Direct Investigation of Subsurface Interface Electronic Structure by Ballistic-Electron-Emission Microscopy

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(Received 10 December 1987)

A new technique for spectroscopic investigation of subsurface interface electronic structure has been developed. The method, ballistic-electron-emission microscopy (BEEM), is based on scanning tunneling microscopy. BEEM makes possible, for the first time, direct imaging of subsurface interface properties with nanometer spatial resolution. We report on the first application of BEEM to subsurface Schottky-barrier interfaces.

PACS numbers: 61.16.Di, 68.35.−p, 73.20.−r, 73.30.+y

The formation and properties of semiconductor interfaces have been of central importance in solid-state physics for many decades. However, a complete understanding of the fundamental characteristics of semiconductor surfaces, the influence of thin-film deposition on semiconductor surfaces, and the properties of the resulting interface system is still lacking. Metal-semiconductor Schottky-barrier (SB) interface systems have attracted the greatest attention.[1] The complexity of SB formation phenomena, including the role of interface defect formation,[2,3] electrode interdiffusion, and chemical reaction, is expected to induce inhomogeneity in interface structure and electronic properties.[1] Subsurface interface electronic properties are not directly accessible to conventional surface analytical techniques. Therefore, experimental investigation of interface phenomena is complicated by the necessity to probe interfaces buried below a heterojunction surface. In addition, conventional SB characterization methods, including photoemission, photoresponse, current-voltage, and other techniques, are limited by their lack of spatial resolution for probing the variation of SB properties over the interface plane. The conventional methods yield only a complicated spatial average of SB properties. The recently developed scanning tunneling microscopy (STM) method[4] makes possible high-resolution imaging of surface geometric and electronic structure.[5-7] However, previously developed STM techniques are insensitive to subsurface properties.

We report the first method for direct spectroscopic investigation and imaging of *subsurface* interface electronic structure with high spatial resolution. The method, ballistic-electron-emission microscopy (BEEM), employs STM for investigation of SB systems, semiconductor heterojunctions, and other interfaces. In this Letter, we describe BEEM and its first application to important SB interfaces.

Figure 1 shows a three-terminal configuration for BEEM investigation of a metal-semiconductor SB heterojunction. An STM tunnel tip is positioned near the surface of the heterojunction to permit transmission of tunnel current between tip and base (metal) electrodes. Electron tunneling from the tip to the base electrode injects ballistic electrons into the base. With typical attenuation lengths greater than 100 Å,[8] the injected ballistic electrons may propagate through a surface layer to probe a subsurface interface region. For base-tip tunnel bias less than the base-collector barrier height V_b, there is no ballistic-electron current into the collector. But, as base-tip bias V is increased above V_b [see Fig. 1(b)], a dramatic increase in base-collector current I_c occurs. The I_c-V spectrum provides a direct probe of interface electronic structure, including the important SB height, quantum-mechanical reflection of electrons at the interface, and ballistic-electron transport properties of the base film. In addition, scanning of the tunnel tip over the heterostructure during simultaneous measure-

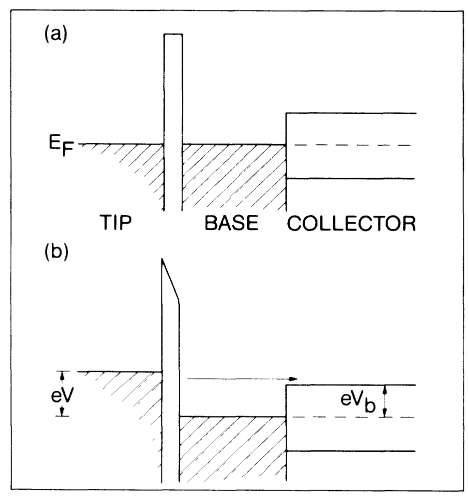

FIG. 1. Schematic energy-band diagram for the three-terminal BEEM experiment. The tunnel tip is separated by a vacuum barrier from the base metal. Terminals are applied to the tunnel tip, metal base, and semiconductor collector. Collector current I_c is measured between the base and collector. (a) The energy-band diagram for zero tunnel bias, $V=0$. (b) The energy-band diagram for tunnel bias greater than the barrier voltage, $eV > eV_b$.

ment of I_c (or I_c-V spectra) makes possible direct spatial imaging of subsurface interface structure.

Two important SB interfaces were selected for the first application of BEEM: Au-Si and Au-GaAs SB heterojunctions fabricated by standard methods. Both SB systems have been widely studied by many techniques. The Au-GaAs SB interface shows properties which are strongly affected by interface defect formation[2] and pronounced interdiffusion and alloy-formation phenomena between the Au and GaAs electrodes.[9] A wide range of SB-height values have been reported for the Au-GaAs interface.[1] In contrast to Au-GaAs, the Au-Si SB shows simple, reproducible SB characteristics.[1] The SB heterojunctions used for this study were prepared by evaporation of 1.6-mm-diam Au disk electrodes, 100 ± 5 Å thick, on chemically etched[10] n-type Si(100) ($n = 2 \times 10^{15}$ cm^{-3}) and chemically etched[11] n-type GaAs(100) ($n = 3 \times 10^{16}$ cm^{-3}) wafers. Au evaporation was performed in an ultrahigh-vacuum chamber at a pressure of 1×10^{-9} Torr with quartz-crystal microbalance control of film thickness. Current-voltage (I-V) measurements yielded SB heights of 0.85 and 0.80 eV for the Au-Si and Au-GaAs SB heterojunctions, respectively.[12]

The STM apparatus, described elsewhere,[13] is enclosed in a chamber purged with dry N_2 gas at atmospheric pressure. Au tunnel tips were employed for this work. Stable and reproducible images of the Au electrode surface were routinely obtained for all samples studied. The collector current was measured with zero applied bias between base and collector with use of a high-sensitivity (gain $= 10^{11}$ V/A), low input-impedance (10 Ω) current amplifier. From ten to forty BEEM spectra were averaged at each surface location to improve the spectral signal-to-noise ratio. The measurements reported here were made at room temperature.

Figure 2 shows typical BEEM spectra obtained at a single location on the Au electrode surface of a Au-Si SB heterojunction. The spectra were obtained by our sweeping V while holding tunnel current I_t constant under feedback control of tip-sample separation. During the sweep of V, I_c is measured. For negative V (tip positive with respect to the Au electrode) electron tunnel current originates from filled states in the Au electrode. As expected, no current has been observed between base and collector for negative V over the voltage range studied ($-2\text{ V} < V < 0$ V). Also, as expected, I_c is zero for V less than a threshold voltage. However, for V greater than $\simeq 0.8$ V, the spectra of Fig. 2(a) exhibit an abrupt threshold and a rapid increase in I_c.

A simple, one-dimensional theory explains the fundamental characteristics of BEEM. Following the treatment of photoresponse,[8] the ballistic-electron mean free path in Au is assumed to be independent of energy E over the narrow range from 0 to 2 eV above the Fermi energy, E_F. Further, the density of states in the tip and

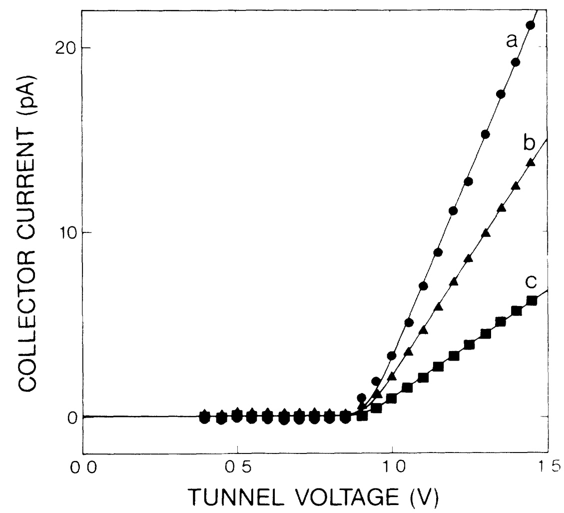

FIG. 2. BEEM spectroscopy results for the Au-Si heterojunction. BEEM spectra of collector current I_c vs tunnel voltage V are shown. Spectra a (dots), b (triangles), and c (squares) were measured at tunnel currents of 0.87, 0.57, and 0.27 nA, respectively. The calculated spectra (solid lines) correspond to barrier height values, eV_b, of 0.92 eV, and R values of 0.045, 0.045, and 0.043 eV^{-1} for spectra a, b, and c, respectively.

base electrodes is taken to be constant. Also, the energy-dependent transmission probability of ballistic-electron current through the interface with barrier height eV_b is approximated by a step function. Thus the collector current as a function of tunnel bias voltage at constant tunnel current is

$$I_c(V) = RI_t \int dE[f(E) - f(E - eV)] \times \theta(E - (E_F - eV + eV_b)), \quad (1)$$

where R is bias independent and the Fermi function, $f(E)$, is defined as $f(E) = \{1 + \exp[(E - E_F)/kT]\}^{-1}$.

A comparison of the experimental BEEM spectra with spectra calculated with use of Eq. (1) is shown in Fig. 2. Equation (1) was fitted by least squares to the experimental spectra by adjustment of R and V_b. Agreement between the simple theory and the experimental BEEM spectra is excellent. The BEEM spectra of Fig. 2 were reproduced at each location probed on the surfaces of three separate Au-Si SB heterostructures. The variation in the value of eV_b for spectra obtained at different I_t values is less than 0.01 eV at a single location on the heterostructure surface. However, experimentally derived values of eV_b varied over the narrow range from 0.86 to 0.92 eV for different regions of the three Au-Si heterostructures. The observed variation in eV_b is a direct observation of spatial variation in interface structure. It is important to note that for the Au-Si SB heterojunctions the barrier-height values determined by BEEM, 0.86–0.92 eV, are in close agreement with the spatially aver-

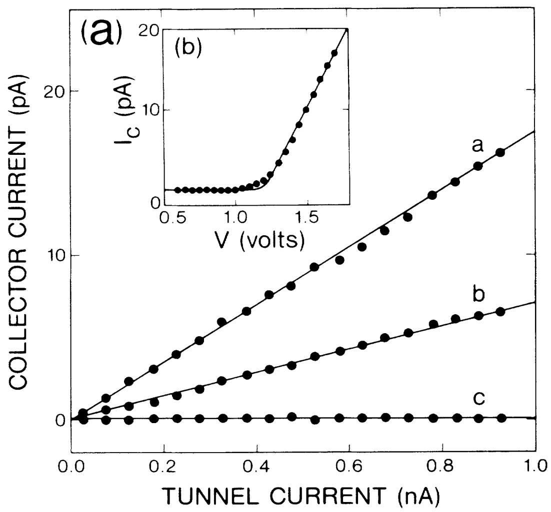

FIG. 3. (a) BEEM spectra of collector current I_c vs tunnel current I_t for the Au-Si SB. Spectra *a*, *b*, and *c* (dots) are measured at tunnel voltage, V, values of 1.4, 1.1, and 0.8 V, respectively. Included for comparison are straight-line fits to the spectra. (b) BEEM I_c-V spectrum (dots) for the Au-GaAs SB heterojunction obtained at $I_t=1.0$ nA. The calculated spectrum (solid line) corresponds to an eV_b value of 1.2 eV and an R value of 0.034 eV^{-1}.

aged value determined from I-V measurements, 0.85 eV.[14]

The linear dependence of collector current on tunnel current of Eq. (1) was tested experimentally. First, it is seen that the three spectra of Fig. 2 scale linearly with I_t. Second, spectra of I_c vs I_t at constant values of V were measured. Typical I_c-I_t spectra are shown in Fig. 3(a), where the predicted linear dependence of I_c on I_t is clearly displayed.

BEEM permits direct, spatially resolved probing of heterostructure interface properties by imaging of the variation in I_c at fixed V and I_t during scanning of the tunnel tip over the heterostructure surface. Spatial variations in interface properties are revealed as spatial variations in I_c. The BEEM-imaging capabilities have been demonstrated by an investigation of the subsurface electronic properties of the Au-Si and Au-GaAs SB heterostructures. Figure 4 shows typical STM topographic and BEEM images of the Au-Si and Au-GaAs heterostructures. The STM and BEEM images were acquired simultaneously. The STM images map the topography of the heterojunction surface, shown in Figs. 4(a) and 4(c), while the BEEM images, shown in Figs. 4(b) and 4(d), display subsurface interface structure.

The STM topographic image in Fig. 4(a) shows smooth topography at the Au electrode surface for the Au-Si heterostructure. The BEEM image for Au-Si at the same location, shown in Fig. 4(b), indicates negligible spatial variation in I_c. The BEEM image, therefore, shows that the subsurface Au-Si SB interface has homogeneous electronic properties.

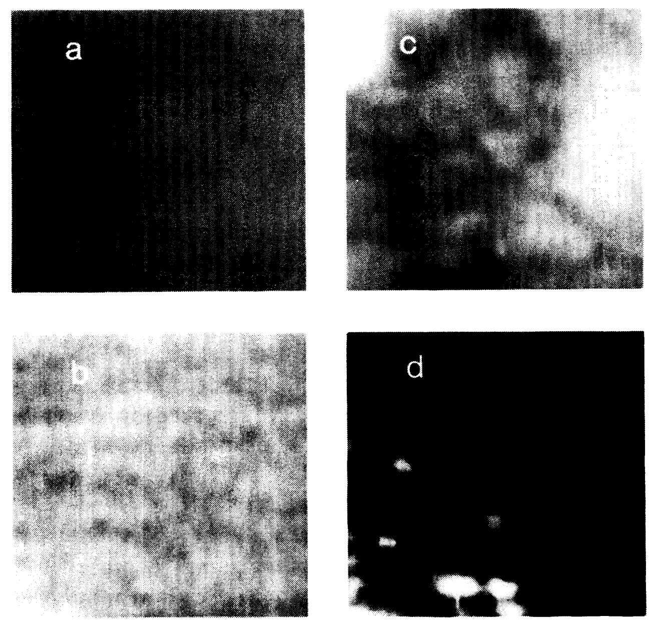

FIG. 4. STM topographic and BEEM images of the Au-Si and Au-GaAs SB heterojunctions. STM and BEEM images were acquired simultaneously. All images show a 250×250-$\mathrm{Å}^2$ area. (a) STM image of the Au-Si SB. Surface height is represented by grey level, over a range from darkest (minimum height) to lightest (maximum height) of 22 Å. (b) BEEM image of the Au-Si SB obtained at $V=1.0$ V and $I_t=1.0$ nA. Local value of I_c is represented by grey level, over a range from darkest (minimum I_c) to lightest (maximum I_c) of 1.5 pA. The average value of I_c is 2 pA. (c) STM image of the Au-GaAs SB. Grey level extends over a range from darkest (minimum height) to lightest (maximum height) of 72 Å. (d) BEEM image of the Au-GaAs SB obtained at $V=1.5$ V and $I_t=1.0$ nA. Grey level extends over the range from darkest (zero I_c) to lightest (maximum I_c) of 14 pA.

Figure 3(b) contains a typical BEEM I_c-V spectrum for the Au-GaAs SB heterostructure. In contrast to the Au-Si heterostructure, indications of interface heterogeneity of the Au-GaAs system are manifested as large spatial variations in the characteristics of BEEM spectra acquired at different locations at the Au-GaAs heterojunction surface. Figures 4(c) and 4(d) compare the surface topography of a typical region of a Au-GaAs heterojunction with the subsurface interface electronic structure. The Au-GaAs BEEM images display large-amplitude spatial variation in I_c. Pronounced maxima appear in the BEEM image in Fig. 4(d) along with large regions exhibiting no detectable collector current. It is important to note that the observed spatial variations in I_c are not correlated with surface topography. The dramatic level of heterogeneity revealed by BEEM imaging may be the result of multiphase structure at the Au-GaAs SB interface.[15]

This first application of BEEM demonstrates that this new method is a unique and powerful probe of subsurface interface properties. BEEM combines STM capabilities for investigation of surface structure with high-spatial-resolution probing of subsurface layers. Experimentally measured spectra present an abrupt threshold marking the interface barrier height. This method is shown to be versatile for study of both near-ideal Au-Si and complex Au-GaAs SB systems. BEEM images indicate homogeneous subsurface interface electronic properties for Au-Si. Also, BEEM images provide direct evidence for heterogeneity at the Au-GaAs SB interface on a lateral scale as small as 20 Å.

A simple theory predicts spectra which are in excellent agreement with measured BEEM spectra. Further, it is expected that a more detailed theoretical treatment should make possible additional investigation methods for the understanding of interface physics. For instance, detailed analysis of the BEEM spectrum threshold region may yield the quantum-mechanical reflection spectrum of carriers at interface barriers. In addition, BEEM is not limited only to the investigation of SB heterojunctions, but should be applicable to the investigation of many interface systems. For example, a transmission microscopy may also be performed on free-standing thin-film materials where the collector electrode is in vacuum, thus providing a probe of the base layer and the base-vacuum interface.

The authors thank H. G. LeDuc, R. C. Jaklevic, and J. Lambe for many stimulating discussions. This work was performed by the Jet Propulsion Laboratory, California Institute of Technology, as part of its Innovative Space Technology Center, which is sponsored by the Strategic Defense Initative Organization/Innovative Science and Technology Office through an agreement with the National Aeronautics and Space Administration (NASA).

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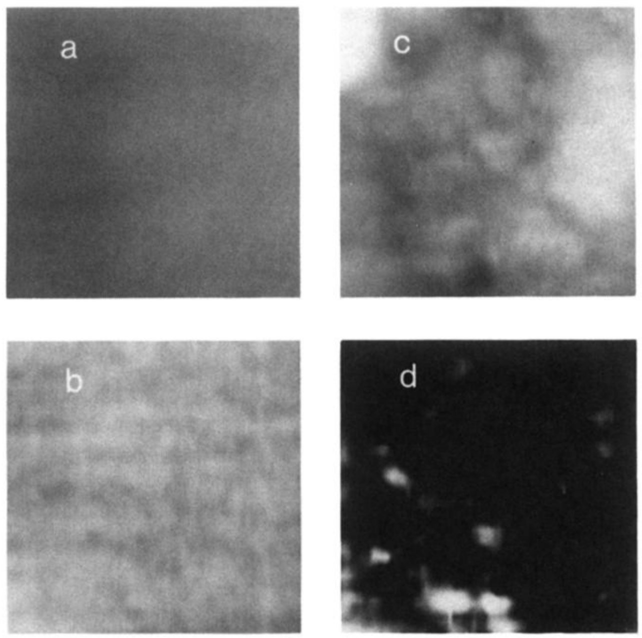

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