostriction, λ_{100} and λ_{111} are also 0.1×10^{-6} in the magnetic field of 0.05 T. The value is not negligible taking into account of 0.9 nm tunnel gap. The vibration due to the magnetostriction must be

solved to atomic resolution. The vibration did not influence upon the measurement of mutual inductance, because the tunnel gap is feedback controlled by the tunnel current.

- 5) The magnetic permeability of the iron needle tip, μ is assumed to be 2000. The intensity of magnetic field in the iron needle of the coil is calculated from the equation, $H = nI(\cos \theta_2 - \cos \theta_1)/2$, where n is the turn number of the coil, I is the electric current, θ_1 is the angle between the axis of the coil and the segment from a starting point of the coil to the center on the axis of coil, the angle θ_2 from the endpoint of the coil is defined same as above.

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