Effect of Annealing on Ion Implantation Process in 4H-SiC power semiconductor devices

Huan Ge¹, ²⁺, Rui Liu¹, ², Jialin Li¹, ²

¹State Key Laboratory of Advanced Power Transmission Technology, Beijing 102209, China
²China Global Energy Interconnection Research Institute Co., Ltd., Beijing 102209, China

*Corresponding author: gehuan@geiri.sgcc.com.cn

Abstract. In this paper, the effect of annealing at 1750 °C for 30min on ion implantation results is analyzed in 4H-SiC power semiconductor devices are studied. The main method is to prepare the injection mask to separating P and P-space by lithography, etching and other processes. Then, the concentration of 5E18cm⁻³ Al ion is implanted at the high temperature of 500 °C, and the 1# sample is retained. After the removal of the mask, the remaining samples are annealing at high temperature for 30min, and the 2# sample is retained. Schottky contact and Ohmic contact was prepared on the front and back side respectively, and sample 3# was prepared. Scanning electron microscopy (SEM), electron energy spectroscopy (EDX), secondary mass spectrometry (SIMS) and capacitance-voltage (C-V) tests were used to test the injection line and activation rate before and after annealing. The test results show that the P region of the ion implantation line of the 1# sample changes from 1.53um to 1.65um of the 2# sample before and after annealing, which indicates that the annealing at 1750 °C will make the implanted ion Al diffuse in SiC to a certain extent, resulting in a decrease in the implanted concentration per unit area. This is also proved by the results of the SIMS test. At the same time, high temperature annealing will repair the lattice, impurity ion Al replaces Si ion at high temperature, and bonds with C ion, so as to play a role and provide holes. Its activation rate has a very low value of 40%, which can be close to 100% after annealing.

Keywords: 4H-SiC, ion implantation, ion concentration, high temperature annealing, activation rate.

1. Introduction
In the past decades, power semiconductor devices based on SiC have developed rapidly in academic research and technical manufacturing due to its excellent material properties, such as high thermal conductivity, high electron saturation drift velocity, high breakdown electric field, wide band gap and large Si-C bond energy [1], [2], [3]. Doping process which as a most important part of the preparation of semiconductor devices is already very mature in Si, but because of the SiC structure has very strong molecular bonding energy, make it to the outside world all effect is stable, and the diffusion coefficient of impurities in the SiC is low, therefore, realize regional selective doped by diffusion process is not
realistic. Ion implantation [4], [5], [6] is the only method to achieve selective region doping in SiC power devices.

The distribution of implanted ions can be accurately controlled by adjusting the process parameters such as the type of implanted ions, the injected energy and the dose.

However, the single-step ion implantation process does not enable the majority of implanted ions to participate in the device's work. After the completion of ion implantation, most of the implanted ions do not occupy positions on the crystal lattice and cannot provide charge carriers to participate in the work of the device. Only by occupying a position on the lattice and becoming a surrogate ion can it be electrically activated and contribute electrons and holes to participate in the device work as carriers. At the same time, when the implanted ions collide with the atoms of the original material, the energy is lost and finally stops at a certain depth. In the meantime, the atoms of the collided material are also knocked out of their original position and stay in the non-lattice position, and the vacancy - gap defect is produced.

When the injection dose is high, with the continuation of ion implantation bombardment, the collisions between implanted ions and target atoms are more and more, and the proportion of target atoms lost in the implanted region continues to increase. The dislocation dense region may become amorphous while impurity atoms and target atoms in the lattice gap occupy the main body. During ion implantation, the damage accumulation and injection dose increased in proportion until the occurrence of amorphism. Due to the low displacement energy threshold of C atom, the damage accumulation rate of C sublattice in SiC material is faster than that of Si sublattice at low injection dose. However, the dose of amorphization of C and Si sublattice is basically the same. In the case of high temperature injection, the injected region retains the original crystal structure and can be easily recovered. This is a characteristic of hexagonal SiC crystal ion implantation, with similar results for atoms of Al, B, N, and P. The implanted ions need to be activated and the lattice damage repaired. High temperature annealing is a traditional process used to repair the lattice damaged by high-energy ion implantation and activate implanted ions [7, 8].

In general, the annealing temperature of 1000°C can realize the displacement of implanted ions. However, the impurity ions entering the lattice are not completely ionized, and the ionization rate of impurity is positively correlated with the activation rate. In order to improve the ionization rate of impurity ions, a higher annealing temperature than lattice repair is needed [9, 10]. To avoid the injection damage, post-injection annealing at high temperature (> 1500~1600°C) is usually required to repair the lattice and achieve high electrical activation rate. The annealing temperature required for different implanted ions is also different. For example, the activation energy of N ion is 80MeV and the required temperature is above 1300°C, while the activation energy of Al ion is 240MeV and the required temperature is above 1500°C. In the actual process of SiC devices, the temperature of activation annealing by ion implantation is generally greater than 1500°C.

This article studied the 4 H - SiC wafers material first positive deposition at the expense of oxide layer mask, after lithography graphics, etching hole, and then high temperature 500°C injection process to remove oxide layer mask, return some samples, the rest of the sample preparation of carbon membrane to protect the surface of the wafer, and then under the 1700°C high temperature annealing activation, the final preparation of ohmic contact and the schottky contact, thus a measurable device was formed. And the effect of annealing on the diffusion and activation rate of implanted ions was studied according to the results of SIMS test, SEM test, CV test and ion implantation process simulation.

2. Simulation of Al ion implantation process in silicon carbide

The doping required for SiC devices is generally box-type and needs to form a uniform concentration of doping in the depth range of less than 1um. Due to the Gaussian distribution of single injection, multiple steps of different energy and dose injection are needed to achieve this. If the deviation between the actual doping value and the design value is too large, the conduction and voltage resistance of the device may be greatly reduced. Therefore, it is necessary to measure the ion distribution after the actual injection and compare it with the design value to ensure the normal operation of the device.
The simulation software of Trim is used to calculate the range of Al ions in silicon carbide. The program can only calculate for one particle at a time, and the accuracy is determined by the number of ions used in the simulation. Typically, calculations with 1000 ions will yield better than 10% accuracy.

Generally speaking, for silicon carbide diode power device, the distribution of injection concentration in depth is box-type distribution. Table 1 gives the requirements of Al ion implantation in the preparation process of silicon carbide diode power device, taking 4H-SiC Schottky diode as an example. Different energies and different doses of Al ion implantation in the energy range of 30~450keV were used to form a box-type distribution of about 0.75mm deep, with an average doping concentration of 5e18cm-3. Figure 1 shows the distribution of Al ion implantation with depth obtained through Trim ion implantation process simulation, which is consistent with the injection conditions used in the experiment. Due to the limitations of process simulation, the results after annealing cannot be simulated, so this result is only the distribution of implanted ions after implantation and before annealing. In the figure, the distribution of injection concentration with depth is roughly box-type, and taking into account the precipitation effect of ions in the annealing process, the injection concentration near the surface is larger.

**Table 1.** Al injection process requirements for 4H-SiC diode devices

| Energy/kev | Dose/cm-2 | Depth/mm |
|------------|-----------|----------|
| 450        | 7.6e13    | 0.75     |
| 350        | 7.2e13    | 0.60     |
| 220        | 4.9e13    | 0.45     |
| 130        | 4.0e13    | 0.30     |
| 70         | 2.6e13    | 0.20     |
| 30         | 2.4e13    | 0.10     |

**Figure 1.** Trim simulation results of concentration distribution of injected Al ions with depth

3. **SIMS measurement before and after high temperature annealing**

Secondary mass spectrometry ion test (SIMS) mainly uses high-energy ions to bombard the surface of materials to generate sputtering ions. By analyzing the mass spectra of these secondary ions, a mass spectrum with surface characteristics can be presented, and information of elements, isotopes and molecules can be generated at the same time. The sensitivity range can be up to PPM to PPB.
Figure 2. Comparison of concentrations by Secondary Ion Mass Spectrometry and Simulation

After high temperature ion implantation for 4H-SiC Devices, part of sample #1 is retained for secondary ion mass spectrometry (SIMS) and Scanning electron microscopy (SEM) measurement. The same as sample #2 after annealing 30 minutes at temperature 1750 °C. Figure 2 shows the comparison of concentrations by Secondary Ion Mass Spectrometry before and after high temperature annealing and Simulation results. It can be seen from the figure that the results before high temperature annealing as ion implantation are basically consistent with the simulation results.

For the sample #2 which is annealing 30 minutes at the high temperature of 1750 °C. It is found the concentration of the ions is decreased after high temperature annealing, This also prove that Al ions in annealed SiC at higher temperatures may diffuse outward, and it can also be seen that the concentrations of Al ion on the surface of Devices is significantly low after annealing. Therefore, attention should be paid to the total surface injection dose when designing the injection process.

4. SEM test before and after high temperature annealing

Scanning electron microscopy (SEM) is a type of electron microscope that produces an image of a sample by scanning a surface with a focused electron beam. Electrons interact with atoms in the sample to generate a variety of signals that contain information about the surface morphology and composition of the sample. The scanning path of the electron beam is like a grating, and the image can be output by combining the position of the electron beam with the intensity of the detected signal.

Scanning electron microscopy (SEM) was used to test the samples #1 and #2 before and after annealing after injection process at the same time. Table 2 shows the design and actual graphic dimensions, because of the devices are formed by lithography, etching and other processes, there will be a certain loss of line width. The final injected size is increased by about 0.23μm compared with the design size by measurement. At the same time, when observing the injection cross section which has annealed at 1750°C for 30 minutes, it is found that the size of the injection surface presents a diffusion trend, a total of 0.12μm was diffused on the lateral side and 0.45μm in the longitudinal depth by measurement. This may be due to the anisotropy of the SiC material in different directions.

As shown in Figure 3, the cross section of samples by SEM shows that the injection area does change before and after annealing. Meanwhile, it is found in Figure 3 (b) that there are some Al ions under the mask. It also proves that part of Al ions on the surface will precipitate after annealing, which is consistent with the results of the SIMS test.
Table 2. Dimension of injection and non-injection zone

|                | Implantation Region | Implantation Section | Depth    |
|----------------|---------------------|----------------------|----------|
| Design         | 1.30μm              | 3.50μm               | 0.750μm  |
| Process (#1)   | 1.53μm              | 3.27μm               | 0.731μm  |
| Process (#2)   | 1.65μm              | 3.15μm               | 0.776μm  |

Figure 3. SEM. (a) sample #1 before annealing, (b) sample #2 after annealing

5. Activation rate test before and after high temperature annealing

In order to further analyze the effect of annealing process on ion implantation, the activation rate of the samples was measured.

The activation rate was measured by a capacitance-voltage (C-V) test. The C-V test is performed based on the formation of a Schottky contact above the injection area. The C-V test takes advantage of the phenomenon that the width of the inverse biased Space charge region (SCR) of semiconductor junction devices depends on the applied voltage. This test method is only effective when the doping concentration is relatively low. When the doping concentration is too high, it is easy to produce breakdown phenomenon, which makes it impossible to test a larger depth.

Figure 4. Comparison of Activation rate

In this paper, due to the high doping concentration used by Schottky diode, only the ion concentration within 0.07μm can be measured. As the concentration obtained by TRIM simulation and SIMS
measurement is basically consistent with the change of depth, the SIMS measurement results after high temperature annealing are used here to calculate the ion activation rate. Figure 4 shows the results of Al ion concentration distribution for samples #1, #3 and SIMS. Compared with the results obtained by SIMS before annealing, the ion activation rate can be calculated to be only 30-40%, while after annealing at 1750°C for 30min, the ion activation rate can be close to 100%. In the process of injecting Al ions, the lattice damage of the material will inevitably be caused when the Al ions bombard the target material due to the large mass of Al ions. At the same time, the implanted ions by the single-step process only occupy the lattice but are in the void position, leading to the majority of implanted ions and acting on them. The annealing process can repair the lattice defects and make the implanted Al ions replace Si atoms to form covalent bonds with C atoms.

6. Conclusion

In this paper, the ion implantation annealing process in 4H-SiC power semiconductor devices are studied. After conventional high-temperature ion implantation process, part of the samples retained are tested by secondary mass spectrometry, slice SEM and C-V, and the rest are analyzed again after annealing. The test results show that the annealing process will precipitate the Al ions near the surface, and there will be a certain amount of diffusion after the annealing at 1750°C. Therefore, the design of the injection concentration near the surface should be slightly higher, and the design of P and P space should be based on the specific process. In addition, the activation rate of Al ions is significantly increased from 40% before annealing to close to 100% after high temperature annealing, which proves that high temperature annealing can indeed repair the lattice and make Al ions replace. However, it should be noted that the injection concentration decreases in the annealing process, and it needs to be combined with the actual process in the design of the injection process.

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References

[1] Kimoto, Tsunenobu. Material science and device physics in SiC technology for high-voltage power devices [J]. Japanese Journal of Applied Physics, 2015, 54(4): 040103.
[2] Chen S Z, Sheng K, Wang J. 1.4kV 4H-SiC PiN diode with a robust non-uniform floating guard ring termination. J Semicond, 2014, 35(5): 054003
[3] Mahajan A, Skromme B J. Design and optimization of junction termination extension (JTE) for 4H-SiC high voltage Schottky diodes. Solid-State Electron, 2005, 49(6): 945
[4] A. Renau, in Proc. 16th Int. Conf. on Ion Implantation Technology (IIT 06), AIP Conf. Proc. American Institute of Physics, Melville, 2006, Vol. 866, p. 345.
[5] N. White et al., in Proc. 16th Int. Conf. on Ion Implantation Technology (IIT 06), AIP Conf. Proc. American Institute of Physics, Melville, 2006, Vol. 866, p. 335.
[6] C. Campbell et al., in Proc. 19th Int. Conf. on Ion Implantation Technology (IIT 12), AIP Conf. Proc. American Institute of Physics, Melville, 2012, Vol. 1496, p. 296.
[7] Zhang, Y., Weber, W.J., Jiang, W. et al. Damage evolution and recovery in Al-implanted 4H-SiC. Mater. Sci. Forum, 2002, 389–393, 815.
[8] Henkel, T., Heera, V., Kogler, R. and Skorupa, W., In situ laser reflectometry study of the amorphization of silicon carbide by MeV ion implantation. J. Appl. Phys., 1998, 84, 3090.
[9] Saks N S, Suvorov A V, Capell D C. High temperature high-dose implantation of aluminum in 4H-SiC [J]. Applied Physics Letters, 2004, 84(25):5195.
[10] M. Spera, D. Corso, S. Di Franco, G. Greco, A. Severino, P. Fiorenza, F. Giannazzo, F. Roccaforte, Effect of high temperature annealing (T>1650 °C) on the morphological and electrical properties of p-type implanted 4H-SiC layers, Materials Science in Semiconductor Processing, Volume 93, 2019, Pages 274-279.