Study of the lateral distribution of neodymium ions implanted in silicon*

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Due to the need to reduce electronic device sizes, it is very important to consider the depth and lateral distribution of ions implanted into a crystalline target. This paper reports that Nd ions with energies of 200 keV to 500 keV and dose of 5×10^{15} ions/cm^2 are implanted into Si single crystals at room temperature under the angles of 0°, 30°, and 45°, respectively. The lateral spreads of 200 keV–500 keV Nd ions implanted in Si sample are measured by Rutherford backscattering technique. The results show that the measured values are in good agreement with those obtained from the prediction of SRIM2010 codes.

Keywords: Nd ion implantation, silicon, lateral distribution, Rutherford backscattering technique

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1. Introduction

Silicon (Si) plays an important role in microelectronics, but its application in optoelectronics is limited because of its indirect energy gap. The rare-earth (RE) doping of Si and Si-related materials in recent years has been studied extensively[1−7] for the development of light-emitting devices in Si-based optoelectronics initiated by reports on photoluminescence and electroluminescence centred at around 1.54 μm of Er^{3+} ($^4I_{13/2} \rightarrow {}^4I_{15/2}$) in Si.[2] As for RE-doped materials, much attention has been paid to the Er-doped Si and Si-related semiconductors,[8−13] because its characteristic emission at 1.54 μm occurs in the minimum absorption of optical fibres. Few reports can be found on neodymium (Nd)-doped silicon. Nevertheless, it is important to investigate the luminescence in Nd^{3+}-doped crystals owing to the excitation of strongly quenched high energy levels,[14,15] because not only infrared emission is produced from the $^4F_{3/2}$ level but also ultraviolet and visible luminescence from the upper levels, such as $^4D_{3/2}$. And this ion is the most popular RE ion used as the active medium in solid-state lasers. So it is very important to investigate the range and lateral distribution of Nd ions implanted in crystal Si (c-Si), especially for today's deep-submicrometer devices. To our knowledge, there has been no report on the study of the lateral spread of implanted keV Nd ions in single c-Si.

In the present work, the depth distribution and lateral spread of implanted Nd ions in c-Si were obtained by the Rutherford backscattering (RBS) technique. The experimental lateral spread is compared with that obtained by the simulation from SRIM2010 (Stopping and Range of Ions in Matter) code.[16]

2. Experiment

Some polished n-type single c-Si wafers (named samples I to III) of (100) orientation with 5-Ω · cm resistivity were used as samples. The implantation of ions was performed on an ion implanter at the Institute of Semiconductors at the Chinese Academy of Sciences. The samples were cleaned by the standard procedure before the irradiation. The c-Si samples were implanted at room temperature (RT) with energies of 200 keV to 500 keV Nd ions (at a dose of 5×10^{15} ions/cm^2). Sample I was implanted with Nd ion beams perpendicularly with different energies (in fact, in order to avoid the channeling effect, ion implantation was performed at titled 7° off the normal

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plane of the sample surface, which would result in an error of less than 1%). To obtain the lateral spread, tilted angle implantations have been performed at 30° and 45° for samples II and III with different energies. The voltage (it decided 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 RBS measurements were carried out on the 1.7 MV-tandem accelerator at Shandong University. The depth distribution of Nd ions implanted under differently tilted targets was analysed by the RBS technique. RBS spectrometry was performed by using a 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 backscattering spectra were carried out by using a multi-channel analyser. The distribution of implanted ions was nearly Gaussian, so the depth profile could be described by using the projected range and range straggling, which was the standard deviation of the Gaussian distribution in depth. The range straggling was evaluated from the measured full width at half maximum (FWHM) after performing the deconvolution process on the assumption that the estimated energy straggling of He ions in Si and the system resolution were both Gaussian.[17] Calculated values of the He ion energy straggling normalized to Bohr's theory were used.[17] The He stopping power used here was presented in Ref. [17].

According to the work by Furukawa and Matsumura,[18] the lateral straggling of an implanted ion in c-Si can be put into the depth distribution of a target under tilted angle implantation. If the spatial probability distribution of the deposited ions is a three-dimensional Gaussian distribution, the depth distribution for a target tilted at an angle to the incident ion beam also becomes a Gaussian distribution 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,[18]

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

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 distributions absolutely; only in a small energy range of the incident ion is the distribution close to Gaussian. Therefore, Furukawa and Matsumura's method can only be approximately correct.

3. Results and discussion

All backscattering energy spectra show a nearly Gaussian distribution for Nd ions implanted in Si. These spectra were fitted via a computer program to obtain the values of the peak position and FWHM of depth distribution of implanted Nd ions. These were related to the projected range and range straggling of Nd ions, respectively. In Fig. 1, a typical RBS spectrum for a Si sample vertically implanted with 400 keV, 5×10^{15} ions/cm^2 Nd ions at room temperature is presented. From the spectrum, the average projected range $R_{\rm p}$ and the range straggling $\Delta R_{\rm p}$ of Nd ions in c-Si can be calculated by the surface energy approximation if the depth distribution of Nd ions is Gaussian.[17]

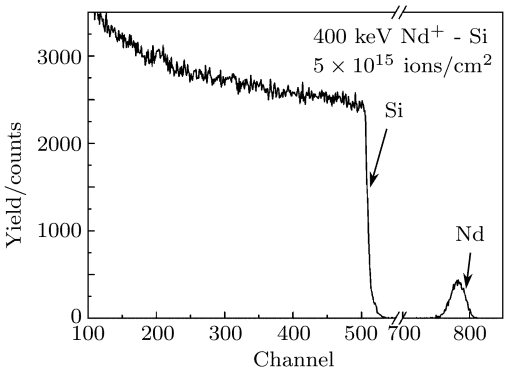


Fig. 1. Typical RBS spectrum for a Si sample vertically implanted with 400 keV, 5×10^{15} ions/cm^2 Nd ions at room temperature.

Figure 2 shows the depth distribution of 400-keV Nd ions implanted in a Si sample at 0° and 30° by normal RBS spectra of 2.1-MeV He ions. The distribution shapes denoted by circles and triangles corresponding to the samples were performed at 0° (sample I) and 30° (sample II) incident angles of the implanted ion beam, respectively. The solid lines represent the Gaussian fit curves. It is obvious that both distribution shapes show nearly Gaussian profiles for the implanted ions. It is interesting that there is no evident channeling tail in the Nd spectrum (0°) in Fig. 2,

which indicates that the channeling effect in c-Si was almost avoided by ion implantation performed at a tilted angle of 7°. The values of the range straggling $\Delta R_{\rm p}$ (sample I) and ΔD_1 (sample II) can be derived from the measured FWHM after taking into account the energy resolution of the measuring 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 an increasing angle θ. The profile shapes 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 the RBS energy spectra to depth profiles. This work was done by using the theory of Chu, Mayer, and Nicolet.[17] The values of $\Delta R_{\rm p}$ and ΔD_1 are 44.6 nm and 41.1 nm, respectively. Using Furukawa's formula (1), we obtain the lateral spread $\Delta X_{\rm L}$ of 400-keV Nd ions implanted in the Si sample, $\Delta X_{\rm L1} = 28.1$ nm.

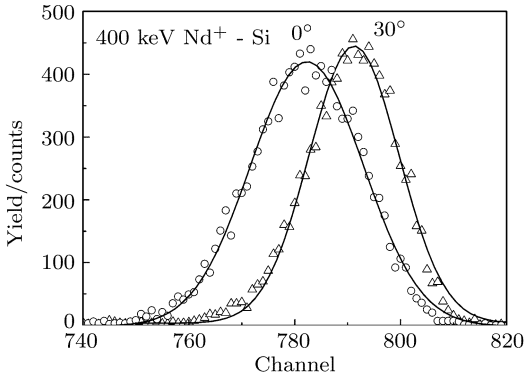


Fig. 2. Depth distribution of 400-keV Nd ions implanted in a Si sample at 0° and 30° by normal RBS spectra of 2.1-MeV He ions. The circles, triangles and solid line represent the data of the ions implanted at 0°, 30° and the Gaussian fit, respectively.

Figure 3 represents the depth distributions of 400 keV Nd ions implanted in a Si sample under 0° and 45° (sample III) by normal RBS spectra of 2.1 MeV He ions. This gives the Gaussian fit curves (solid lines) too. It is seen that the distribution shape shows nearly Gaussian profiles for the 45° implanted Nd ions. The range straggling of the 45° implanted Nd ions $\Delta D_2 = 37.4$ nm is calculated from the surface energy approximation.[17] Then we obtain another value for the lateral spread $\Delta X_{\rm L}$ of 400 keV Nd ions implanted in a Si sample from formula (1), $\Delta X_{\rm L2} = 28.4$ nm.

The mean experimental value of the lateral spread $\Delta X_{\rm L}$ of 400 keV Nd ions implanted in a Si sample is obtained from the data of $\Delta X_{\rm L1}$ and $\Delta X_{\rm L2}$, $\Delta X_{\rm L} = 28.3$ nm.

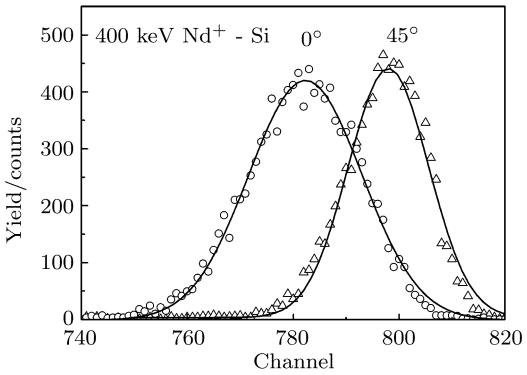


Fig. 3. Depth distribution of 400 keV Nd ions implanted in a Si sample at 0° and 45° by normal RBS spectra of 2.1 MeV He ions. The circles, triangles and solid line represent the data of the ions implanted at 0°, 45° and the Gaussian fit, respectively.

The main purpose of this work was to compare the experimental lateral spread with theoretical values. We have used SRIM2010 code to calculate the lateral straggling $\Delta X_{\rm L}$, respectively. The value of the lateral spread of 400 keV Nd ions implanted in Si calculated by SRIM2010 is 26.4 nm. Comparing the experimental data with the numerical simulations, we see that the value of the lateral spread of 400 keV Nd ions implanted in Si calculated by SRIM2010 is less than the experimental data a bit. The difference between the experimental result and that of SRIM2010 is about 7.2%, which is in good agreement.

A summary of our experimentally determined values of $\Delta X_{\rm L}$ (Exp.) for all implant energies (200 keV–500 keV) is shown in Table 1, together with values $\Delta X_{\rm L}$(SRIM) obtained from SRIM2010. As seen in Table 1, the maximum difference between the experimental results and those of SRIM2010 is less than 10%.

Table 1. Summary of $\Delta X_{\rm L}$ values measured for Nd ions in Si. The values calculated by using SRIM2010 are also shown.

E/keV	$\Delta X_{\rm L}$(Exp.)/nm	$\Delta X_{\rm L}$(SRIM)/nm	Difference
200	17.1	15.7	8.9%
300	21.9	20.8	5.3%
400	28. 3	26.4	7.2%
500	33.1	30.6	8.2%

4. Summary

The 200 keV–500 keV Nd ions at a dose of 5×10^{15} ions/cm^2 were implanted in Si single crystal samples at RT under the angles of 0°, 30°, and 45°, respectively. The RBS technique was used to measure the depth distribution and lateral distribution of Nd ions in Si. All depth distributions of the Nd ions

implanted in crystal Si at 0°, 30°, and 45° are approximately Gaussian. It is seen that the channeling effect in c-Si was almost avoided by ion implantation performed at a tilted angle of 7°. The lateral spreads ΔX_{L} of 200 keV–500 keV Nd ions implanted in a Si sample were obtained by using the data of Chu, Mayer and Nicolet and Furukawa's method. The measured lateral spreads are compared with SRIM2010 prediction. The results show that the experimental lateral spread agrees well with theoretical values.

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