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Enhancing the breakdown voltages of Au/n-Si Schottky diodes by boron ion beam-induced edge termination

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Abstract

Boron ion implantation for edge termination of Au/n-Si Schottky diode has been studied to enhance the breakdown voltages of the diodes. Ion energies of 30 and 50 keV were adopted to achieve edge-terminated Schottky diodes. Four doses of 1×10^{13}, 1×10^{14}, 1×10^{15} and 1×10^{16} B cm^{-2} were used for each energy. The Schottky diodes with edge termination show much higher breakdown voltages than the diodes without edge termination if the ion dose is controlled. For instance the diodes treated with low doses achieve high breakdown voltages while the diodes with high doses of 1×10^{15} and 1×10^{16} B cm^{-2} easily fail at low voltages showing early breakdown and high current leakage. According to the results from current–voltage (I–V), the current leakage is reasoned to result from deep level defects introduced by B ion implantation and the leakage at a reverse bias of −40 V is maintained low up to an elevated temperature of 160°C.

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Keywords: Ion implantation; Defects; Schottky diode; Edge termination; Breakdown voltage

1. Introduction

A Schottky barrier diode is the least complex power device. In general, Schottky diodes are of interest because they are majority carrier devices and have very fast switching times and no reverse recovery current [1]. In recent years, silicon carbide has received more attention as the potential material for a wide variety of high power devices [2–4]. Silicon Schottky diodes are severely limited by the low critical field which is only 6×10^5 V cm^{-1} when the Au/n-Si diodes have an n-type doping concentration of 1×10^{17} cm^{-3} [5]. In the case of high voltage devices, the edge termination plays a crucial role in determining the

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breakdown voltages. Alok et al. [6] successfully tried to enhance the blocking voltage of SiC Schottky diodes from 1000 to 1400 V by an edge termination technique using energetic Ar ions with 30 keV. According to their results, the breakdown voltage increased with the employed Ar dose. Their process is simply self-aligned to the Schottky contact because the Schottky metal acts as a mask preventing damage under the contact [7]. However, the ion beam-induced edge termination on Si Schottky diodes has never been reported and it is worthy of investigation. In this paper, we report our results on the optimum implantation conditions for the ion beam-induced edge termination in Au/n-Si Schottky diodes.

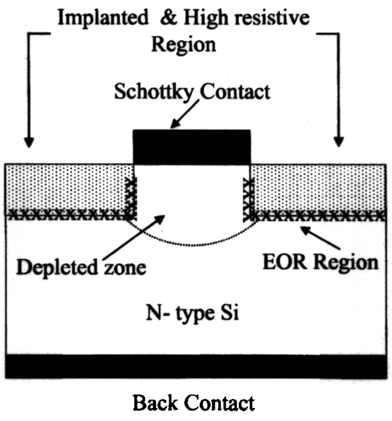

Fig. 1. Cross-sectional view of a Au/n-Si Schottky diode implanted with boron ions for edge termination.

2. Experiment

N-type Si samples (1 Ω cm) have been used to fabricate the Schottky diodes. Boron ion was selected for edge termination to effectively suppress the effect of field-crowding although other ion species were already demonstrated for the same purpose on SiC Schottky diodes [8]. Prior to the edge termination by boron ions, approximately 500 nm-thick Au-dots (300 μm-diameter) were deposited on n-Si as a pattern for the implantation mask. Then, the Au-patterned Si was implanted at room temperature with energies of 30 and 50 keV B ions to four doses of 1×10^{13}, 1×10^{14}, 1×10^{15} and 1×10^{16} B cm^{-2}. Blank implantation was also performed into bare n-Si wafers to be used as references, so that the crystalline damage of each implanted sample might be measured by MeV $^4He^{2+}$ backscattering/channeling spectrometry. The implantation energies were intentionally chosen according to TRIM-95 simulation, so that the ions might be completely stopped by the Au metal mask for the Schottky region. In order to study the thermal stability of this edge-termination in terms of current leakage, the Schottky diodes were annealed in a nitrogen ambient at temperatures of 160°C, 350°C and 500°C for 30 min. Large area backside contacts were formed using indium paste. Au thermal diffusion after annealing the diodes at 160°C, 350°C and 500°C was characterized by MeV backscattering spectrometry for which test samples without the dot pattern were prepared by annealing 120 nm-thick Au on n-Si wafers at the same temperatures. Fig. 1 shows a schematic cross-section of the Schottky diode structure fabricated by B ion implantation for testing. To study the effect of the edge termination on the breakdown voltage of the Schottky diodes, reverse current–voltage (*I–V*) measurements were performed using a Tektronix Curve Tracer 370A. Reverse biased capacitance–voltage (*C–V*) measurements were also done to check the n-type doping concentration of the substrate using a Hewlett Packard capacitance meter (model 4284A). Unimplanted reference sample is found to have an average donor concentration of 4×10^{15} cm^{-3} which is in consistence with the resistivity value.

3. Results and discussion

The typical reverse *I–V* characteristics for implanted and unimplanted Au/n-Si Schottky diodes are shown in Fig. 2 (a)–(b). Curves 1, 2, 4 and 5 in Fig. 2(a) present the reverse current leakage and the breakdown voltage of the Schottky diodes implanted with a B ion energy of 30 keV to doses of 1×10^{13}, 1×10^{14}, 1×10^{15} and 1×10^{16} cm^{-2}, respectively. The curve 3 is for a reference Schottky diode that has not been implanted. This curve is referred to as the unterminated diode. The breakdown point is defined by the voltage where the leakage current begins to increase sharply. The breakdown voltage of the unterminated diode is found to be 216 V. The breakdown voltages of

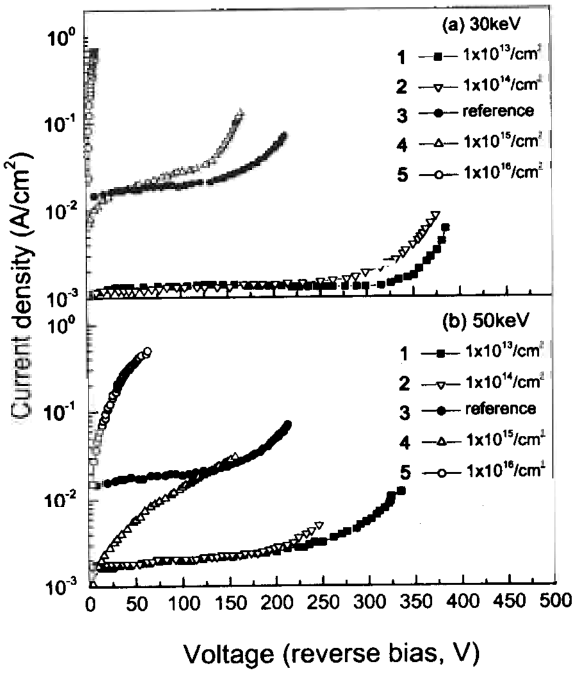

Fig. 2. Reverse current–voltage (I–V) characteristics for an unimplanted Au/n-Si Schottky diode (curve 3) and the diodes implanted to doses of 1×10^{13} (curve 1), 1×10^{14} (curve 2), 1×10^{15} (curve 4), 1×10^{16} cm^{-2} (curve 5) with the implantation energies of (a) 30 and (b) 50 keV.

terminated diodes of curves 1 and 2 are 386 and 330V, respectively, while those of the diodes in curves 4 and 5 are 166 and 20 V as shown in Fig. 2(a). The current leakage prior to breakdown occurring in the curve 1 is about 1.5×10^{-3} A cm^{-2} while that in the curve 3 is 5×10^{-2} A cm^{-2}. During the diode action, the edge termination confines the current-path with the high resistive region as shown in Fig. 1. The leakage of the terminated diodes is one order lower than that of the unterminated diode. However, if the implantation dose is over 1×10^{15} cm^{-2}, those benefits in terms of both the leakage and breakdown behaviors seem to be lost. These electrical behaviors are confirmed in Fig. 2(b) through the samples implanted with the B ions of 50 keV to the same series of doses. The breakdown voltages of terminated diodes of curve 1 and curve 2 in Fig. 2(b) are 337 and 268 V, while those voltages in curves 4 and 5 are only 150 and 83 V, respectively. As the implantation dose increases up to 1×10^{15} cm^{-2}, these effects are again lost.

It is interesting to note that the effects of the edge termination are pronounced only in the low doses of 1×10^{13} and 1×10^{14} cm^{-2}. Particularly, the best result is from the sample implanted with the lowest dose for which the breakdown occurs at 386 V with the low leakage. It is well known that the region surrounding the depletion zone of a metal Schottky diode should be electrically resistive and also that

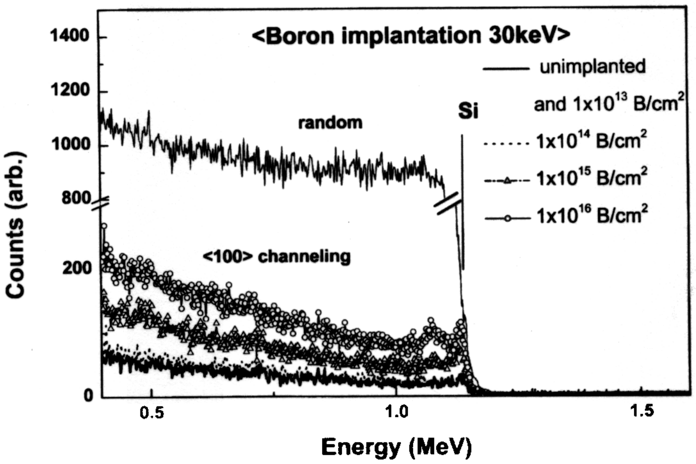

Fig. 3. The 2 MeV $^4He^{2+}$ ⟨1 0 0⟩ channeling spectra for unimplanted sample and samples implanted to different doses of 1×10^{13}, 1×10^{14}, 1×10^{15} and 1×10^{16} cm^{-2} with an implantation energy of 30 keV.

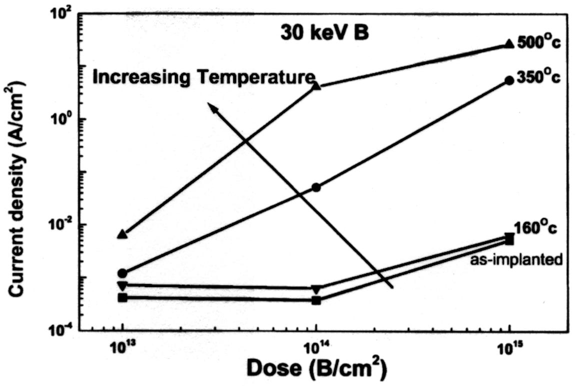

Fig. 4. Plots of B ion dose versus the average current leakage of the B implanted diodes at a reverse bias of −40 V. The samples were implanted with three doses of 1×10^{13}, 1×10^{14} and 1×10^{15} cm^{-2} and then annealed for 30 min in N_2 ambient. (T_1) room temperature, (T_2) 160°C, (T_3) 350°C and (T_4) 500°C.

making the region more resistive is more desirable for the edge termination [8]. As shown in the MeV $^4He^{2+}$ ⟨1 0 0⟩ channeling spectra of Fig. 3, the samples implanted to high doses of 1×10^{15} and 1×10^{16} cm^{-2} exhibit higher channeling yields due to the implantation-induced damages than the unimplanted sample or the samples with the low doses of 1×10^{13} and 1×10^{14} cm^{-2} where the channeling yields are too low to distinguish one another. It simply means that the higher the dose the larger the crystalline damage. In spite of the plain fact that the more damaged layer must be electrically more resistive, the less damaged one is found more favorable in our experimental Schottky diodes. It is highly probable that the high density of interstitials and vacancies exist as deep donors and acceptors near the end-of-range (EOR) region after implantation as indicated by an arrow in Fig. 1 particularly when the implanting dose is high. They trap electrons at the deep levels and deactivate the preexisting shallow donors, but the trapped electrons will be released to drift under a high electric field. As the field increases, the depletion zone of the diode expands to contact more of this EOR region where the deep level defects exist. It is understandable that the generation currents due to the carrier release cause the high current leakage before breakdown or lead to the early breakdown failure. Compared to the high dose case, the low dose implantation leads to a low density of deep defects even though it results in a less resistive region. A trade-off between the defect density and the resistivity in the implanted region should be made to determine B doses for an optimum edge termination to achieve the highest breakdown voltage and the lowest current leakage.

Fig. 4 exhibits a plot of B ion dose versus the average current leakage of the B-implanted diodes at a reverse bias of −40 V after the samples implanted with 30 keV B ions have been annealed for 30 min in an N_2 ambient. The current leakage of

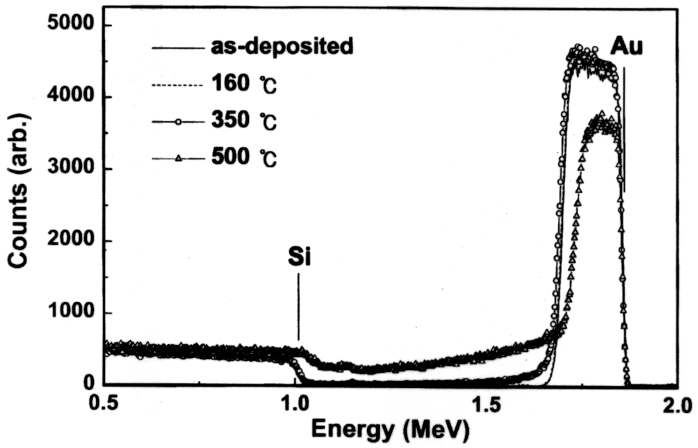

Fig. 5. The 2 MeV $^4He^{2+}$ backscattering spectra for test samples of 120 nm-thick Au on a unimplanted n-type Si. Those samples were annealed at an N_2 ambient for 30 min.

the samples annealed at 160°C seldom changes with respect to those of as-implanted samples. But if the annealing temperature increases over 350°C, all the samples except for the one implanted with the lowest B dose show much increased leakage losing their thermal stability. This degradation of thermal stability may be because the thermal diffusion of Au atoms may act as a source for the degradation of metal/n-Si Schottky junction, particularly when high density of interstitial Si atoms exists near the Au layer. The Au diffusion is proved by the MeV $^4He^{2+}$ backscattering spectra of Fig. 5 where the spectra are obtained by annealing test samples of 120 nm-thick Au on n-Si at 160°C, 350°C and 500°C for 30 min. No visible diffusion of Au is observed from the sample annealed at 160°C while the diffusion is clearly observed from the samples annealed at higher temperatures.

4. Conclusion

In summary, B ion implantation has been performed with four doses of 1×10^{13}, 1×10^{14}, 1×10^{15} and 1×10^{16} cm^{-2} to investigate the optimum dose condition for the edge termination of Au/n-Si Schottky diodes in terms of the breakdown and reverse leakage properties. The Schottky diodes with edge termination show much higher breakdown voltages than the diodes without edge termination if the ion dose is controlled to a low dose regime. The diodes with high doses of 1×10^{15} and 1×10^{16} B cm^{-2} easily fail at low voltages showing early breakdown and high current leakage. A high dose implantation introduces a high density of deep level defects near the EOR region where trapped carriers are released under the conditions of high electric fields. In the present dose conditions, the low dose implantation results in the effective edge termination introducing less amount of the deep defects even though it makes less resistive region surrounding the Schottky diode than the high dose implantation does. The current leakage at a reverse bias of −40 V is maintained low up to an elevated temperature of 160°C.

Acknowledgements

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