RAPID COMMUNICATIONS

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Ultrahigh vacuum scanning-tunneling microscope for *in situ* studies of annealing and electromigration behavior of thin films

G. Reiss, L. E. Levine, and D. A. Smith[a)]
IBM T. J. Watson Research Center, Yorktown Heights, New York 10598

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High resolution *in situ* imaging of metal surfaces during annealing and/or current transport is of great interest both for the application of metal lines in electronic devices and for extending our basic knowledge of the related complex physical phenomena. Due to its high resolution, the scanning tunneling microscope (STM) is a promising tool for *in situ* investigations of the structural changes of metals with respect to temperature (annealing) and current transport (electromigration). In this article, the instrumental modifications necessary for *in situ* scanning tunneling microscopy of heated and/or current carrying thin films under ultrahigh vacuum conditions are discussed. Using results obtained on Ag films, the ability of our STM to image the surface dynamically is demonstrated, while structural changes induced by the current transport are taking place.

I. INTRODUCTION

Annealing treatments as well as high current densities usually cause structural changes in polycrystalline metallic films. In the case of annealing, these modifications are due to the minimization of surface, grain boundary, and interface energies of the film. In current carrying thin films, the electric field and the related flow of electrons create additional forces which result in a directed flow of material (electromigration). This mass transport along with thermal gradients cause stress gradients in the films, which can counteract or enhance the migration of the material. For recent reviews of the related problems see, for example, the discussions given by Ho and Kwok[1] or Scorzoni *et al.*[2]

Due to the complexity of these phenomena, current theories fail to make even qualitatively correct predictions for many experimental results. This lack of basic understanding is particularly true for electromigration in polycrystalline films and lines.[2] In this case, one has to consider three different diffusivities (bulk, grain boundary, and surface), the sizes and orientations of the grains, the dimensions of the investigated structures, and the role of second phase precipitates. The importance of these factors varies for different temperature and current density regimes. As a simple example of this lack of understanding, hillocks and voids in lines are correlated with triple points, yet it is not possible to accurately predict such damage sites in polycrystalline materials.[3]

Microscopic studies of the structural changes that occur during heat or current treatment are, therefore, important for the basic understanding of the related physics as well as for the application of thin films and lines in electronic devices. To date, most of the experimental work on electromigration has used a combination of statistical median time to failure (MTF) analysis with subsequent *ex situ* scanning electron microscopy (SEM) or transmission electron microscopy (TEM).[4,5] Only a small number of publications reported microscopic *in situ* studies of electromigration with the SEM[3] or TEM.[6] *In situ* microscopic studies, however, allow continuous monitoring of the electromigration process and promise to provide new insights into the observed structural modifications. Since divergences in the mass flow are caused by microscopic structures (e.g., triple points), a very high resolution is mandatory.

SEM and scanning tunneling microscopy (STM) seem to be especially appropriate for this purpose. The established *in situ* SEM technique offers both large scale and microscopic imaging with a resolution down to about 10 nm. *In situ* STM gives the opportunity of imaging the surfaces with a resolution well below 1 nm and provides quantitative height profiles. Up to now, however, there are no published reports of *in situ* STM studies of electromigration in thin metal films. We are in communication with a research group, however, that is currently working on in-air STM studies of electro-migration in Au films.[7]

In this publication, we first discuss the modifications we made on a conventional STM to enable imaging on heated, current carrying thin films. Using results obtained on Ag films in ultrahigh vacuum (UHV), we then demonstrate the possibility of imaging structural changes while the film carries large current densities.

II. INSTRUMENTAL

An experimental setup for STM studies on current carrying thin films has to take into account two main difficul-

[a)]Present address: Stevens Inst. Technol., Dept. Mater. Sci. Eng., Castle Point on the Hudson, Hoboken, New Jersey 07030.

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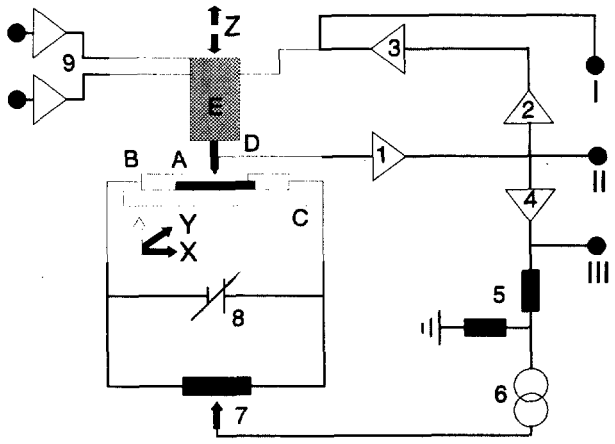

FIG. 1. Diagram of the instrumental setup of our UHV-STM. The STM stage includes the Ag film (a), contacts (b), mica substrate (c), tunneling tip (d), single tube scanner (e), and inchworms (directional arrows). The electronic circuit consists of a current to voltage converter (10^8 V/A dc amplification, 10^7 V/A at 7 kHz) (1), band pass and rectifier (2), proportional/integral feedback and high voltage amplifier (3), integrator (5 ms) (4), divider 1:1000 (5), ac voltage source (7 kHz) (6), potentiometer (bridge attenuation) (7), floating dc voltage source (8), and the amplifiers for the X–Y scan voltages (9). The outputs are the topographic signal (z voltage) (I), the total tunneling current (II), and the local potential (1000:1) (III).

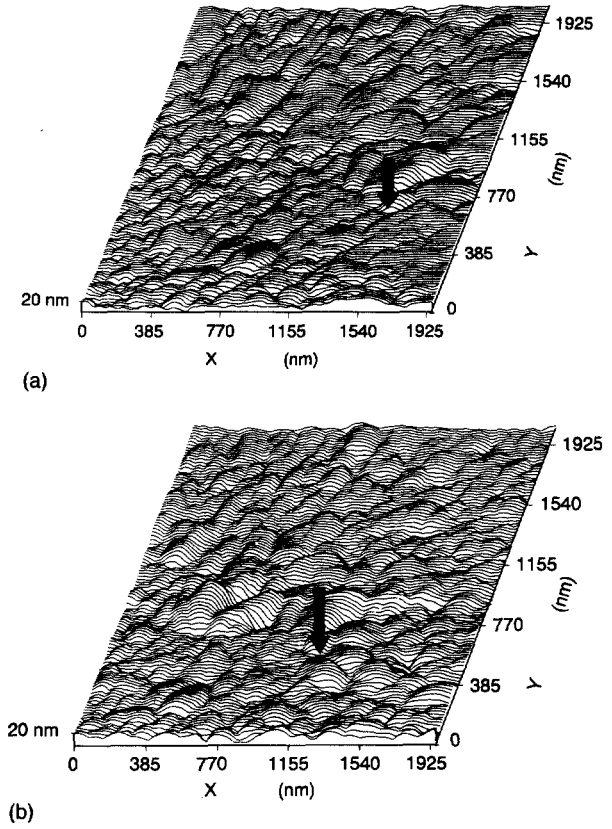

FIG. 2. (a) Large area scan of the as deposited Ag film on mica. (b) Topography of approximately the same area after six days and an increase in current density to 3×10^4 A/cm^2. The arrows mark the same location for easier orientation.

ties. First, due to the current flow and optional additional heating, the temperature difference between scanner unit and sample may change by up to some hundred Kelvin during a scan series. Since the thermal expansion coefficients are typically of the order of 10^{-6}/K and the typical STM dimensions are some centimeters, the resulting drifts are expected to be considerably larger than 1 μm. This is out of the range of conventional scanner units. Second, due to the voltage drop over the sample, the tunneling current cannot be obtained in the usual manner, i.e., by applying a direct-current (dc) voltage between tip and sample.

In order to overcome the problems caused by the thermal drift, we used a custom designed commercial UHV-STM. In this setup, the single tube scanner unit is mounted on an inchworm which provides controlled motion of the whole scanner with a range of some millimeters and a nominal resolution of 2 nm. This z inchworm is used for the coarse and fine approach of the tip and for the compensation of z drifts. The sample holder is mounted on a stack of two additional inchworms providing a net coarse motion of the sample relative to the tip in x and y direction with an accuracy of about 0.5 μm.[8]

Compared with conventional STMs, this setup gives rise to an enhanced sensitivity to noise despite the use of a pneumatically damped table as a base for the UHV system. After considerable modifications to the stiff electrical wiring of the STM stage, the amplitude of the vibrational noise was reduced to about 1.5 Å.

The second main difficulty is the electric field needed to drive current through the films; for most samples these fields are typically a few volts per centimeter. Since the resulting local potential varies across the surface, the dc voltage drop over the sample cannot be used simultaneously for tunneling. The electronic circuity we built for our STM is, therefore, similar to that used for potentiometric STM investigations.[9,10] Figure 1 shows a diagram of our setup.

Whereas the rectified alternating-current (ac) component (7 kHz) of the tunneling current is kept constant by a conventional feedback (proportional/integral amplifier), the dc component is integrated. The output of the integrator plus the ac tunneling voltage serves as reference for the floating dc voltage used for obtaining the sample current. This setup basically corresponds to a tunable Wheatstone bridge and allows for simultaneous measurements of the topography and the potential on current carrying thin films. Identical circuitry gave a resolution of the potential of about 5 μV for electric fields of 10 V/cm.[11]

III. EXPERIMENTAL RESULTS

As a demonstration of the performance of our STM, Fig. 2 shows two large scale (2 μm$\times$2 μm) images of the surface of a 2100 Å thick Ag film obtained under UHV conditions. This film was grown by thermal evaporation on mica at room temperature.

Since the topography of the film did not change for current densities j_F smaller than about 1.6×10^4 A/cm^2, the image shown in Fig. 2(a) was taken at this value of j_F. The topography of the Ag film [Fig. 2(a)] corresponds well with previously published STM images of Ag on mica

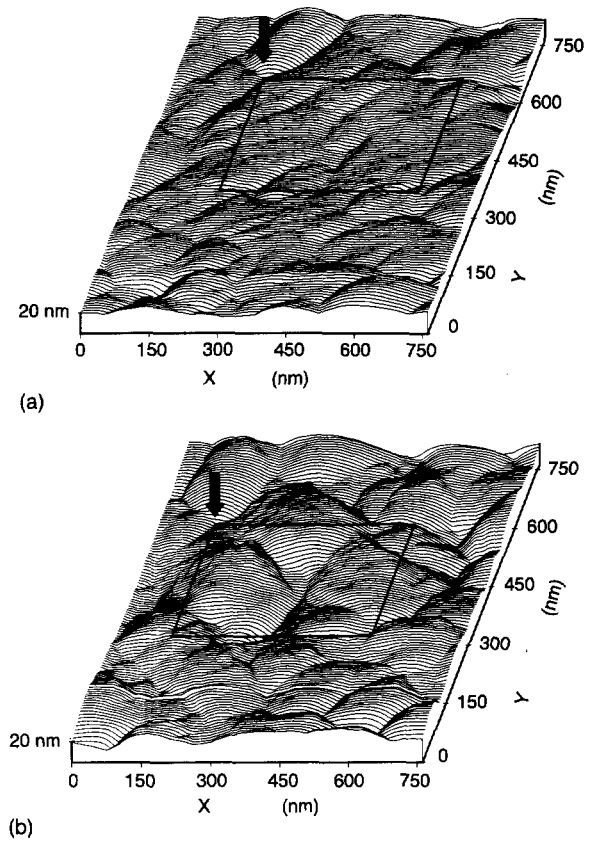

FIG. 3. (a) Smaller scale scan of a section of the topography shown in Fig. 2(a). (b) The same area as shown in (a) after eight days and structural modifications due to the current transport and the related joule heating. The sample current density was 4.4×10^4 A/cm^2. The squares mark identical locations and the arrows correspond to the position marked in Fig. 2.

grown under comparable conditions.[12] The image shown in Fig. 2(b) was taken approximately six days after the scan in Fig. 2(a). During this time, the dc current density flowing through the Ag film was gradually increased to 3×10^4 A/cm^2. Although the temperature of the film increased only by about 5 °C due to the joule heating, considerable effort was necessary in order to follow the same imaging area. Since the mica substrate is relatively flexible and additionally has a significantly lower coefficient of thermal expansion than the Ag, the thermal drift was much smaller than the movements caused by the buckling of the bimetal-type combination of (heated) Ag film and mica. In order to compensate for the resulting relatively large displacements between tip and original surface area [Fig. 2(a)], the inchworms had to be used frequently between subsequent scans. It was nevertheless possible to follow the image area during the six days between Figs. 2(a) and 2(b) with an accuracy of better than 0.4 μm [see, for instance, the corresponding corrugations marked by arrows in Figs. 2(a) and 2(b)]. Stiffer substrates will be used for future investigations.

Since the maximum scan range of the single tube scanner is 2 μm, small scale scans of certain areas of interest could be taken and compared in order to obtain detailed information about the changes in the surface topography visible in Fig. 2(b). Figures 3(a) and 3(b) show an example of such changes. The image in Fig. 3(b) was taken eight days after the scan in Fig. 3(a); the current densities and temperatures were 1.6×10^4 A/cm^2 and 26 °C for Fig. 3(a) and $j_F=4.4\times10^4$ A/cm^2 and 35 °C for Fig. 3(b). The increase of the current density in the film was accompanied by striking modifications of the surface topography. The relatively smooth area marked by a square in Fig. 3(a) is changing into a triple point arrangement in Fig. 3(b). This change was accompanied by extensive grooving of the grain boundaries. Although this modification appears to be an example of classical thermally induced crystal growth in a fiber-textured (111) Ag film, the increase of the temperature due to the joule heating was far too low to justify this interpretation. We, therefore, suggest that the current flowing through the film together with the relatively high surface and grain boundary mobility of the Ag atoms initiate the structural modifications shown in Figs. 3(a) and 3(b). This implies that electromigration can have a significant influence on the thin film microstructure even at relatively low temperatures. Detailed reports of the annealing and electromigration behavior of the Ag films will be published elsewhere.[13]

Potentiometric measurements were attempted, but since the voltage drop was smaller than 0.5 V/cm, it was not possible to obtain worthwhile potentiometric information on the Ag films. Further experiments on combined topographic and potentiometric imaging of current carrying thin lines are in progress.

IV. CONCLUSIONS

In summary, we discussed the instrumental setup of a UHV-STM used for *in situ* investigations on heated and/or current carrying thin films. Two major problems were overcome. The first difficulty is the thermal drift which can be handled using an arrangement of three inchworms in addition to the single tube scanner. The second problem is the decoupling of the STM electronics from the dc voltage drop over a current carrying sample. This problem can be solved by using a potentiometric STM design, which involves basically a Wheatstone bridge arrangement and a feedback responding only to selected ac components of the tunneling current.

Early results demonstrated the feasibility of this STM application. Even under extreme conditions (i.e., imaging an Ag film on a flexible mica substrate), the position of the tunneling tip can be kept well within the limits of conventional single tube scanners while increasing the temperature and/or the current density. Using an example of grain boundary grooving, we demonstrated the capability of imaging topographical changes *in situ* during the increase of the temperature and/or the current density.

A deeper understanding of annealing and electromigration processes in thin films and lines is important both for the electronic applications and for extending our basic knowledge of these complex phenomena. We have demonstrated that our new STM system is capable of obtaining high resolution data that are unobtainable using any other available technique. We believe that such information will

prove invaluable in future studies of these important physical processes.

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