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 \( I_{\text{mm}} \) 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 \( \text{Z}_0 \) and bias voltage \( V_A \), the tunneling factor is modulated by the gap voltage \( V_{\text{gap}} \) as shown in Fig.1. According to the Gauss’s law, \( V_{\text{gap}} \) relates to the total charge density per unit surface area \( \left( Q_3 \right) \) as [5]

\[
\frac{V_{\text{gap}}}{\text{Z}_0} = \frac{Q_3}{\varepsilon_0} = \frac{Q_{\text{i}} + Q_{\text{mob}} + Q_{\text{trap}}}{\varepsilon_0} 
\]

(1)

where \( \varepsilon_0 \) is the dielectric permittivity in vacuum gap. \( Q_3 \) is defined by a sum of donor and acceptor charges \( Q_{\text{i}} \) in the band bending region, mobile charge carriers \( Q_{\text{mob}} \) supplied from the bulk, and surface traps \( Q_{\text{trap}} \). Because \( Q_{\text{i}} \) and \( Q_{\text{mob}} \) depend on the band-bending potential \( V_{\text{bb}} \) \( V_A \) - \( V_{\text{gap}} \), both the tunneling factor and the amount of supplied carriers determine the \( I_{\text{mm}} \) 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 \( \Delta f \) in resonance frequency of a quartz linear-extension-resonator cantilever (qLER) operating at \( \sim 1 \) MHz and a vibration amplitude of \( \Delta Z = 0.3 \) nm.[6] The mean \( I_{\text{mm}} \) was recorded when the probe-sample distance was stabilized at \( \Delta f = 1.5 \) Hz.

![Image](image1.png)

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

![Image](image2.png)

Fig.2 Calibration of the tunneling gap for oxidized Si surfaces. (1)\( \Delta f \) and (2) \( I_{\text{mm}} \) as a function of probe-sample distance \( Z \).

To calibrate the probe-sample distance, a \( (\Delta f-Z) \) spectrum was measured as shown in Fig.2. A position in the \( (\Delta f-Z) \) curve (marked by \( \lambda \)) equals to \( (\Delta Z + a_0) \), 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 \( Z_0 \sim 0.75 \) nm for \( \Delta f = 1.5 \) 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 \((5 \pm 10^{19}) \) /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 O₂ 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 nm²) and (c,d) |I₁|₀ maps taken at Vs=+1.2 V (c) and -1.2 V (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 |I₁|₀ 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 X₀. Insert is X₀ 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 X₀ was clearly seen in tunneling current profiles in Fig.4. From the observed shift of X₀ with bias voltage we determined the depth of the metallurgical junction to be X₀=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 Z₀=0.6-1.4 nm.

**Fig.5** Calculated (Iₓ₀-Z₀) curves for STM and AFM modes (solid lines), and different measurements (symbols) for p-Si.

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 10¹⁶-10²⁰ 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.

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**References**