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Multi-Layer Compound Passivation and Dual-P Diffusion Enhanced Si Power Diode Performance

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Abstract. Power diode with multi-layer compound passivation and dual-P typed diffusion are studied and manufactured. Combine multiple advantages, a power diode with reverse breakdown voltage higher than 2200V, static on-resistance 1.11Ω and leakage current of 8.3mA can be obtained on silicon with a drift layer thickness of 280um and a resistivity of 60Ωcm. Simulation shows multilayer passivation layer with polysilicon contact can effectively change the edge carrier distribution, thus reducing the transverse current generation and improving the voltage withstand. Inserting a light and deep aluminum doped layer into PIN diode can increase the reverse withstand voltage by more than 16% through expanding depletion layer. And the moat structure of the device can further reduce the edge peak electric field, thus reducing the risk of breakdown. This device can be used in switching power supply and inverter.

Keywords. Power diode, Al diffusion, breakdown, passivation, silicon

1. Introduction

With the rapid development of economy and technology, demand for high-power devices has also growing. Power diode as the basic device is intensively used in new energy vehicles, solar energy and many other aspects. In recent years, the third generation semiconductor diode has a tendency to blowout for its material properties, however, the silicon-based diodes cannot be completely replaced due to the huge cost advantage and mature manufacturing process. Power diode based on PN junction theory has been deeply studied and various structures have been proposed, which make significant progress for the performance, while the high reverse blocking capabilities are still strongly demanded [1-2].

A typically and commercially available power diode (PIN diode) have very low resist drift layer, a backside of heavy doped N type Si and a top layer of heavy doped P type Si [3]. The main yield loss of this device is related to low reverse breakdown and high reverse leakage because of the strong edge electric field and strong surface recombination effect which could not be described by small signal model [4]. Now the

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technology mainly focuses on how to balance the cost, breakdown voltage and reliability. Lifetime control techniques [5] and low injection efficiency techniques was introduced to reach fast reverse recovery time and the forward voltage drop based on the classical structure [6]. Employing Schottky contact on anode side can effectively reduce the reverse recovery loss because it lowers the hole injection efficiency with the concept of metal semiconductor contact [7, 8].Overcoming low solubility in silicon and its high reactivity with oxygen, aluminum as dopant can be introduced to improve reverse withstand voltage [9]. Device passivation is an old and developing subject, whether in traditional diodes or new devices. Glass, Si_3N_4 and SiO_2 are often used to passivate silicon devices, which can provide good thermal stability and insulation, but it's not necessarily the best choice because of quantum effect and surface recombination. Semi-insulating polycrystalline-silicon (SIPOS) film has been used to passivate transistors [10], P-type poly silicon was used to passivate the solar cell to improve the quantum efficiency [11]. Several advantages of compound passivation, edge termination optimization and dual-P diffusion are combined into a high-power diode to form a new structure, which, to our knowledge, has not been reported.

In this paper, based on the simulation, different structures with multi-layer passivation, deep aluminum doping and edge terminations are compared and analyzed. Finally, a high-power diode over 2200V is fabricated and tested.

2. Simulation and Fabrication

2.1. Simulation

We use multi-step diffusion, etching and epitaxial process to setup the diode. The finite element method is used to analyze the model [4]. The mobility dependent, recombination rate concentration dependent, band gap narrowing and mobility field dependent models are used to study the device. Newton method is used for convergence standard and SILVACO code is used for all simulations [12].

A typically PIN diode is used to design and analysis as a basis, which have very low resist substrate of ~60Ωcm (intermediate drift layer, $\sim 6.3\times10^{13}/cm^3$), a backside of heavy dope N typed Si(concentration$\sim 1.6\times10^{20}/cm^3$) and a top layer of heavy doped P type Si(concentration $\sim 1.5\times10^{20}/cm^3$), a basic glass passivation layer always includes SiO_2, Si_3N_4 and BPSG. The electrodes are set in ohmic contact. Based on the basic parameters of the structure, the diffusion design, edge termination effect and passivation layer were studied to obtain an improved structure.

2.2. Fabrication

A 4-inch N type (111) substrate with a resistivity of 60Ωcm is used to fabricate optimized devices. Following with rinsing in diluted HF acid, two-step lithography and etching were carried out, and multilayer passivation layers were deposited by LPCVD. The ohmic contact electrodes were formed by nickel and gold plating. After cutting and cleaning, the device was packaged with copper lead on a substrate. Finally, the electrical performances of the device were tested.

3. Design and Results

3.1. P type Dual-Diffusion for Breakdown Enhancement

In the case of PN abrupt junction, the critical electric field limits the reverse bias voltage, beyond which the diode will be broken down. According to the doping concentration, the critical electric field of silicon is 0.2 ~ 0.6MV/cm [3,13]. Therefore, in order to improve the reverse breakdown voltage, it is necessary to reduce the doping concentration or increase the depletion region width. In a PIN structure, a light doped or intrinsic drift region is inserted between the heavily doped P and N regions, forming the so-called $P^+/N^-/N^+$ structure(structure (a)). However, to further improve the width of depletion layer and improve the breakdown voltage, We further insert a low concentration Al(~10^{14}/cm3) doped layer into high concentration P^+ and N^- layer, forming a $P^+/P^-/N^-/N^+$ structure(structure (b)). For comparison, we also use boron doping to form P^- layer in $P^+/P^-/N^-/N^+$ structure (structure (c)). The impurity concentration distribution of these three structures is consistent, and the termination layer is not added.

The forward and reverse IV curves of structure (a)~(c) are shown in figure 1. By fitting the linear region of the forward curve, we can get that the on-resistance (Ron) of the three structures is almost the same, about 1.10 Ω, the difference of saturation current is only 2A. But the reverse characteristic curves show that the breakdown voltages are very different. The reverse breakdown voltage of structure (b) and (c) is 191V higher than that of structure (a), reaching 1377V, reverse withstand voltage increased by 16%, indicating that adding a deep P^- layer can effectively improve the withstand voltage no matter the impurity is aluminum or boron. The peak electric field of the three structures appears at the interface of PN junction approaches the maximum value of the theory at breakdown state (~0.19MV/cm). The depletion layer width of structure (b) and (c) is 220 um, while that of the other is only 200 um. These results show that the width of depletion layer can be extended and the breakdown voltage can be greatly improved by introducing deep aluminum layer, and P type dual-diffusion is a feasible manufacturing method of power diode.

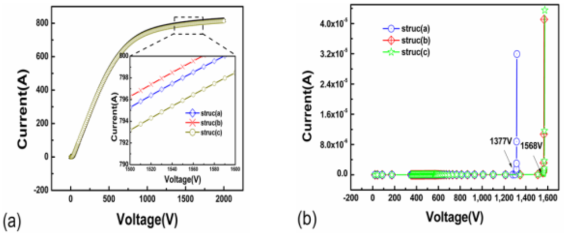

Figure 1. Forward and reverse IV curve of structure (a), (b) and (c). Figure 1 (a) is the forward curve. The insert in figure 1 (a) is a partial enlargement of the curve. Figure 1 (b) is the reverse characteristic curve.

3.2. Edge Etching Shape Comparison

In ordinary diodes, the total electric field is the vector sum of longitudinal electric field and transverse electric field. The electric field of semiconductor at the bottom of passivation layer is obviously lower than that at the bottom of electrode, and the etching of edge semiconductors forms various shapes, enhancing horizontal electric field, cause a series of device performance problems.

We compare three kinds diode with different edge shapes covered same passivation layers. Among them, A $P^+/N^-/N^+$ doping diode with edge horizontal plane is named structure (d), the other with same doping profile is 45° to vertical line is named structure (e), and the third one also with the same doping profile has moat structure termination is named structure (f). Figure 2 shows the forward and reverse IV curves of the corresponding structures.

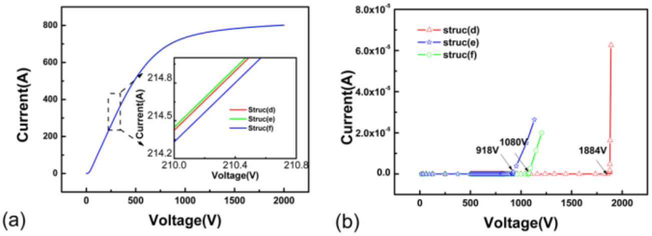

Figure 2. Forward and reverse IV curves of structure (d), (e) and (f). Figure 2 (a) is the forward curve. The insert in figure 2 (a) is a partial enlargement of the curve. Figure 2 (b) is the reverse characteristic curve.

For the forward case, IV curves of structure (d) ~ (f) are almost indistinguishable. By local magnification (figure 2(a) insert), it can be calculated that the slope of the linear region is 0.85. The anode current is mainly hole drift current, the cathode current are both hole and electron drift current. Further, according to X-Y decomposition, the drift current is mainly the longitudinal current, and the horizontal current is very small.

For the reverse case, among the three structures, the directional breakdown voltage of structure (d) is significantly higher than that of the other two, reaching 1884V, while that of structure (f) with moat structure is 1080V, and that of structure (e) is only 918V. At the reverse breakdown state, the transverse electric field values of these structures are different. Structure (d) has no transverse electric field at the edge and center of the device. However, structure (e) and (f) also have no transverse electric field in the center, and have electric field of 0.13MV/cm at the edge. The vertical electric field of the three structures is also completely different. The edge and center electric field of structure (d) are the same with absolute value as high as 0.18MV/cm; The edge electric field of structure (e) is close to 0.20MV/cm, and the center electric field is only 0.147MV/cm; the edge electric field of structure (f) is also 0.20MV/cm, but the center electric field is only 0.140 MV/cm. Note that these electric field values are extracted after breakdown state, indicating that the breakdown is mainly affected by horizontal component of total electric field. The structure (f) can reach higher withstand voltage and the edge can reach the critical electric field value.

3.3. Multilayer Compound Passivation

Under some special conditions, especially at high power or high voltage, ion charge and semiconductor surface state will have an important impact on device performance, for this purpose, passivation layer is optimized [14].

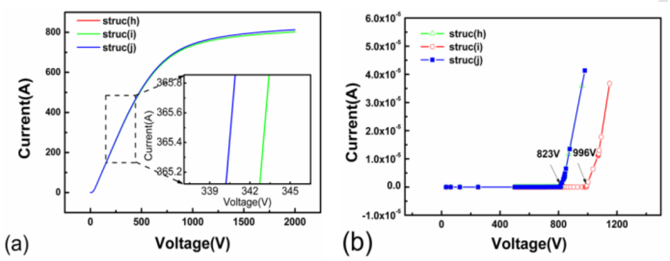

Figure 3. Forward and reverse IV curves of structure (h), (i) and (j). Figure 3 (a) is the forward curve. The insert in figure 3 (a) is a partial enlargement. Figure 3 (b) is the reverse characteristic curve.

The different passivation layers with moat shape are simulated. Among them, diode has vertical $P^+/N^-/N^+$ doping structure covered with glass passivation layer is named structure (h); the other diode has the same doping terminated with polysilicon and then covered with silicon nitride layer is named structure (i); and the third also has the same doping and covers with glass layer on the contact of Si_3N_4 layer on silicon, which is named structure (j)

Figure 3 shows the forward and reverse IV curves of the corresponding structures. From figure 3(a), it can be found that the Ron of these diodes has little difference, which is about 1.11Ω; And from figure 3(b), it is obvious shows that the breakdown voltage is different. Structures (h) and (j) exhibit the lowest reverse breakdown voltage, and they have no polysilicon edge passivation, indicating polysilicon enhances the breakdown performance. The transverse electric field is basically the same. There is no transverse electric field in the center, but the edge electric field is 0.12MV/cm. The vertical electric field presents different results. The peak value of the edge electric field is 0.186 MV/cm, while the electric field of diode with polysilicon passivation (0.142MV/cm) is significantly higher than that of the others (0.128 MV/cm).

4. Analysis and Discussions

4.1. Analysis

From above results, the forward characteristics of diodes with different structures have little difference. In the case of high current levels, the current transport is dictated by the presence of a high concentration of both electrons and holes in the drift region.

At 2000V, drift current is the main component of total current, and the electric field plays a major role. The heavily doped P^+ region has very low electric field (4.5×10^4cm/V) and low voltage drop (~150V), as shown in figure 4(a). In this region, the majority carrier concentration is very high, and the drift current density is ~ 10^7A/cm^2, as shown in figure 4(b). In addition, there is a concentration gradient of the majority and minority carrier resulting in diffusion current density as 4000 ~ 6000A/cm^2. It should be noted that when electrons are injected into the P^+ region, the hole recombination in the anode region converges, resulting in a recombination rate of 6.5×10^{28}/cm^{3}s, as also shown in figure 4(b). In the depletion region of P^+/N^- junction, the voltage drop is 1200V; the current is controlled by recombination in the depletion layer. In the drift region, the electron neutral condition requires the same concentration of minority and majority carriers, which makes the drift current mainly affected by electrons shown in figure 4(b), because its mobility is more than twice that of the hole. In the N^-/N^+ junction, the situation is similar to that in the P^+/N^- region, which will not be described in detail. It should be pointed out that drift current is the main current of forward diode, and other factors such as boundary recombination and transverse electric field have little influence on forward characteristics, so that the difference of forward characteristic curves obtained by the above structures is very small and almost indistinguishable.

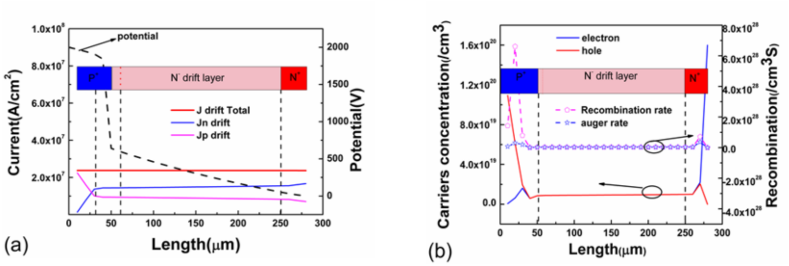

Figure 4. Longitudinal physical parameter distribution of the PIN diode at 2000V forward bias. Figure 4(a) shows electron, hole, total drift current values, and longitudinal voltage drop; Figure 4(b) shows the section distribution of electron and hole, the section distribution of recombination rate;

At reverse bias state, the total current is very small, only mA level. The final current value is equal to the recombination current. However, the current in the P^+ region near the anode and the N^+ region near the cathode is larger, but they are opposite and counteract each other. The current in P^+ region is composed of drift and diffusion of holes, while that in N^+ region is electrons, which can be calculated by the current density equation. The voltage drop is mainly concentrated in the drift region and the recombination mainly occurs at the depletion center. However, the total recombination rate is ~10^{18} /cm^{3}s level and the auger recombination rate is ~10^5/cm^{3}s level.

From the reverse process of diode, the withstand voltage of diode depends on the punch through voltage of drift layer, which can be expressed by $V_{PT} = \frac{qN_D(2d)^2}{2\xi_s}$. Where, the V_{PT} is the punch through voltage, the N_D is the drift layer doping concentration; the $2d$ is the drift layer width and ξ_s is the material dielectric constant. After Al doping, the width of depletion layer becomes wider and the breakdown voltage increases.

Additionally, from the perspective of electric field, the peak of vertical electric field occurs at the P^+/N^- interface, and the edge electric field is even larger than that in the center, which is ~8um away from the boundary of passivation layer and silicon as shown in figure 5. This electric field is the one that really decides the breakdown, which is influenced by the surface state and can be changed with different terminal materials. The conduction band energy of silicon nitride or glass is higher than that of silicon, resulting in the potential energy difference between the interface and the center, making the ratio of the two carrier concentration distributions to the center is no longer the same shown as figure 5(c).The increase of the electron concentration and the decrease of the hole concentration in the semiconductor near the interface counteracts the surface electric field, making the peak of the electric field at the interface move towards the bulk. If the polysilicon contacts with the silicon, the carrier can diffuse to the polysilicon layer, so that the electron concentration will exceed the hole concentration. As shown in figure 5(d), the total charge will be accumulated and further consistent with the electric field on the silicon surface, which will further enhance the withstand voltage capability.

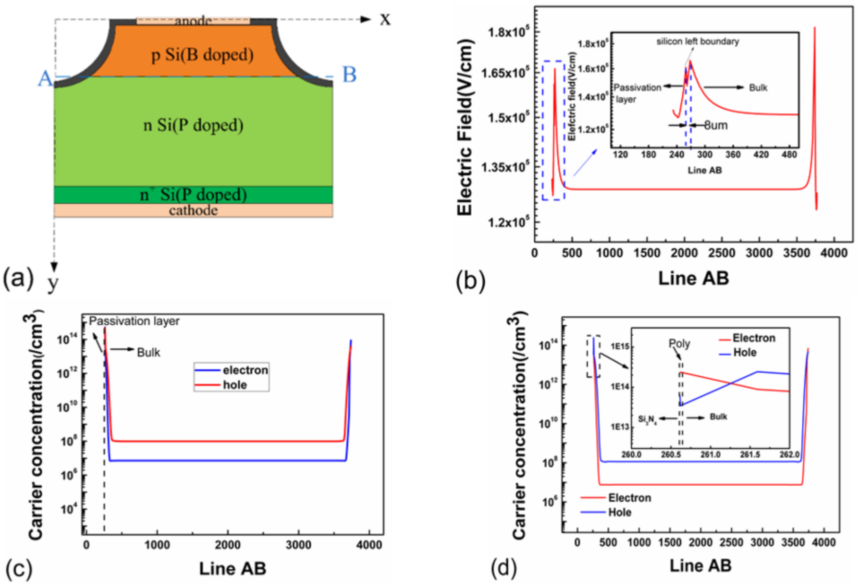

Figure 5. Carriers and electric field distribution at reverse bias of PIN diode. Figure 5 (a) shows the coordinate system, section line AB is used to extract various parameters. Figure 5 (b) shows the electric field distribution along line AB; Figure 5 (c) shows carrier concentration distribution for the structure without poly termination along line AB; Figure 5 (d) shows carrier concentration distribution for the structure with poly termination along line AB.

In addition, the shape of passivation layer can affect the electric field distribution on the surface. Compared with the inclined plane and the plane, the moat surface area is larger, which can reduce the electric field peak value [3].

4.2. Verification

Through the above simulation, we combine the advantages of several structures to form a power diode with polysilicon contact multilayer compound moat passivation and light doped aluminum structure, and test it by simulation and experiment.

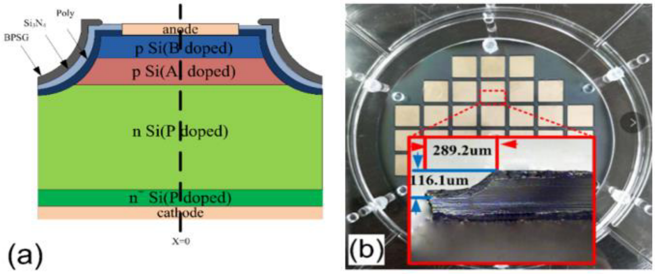

Figure 6. Final simulation and experimental structure. Figure 6 (a) is the simulation structure of double P-type diffusion with moat polysilicon passivation layer. Figure 6 (b) is an experimental pattern figure, the inert is cross section enlargement edge passivation.

Figure 6 shows the structure of the final simulation and the fabricated device. Figure 6(a) shows the final longitudinal structure, in which a P-type layer with aluminum light doping is inserted into the PIN structure, and a moat polysilicon /Si_3N_4/glass passivation layer is used as the termination. Figure 6(b) shows a power diode pattern fabricated by a semiconductor process. The inert is cross-section multi-passivation layer. The geometry data show that the device size is 280um both for simulation and experiment. The doping concentration data measured by SIMS technology show that the P^+ concentration is about $10^{20}/cm^3$, while P^- concentration is about $10^{14}/cm^3$. The N^- concentration is about 10^{14}/cm3, N^+ concentration is about $10^{19}/cm^3$. The center of depletion layer from anode to cathode is at 100um.

Table 1. Parameter of sever power diode.

Structure	Simulation	Experiment
Dimension (um ,L×W×H)	4064×280	4064×4064×280
Ron(Ω)	1.13	1.11
BV(V)	2230	2147
Reverse leakage current(mA)	6.2	8.3

Table 1 shows the simulated and fabricated device test data. Their characteristic parameters are almost the same. The tested Ron is 1.11Ω, the reverse breakdown voltage is 2230V and the leakage current is 8.3mA. It is worth noting that the performance of the device fabricated in the experiment is slightly lower than the simulation value. The main reason is that the breakdown voltage is lower than 83V. The possible reason is that the defects in the preparation increase the risk of breakdown. Similarly, the leakage current is also increased, which is also due to this reason.

5. Conclusion

This paper introduces the preparation principle of a $P^+/P^-/N^-/N^+$ diode, analyzes its semiconductor characteristics, and verifies the device by test. Through research and analysis, we can draw the following conclusions.(1) In PIN structure, insertion of light doped Al P- type semiconductor can move the center of depletion layer to the depth of the device, expand the width of depletion layer, and significantly improve the reverse withstand voltage. (2) Covering a layer of polysilicon as passivation layer can improve the edge carrier distribution concentration, reduce the surface electric field and reduce the risk of breakdown. (3) The diode with moat passivation structure, polycrystalline silicon coating and Al deep diffusion has a withstand voltage of more than 2200V and a reverse leakage current of mA level. Combined with these advantages, the diode can be used in switching power supply, inverter and other aspects.

Acknowledgements

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