

Dual-probe scanning tunneling microscope for study of nanoscale metal-semiconductor interfaces

W. Yi^{a)}

Gordon McKay Laboratory of Applied Science, Harvard University, Cambridge, Massachusetts 02138

I. I. Kaya^{b)}

Rowland Institute at Harvard University, Cambridge, Massachusetts 02142

I. B. Altfeder

Gordon McKay Laboratory of Applied Science, Harvard University, Cambridge, Massachusetts 02138

I. Appelbaum

Electrical and Computer Engineering Department, University of Delaware, Newark, Delaware 19716

D. M. Chen

Rowland Institute at Harvard University, Cambridge, Massachusetts 02142

V. Narayanamurti

Gordon McKay Laboratory of Applied Science, Harvard University, Cambridge, Massachusetts 02138

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Using a dual-probe scanning tunneling microscope, we have performed three-terminal ballistic electron emission spectroscopy on Au/GaAs(100) by contacting the patterned metallic thin film with one tip and injecting ballistic electrons with another tip. The collector current spectra agree with a Monte-Carlo simulation based on modified planar tunneling theory. Our results suggest that it is possible to study nanoscale metal-semiconductor interfaces without the requirement of an externally-contacted continuous metal thin film. © 2005 American Institute of Physics. [DOI: 10.1063/1.1938969]

I. INTRODUCTION

Metal-semiconductor (m-s) contacts are long standing research topics due to their crucial roles in electronic devices. The continuous trend of device miniaturization requires accurate understanding and control of m-s interfaces to the nanometer scale. As a scanning probe method, ballistic electron emission microscopy (BEEM) utilizes the scanning tunneling microscope (STM) in a three-terminal configuration, by injecting ballistic electrons from a STM tip emitter through a thin metal base over a Schottky barrier into a semiconductor collector. BEEM enables energy spectroscopy of local carrier transport through m-s interfaces and semiconductor heterostructures buried underneath. The nanometer spatial resolution and meV energy resolution make BEEM a powerful nondestructive characterization tool for m-s interfaces and semiconductor heterostructures.^{1,2}

Most previous BEEM studies have used continuous metal thin films as the base to ensure good electrical contact with a wire or mechanical clip. Therefore the base contacts have been modeled in the limit of a free-electron metal. When the dimensions of metal contacts scale down to lengths comparable to Fermi wavelength, such as in the cases of metallic quantum wires³ or quantum wedges,^{4,5} quantum size effects and strong electron-electron interac-

tions start to play important roles in electrical transport. Restriction of BEEM measurements on continuous metal films excludes the possibility of studying the interfaces between isolated metallic nanostructures and semiconductors, but by replacing the traditional bonding wire with a scanning probe, such as a STM tip or conductive AFM tip, the above difficulties can be overcome by locating and making controllable electrical contact to individual metallic nanostructures. The principle of such “scanning” point-contact measurements with a single-probe STM has been reported previously. By two-terminal current-voltage spectroscopy, Schottky barrier heights of nanoscale m-s contacts have been measured and found to deviate from results of macroscopic contacts.⁶⁻⁸ Without a separate control of carrier energies, these two-terminal measurements can only extract limited information. In principle, a three-terminal BEEM measurement on nanoscale m-s interfaces can be performed taking advantage of two STM probes, both of which can work reversibly in tunneling and point contact regimes. There have been several reports on the construction of dual-probe STM.⁹⁻¹² However, few efforts have been made on studying nanoscale electrical transport using both STM probes.¹²

II. EXPERIMENTAL METHOD

Here we demonstrate that by using a dual-probe STM, a three-terminal ballistic electron emission spectroscopy (BEES) can be made without introducing macroscopic bonded contacts. As a proof of concept, Au/GaAs(100) is

^{a)}Electronic mail: wyi@fas.harvard.edu

^{b)}Also with: Sabanci University, Faculty of Engineering and Natural Sciences, Istanbul, TR-34956 Turkey.

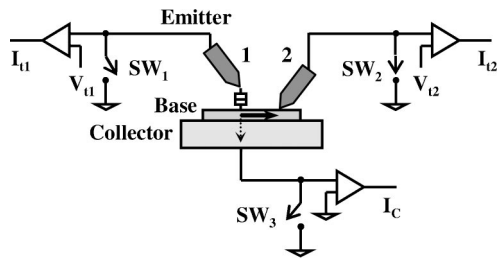


FIG. 1. (Color online) Schematics of dual-probe BEES setup. Tip 1 is negatively biased (V_{11}) to inject ballistic electrons through a vacuum tunnel junction into the metal base. Tip 2 forms a grounded point contact with the base. Collector current (I_C) is measured with a third amplifier connected to the back of the semiconductor substrate. Directions of electron flows are indicated with arrows.

chosen as the material system since it has been thoroughly studied both experimentally and theoretically. The n-type GaAs sample for this study is prepared on a (100) n^+ -GaAs substrate doped to $5 \times 10^{18} \text{ cm}^{-3}$. To ensure a Schottky barrier formation with Au, a cap layer of 200 nm n -GaAs doped to $2 \times 10^{17} \text{ cm}^{-3}$ is grown via molecular beam epitaxy with Si as the epitaxial dopant. The Schottky diodes were prepared *ex situ* by cleaning the GaAs surface with dilute NH_4OH , then Au films with thickness of 80 Å are thermally evaporated into an array of 500×500 micron squares by shadow mask method under high vacuum (1×10^{-7} Torr) to form a base Schottky contact. Measurements are performed with a home-made dual-probe STM consisting of two electrically and mechanically independent probe tips. All the measurements are performed at room-temperature under high vacuum (1×10^{-8} Torr). We chose electrochemically etched Pt-Ir tips rather than W tips partly because of their chemical inertness and, more importantly, the metallic adhesion forces between Pt-Ir and Au help to sustain the point contact against possible tensile overstretching due to thermal drift.¹³ All the measurements are carried out in a dark room to avoid photovoltaic effects.

The schematic measurement setup is shown in Fig. 1. For the two scanning tips to operate independently in STM mode, two voltage-biased low-noise current pre-amplifiers with gain of 10^8 V/A are connected to the two STM tips separately. The sample is grounded through the Ohmic contact on the backside of the substrate. In BEES mode, one of the STM tips has to be driven into point contact with the base metal and be used as a grounded reference electrode. The current input of the STM pre-amplifier connected to the landed tip is then shunted to ground. This is done remotely using an electrical relay (SW1 and SW2 in Fig. 1) to prevent introduction of any mechanical vibration. An unbiased amplifier with gain of 10^9 V/A is then connected to the backside of the substrate to measure the collector current spectra. Note that during tip approach, the transient AC response coupled through stray capacitance can possibly drive the collector amplifier into saturation and null the grounding condition of the sample. Therefore, a third shunt relay (SW3 in Fig. 1) is used to physically ground the collector which is only opened during the BEES measurement. The steps we used to measure BEES are the following: Two STM tips are coarse approached into tunneling contact with the Au-covered GaAs

surface using stepping piezo actuators. Negative tip bias of -2 V is used for tip 1 which is going to be used as the tunneling emitter. Positive tip bias of 2 V is used for tip 2 which is going to be used to contact the Au base. This way we can utilize the fast growing current of the forward-biased Schottky diode to control the extent of point contact without permanently disrupting the tip and the surface. Before the tip landing starts, the tip bias (V_{12}) is first reduced to 0.5 V to prevent overheating of the junction. Then tip 2 is driven into point contact with the Au base by turning off the feedback loop and adding an offset voltage to the scanning piezo tube. Care is taken that the tip is not driven too deep into the base layer, which may cause damage to the substrate as well as the tip itself. The tip landing is stopped once the monitored tip current reaches a saturation value, then the STM pre-amplifier is immediately shunted to ground and the collector pre-amplifier is connected. During tip landing, avalanche-like current jumps are frequently observed, probably due to the atomic connective necks formed by metallic adhesion forces, which have been extensively studied before but are not in the scope of this work.¹³ Collector current spectroscopy is measured by sweeping the voltage bias of the tunneling STM tip at a constant tunnel current of 1 nA . Since the base contact stability is crucial for reliable results, contact formation and BEES measurements have been carried out within less than a few seconds. The corresponding maximum thermal drift of the STM tip with respect to the substrate surface is estimated to be less than one Å. By applying a feedback control on the base current from the landed STM tip (tip 2), it is possible to obtain a spatially resolved BEEM image which requires several minutes of stable base contact.

III. MEASUREMENTS AND RESULTS

To test the Ohmic contact nature of landed STM tip to base metal, two-terminal current-voltage measurements are carried out using the STM pre-amplifier by sweeping the tip bias from 0.5 V to -0.5 V after the tip is landed. If there is a good Ohmic contact between the tip and base metal, then the current-voltage characteristics should show a rectifying behavior due to the Schottky interface between base metal and semiconductor collector. As shown in Fig. 2, we do observe a very asymmetrical current-voltage shape with exponential increase of current at positive tip bias but very small current at negative tip bias.

Figure 3 shows a typical three-terminal BEES spectrum from Au/GaAs(100) obtained using the two-probe method described above. The data is the average of six voltage scans and is normalized for comparison with existing BEES theory. The amplitudes of raw spectra are on the order of 10 pA . The thresholded response of collector current as a function of emitter-base voltage is clearly seen. The current is zero until the emitter-base voltage increases beyond the Schottky barrier height, then the hot electrons emitted from the tip can couple to available states in the semiconductor. The Schottky barrier height of about 0.9 eV is comparable to previous reports.¹⁴ For a detailed analysis of the shape of the spectrum past threshold, contributions from multiple conduction band minima of GaAs have to be considered. Intuitively, contribu-

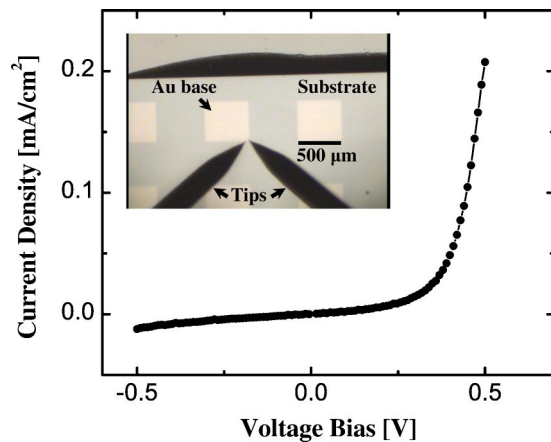


FIG. 2. (Color online) A typical current-voltage spectrum of the Schottky diode by a STM point contact (tip 2 in Fig. 1). Inset is an optical image of the Au patterned n-GaAs substrate with two STM tips brought together to a distance of a few microns.

tions from the Γ valley at the interface Brillouin zone center should dominate due to the small parallel momentum of highly forward-directed ballistic electrons. However, experiments have found that the L valley contribution is typically three to four times stronger than Γ . Interfacial scattering at the m-s interface has to be considered to fix this discrepancy. We carried out a Monte-Carlo simulation using a modified planar tunneling model including inelastic attenuation inside the base metal, quantum-mechanical reflection at m-s interface, parallel momentum conservation, and interfacial scattering.^{15,16} Good agreement between the measured BEES spectra and fitted Monte-Carlo simulation is found. In the simulation, we used scattering probability of 88%. The current density is chosen to be 0.1 nA/nm², corresponding to an effective tunneling area of about 10 nm². The Schottky barrier heights used for the Γ and L valley are 0.94 and 1.26 eV respectively. No contributions from the X valley is considered due to intervalley scattering. To match experimental conditions, the vacuum gap is adjusted to keep the tunnel current constant to within a fraction of 10⁻³ for each voltage point.

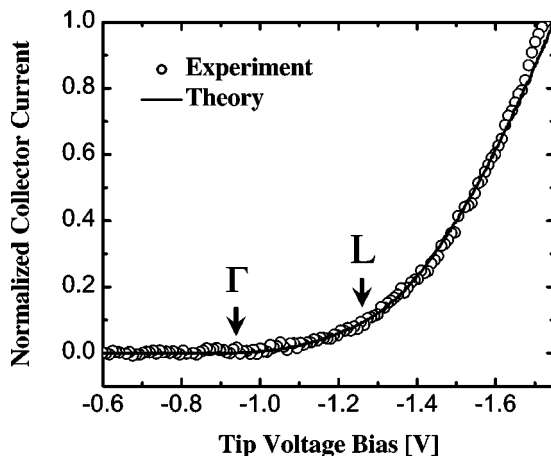


FIG. 3. A typical three-terminal BEES voltage spectrum on Au/GaAs(100) using the two-probe method described in the text. Results of the Monte Carlo simulation are superimposed on the experimental spectrum. The conduction-band thresholds used in the simulation are shown with arrows.

Our results suggest that there should be no fundamental obstacle from doing a three-terminal BEES on *in situ* prepared m-s interfaces⁶⁻⁸ without introducing a continuous metal thin film. To do this two probes should be able to address the same nanostructure on the surface. Several methods have been developed to allow the two probes to be brought together into close proximity without crashing to each other.^{10,11} The smallest possible feature size that can be measured is the sum of the radius of two STM tips, which can be less than 10 nm. Another possible issue is to ensure stable tunneling contact with surfaces of lightly-doped or semiinsulating semiconductors, which requires that most of the applied voltage bias is consumed over the vacuum junction rather than the substrate itself. At unpinned semiconductor surfaces, the electric field can penetrate into the semiconductor and introduce a large band bending, which results in drastic reduction of tunnel barrier height at small tip-sample distance.¹⁷ However, if the voltage bias is large enough to introduce charge accumulation or inversion, then the electric field is screened at the semiconductor surface. This ensures that most of the voltage drop occurs across the vacuum gap. In this way atomic STM images of semi-insulating GaAs with resistivity as high as 10⁷ Ω cm have been acquired.¹⁸ As a test, we have carried out current-distance measurements on the GaAs surface with and without Au base coverage. The exponential dependence of tip current versus tip-sample distance is confirmed both on Au-covered and bare GaAs areas.¹⁹ At positive tip bias of 2 V, the apparent barrier heights averaged from the slope of the current-distance curves is 3 and 3.85 eV for Au/GaAs and GaAs respectively. The STM images on the Au-patterned area reveal the granular nature of evaporated Au films with typical grain size and height on the order of 100 Å and 10 Å respectively. The STM images on bare GaAs are featureless except for occasional local bright features that are attributed to nonconducting impurities or oxides due to the *ex situ* fabrication process.²⁰

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