The fabrication of MgB$_2$ superconducting STM tips
Mingxiang Xu$^1$, Yoshihiko Takano, Takeshi Hatano, Masayo Kitahara, Daisuke Fujita
National Institute for Materials Science, 1-2-1, Sengen, Tsukuba 305-0047, Japan

Abstract
We demonstrate a simple method for the fabrication of reproducible, clean and stable MgB$_2$ superconducting tips. The quality of these tips has been verified by imaging the surface of a thin Au(111) film sample using a low temperature scanning tunneling microscopy (STM). High-quality semi-atomically resolved STM surface images of the Au(111) sample have been observed using the MgB$_2$ superconducting tip, which unambiguously indicates that the fabrication of relatively superconducting MgB$_2$, suitable for use as STM tips, is feasible.

Key words: MgB$_2$; scanning tunneling microscopy (STM); Au(111) surface

1. Introduction
The scanning tunneling microscopy (STM) has provided unique insights into the local density of electronic states (LDOS) of metal, semiconductor and superconductor surfaces [1–3]. STM studies of superconducting materials are conventionally performed in the superconductor/insulator/normal-metal (S/I/N) configuration using a sharp normal-metal tip. A natural and intriguing extension of the capabilities of STM studies would be to use a superconducting tip, thus allowing for S/I/S measurements. The use of superconducting tips for tunneling experiments into high-$T_c$ superconductors has been predicted by theoretical calculations [4,5]. Quasiparticle tunneling from a superconducting atomically sharp Nb tip has been verified to be indeed feasible [6]. The idea of STM experiments in which the Josephson effect would be observed between the tip and the surface was also suggested [6].

Since the recent discovery of 39 K superconductivity in magnesium diboride MgB$_2$ [7], a variety of its high potential applications have also been discussed [8]. However, the idea of using MgB$_2$ as the material for the STM tip has not yet been reported in the literature. In this article, we demonstrate a simple method for the fabrication of reproducible, clean and stable MgB$_2$ superconducting tips. The quality of these tips has been verified by imaging the surface of a thin Au(111) film sample using a low temperature STM.

2. Fabrication and Characterization
The superconducting MgB$_2$ tips used in this study were made of dense polycrystalline samples. The highly dense (density $\sim$ 2.63 g/cm$^3$) MgB$_2$ bulk samples were synthesized under high pressure (3.5 GPa) at high temperature (1273 K) for 2 h in a BN crucible as described elsewhere [9]. X-ray diffraction reveals that the sample is single phase. Magnetization measurements show a superconducting transition with an onset and a midpoint at 38.3 and 37.8 K, respectively. A small (about 2 mm in length) piece was first cleaved from the MgB$_2$ sample and glued with silver paint on a STM tip holder, then immediately loaded in an ultrahigh vacuum (UHV) STM chamber. The surface was finally cleaned with Ar ion sputtering (1 keV) in UHV. Using such a simple method, we have thus obtained clean MgB$_2$ superconducting tips with a high degree of reproducibility. The thin Au(111) film sample was made by vapor deposition of pure gold on a single-crystal mica substrate at 500 K in vacuum. The surface was
cleaned with Ar ion sputtering at the acceleration energy of 1 keV, followed by annealing at 500 K in UHV. By this method, epitaxially grown Au(111) surfaces with atomically flat terraces were routinely obtained.

In order to characterize the MgB$_2$ tips, we have performed surface imaging on the thin Au(111) film sample, using a low temperature STM (UNISOKU, Japan) operated in UHV with a base pressure of $3 \times 10^{-9}$ Pa. STM images of the Au(111)-(23 $\times \sqrt{3}$) reconstructed surfaces were observed with semi-atomic resolution using a constant-height imaging mode.

3. Results and Analyses

Figure 1 shows a wide-area STM image (104 $\times$ 104 nm$^2$) at the constant-height mode ($V_T = -2.00$ V, $I_T = 0.20$ nA) of the reconstructed Au(111) surface observed at 30 K, clearly showing the steps of monoatomic height and the herringbone patterns.

Fig. 1. A wide-area STM image (104 $\times$ 104 nm$^2$) at the constant-height mode ($V_T = -2.00$ V, $I_T = 0.20$ nA) of the reconstructed Au(111) surface observed at 30 K, clearly showing the steps of monoatomic height and the herringbone patterns.

stable and practicable.

4. Conclusions

In conclusion, we have demonstrated a method for the fabrication of clean and stable MgB$_2$ superconducting tips. Herringbone reconstruction of Au(111) surface was clearly resolved by the MgB$_2$ tip using a low temperature STM. A semi-atomically resolved STM surface image of a Au(111) sample was observed, which unambiguously confirms that the cleaved MgB$_2$ tip has the capability of high atomic resolution.

Our superconducting-tip STM can, hence, open the door for many important future applications. Most notable example is Josephson tunneling in SS-STM, which would provide a new type of tunable Josephson junction. It could also become a useful instrument to study, for example, spatial variations of the order parameter in exotic superconductors. Using the MgB$_2$ superconducting tip, further STM studies on MgB$_2$ superconductor are now in progress.

Acknowledgements

The authors would like to thank Dr. Taizo Ohgi for useful helps. This study was performed through Active Nano-Characterization and Technology Project, Special Coordination Funds of the Ministry of Education, Culture, Sports, Science and Technology of the Japanese Government.

References