Observation of dopant profile of transistors using scanning nonlinear dielectric microscopy

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Abstract. We have demonstrated that scanning nonlinear dielectric microscopy (SNDM) exhibits high performance and high resolution in observing the dopant concentration profile of transistors. In this study, we have measured standard Si samples, which are known to have one-dimensional dopant concentration values, calibrated by using conventional secondary ion mass spectrometry (SIMS). Good quantitative agreement between the SNDM signals and dopant density values was obtained by SIMS. We succeeded in visualizing high-resolution dopant profiles in n- and p-type channel MOSFET with 40 nm gate channels. It is considered that SNDM would be an effective method in measuring the quantitative two-dimensional dopant profiles of semiconductor devices. Finally, we have observed the dopant depth profiles of an SRAM memory cell by using SNDM, and succeeded in detecting the insufficient extension ion implantation in the PMOS transistor area.

1. Introduction

It is very important to design and analyze Large Scale Integrated Circuits (LSIs) to measure two-dimensional density profiles of the dopant injected into the source/drain and channel area of transistors with high accuracy. In this regard, several analytical methods, which include Scanning Probe Microscopic methods such as Scanning Capacitance Microscopy (SCM) [1] and Scanning Spreading Resistance Microscopy (SSRM) [2], and Electron Holography with a Transmission Electron Microscope [3], have been developed. In those methods, the Scanning Probe Microscopy (SPM) technology is thought to be the most advantageous mainly due to the ease of the sample preparation. The SPM method uses an Atomic Force Microscope (AFM) especially equipped with an electrically conductive cantilever. SCM is a method to measure the distribution of the capacitance change due to an external impressed voltage by using conductive AFM, and SSRM is a method to measure the resistivity distribution.

From our previous studies we have shown the effectiveness of Scanning Nonlinear Dielectric Microscopy (SNDM) of the SPM category [4-7]. This technique has been mainly applied to observe the distribution of the polarization on the surface of ferroelectric materials, for example the polarization distribution of LiTaO₃, the thickness observation of the polarization wall of PbₓZr₁₋ₓT, and the application of the ferroelectric memory that uses nano-size domains, and so on.

In the case of semiconductor applications, the 7×7 surface reconstruction of clean Si surfaces was detected by the high-resolution observation in a high vacuum [8]. We have also succeeded in visualizing the charges in nonvolatile flash memory by using SNDM [9, 10]. In order to apply SNDM...
to LSI analysis here, we report on the measurement of the dopant concentration profile of the source-channel-drain area in transistors.

2. SNDM

A schematic diagram of the SNDM system [4-7] is shown in Figure 1. SNDM is one of the microwave microscopy measurement techniques that use an AFM where a ring electrode is used together with a cantilever. In this method, an alternating electric field $E \cos \omega t (E = V/d$, where $V$ is the amplitude of the applied voltage, $d$ is sample thickness, and $\omega_p$ is angular frequency) is applied between the electrode and the sample, and the capacitance ($C(t)$ of Figure 1) variation of the sample surface under the cantilever tip is detected as a change in the resonance frequency of the $LC$ resonant circuit: due to the change in capacitance, the SNDM probe generates a frequency shift of the $LC$ circuit as a frequency modulated (FM) signal. By detecting the FM signal with an FM demodulator and a lock-in amplifier, we can obtain a voltage signal proportional to the capacitance variation. In Figure 1, the distance between the ring electrode and the tip is much shorter than the wavelength of the oscillating microwave, so that the stray impedance in the electrical circuit is sufficiently small, and consequently quite a small variation in capacitance is able to be detected. The sensitivity of the capacitance variation of SNDM is about $10^{-22}$, consequently quite a small variation in capacitance is able to be detected. The sensitivity of the oscillating microwave, so that the stray impedance in the electrical circuit is sufficiently small, and consequently quite a small variation in capacitance is able to be detected. The sensitivity of the capacitance variation of SNDM is about $10^{-22}$, consequently quite a small variation in capacitance is able to be detected. The sensitivity of the capacitance variation of SNDM is about $10^{-22}$, consequently quite a small variation in capacitance is able to be detected.

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3. Results and Discussion

3.1 Standard Sample

As the first stage, the measurement of the distribution of the dopant profile of standard samples with control dopant density was made by SNDM. The standard samples used in this study were epitaxial multilayer Si on n- and p-type wafers. The dopant densities were different from layer to layer. For SNDM studies, the epitaxial Si wafers were cut, and their cross sections were mirror polished.

The dopant concentrations were measured by SIMS, and the SNDM signals and the dopant concentrations obtained from SIMS were correlated. Figure 2 shows an example of the SNDM measurement result of the epitaxial multilayer film of the standard specimen. Figures 2(a) and 2(b) are SIMS images of n-type and p-type samples, respectively. Figures 2(c) and 2(d) are the SNDM signal strength distributions obtained by averaging the scanning data of each image of 32 SNDM lines. In the SNDM images of 2(c) and 2(d), the highly doped layer exhibits a black contrast in the n-type sample whereas a bright contrast in the p-type sample. The existence of 5 layers and 7 layers with different dopant concentrations were confirmed in n-type and p-type samples, respectively. The width of the plateau area corresponding to each layer was found to be about 4-5 μm, and this was found to be in good agreement with the SIMS results. Figure 3(a) gives the calibration curves of the SNDM signal vs. density distribution (obtained from SIMS) and Figure 3(b) provides calibrated results. SIMS and SNDM agree well in the density range from $1 \times 10^{17}$ cm$^{-3}$ to $1 \times 10^{19}$ cm$^{-3}$ for p-type and from $1 \times 10^{16}$ cm$^{-3}$ to $1 \times 10^{18}$ cm$^{-3}$ for n-type. The higher concentration ranges of these calibration curves can be approximated by a simple power law. As mentioned above, SNDM signals corresponding to the dopant density of each level of the epitaxial multilayer film were obtained.

3.2 Transistor Observation

Next, the dopant profile of a transistor was observed as a true application of the above mentioned experiments. We succeeded in obtaining density profiles of the cross sections of both n- and p-channel transistors by measuring SNDM and using the calibration curves of the correlation samples. Figure 4 gives SNDM data of the cross section of a 90 nm node p-channel transistor. This transistor sample was made using the same conditions as for the standard specimen. Figure 4(a) illustrates SNDM image of the transistor of the cross section and Figure 4(b) gives the y-y’ line signal strength distribution across the source and the drain. We used the calibration curve of Figure 3 to calculate the SNDM signal of the density distribution. As a result, two dimensional concentration profiles of the transistor sections were obtained.
obtained. Therefore, a quantitative measurement of the two-dimensional distribution of the dopant concentration in the semiconductor device is thought to become possible by using the method mentioned above. However, it is necessary to compare this data with SSRM to find out whether the dopant profiles by the SNDM measurement are correct. Figure 5 shows the SNDM image of 65 nm node N- and PMOS transistors. Both NMOS and PMOS, 40 nm length channel areas were clearly resolved by this method [11].

3.3 Application to failure analysis

We will explain an example of analyzing a single defective bit of SRAM of 90 nm design as an application of this method to defect analysis. Figure 6 shows a section of a TEM image of p-channel of an SRAM cell transistor together with the SNDM image of the same part. As can be seen from this figure, the source/drain and the channel of a pair of transistors are clearly visible.

Next we will explain the results of a failed SRAM transistor. From the results of the failed PMOS transistor, it can be said that the main causes of the transistor defects would be the high resistance due to a lack of injection of ions into the diffusion area of the transistor, the abnormal high resistivity of the contact, and so on. Figure 7 shows an electron beam induced current (EBIC) image of a failed bit cell transistor and the SNDM image of the same part. In this figure, the diffusion area is marked with a dotted circle. The response is weak in this area in the EBIC image. On the other hand, the extension part of one side of the diffusion zone seems to be narrower than the other side of the SNDM image, and the channel seems to be longer. This shows that the amount of the ion implantation into this area is insufficient. In this study, we have succeeded in making visible the lack of extension of ion implantation into the region underneath the spacer of a PMOS transistor in an actual device of a 90nm SRAM cell.

4. Conclusion

With the present study we have successfully paved the way to determining dopant profiles and analyzing the defects of transistors through SNDM measurements.

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