Brief Reports

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Ballistic-electron emission into vacuum from a scanning-tunneling-microscope tip through free-standing gold films

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We report an experimental setup of the ballistic-electron-emission microscope (BEEM) that is applicable to the study of thin free-standing metal films and metal-vacuum interfaces. We have used the technique to obtain spatially averaged BEEM spectra of thin free-standing gold films. Using such a spectrum, we obtained a rather coarse value of the work function for gold, which is compatible with some other reported values.

Ballistic-electron-emission microscopy (BEEM) was developed by Kaiser and Bell in 1988 for the study of buried interfaces.[1] In the original application of the technique, they measured the Schottky barrier heights and the variation of Schottky barrier heights over the gold-semiconductor interfaces. Since then, the technique has been applied to many different systems. One simple system to which the BEEM can be applied is the metal surface itself. This can be achieved by having the tip of a scanning-tunneling microscope (STM) inject energetic electrons into a thin free-standing metal film (base) in a vacuum ambient. A fraction of these electrons will traverse through the film without scattering, and then will impinge on the opposite surface of the free-standing metal film. If the energy of these electrons is larger than the work function of the metal, some of these impinging electrons will enter into the vacuum. These electrons can be detected by the use of an electron multiplier. By studying the dependence of the emitted electron current (that is, the collector current) on the tunnel bias voltage, one can learn many different properties of the metal film, with high spatial resolution. For example, by measuring the threshold tunnel bias voltage at which the collector current appears, one can obtain the work function of the metal. The area involved in such a measurement can be as small as a few nm^2.[1] Although the idea behind this experiment is straightforward, the actual implementation is far from being simple. One major challenge is to prepare free-standing thin films that are thin enough to give a reasonable ballistic electron transmission, and yet strong enough to withstand STM experimentation. In this Brief Report, we report a successful utilization of the BEEM technique on thin free-standing gold films.

One might wonder that simply using an STM would be superior for the study of surfaces. Although the STM yields higher spatial resolution, there are situations where the presence of the tip at close proximity to the sample can create complications.[2–4] For example, work function (or barrier height) measurements that were performed previously by using an STM most often yielded anomalously low values.[5] The BEEM technique that is implemented as described in this paper can yield measurements that are free of some artifacts that often complicate the STM measurements.

This experiment was performed in a stainless-steel vacuum chamber that was pumped by a 270 l/s Varian ion pump. The STM that was used was a homemade one, and it was designed around a single tube scanner.[6] The tip was mounted on the tube scanner, while the sample was mounted at the end of a piezoelectric bimorph. The bimorph had a range of motion of about 60 μm for an applied voltage range of ± 100 V. The coarse-tip-sample approach was done by using an 80-pitch screw, and the final positioning was done by applying a voltage to the bimorph. In our current preliminary setup, sample mounting and coarse-tip positioning were done while the STM was outside the vacuum chamber. Then the STM was loaded into the chamber and afterwards, the chamber was evacuated. The base pressure was limited to 10^{-8} Torr range.

The samples that were used were free-standing gold films of various thicknesses. They were supported on copper grids that are typically used in transmission electron microscopy. The films that we prepared had thicknesses ranging from 17 to 80 nm. To prepare the free-standing films, first, gold was evaporated onto the (100) face of NaCl crystals. The thicknesses of the gold films were controlled during the evaporation by using a quartz crystal rate meter. Then, the NaCl substrate was dissolved in a 50-50 mixture of distilled water and ethyl

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alcohol. At the end of this procedure, the films floated onto the surface of the solvent. These films were caught onto the copper grids. To reduce the NaCl residues on the films, the films were rinsed again. In this way, we were successful in preparing free-standing gold films as thin as 17 nm. Inspection by optical microscopy and by transmission electron microscopy revealed that the free-standing thin films that were prepared in this manner were free of holes and ruptures. Grains of sizes up to a few tenths of a micrometer could be seen on these films. By annealing the free-standing films, we could increase the grain size and also improve the bonding between the Cu grid and the films. These films were rigid enough to be imaged by an STM, even though the STM operation on these free-standing thin films were generally noisier compared to the STM operation on typical samples. We will present further details of the film preparation and characterization elsewhere.

A channel electron multiplier (CEM) was mounted on the STM for the purpose of detecting the emitted electrons, thus completing our BEEM apparatus. The free-standing thin film samples (bases) were mounted between the STM tip and the channel electron multiplier (CEM) as seen on the sketch of the experimental arrangement in Fig. 1. The CEM, whose entrance aperture was 3-mm in diameter, was located about 1 mm behind the sample. The CEM had a gain exceeding 5×10^7 and a typical dark current of 0.1 counts/s. The complete detector system could track a maximum count rate of over 10^6 counts/s. The output pulses from the CEM detector were counted by a computer-controlled counter for a predetermined period, typically 10 msec.

By using our apparatus, we obtained the BEEM spectra for thin, free-standing gold films. We did this by ramping the tunnel bias (the tip, negative) from the 0.3-V starting value up to about 10.5 V in 128 increments. At the end of the each increment, we counted the pulses from the CEM for 10 msec. The spectra so obtained displayed considerable variations with time and sample position.

Such variations in the spectra are not surprising given the known sensitivity of the electron emission phenomena to the surface conditions. We did not perform any sample cleaning after the samples were loaded into the chamber, and the lowest chamber pressure was in the range of 10^{-8} Torr. Thus, various contaminants were

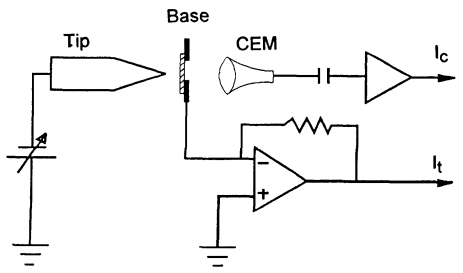

FIG. 1. Schematic diagram of the experimental setup. I_c denotes the collector current measured as number of pulses per second. I_t denotes the tunnel current.

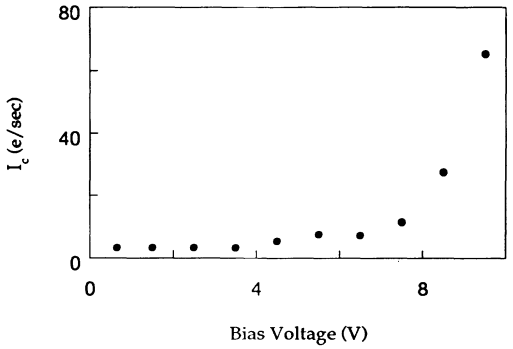

FIG. 2. A plot of the collector current I_c averaged over a scan area of 375×375 nm^2 against the tunnel voltage. The sample was a 60-nm thick, free-standing gold film.

inevitably present on the sample surface. Further, under the tunnel biases of a few volts, nanostructures of contamination could be formed in the tunnel vicinity.[7] Such structures could scatter the tunneling electrons.

Rather than changing the experimental setup in search of improved cleanliness of the experiment, at this stage, we opted to measure spatially averaged BEEM spectra. Figure 2 shows such a measurement. Here, we scanned an area of 375×375 nm^2, in the constant current mode at different tip biases. After every 3.75 nm, we paused for 10 msec, while counting the output pulses from the CEM, thus collecting 10 000 values of collector currents. Finally, the average of those 10 000 collector current values was plotted against the tunnel bias. The sample was a 60-nm-thick free-standing gold film. The tunnel current was about 1 nA. As can be seen from Fig. 2, until 3.5 V, the count rate stays small and independent of the tunnel bias. This value signifies the background counts which are mainly due to the charged particles originating from the ion pump. This background count rate is fairly constant as evidenced from the figure. At 4.5 V, the count rate clearly exceeds the background indicating that the electron emission has begun. For biases larger than 4.5 V, the collector current (count rate) keeps on increasing systematically with the bias. From this data, we can conclude that the lowest value of the work function that is found in this 375×375-nm^2 area is 4 ± 0.5 eV. The value of the work function of gold, as listed in modern references, is around 5 eV.[8] However, this value of work function was obtained under UHV conditions (ambient pressure below 10^{-9} Torr), on clean surfaces.[8,9] The values of the work function of gold, that were not measured under such strict UHV conditions, are listed in older references to be somewhere from 4 to 4.92 eV.[10,11] Thus, it is not unreasonable that we obtained a value close to 4 eV for the work function of our gold film.

In conclusion, we have succeeded in obtaining ballistic electron emission into vacuum from an STM tip by using thin free-standing gold films as samples. By using the threshold voltage for electron emission, we have obtained a somewhat crude measurement of the work function of gold thin films. The method can be developed into a novel way to measure work functions of different metals, and

their variations with very high spatial resolution. Other possible applications of this method are in the study of the band structure of metals and in the study of energy-loss spectra of metals. The use of this technique for imaging, analogous to transmission electron microscopy, is also a possibility.[1]

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[1]W. J. Kaiser and L. D. Bell, Phys. Rev. Lett. **60**, 1406 (1988).

[2]G. Binnig, N. Garcia, H. Rohrer, J. M. Soler, and F. Flores, Phys. Rev. B **30**, 4816 (1984).

[3]N. D. Lang, Phys. Rev. **37**, 10 395 (1988).

[4]J. M. Soler, A. M. Baro, N. Garcia, and H. Rohrer, Phys. Rev. Lett. **57**, 444 (1986).

[5]J. H. Coombs and J. B. Pethica, IBM J. Res. Dev. **30**, 455 (1986).

[6]G. Binnig and D. P. E. Smith, Rev. Sci. Instrum. **57**, 1688 (1986).

[7]E. E. Ehrichs, S. Yoon, and A. L. de Lozanne, Appl. Phys. Lett. **53**, 2287 (1988).

[8]*Handbook of Chemistry and Physics,* 74th ed., edited by D. R. Lide (CRC, Ann Arbor, 1993), p. 12-105.

[9]D. E. Eastman, Phys. Rev. B **2**, 1 (1970).

[10]*Handbook of Chemistry and Physics,* 57th ed., edited by R. C. Weast (CRC, Ohio, 1976), p. E-81.

[11]N. W. Ashcroft and N. D. Mermin, *Solid State Physics* (Saunders, Philadelphia, 1976), p. 364, Table 18.1.