Discussion on the Principle, Process, Equipment and Application of Ion Implantation Technology

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Abstract. Ion implantation is a way to regulate the material's electronic, optical and mechanical properties through injecting impurity ions into the target substrate, aiming at making it acquire properties that are more in line with practical scenarios and finally producing electronic components with better performance. At present, the process of ion implantation first involves the generation of required ions, which happens in the ion source of the ion implanters. In it, the required ions are ionized by high-energy electron beams. Then, after the separation and purification through systems such as mass screening, the target material is finally implanted through a scanning system. The technology is already quite mature, but with the continuous development of semiconductor technology, the higher requirements in precision put forward higher demands on ion implantation doping. This article mainly studies the principle, process, equipment and application of ion implantation. The results indicate that the academic community has made considerable innovations in the types of doped atoms. Besides traditional elements such as nitrogen and phosphorus, oxygen, iodine and similar elements in the same group have already under research in terms of doping performance. The future development areas will focus on more types of element doping, more precise in doping processes, more stable in doping at the single atomic layer, and so on, to meet the continuously increasing size requirements in the semiconductor field and to achieve breakthroughs in quantum effects at the atomic scale.

Keywords: Ion implantation; Process; Equipment, Electronic property, Optical performance.

1. Introduction

In the modern semiconductor technology, ion implantation is a crucial part of it. By injecting atoms with specific electron structures to high-purity target materials can their electronic, optical and mechanical performance be improved, so obtaining products more in line with the application [1]. When the ion beam is incident to the surface of the target material, there are two phenomenon: the first one is that ions are scattered by the atoms of the surface material, which can be used for surface analysis; the other one is that ions get into the interior of the solid and finally stay in the lattice, known as ion implantation [2]. Compared with previous doping methods such as diffusion and alloying, due to its advantages including good doping uniformity, high control over impurity elements, and high automation in the manufacturing process, ion implantation have been widely applied in the semiconductor field [1].

This passage will provide a review of ion implantation, including concepts, processes, equipment, application, and influences on the performance of materials according to the current research process.

2. Basic Principle of Ion Implantation

2.1. Physical Process of Ion Implantation

The process of ion implantation can be divided into four steps. First, the gases or sublimated solids containing the doped elements are introduced into an ion source, where these gases are ionized after being collided by a high-energy electron beam, thus producing desired ions. Second, the desired ions need to be separated and purified: the already ionized gases are leaded out of the ion source and be applied an electromagnetic field, with the direction perpendicular to its movement trajectory. Due to the Lorentz force acting on charged particles in the electromagnetic field, their trajectories will change. Based on the principle that ions with different charge-to-mass ratios receive different magnitudes of force and thus have different degrees of trajectory deflection, a slit is set at a specific position to collect specific ions, so realizing separation and purification. Then, the plasma gases are introduced into the accelerator, which is a high vacuum tube applied with a strong electric field. In it, the electric field force exerted on the charged particles is utilized to accelerate them, enabling them to obtain the energy required to complete the final doping and to reach the specified junction depth of the device. Ultimately, by introducing this beam of high-energy ions into the scanning chamber, the scanning and injection can begin [1]. It should be noted that during transportation, due to the interaction between the ion beam and the thermal electrons as well as the mutual collision between ions, some neutral particles will be produced. At this time, the ion beam needs to pass through the neutral beam gate ,taking advantage of the fact that neutral particles are not subjected to force in the electric field. So, they are removed because that their motion state does not change. In addition, due to the mutual repulsion between ions of the same charge, the ion beam is unstable in space, and its volume will expand over time, causing uneven doping. Therefore, the method of secondary electron neutralization is needed to alleviate this.

2.2. Microscopic Process of Ion Implantation2.3 Energy loss in ion implantation

When an ion beam enters the surface of a solid, it goes through five stages [2].

As can be seen in the figure1, the incident ions first collide inelastically with particles on the surface, generating secondary electrons and photons.

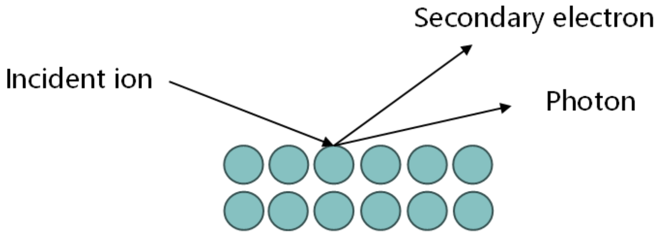

Fig. 1 Surface collision

Then, figure 2 shows that the incident ions pass through the surface of the solid, entering the interior and being neutralized by the electrons within it. They will undergo elastic collisions with the solid particles within and is bounced back, forming backscattered ions.

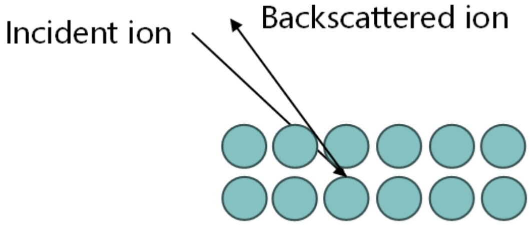

Fig. 2 Backscattered collision

As is shown in Figure 3, the incident particles will collide with the atoms inside the solid, causing the solid particles to undergo lattice displacement. Some high-energy atoms can collide with multiple internal particles, causing more displacements. The displaced solid atoms can further collide with other particles, thus generating complex motion processes, which are called secondary collisions.
During the process, some of the atoms knocked out pass through the lattice gaps and escape from the surface, becoming sputtered atoms.

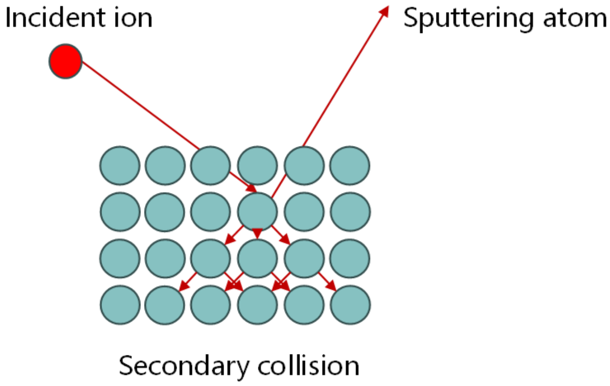

Fig. 3 Secondary collision and sputtering atoms

Finally, Figure 4 shows that the incident particles have exhausted their energy and stop inside the solid, forming a doping distribution.

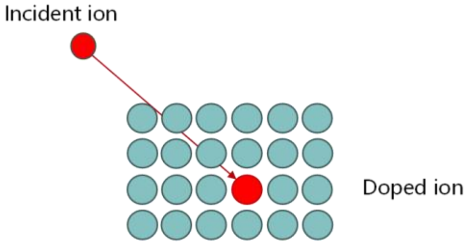

Fig. 4 Doping distribution

2.3. Energy Loss in Ion Implantation

During the process of ion implantation, the energy loss of ions is divided into two parts: nuclear collision and electron collision.

Nuclear collision refers to the collision between the injected ions and the atomic nuclei inside the wafer. Due to their similar masses, the injected ions will undergo large-angle scattering after the collision.

Nuclear collision can be defined as

$$S_n(E) = \left(\frac{dE}{dx}\right)_n \tag{1}$$

Electron collisions refer to the collisions between ions and free or bound electrons within the wafer. Due to the significant mass difference between them, such collisions cause less energy loss and result in smaller changes in their movement paths, which can generate instantaneous electron-hole pairs. Electron collision can be defined as

$$S_e(E) = (\frac{dE}{dx})_e \tag{2}$$

The influence of the former on the energy of the injected ions is defined as nuclear block, while that of the latter is electron block.

Both jointly affect the range of the injected ions [3].

$$R = \int_0^{E_0} \frac{dE}{S_n(E)+S_e(E)} \tag{3}$$

E_0 represents the initial energy of the injected ion, and R is the energy loss during ion implantation.

2.4. Distribution of Ion Implantation

For each ion, the collision it receives in the wafer is a random process. For a large number of injected ions, their distribution can be regarded as a certain statistical law, namely the Gaussian function.

Under the first-order approximation, the longitudinal distribution of ions within an amorphous target can be approximated as

$$N(x) = N_0 e^{[\frac{-(x-R_p)}{2\Delta R_p{}^2}]} \tag{4}$$

$$N_0 = \frac{\emptyset}{\sqrt{2\pi}\Delta R_p}\ ,\ \emptyset = \int_0^{\infty} n(x)dx = \sqrt{2\pi} N_0 \Delta R_p \tag{5}$$

2.5. Injection Effect and Defect Characteristics

During the ion implantation process, the lattice structure of the target material is often damaged, resulting in point defects, dislocation rings, amorphous layers and other defects, which have a significant impact on carrier transport. In severely damaged areas, amorphous layers will form, and the lattice structure needs to be restored through annealing [4].

In addition, when the incident direction of ions is parallel to the main crystal axis, they undergo fewer nuclear collisions, and the ions will move along the channel, with a deeper injection depth, causing a tailing in the concentration distribution of the injected ions, which is called the channel effect. When light atoms are injected into heavy atom targets, the channel effect is particularly obvious [4].

2.6. Solutions to Common Defects in Ion Implantation

At present, there are several common solutions and preventive measures for the defects caused by ion implantation.

The first method is high-temperature annealing. Its principle is to heat the doped target material to a high temperature, so that the atoms in the wrong lattice positions can obtain sufficient energy to perform thermal motion, thereby reducing lattice dislocations and obtaining materials with better performance and more in line with expectations. However, in practical applications, due to the difficulty in accurately locating the microstructure in the lattice, the damage caused during the ion implantation process is a statistical concept. Therefore, it is also difficult to specifically understand the types and quantities of damage after annealing is completed [4].

The second approach is to strictly control the impurity ions that may exist during the processing. Both raw materials and wafers during the processing must be operated in a clean, sterile and highly vacuum environment. Therefore, the requirements for the vacuum system are also very demanding. So the processing workshop must use reliable vacuum equipment [4].

There are also some more scattered methods, such as using inclined Angle injection during the ion implantation process to mitigate the influence of channel effects [3], adding high-precision sensors that can reflect the true internal state of the equipment to the device for electrical detection and utilizing specialized software programs are adopted for monitoring to achieve precise control during the processing and timely troubleshooting of existing faults [5,6].

3. Equipment of Ion Implantation

3.1. Classification of Ion Implanters

There are various classification methods for ion implanters. According to energy size, they can be classified into low-energy injectors (5-50 KeV), medium-energy injectors (50-200 KeV), and high-energy injectors (0.3-5 MeV). According to the beam intensity, they can be classified into low/medium beam injectors (micro/milliampere level) and high beam injectors (several to tens of milliamperes). According to the beam working state, they are classified into steady flow injectors and pulse injectors. According to type, they can be classified into quality analysis injectors (in the semiconductor field), industrial gas injectors, plasma source ion injectors [2].

3.2. Composition of Ion Implantation

The ion implanter is composed of an ion source, a purification chamber, a scanning system, a vacuum system and a target chamber [2].

The main function of the ion source is to generate the ions required for doping. Its main structure consists of an ionization chamber made of stainless steel, with an electromagnetic coil on the outside for guiding the magnetic field and a discharge chamber. One side of the interior has a positive potential, and the other side has a 1-2mm small hole to lead out the electrode, serving as a negative potential [3].

The main function of the purification chamber is to screen out useful ions. The main structure consists of a separation magnet and a light bar. When ions are shot into a vertical magnetic field, they will be subjected to the Lorentz force and start to move in arcs with different radii according to the core-mass ratio. By setting the light bar reasonably, the ions one needs can be obtained. The relationship between the radius of motion, the charge-to-mass ratio and the magnetic field intensity is

$$r = \sqrt{\frac{2M}{qB}} \tag{6}$$

q refers to charged quantity [3].

The function of the scanning system is to use the ion beam drawn from the purification chamber to inject largely and uniformly to the target material. There are mainly three types. The first type is called electrical (electromagnetic) injection, which refers to the application of an orthogonal electromagnetic field to the ion beam, allowing the ion beam to inject into the target material from two directions. The second type is mechanical injection, which achieves injection in different directions through the simple relative movement between the ion beam and the target material. The third type combines the above two, which is called mixed injection. Among them, electromagnetic injection has a relatively high precision and is often used in high-precision injection requirements of 6 inches or less. Mixed injection is mostly used in processes larger than 8 inches [3].

The vacuum system is used to keep the entire instrument in a high vacuum state during the process, thereby avoiding the scattering of the ion beam and the neutralization between ions caused by the collision of the ion beam with air molecules in the air, and ensuring that there is no additional pollution [3].

4. Changes in Material Properties Caused by Ion Implantation

The main function of ion implantation is to inject impurity ions into the target material, that is, the acceptor, thereby changing its phase and crystal structure, and ultimately improving the electrical, optical and physical properties of the material, obtaining materials with better performance and more practical requirements [1].

In the field of integrated circuits, ion implantation is more widely applied. As it requires integrating hundreds of millions of components on chips with a size of only the square millimeter level, it is extremely sensitive to size control and precision. Ion implantation have the characteristics of high control accuracy and controllable distribution, perfectly meeting the requirements of integrated circuit manufacturing. By doping the material with different atoms through ion implantation, the application requirements in various environments can be met [1].

4.1. Alteration of optical properties of materials by Ion Implantation

Chen Rui regulated the charge centers, Fermi levels and the concentration of doping defects of the carriers contained in the single-atom-layer silica substrate by injecting metal ions for doping, thereby improving the lifetime and distribution of the carriers and greatly increasing the optical signal response rate of the components. Meanwhile, thanks to the high dielectric constant of metal ions, the damage caused during the ion implantation process has also been greatly reduced [7].

Wang Xuan discovered that the light transmittance of single-crystal silicon substrates could be altered by injecting elements such as oxygen, nitrogen, and sulfur into them. The core principle is that during the ion implantation process, structural damage and N-doping effects occur. Under the combined effect of these two factors, the light transmittance of the material decreases. Under the irradiation of an electron beam of 170 keV, when the concentration of nitrogen ion implantation reaches 1×1016cm-2, the light transmittance of the material begins to decrease significantly. When the nitrogen ion implantation concentration reaches 2×1016, the light transmittance of the material will drop to 0 [8]. In practical applications, more optical functions can be obtained by improving basic optical properties such as light transmittance and refractive index, thereby manufacturing electronic components with better performance to meet the demands of more diverse semiconductor devices.

Yuan Zhizhong's research indicates that doping Tb ions in silicon-based PN junctions can endow them with the ability to emit light at room temperature. As the ion implantation dose increases continuously, the luminescence intensity decreases continuously. At the same time, the annealing temperature also affects the luminescence performance of the PN junction. Hydrogen annealing has the best effect, followed by conventional annealing, and rapid annealing is the least effective. Moreover, the higher the annealing temperature is, the better the luminescence performances are [9]. This research demonstrates a significant improvement in the optical properties of materials by ion implantation doping. This technology has a very broad application prospect, including display content, application in various sensors and detectors, and after further development, usage as laser emitters.

4.2. Alteration of the Electrical Properties of Materials by Ion Implantation

Doping nitrogen and phosphorus in silicon-based substrates can alter their electrical properties, making them more inclined towards P-type or N-type semiconductors, which is the foundation of semiconductor preparation. With the continuous development of semiconductors and the constant progress of technology, the performance requirements for semiconductor devices are also constantly increasing. Therefore, new requirements have been put forward for substrate materials, doping elements, doping techniques [7].

Geng Fangjuan discovered that incorporating sulfur as the acceptant ion in γ-CuI films could improve their resistivity, carrier mobility and carrier concentration. This technology has a very broad application prospect due to its low resistance, high carrier concentration and low carrier mobility. The largest application market lies in its ability to serve as a substitute for the currently widely used ITO, as the indium contained in ITO is limited in source and expensive, and there is an urgent need for breakthroughs in related technologies to find substitutes [10].

Li Nian demonstrated in his research that for diamond films with inherently excellent electrical properties, injecting oxygen ions into them can improve their surface performance and electrical performance. Moreover, by improving the annealing process, the properties can be regulated to favor P-type or N-type, laying a foundation for the research and application of diamond-type PN junctions [11]. This technology still has some technical difficulties to be overcome, such as the instability of N-type conductive centers, lattice damage, doping efficiency, etc. However, it still has relatively broad application prospects, such as in high-temperature electronic devices, radiation sensors, biological detectors.

4.3. The alteration of mechanical properties of materials by ion implantation

In addition to the optical and electrical properties, the mechanical properties of the material also largely determine its application. Through the analysis of surface stress, including tension and shear force, a more comprehensive understanding can be gained of the material's application, lifespan, and damage caused during manufacturing and production.

Liu Donghao found that during the process of ion implantation, it would cause nonuniformity on the material surface, especially on relatively thin surfaces. Therefore, during the processing, the amorphous thickness on the material surface need to be paid attention. If the thickness of the amorphous material is too large, it is prone to irreversible damage to the material during the processing. An appropriate amorphous thickness can effectively alleviate the problem of stress concentration, thereby reducing the damage to the material during processing. In addition, for the protrusions caused by ion implantation, the longitudinal protrusions have a greater impact on stress (tangential force and normal force) compared to the transverse protrusions, while the transverse spacing has a certain influence on the normal force [12].

The research group of Muhammad Usman performed phosphorus ion implantation on ZnO thin films and carried out thermal annealing, successfully repairing the structural damage caused during the ion implantation process. During the injection process, ions undergo surface collisions with the material and lose energy simultaneously, resulting in various defects. These defects jointly affect the performance of the material. This technology has achieved stable P-type doping of ZnO films, which has enabled this material with high surface area, directional charge transport and excellent electronic properties to gain more applications, showing broad prospects in the application of nanodevices such as nanogenerators and solar cells [13].

Jiang J discovered that when carbon-atom doping was carried out on diamond tools by ion implantation, the wear resistance of the tools could be significantly improved, thereby enhancing the tool performance and enabling the tools to obtain better practical capabilities. This technology still needs to overcome the problem of making the cutting tool brittle due to the generation of hydrides during processing and use. However, overall, the doping of hydrogen atoms will induce a large number of defects such as dislocations within the material, forming an amorphous layer. This can further reduce the anisotropy of grains, resulting in reducing the intergranular wear and endowing the tool with better processing capabilities for composite materials such as silicon carbide. Its future application prospects are also very broad [14].

5. Conclusion

Ion implantation is a technology that improves the electrical, optical and mechanical properties of target materials by injecting impurity ions into their surface, thereby achieving wider applications. The main process involves first generating the required ion beam, followed by separation and purification, and then performing scanning implantation. The equipment required for ion implantation mainly consists of an ion source, a purification chamber, a scanning system, a vacuum system, and a target chamber. Each section plays a crucial role.

Finally, there has been a great deal of very mature research on doped atoms at present, not limited to nitrogen, phosphorus and their homologous elements, but also oxygen, iodine and their homologous elements have begun to explore their doping properties. In the future, with the development of integrated circuit technology, doping technology will also keep pace with The Times and continue to evolve. The future development field will focus on the stable doping of single atomic layers to meet the constantly increasing size requirements in the semiconductor field and achieve breakthroughs in quantum effects at the atomic scale.

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