Preparation of a silicon micro-strip nuclear radiation detector by a two-step annealing process

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Abstract: The annealing process for boron implantation is a crucial step during large size nuclear radiation detector fabrication. It can reduce the lattice defects and the projection straggling. A two-step annealing process for boron implantation was developed instead of a one-step annealing process, and the reverse body resistance of a silicon micro-strip detector was significantly increased, which means that the performance of the detector was improved.

Key words: nuclear radiation detector, two-step annealing, reverse body resistance

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1 Introduction

With the development of the ultra large scale integrated circuit, a device with smaller crucial sizes and a larger chip area is needed, and the traditional thermal diffusion process is commonly replaced by the implantation technique. Ion implantation has a unique advantage that the number and the depth of the implanted ions in the device can be precisely controlled, so the device can be easily duplicated. Compared to the high-temperature diffusion process, ion implantation working at room temperature can also reduce the value of the thermal budget. Unfortunately, the implantation also has some disadvantages, such as a) more lattice defects are produced by the ion implantation; and b) the depth of the implanted ions in the device would have a projection straggling $\sigma_{\rm p}$. These disadvantages can mostly be ectified by a proper annealing process [1–10].

Conventional diffusion annealing and Rapid Thermal Annealing (RTA) are the commonly used annealing methods. They can be adopted individually or combined. In the fabrication of the silicon strip detector, we found that only one-step RTA for boron implantation could not reduce the lattice defects and thus activate the implanted ions quite well, so the detector fabricated in this way could not meet our application requirements. Consequently, a two-step annealing process was suggested, which means that a RTA annealing process was followed by a diffusion annealing process.

2 Experimental

The silicon micro-strip detector is a kind of nuclear radiation detector commonly used in nuclear experiments. It can be fabricated by MEMS (Micro Electro Mechanical Systems). The 4-inch wafers were light doped with 10^{12} atom/cm^3 N-type dopant to achieve a good surface resistivity greater than 2000 Ω·cm. First, the wafers were cleaned with a routine RCA cleaning procedure. Then an oxidation film with a thickness of 6000 Å or so was grown on the wafers in the oxidation furnace at 1030 ℃ for 4 h. After that, the micro-strip patterns were transferred to the wafers by a lithography machine. The wafers were further treated with boron implantation at the top surface and a phosphorus implantation at the back surface by a medium-energy ion implanter, and a silicon strip detector sample was thus achieved.

It was found that the annealing process for boron implantation played a key role in the detector fab-

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rication. The doped boron ions had an energy of 40 KeV and an intensity of 2×10^{14} ions/cm^2. The N-type wafers with micro-strip patterns were annealed by RTA at 650 ℃ (55 s), 750 ℃ (55 s), 850 ℃ (55 s), 950 ℃ (55 s), 1050 ℃ (55 s) and 1130 ℃ (55 s), respectively. PN junctions should have been formed and the reverse body resistance for the samples should be as large as possible. But unfortunately, the largest reverse body resistance for the detector samples was measured to be only 30–40 MΩ, which means that the performance of the junctions was rather poor.

The RTA-annealed wafers were further annealed by a thermal diffusion furnace at 1030 ℃ for 30 min. It was found that the reverse body resistance had been obviously increased to 100–200 MΩ only for the wafers pre-annealed at 650 ℃ (55 s). But for the other wafers pre-annealed at higher temperatures, no significant improvement was observed for the reverse body resistance of the samples.

Figure 1 shows a photograph of the top surface of the detector profile. 96 micro-strips were formed inside the effective area.

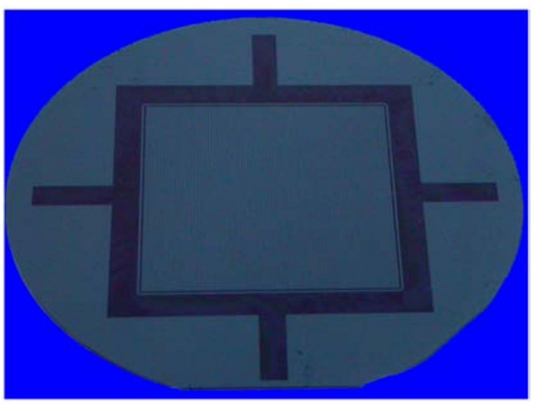

Fig. 1. (color online) Photograph of a nuclear radiation detector with only one-step annealing process.

3 Results and discussion

Two detector samples were fabricated and the reverse body resistance for each strip of the detectors was measured at room temperature. Table 1 shows the results from one-step RTA annealing. It should be mentioned that the data in Table 1 is for all strips in the detector samples. These two samples with 30 MΩ or 40 MΩ maximum reverse body resistance are not good enough to meet the detector requirements.

Then the samples were further treated by diffusion annealing at 1030° for 30 minutes. The reverse body resistances for each strip of the detectors were also measured and are summarized in Table 2. It is obvious that the reverse body resistance had been improved significantly. The detector samples were tested with a ^{241}Am α-source, and the energy resolution was about 3% for 5.486 MeV alpha peaks, and the leak current for the detector at 100 V bias voltage was about 0.3 μA. The performance of the detector needs to be further improved.

Table 1. The results for detector Ⅰ and Ⅱ from one-step RTA at 650 ℃.

detectors	one-step RTA	body resistance	
		forward/Ω	reverse/MΩ
Ⅰ	T = 650 ℃	∼20 K	⩽30
Ⅱ	t=30 s	<20 K	⩽40

Table 2. The results for detector Ⅰ and Ⅱ from two-step annealing at 650 ℃ and 1030 ℃ consecutively.

detectors	two-step RTA	body resistance	
		forward/Ω	reverse/MΩ
Ⅰ	T=1030 ℃	∼30 K	⩾100
Ⅱ	t = 30 min	<20 K	⩾200

The results in Table 1 and Table 2 tell us that the two-step annealing process is more effective than the one-step RTA process. Some possible reasons were suggested. One reason is that the lattice destruction induced by the ion implantation was not well recovered by the one-step RTA annealing in our situation. A scanning electron micrograph of the detector samples is shown in Fig. 2, which supports our conclusion. The more important reason is that the depth of these implanted ions should have a reasonable projection straggling $\sigma_{\rm p}$, but a few of the ions were implanted more deeply into the silicon wafer due to the ion-channel effect (as schematically shown in Fig. 3). The marginal discharge would occur at that point, broken through the PN junctions of the detector, and thus reduced the reverse body resistance. This problem would be more serious for a large nuclear radiation detector. It cannot be repaired by the short time RTA annealing but could be well repaired by the long-time diffusion annealing.

The reason is that during the second-step annealing process, most of the ions would diffuse forward a little distance due to the dense concentration of the ions, but no movement would occur for the more deeply penetrated ions because of their low concentration. At the end, the projection straggling $\sigma_{\rm p}$ is reduced and almost all of the implanted ions reach the same depth (as shown in Fig. 4).

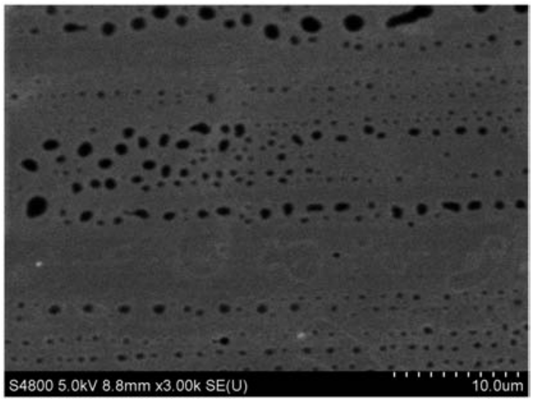

Fig. 2. A scanning electron micrograph of this interface shows a lot of defects after only one-step RTA.

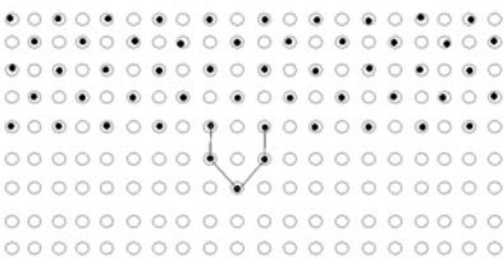

Fig. 3. Ions in the Si lattice after a one-step anneal, and the ion-channel effect occurs. Blank circles represent silicon atoms, and circles with a dark point inside represent implanted ions.

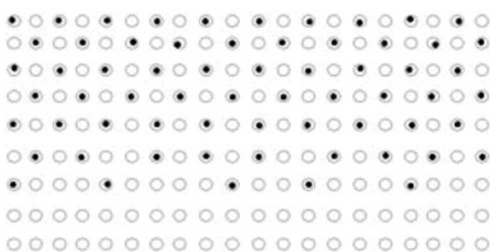

Fig. 4. Irons in the Si lattice after two-step annealing and no point discharge occurs. Blank circles represent silicon atoms and circles with a dark point inside represent implanted ions.

After the two-step annealing process, the lattice defects and the ion-channel effect can be perfectly recovered, and most of the implanted ions were activated as substitution atoms and could make contributions to the charge carriers. A scanning electron microscope micrograph of this interface for the detector sample is shown in Fig. 5, which looks perfect.

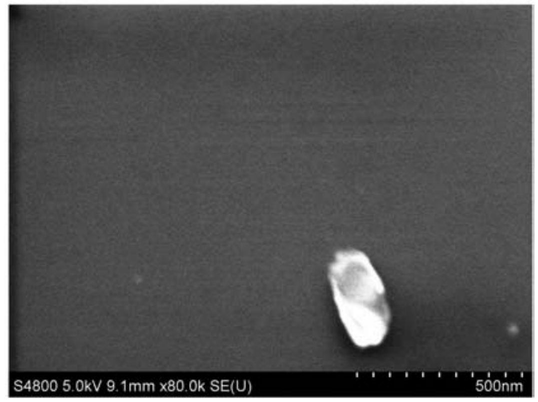

Fig. 5. A scanning electron micrograph of this interface shows few defects after two-step RTA.

4 Conclusions

One-step RTA could partially repair the lattice defects, reduce the thermal budget and activate the ions, but a lot of the lattice defects still remain and the ion-channel effect has not vanished. A two-step annealing process at 650 ℃ (55 s) and at 1030 ℃ (30 min) consecutively could reduce the lattice defects and the ion-channel effect reasonably, and thus form a typical PN junction. The silicon micro strip detector was fabricated by the two step annealing process, and their performance could meet the basic requirements of nuclear experiments. Further efforts should be made.

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