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To cite this article: Terukazu Nishizaki and Norio Kobayashi 2009 J. Phys.: Conf. Ser. 150 012031

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Development of high-field STM for 18 T cryocooled superconducting magnet

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Abstract.
To study the nanoscale electronic order in strongly correlated electron systems and vortex states in high-\( T_c \) superconductors in high magnetic fields, we have developed scanning tunneling microscopy (STM) for the 18 T cryocooled superconducting magnet (18T-CSM). The test results of the STM operation in the 18T-CSM at room temperature indicate that our STM has a good atomic resolution up to 18 T when we use the nonmagnetic vibration-isolation table which reduce the vibration noise from the cryocoolers of the 18T-CSM. In this paper, we report on the design of the high-field STM system for large-scale magnets and its performance.

1. Introduction
Scanning tunneling microscopy (STM), since its invention by Binning and Rohrer [1], has been widely used for surface science and physics. In addition to the STM topography with high spatial resolution, scanning tunneling spectroscopy (STS) has a great ability to give the local density of state (LDOS). The possibility for studying superconductors by STM/STS have been realized when the spatial variation of the superconductivity in Nb3Sn [2], and the Abrikosov vortex lattice and the electronic structure of the vortex core in NbSe2 [3] have been demonstrated in combined conditions of low-temperatures and magnetic fields [3].

Recently, a variety of experiments and theoretical studies have presented that the transition metal oxides, in which the electrons are strongly correlated, show the spatially inhomogeneous electronic states. The strongly correlated electron systems have several competing states and show many electronic phase transitions into the novel electronic states. In high-\( T_c \) superconductors (HTSC), STM/STS studies have provided important information on the nanoscale spatial variation of the electronic state: inhomogeneity of the superconductivity [4], superstructure of LDOS in the superconducting state [5], pseudogap state (\( T > T_c \)) [6], vortex core state [7] for Bi2Sr2CaCu2Oy and zero temperature pseudogap (ZTPG) state for Ca2-\( x \)Na\( x \)CuO2Cl2 [8]. Since these self-organized electronic patterns tend to appear when the superconductivity is suppressed, the magnetic field strong enough can be an important parameter to study the electronic state in HTSC. However, previous STM/STS studies have been mainly performed in the field region below \( \sim 10 \) T [9] which is limited by the ability of the superconducting magnet. In addition, the superconducting magnet cooled by the liquid helium for usual STM system has a cold bore; thus it is difficult to apply STM/STS in high fields and high temperatures at which other interesting phenomena such as colossal magnetoresistance in manganites, pseudogap state in HTSC, etc. are observed.
To study the field dependence of nonoscale electronic states in strongly correlated electron systems in the wide temperature region up to room temperature, we have developed a new STM system for the 18 T cryocooled superconducting magnet (18T-CSM). In this paper, we report on details of the STM design and its performance in the 18T-CSM.

2. Design of STM system for 18T-CSM

Figure 1 shows schematic illustration of the high-field STM system installed on the 18T-CSM [10] at the High Field Laboratory for Superconducting Materials, IMR, Tohoku University. The 18T-CSM is a large-scale magnet with a total weight of 5.8 tons and the superconducting coils (NbTi, Nb₃Sn, Ag/(PbBi)₂Sr₂Ca₂Cu₃O₁₀) and a radiation shield are cooled by Gifford-McMahon-Joule-Thomson (GM-JT) cryocooler and two GM cryocoolers, respectively [10]. It is expected that the mechanical vibration and/or sound generated from three cryocoolers become crucial noise for STM/STS measurements. To make a stable tunneling contact with an atomic-scale stability, we have developed the compact vibration-isolation table (Tokkyokiki Corporation, Hyogo, Japan) which consists of the diaphragm type air springs (f ∼ 3 Hz) with automatic leveling sensors. The vibration-isolation table should be completely nonmagnetic without any electric circuits because the stray field near the top flange becomes ∼1 T when H = 18 T. The STM insert and the cryogenic Dewar with a narrow tail are decoupled from the 18T-CSM which has a 52 mm room temperature bore.

We have designed the small and rigid STM head (20 mm in diameter × 55 mm in length) to enhance the resonant frequency. We selected nonmagnetic materials such as titanium, copper, beryllium copper, tungsten, Macor, etc. for parts of the STM head. To reduce the size of the STM head, a tube scanner supporting PtIr tip and a coarse approach unit with a sample holder are facing each other, as shown in the left photograph in figure 1. The axis of the coarse

![Figure 1. Schematic illustration of the high-field STM installed on the 18T-CSM [10]. Main parts for the STM head are shown in the left photograph. The nonmagnetic vibration-isolation table (upper right photograph) is set up between the 18T-CSM and the STM insert.](image)
approach motor, which is supported by three shear piezo stacks using a leaf spring, is driven in stick-slip mode and a step width is $\sim 500$ nm at 150 V at room temperature.

3. Vibration measurements and system performance

To evaluate the vibration noise of the 18T-CSM and the performance of the vibration-isolation table, we have measured the vibration acceleration signal for the vertical ($z$) and two horizontal ($x, y$) directions by using a piezoelectric accelerometer (Ono Sokki, NP-7310) and the FFT analyzer (Ono Sokki, DS-2000). Figures 2(a) and 2(b) show the time evolution of the vibration acceleration for the $x$-direction on the top flange of the 18T-CSM (Position A in figure 1) and on the vibration-isolation table (Position B), respectively. The results for $y$- and $z$-directions are essentially similar to that for $x$-direction. The vibration noise is effectively reduced by the vibration-isolation table and the signal is almost similar level of the usual STM environment using the superconducting magnet cooled by the liquid helium. Figure 2(c) shows corresponding vibration spectra defined by the acceleration level $L_a = 20 \log(a/a_0)$, where $a$ is a root-mean-square of the acceleration signal and $a_0 (= 1 \text{ m/s}^2)$ a reference value. The vibration spectra shows sharp peak at 200 Hz; the frequency is considered to be the resonant frequency of 18T-CSM and is much larger than the driving frequency of the cryocoolers. Although the vibration acceleration is two orders magnitude reduced by the vibration-isolation table, small resonance peaks remain at 50 Hz and its higher harmonics.

Figures 3(a) and 3(b) show STM images of highly oriented pyrolytic graphite (HOPG) at room temperature in zero field. As shown in figure 3(a), the atomic resolution is strongly hindered by the vibration noise from cryocoolers when the vibration-isolation table is not active. However, the resolution is dramatically improved by the vibration-isolation table as expected from the vibration noise measurements, and STM image shows clear atomic arrangement with a lattice constant of 2.5 Å for HOPG (see figure 3(b)). Figure 3(c) demonstrates the STM atomic image at $H = 18$ T and the STM image is almost the same quality as the zero field data. The result indicates that the performance of STM measurements does not degrade in high fields and the stray field ($\sim 0.2$ T at the top part of the STM insert) does not affect very much on the preamplifier for the tunneling current signal. Thus, the STM results in this study have expanded the field-range for STM measurements beyond previous STM studies. In order to examine the stability of the STM head in the magnetic field, we performed continuous STM measurements in the field-sweep condition with a sweep rate of 18T/60min. In this condition, the magnetic

Figure 2. Vibration acceleration signal on (a) position A and (b) position B in figure 1. (c) Corresponding vibration acceleration level.
Figure 3. STM images of HOPG ($I = 0.1$ nA, $V = 200$ mV). (a), (b) $H = 0$ T, 23.6 Å × 11.8 Å. (c) $H = 18$ T, 35.4 Å × 35.4 Å. (d) $H = 7$ T (field-sweep condition), 54 Å × 54 Å. The vibration-isolation table is not active in (a), but is active in (b), (c), (d).

field changes $\sim 0.3$ T during a STM scanning for one image. Figure 3(d) shows the STM image at $H = 7$ T in the field-sweep condition. The deformation of the STM image is very small and the atomic arrangement is clearly resolved. These results indicate that the STM head developed in this study has a good stability in the scanning ($x, y$) and also feedback ($z$) directions even in the varying magnetic field.

In summary, we have developed high-field STM and succeeded in STM measurements with atomic resolution up to 18 T applied by the cryocooled superconducting magnet for the first time. Using the STM system, we are going to STM/STS measurements for HTSC in low temperatures. Since the STM system is compatible with the 30T-HM, we are planning to extend the possible field-range for STM/STS up to 30 T in the future.

Acknowledgments
This work was supported by Grant-in-Aid for Scientific Research on priority Areas “High Field Spin Science in 100T” (No.451) from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), and also by Grant-in Aid for Scientific Research from the Japan Society for the Promotion of Science (JSPS). The authors thank T. Hanaguri (RIKEN), A. Troyanovskiy (RAS) and T. Sasaki (Unisoku Co., Ltd.) for their valuable comments on STM design. We also thank K. Watanabe, S. Awaji, and G. Nishijima for supporting STM measurements in High Field Laboratory for Superconducting Materials, IMR, Tohoku University.

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