Extended Abstracts of the 2003 International Conference on Solid State Devices and Materials, Tokyo, 2003, pp. 812-813

D-8-4L

Nanoscale Profiling of Surface Potential Across Silicon p-n Junctions by Scanning Resonance Tunneling Spectroscopy

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1. Introduction

Progressive shrinkage of electron devices requires reliable quantitative carrier profile measurements capable of ultimate spatial resolution down to 1 nm. While scanning tunneling microscopy (STM) has been used for visualization of Si p-n junctions [1] and MOSFET's [2], quantitative evaluation of carrier density has not yet achieved. Moreover, the lack of available carriers makes it difficult to maintain tunneling conditions in the depletion region, leading to unusual variation in STM probe/ sample surface distance at p-n junctions [2].

Here, we present a new approach to surface potential profiling making use of resonant electron tunneling (RET) through discrete energy levels of marker molecules (e.g. C_{60} molecules) placed on top of oxidized Si surfaces. We show that energy levels of C_{60} shift with carrier concentration at p-n junctions, which provides direct, quantitative technique for measurements of the surface potential profile.

2. Results and Discussion

Measurement principles

Figure 1 illustrates basic principles of surface potential measurements with marker molecules. When C_{60} molecules are placed within the STM tunnel junction, enhanced conductance of the junction occurs at a bias voltage $V = E_{RET}$ corresponding to resonance electron injection into the Si bulk through discrete levels of C_{60}. The energy E_{RET} varies with the Si Fermi energy E_f and, thus traces the surface potential.

Sample structure

Planar p-n junctions were prepared in a Si(100) wafer (B-doped, ~10^{17} cm^{-3}) by As ion implantation at 30 keV to a dose of 10^{15} cm^{-2}. The mask pattern was defined by e-beam lithography, and consisted n-type stripes with a nominal width of ~350 nm separated by non-implanted p-type regions of ~150 nm and 2 μm widths. After dopant activation in N_2 gas at ~800ºC for 30 min., the sample was chemically cleaned and etched in HF:HCl (1:19) solution.

Oxidation was performed by exposing the surfaces to molecular oxygen at a pressure of ~10^{-5} Torr and either (i) 490ºC for 10 min. or (ii) room temperature (RT) followed by annealing at 400ºC, resulting in a smooth, ultra-thin (~0.3 nm) oxide layer [3]. Mono-molecular thick C_{60} films were obtained by vapor deposition of C_{60} at RT followed by short annealing at 150 – 170ºC; details on this technique have been described elsewhere [4].

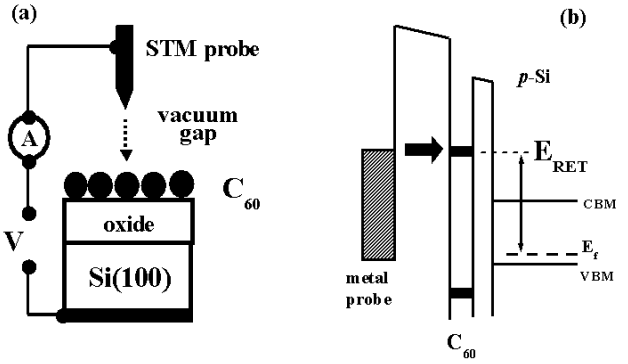

Fig. 1 Sample structure (a) and energy diagram (b) of STM tunnel junction for surface potential profiling.

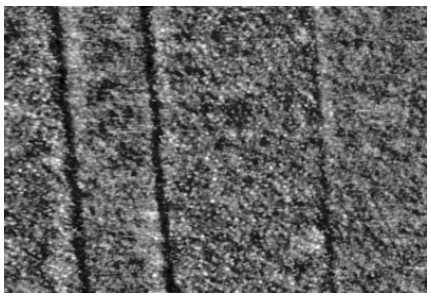

Fig. 2 STM topograph of narrow (p-type) and wide (n+-type) stripes covered with 1-ML C_{60} film. The gray-scale is 2.7 nm (image area 600x400 nm^2; sample bias +2.5 V, tunneling current 0.15 nA). The black vertical lines are the geometrical trenches.

STM measurements

Tunneling spectroscopy measurements were done in ultra-high vacuum (~4 10^{-9} Pa) at RT. STM probe tips (~10 nm in diameter) were prepared from a single crystalline W(111) wire and cleaned *in-situ* with field-emission microscopy. Current-voltage (I-V) characteristics were obtained by opening the current feed-back loop and ramping sample voltage while measuring tunneling current. The initial tunneling conditions were set by tuning the tunneling current in the range of 0.1 – 5.0 nA under an applied bias voltage of 1.2 - 2.8 V corresponding to electron injection from the probe tip into the substrate. Conductance (dI/dV) spectra were obtained by superimposing a small *ac* voltage (15 mV_{pp}, 30 kHz) on the bias voltage, and current response was measured with a lock-in amplifier simultaneously with I-V acquiring under

dark conditions.

The geometrical trenches (~1 nm in depth) separating p- and n- regions (Fig. 2) were produced by implantation process and used as good fiducial for junction edges.

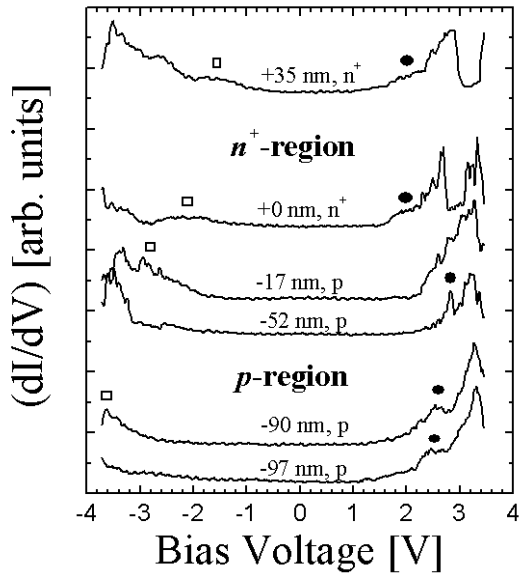

Fig. 3 (dI/dV) spectra across a p-n junction. The numbers are distances from the junction edge. The symbols indicate RET peaks of C_{60}. (initial tunneling conditions: +2.5 V, 1 nA)

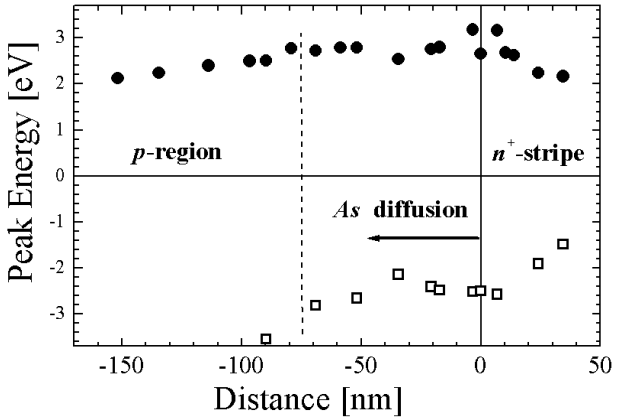

Fig. 4 Energy position of RET peaks *vs* distance to the junction edge. The As diffusion length agrees with the SIMS profile (As ~2 10^{21} cm^{-3}).

We found that height difference between p- and n-stripes was ~1 nm for C_{60} overlayer at a bias voltage of +2.5 V (see Fig.2), while the height difference was ~ 3 nm in the depletion region without the overlayer. This fact indicates that conductance of the C_{60} overlayer maintains constant tunneling gap even in the highly resistive depletion region between p- and n- stripes.

Resonant tunneling spectroscopy of C_{60}

I-V characteristics demonstrated diode-like behavior of the metal probe/insulator/ silicon junction for moderately doped substrates. With the C_{60} overlayer, the STM current increased non-monotonically with bias voltage, and two peaks in (dI/dV) spectra reproducibly appeared at positive bias voltage both in p-type and n-type regions, while no structure was observed in the p-type region at negative bias voltage (Fig.3). Conductance (dI/dV) maps showed that the peaks were localized within the C_{60} molecules (~1 nm), indicating that they originated in resonance-like tunneling mediated by the unoccupied C_{60} orbital.

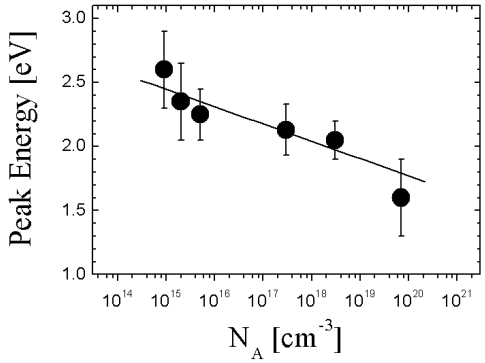

Fig. 5 Energy of the RET peak *vs* dopant concentration N_a.

Potential profile at p-n junction

The RET peaks energies shifted across the p-n junction (Fig. 4), indicating the presence of surface potential variation in this region. The appearance of RET peaks at negative bias shows that the n-region extends to ~70 nm from the geometrical junction edge owing to As diffusion. The energy shift of RET peaks was also observed for bulk substrates with different doping concentrations (Fig. 5), which served as a calibration standard. Using the calibration we obtained a hole concentration of N_a= ~3 10^{17} cm^{-3} in the p-region in agreement with the SIMS profile (B ~2 10^{17} cm^{-3}). Similar RET energy shift was obtained for 5 other potential profiles of p-n junctions, demonstrating the reproducibility.

3. Conclusions

The results demonstrate that the discrete resonance level of C_{60} placed on oxidized Si surfaces can be used as an energy marker for quantitative surface potential profile measurements with a spatial resolution down to the molecule diameter (~1 nm).

Acknowledgements

The work was supported in part by NEDO (Japan).

References

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