Investigation of the lateral spread of erbium ions implanted in silicon crystal*

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The erbium ions at energy of 400 keV and dose of 5×10^{15} ions/cm^2 were implanted into silicon single crystals at room temperature at the angles of 0°, 45° and 60°. The lateral spread of 400 keV erbium ions implanted in silicon sample was measured by the Rutherford backscattering technique. The results show that the measured values were in good agreement with those obtained from the prediction of TRIM'98 (Transport of Ions in Matter) and SRIM2006 (Stopping and Range of Ions in Matter) codes.

Keywords: erbium ion implantation, silicon, Rutherford backscattering technique, lateral spread
PACC: 3450D, 6170T, 6630J

1. Introduction

Along with the integrated density of integrated circuits chips becoming more and more high, the influence of lateral spread of implanted ions becomes more and more important. Especially for today's deep-submicrometer devices, lateral straggling of the impurity concentration profiles of implanted ions significantly affects the device characteristics. Therefore, the data of the lateral spread of implanted ions in solids are significant in semiconductor device technologies. Since the early 1960s a great deal of work,[1−6] both theoretical and experimental, have been performed to investigate the range profiles and range straggling of ions implanted into solids. In the early 1960s, several researchers partially estimated the lateral spread of implanted ions as well as the projected range $R_{\rm p}$ and the projected standard deviation $\Delta R_{\rm p}$, based on the theory of Lindhard, Scharff and Schiøtt[1] (LSS theory). In 1970s, Furukawa and Matsumyra H[7] presented some improved theoretical analysis on the lateral spread of the distribution for implanted ions in solid targets, and proposed a new method to measure the lateral spread, but only a few of experimental studies have been reported.[8,9] However, the works concerning the lateral spreads of ions implanted in solids have not been done sufficiently, especially in experimental studies.

Erbium (Er) ions are of great importance is modern communication systems due to its photoluminescence emission at 1.5 μm band.[10] Ennen and Schneider *et al.*[11] first reported the observation of 1.54 μm photoluminescence (PL) due to Er in GaAs and Si, and later related research interest in Er-doped Si is growing rapidly because this substrate is one of the interesting semiconductors that has wide applications in the fibre optics telecommunication systems. PL and electroluminescence (EL) of Er-doped Si have been studied extensively.[11−17] And several papers[18,19] reported the measurements of the range distributions of Er ions implanted into Si crystal. To our knowledge, there has been no report on the study of the lateral spreads of implanted keV Er ions in single crystal Si.

In the present work, the depth distribution and the lateral spreads of implanted Er ions in Si are obtained by Rutherford backscattering (RBS) technique. The experimental lateral spreads are compared with those obtained by the simulation from the TRIM'98 (Transport of Ions in Matter) and SRIM2006 (Stopping and Range of Ions in Matter) code.[20]

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2. Experiment

Three polished n-type single crystal silicon wafers (named sample 1 to 3) of [100] orientation with 5 $\Omega \cdot$cm resistivity were used as samples. They were cleaned by the standard procedure before irradiation. The Si single crystal samples were implanted at room temperature (RT) with 400 keV Er ions (at dose of 5×10^{15} ions/cm^2). Sample 1 was implanted with Er ion beams perpendicularly (in fact, in order to avoid the channeling effect, ion implantation has been performed at a titled 7° off the normal plane of the sample surface, which would result in an error less than 1%). In order to obtain the lateral spread, tilted angle implantations have been performed at 45° and 60° for sample 2 and 3. The voltage (determining the energy of the implanted ions) of the implanter was calibrated by high-tension voltmeter. To avoid excessive heating of the samples, the incident current density was less than 1 μA/cm^{-2}. In order to ensure uniformity over the implanted area, an electrostatic scanning system was used.

The depth distribution of Er ions implanted under differently tilted target was analysed by the RBS technique. RBS spectrometry was performed using 2.1 MeV He^{2+} ion beam generated by a 1.7 MV tandem accelerator with a beam current around 10 nA. The samples were mounted on a three axis goniometer driven by a pulse motor in a vacuum chamber. A surface barrier detector at an angle of 165° with respect to the incident beam was used to detect the backscattered particles. All the experiments were performed in a vacuum of 2.66×10^{-4} Pa.

The implantations of ions were performed on an ion implanter at the Institute of Semiconductors, Chinese Academy of Sciences. The RBS measurements were carried out at 1.7 MV tandem accelerator of the Shandong University.

3. Results and discussion

According to the work by Furukawa and Matsumura,[7] the lateral straggling of an implanted ion in Si crystal can be put into the depth distribution of a target under tilted angle implantation. If the spatial probability distribution of the deposited ions is three-dimensional Gaussian, the depth distribution for a target tilted at an angle to the incident ion beam also becomes Gaussian with standard deviation ΔD. We have denoted the lateral straggling and range straggling (longitudinal straggling) by $\Delta X_{\rm L}$ and $\Delta R_{\rm p}$, respectively. Then the lateral spreads could be calculated by using Furukawa's formula:[7]

$$(\Delta D)^2 = (\Delta R_{\rm p})^2 \cos^2\theta + (\Delta X_{\rm L})^2 \sin^2\theta. \quad (1)$$

The lateral straggling $\Delta X_{\rm L}$ can be estimated from two measurements of ΔD for two different implantation angles θ. In general, the depth distributions are not Gaussian absolutely; only in a small energy range of the incident ion is the distribution close to a Gaussian. Therefore, Furukawa and Matsumura's method can only be approximately correct.

In Fig. 1, a typical RBS spectrum for Si sample vertically implanted with 400 keV, 5×10^{15} ions/cm^2 Er ions at RT is presented. From the spectrum, the average projected range $R_{\rm p}$ and the range straggling $\Delta R_{\rm p}$ of Er ions in Si crystal can be calculated by the surface energy approximation if the depth distribution of Er ions is Gaussian.[21]

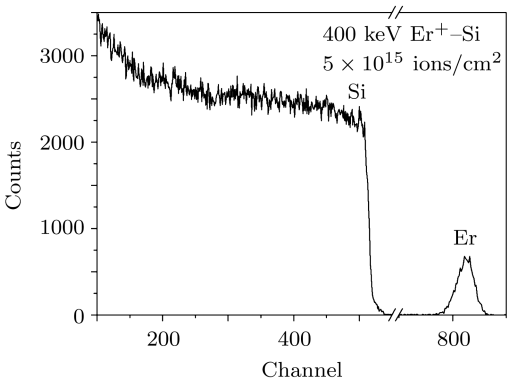


Fig. 1. Typical RBS spectrum for Si sample vertically implanted with 400 keV, 5×10^{15} ions/cm^2 Er ions at RT.

Figure 2 shows the depth distributions of 400 keV Er ions implanted in the Si sample at incident angles 0° and 45° by normal RBS spectra of 2.1 MeV He ions. The distribution profiles expressed by circles and triangles correspond to those of the samples implanted at 0° (sample 1) and 45° (sample 2) incident angles with the ion beam, respectively. The solid lines represent the Gaussian fit curves. It is obvious that both distribution profiles show nearly Gaussian for the implanted ions. The values of the range straggling $\Delta R_{\rm p}$ (sample 1) and ΔD_1 (sample 2) can be derived from the measured full width at half maximum (FWHM) after taking into account the energy resolution of the measured system and the energy straggling of He ions in the target. It is seen that the peak position of the distribution of implanted ions shifts toward the surface with increasing angle θ. The profiles closely resemble each other except for a difference in FWHM.

The FWHM becomes narrower with increasing tilted angle. The main step in data analysis is the conversion of RBS energy spectra to depth profiles. This work was done by using the theory of Chu, Mayer, and Nicolet.[21] The values of $\Delta R_{\rm p}$ and ΔD_1 are 33.27 nm, 29.21 nm, respectively. Using Furukawa's formula (1) we obtain the lateral spread $\Delta X_{\rm L}$ of 400 keV Er ions implanted Si sample, $\Delta X_{\rm L1} = 24.49$ nm.

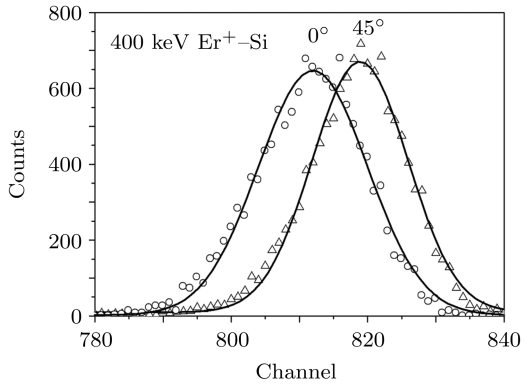


Fig. 2. Depth distributions of 400 keV Er ions implanted in Si sample at incident angels 0° and 45° by normal RBS spectra of 2.1 MeV He ions. The circles, triangles, and solid line represent the data of the ions implanted at 0°, 45° and the Gaussian fit, respectively.

Figure 3 displays the depth distributions of 400 keV Er ions implanted in Si sample at incident angles 0° and 60° (sample 3) by normal RBS spectra of 2.1 MeV He ions. It also shows the Gaussian fit curves (solid lines). It is seen that the distribution curve nearly has a Gaussian profile for the 60° implanted Er ions. Similarly, the range straggling of the 60° implanted Er ions $\Delta D_2 = 26.39$ nm is calculated from the surface energy approximation.[21] Then we obtain another value of the lateral spread $\Delta X_{\rm L}$ of 400 keV Er ions implanted in Si sample from formula (1), $\Delta X_{\rm L2} = 23.66$ nm.

The mean experimental value of the lateral spread $\Delta X_{\rm L}$ of 400 keV Er ions implanted in Si sample is obtained from the data of $\Delta X_{\rm L1}$ and $\Delta X_{\rm L2}$, $\Delta X_{\rm L} = 24.08$ nm.

The main purpose of this work is to compare the experimental lateral spread with theoretical values. We have used TRIM'98 and SRIM2006 codes to calculate the lateral straggling $\Delta X_{\rm L}$. The value of the lateral spread of 400 keV Er ions implanted in Si calculated by TRIM'98 is 23.54 nm, and the SRIM2006 table data of the lateral spread of 400 keV Er ions implanted in Si is 21.3 nm. Comparing the experimental data with the numerical simulations, we see that both values of the lateral spread of 400 keV Er ions implanted in Si calculated by TRIM'98 and SRIM2006 are slightly smaller than the experimental data. The difference between the experimental result and that of SRIM2006 is about 11.5%, that is in agreement with each other. The difference between the experimental value and that of TRIM'98 is about 2.2%, that is in a better agreement. We estimate the uncertainties in the present experimental values to be ∼5% for the lateral straggling $\Delta X_{\rm L}$, including the uncertainties induced by the deviation of He^{2+} ion incident energy in RBS analysis and by the surface energy approximation in data calculation, as well as the uncertainties in the applied stopping power values.

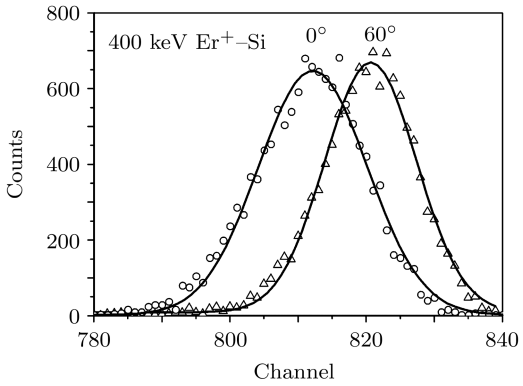


Fig. 3. Depth distributions of 400 keV Er ions implanted in Si sample at incident angles 0° and 60° by normal RBS spectra of 2.1 MeV He ions. The circles, triangles, and solid line represent the data of the ions implanted at 0°, 60° and the Gaussian fit, respectively.

4. Summary

The 400 keV Er ions at dose of 5×10^{15} ions/cm^2 have been implanted in Si single crystal samples at room temperature at the incident angles of 0°, 45° and 60°. RBS technique was used to measure the depth distribution and the lateral distribution of the 400 keV Er ions in Si. All depth distributions of the Er ions implanted in crystal Si at 0°, 45° and 60° are approximately of Gaussian profiles. The lateral spreads $\Delta X_{\rm L}$ of 400 keV Er ions implanted in Si sample were obtained using the data of Chu, Mayer and Nicolet and Furukawa's method. The measured lateral spread is compared with TRIM'98 and SRIM2006 table data prediction. Results show that the experimental lateral spread agrees well with the theoretical values. It is found that the TRIM'98 code predicts value of lateral spread of 400 keV Er ions implanted in Si is better than that of the SRIM2006 code.

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