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Research Progress and Application of Ion Implantation in Semiconductor Devices

Wenze Li[1, *],

Haoran Zhang [2]

[1]BEng Microelectronic Science and Engineering, Xi'an Jiaotong-Liverpool University, Suzhou, China
[2]Optical and electronic information, Suzhou City University, Suzhou, China
*Corresponding author: zhaojianbailu@outlook.com

Abstract:

Ion implantation, which emerged in the 1930s, has evolved into a core technology in the semiconductor field.In recent years, it has addressed numerous academic issues—for instance, achieving performance breakthroughs in certain devices and expanding the boundaries of semiconductor functionality. This paper systematically reviews the research progress in the integration of semiconductor materials and ion implantation technology, and looks ahead to future development directions. Firstly, it sorts out the origin and principle of the technology. Secondly, it elaborates on the modern applications of ion implantation, such as its use in semiconductor manufacturing, optical material processing, and other fields. Furthermore, it focuses on the application of typical ions—including impurity ions like boron ions, phosphorus ions, arsenic ions, indium ions, and germanium ions—in ion implantation. Finally, looking forward to, the paper discusses the new challenges that ion implantation will face, such as the requirements for low damage, atomic-level control, and reduced equipment costs. It proposes directions such as developing low-energy implantation and breaking through single-atom positioning technology, providing a reference for the development of semiconductor technology. The purpose of this study is to sort out the current development and applications of ion implantation, achieve the integration of information, and provide clear directional guidance for subsequent research.

Keywords: Ion Implantation; Doping Process; Semiconductor

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1. Introduction

Ion implantation was first used in the 1950s with the invention of early ion implanters and is still employed in semiconductor manufacturing processes today. Ion implantation is one of the methods that precisely injects specific impurity atoms into the surface of solid materials through high-energy ion beams to achieve selective doping and change the physical and chemical properties of solid materials. This technology is widely applied in various fields, such as semiconductor manufacturing, optics and biomedicine. For instance, in semiconductor materials, ion doping with boron, phosphorus, etc. is carried out to alter their electrical conductivity. Furthermore, by injecting specific ions into special materials, such as Au into SiO_2, the optical properties can be altered. At present, ion implantation technology is still constantly advancing to meet the demands of more complex chip manufacturing or other instruments in the future. This article discusses and summarizes the development history of ion implantation and the selection of ions in ion implantation, and will also explore the development of ion implantation and its future prospects. I. The principle of ion implantation and its applications in the fields of optics, semiconductors, and biology. Second, the application of specific ions and the development of new devices. Understanding the development process of ion implantation technology, the utilization of impurity atoms, and predictions for future development is conducive to a deeper understanding of the doping process in semiconductor manufacturing and has a positive effect on subsequent learning of semiconductor manufacturing.

2. The Principle of Ion Implantation

The principle of ion implantation is to ionize the injected element into plasma through electric discharge and other methods in the ion source, forming positively charged or negatively charged ions. These generated ions are introduced into the accelerator tube, accelerated to the desired speed under the action of a high-voltage electric field, and then the target ions are screened out by the mass analyzer to remove impurity ions to ensure the purity of the injected ions. These screened ions bombard the target surface and gradually lose energy in the target through electron blocking and nuclear blocking with the target atom's electron cloud and nucleus until they are captured at a specific depth, forming a doping distribution [1]. The core of this technology is to accelerate the injection of high-energy ions into solid targets, and then slow down and stay on the surface layer to form a doping layer, which can make the doping concentration and depth controllable, good uniformity, and accurate selection. It has realized the customized transformation of material properties and is widely used in semiconductor manufacturing, material surface modification and other fields.

3. Modern Applications of Ion Implantation

Ion implantation has evolved significantly since the 1960s, establishing itself as a pivotal technique for material modification. It enables precise tailoring of the physical and chemical properties of materials through the controlled incorporation of dopant ions

3.1 Semiconductor Manufacturing

Semiconductor manufacturing, as the core field of ion implantation, generally changes the conductivity and resistivity of semiconductor materials by injecting boron, phosphorus and other doped elements into semiconductor materials. In the past, British scientist John Burton and others found that by incorporating donor impurities (forming N-type) and recipient impurities (forming P-type) into semiconductor materials, the interface between the two regions will form a special electric field region, that is, the prototype of PN junctions, laying a solid foundation for the subsequent development of semiconductors. Nowadays, ion implantation not only has strong controllability of doping concentration and depth, but also can be carried out at lower temperatures, avoiding damage to silicon wafers and other prepared structures at high temperatures, and can meet the ultimate requirements of advanced process chips for transistor performance. TSMC uses ion implantation technology to accurately inject arsenic ions into silicon wafers. This solves the problem of precise regulation of transistor conductivity in chips, allowing transistors to maintain stable and efficient current control capabilities in small sizes.

3.2 Optical Material Processing

In the field of optical materials, ion implantation technology is widely employed to modify optical properties such as refractive index for the fabrication of optical components including waveguides and switches. Taking aluminum nitride (AlN) as an example, this material exhibits significantly superior thermal management capabilities compared to conventional ceramics, achieves excellent thermomechanical compatibility with silicon chips without cracking, and demonstrates exceptional tolerance to high voltage and temperature conditions. These characteristics make it a critical material in high-voltage grid communication equipment.In recent years, researchers such as Yu Sen have proposed a novel nucleation induction method to obtain high-quality AlN. By pre-treating nanopatterned sapphire substrates with nitrogen ion implantation at varying doses, followed by epitaxial growth of AlN via metalorganic chemical vapor deposition, the quality of heteroepitaxial AlN materials has been substantially improved. This demonstrates the considerable potential of ion implantation-induced nucleation technology for manufacturing high-performance AlN-based devices, and high-performance LED devices have been successfully

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fabricated based on this methodology.The advent of such high-performance AlN materials effectively overcomes the limitations of conventional materials under high-temperature and high-pressure conditions, leading to significant enhancements in the efficacy of ultraviolet-based disinfection systems and biochemical sensing devices. This progress provides more reliable hardware support for related application fields.

3.3 Biomedical Field

The applications of ion implantation technology in the medical field mainly focus on material modification and tumor treatment. By implanting specific ions into the surface of biomedical materials, the properties of these materials can be altered. In daily life, accidents or injuries are inevitable, and the advancement of medical science becomes particularly crucial in such cases. Researcher Wu Zhengwei and his team successfully prepared titanium-based bone implants containing cobalt elements using Plasma Immersion Ion Implantation (PIII) technology. Experiments have shown that this material can alleviate tissue inflammation, accelerate the formation of new bone, and inhibit the formation of bacterial biofilms. Taking methicillin-resistant Staphylococcus aureus (MRSA) as an example to illustrate its antibacterial properties, the adhesion rate of MRSA on the material is reduced by more than 80% [2][3]. This type of titanium-based bone implant can significantly reduce the body's rejection response in patients and form “osseointegration” with the patient's own bone. After implantation, it can remain in the human body for a long time, with stability far exceeding that of traditional materials such as stainless steel and cobalt-chromium alloys, thereby alleviating the pain suffered by patients during the treatment process.

3.4 New Energy Materials

Solar cells can have enhanced properties such as improved photoelectric conversion efficiency when certain ions are implanted into the original materials. Tin dioxide (SnO_2) serves as a high-performance anode material for various batteries (lithium-ion batteries/sodium-ion batteries). Doped ions can form doping energy levels in the band gap of SnO_2, which improves the material's ability to absorb photons. The generated trap energy levels can enhance the capture of electrons and holes, inhibit the recombination of photogenerated carriers, and thus improve the separation efficiency of photogenerated carriers. Additionally, doped vacancies and defect states act as electron-hole recombination centers; as the defect states of the dopant increase, the band gap of the material narrows, further boosting the utilization efficiency of light [4]. Zinc telluride oxide (ZnTe:O) also plays a crucial role in the new energy field by enhancing the photoelectric conversion efficiency of solar cells. It is mainly applied in the key direction of “intermediate-band solar cells”, addressing the pain point that traditional solar cells cannot efficiently utilize low-energy photons. Zhen Kang and his colleagues discovered that implanting ions into ZnTe single crystals can form ZnTe:O high-misfit alloys. They found that an appropriate dose of oxygen ions would form an intermediate band at 1.8 eV in the ZnTe:O alloy. Therefore, optimizing the oxygen implantation conditions and reducing the system disorder are conducive to the transition of the intermediate-band electronic states from localized states to extended states, which lays a foundation for the realization of ZnTe:O-based intermediate-band photovoltaic cells [5].

3.5 Material Surface Modification

Ion implantation into materials such as metals, ceramics, and polymers can significantly enhance properties including hardness, wear resistance, and corrosion resistance, thereby substantially improving functionality and service life. Academician Zou Shichang pioneered early research in China on ion beam material modification and ion beam analysis, and was the first to apply ion implantation to semiconductor integrated circuits in the country. Ion beam enhanced deposition for surface modification plays a major role in improving mechanical, optical, electromagnetic, and anti-corrosion properties of material surfaces, as well as in enhancing thin film adhesion [6]. His research laid a solid foundation for the application of ion implantation technology in modifying surfaces of semiconductors and other materials, driving development in related industries.For example, in smartphone chip manufacturing, silicon wafers are bombarded with ion beams to alter local conductivity characteristics, enabling the precise „drawing“ of conductive pathways only 几十 to several nanometers wide on the wafer. This directs current flow along designed routes, thereby realizing computing and memory functions in chips. In daily applications, tools such as knives tend to dull and rust over time, but after surface modification via ion beams, their surface hardness is greatly increased, resulting in significantly extended service life.

4. Common impurity atoms used in ion implantation

Next, a brief explanation will be given for the specific ion, such as boron ions, phosphorus ions, arsenic ions, indium ions, germanium ions, etc. We can understand clearly the concept of ion implantation through this section.

4.1 Application of Boron Ions

The application of boron ions is mainly in silicon processes. When injecting p-type impurities into silicon, boron ion implantation is the most common method. The depth distribution after implantation can strictly control the electrical performance of semiconductor devices [7]. The commonly used ion sources for boron element are boron trifluoride (BF_3) or diborane (B_2H_6), among which BF_3 is the most frequently used ion source. By colliding an electron and an ion source, the ion source is transformed into various ions in different quantities, such as B, B+, BF_2+, F+, etc. After the boron atoms were selected by mass spectrometry and accelerated, they were screened once again and then implanted into the silicon single crystal.

4.2 Application of Phosphorus Ions

The application of phosphorus ions is the same as that of boron ions, and the application of phosphorus ions is also often seen in silicon processes. Unlike boron ions, phosphorus ions are N-type dopants, but they can also alter the conductivity of silicon. The difference lies in the number of electrons they carry. N-type dopants have one more electron than silicon, while P-type dopants have one less electron than silicon. Different injection types can be selected or combined according to different needs. The ion source of phosphorus ions is usually PH_3. The injection sequence is as above as the boron ions.

4.3 Some innovative ions

With the continuous development of semiconductor manufacturing, the commonly used ions are no longer sufficient to meet all applications. Scientists have discovered that other ions can be utilized, and after their injection, different performance alterations can be achieved to meet various requirements. Ar ion implantation-induced nucleation can form high-quality GaN epitaxial layers [8], and Au ion implantation into SiO_2 substrates can synthesize LSPR sensors [8].

4.1.1 Ar Ion Implantation

Ar ion implantation-induced nucleation can form high-quality GaN epitaxial layers [8], and Au ion implantation into SiO2 substrates can synthesize LSPR sensors [8]. The Anxia team has achieved induced nucleation through Ar ion implantation to influence the quality of GaN epitaxial layers [8]. This is a method of improving new semiconductor materials through ion implantation, in which an uncommon ion, Ar, is utilized. It provides a good idea for the development of semiconductors.

4.1.2 Utilization of Au Ions

The Au ions, by virtue of the characteristics of ion implantation, can alter the properties of SiO_2 materials, such as optical properties. An LSPR sensor was fabricated by injecting Au ions of a certain intensity and dose into a SiO_2 substrate of specific thickness using an ion implanter, thereby enhancing the accuracy of measuring the refractive index and target substances in mixtures [9]. The application of LSPR sensors in some fields, such as petroleum, chemical engineering, food, and environment, has been provided with a basis [9].

5. Challenges Faced by Ion Implantation

As industries such as semiconductors move toward higher precision and lower power consumption, ion implantation technology is confronted with numerous challenges. In terms of low damage: Traditional ion implantation may cause significant damage to the material lattice, which impairs material performance. Therefore, the development of low-energy implantation technology is imminent—it can not only achieve the goal of doping but also reduce damage to the material. Atomic-level control is also a key challenge: Currently, device sizes are continuously shrinking, making them more portable in various aspects. However, this imposes an atomic-level requirement on the precision of ion implantation. It is essential to make breakthroughs in single-atom positioning technology to accurately control the position and quantity of implanted ions, thereby meeting the manufacturing needs of advanced devices in the future. Additionally, the persistently high equipment cost limits the wide application of ion implantation technology in more fields. Reducing equipment costs has become a crucial demand for industrial development. Only by lowering costs can this technology develop more rapidly and better benefit modern society.

6. The Future Development of Semiconductors

The prospects of ion implantation have two major aspects. One is the demand for the output of ion implanters. A greater output of ion implanters means that more ion implantations can be met. Second, the continuous improvement of ion implantation technology, which includes: higher energy, higher precision, better uniformity and lower contamination. Due to the continuous miniaturization of chips, ion implanters require a large amount of energy and higher precision to achieve stable and effective ion implantation. We need to optimize the beam and improve the ion source, meanwhile we should have industrial innovation, combined with intelligentization and other means. And then to ensure the yield of equipment, better uniformity is a key factor. This can be achieved by upgrading the scanning system and introducing artificial intelligence algorithms, we can promptly make corrections once the problems are identified, as well as enhancing the uniformity and guaranteeing the equipment yield through the upgrade of the process data collection and analysis system [10]. Finally, for the high-purity requirements of material, it is necessary to minimize metal contamination, particle contamination, cross-contamination, etc., in order to reduce device damage. The applications of emerging material systems may consider.

7. Conclusion

This study discusses the development of ion implantation technology and the application of specific ions, including different domain and different ions. We gain a deeper understanding of the unique advantages of ion implantation technology, such as precise atomic-level doping control, the doping concentration is not limited by the solid solubility of the material etc. At the same time, this technology can connect and coordinate different fields together. For example, semiconductor and equipment manufacturing drive each other. However, ion implantation still has issues such as the need for higher precision and energy, as well as high costs. To address the above issues, diversification of application materials, Technological breakthrough and combined with digitalization all of them are crucial parts. For instance, in the deep integration of artificial intelligence and the field of quantum computing, such as the precise positioning of phosphorus ion injection in silicon-based quantum dots. Finally, ion implantation technology is bound to continue to shine and contribute to the various field in the future.

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