H.D. Hallen and R.A. Buhrman, "BEEM, A probe of nanoscale modifications," *Atomic and Nanometer-Scale Modification of Materials: Fundamentals and Applications*, edited by Ph. Avouris (Kluwer, Dordrecht, 1993).

BEEM: A PROBE OF NANOSCALE MODIFICATION

H. D. HALLEN
Physics Division
AT&T Bell Laboratories
600 Mountain Avenue
Murray Hill, NJ 07974
USA

R. A. BUHRMAN
School of Applied and Engineering Physics
212 Clark Hall
Cornell University
Ithaca, New York 14853
USA

ABSTRACT. Hot electrons injected by a scanning tunneling microscope (STM) tip with a few volts tunneling bias scatter and modify a gold film not only at the top surface of the film, but throughout the film and at the inner or interfacial surface. The ballistic electron emission microscopy (BEEM) measurement technique is a powerful method with which one can probe such modifications. In particular, the production of adatoms and their subsequent coagulation into atomic terraces on the inner surface of the gold is demonstrated. Quantitative measurements of the adatom production rate are in good agreement with that predicted by a model including bond breaking by the hot electrons. The stability of the created structures is shown to be related to the physical properties of the gold film.

1. Introduction

Traditionally the Scanning tunneling microscope (STM) has been used as a surface sensitive instrument, with little concern for the fate of the electrons once they have entered the sample. Recently, with the innovation of ballistic electron emission microscopy (BEEM) [1], the power of STM-related techniques for the study of buried interfaces has become apparent. We use the BEEM technique as a tool to study the subsurface modifications of a thin metallic film. Hot electrons injected by the STM tip are used to produce the modifications. This paper will focus on modification of a gold film deposited on silicon. A carbon-based passivation layer lies between the film and substrate.

The types of hot electron induced effects can be grouped into two categories: those that occur at a surface and those in the bulk of the film. Examples of each type are seen. By surface we refer to the outside of a grain: the top surface is the side of the grain scanned by the STM; the inner surface is opposite, i.e. at the interface of the gold and silicon; the grain boundaries are lateral surfaces which can be important during grain growth. At surfaces, the hot electrons induce the formation of adatom-vacancy pairs. The adatom is a gold atom which has moved out onto a surface. It may combine with other adatoms to form a terrace or diffuse to a sink such as a step edge, vacancy or grain boundary. The vacancy diffuses into the film. We have observed[2-4] terrace growth on the inner surface, grain growth on the lateral surfaces, and mound growth on the top surface of the films. The stability of the structure is found to depend strongly on the properties of the gold film.

The hot electrons can scatter from vacancies once they are in the bulk of the film. This can result in an enhanced, non-thermal motion of the vacancies. We have observed[2-4] the creation of large areas of defect-filled film. Such areas strongly scatter even lower energy electrons. The system begins to react to the induced changes even while still under hot electron bombardment, and continues after the stress is removed. The reaction of the system can be a measure of the stability of the structures which were created, but also can reflect further development of the structures. One example of the latter occurs when several layers of terraces have been grown on the inner surface of the gold film, bringing the gold into contact with the silicon. As has been well documented[5], silicon will diffuse into a gold film evaporated into intimate contact with it, provided that the terrace is large enough. The resulting gold-silicon alloy scatters all electrons strongly. The resultant structure is very stable. A benefit of the BEEM technique is that the stability of bulk and subsurface interfacial structures can be observed in addition to changes of the film topography. Correlations between topography and subsurface properties can be used to understand the mechanism by which mounds on metal surfaces are formed, and what parameters are important in their decay. We believe that the BEEM technique will also be of aid in understanding other systems.

2. Experimental Technique

The sample preparation has been described elsewhere[3]. In brief, a few monolayer thick carbon-based passivation layer is deposited on a prepared silicon surface, followed by evaporation of a 150 Å thick gold film - the system under investigation. The choice of sample geometry is governed by the BEEM measurement technique. The gold film must be thin enough so that most of the electrons pass through it without scattering[4]. The gold/silicon interface provides a Schottky barrier to filter the electron distribution so that only those electrons within the proper transverse wave vector and energy ranges pass into the silicon. The BEEM current is that current which is collected in the silicon after having passed over the Schottky barrier.

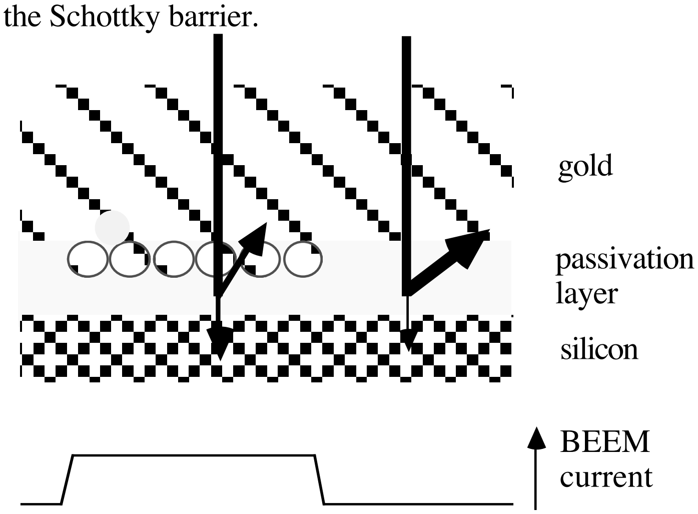


Figure 1. A schematic drawing which illustrates how an inner surface terrace can increase the BEEM current due to a high scattering rate in the passivation layer material which it displaces. The BEEM electrons pass through a thinner layer of passivation material where a terrace exists. The electrons which are scattered back, in addition to many which cross the passivation layer but are not able to surmount the Schottky barrier, are eventually collected to maintain the tunnel current.

To understand how the technique can be used to study terrace growth on the inner surface of the gold film, consider Figure 1. The passivation layer scatters electrons strongly and to a good approximation, independent of the electron's energy[3]. A variation in the thickness of this passivation layer caused by the presence of a terrace layer induces a large change in the magnitude of the BEEM current. Therefore a measure of the BEEM current in this system acts as a sensitive detector of single atom high terraces on the inner gold surface. By scanning the tip laterally over the top gold surface while maintaining a constant tunnel current, one obtains concurrently a standard constant current STM image by monitoring the tip height displacement, and a BEEM image. One would expect to find regions of higher BEEM current while the tip scanned over a terrace region, and a lower but non zero current elsewhere. An experimental image is shown in Figure 2. Figure 2(a) shows the STM topograph taken simultaneously with the BEEM image in (b). The constant 1 nA current STM image shows that the grain size is typically a few hundred angstroms. All of the whitish areas in the BEEM image are regions where inner surface terraces were produced in the following manner with the parameters for each given in the figure caption: Initially, the STM tunnels to the sample with the sample to tip bias used for imaging (~1.4 eV), which was chosen to be below any thresholds for modifying the system. The tip is then scanned to the point where stressing is to be done. The sample to tip bias is swept to the stressing level at a rate slow enough that the feedback loop easily maintains the constant current. The voltage is held at this higher level for a specified amount of time - always with the feedback maintaining constant current. The tunnel bias is then reduced to the imaging value at the same rate as it was increased. One or a sequence of topographic and a BEEM images are then taken.

Figure 2. 1. Gray scale 1.4 eV constant 1 nA current STM (left) and corresponding BEEM (right) images illustrate enhancement type modifications of a sample. The images are 800 Å square. (a) shows the STM topograph which did not visibly change as a result of the modifications. (b) is the BEEM image where all the whitish areas were individually created by stressing with the STM current. The BEEM image before any stressing was uniformly gray. Clockwise from the two largest (just touching, in the lower left) the modifications were created with a 2.5 eV for 3.8 sec, an voltage sweep 0.4->2.88 eV in 5.7 sec, 2.1 eV for 6.7 sec, 2.0 eV for 6.5 sec, 2.25 eV for 3.3 sec, and the at the bottom center 2.25 eV for 7.0 sec.

3. Qualitative Results

3.1 TERRACE GROWTH - INCREASES IN THE BEEM CURRENT

Consider the image shown in Figure 2. The STM topograph figure 2(a) exhibits the gold grain structure and did not change noticeably during the production of the inner surface terraces seen in the BEEM image of figure 2(b). Recall that the terraces are on the inner surface of the gold so are not observed in the STM image. The resolution of the BEEM image is not as high as the STM image because it is quite far (~150 Å) from the tip. The resolution is better than one would naively expect at this distance, however, due to the constraints on transverse momentum imposed on electrons before they are allowed to cross the Schottky interface[1]. One can tell that the BEEM resolution is quite high by looking at the BEEM image profile near a inner surface terrace edge. The resolution can also be measured while creating small terraces at the inner surface as will be described below. The measured resolution for this system is ~10-20 Å.

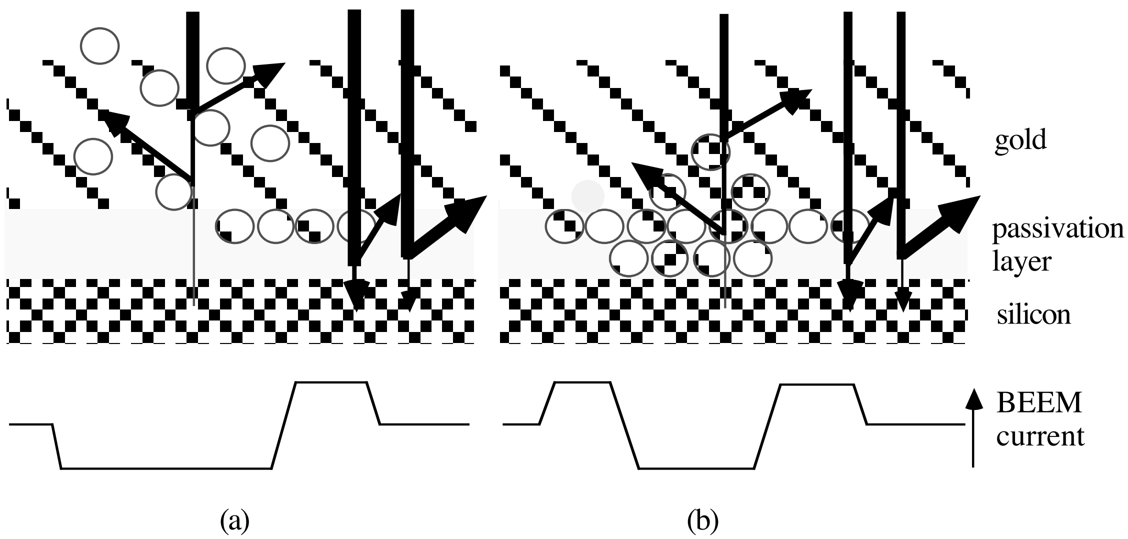


Figure 3. Sketches of mechanisms which can result in the local decrease of the BEEM current from surrounding values.

3.2 MECHANISMS FOR DECREASES IN THE BEEM CURRENT

The mechanisms which can result in the decrease of the BEEM current from the surrounding area are sketched in figure 3. As mentioned above, a high density of vacancies within the gold film can strongly scatter electrons. Such is the situation depicted in figure 3(a). The inelastic scattering of hot (> 2 eV above the gold Fermi level) electrons can stimulate the motion of the vacancies. Lower energy electrons, such as those used to image the modification results, where a typical bias of 1.4 V is used, do not substantially alter the structure but probe it. The imaging electrons do not scatter as strongly from the vacancies so are less sensitive to vacancies in the film. Thus a very high density of vacancies is required before a noticeable structure will be seen in an image taken at 1.4 V. Such a high density of defects in a small area can be expected to be unstable. Indeed, defect structures of this type will often disappear within a time scale of minutes accompanied by changes in the topography of the gold film as seen in the STM image. Examples of such defects have been previously shown[3,4]. These observations underline the reversibility of the vacancy motion process.

Another method through which the BEEM current can be reduced in a local region is given in figure 3(b). This effect depends on the nature of the gold/silicon system and results when a second layer of gold grows on the inner surface which brings the gold into intimate contact with the silicon. A much higher rate of adatom/vacancy production is required to nucleate this second terrace due to the high loss rate of adatoms to grow the first terrace. The loss rate is higher since the first terrace is much closer to the production site than the nearest adatom sink was to the production site while nucleating the first terrace. The narrow ring of enhanced BEEM current shown in figure 3(b) over the region at the edges of the modification where only one terrace exists is an identifying feature of this type of modification. The upper left hand part of figure 4 shows an region containing such structures. The BEEM image of figure 4(b) shows the ring of enhancement surrounding a region of immeasurably small BEEM current. The existence of a region in which the BEEM current is enhanced implies that the density of silicon scattering centers in the gold falls rapidly with distance into the gold. Otherwise one would expect to find larger regions with reduced BEEM current and a less reproducible width to the enhanced ring. Of course the strongly reduced BEEM current in the degraded regions then implies that silicon within gold is a very strong scatterer of electrons within the energy range used for imaging. Note that this type of modification is irreversible at room temperature by the second law of thermodynamics.

Figure 4. 1. Gray scale 1.4 V constant 1 nA current STM (left) and corresponding BEEM (right) images illustrate various modifications of a sample. The images are 1800 Å square. (a) shows the STM topograph which exhibited some grain growth as a result of the intermixing modifications. (b) is the BEEM image which was uniformly gray before stressing with the STM current. The top, left and center intermixing modifications were created with 3.1 V and 3 nA for 5.4 sec, 0.1 nA for 5.4 sec, and 3 nA for 2.7 sec, respectively. The creation of the lines near the bottom and right is described in the text.

3.3 DRAWING LINES

At the bottom and right hand sides of figure 4 are some terraces which appear as lines. These are literally the first attempts at making any structures besides dots with the technique. First the line near the bottom was made by positioning the tip at the left end, raising the tip bias to 2.3 V@1 nA tunnel current, and moving 700 Å to the right at 230 Å/sec and back to the starting position at the same rate. When no increase in BEEM current under the tip was observed, the tip was swept again to the right at 47 Å/sec, leaving the line in the figure. The lines at the right of figure 4 were formed by moving to the right hand end of the upper line, where the tip bias was increased to 2.3 V@1 nA tunnel current. The line segments were then swept in order -- the last one is vertical in the image right at the edge of the figure. The horizontal lines are 350 Å long and the vertical lines 400 Å long, all swept at ~30 Å/sec.

In principal, arbitrarily shaped and sized structures can be created. The limitation is thermodynamic stability of the structures, i.e. they must be large enough that surface energy does not cause them to evaporate, and diffusion rates of the terrace atoms on the surface and vacancies within the film. Stability issues will be discussed at the end of section 4.

4. Quantitative Results and Discussion

Before embarking on a quantitative analysis of the data, we must first remark about its generality. We have found that the quantitative behavior of the modification properties, including threshold levels, rates and stability, depend on the nature of the gold film under study and the interface condition. This is presumably due to differing diffusion rates of vacancies and inner surface adatoms, in addition to other extended defects in the system which interrupt vacancy motion. A striking example of interface preparation dependence is given when the carbon-based passivation layer is replaced by 1-2 monolayers of SiO_2, which is grown in an ultra high vacuum (UHV) chamber following silicon cleaning. The oxide thickness is estimated[3] from the ratio of the substrate to oxide silicon 2p photoelectron peaks measured by x-ray photoemission. The oxide scatters electrons very strongly so the background BEEM current levels are reduced by a factor >20 from those with a few monolayer thick carbon passivation layer. The modification properties also differ. To within the signal to noise of the images, we have seen no evidence for an enhancement of the BEEM current following stressing of an oxide-passivated sample. One explanation for this difference is that the carbon-based passivation layers are easily compressed or incorporated into the inner surface gold terraces as they grow, but that the oxide is much harder to displace, prohibiting growth on the inner surface of the gold. To insure that such systematic errors do not effect the data presented in this section, all data in this section, except where explicitly noted, was taken on a particular carbon-layer-passivated sample within a few microns of each other and a few days of each other.

For the hot electron scattering model for gold adatom formation one expects the number of adatoms created to depend on the number of injected electrons. Indeed for the modification parameters studied here the effect of longer stressing time was found to be redundant with that of higher current over the range of tunnel currents (0.1-10 nA) used. The relevant parameter is the electron dose given as the product of the current times the stressing time. This is not a surprising result since for a 1 nA tunnel current, the average time between electron arrivals is $\sim 10^{-10}$ sec for a region the size of the BEEM resolution. This time is much longer than electron relaxation times and phonon periods. Thus one would expect the electron system to have settled into an equilibrium or metastable state before the next electron arrives.

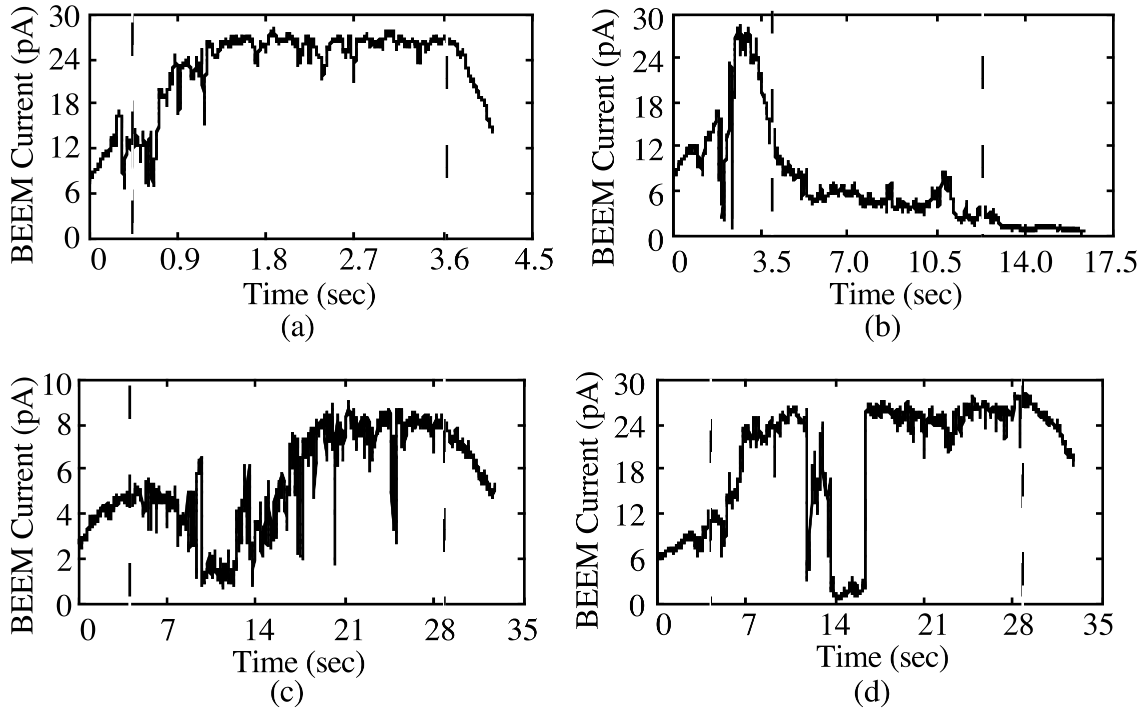


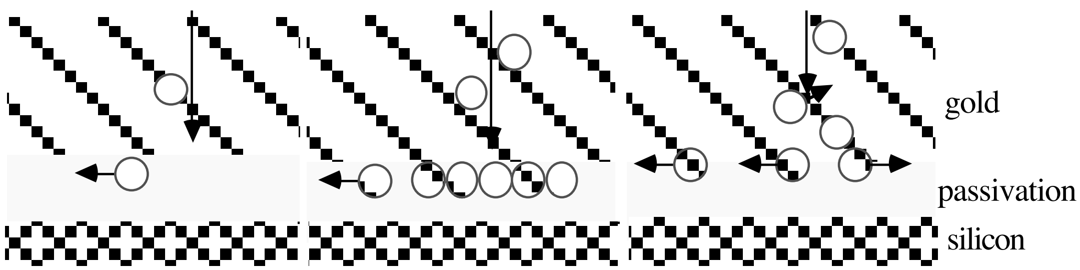
Figure 5. Plots of the BEEM current taken in real-time during modifications of the sample. The sample-tip bias was increased from the imaging value of 1.4 V linearly to the stressing value, at which it was held constant for a period of time, then decreased linearly back to the imaging value. The dotted lines indicate the times at which the bias reached and left the highest stressing value. The stressing voltages and tunnel current values for the plots are: (a) 2.25 V, 1 nA, (b) 3.1 V, 1 nA, (c) 2.1 V, 0.3 nA, and (d) 1.9 V, 1 nA. Note that the time axes differ between the plots.

4.1 REAL TIME OBSERVATIONS -- TERRACE NUCLEATION

The modification which occurs due to the stressing with hot electrons as described in section 2 can be followed in real time by monitoring the BEEM current. Experimental data are shown in figure 5(a-d). Note that there are several distinct phases which occur while the voltage is held constant. Before describing the properties of each phase in detail, it is important to recall that the BEEM current is only sensitive to what is occurring in a region the size of the BEEM resolution (~10-20 Å in diameter) at the interface. We have seen that the modification process often creates structures much larger than this. The real time BEEM current plot will reflect only what is occurring at the region underneath the tip (usually the center of the region unless the tip is nearly over a grain boundary). Following along figure 5, one finds that a latency period during which the BEEM current does not change follows the ramp to the stressing bias, then the current rises, saturates, and decreases if the bias is held at a high enough level. The time scales for the various phases depends on the stressing bias. There are noisy periods in the plots, especially (c) and (d). These are expected as will be discussed below and are the result of inelastic scattering as the interface through which the BEEM electrons pass is modified.

The latency period is best described by the picture in figure 6(a). We know that hot electrons at these energies stimulate the production of adatoms at the inner surface of the gold. When no terrace exists, however, the adatom will tend to diffuse away, inhibiting the formation of a terrace. It is found that the latency time for a given dose is either close to zero or depends on voltage in a roughly exponential manner as exp[(-6.6 ± 1.7) V]. The cases when the latency time is near zero occur when the new modification is within 10-30 Å of a previous modification. In these cases, the nearby terrace presumably prevents the adatoms from freely diffusing.

When the BEEM current begins to rise, some adatoms must be localized at the inner surface underneath the tip. Figure 6(b) depicts the situation. A small terrace has formed. The evaporation rate from such a small terrace is expected to be very high due to its thermodynamic instability[6]. Thus, the initial growth rate of the terrace will be much slower than the growth rate when the terrace is larger. This is simply checked by comparing the time it takes for the real-time BEEM plot to saturate compared to the time it would take to grow a region the size of the BEEM resolution using the rates measured for larger terraces. One finds that the initial growth is ~10 times slower. A measure of this rate is given by the time it takes for the BEEM current to reach half its saturated value, a quantity which behaves ~exp[(-6.8 ± 0.4) V] up to ~2.5 V stressing bias. The functional form of the current rise is approximately proportional to the square root of time. Figure 5(b) decreases before reaching a saturation level. This decrease is exponential in time as is expected if a layer of material with a short mean free path was growing in thickness. This material is silicon intermixed with gold.



(a) (b) (c)

Figure 6. Schematic drawings of the state of the interface at various stages of the terrace growth process. (a) During the latency period, the adatoms which are created diffuse away. (b) Eventually some adatoms coagulate to form a small terrace, but the terrace is not thermodynamically stable since the curvature is very large. The evaporation rate of atoms is high so the terrace grows slowly. The small terrace allows the BEEM current to increase somewhat. This is the situation as the BEEM current rises in the plots of figure 5. (c) Vacancies are formed in the bulk of the film at all stages. Hot electrons scatter from the vacancies if they are in the path of the incident beam as is shown here during the initial growth phase.

4.2 VACANCIES

Note that vacancies are produced with adatoms. A hot electron can scatter from a vacancy similarly to the way it scatters at the inner surface, so one would expect that whenever a vacancy gets into the (resolution-sized) region in the path of the incident electrons, it would decrease the BEEM current. A cartoon of such an event is shown in figure 6(c). Eventually the vacancy is driven out of the path of incident electrons. Bursts of such decreases are seen at all parts of the real-time BEEM plot. For example one is found near the end of the latency period in figure 5(c) and in the saturated region of figure 5(d).

After the real-time BEEM current plot saturates, the terrace is larger than the resolution of the BEEM technique. This provides a convenient way to measure the BEEM resolution. The stressing is stopped as soon as the BEEM current is found to saturate. A BEEM image shows the size of the structure. Subsequent images reveal if the terrace is evaporating or if it retains its size. This is the origin of the ~10-20 Å BEEM resolution quoted above. After the sample-tip bias has returned to the imaging value, one can compare it to the starting value to ascertain whether the region directly under the tip has had a net increase or decrease in transmittance. The results of the stressings shown in figure 5(a,c,d) was a net increase. Subsequent area scans showed terrace formation. The stressing shown in figure 5(b) caused an intermixing modification.

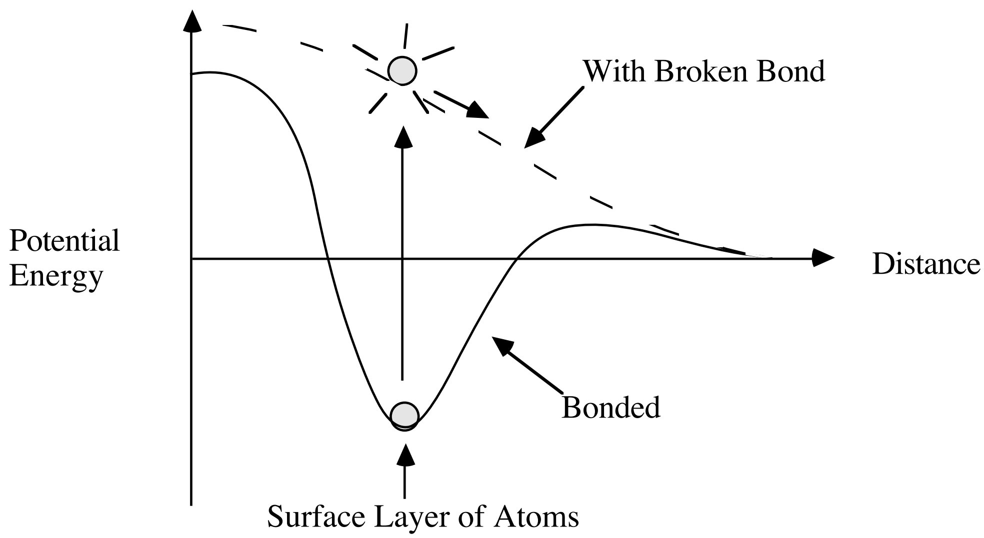


Figure 7. When a hot electron inelastically scatters from a gold atom, it may break a bond causing the atom to become unstable in its present location. A schematic potential energy vs. position is shown indicating how an atom can be accelerated onto a surface by a potential energy gradient if the bond remains broken long enough.

4.3 ADATOM PRODUCTION

Terrace growth rate can be measured from a BEEM image (e.g. figure 2) as a function of electron dose and bias voltage. The initial increase of the area of the terrace is linear with the dose as is expected if the growth is limited by the adatom production rate. The size of the terrace eventually saturates, probably due to annihilation of adatoms with vacancies from within the grain or loss of adatoms to nearby grain boundaries. The initial terrace growth rates can be converted into a lower limit on the adatom production rate. It is a limit since some adatoms are lost through annihilation with vacancies. The adatom production rate depends upon voltage as exp(5.9 V) at lower voltages, and begins to saturate ~2.5 V. It is not surprising that the voltage dependence of the latency time, the rate of BEEM current rise and the adatom production rate all share the same voltage dependence. They all depend on the rate at which adatoms are produced.

So far we have attributed the adatom-vacancy production to 'inelastic scattering of hot electrons.' A model has been proposed for this process[4]. It is similar in nature to electron stimulated desorption (ESD), which has recently been reviewed in [7]. The difference from ESD is that the electron energies are much lower in the present investigation, and the ions are not ejected from the surface. The similarities are that an injected electron breaks a bond of an atom in the sample. This makes the atom unstable in the lattice -- it undergoes a Franck-Condon transition. A picture is given in figure 7. The atom was originally sitting in a potential well formed by the bonding to its neighbors. When the bond is broken, it shifts to the upper potential energy curve which is shown for a surface atom. If the bond remains broken for a long enough period of time for the atom to be accelerated by the potential energy gradient and move out onto the surface, an adatom-vacancy pair will have been created. Typically a bond will not remain broken for such a long time unless it has been stabilized by a lattice distortion. Instead, the hole (broken bond) will jump from one atomic site to another through the lattice until either it is localized or decays. Atoms near surfaces or defects in the bulk (e.g. vacancies) do not have as high a coordination number so generally have softer bonds. These bonds can therefore deform more easily to localize the hole than others. Thus a hole created in the bulk of the film can move to a defect or surface and get localized. It must be fairly close, however, or it will decay on the way. We hope to be able to measure such decay lengths and localization probabilities in the future using this BEEM technique with an appropriate range of samples. Some discussion of hole localization is given in [7].

A model to predict the voltage dependence of the adatom production rate was given in [4]. The model used an approximate calculation of the hole formation rate at finite temperatures for a system with a gaussian broadened threshold energy. A broadened threshold for hole creation is not unrealistic: the bonds involved are near defects so are strained and in a variety of environments. A good fit to the latency time, half-time for BEEM current rise and the areal growth rate of the terraces, all of which depend on the adatom production rate, is found for a broadened threshold centered at 2.5 eV with a full width of 0.4 eV. The model predicts a nearly exponential voltage dependence below threshold, with the exponential factor depending on temperature and the width of the threshold distribution.

4.4 STABILITY

The stability of the structures created within the film or on any of the surfaces is strongly tied to the nature of the film itself. Most of the data discussed here were from samples evaporated at a fairly high rate in high vacuum. The inner surface structures are quite stable on such a film. The terraces of figure 2 and the lines and other modifications in figure 4 stay close to their original form for at least hours (as long as we observed them). Vacancy structures within the films do anneal at least somewhat on the minutes time scale, then are either gone or stabilize. The top surface structures viewed in the STM scan change some as the vacancy structures anneal. If a top surface mound is formed on such a sample, it will usually remain with only minor changes.

At another extreme, we have grown samples very slowly (0.1 Å/sec) in ultra high vacuum. These samples will anneal as they grow so presumably will have fewer internal defects in addition to being cleaner. Generally speaking all the structures decay on the minutes time scale. The inner surface terraces decay very quickly -- vacancy diffusion in the film is unimpeded so the vacancies can move to the inner surface where they can annihilate terrace atoms. The top surface structures change greatly. In general they do not return to their initial configuration (observe with STM topography) but vary considerably as the internal vacancy structures (observed with BEEM) anneal. Another feature of this type of sample is that we are not able to grow two layers of terraces on the inner surface, so we do not produce any intermixing type modifications. The terrace annihilation rate is very high so we are not able to produce inner surface adatoms at a high enough rate to nucleate a second terrace.

A final word about stability involves that of the sample structure itself. If one uses hydrogen, chlorine, hydrocarbons, or nothing for the passivation layer, the lifetime is a few days, a few months, around a year or more, or zero, respectively. The lifetime is defined as the time before a significant portion of the sample has had the passivation layer break down and gold-silicon intermixing occur. This problem could be overcome by using multiple types of terrace layers.

5. Summary

We have shown that hot electrons injected by an STM tip scatter and modify a gold film throughout its volume and at all its surfaces. The BEEM measurement technique is found to be a powerful method for probing such buried structures. With an appropriate choice of passivation layer between the gold film and silicon substrate, small single atom high terraces can be studied. This is important as it allows observation of hot electron effects at high spatial resolution without the effects of a high electric field from an STM tip or other tip-surface interactions. The growth of buried-surface terrace structures is observed in real-time. One can measure the effects of the thermodynamic instability of the initially very small terraces by comparing the initial growth rate to the growth rate of larger terraces. The growth rate is related to the rate of adatom production, which can be determined quantitatively as a function of voltage from such measurements. Vacancy formation accompanies adatom formation. The structures formed by the vacancies can effect the BEEM images, which then allows a glimpse into their evolution. The BEEM image is correlated with an STM image to relate vacancy structure changes and topographic changes. The mechanisms of mound formation and stability can be addressed. The stability of the created structures is shown to be related to the physical properties of the gold film.

6. Acknowledgments

We wish to acknowledge the contributions of Tony Huang and Andres Fernandez and constructive discussions with David Peale, Andres Fernandez, Tony Huang, Wilson Ho, John Silcox, and Dan Ralph. We thank Bill Kaiser, Carl Kukkonen and the Jet Propulsion Lab for helping us to get started in STM. During part of the time this work was done, HDH was supported by an IBM Graduate Fellowship. Research support was provided by the Office of Naval Research and the Semiconductor Research Corporation. Additional support was provided by the National Science Foundation through use of the National Nanofabrication Facility and the facilities and equipment of the Cornell Materials Science Center.

7. References

[1]. Kaiser, W. J. and Bell, L. D. (1988) 'Direct investigation of subsurface interface electronic structure by ballistic-electron-emission microscopy', Phys. Rev. Lett. **60**, 1406-1409; and Bell, L. D. and Kaiser, W. J. (1988) 'Observation of interface band structure by ballistic-electron-emission microscopy', Phys. Rev. Lett. **61**, 2368-2371.

[2]. Hallen, H. D., et al..(1990) 'Gold-silicon interface modification studies', *Proceedings of the Fifth International Conference on Scanning Tunneling Microscopy/Spectroscopy*, (Baltimore, July 23-27, 1990) in (1991) J. Vac. Sci. Technol. **B9**, 585-589; and (1990) 'Ballistic electron emission microscopy of metal-semiconductor interfaces',*Proceedings of the Ballistic Electron Emission Microscopy Workshop 1990* , Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, March 9, 1990.

[3]. Hallen, H. D. (1991), Ph.D. thesis, 'Ballistic electron emission microscopy studies of

gold-silicon interfaces', Cornell University.
[4]. Hallen, H. D. and Buhrman, R. A. (submitted) 'Hot electron induced atomic motion and structural change at the gold-silicon interface'.
[5]. For example Brillson, L. J., Katnani, A. D., Kelly, M., and Margaritondo, G., (1984), J. Vac. Sci. Technol. A **2**, 551.
[6]. Peale, D. and Cooper, B. H., (private communication); and Peale, D.(1992), Ph.D. thesis, 'Diffusion and mass flow dynamics on the gold (111) surface observed by scanning tunneling microscopy', Cornell University.
[7]. Ramsier, R. D. and Yates, J. T., Jr.(1991) 'Electron-stimulated desorption: principals and applications', Surface Science Reports **12**, 243-378.

KEYWORDS / ABSTRACT: hot electrons / interface modification / ballistic electron emission microscopy / electron stimulated desorption / gold mound formation / vacancy motion

Hot electrons injected by a scanning tunneling microscope (STM) tip with a few volts tunneling bias scatter and modify a gold film not only at the top surface of the film, but throughout the film and at the inner or interfacial surface. The ballistic electron emission microscopy (BEEM) measurement technique is a powerful method to probe such modifications. The production of adatoms and their subsequent coagulation into atomic terraces on the inner surface of the gold is demonstrated. Quantitative measurements of the adatom production rate are in agreement with that predicted by a model including bond breaking by hot electrons. The stability of the created structures is shown to be related to the physical properties of the gold film.