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Analysis of Semiconductor Dopant Profiling by Measurement of Voltage Distribution on Surface with Electrostatic Force Microscope

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Abstract: Electrostatic force microscope (EFM) we developed can measure voltage on surface (V_s) up to 1 kV in atmosphere with extremely high sensitivity (~20 mV) as well as high spatial resolution (~10 μm). We applied the EFM to measure impurity distribution. It is revealed that the measured V_s showed opposite voltage in polarity depending on n- or p-type dopant. The V_s should correspond to work function difference between sensor metal and Si substrate to keep flat-band condition of Si substrate. We could observe density distribution of impurities with EFM by this method.

1. Introduction

Density distribution of doped impurity in semiconductor is one of the key factors to determine device characteristic. In particular, evaluations of semiconductor in fabrication process are important to ensure the functionalities of new devices.

Atomic Force Microscope (AFM) and Kelvin Force Microscope (KFM) applied with cantilevers are useful for evaluation of electronic devices evaluation for including semiconductor devices. However, the sensor (electrode needle) which is located at the free end of the cantilever was too short to measure accurate voltage for conventional KFMs, because the electric field between the cantilever and the surface under test caused unnecessary electrostatic force and developed critical errors[1].

Electrostatic Force Microscope (EFM) we developed can measure highly accurate surface voltage because (1) we have selected a long sensor of which length is 100 μm and (2) we have deployed an electrostatic shield so that we were succesful to reduce measurement error from 42% to 0.1% from fringing electric field[1][3]. We successfully observed surface potential over an organic photoconductor film by our system[2]. We also applied the EFM to measure impurity distribution. The voltage on surface (V_s) should correspond to work function difference between sensor metal and Si substrate to keep flat-band condition of Si substrate. We also succeeded in measuring V_s depending on impurity types. It suggests that impurity density in semiconductor can be measured by EFM.

2. Surface voltage and band condition

In our method, the V_s (voltage on surface) is measured under the condition to keep zero electric force at the sensor. The condition corresponds to keeping flat-band condition of Si substrate, because the charge at the surface of Si substrate is zero under the flat-band condition. Therefore, V_s of semiconductor must depend on density of impurities as shown in Fig. 1. When the sensor voltage is kept at V_s must be equal to the difference between work function of sensor metal φ_m and work function of Si φ_s ($\varphi_m - \varphi_s$).

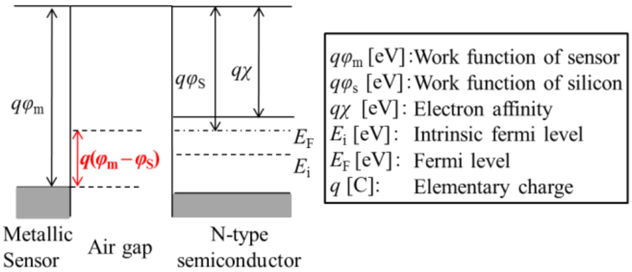

Fig. 1 Band conditions for Si electrically connected with the biased sensor by $\varphi_m - \varphi_s$.

3. Voltage on doped Si wafer evaluation

In our system, we apply AC bias voltage ($V_{AC}\sin\omega t$) to the sensor to vibrate the cantilever. We also apply DC bias voltage (V_{DC}) to the sensor in order to seek out zero electrostatic force (F_ω) condition. When the force F_ω is zero, V_{DC} must be equal to V_s[3].

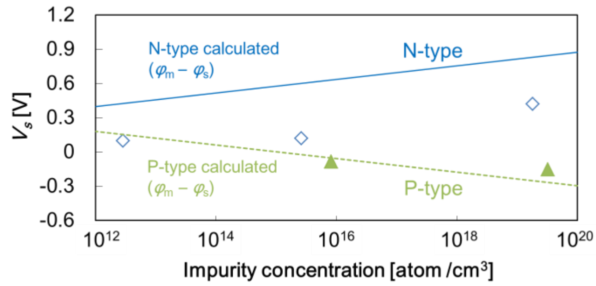

Fig. 2 Measured and calculated voltage on suraface of doped Si, as shown dots and lines, respectively.

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We measured V_s for some Si substrates which were doped with different dopant type and density: N-type (4×10^{12}, 4×10^{15}, 2×10^{19} atom/cm^3), P-type (1×10^{16}, 3×10^{19} atom/cm^3). Measured and calculated work function diffrence between sensor metal and Si substrate ($\varphi_m-\varphi_s$) are shown in Fig. 2. Polarity of measured V_s of N-type and P-type are positive and negative, respectively. Absolute value of V_s increases with impurity density for both types as shown in Fig. 2. The measured V_s depending on dopant density tends to liner relationship as the estimated voltage $\varphi_m-\varphi_s$, even though the value of V_s for N-type is not equal to the estimated value of $\varphi_m-\varphi_s$. Therefore, we can evaluate impurity density distribution of Si substrate by this method. At the next section, the trial for measurement over patterned impurity density is reported.

4. Voltage on surface of partially doped Si evaluation

We measured V_s of partially P-type doped Si. A P-type Si substrate under test is partially doped with boron (10^{19} atom/cm^3) about 0.7 μm in depth by thermal diffusion method on the Si doped with boron (10^{15} atom/cm^3). The doped pattern is a comb structure and its width and period are 100 μm and 200μm, respectively.

The line profiles of measured V_s of doped Si is shown in Fig. 3 (a). The V_s shows the similar result as the previous result shown in Fig. 2. Higher doped area shows low voltage, and lower doped area shows high voltage. The line profile of calculated work function diffrence $\varphi_m-\varphi_s$ between sensor metal and Si substrate is also shown in Fig. 3 (b). The profile of V_s shows similar profile of $\varphi_m-\varphi_s$.

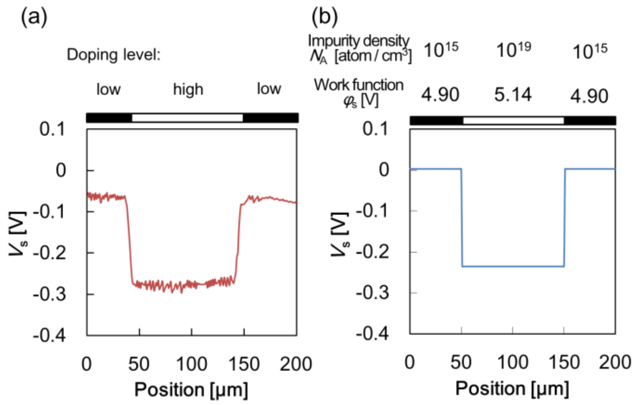

Fig. 3 Measured and calculated voltage distribution on surface over the high doped and low doped Si substrate.

We believe that the work function determines the voltage on surface (V_s), and we expect that the impurity density can be detected by our system, according to the idea of flat-band condition. We will analyze our result and study more details by additional quantitative measurement.

5. Conclusions

We have developed an Electrostatic Force Microscope having a special sensor (extremely long sensor part with an electrostatic shield under cantilever) to minimize measurement error due to fringing electric field. We measured voltage on Si substrate for different dopant densities by the EFM. V_s obtained with EFM shows very close to the work function difference $\varphi_m-\varphi_s$ between metal and semiconductor to keep flat-band condition in semiconductor. We could observe density distribution of impurities well with EFM by this method.

6. References

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