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Development of a new ULT Scanning Tunneling Microscope at University of Tokyo

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We describe design concepts and some technical details of a new ultra-low temperature scanning tunneling microscope (ULT-STM) which is now under construction at University of Tokyo. It is designed to work with an atomic resolution at temperatures down to 20 mK and in magnetic fields up to 6 T. It is possible to change samples and STM tips keeping ultra high vacuum and low temperature environments, which allows us to study almost all conducting materials and adsorbed samples.

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1. INTRODUCTION

Fukuyama *et al.*[1] made first an ultra-low temperature scanning tunneling microscope (ULT-STM) at University of Tsukuba, which works at a dilution refrigerator (D.R.) temperature range (T_{min} = 80 mK) with an atomic resolution. They observed superlattice structures caused by individual ^{4}He atoms adsorbed on graphite surfaces with this STM.[2,3] It is, however, not designed for operation in magnetic fields, and samples are restricted to layered materials with van der Waals interlayer bonding. Pan *et al.* built a low temperature STM based on a ^{3}He refrigerator (T_{min} = 240 mK) with a low temperature cleavage mechanism[4] to study impurity effects in high-T_c oxide superconductors.[5] Samples of their STM are also limited to cleavable materials.

In order to extend possibilities and applications for this powerful tool for low temperature experiments, we are currently constructing a new generation ULT-STM at University of Tokyo. This system has many outstanding features over the previous ones. For example, it is designed to work with an atomic resolution at temperatures down to 20 mK and in magnetic fields up to 6 T. Clean sample surfaces are prepared and characterized in an ultra high vacuum (UHV) chamber and then transferred to an experimental chamber keeping the UHV and low temperature environments. This feature allows us to study almost all conducting materials, ranging from exotic low T_c superconductors to low dimensional charge-density-wave (CDW) conductors, regardless of whether they are easily oxidized or cleaved. Monolayer samples adsorbed on various solid surfaces can be also studied, since the experimental space is isolated from vacuum for the D.R. In this paper, we describe design concepts, some technical details and future applications of this high performance ULT-STM.

2. INSTRUMENTAL DESIGN

Fig. 1 shows an overview of our ULT-STM system. The schematic diagram of its central part is shown in Fig. 2.

The STM head, which contains the sample, tip, scanner, Z coarse slider and XY coarse positioner, is located at the center of a superconducting magnet ($B_{max} = 6$ T) immersed in a liquid helium bath. Magnetic materials have been carefully eliminated from the head. The main body is made out of hard silver[6] and silicon silver[7] rather than copper or copper based alloys to prevent eddy current heating and large nuclear-spin heat capacities at very low temperatures and in high magnetic fields. In addition, they have better mechanical strength compared to pure silver. The whole STM head except the sample and tip is linked thermally to the mixing chamber (M/C) of the D.R.[8] through a copper rod with appropriate slits to avoid eddy current heating. On the other hand, the STM sample and tip are cooled by a special thermal link made of three sintered silver-powder heat exchangers packed in an epoxy capsule which is filled with liquid ^{3}He-^{4}He mixture. This link connects the sample to the M/C thermally, but not electrically to the ground. This arrangement should be important to improve the lowest operation temperature for the previous STM at Tsukuba.[1]

The maximum scan area is about 1.5 μm × 1.5 μm at the base temperature ($T = 20$ mK), while 4.5 μm × 4.5 μm at room temperature. The sample can be moved over a millimeter in XY directions with piezo motors. The Z coarse slider moves the scanner by a few millimeters vertically in piezo-electric “stick and slip” motion.

The experimental UHV chamber is isolated from that for D.R. by thin wall stainless steal tubes which are carefully designed to minimize heat leaks from higher temperature stages. The UHV environment in this chamber is maintained automatically at very low temperatures after closing the gate

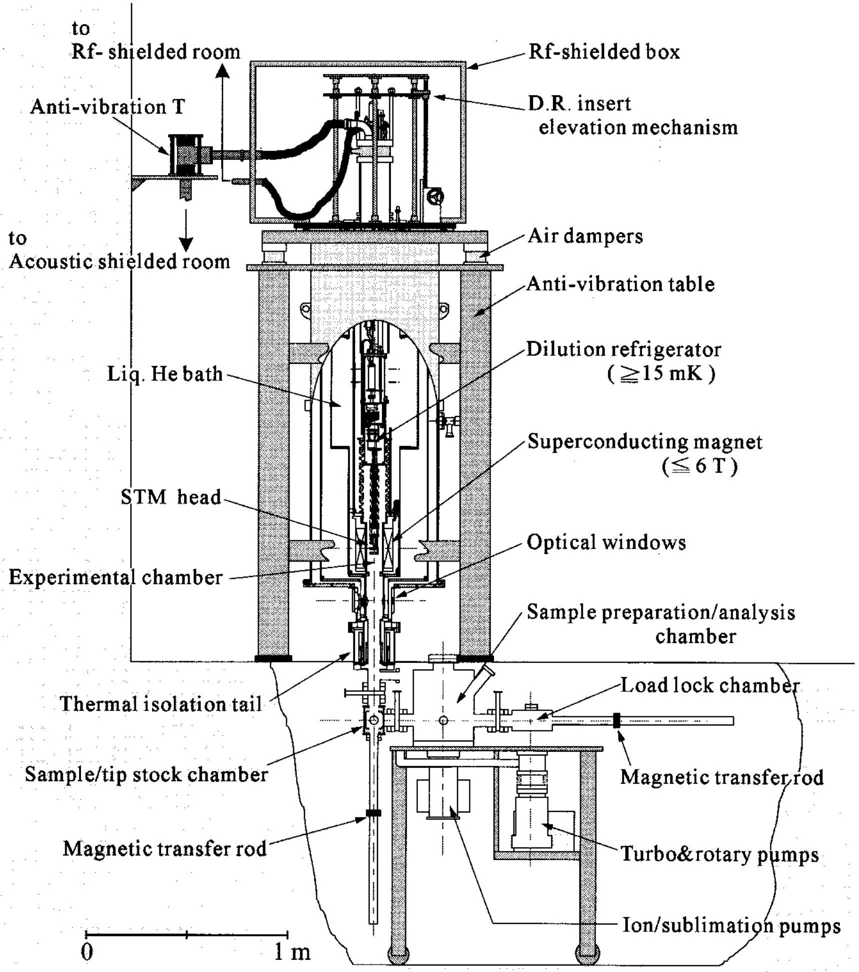

Fig. 1. Overview of the ULT-STM system. The UHV components are located in the experimental pit.

valve (see Fig. 2).

The sample and tip are transferred from the bottom of the cryostat by a magnetic transfer rod and then be screwed onto the STM head. Two radiation baffles are also screwed onto bottom flanges of the 4 K and 80 K radiation shields in the same way. The bottom loading configuration has several advantages over the ordinary top loading one. First, one can shorten the access length. Second, it is not necessary to use a specially designed D.R. except for a special dewar with a demountable tail.

The sample is prepared, characterized and stored in the UHV environment before being loaded to the STM head. The atomically flat and clean sample surface is prepared by the ion sputtering and resistive heating, if necessary, and then characterized by the low energy electron diffraction (LEED). The STM tip is sharpened by electron beam in the same chamber. In the stock chamber, an octagonal sample/tip holding cylinder stores eight samples, eight tips and two radiation baffles which are pre-cooled to about 5 K with a helium flow-type refrigerator (see Fig. 2). It is also possible there to cleave the samples at such low temperatures. Therefore, it takes only a few hours to cool the system back to the base temperature after changing the sample or tip. The stock chamber is a part of an anti-vibration T with soft welded bellows which isolates the experimental chamber mechanically from the rest.

For STM experiments, filtering out of mechanical and acoustic vibrations from external sources is one of the central issues. The D.R. is hung on an anti-vibration table with air dampers for mechanical isolation from the floor. It is also isolated from rotary pumps by inserting welded bellows into the pumping lines. The pumps are placed in an acoustic shielded room and are floated from the floor with rubber dampers. We do not install any additional vibration isolators for the STM head at low temperatures based on the previous experiences.[1] Instead, we installed a fixed impedance along the 1 K pot pick-up siphon, which bypasses the needle valve, to reduce mechanical vibrations caused at the needle valve.[1] The superinsulation dewar holds liquid helium for three days without refilling which produces large mechanical and acoustic noises.

3. EXTENSIBILITY

The STM head can travel by 260 mm from the center of the magnet to the tail section of the dewar due to the vertical elevation capability of the D.R. insert with a flexible UHV can (see Fig. 2). Because of this, our ULT-STM has wide extensibility. For example, we can carry out STM experiments

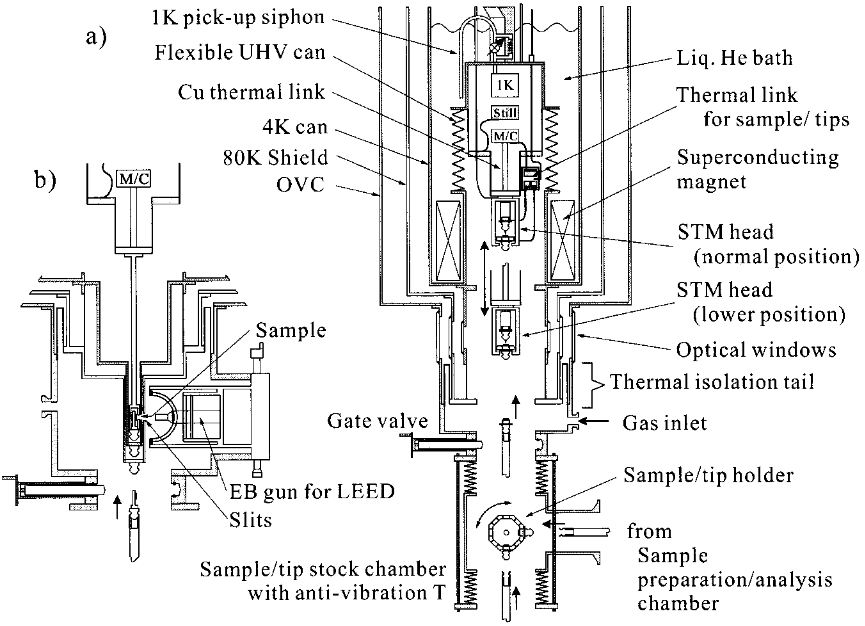

Fig. 2. (a) Schematic diagram of the central part of the ULT-STM with the optical window tail. (b) The LEED tail for surface diffraction experiments.

for sample surfaces excited by optical beams introduced through windows attached to the tail. Surface diffraction experiments can be performed below 0.5 K by replacing the optical window tail by another one with the LEED apparatus. In addition, one can fix troubles or make modifications on the STM head only by disassembling the tails not by lifting the dewar down. We can also implement the atomic force microscopy (AFM) capability into this system by using the needle sensor instead of the STM tip.

4. FUTURE APPLICATIONS

There are many future applications for this new ULT-STM. The behavior of adatoms on solid surfaces, especially helium atoms on graphite surfaces, is one of the main interests of us. It is possible to test the local deformation model[3] which was introduced to explain why helium atoms are visible with STM. We are planning to study crystalline structures and possible domain wall structures in ^{3}He monolayers in combination with the LEED measurements. These experiments will give us important information to understand novel two-dimensional nuclear magnetism in this system,[9] because the exact lattice structures are not known yet.

Various exotic superconductors with low T_c are also interesting. For instance, Sr_2RuO_4, a quasi two-dimensional conductor, and UPt_3, a heavy fermion system, are candidates of the spin-triplet superconductors which have $T_c = 1.5$ K and 0.5 K, respectively. Scanning tunneling spectroscopy studies near the quantum vortices in these materials are important to identify the symmetry of the wave functions of the cooper pairs.

The new ULT-STM will be ready for its operation in September 2000.

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