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Quantitative Evaluation of Dopant Concentration in Shallow Silicon p-n Junctions by Tunneling Current Mapping with Multimode Scanning Probe Microscopy

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1. Introduction

In LSI device fabrication, distribution of dopant atoms and carriers in shallow structures has been a critical factor altering the device performance. The ability of scanning tunneling microscopy and spectroscopy (STM/STS) to visualize individual dopant atoms and the electric potential have been demonstrated.[1-3] However, quantitative evaluation of actual impurity profile is a tremendous challenge because the probe-sample distance (a tunnelling gap) changes to maintain the predetermined tunneling current in p-type and n-type regions. *Variable* tunneling gap in the STM mode requires a sophistication of the current simulation technique to extract the impurity profile.[4] Here, we presented a modified SPM-based method where the tunneling gap maintained constant across regions with different dopant concentration by using an repulsive force acting on the SPM probe. We showed the advantages of the *constant-gap* method for *quantitative* analysis of impurity profiles in shallow Si *p-n* junctions.

2. Tunneling current at constant gap

Quantitative evaluation of impurity profiles is based on the sensitivity of STM tunneling current (I_{tun}) to the impurity concentration through: (i) amount of mobile carriers supplied from the semiconductor, and (ii) transparency of the tunneling barrier, the tunneling factor. For a given tunneling gap Z_0 and bias voltage V_S, the tunneling factor is modulated by the gap voltage (V_{gap}) as shown in Fig.1. According to the Gauss's law, V_{gap} relates to the total charge density per unit surface area (Q_S) as [5]

$$\frac{|V_{gap}|}{Z_0} = \frac{|Q_S|}{\varepsilon_0} = \frac{|Q_{fix} + Q_{mob} + Q_{trap}|}{\varepsilon_0} \qquad (1)$$

where ε_0 is the dielectric permittivity in vacuum gap. Q_S is defined by a sum of donor and acceptor charges (Q_{fix}) in the band bending region, mobile charge carriers (Q_{mob}) supplied from the bulk, and surface traps (Q_{trap}). Because Q_{fix} and Q_{mob} depend on the band-bending potential ($V_{bb} \approx V_S - V_{gap}$), both the tunneling factor and the amount of supplied carriers determine the I_{tun} value. Thus, the impurity concentration can be obtained from tunneling current.[4]

To keep the same tunneling gap across regions with different impurity concentration, we employed an atomic force microscopy (AFM) mode where force acting on the sharp metal probe maintained constant. To reduce the electrostatic force effect, we measured the force gradient in the repulsive regime as a shift (Δf) in resonance frequency of a quartz linear-extension-resonator cantilever (qLER) operating at ~1 MHz and a vibration amplitude of ΔZ=0.3 nm.[6] The mean I_{tun} was recorded when the probe-sample distance was stabilized at Δf=1.5 Hz.

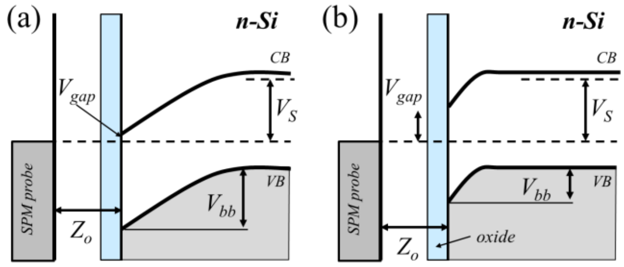

Fig. 1 Energy band diagrams of tunneling junctions (not to scale) for n-Si under external bias voltage Vs<0 for a donor concentration of N_1 (a) and N_2(b), $N_1 < N_2$.

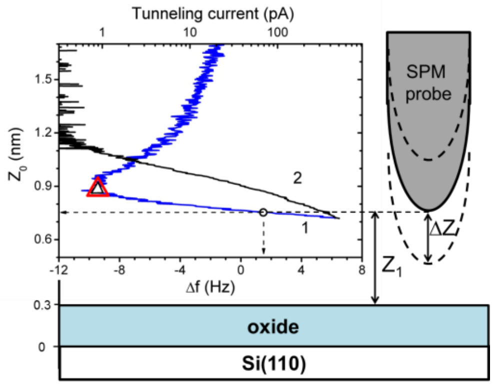

Fig.2 Calibration of the tunneling gap for oxidized Si surfaces. (1)Δf and (2) I_{tun} as a function of probe-sample distance Z.

To calibrate the probe-sample distance, a (Δf-Z) spectrum was measured as shown in Fig.2. A position in the (Δf-Z) curve (marked by Δ) equals to (ΔZ + a_0), where a_0=0.28 nm is the minimum in force gradient of the Lennard-Jones potential.[7] Thus, including the oxide thickness (0.3 nm), we obtained Z_0 ~0.75 nm for Δf=1.5 Hz.

3. Tunneling current profiles across *p-n* junction

Sample structure

Samples with *p-n* junctions were prepared according to the nominal CMOS fabrication process where Sb ions were implanted to a peak concentration of ~5x10^{19} /cm^3 into a p-Si(001) substrate (boron, 1x10^{17} /cm^3). To expose the *p-n* junction, cross-sectional surfaces were made by polishing, and passivated by ultra-thin oxide layers (~0.3 nm) grown at 600°C under an O_2 pressure of $3x10^{-3}$ Pa as described in ref. [1]. Current measurements were done in vacuum at room temperature in dark conditions.

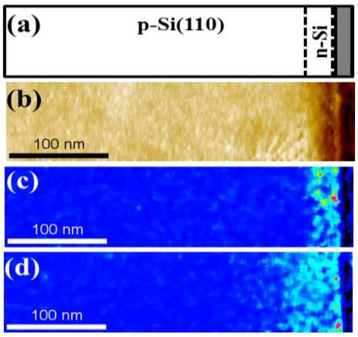

Fig.3 (a) Sample structure, (b) AFM topograph (350x85 nm^2) and (c,d) $|I_{tun}|$ maps taken at Vs=+1.2V (c) and -1.2V (d) with Δf=1.5 Hz and ΔZ=0.3 nm. Color scales are 7 nm (b), 2 nA(c), 1.2 nA(d).

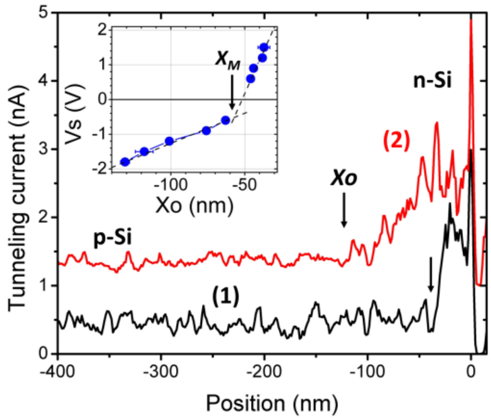

Fig.4 Line profiles of $|I_{tun}|$ as a function of position from the sample edge taken at Vs=+1.2 V (1) and -1.5 V(2). Arrows indicate the electric junction position X_0. Insert is X_0 vs. bias voltage.

Tunneling current profiles

A typical AFM topograph of the *p-n* junction and corresponding current maps are shown in Fig.3, where large absolute values of the AFM tunneling current was observed in the implanted n-Si region near the sample edge at both bias voltages. Current fluctuations in n-Si seen in Fig.3(c,d) were attributed to inhomogeneous impurity distribution.

The electrical junction depth X_0, was clearly seen in tunneling current profiles in Fig.4. From the observed shift of X_0 with bias voltage we determined the depth of the metallurgical junction to be X_M = 60±4 nm.

4. Device simulations

To compare accurately the measured and simulated current values, the measured AFM current value was adjusted by a STM/AFM current ratio of 95. It is because the tunneling current decays exponentially with the gap increase, and mean tunneling current in the AFM mode with a vibrating probe was larger than that in the STM mode with a stationary probe. In fact, measured and simulated AFM currents coincided as seen in Fig.5 for our setup, justifying the calibration relation for Z_0 = 0.6-1.4 nm .

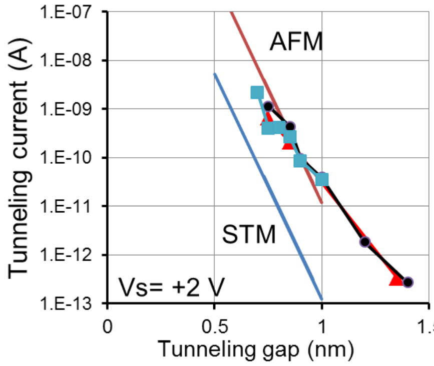

Fig.5. Calculated (I_{tun}-Z_0) curves for STM and AFM modes (solid lines), and different measurements (symbols) for p-Si.

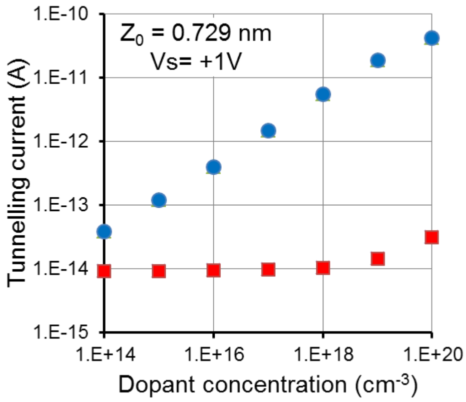

Fig.6. Calculated relationship between STM current and dopant concentration for n-Si (dots) and p-Si (squares) for Z_0=0.73 nm.

The relationship between STM current and dopant concentration such as shown in Fig.6 allows us to translate the current amplitude into dopant concentration in a range of 10^{16}-10^{20} cm^{-3}.

5. Conclusions

We presented a *constant-gap* SPM method for evaluation of impurity concentrations in underlying semiconductor by tunneling current mapping. The results show the ability of the method for *quantitative* analysis of shallow Si *p-n* junctions with improved sensitivity and easy calibration.

Acknowledgements

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