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Nanometer-Scale Current-Voltage Spectra Measurement of Resonant Tunneling Diodes Using Scanning Force Microscopy

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This paper demonstrates that current-voltage (I-V) spectra measurement by scanning force microscopy (SFM) reveals local electrical characteristics of resonant tunneling diodes (RTDs) on a nanometer scale. Measured SFM I-V spectra of RTDs show negative differential resistance features, and the spatial resolution of this method was found to be 20 nm. High spatial resolution of this method was confirmed by an experimental evidence for a quantized nature in an SFM point-contact and a simple calculation for the current flowing area through RTD.

1. Introduction

Characterization of electrical properties on a nanometer scale is important for fabricating deep submicron Si devices and quantum-effect compound-semiconductor devices. Among the most important properties to be characterized are the electrical properties of subsurface interfaces. Scanning tunneling microscopy (STM) and scanning force microscopy (SFM) has been widely used to characterize semiconductor devices because of their high spatial resolution. To date these techniques have enabled two-dimensional delineation of p-n structures,[1] doping profiling,[2] and potential distribution measurement.[3] However, these measurements only deal with local electrical properties on sample surfaces or on cleaved surfaces, and gave no information about local current-voltage (I-V) characteristics or local properties of subsurface interfaces. One unique technique that makes it possible to observe the subsurface interface properties is ballistic electron emission microscopy (BEEM).[4] It reveals large spatial variation in Au/GaAs Schottky characteristics on a nanometer scale. However, most of the reported work has been limited to the characterization of Schottky barrier structures.

In this paper, we demonstrate that SFM I-V spectra measurement can reveal the local I-V characteristics of a resonant tunneling diode (RTD) on a nanometer scale. High spatial resolution of this method was confirmed by an experimental evidence for a quantized nature in the SFM point-contact and a simple calculation for the current flowing area through RTD.

2. Experimental

A schematic diagram of SFM I-V spectra measurement is shown in Fig. 1. The spectra were measured in the SFM contact mode. A ramp bias voltage with a typical sweeping time of 100 ms was applied between the conductive tip and the lower electrode of the sample. Current was monitored with a highly sensitive current-voltage amplifier connected to a conductive tip. The minimum detectable current is 10 pA and the maximum current is 100 nA. The measurements were carried out in an air ambient at room temperature. An Au/Cr-coated Si cantilever with a spring constant of 0.16 N/m was used for the measurement. RTDs with a GaAs(well)/$Al_{0.3}Ga_{0.7}As$(barrier) heterostructure were fabricated by metalorganic vapor phase epitaxy.[5] The well layer is 14 monolayers (ML) thick and the barrier layer is 12 ML thick. A 30-nm-thick undoped GaAs layer, which is not shown in Fig. 1 for the simplicity, was used as a spacer layer between the n^+-GaAs layer and the $Al_{0.3}Ga_{0.7}As$ barrier layer. A 300-nm-thick metal electrode and a 350-nm-thick n^+-GaAs layer were use to make ohmic contact with the heterosructure.

3. Results and Discussion

3.1 SFM I-V spectra of RTD

Figure 2 shows typical I-V spectra of an RTD measured by a conventional prober and ah SFM methods. An SFM I-V spectrum shows negative differential resistance (NDR) feature that is similar to those obtained by a conventional prober method. We observed the peak-to-valley current ratio of 1.8 with a small peak voltage shift, as shown in Fig. 2(b). The observed small peak current in the SFM spectrum, which is one-millionth of that observed by a conventional prober method, indicates that the current flows in a small area a few hundreds square nanometers. The peak voltage shift is attributable to the potential drop in the n^+-GaAs layer, which will be described in the later section.

The spatial resolution of this method was experimentally determined as the minimum distance between the normal site showing an RTD feature (solid line in Fig.2(b)) and the breakdown site showing a linear feature (dotted line in Fig.2(b)) intentionally obtained by applying excess current through RTD. The spatial resolution was measured to be 20 nm for the RTD used in this work. Moreover, we found that the spatial resolution of this method depends on a sample structure and the spatial resolution for Au/GaAs Schottky diodes is 5 nm.

The measured I-V spectra reflect the electrical characteristics of the subsurface interface and layer when the tip is located within a grain boundary of the electrode metal. Hence, a two-dimensional current image at a constant bias voltage obtained with scanning the tip can provide spatial variation of subsurface electrical characteristics. Our recent result revealed one-monolayer fluctuation of thickness and deviation of the In mole fraction for InGaAs well with a 20 nm spatial resolution.[6]

3.2 Analysis of high spatial resolution

A high spatial resolution of this method is explained by the collimated carrier injection[7] from the quantized point-contact[8] to the metal electrode, the potential drop in the n^+-GaAs region, and the nonlinear feature of RTD spectra.

3.2.1 Quantized point-contact nature and collimated carrier injection

An evidence for the quantized nature of an SFM point-contact was obtained through the contact resistance measurement with varying force imposed on an SFM tip. An SFM tip covered with thin metal film shows a high contact resistance of more than $1\text{x}10^7\ \Omega$, and the contact resistance can easily become infinite during the measurement. However, by employing a 40-nm-thick Au/10-nm-thick Cr double metal layer, contact resistance of an SFM tip was reduced to about $1\text{x}10^4\ \Omega$. This SFM tip shows the quantized point-contact nature. Figure 3 shows the imposed force dependence of the contact resistance between an SFM tip and sample (graphite). We used graphite as a standard sample for the measurement because it has an atomically flat surface with uniform electrical characteristics. If contact resistance follows macroscopic characteristics, the contact resistance should be proportional to the minus two-third power of the force imposed on an SFM tip. In contrast, the observed contact resistance drastically decreases in the low force region and is quantized in units of $h/2e^2$.

In addition to the point-contact nature, a blunt SFM tip with 25 nm radius and a small contact radius of 1 nm can provide a collimation effect on the carrier beam injected from an SFM tip into the metal electrode due to the flaring of the potential boundary of the SFM tip. The full opening angle of carrier beam was calculated as small as 6 degrees. Moreover, the electric field perpendicular to the electrode in the metal region suppresses lateral carrier diffusion, and results in a small current injected area at the electrode/n^+-GaAs interface. We estimated an injected current-radius r_i at this interface is about 10nm.

3.2.2 Current flowing area in the heterostructure

The current injection in a small area at the electrode/n^+-GaAs interface allows us to assume a conical current flow through the n^+-GaAs and the heterostructure for calculating an effective current-radius r_e in the heterostructure. For the calculation, we took account of the nonlinear I-V characteristics of RTD. Nonlinearity was estimated from the spectrum shown in Fig.2(a); when the applied voltage to the sample decreases from the peak voltage V_p to a half of that, the current decreases by 80 %.

Figure 4 shows the calculated result for the dependence of the effective current-radius r_e in the heterostructure on the injected current-radius r_i at the electrode/n^+-GaAs interface. An r_e increases with r_i and has a small value of five times larger than r_i even though carriers travel a long distance in the n^+-GaAs and the heterostructure. This current concentration in a small area is ascribed to a potential drop in the n^+-GaAs region and the nonlinear I-V characteristics of RTD. A potential drop is caused by the different current-radius r dependence of resistance for the n^+-GaAs and the heterostructure. Resistance of the n^+-GaAs layer was calculated as being proportional to r^{-1} while that of the heterostructure to r^{-2}. Then, the potential drop in n^+-GaAs layer increases with a current-radius. This result in a decrease in the voltage across the heterostructure, and a decrease in a current acording to the nonlinear I-V characteristics of RTD. With an injected current-radius r_i of 10 nm, an effective current-radius r_e in the heterostructure was calculated as 55 nm, which is in agreement with the measured spatial resolution.

4. Conclusion

A novel nanometer-scale electrical characterization method using SFM was proposed and successfully applied to GaAs/AlGaAs RTDs. The measured spatial resolution of this method was found to be 20 nm. The quantized nature of SFM tip point-contact was first observed. A simple calculation manifests that the spatial resolution is determined by the collimated carrier injection from the quantized point-contact to the metal electrode, the potential drop in the n^+-GaAs region, and the nonlinear feature of RTD spectra.

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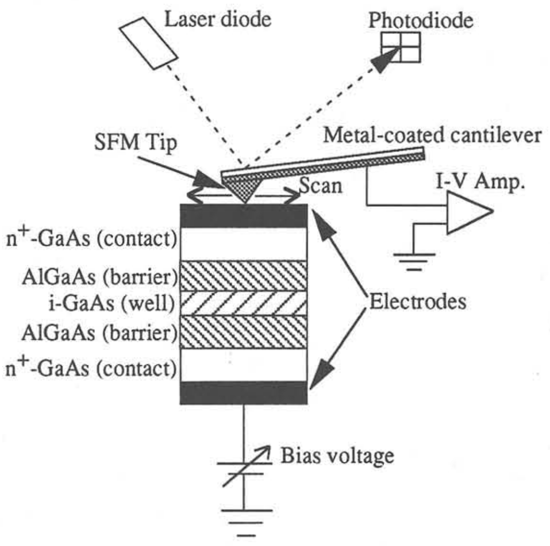

Fig.1 Schematic diagram of SFM I-V measurement of RTD. Bias voltage is applied between a conductive tip and the lower electrode of RTD. The current is monitored by a current-voltage amplifier connected to a tip.

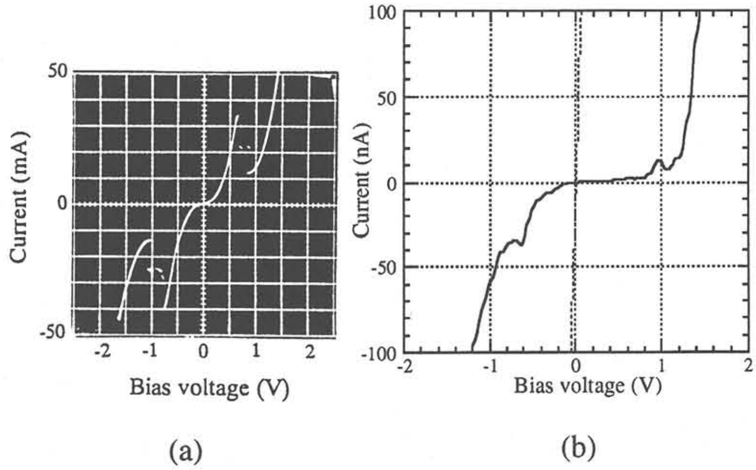

Fig.2 I-V characteristics of RTD measured by (a) a conventional prober method and (b) an SFM I-V method. Solid line in (b) shows normal NDR features and dotted line shows a degraded I-V characteristics obtained by applying an excess current through the RTD. These two spectra were obtained at two different sites 20 nm apart.

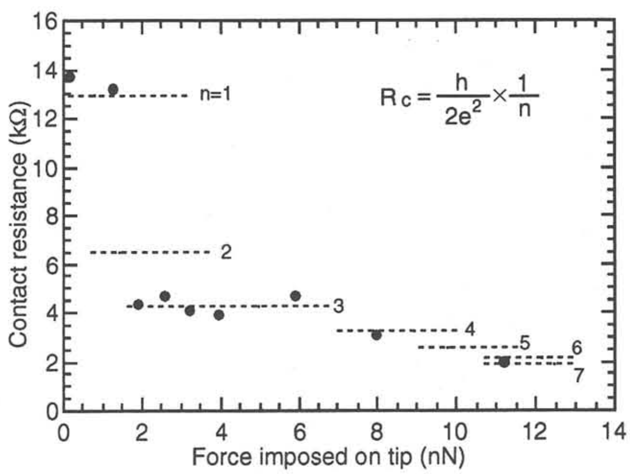

Fig.3 Imposed force dependence of a contact resistance between SFM tip and sample (graphite). Observed contact resistance is quantized in units of $h/2e^2$. Dotted lines parallel to the horizontal axis correspond to the calculated resistance values of $h/2ne^2$ (n integer).

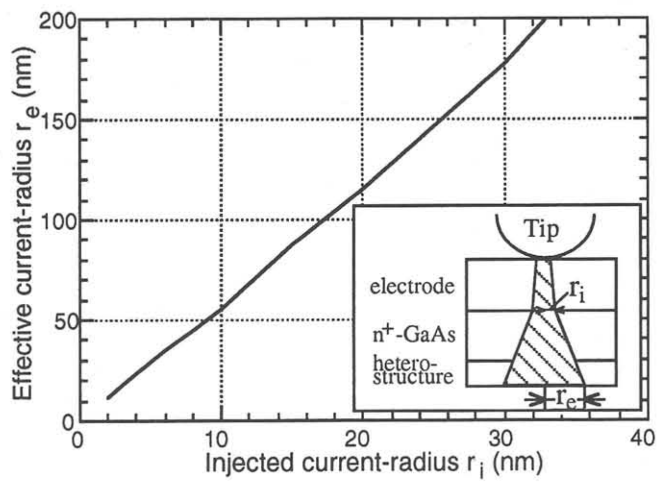

Fig.4 Dependence of the effective current-radius r_e in the heterostructure on an injected current-radius r_i which is a radius of the current flowing area at the electrode/n $^+$-GaAs interface. The injected current-radius r_i was estimated about 10 nm by taking account of a carrier collimation. In addition, a potential drop in the n $^+$-GaAs and nonlinear I-V characteristics of RTD result in a current concentration in a small area with 55 nm in diameter. Inset shows schematic drawing of the current flow.