Optimum B^+ implantation conditions for the edge termination of the Au/n-Si Schottky diodes

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Boron ion implantation for edge termination was performed as a simple technique to improve the breakdown characteristics in Au/n-Si Schottky diodes. Four doses of 1×10^{13}, 1×10^{14}, 1×10^{15}, and 1×10^{16} B cm^{-2} were implanted at the ion energy of 30 keV. The Schottky diode implanted with the dose of 1×10^{13} B cm^{-2} shows the best edge termination characteristics. In addition, 20, 40, and 50 keV ion energies were also adopted to investigate the influences of implantation energies on edge termination in the Schottky diodes. The current–voltage measurement results show that the diode implanted with 1×10^{13} B cm^{-2} at 30 keV has the highest breakdown voltage of 386 V while the diode treated at 20 keV has the abrupt breakdown at only 150 V. Leakage currents at the reverse bias are attributed to the deep level defects introduced by ion implantation. Using two-dimensional simulation, it is verified that the anomalous breakdown phenomena in the diode implanted at 20 keV result from the high electric field near the Au contact edge.
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I. INTRODUCTION

Power semiconductor devices play an important role in the regulation and distribution of high electric power and energy. In general, Schottky diodes are of interest as the least complex power devices. They have fast switching times with no reverse recovery currents because they operate with only majority carriers.[1] In recent years, silicon carbide (SiC) has received significant attention due to its potential for a wide variety of high power devices,[2–4] even though the cost of SiC is much higher than that of silicon (Si). That is because Si Schottky diodes are severely limited by the low critical field.[5] Since the maximum electric fields are usually formed near the contact edge of the Schottky metal, the edge termination may be an important technique to improve the breakdown voltages of Si or SiC Schottky diodes. In order to take full advantage of the edge termination, several techniques, such as the use of diffused guard rings or field plates, have been suggested for Si power devices.[6,7] Although these techniques have an advantage on the breakdown characteristics of Si Schottky diodes, their fabrication processes have an inherent difficulty because they require an additional mask and precise alignment. In a SiC Schottky device, an ion implantation technique for edge termination has been proposed and analyzed.[2–4] This technique is based upon the formation of locally resistive layers at the periphery of a Schottky contact using high dose ion implantation. The main advantage of ion implantation for edge termination is that it is a self-aligned process with the Schottky metal acting as a mask preventing ion-induced damage under the contact.[8] Under a reverse bias, highly resistive layers with a certain thickness promote the reduction of the edge electric field. Alok *et al.* tried to increase the blocking voltage of SiC Schottky diodes from 1000 to 1400 V by the edge termination technique using energetic Ar implantation with 30 keV.[9] On the other hand, the ion-beam-induced edge termination for Si Schottky diodes has been recently reported and the results show that increasing boron (B) dose may degrade the breakdown properties of the diodes.[10,11] In this article, we report the experimental and simulated results on the impact of B ion implantation on the edge termination characteristics and offer the optimum energy and dose conditions for the enhanced breakdown properties in the Au/n-Si Schottky diodes implanted with B ions.

II. EXPERIMENTS AND SIMULATIONS

n-type Si (100) wafer substrates (1 Ω cm) were used to fabricate the Si Schottky diodes. Boron (B) was selected for edge termination to effectively suppress the field-crowding effect at the contact edge although other ion species were already demonstrated for the same purpose on SiC Schottky diodes.[12] Prior to implanting the B ions, 500 nm thick Au dots (300 μm diameter) were deposited by thermal evaporation at room temperature as an implantation mask and Schottky metal. Next, the Au-patterned n-Si was implanted at room temperature with 30 keV B ions at four doses of 1

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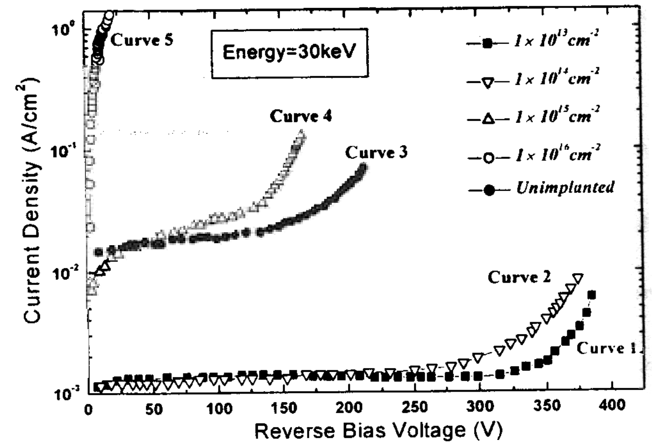

FIG. 1. Measured reverse $I-V$ characteristics for the unimplanted Au/n-Si Schottky diode and the diodes implanted with doses of 1×10^{13}, 1×10^{14}, 1×10^{15}, and 1×10^{16} B cm^{-2} at the ion energy of 30 keV.

$\times10^{13}$, 1×10^{14}, 1×10^{15}, and 1×10^{16} B cm^{-2}. Other ion energies of 20, 40, and 50 keV were also employed at a dose of 1×10^{13} B cm^{-2}. Indium was applied on the backside of the substrate to form an ohmic contact. The crystalline damages produced by ion implantation were measured by MeV $^4He^{2+}$ backscattering/channeling spectrometry. The channeling spectra showed that increasing B dose monotonically increases the channeling yield at the implanted region of Si.[10] To study the effects of the edge termination on the breakdown voltage in the Au/n-Si Schottky diodes, reverse current–voltage ($I-V$) measurements were performed using a Tektronix Curve Tracer 370A. Capacitance–voltage measurements were also performed to check the n-type carrier concentration in the substrate of the Schottky diodes using a Hewlett–Packard capacitance meter (model 4284A). The unimplanted diode for reference is found to have a donor concentration of 4×10^{15} cm^{-3}, which is consistent with its resistivity.

The ion implantation simulator TRIM-95 and the two-dimensional process simulator TSUPREM-4 with the implant damage and the point defects models,[13,14] were used to calculate interstitial and vacancy concentrations in the Au/n-Si Schottky diodes. Based on the process simulation results, we analyzed device characteristics of the Schottky diodes using the device simulator MEDICI.[15]

III. RESULTS AND DISCUSSION

A. Effects of B ion dose

The measured reverse $I-V$ characteristics for implanted and unimplanted Au/n-Si Schottky diodes are shown in Fig. 1. Curves 1, 2, 4, and 5 in Fig. 1 present the leakage currents at the reverse bias and the breakdown voltages of the Schottky diodes implanted with the B ion energy of 30 keV to the doses of 1×10^{13}, 1×10^{14}, 1×10^{15}, and 1×10^{16} cm^{-2}, respectively. Curve 3 is from the Schottky diode that was not implanted for comparison. This curve is referred to as the unimplanted diode. The breakdown voltage was defined by the voltage where the leakage current begins to increase sharply. The breakdown voltage of the unimplanted diode is found to be 216 V from curve 3. The breakdown voltages of terminated diodes (curves 1 and 2) are 386 and 330 V, respectively, while those of the diodes represented by curves 4 and 5 are 166 and 20 V as shown in Fig. 1. The leakage current prior to breakdown occurring in curve 1 is about 1.5×10^{-3} A cm^{-2}, while that in curve 3 is 5×10^{-2} A cm^{-2}. During the diode operation, the implanted high-resistivity region confines the current-path efficiently. 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 such as the low leakage current and high breakdown voltage seem to be lost.

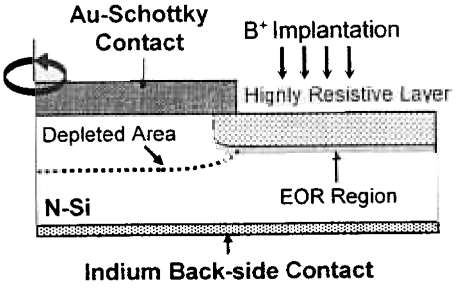

FIG. 2. Schematic cross section of a B ion-beam treated Au/n-Si Schottky diode. B ion implantation introduces both the highly resistive layers and the EOR defect region to the diode.

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 edge-terminated characteristic is shown in the diode implanted with the lowest dose. The diode with doses of 1×10^{13} cm^{-2} shows that the breakdown occurs at 386 V with a low leakage level. In spite of the intuition that the more damaged layer must be electrically more resistive, the less damaged one is found to be more favorable in our experiments. 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 when the high-dose implantation is applied. They trap electrons at the deep levels causing deactivation of the pre-existing shallow donors, but the trapped electrons will be released to drift under a high electric field. As the reverse voltage increases, the depletion area of the diode expands to contact more of this EOR region where the deep level defects exist. It is understandable that the generated currents due to the released carriers cause the high current leakage before breakdown and lead to the early 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 tradeoff between the defect density and the resistivity in the implanted region should be made to determine B ion doses for an optimum edge termination to achieve the highest breakdown voltage and the lowest leakage current. Figure 2 is the schematic cross section of the Au/n-Si Schottky diode, illustrating the ion-beam-induced edge termination and the existence of the EOR region.

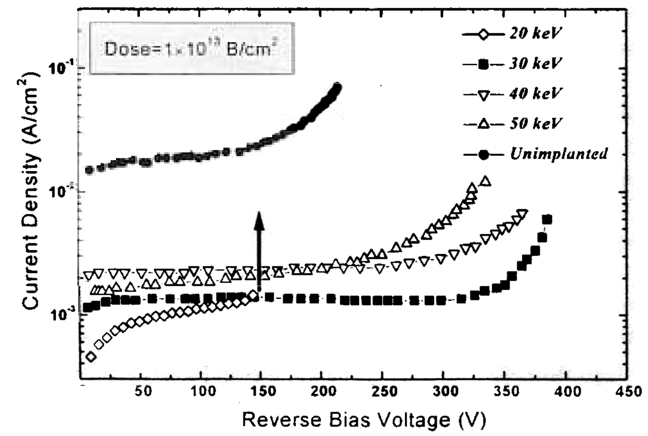

FIG. 3. Measured reverse $I-V$ characteristics for the unimplanted Au/n-Si Schottky diode and the diodes implanted at the ion energies of 20, 30, 40, and 50 keV with dose of 1×10^{13} B cm^{-2}.

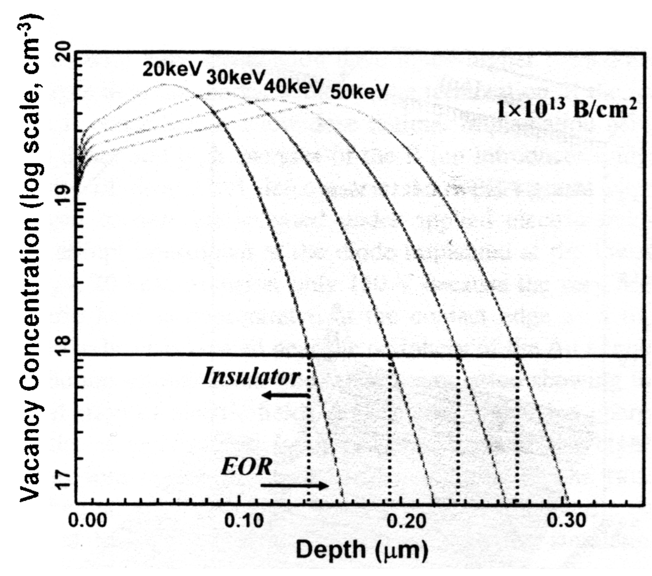

FIG. 4. Damage distribution simulated by TRIM-95. EOR region is defined as an end region beyond level of vacancy concentration (1×10^{18} cm^{-3}) and highly resistive insulator is above the level.

B. Effects of B ion energy

The measured reverse $I-V$ characteristics of the Au/n-Si Schottky diodes implanted with B ions at 20, 30, 40, and 50 keV to a dose of 1×10^{13} cm^{-2} are shown in Fig. 3. The highest breakdown voltage of 386 V is obtained from the diode implanted at an energy of 30 keV. In the case of the diode implanted at 20 keV, the lowest energy in this work, an abrupt breakdown occurs at about 150 V while the leakage current is less than that of any other diodes. The diodes implanted at higher ion energies show higher breakdown voltages than 216 V, which is the breakdown voltage of the unimplanted diode. Figure 3 also shows that the diode prepared with the B ion energy of 30 keV has a higher breakdown voltage by about 50 V than the diode implanted at 50 keV.

For the analysis of the leakage current behaviors accompanied by the breakdown characteristics in these diodes, we simulated the beam induced damage profiles using the TRIM-95 implantation simulator as shown in Fig. 4. It simply shows that the vacancy profiles are dependent upon the B ion energy. Assuming that the EOR region is defined as a region beyond a certain level of vacancy concentration (1×10^{18} cm^{-3}) and a resistive insulator region is physically above this level, the integrated amount of vacancy defects beyond the EOR region becomes larger as the ion energy increases. This suggests that the diodes treated with the lower ion energy should have lower leakages due to lower amounts of deep level defects. According to this hypothesis, it is understandable that the diode implanted at 20 keV has the minimum level of the leakage current. However, the TRIM-95 simulation does not directly explain the anomalous breakdown in the diode implanted at 20 keV, although it supports the result that the diode has the lowest leakage level before the breakdown.

In order to explain the unexpected breakdown characteristics in the diode implanted at 20 keV, process and device simulations were performed using TSUPREM-4 and MEDICI simulators. The two-dimensional process simulation using TSUPREM-4 was performed based on the results from TRIM-95 simulation. Figure 5 is the simulated results showing the contours of ion-beam induced insulators which have more than 1×10^{18} cm^{-3} vacancies. It clearly shows that the highly resistive or insulating layers expand with increasing ion energies.

Simplifying the highly resistive layer geometry as a rectangular insulator, we have obtained three-dimensional distributions of the electric field near the contact edge as shown in Fig. 6. Many works indicated that the space charges and electric fields at the boundary of the ion-implanted region must be considered where the dielectric constant changes. Additionally the material difference between Si and SiO_2 may also affect the device characteristics. Therefore the results from our simulations presented here should provide a relative comparison among the structures with different ion-energy conditions but do not provide absolute numbers. The

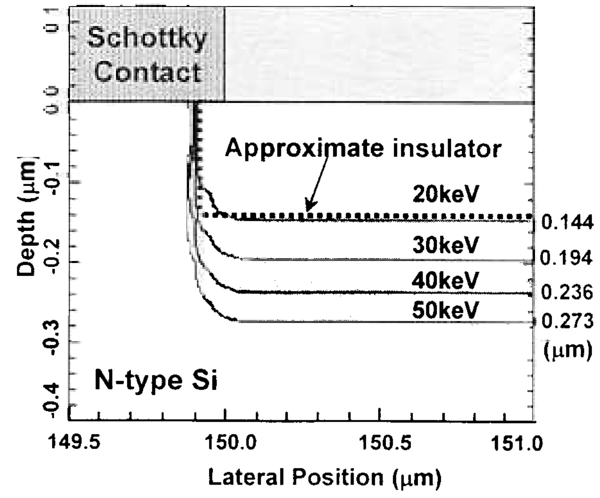

FIG. 5. Two-dimensional contour lines of vacancy concentration (1×10^{18} cm^{-3}) for the diodes implanted at 20, 30, 40, and 50 keV. Those have been simulated by TSUPREM-4.

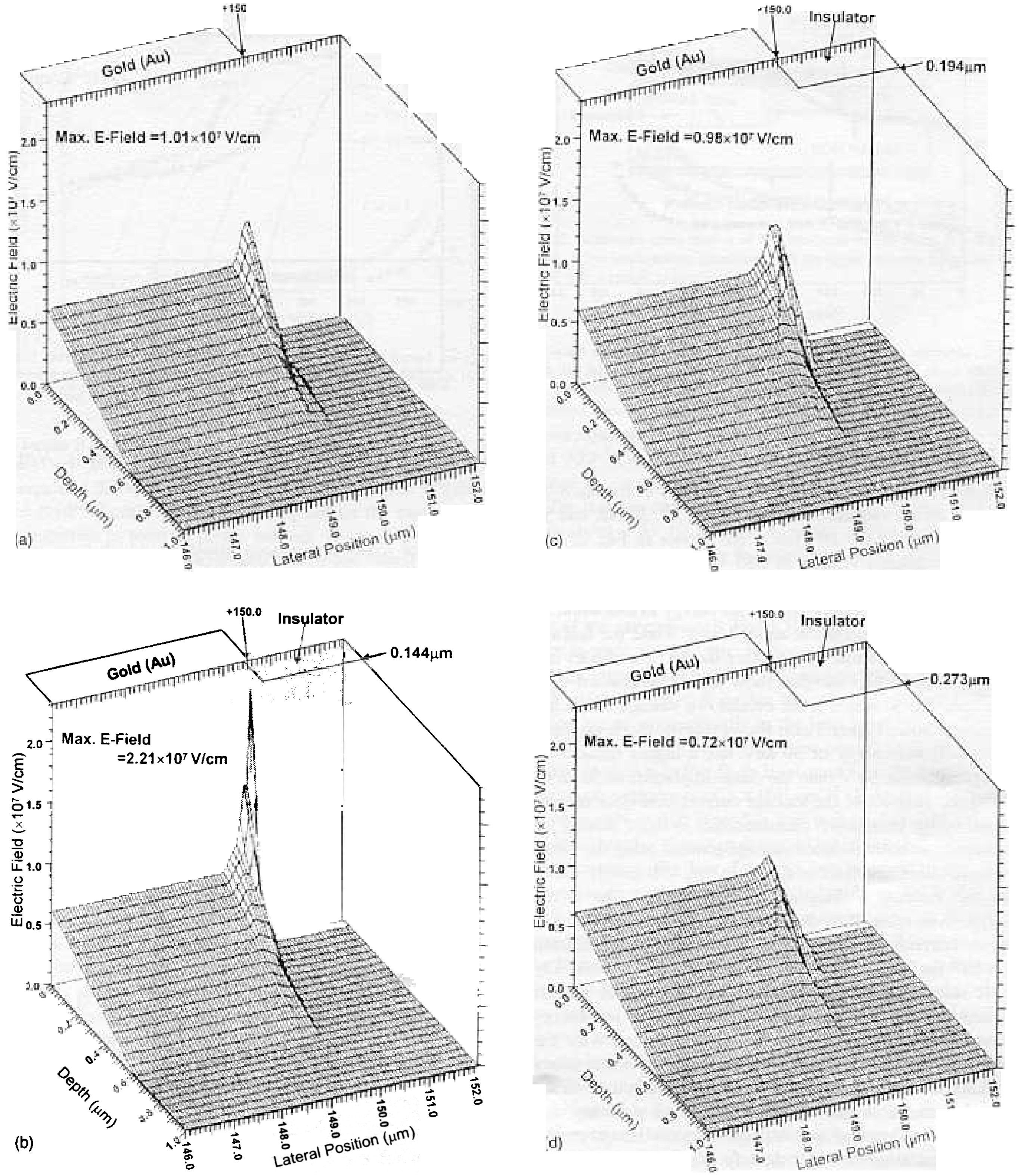

FIG. 6. Three-dimensional distributions of the electric fields formed at 200 V in the Au/n-Si Schottky diodes. Those have been simulated by MEDICI: (a) without insulating layers; (b) with insulating layers having the thickness of 0.144 μm; (c) with insulating layers having the thickness of 0.194 μm; and (d) with insulating layers having the thickness of 0.273 μm.

two-dimensional simulation was performed by MEDICI under the reverse bias condition of 200 V. The insulating layers of the diodes implanted at 20, 30, and 50 keV were approximated to the silicon dioxide layers having thicknesses of 0.144, 0.194, and 0.273 μm, respectively, because those layers have vacancy concentrations higher than 1×10^{18} cm^{-3} as shown in Fig. 5. Figure 6(a) shows that the unimplanted diode has the maximum electric field of 1.01×10^{7} V/cm at the contact edge while the field rapidly decreases to the flat level of 0.62×10^7 V/cm as the contact region moves away from the contact edge. This result shows that the breakdown in a Schottky diode originates from the contact edge due to a locally high electric field. Figures 6(b)–6(d) show that the diodes with the insulating thicknesses of 0.144, 0.194, and 0.273 μm have the maximum electric fields of 2.21×10^7, 0.97×10^7, and 0.73×10^7 V/cm at the contact edge, respectively.

It is noted that the maximum electric field of the diode with insulating layers of 0.144 μm is much higher than that of the unimplanted diode. However, the diodes with insulating layers of 0.194 and 0.273 μm have lower electric fields at the contact edge than the unimplanted diode. The results shown in Fig. 6 indicate that a maximum electric field at the contact edge increases as the thickness of insulating layers decreases. According to these results, the degraded breakdown properties are expected at the diode with a thin insulating layer, while the diode with a relatively thick insulating layer should have effective edge-termination characteristics. It has not been reported but is interesting that the thin insulating layers formed at the periphery of the contact may seriously deteriorate breakdown characteristics of the Schottky diodes under a certain thickness.

From the previous analysis, it is clearly explained why the early breakdown occurs at 150 V in the diode implanted at 20 keV. In this diode, the sharp increase of electric field takes place at the contact edge, because the created insulating layer is too thin. It means that the diodes with thick insulating layers are expected to have high breakdown voltages. However, the experimental results of Fig. 3 are not exactly the same as the expectation from the simulations. From the simulation results, the diodes implanted at the higher ion energies should have the thicker insulating layers and higher breakdown voltages as well. It is not necessarily true in the cases of the diodes implanted at high ion energies over 30 keV. The diode implanted at 50 keV shows slightly lower breakdown voltage than the one implanted at 40 keV, which has about 370 V as the breakdown point. The best result of 386 V comes from the diode implanted at 30 keV. These results are due to the high density of deep level defects in the EOR regions as shown in Fig. 4. As the reverse bias increases up to critical points in the edge-terminated diodes, large leakage currents are generated with the help of the vacancies and interstitials near the lateral and vertical EOR region before the actual breakdown. It is thus considered that the breakdown voltage may not monotonically increase with the B ion energy, and an optimum ion energy exists. It is because the higher ion energy induces not only the thicker resistive layer but also the higher density of the EOR defects in a diode.

IV. CONCLUSION

B ion implantation has been performed with various energies and doses to investigate the optimum condition for the edge termination of Au/n-Si Schottky diodes. The Schottky diodes with edge termination have much higher breakdown voltages than the diodes without edge termination, if the ion dose is controlled at a low-dose regime. Implantation using high doses and high energies of the B ion introduces a high density of deep level defects near the EOR region where trapped carriers are released under applied electric fields. The abrupt breakdown at the diode implanted at the lowest energy, 20 keV, occurs at only 150 V because the very high electric field is concentrated at the contact edge as a thin resistive layer is created near the periphery of the Au contact by the ion implantation. The MEDICI simulation showing the distribution of electric fields suggests the higher ion energy for the enhanced breakdown property, because the higher energy ions may create a thicker insulating layer. The TRIM-95 simulation proposes the lower energy of ion for the enhanced leakage property. Considering both the simulation and experimental results, it is concluded that there is an optimum range of ion energy for an effective edge termination. In the present study, the optimum condition of leakage and breakdown property is acquired from the diode implanted with 30 keV B ions at a dose of 1×10^{13} cm^{-2}.

ACKNOWLEDGMENTS

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