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# Effects of Carbon Impurity in Monocrystalline Silicon on Electrical Properties and the Mechanism Analysis of PIN Rectifier Diodes

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**ABSTRACT** Carbon impurities are common defects in monocrystalline silicon and have negative effects on the electrical performance of electronic devices. In the present work, the effects of carbon impurities in monocrystalline silicon on the electrical properties of PIN rectifier diodes with different carbon concentrations were investigated by electrical performance tests, anisotropic preferential etching, Fourier-transform infrared spectroscopy (FTIR), transmission electron microscopy (TEM), and energy-dispersive spectroscopy (EDS). It was found that with the increasing carbon concentration, the reverse leakage current (IR) increased rapidly, the time of reverse recovery (TRR) and the ratio of the average reverse withstand voltage to the theoretical value decreased rapidly, and the forward voltage drop ( $V_f$ ) increased significantly. Further, with the rising carbon concentration, bulk oxidation-induced defects (B-OSF) changed from dislocation-dominated to stacking fault-dominated and the stacking fault length increased gradually.  $[C_i-O_i]$  carbon centers of interstitial carbon and interstitial oxygen with a wide absorption band were detected by FTIR. The existence of stacking dislocation defects and carbon-oxygen complexes  $[C_i-O_i]$  was confirmed by TEM and EDS. It was pointed out that substitutional carbon ( $C_s$ ) captured interstitial silicon atoms, changed into interstitial carbon ( $C_i$ ) in the silicon substrate, and formed  $[C_i-O_i]$  complexes of interstitial carbon and interstitial oxygen after high-temperature diffusion, and these complexes acted as heterogeneous nucleation centers to promote the formation and growth of oxygen precipitation. Due to the volume strain energy, interstitial silicon atoms and dislocations were continuously released to promote oxygen atoms during the growth process of carbon-oxygen complexes. The formation and growth of B-OSF defects caused the "impurity piercing pipe" effect. These defects acted as defect recombination centers and deteriorated the electrical performance of the PIN rectifier diodes.

**INDEX TERMS** Carbon impurity, PIN rectifier diode, monocrystalline silicon, electrical properties, bulk oxidation-induced defect (B-OSF).

## I. INTRODUCTION

Power devices are characterized by their high voltage and high current, and they are core power conversion devices of power electronic systems. Silicon-based PIN power diodes are widely used in household electronic appliances, industrial electronic systems, automotive and power locomotive electronic systems, smart grids, and ship and aerospace

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navigation systems [1], [2]. With the development of intelligent, integrated, and miniaturized power conversion systems, the use of PIN power diodes has become indispensable. Monocrystalline silicon, as the core material, has a profound impact on the electrical properties of PIN power diodes. Therefore, it is of great significance to study the effects of common carbon impurities in monocrystalline silicon on the electrical properties of PIN power diodes.

Carbon impurities are common defects in monocrystalline silicon [3]–[6], and they mainly come from the thermal field

of graphite [7] or organic contamination during monocrystalline growth [8]. Carbon impurities mainly exist in the form of substitution sites in monocrystalline silicon [9], and they can be calibrated by measuring their concentration at the absorption peak of  $607\text{ cm}^{-1}$  by Fourier-transform infrared spectroscopy (FTIR) [10]. It is widely recognized that carbon impurities have negative impacts on the electrical performance of PIN rectifier diodes [11]–[15]. However, the effects of carbon, oxygen, silicon interactions on the electrical performance of PIN rectifier diodes still need to be explored. The present work focused on the effects of different carbon concentrations on the electrical properties of PIN rectifier diodes. The morphological changes in the PIN diodes before and after the diffusion of carbon impurities and the interaction with oxygen impurities were studied in detail. The effects of carbon impurities on the electrical properties of the PIN diodes were expounded from the microscopic level.

## II. EXPERIMENTAL SECTION

### A. SAMPLE

An N-type phosphorus-doped  $\langle 111 \rangle$  monocrystalline silicon ingot of 100 mm diameter was cut into silicon wafers with different carbon concentrations. In order to minimize the effects of impurity metals and as-grown swirl defects, the monocrystalline silicon ingot had a minority carrier lifetime of greater than 100  $\mu\text{s}$ , a low heavy metal concentration, and no as-grown swirl defects (Table 1). Oxygen and carbon concentrations in the samples were measured according to the ASTM F 1188:1993 standard. The samples were cut into 340  $\mu\text{m}$  thick slices and 2 mm thick plates. The 2 mm thick plates were polished with a mixed solution of  $\text{HNO}_3$  and HF, and the 340  $\mu\text{m}$  thick slices were chamfered and ground to  $290 \pm 5\ \mu\text{m}$  thick surfaces after being heat-treated at  $650^\circ\text{C}$ .

TABLE 1. Wafer properties.

Carbon NO.	Carbon content ( $10^{16}\text{ at/cm}^3$ )	Diameter (mm)	Orientation	Dopant	Oxygen				As-grown swirl defects
					Resistivity ( $\Omega\cdot\text{cm}$ )	content ( $10^{17}\text{ at/cm}^3$ )	Lifetime ( $\mu\text{s}$ )	Dislocation ( $\text{pcs/cm}^2$ )	
1	$0 \times 10^{16}$	100	$\langle 111 \rangle$	P	20–40	7–10	>100	<100	No
2	$4.85 \times 10^{16}$	100	$\langle 111 \rangle$	P	20–40	7–10	>100	<100	No
3	$6.10 \times 10^{16}$	100	$\langle 111 \rangle$	P	20–40	7–10	>100	<100	No
4	$10.55 \times 10^{16}$	100	$\langle 111 \rangle$	P	20–40	7–10	>100	<100	No
5	$15.75 \times 10^{16}$	100	$\langle 111 \rangle$	P	20–40	7–10	>100	<100	No
6	$17.50 \times 10^{16}$	100	$\langle 111 \rangle$	P	20–40	7–10	>100	<100	No
7	$26.00 \times 10^{16}$	100	$\langle 111 \rangle$	P	20–40	7–10	>100	<100	No
8	$30.05 \times 10^{16}$	100	$\langle 111 \rangle$	P	20–40	7–10	>100	<100	No

The production process of a PIN rectifier diode is illustrated in Fig. 1. Each group of silicon wafers was ground on both sides, and four pieces from each group were put on the PIN rectifier diode. The size of the PIN rectifier diode on the silicon wafer was  $1.143 \times 1.143\text{ mm}^2$ . In order to analyze the effects of impurity oxygen on the high-temperature performance of the diode, the diffusion processes of the 2 mm thick samples during phosphorus pre-sintering

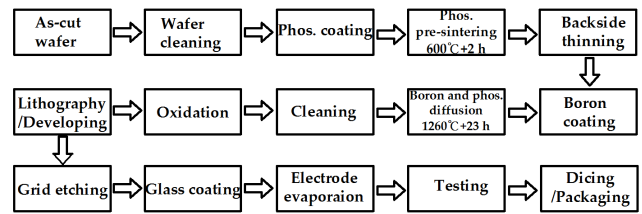


FIGURE 1. Flowchart of the PIN rectifier diode production process.

( $600^\circ\text{C}$ , 2 h) and also during boron and phosphorus diffusion ( $1260^\circ\text{C}$ , 23 h) were studied.

### B. TEST EQUIPMENT

The thickness and resistivity of the resultant silicon wafers were measured by a JXNRT-1 non-contact thickness tester and a SDY-4 four-probe tester, respectively. The initial oxygen and carbon contents in monocrystalline silicon were measured by a Perkin Elmer PE-C99158 FTIR. The minority carrier lifetime of monocrystalline silicon was measured by a LT-100C digital minority carrier lifetime tester. A silicon PT-301 point tester and a SD-DS-600S tester were used to evaluate the electrical properties of the wafers (VB [0–1800 V], VF [I = 1 A], and IR [V = –1100 V, 0–5  $\mu\text{A}$ ]). A JEM-2100F transmission electron microscope (TEM) was employed to observe oxygen precipitations and induced defects, and the detected precipitates were further analyzed by an energy-dispersive spectrometer (EDS). All of the above tests were executed at  $23^\circ\text{C}$ .

## III. ANALYSIS AND DISCUSSION

### A. EFFECTS OF CARBON CONCENTRATIONS ON THE REVERSE LEAKAGE CURRENT OF THE PIN RECTIFIER DIODES

The influences of different carbon concentrations on the reverse leakage current of the PIN rectifier diodes were examined at  $V_b = 1100\text{ V}$  and  $IR < 5\ \mu\text{A}$ , and the relationship between the average reverse leakage current and the carbon concentration was obtained (Fig. 2). When the

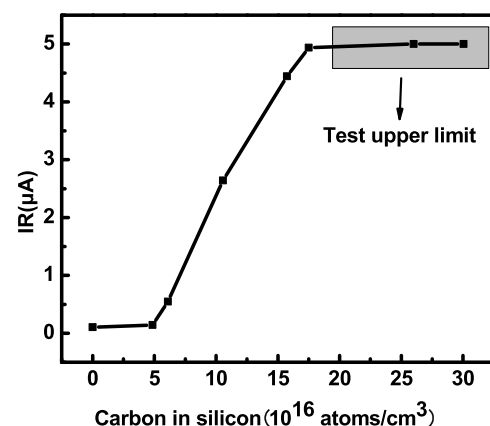


FIGURE 2. Relationship between reverse leakage current and carbon concentration.

carbon concentration was less than or equal to  $4.85 \times 10^{16}$  at/cm<sup>3</sup>, the reverse leakage current did not change significantly. When the carbon concentration was greater than  $6.10 \times 10^{16}$  at/cm<sup>3</sup>, the reverse leakage current increased rapidly with the increasing carbon concentration. When the carbon concentration was greater than or equal to  $26.00 \times 10^{16}$  at/cm<sup>3</sup>, the upper limit of the reverse leakage current was 5  $\mu$ A.

TRR refers to the time from on to off after the diode is cut off. Generally speaking, the TRR of PIN rectifier diode should be as large as possible, and the TRR of fast recovery diode should be decreased through heavy metal diffusion. The relationship between the TRR of the PIN rectifier diodes and the carbon concentration is presented in Fig. 3. It is noticeable that the average TRR of the die continuously decreased with the increasing carbon concentration. When the carbon concentration was greater than or equal to  $26.00 \times 10^{16}$  at/cm<sup>3</sup>, the time of reverse recovery was less than 200 ns. This indicates that the recombination center at the P-N junction increased rapidly with the increasing carbon impurity concentration, resulting in a significant decrease of TRR. Therefore, carbon impurities in monocrystalline silicon promoted the formation of composite centers during high-temperature diffusion and reduced the TRR of the PIN rectifier diodes. The higher the carbon concentration, the lower the TRR of the diodes.

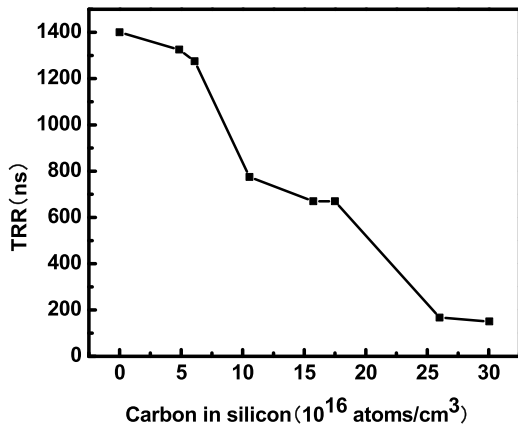


FIGURE 3. Relationship between TRR and carbon concentration.

The reverse withstand voltage of a silicon-based PIN rectifier diode is related to the doping concentration of the intrinsic region.

$$V_{BR}(Si) \approx 5.3 \times 10^{13} N_B^{-\frac{3}{4}}, \quad (1)$$

where  $V_{BR}$  is the reverse withstand voltage and  $N_B$  is the doping concentration in the intrinsic region. According to Equation 1 [16]–[18], the theoretical values of the average reverse withstand voltage of the PIN rectifier diodes were calculated based on the average resistivity of the silicon wafers. The relationship between the ratio of the actual reverse withstand voltage to the theoretical reverse withstand voltage and the carbon impurity concentration is exhibited

in Fig. 4. It is clear that the ratio decreased from 1.1 to 0.6 with the increasing carbon impurity concentration and the reverse withstand voltage was lower than the theoretical value. Therefore, this indicates that the presence of carbon impurities reduced the reverse withstand voltage of the PIN rectifier diodes. On the contrary, it is evident from Fig. 5 that the forward voltage drop ( $V_f$ ) increased with the increasing carbon impurity concentration, especially when the carbon concentration was greater than  $6.10 \times 10^{16}$  at/cm<sup>3</sup>, the scattering center at the P-N junction, conductive voltage, and power consumption of the diodes increased with the increasing carbon impurity concentration; thus, the die was easy to heat up. This observation is consistent with the finding of Akiyama *et al.* [19] — carbon impurities lead to the “soft” electrical characteristics of reverse-biased P-N junctions.

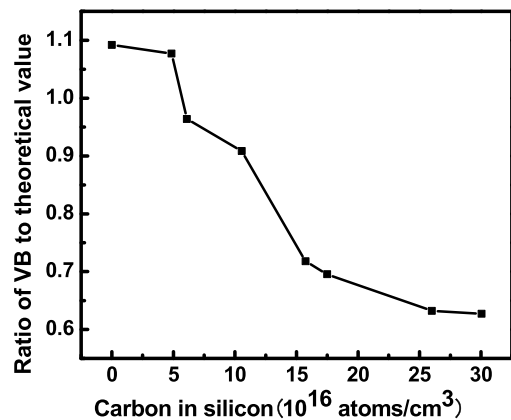


FIGURE 4. Relationship between the ratio of the average reverse withstand voltage to the theoretical value and carbon concentration.

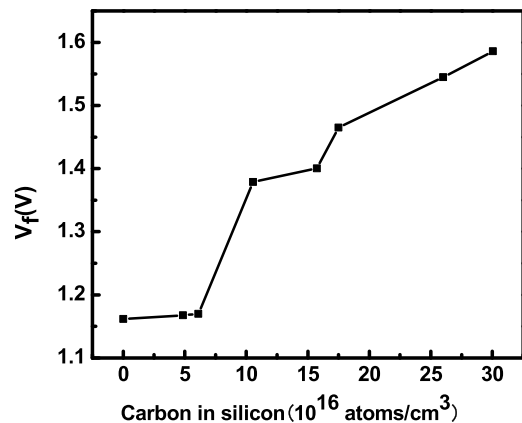
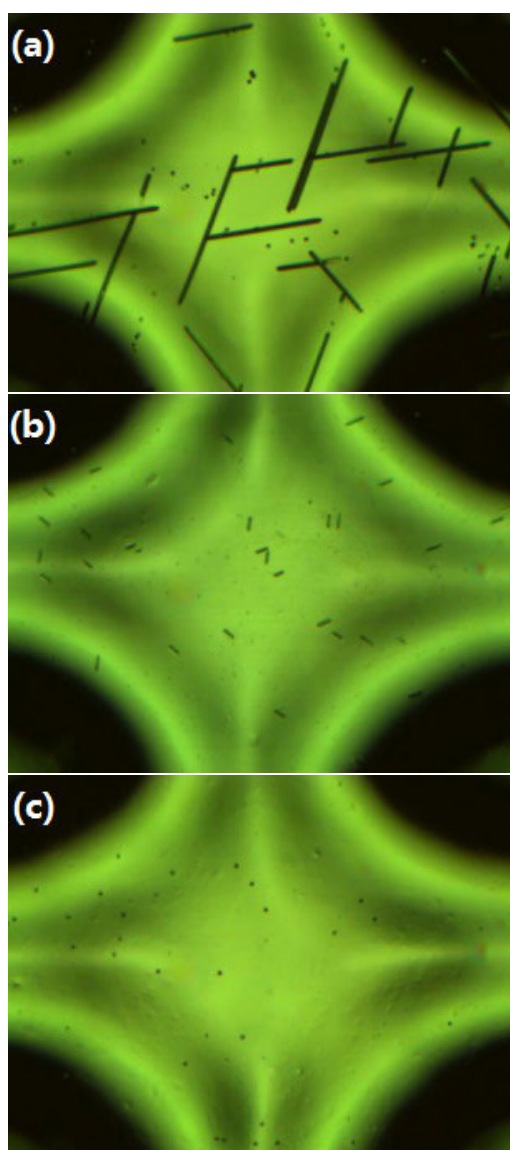


FIGURE 5. Relationship between forward voltage drop and carbon concentration.

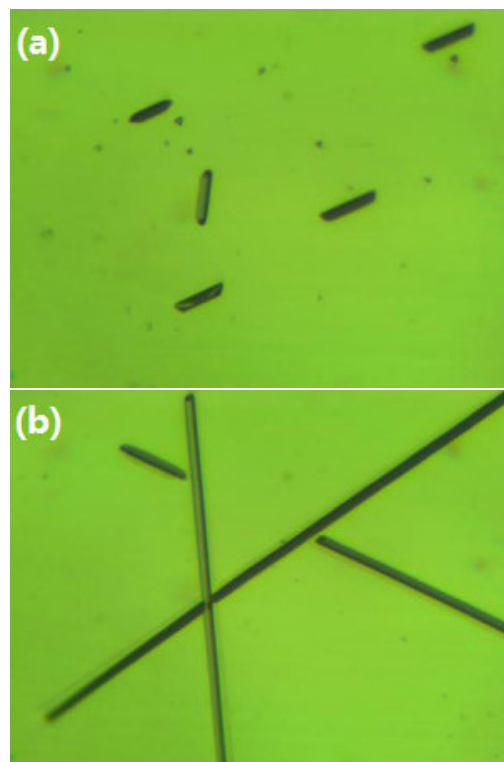
**B. EFFECTS OF CARBON IMPURITIES ON THE ELECTRICAL PROPERTIES OF THE PIN DIODES**

In order to further analyze the effects of initial oxygen concentrations on the leakage current of the PIN rectifier diodes, glass passivation was carried out to remove grids from the intrinsic region, and subsequently, induced

defects after anisotropic preferential etching were observed. As non-defect samples were selected before the experiment, secondary induced defects were observed in them. It is noticeable from Fig. 6 that the number of defects increased continuously with the increasing carbon impurity concentration; thus, dislocation etch pits gradually changed into stacking fault corrosion pits and the length of stacking fault corrosion pits increased with the increasing carbon concentration. The detected stacking faults had regular angles of  $60^\circ$ ,  $120^\circ$ , and  $180^\circ$  along the  $\langle 110 \rangle$  orientation, revealing the anisotropy characteristics of  $\langle 111 \rangle$  monocrystalline silicon. Carbon impurities promoted the formation of bulk oxidation-induced stacking faults (B-OSF), and the density and size of these B-OSF defects increased with the increasing carbon concentration. It is evident from Fig. 7 that when the carbon



**FIGURE 6.** Etch pit photos of the samples with the carbon concentrations of (a)  $30.05 \times 10^{16}$  at/cm<sup>3</sup>, (b)  $6.10 \times 10^{16}$  at/cm<sup>3</sup>, and (c) 0 at/cm<sup>3</sup> under  $100\times$  optical microscopic resolution.



**FIGURE 7.** Etch pit photos of induced stacking fault defects in the samples with the carbon concentrations of (a)  $6.10 \times 10^{16}$  at/cm<sup>3</sup> and (b)  $30.05 \times 10^{16}$  at/cm<sup>3</sup> under  $400\times$  optical microscopic resolution.

concentration was less than  $6.10 \times 10^{16}$  at/cm<sup>3</sup>, B-OSF defects mainly existed in the form of dislocations. When the carbon concentration was greater than or equal to  $6.10 \times 10^{16}$  at/cm<sup>3</sup>, they mainly existed in the form of rod-shaped stacking faults, and the length of these rod-shaped stacking faults also increased with the increasing carbon concentration. Due to the existence of these induced defects, the electrical properties of the PIN rectifier diodes were greatly affected. The “impurity piercing pipe” effect of these induced defects increased the reverse leakage current of the P-N junction, reduced the reverse withstand voltage, formed scattering centers and effective composite centers, reduced the time of reverse recovery, and increased the forward conduction voltage drop.

### C. EFFECTS OF CARBON IMPURITIES ON BULK OXIDATION-INDUCED DEFECTS

Carbon impurities mainly exist in the form of substitution sites ( $C_s$ ) in monocrystalline silicon, which can interact with different impurities in silicon substrate [20]. There was direct evidence that there were close carbon oxygen pair complexes in the growing silicon [21], and more complex compounds were produced in heat-treated materials [22]. In order to further study the effect mechanism of carbon impurities on the electrical characteristics of PIN rectifier diodes, Fourier transform infrared spectroscopy (FTIR) was carried out

on 2 mm sample before and after high-temperature diffusion to study the state change of carbon, oxygen and silicon ternary system. Compared with the sample before and after diffusion by the Fourier transform infrared (FTIR) spectra of samples with interstitial carbon concentrations of  $26.00 \times 10^{16} \text{ at/cm}^3$ . It is evident from Fig. 8 that the absorption peak  $607 \text{ cm}^{-1}$  corresponding to the interstitial carbon decreased after high-temperature diffusion, which indicated that the substitution site carbon  $C_s$  in the original silicon was reduced and the morphology had been changed. The results showed that the interstitial oxygen ( $O_i$ ) of silicon had been changed and appeared a wide absorption band at  $850 \text{ cm}^{-1}$ , which was similar to the complex  $[C_i-O_i]$  of interstitial carbon and interstitial oxygen observed by Shimura [23] and K. Shinoda and Ohta [24]. It was also known as carbon center with wide absorption peaks, which indicated that the substitution carbon  $C_s$  in silicon transformed into interstitial carbon  $C_i$ , and formed a complex carbon center with interstitial oxygen  $O_i$  after high-temperature diffusion. By calculating the decrease number of interstitial carbon and interstitial oxygen atom, the ratio of carbon atom to oxygen atom was 2.4, which was equivalent to one carbon atom and 2.4 oxygen atom to constitute carbon-oxygen recombination. This was consistent with previous studies [25], [26]. Similarly, the  $850 \text{ cm}^{-1}$  wide absorption band corresponding to the relevant carbon center was not observed before and after diffusion for sample without carbon impurities [27]. In addition, it is noticeable from Fig. 9 that the decrease of the substitution site carbon

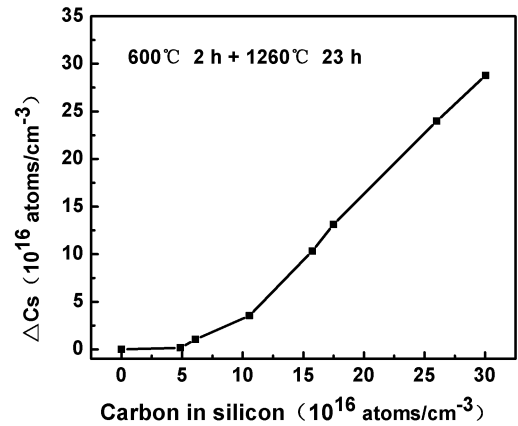


FIGURE 9. Relationship between carbon precipitation and initial carbon concentration after diffusion.

concentration increased with the increasing the initial carbon concentration, which indicated that the higher the initial carbon concentration, the more carbon impurity involved in and the more carbon centers generated, the easier they was to promote the nucleation and growth of the carbon oxygen complex, and promote the production of bulk oxidation-induced defects B-OSF. This was consistent with the previous observation that the density and length of bulk oxidation-induced stacking faults (B-OSF) with the change trend of the initial carbon concentration.

**D. EFFECTS OF CARBON IMPURITIES ON INDUCED DEFECTS AND COMPLEXES**

The current analysis was carried out on the sample with the initial carbon content of  $26.00 \times 10^{16} \text{ at/cm}^3$  and the carbon-free sample by TEM. It is evident from Figs. 10–11 that a large number of dislocations, stacking faults, and precipitates (size of about 100 nm) existed in the high-carbon sample. The EDS analysis revealed in Fig. 12 that carbon, oxygen, and silicon existed in the precipitates at a ratio of 31.40:36.41:32.19. Therefore, the broad absorption band of the typical C-O-Si complex was consistent with that of the C-O complex observed at the  $850 \text{ cm}^{-1}$  FTIR peak. Although some differences were present between the two testing methods, the difference in the ratio of carbon and oxygen atoms mainly occurred due to the formation of carbon-oxygen complexes and oxygen precipitates by interstitial oxygen. A small amount of oxygen precipitates with a size of about 20 nm existed in the carbon-free sample, and EDS testing confirmed in Fig. 13 that these precipitates were composed of  $\text{SiO}_2$ , which was consistent with the situation observed by Xu [28], and was obviously different from the oxygen concentration in the silicon substrate. However, no obvious dislocation stacking faults were detected in the carbon-free sample, indicating that carbon impurities played an important role in the formation of induced defects.

When substitutional carbon atoms ( $C_s$ ) in the silicon substrate captured self-interstitial silicon atoms during

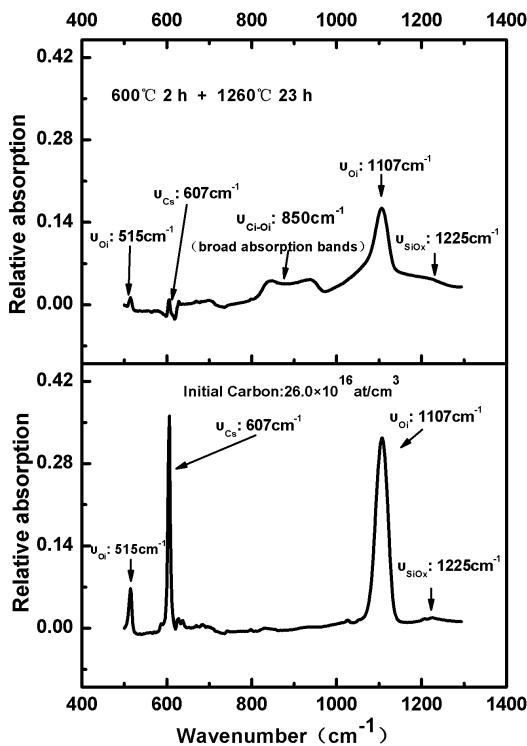
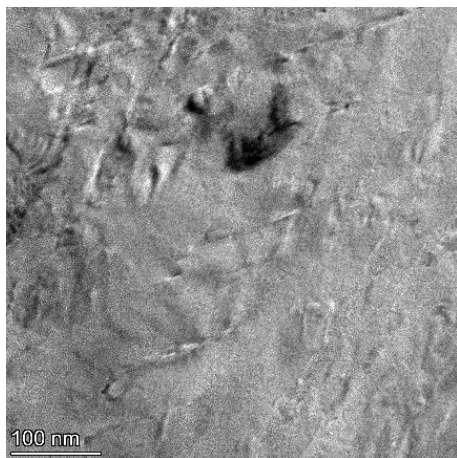
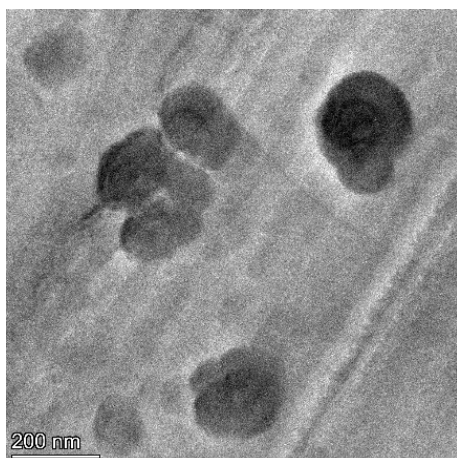


FIGURE 8. Comparison of FTIR spectra before and after diffusion.

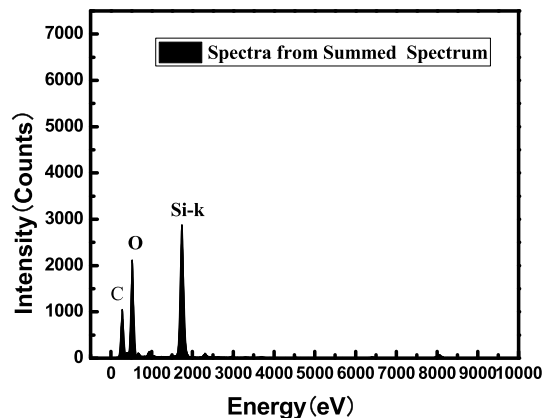


**FIGURE 10.** EM morphology of oxidation-induced dislocations and stacking faults in the sample with the carbon content of  $26.00 \times 10^{16}$  at/cm<sup>3</sup>.

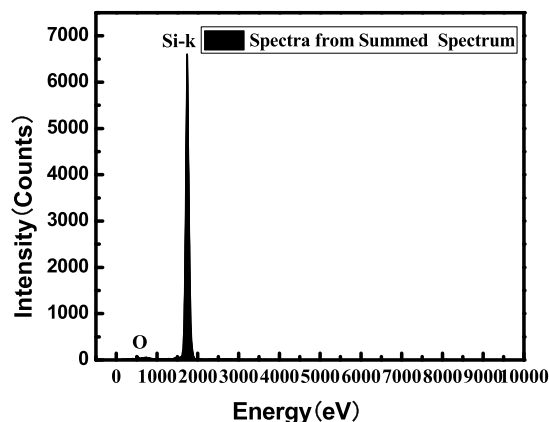


**FIGURE 11.** TEM morphology of carbon-oxygen complex precipitates.

high-temperature diffusion (1260°C, 23 h), they changed into interstitial carbon ( $C_i$ ) and formed a  $[C_i-O_i]$  complex carbon center of interstitial oxygen and interstitial carbon. This carbon center became the heterogeneous nucleation center of oxygen precipitation in the process of silicon substrate annealing and captured interstitial oxygen, interstitial carbon, silicon atoms, other impurities to promote oxygen precipitation. The existence of the carbon center effectively reduced the volume strain energy of the interface between oxygen precipitation and the silicon substrate, promoted the growth of oxygen precipitation, continuously diffused interstitial silicon atoms and dislocations, and released the volume strain energy to facilitate the formation and growth of B-OSF defects. It is noticeable from Fig. 9 that the substitution site carbon concentration decreased significantly with the increasing initial carbon concentration. B-OSF defects mainly existed in the form of dislocations and stacking faults, and the length and density of stacking faults increased with the increasing carbon concentration, and this observation is



**FIGURE 12.** EDS energy spectrum of C-O complexes in the sample with the carbon content of  $26.00 \times 10^{16}$  at/cm<sup>3</sup>.



**FIGURE 13.** EDS energy spectrum of the silicon matrix of the carbon-free sample.

almost consistent with the etch pit characteristics of induced defects presented in Fig. 6. The size of induced stacking fault defects increased with the rising carbon concentration. These B-OSF defects caused the “impurity piercing pipe” effect to form composite carbon centers, resulting in an increase of the reverse leakage current, a decrease of the reverse withstand voltage, a decrease of the reverse recovery time, an increase of the forward conduction voltage, and poor electrical performance.

#### IV. CONCLUSION

In the present study, PIN rectifier diodes were fabricated from silicon wafers with different carbon concentrations and their electrical properties were tested. It was found that carbon impurities in monocrystalline silicon had an obvious effect on the electrical properties of the PIN rectifier diodes. With the gradually increasing carbon concentration, especially when the carbon concentration was greater than or equal to  $6.10 \times 10^{16}$  at/cm<sup>3</sup>, the reverse leakage current increased rapidly, the time of reverse recovery and the ratio of the reverse withstand voltage to the theoretical value decreased rapidly, and the forward voltage drop increased significantly,

degrading the electrical performance of the diodes. Further, with the rising carbon concentration, bulk oxidation-induced defects (B-OSF) changed from dislocation-dominated to stacking fault-dominated and the stacking fault length increased gradually. It was believed that these induced defects caused an increase of the reverse leakage current, a decrease of the time of reverse recovery, a decrease of the ratio of the average value of reverse withstand voltage and the theoretical value, and an increase of the forward voltage drop. In order to further analyze the formation mechanism of these dislocations and stacking faults and also the role of carbon impurities in monocrystalline silicon, FTIR was employed to evaluate the samples before and after high-temperature diffusion. It was observed that substitutional carbon sites decreased or even disappeared at the absorption peak of  $607\text{ cm}^{-1}$  after high-temperature diffusion, and consequently, the absorption peaks at  $515\text{ cm}^{-1}$  and  $1107\text{ cm}^{-1}$  corresponding to interstitial oxygen atoms decreased significantly. A  $[C_i-O_i]$  carbon center of interstitial carbon and interstitial oxygen with a wide absorption band was formed at the absorption peak of  $850\text{ cm}^{-1}$ . No carbon center at  $850\text{ cm}^{-1}$  was observed in the sample without carbon impurities before and after high-temperature diffusion. TEM and EDS results revealed the existence of a large amount of stacking faults, dislocation defects, and carbon-oxygen-silicon complex in the sample with the carbon content of  $26 \times 10^{16}\text{at/cm}^3$ . The presence of carbon impurities formed carbon-oxygen complexes and promoted the formation and growth of oxygen precipitation and B-OSF defects. When substitutional carbon ( $C_s$ ) captured self-interstitial silicon atoms existing in the silicon substrate at high temperatures, substitutional carbon was transformed into interstitial carbon ( $C_i$ ) and formed  $[C_i-O_i]$  carbon centers in the silicon substrate. These carbon centers acted as heterogeneous nucleation centers of oxygen precipitation in the silicon substrate annealing process, captured interstitial oxygen ( $O_i$ ), interstitial carbon ( $C_i$ ), and other impurities, and also promoted the formation of oxygen precipitation. The existence of carbon centers effectively reduced the volume strain energy of the interface between oxygen precipitation and the silicon substrate, promoted the growth of oxygen precipitation, and continuously diffused interstitial silicon atoms and dislocations to release the volume strain energy for the formation and growth of B-OSF defects. The existence of B-OSF defects changed the electrical properties of the PIN rectifier diodes.

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## REFERENCES

- [1] N. Yang, T. Duong, J.-O. Jeong, J. M. Ortiz, A. Hefner, and K. Meehan, "Automated parameter extraction software for silicon and high-voltage silicon carbide power diodes," in *Proc. IEEE 12th Workshop Control Modeling Power Electron. (COMPEL)*, Jun. 2010, pp. 1–8.

- [2] F. Chunen, L. Wei, L. Xianmin, R. Xiao, and L. Xing, "PIN power diode dynamic behavior and physics-based model parameter extraction method," *China Electrotech. Soc.*, vol. 30, pp. 208–215, Mar. 2015.
- [3] E. V. Lavrov, L. Hoffmann, and B. B. Nielsen, "Local vibrational modes of the metastable dicarbon center(Cs–Ci)in silicon," *Phys. Rev. B, Condens. Matter*, vol. 60, no. 11, pp. 8081–8086, Sep. 1999.
- [4] G. Davies and R. C. Newman, *Handbook of Semiconductors*, vol. 3, T. S. Moss, and S. Mahajan, Eds. New York, NY, USA: Elsevier, 1994, pp. 1557–1635.
- [5] C. A. Londos, M. S. Potsidi, and E. Stakakis, "Carbon-related complexes in neutron-irradiated silicon," *Phys. B, Condens. Matter*, vols. 340–342, pp. 551–555, Dec. 2003.
- [6] E. V. Lavrov and M. Fanciulli, "Interstitial carbon-substitutional tin center in silicon (?)," *Phys. B, Condens. Matter*, vols. 302–303, pp. 263–267, Jan. 2001.
- [7] B. Gao and K. Kakimoto, "Global simulation of coupled carbon and oxygen transport in a czochralski furnace for silicon crystal growth," *J. Cryst. Growth*, vol. 312, no. 20, pp. 2972–2976, Oct. 2010.
- [8] X. Liu, B. Gao, and K. Kakimoto, "Numerical investigation of carbon contamination during the melting process of czochralski silicon crystal growth," *J. Cryst. Growth*, vol. 417, pp. 58–64, May 2015.
- [9] H. M. Ayedh, A. A. Grigorev, A. Galeckas, B. G. Svensson, and E. V. Monakhov, "Annealing kinetics of the interstitial carbon-dioxygen complex in silicon," *Phys. status solidi (a)*, vol. 216, no. 14, Jul. 2019, Art. no. 1800986.
- [10] H. J. Stein, "Self-interstitials and the  $935\text{ cm}^{-1}$  band in silicon," *Appl. Phys. Lett.*, vol. 55, no. 9, pp. 870–872, Aug. 1989.
- [11] C. A. Londos, M. S. Potsidi, and V. V. Emtsev, "Effect of carbon on oxygen precipitation in czochralski silicon," *Phys. Status Solidi (c)*, vol. 2, no. 6, pp. 1963–1967, Apr. 2005.
- [12] B. O. Kolbesen and A. Mühlbauer, "Carbon in silicon: Properties and impact on devices," *Solid-State Electron.*, vol. 25, no. 8, pp. 759–775, Aug. 1982.
- [13] Y. Wu, S. Yuan, X. Yu, X. Qiu, H. Zhu, J. Qian, and D. Yang, "Impact of carbon co-doping on the performance of crystalline silicon solar cells," *Sol. Energy Mater. Sol. Cells*, vol. 154, pp. 94–98, Sep. 2016.
- [14] C. Lin, C. Bin, Z. Qigang, D. Xiaolin, W. Zhiqiang, and X. Qinghua, "Numerical simulation of crystal growth velocity on micro-defects in CZ-Si," *Semicond. Mater. Equip.*, vol. 37, pp. 206–211, Mar. 2012.
- [15] M. Zhihui, Z. Wentao, T. Qi, Z. Jianwei, and J. Bo, "Methods for determination of impurity elements in crystalline silicon," *Chem. Anal. Meterage*, vol. 24, pp. 102–105, Mar. 2015.
- [16] R. F. Pierret, *Semiconductor Device Fundamentals*, R. Huang, Y. Wang, J. Wang, and H. Jin, Eds. Beijing, China: Publishing House Electron. Ind., 2004, pp. 206–207.
- [17] V. Bench, J. Gowar, and A. D. Grant, *Power Semiconductor Devices: Theory and Applications*, Y. Wu, W. Zhang, and X. Liu, Eds. Beijing, China: Chemical Industry Press, 2005.
- [18] W. Zhang, "Development of a surge protection device," M.S. thesis, School Microelectron., Xidian Univ., Xi'an, China, 2007.
- [19] N. Akiyama, Y. Yatsurugi, Y. Endo, Z. Imayoshi, and T. Nozaki, "Lowering of breakdown voltage of semiconductor silicon due to the precipitation of impurity carbon," *Appl. Phys. Lett.*, vol. 22, no. 12, pp. 630–631, Jun. 1973.
- [20] R. C. Newman, "Defects in silicon," *Rep. Prog. Phys.*, vol. 45, p. 1163, Oct. 1982.
- [21] R. C. Newman and R. S. Smith, "Vibrational absorption of carbon and carbon-oxygen complexes in silicon," *J. Phys. Chem. Solids*, vol. 30, no. 6, pp. 1493–1505, Jun. 1969.
- [22] A. R. Bean and R. C. Newman, "The solubility of carbon in pulled silicon crystals," *J. Phys. Chem. Solids*, vol. 32, no. 6, pp. 1211–1219, Jan. 1971.
- [23] F. Shimura, "Carbon enhancement effect on oxygen precipitation in czochralski silicon," *J. Appl. Phys.*, vol. 59, no. 9, pp. 3251–3254, May 1986.
- [24] K. Shinoda and E. Ohta, "Interstitial carbon-oxygen complex in near threshold electron irradiated silicon," *Appl. Phys. Lett.*, vol. 61, no. 22, pp. 2691–2693, Nov. 1992.
- [25] Y. Shirakawa and H. Yamada-Kaneta, "Annealing behavior and atomic composition of substitutional carbon-oxygen complexes in silicon crystals," *J. Appl. Phys.*, vol. 80, no. 7, pp. 4199–4201, Oct. 1996.
- [26] Y. Shirakawa, H. Yamada-Kaneta, and H. Mori, "Annealing behavior of carbon-oxygen complexes in silicon crystals observed by low-temperature infrared absorption," *J. Appl. Phys.*, vol. 77, no. 1, pp. 41–46, Jan. 1995.

- [27] J. Chen, D. Yang, X. Ma, and D. Que, "Denuded zone in czochralski silicon wafer with high carbon content," *J. Phys., Condens. Matter*, vol. 18, no. 49, pp. 11131–11138, Dec. 2006.
- [28] J. Xu, "Transmission electron microscopy investigation of oxygen precipitation and induced defects in czochralski silicon," Ph.D. dissertation, Dept. Mater. Sci. Eng., Zhejiang Univ., Zhejiang, China, 2003.



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