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THE ROLE OF TECHNOLOGICAL FACTORS IN IMPROVING THE ELECTRICAL PARAMETERS OF SILICON POWER DIODES

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Abstract. This article analyzes the role and significance of technological factors in improving the electrical parameters of silicon power diodes. It examines the influence of the quality of the initial silicon material, doping level, thickness and resistivity of the epitaxial layer, diffusion and ion implantation processes, thermal treatment, surface passivation, and metal contact formation technology on the electrical characteristics of diodes. Furthermore, the physical significance of the main electrical parameters, including forward voltage drop, reverse current, breakdown voltage, reverse recovery time, and reverse recovery charge, is considered. Directions for improving the static and dynamic electrical characteristics of diodes and enhancing their operational reliability through the coordinated optimization of technological processes are substantiated.

Keywords: silicon power diode, electrical parameters, technological factors, doping, epitaxial layer, diffusion, ion implantation, thermal treatment, surface passivation, reverse recovery time, breakdown voltage, power losses.

Introduction

The rapid development of semiconductor electronics, power engineering, automation, and electrical energy conversion devices in recent years has necessitated the development of high-efficiency semiconductor devices and the improvement of their operational characteristics [1]. In particular, power diodes used in electrical energy rectification, control, and conversion systems are among the most important electronic components. They are widely used to convert alternating current into direct current, ensure unidirectional current flow in electrical circuits, and control the operation of various power electronic devices.

Silicon power diodes are distinguished by their high electrical strength, well-established manufacturing processes, relatively good thermal properties, and ability to operate across a wide range of voltages and currents. However, the performance of such diodes depends not only on the properties of the semiconductor material but also directly on their structural design, the formation of the p–n junction, doping concentration, crystal quality, surface condition, and technological processes employed during manufacturing.

The main electrical parameters of power diodes include forward voltage drop, maximum permissible forward current, reverse voltage, reverse current, breakdown voltage, reverse recovery time, and power losses. These parameters are interrelated, and improving one of them may lead to changes in others. For example, increasing the concentration of charge carriers to reduce the forward voltage drop of a diode may affect its reverse recovery process [2]. Therefore, ensuring an appropriate balance among the electrical parameters is an important scientific and technological challenge in the design and manufacturing of power diodes.

Technological processes play a particularly important role in determining the electrical properties of silicon power diodes. Specifically, the quality of the initial silicon wafer, the selection of epitaxial layer parameters, diffusion and ion implantation processes, thermal treatment, geometrical formation of the p–n junction, surface passivation, and formation of metal contacts all influence the static and dynamic electrical characteristics of the diode.

The aim of this article is to analyze, from a physical perspective, the technological factors that are important for improving the electrical parameters of silicon power diodes, to elucidate the mechanisms through which these factors affect their principal electrical characteristics, and to substantiate scientific and technological approaches to parameter optimization.

Main Part

1. Structure and Operating Principle of Silicon Power Diodes

A silicon power diode is a semiconductor device containing a p–n junction. Its operating principle is based on the potential barrier and electric field formed at the interface between p-type and n-type semiconductor regions.

Under forward bias, the applied voltage reduces the potential barrier, allowing majority charge carriers to cross the junction and produce an electric current. Under reverse bias, the potential barrier increases, restricting majority carrier movement, while a small reverse saturation current flows through the diode.

The lightly doped semiconductor region, known as the drift layer, plays a key role in enabling power diodes to withstand high reverse voltages. It helps distribute the electric field under reverse bias and determines the breakdown resistance of the p–n junction.

The main electrical parameters used to evaluate silicon power diodes are:

- Forward voltage drop V_F;
- Forward current I_F;
- Reverse voltage V_R;
- Reverse current I_R;
- Breakdown voltage V_{BR};
- Reverse recovery time t_{rr};
- Reverse recovery charge Q_{rr};
- Power losses in the diode.

These parameters depend on the physical properties of the semiconductor structure and the technological processes used in its fabrication. Therefore, controlling these processes is essential for improving diode performance.

2. Quality of the Initial Silicon Material and Its Effect on Electrical Parameters

The quality of the initial semiconductor material is essential in silicon power diode manufacturing. The crystallographic perfection, resistivity, dopant concentration, and defect density of silicon single crystals directly affect the electrical properties of the resulting semiconductor structure.

Dislocations, point defects, and impurities in silicon crystals can influence charge carrier mobility and lifetime. In particular, defects acting as recombination centres reduce carrier lifetime [3], thereby affecting the diode's forward conductivity and reverse recovery characteristics.

The resistivity of the initial silicon material is determined by its doping level. Increasing the dopant concentration raises the charge carrier concentration and reduces resistivity. However, excessive doping of the drift layer in high-voltage power diodes can adversely affect electric field distribution under reverse bias [4].

Therefore, silicon wafers should be selected according to the diode's intended operating voltage, current rating, structural design, and operating conditions. Quality control of the initial material is essential for ensuring stable parameter formation during subsequent manufacturing processes.

3. The Role of Doping and Epitaxial Layer Formation Technologies

The doping level and geometrical parameters of semiconductor layers are key factors determining the electrical characteristics of silicon power diodes.

Doping involves introducing donor or acceptor impurities into silicon. Donors produce n-type conductivity, while acceptors produce p-type conductivity. Dopant concentration affects the electrical properties of the p–n junction, potential distribution, resistance, and charge carrier mobility.

In high-voltage silicon power diodes, epitaxial growth enables the formation of semiconductor layers with controlled doping levels and thicknesses. The thickness and resistivity of the epitaxial layer are key technological factors determining the diode's reverse voltage capability.

Increasing the drift layer thickness provides a larger region for electric field distribution under reverse bias. However, it may also increase the diode's forward resistance. Therefore, an optimal balance between layer thickness and doping concentration is essential.

Epitaxial layer uniformity is equally important. Variations in thickness or dopant concentration across the wafer may cause local electric field enhancement, increased reverse current, and reduced breakdown voltage.

Thus, selecting appropriate epitaxial layer parameters according to the required electrical characteristics improves the static and dynamic performance of silicon power diodes.

4. Effects of Diffusion and Ion Implantation on Electrical Characteristics

Diffusion and ion implantation are widely used to form p–n junctions in silicon power diodes.

During diffusion, dopant atoms penetrate the silicon crystal at elevated temperatures. Diffusion depth and dopant distribution depend on temperature, processing time, diffusion ambient, and dopant diffusion coefficient.

The doping profile determines the geometrical and electrical properties of the formed p–n junction. Uncontrolled variations in this profile can affect electric field distribution and the diode's reverse voltage capability.

In ion implantation, accelerated dopant ions are introduced into the silicon wafer. This technique allows precise control of dopant concentration and implantation depth. However, implantation may create radiation-induced defects in the crystal lattice. Therefore, post-implantation thermal annealing is performed to activate dopants and restore the crystal structure.

The choice between diffusion and ion implantation depends on the diode design, manufacturing technology, and required electrical parameters.

Optimizing these processes improves p–n junction formation, electric field distribution, and the stability of diode electrical characteristics.

5. Thermal Treatment and Control of Charge Carrier Lifetime

Thermal treatment is an essential stage in silicon power diode manufacturing. It is used to electrically activate dopants, reduce post-implantation crystal defects, and achieve the required semiconductor properties.

Processing temperature and duration influence dopant diffusion, defect rearrangement, and charge carrier lifetime in silicon.

Controlling carrier lifetime is particularly important for improving the dynamic characteristics of power diodes. During reverse recovery, excess carriers remaining from forward conduction must be removed from the p–n junction or recombine.

An increase in carrier lifetime may reduce the forward voltage drop but also increases the stored charge that must be removed during reverse recovery, potentially increasing reverse recovery time and charge.

Conversely, reducing carrier lifetime can accelerate reverse recovery but may increase the forward voltage drop and conduction losses.

Therefore, carrier lifetime control is essential for balancing the static and dynamic parameters of diodes. Thermal treatment conditions, methods of introducing recombination centres, and the initial material quality must be considered together.

6. Surface Passivation and Electrical Strength of the p–n Junction

The reverse voltage capability of silicon power diodes depends not only on the bulk semiconductor structure but also on the surface termination of the p–n junction.

Surface states, defects, and moisture can cause non-uniform electric field distribution, increasing surface leakage current under reverse bias and potentially leading to premature electrical breakdown.

Surface passivation reduces the electrical effects of surface defects and improves surface stability. Silicon dioxide (SiO_2), silicon nitride (Si_3N_4), and other suitable dielectric layers can be used for this purpose.

The quality, thickness, uniformity, and interface properties of the passivation layer influence the diode's reverse electrical characteristics.

Special edge termination structures are also used to reduce electric field concentration near the p–n junction edges. These include guard rings, field plates, and other edge-field control structures, which can improve reverse voltage capability.

Thus, effective surface passivation and appropriate edge termination are essential for the reliable operation of high-voltage silicon power diodes.

7. Metal Contact Formation and the Effect of Contact Resistance

The quality of metal contacts significantly affects the electrical parameters of silicon power diodes. These contacts provide electrical connections between the semiconductor structure and the external circuit.

Contact properties depend on the physicochemical characteristics of the metal and semiconductor materials, contact formation technology, surface cleanliness, and thermal treatment conditions.

The primary function of an ohmic contact is to ensure current flow between the metal and semiconductor with minimal additional resistance. Increased contact resistance raises the overall forward voltage drop and electrical power losses.

Poor contact formation may cause local current crowding, additional heating, and reduced long-term device reliability.

Therefore, proper surface preparation, selection of the metallization composition, control of the metallization process, and subsequent thermal treatment are essential.

8. Combined Effects of Technological Factors on Key Electrical Parameters

Optimizing the electrical parameters of silicon power diodes requires considering technological factors collectively, as each manufacturing process affects one or more physical properties of the semiconductor structure.

For example, drift layer thickness and doping concentration determine reverse voltage capability and forward resistance. Carrier lifetime control affects forward voltage drop and reverse recovery characteristics, while surface passivation reduces reverse leakage current and prevents surface breakdown.

The main relationships between technological factors and electrical parameters are as follows:

- Forward voltage drop V_F depends on semiconductor resistivity, doping level, carrier mobility and lifetime, and contact resistance.

- Reverse current I_R is influenced by material defects, p–n junction surface conditions, passivation quality, temperature, and electric field.

- Breakdown voltage V_{BR} depends on drift layer thickness, doping concentration, p–n junction geometry, and edge electric field distribution.

- Reverse recovery time t_{rr} is determined by carrier lifetime and distribution, previous operating conditions, and switching conditions.

- Reverse recovery charge Q_{rr} depends on the preceding forward current, carrier lifetime, temperature, and reverse current rate of change.

- Power losses are determined by forward voltage drop, current, reverse leakage, switching processes, and thermal conditions.

Conduction power losses in a diode can be approximately expressed as:

$P_F = V_F * I_F$

where PF is forward power loss, V_F is forward voltage drop, and I_F is forward current.

For power diodes operating under alternating-current and switching conditions, reverse recovery energy losses must also be considered. These losses depend on switching frequency and external circuit conditions.

Therefore, optimization should focus not on improving a single parameter but on balancing forward voltage drop, reverse voltage capability, reverse recovery performance, and thermal stability.

9. Approaches to Optimizing the Electrical Parameters of Silicon Power Diodes

Improving silicon power diode performance requires comprehensive optimization of manufacturing processes. Initially, the diode's application, rated current and voltage, operating frequency, and temperature range must be determined.

The semiconductor structure is then designed by selecting drift layer thickness and doping level, p–n junction depth, edge geometry, and contact system properties.

The following aspects require particular attention:

- Controlling the crystallographic and electrical quality of initial silicon wafers;
- Adjusting semiconductor layer thickness and doping levels to meet electrical requirements;
- Optimizing diffusion and ion implantation conditions;
- Controlling crystal defects and carrier properties through thermal treatment;
- Improving surface passivation and edge electric field distribution;
- Reducing specific contact resistance;
- Ensuring process reproducibility and semiconductor structure uniformity.

Optimization effectiveness should be evaluated by measuring current–voltage characteristics, reverse current, breakdown voltage, reverse recovery parameters, and temperature-dependent properties.

Comparing samples manufactured under different technological conditions helps identify the effects of individual processes on electrical performance. Measurement conditions, including temperature, current, voltage, and switching parameters, must remain consistent.

Thus, improving silicon power diode performance requires more than optimizing individual manufacturing stages. It involves coordinating all processes, from initial semiconductor material selection to final electrical testing.

Conclusion

Technological factors play a crucial role in improving the electrical parameters of silicon power diodes. Their static and dynamic characteristics depend on semiconductor material quality, doping levels, p–n junction geometry, carrier lifetime, surface conditions, and metal contact quality.

Based on the theoretical analysis, the following conclusions can be drawn:

1. The crystallographic quality, resistivity, and defect density of silicon single crystals are key factors determining diode electrical characteristics.

2. Proper selection of drift layer thickness and doping concentration is essential for balancing reverse voltage capability and forward resistance.

3. Controlling diffusion and ion implantation processes enables the formation of p–n junctions with the required geometrical and electrical properties.

4. Thermal treatment and carrier lifetime control affect forward voltage drop and reverse recovery characteristics, thereby influencing dynamic performance.

5. Surface passivation and electric field control at p–n junction edges help reduce reverse leakage current and improve breakdown voltage.

6. High-quality metal contacts and reduced contact resistance minimize additional voltage drops and power losses.

Overall, optimizing silicon power diode parameters requires integrating materials science, semiconductor physics, and microelectronic technologies. Selecting optimal processing conditions, improving semiconductor structure uniformity, and comprehensively controlling electrical parameters provide an essential scientific and technological basis for developing high-efficiency and reliable silicon power diodes.

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