A Facility for Nanoscience Research: An Overview*

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ABSTRACT

We describe the development of an experimental system, consisting of a low temperature scanning tunneling microscope coupled to UHV tip and sample preparation chambers, with the goal of providing new measurement capabilities for the study of quantum and spin electronic systems on the nanometer scale. The physical information desired in such systems includes: the quantized electron energy distributions arising from spatial or magnetic confinement, the spatial extent of electronic wavefunctions, the role of electron-electron interactions in the presence of confining boundaries, the exact physical structure of the system, the shape of the confining potentials, and finally, the physics of electron transport on nanometer length scales. Additionally, we have incorporated a computer controlled facility for automated atom assembly to perform "bottom-up" fabrication of nanostructures. Some initial results will be discussed.

Keywords: STM, FIM, MBE, quantum systems, spin electronic systems

1. SYSTEM OVERVIEW

Several experimental challenges are posed in the study of electronic systems confined to nanoscale dimensions. Cryogenic temperatures are required to obtain high resolution in separating quantized energy level structures, ultra-high vacuum (UHV) is required to study samples without contamination, and scanned probe techniques are required to obtain measurements with atomic resolution. To meet these measurement challenges we have constructed a scanning tunneling microscope (STM), operating in the temperature range from 2-150 K, that is coupled to two molecular beam epitaxy (MBE) systems, and a field ion microscope (FIM) system for tip preparation, as shown in Fig. 1.

The systems are coupled through a rotary transfer chamber. The combination linear and rotary translator in this chamber acts as a lazy susan, enabling samples and tips prepared in the auxiliary chambers to be transferred into the STM without ever removing them from the UHV environment in which they were prepared and initially characterized. A load lock chamber allows the introduction of new tips and samples without breaking vacuum on the rest of the system.

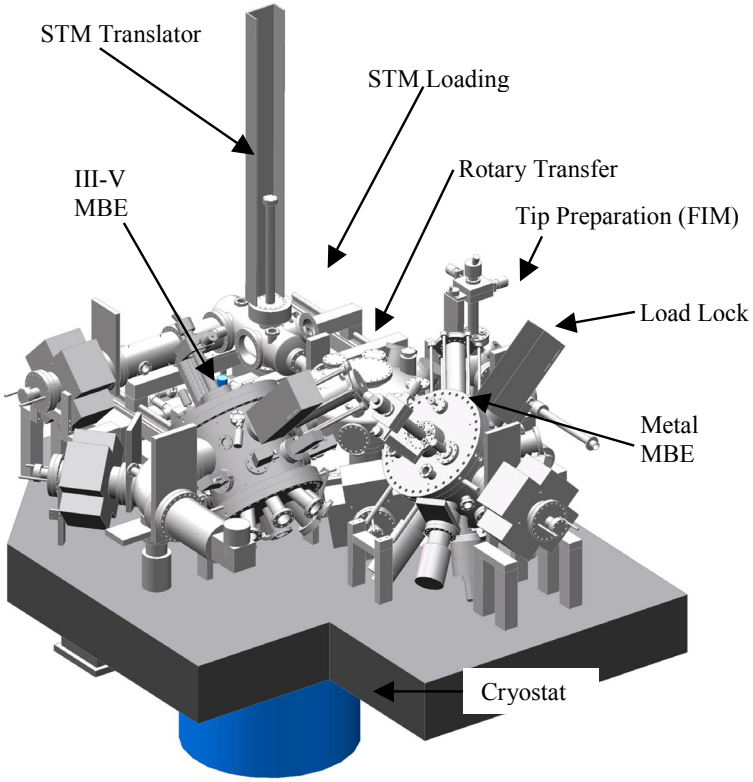

Figure 1: CAD drawing of the Nanoscience System.

2. MICROSCOPE

The microscope is a self-contained module (Fig. 2), milled out of two solid pieces of Mo in order to assure rigidity, high thermal conductivity, and insensitivity to any applied magnetic fields. Coarse positioning between the tip and sample are controlled in all three dimensions, driven by piezo activated motors. Such motors allow movement in approximately 30 nm steps both at low temperatures and room temperature (easily controlled by adjusting the drive voltage), and with adjustable step rates of ~ 100 Hz, can move the walker over its full range of several millimeters in about 10 minutes. Such a design also has the advantage that it holds the tip and sample rigidly when not in use, thus reducing possible vibration modes. A piezo tube based scanner is used for fine motion, allowing a 0.5 μm range of z-motion and a square lateral scan range of 1.5 μm.

Also present in the head are optics, designed to allow visualization of the tip-sample separation from above, when the STM is locked into the cryostat for operation. The lateral position of the tip relative to the sample is easily visualized through a hole in the STM head just above the tip.

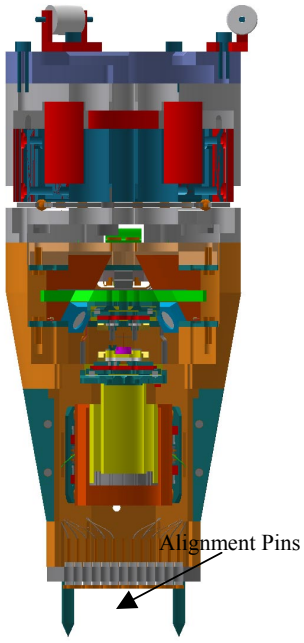

Figure. 2: CAD drawing of microscope body (cut-away view).

3. CRYOSTAT AND MAGNET

While in UHV, the STM is translated between room temperature, where tips and sample are exchanged, and the cryostat, where measurements are made, using the STM translator (Fig. 1). When lowered into the cryostat, the STM is locked into a copper cone which is cooled via He exchange gas to isolate it from the boiling He. A sample temperature of 4.3 K is reached in our design when cooling with 4.2 K He, and an ultimate temperature of 2.3 K can be reached by pumping on a lambda refrigerator in the lower part of the cryostat. Also mounted in the cryostat are two high field magnets. A solenoid can produce fields up to 10 T normal to the sample surface, and a Helmholtz coil can produce a rotating vector field of up to 1.5 T.

4. VIBRATION ISOLATION

Three stages of vibration isolation and an acoustic isolation room serve to isolate the microscope from external noise sources. The first stage, an active isolation system, effectively dampens transmission of building vibrations between the floor and the table on which the entire system is mounted. The second vibration isolation stage consists of three passive piston isolators, which isolate the main experimental table from the cryostat. The final isolation stage consists of internal piston isolators that separate the cryostat from the tube into which the STM is locked, thus reducing transmission of vibrations from the boiling liquid Helium. In all, 100 dB of isolation is achieved by 20 Hz, with the roll-off continuing rapidly above that frequency. During operation, only ion pumps and their controllers remain powered in the shielded room, while operations are performed from an adjacent control room.

5. SAMPLE PREPARATION

Equally challenging to the measurement methodology is the fabrication of quantum electronic systems. The STM is part of a facility that includes separate MBE fabrication systems for III-V semiconductor growth and magnetic and superconductor (metal) material growth. All sample mounts are equipped with ceramic heaters capable of annealing the samples to over 1200 ºC. Each MBE chamber is equipped with a pyrometer in order to monitor substrate temperature during annealing and sample growth. Each chamber is also equipped with a reflection high energy electron diffraction (RHEED) system, useful both for monitoring the surface crystalline integrity and alignment of samples and for measuring and maintaining the rate of epitaxial growth. In addition, the metal chamber is equipped with an Auger system, used for checking the chemical composition of the sample surface. This is particularly valuable in conjunction with the Ar-ion sputter gun, used for cleaning of samples which are introduced from air, in order both to know when the sample is clean and whether any preferential sputtering is unintentionally modifying the surface chemistry.

After samples are cleaned or grown they are transferred to the STM chamber through the rotary transfer chamber, remaining continually within a UHV environment. Typically less than one hour passes between the time at which the final sample cleaning and annealing is performed and the time at which the sample is inserted into the STM and locked into a cryogenic environment, ensuring that the sample remains clean for months of study.

6. TIP PREPARATION – FIELD ION MICROSCOPY

In addition to a suitable sample for study, STM requires the use of a suitable tip. In many STMs, little or no characterization is performed on the tip before using it in the instrument. In order to produce useable tips more reliably, we have created a recipe for preparing and characterizing tips at room temperature before they are inserted into the instrument. Initial sharpening of the tip wire – (111) oriented tungsten – is performed by etching in a KOH solution, using the ring method beneath an optical microscope to obtain a sharp shank.

These tips are then introduced into the tip preparation chamber through the load lock. We begin UHV preparation by heating the tip with an e-beam heater in order to remove surface oxides. We then insert the tip into a field ion microscope, where a bias of several kilovolts is applied to the tip. An imaging gas (He) is introduced into the chamber, and the resultant field ionization pattern, as shown in Fig. 3, is imaged using a microchannel plate. This technique has several benefits. First of all, it allows further cleaning of the tip via field evaporation. Secondly, both the overall sharpness of the tip may be measured, as indicated by the number of rings between different crystal planes (appearing as circular centers), and the particular configuration of the atoms at the very end of the tip (in the case of Fig. 3, a trimer), may be determined.

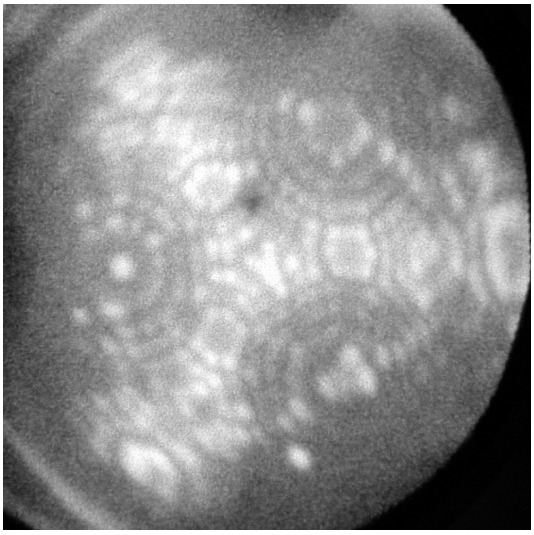

Figure 3: FIM image of a W (111) tip that has been heated to remove surface oxides and then sharpened by field emission.

7. EXPERIMENTAL GOALS AND RESULTS

The initial projects planned for the Nanoscience facility include the study of magnetic impurities in non-magnetic host materials, the study of spin polarized tunneling effects in superconductor-ferromagnetic systems, and the study of confined electron systems, such as in quantum hall devices. Initial testing of the system was a two part process, performed on two different systems. First of all, topographic imaging and lateral stability were tested by imaging a Cu (111) surface. In addition to obtaining atomic resolution (Fig. 4), we also made use of the fact that the noble

metal (111) surfaces contain a 2D surface state that has a partial band gap in the surface Brillion zone. STM images of this surface display constructive interference produced by the scattering of the surface state electrons from step edges and defects, as shown in Fig. 5.

To test the spectroscopic capabilities of our instrument we coated the end of a W (111) tip with Nb and performed SIS tunneling into a Nb sample (Fig. 6). This produces a spectrum with very sharp peaks, and by limiting the effects of thermal broadening on the differential conductance, allows a good check of any noise sources. The spectrum of Fig. 6 was obtained using a standard lock-in technique, and indicates that any broadening due to noise sources is below the driving modulation voltage of V_{mod} = 100 μV.

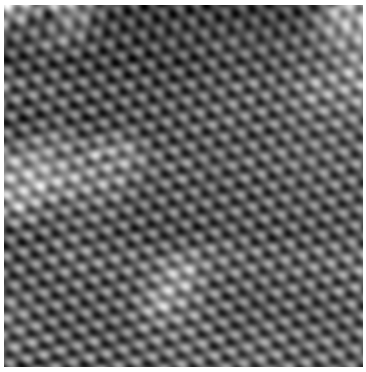

Figure 5: Atomic resolution STM topograph, 6 nm square, of a Cu(111) surface, imaged at 4.3 K. The grayscale range corresponds to 20 pm.

Figure 6: STM topograph, rendered in 3D, of a 50 nm square portion of a Cu(111) surface showing constructive interference produced by the scattering of the 2D surface state from step edges and defects.

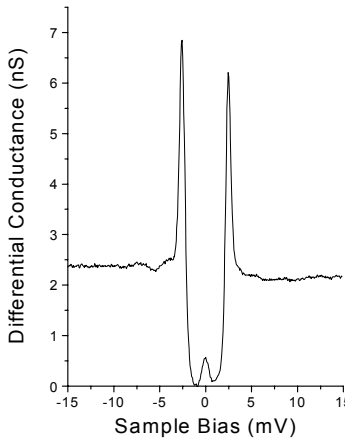

Figure 4: Differential conductance spectrum obtained at 4.3 K for tunneling between a Nb covered tip and a Nb sample.

We also performed initial testing of atomic manipulation, by moving Co atoms on a Cu (111) surface. This test, some of which is shown in Fig. 7, is part of a larger project to develop an autonomous atom assembler, capable of fabricating large scale quantum structures atom-by-atom.

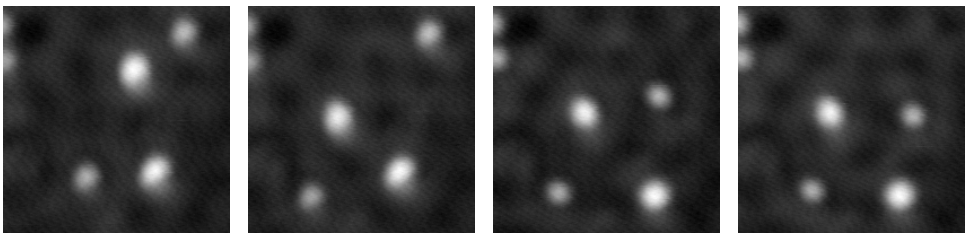

Figure 7: STM topographs showing the capability of an STM to move Co atoms and dimers (brighter) on a Cu (111) surface into any desired shape (here a square).

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