Annealing of Neutron-Irradiated Silicon n-Channel Junction Field-Effect Transistors

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中性子照射されたシリコンnチャンネル接合形電界効果トランジスタの熱処理

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Annealing behavior of neutron-produced defects in n-type silicon was studied in the temperature range 60-390℃ by measuring the phase angle θ of the small-signal transconductance of n-channel junction field-effect transistors (JEET's). Three deep levels introducted by irradiation annealed gradually and the annealing of these levels extended over a broad temperature range. The formation of two new levels during annealing was observed, and their energy levels and electron capture cross sections were determind. From the comparison of n-and p-type silicon, it was found that defect clusters annealed with the recovery of defects introduced by irradiation and that the formation of defects during annealing occured near 300°C in both n-and p-type silicon. It was considered that vacancies liberated from defect clusters during annealing played an important role in the formation of defects. Comparing with other published data, it seemed that defects formed during annealing corresponded to the high-order vacancy defects associated with oxygen.

1. Introduction

It is well known that fast neutrons introduce defect clusters in silicon because of the high energy of the primary knock-ons.(1) Stein(2),(3)has reported that light-sensitive defects are observed following neutron irradiation which are not observed following electron irradiation. He has visualized the light sensitivity as a trapping of illumination-generated minority carriers in the potential wells associated with defect clusters. Whan(4) has shown the growth of an A center upon annealing to 275℃ in neutron-irradiated silicon. She has attributed the growth of an A center to vacancy liberation from defect clusters. Cheng and Lori(5) have reported that the majority of the total volume in localized damage regions produced by neutron irradiation is rich in divacancies. They also have reported that the annealing of divacancies in the neutron case extends over a broad temperature range, which is contrast to the distinct stage observed in the electron case.(6)

In order to investigate the electrical properties of individual defects which make up the cluster, it is useful to use the junction devices.(7) Admittance measurements of p-n junctions(8)-(10) and transconductance,(7) noise(11) and transient drain current measurements(7),(12) of JFET's have been made to determine the energy levels, capture cross sections and concentrations of neutron-produced defects. Oldham and Naik(13) have suggested that the small-signal transconductance in the JFET containing deep levels may be of complex form. Wada et al.(14) have observed the complex transconductance in a Schottky barrier GaAs FEF. Recently, Tokuda and Usami(15) have shown that the measurements of the phase angle of the complex transconductance as a function of temperature and frequency can provide useful information about deep levels. They have reported that three deep levels in n-type silicon and two deep levels in p-type silicon are introduced by neutron irradiation.

In the present paper, we investigate the annealing behavior of neutron-produced defects in n-type silicon by measuring the phase angle θ of the small-signal transconductance in neutron-irradiated n-channel JFET's. In a previous paper,(16) we have reported the isochronal annealing results of neutron-irradiated n- and p-channel JFET's in the temperature range 60−270℃ and 60—360℃, respectively. Then, it has been shown that deep levels introduced by irradiation anneal gradually and that the formation of three new deep levels occurs in p-type

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silicon during annealing near 300℃. In the present paper, the isochronal annealing experiments of n-channel JFET's are performed up to 390℃. Comparison of n- and p-type silicon is also made.

2. Experimental Procedure

Typical values of pinch-off voltage and drain saturation current of n-channel JFET's (2SK48A) before irradiation in the present work are~−0.7 V and~0.8 mA at room temperature, respectively. Small-signal transconductance g_m was measured in the frequency range 100 Hz-10 kHz using an Ithaco dynatrac 391A lock-in amplfier with the phase resolution of 0.1° under the condition that drain-source voltage V_{ds} was 8 Vand gate-source voltage V_{gs} was 0 V (saturation region). The measuring apparatus of g_m is given in Ref. 15. Over the measured temperature range (93−293°K), g_m before irradiation was independent of frequency, and its phase angle was zero. Typical values of g_m before irradiation are~2 mmho at room temperature. The characteristics of g_m at 1 kHz and drain-source current I_{ds} versus V_{gs} with V_{ds}=8Vat 293°K before irradiation are shown in Fig.1.

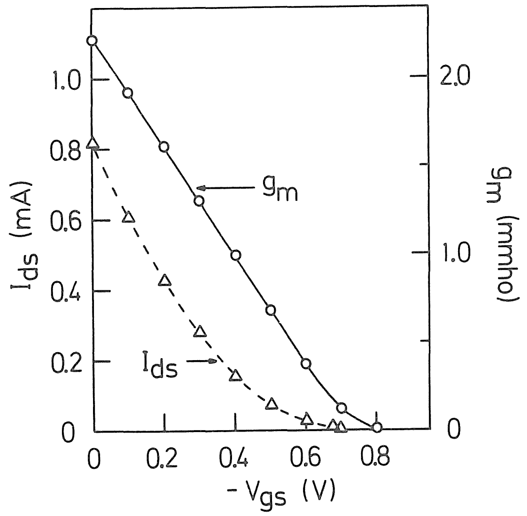

Fig. 1. Characteristic of g_m at 1 kHz and I_{ds} versus V_{gs} before irradiation for an n-channel JFET (2SK48A) used in the present work. g_m and I_{ds} are measured with V_{ds}=8 V. The measured temperature is 293°K.

Samples were irradiated at room temperature in a Rikkyo TRIGA reactor.Total neutron flux is lx10^{14} neutron/cm^2.

After irradiation, g_m was of complex form.(15),(16) The complex transconductance g_m as a function of angular frequency ω is given by(13)-(16)

$$g_m = G_M \frac{1+K+\omega^2\tau^2+iK\omega\tau}{(1+K)^2+\omega^2\tau^2} \tag{1}$$

where

$$K = \frac{W-\lambda}{W}\frac{N_T}{N_S} \tag{2}$$

In the above equations, W is the depth of the depletion layer, λ is the distance between the depletion edge and the plane where the deep level crosses the bulk Fermi level, N_s is the concentration of shallow dopants, and N_T is the concentration of deep traps. G_M is a quantity determined by the carrier mobililty, the dielectric constant, the dimensions of the channel, the field applied along the channel and W. Thus, G_M is dependent on temperature and independent of frequency.(15),(16)The characteristic time constant τ is related to the electron emission rate e_n by $\tau=1/e_n$ in n-channel JFET's.(15),(16)From eq. (1), the phase angle θ of the complex transconductance is given by

$$\theta = \tan^{-1}\frac{K\omega\tau}{1+K+\omega^2\tau^2.} \tag{3}$$

It is seen from eq.(3) that in the temperature and the frequency dependence of θ, the maximum of θ occurs when $\omega\tau=(1+K)^{1/2}$ (13),(15),(16) Then,

$$\theta_{\max} = \tan^{-1}\frac{K}{2(1+K)^{1/2.}} \tag{4}$$

In Fig. 2, the complex transconductance measured at 1 kHz for a neutron-irradiated n-channel JFET is shown as a function of temperature. Figure 2 (a) shows the temperature dependence of θ. It is seen from Fig. 2(a) that θ has three maxima. This means that three deep levels (N-1,N-2 and N-3 levels) are introduced in n-type silicon by neutron irradiation.(15),(16) Figure 2(b) shows the temperature dependence of the real component and imaginary component of g_m. Im(g_m) has three maxima similar to θ. As seen from eq.(1), in the frequency dependence of Im(g_m), Im(g_m) has a maximum value when $\omega\tau = 1+K$.(14) However, in the temperature dependence of Im(g_m), the temperature where the maximum of Im(g_m) occurs, is not equal to the temperature where the $\omega\tau=1+K$ condition is met since G_M is dependent on temperfture.(15),(16)

For these samples, isochronal annealing experiments were carried out within 3℃ temperature control in the temperature range 60−390℃. The isochronal annealing period was 20 min, and the temperature increment was 30℃.

In order to pursue the annealing behavior for each defect, K was calculated from eq.(4) using $\theta_{\max}$ in the characteristic of θ versus temperature at 1 kHz at each annealing temperature since the change of K reflects that of N_T as seen from eq.(2).(16) However, λ/W in eq.(2) will change as N_T changes. As discussed in the previous paper, (16) the decrease of K corresponds

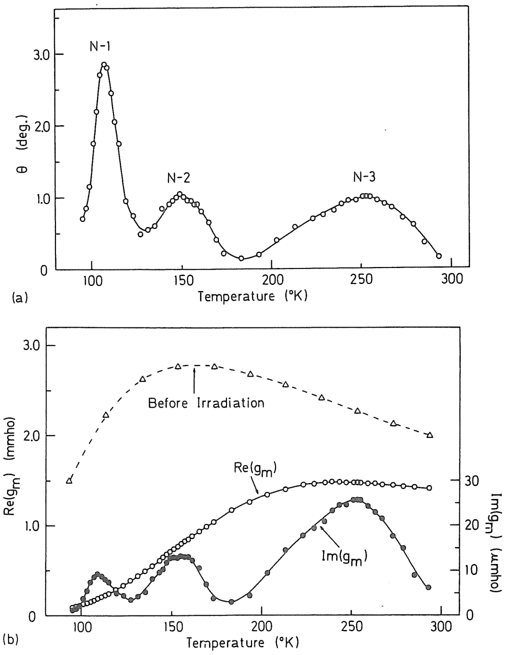

Fig. 2. Temperature dependence of complex transconductance at 1 kHz for an n-channel JFET irradiated at 1×10^{14} neutron/cm^2.
Complex transconductance is measured with $V_{ds}=8$ V and $V_{gs}=0$ V.
(a) Temperature dependence of phase angle θ of complex transconductance. Three deep levels are labeled N-1, N-2 and N-3.
(b) Temperature dependence of Re(g_m) and Im(g_m). g_m at 1 kHz with $V_{ds}=8$ V and $V_{gs}=0$ V before irradiation is also shown.
Over the mesured temperature range, g_m before irradiation was independent of frequency and its phase angle θ was zero.

to a slightly faster recovery than that of N_T. The annealing behavior of Re(g_m) is also studied. The annealing behavior of Re(g_m) will be consistent with that of K.(16)

The measurements of g_m were made in the saturation region of JFET's($V_{ds}=8$V and $V_{gs}=0$V). In the saturation region, K continually varies along the channel since λ/W varies along the channel. K in this case is an effective value.(15) However, it is considered that the annealing behavior of an effective value of K still represents the qualitative manner of the annealing behavior of defects.(16)

3. Experimental Results and Discussion

In Fig. 3, θ at 1 kHz is shown as a function of temperature after irradiation and after a 270℃ anneal. θ_{max} for the N-1 and N-2 levels at a 270℃ anneal decrease compared with those after irradiation, respectively and θ_{max} for the N-3 level is not observed at a 270℃ anneal. It is found that at a 270℃ anneal, two maxima of θ are observed at 213 and 263° K, which are not observed after irradiation. This means the formation of two defects during annealing.(16) Two defects formed during annealing are labeled N-4 and N-5.

In Fig. 4, K for the N-1, N-2, N-3, N-4 and N-5 levels calculated from θ_{max} in the characteristic of θ versus temperature at 1 kHz is shown as a function of annealing temperature. K for the N-1,N-2 and N-3 levels decrease gradually with annealing temperature, and the annealing of these levels extends over a broad temperature range. From Fig.4, it is found that the N-1, N-2 and N-3 levels anneal out around 360, 330 and 270℃,respectively. K for the N-4 level increases in the annealing temperature range 270－300℃ and decreases up to the 360℃ anneal. K for the

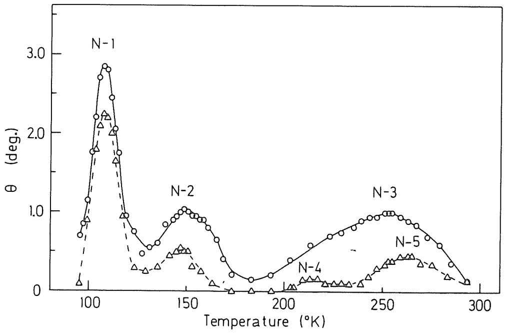

Fig. 3. Temperature dependence of phase angle θ of complex transconductance at 1 kHz after irradiation and after a 270°C anneal for an n-channel JEET. θ is measured with $V_{ds}=8$ V and $V_{gs}=0$ V. Two deep levels observed in annealed n-type silicon are labeled N-4 and N-5. ○, after irradiation; △, 270°C anneal.

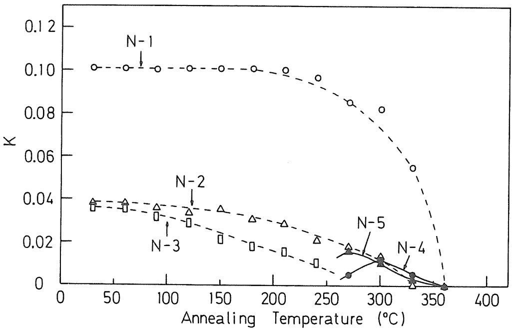

Fig. 4. K for the N-1, N-2, N-3, N-4 and N-5 levels versus annealing temperature.
K is calculated from eq. (4) using θ_{max} in the characteristic of θ versus temperature at 1 kHz.

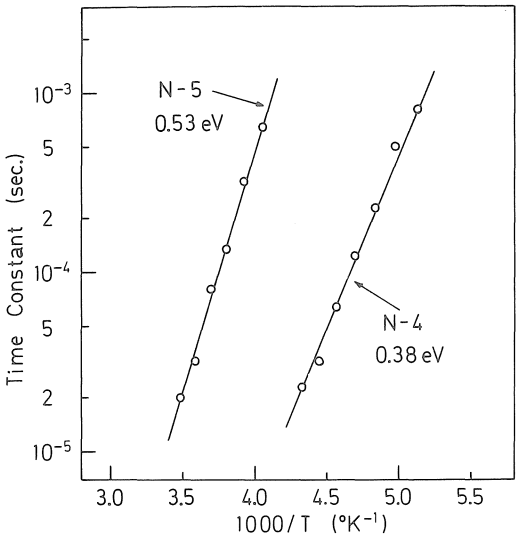

Fig. 5. Time constant τ for the N-4 and N-5 levels versus reciprocal temperature. τ were estimated from θ versus frequency plots. τ for the N-4 and N-5 levels were measured at 300 and 270°C anneals, respectively.

N-5 level decreases in the annealing temperature range 270—360℃. It is found that the N-4 and N-5 levels anneal out around 360℃. Furthermore, it is possible that the N-4 and N-5 levels begin to form around the 240℃ anneal.

It was found that two deep levels (N-4 and N-5 levels) were formed in annealed n-type silicon. In order to obtain the time constant τ for the N-4 and N-5 levels, θ was measured as a function of frequency.(15) In Fig. 5, τ for these levels is shown as a function of reciprocal temperature. τ for the N-4 and N-5 leves were measured at 300 and 270℃ anneals, respectively. From the slope of the temperature dependence curves, activation energies for the N-4 and N-5 levels are estimated to be 0.38 and 0.53 eV, respectively. However, these activation energies do not give the correct activation energies of defects since the preexponential factor in the time constant will be dependent on temperature.(15) We calculate the energy levels and capture cross sections assuming a T^{-2} temperature dependence for the preexponential factor in the time constant. This temperature dependence for the preexponential factor is based on the assumption that capture cross sections are independent of temperature.(17) In Table I, the energy levels and electron capture cross sections for the N-4 and N-5 levels are shown. The previously reported energy elvels and electron capture cross sections for the N-1, N-2 and N-3 levels(15) are also shown in Table 1.

Table 1. Energy levels and electron capture cross sections for the N-4 and N-5 levels observed in an annealed n-channel JEET. These values are calculated from the temperature dependence curves of the time constant assuming that electron capture cross sections are independent of temperature. Energy levels and electron capture cross sections for the N-1, N-2 and N-3 levels reported by Tokuda and Usami (Ref. 15) are also shown.

Defect code	Energy level (eV)	Electron capture cross section (cm^2)
N-4	$E_c-0.34$	8.7×10^{-15}
N-5	$E_c-0.48$	5.7×10^{-14}
N-1	$E_c-0.16$	3.9×10^{-14}
N-2	$E_c-0.19$	1.6×10^{-16}
N-3	$E_c-0.44$	2.3×10^{-14}

In Fig. 6, Re(g_m)at 1 kHz is shown as a function of temperature before and after irradiation, and after 240, 300, 360 and 390℃ anneals. Re(g_m) increases with annealing temperature up to 240℃ over the measured temperature range. This is due to the recovery of the N-1, N-2 and N-3 levels. However, Re(g_m) decreases in the annealing temperature range 240—300°C. This is consistent with the growth of the N-4 and N-5 levels in this annealing temperature range. Re(g_m) increases with annealing temperature in the temperature range 300—390℃. This corresponds to the recovery of the N-1, N-2, N-4 and N-5 levels.

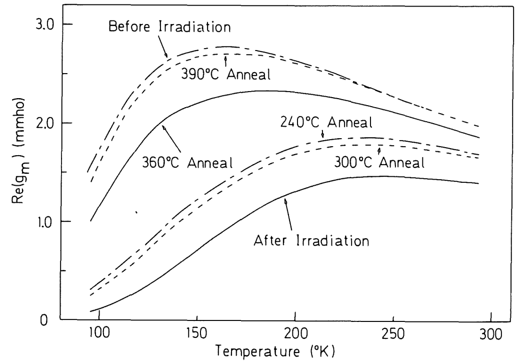

Fig. 6. Temperature dependence of Re(g_m) at 1 kHz for an n-channel JFET. g_m is measured with $V_{ds}=8$ V and $V_{gs}=0$ V. For simplicity, experimental points are not shown.

To study the annealing behavior of Re(g_m) at 1 kHz in more detail, the unannealed fraction of Re(g_m) was calculated. The unannealed fraction of Re(g_m) is defined by

$$f=\frac{\mathrm{Re}(g_{mo})-\mathrm{Re}(g_{ma})}{\mathrm{Re}(g_{mo})-\mathrm{Re}(g_{mi})}, \qquad (5)$$

where g_{mo}, g_{mi} and g_{ma} are the transconductance before irradiation, after irradiation and after annealling respectively. In Fig.7, the unannealed fraction of Re(g_m) at 293°K is shown as a function of annealing temperature. For the purpose of the comparison of n–and p–type silicon, f for both n–and p–channel JFET′s are shown in Fig.7. f for the p–channel JFET was calculated from the data of Fig.9 of Ref. 16. It is found that the general features of the annealing behavior for n–and p–channel JFET′s are similar to each other. f for both n–and p–channel JFET′s decrease gradually with annealing temperature up to 210℃, shows the reverse annealing in the temperature range 240—300℃ and decrease rapidly with annealing temperature above 300℃. It is found that g_m for the n–channel JFET nearly recovers to that before irradiation around the 390℃ anneal. From Fig.7, it is considered that g_m for the p–channel JFET also nearly recovers to that before irradiation around the 390℃ anneal. It seems that the gradual manner of f up to the 210℃ anneal represents the character in the neutron case.(5),(16) Stein(2),(3) has reported that the annealing loss of the light–sensitive defects associated with defect clusters occurs in diffuse stage between 150 and 550°K in neutron–irradiated silicon at 76°K. In Fig. 7, the annealing behavior of the light–sensitive defects (2) is also shown to compare with that of Re(g_m). It is considered that the decrease of f up to the 210℃ anneal is closely related with the recovery of defect clusters. Furthermore, as shown earlier and in Ref. 16, in this annealing temperature range, three deep levels (N–1, N–2 and N–3 levels) in n–type silicon and two deep leves (P–1 and P–2 levels) in p–type silicon, introduced by irraiiation, anneal gradually. This suggests the close relation between the recovery of defect clusters and that of defects introduced by irradiation. It is considered that defect clusters anneal with the recovery of defects introduced by irradiation. It seems that the N-1, N-2, N-3, P-1 and P–2 levels are present within defect clusters. On the other hand, the reverse annealing of f for the n–channel JFET in the temperature range 240—300℃ is due to the growth of the N–4 and N–5 levels. Furthermore, we(16) have reported that three deep levels (P–3, P–4 and P–5 levels) are formed in an annealed p–channel JFET near 300℃. The reverse annealing of f for the p–channel JFET in the temperature range 240—300℃ is due to the growth of the P–3, P–4 and P–5 levels. It is found that for both n- and p-type silicon, the formation of defects during annealing occurs near 300℃. Stein and Gereth(18) have reported that the reverse annealing of the carrier concentration for both n–and p–type silicon is observed near 300℃ in crucible–grown materials but not in float zone materials. This suggests that defects formed during annealing are associated with oxygen. Furthermore, Cheng et al.19) have reported that high-order vacancy defects are formed during annealing near 300℃ in neutron–irradiated p–type silicon. The agreement of the annealing temperature between the P–3, P–4 and P-5 levels, and high–order vacancy defects suggests that the P–3, P–4 and P–5 levels correspond to the high–order vacancy defects.(16) The present results show that two deep levels (N–4 and N–5 levels) are also formed in annealed n–type silicon near 300℃. Jung and Newell,(20) and Lee et al.(21)–(23) have observed the decay and growth of several defects with annealing in neutron–irradiated silicon with paramagnetic resonance measurements. Recently, Lee and Corbett(21)–(24) have suggested the defect models for several defects in neutron- and electron–irradiated silicon. They have reported that a nonplanar five–vacancy cluster (V_5), a divacancy plus two oxygen (V_2+O_2) and a trivacancy plus oxygen (V_3+O) etc., i.e., high–order vacancy defects are formed during annealing in neutron–irradiated silicon. Probably, the N–4 and N–5 levels correspond to the high–order vacancy defects similar to the P–3, P–4 and P–5 levels. Furthermore from above discussion, some of defects formed during annealing may be associated with oxygen. To confirm this speculation, further investigation is necessary. Furthermore, it is seen from Fig,7 that these defects are formed with the recovery of defect clusters. It is considered that vacancies liberated from defect clusters during annealing play an important role in the formation of defects. The decrease of f with annealing temperature above 300℃ for both n–and p–channel JFET′s is due to the recovery of defects grown with annealing. It is noted that f above the

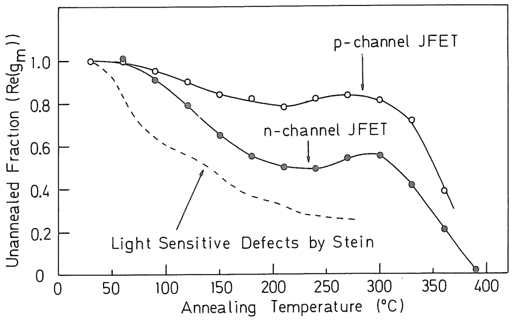

Fig. 7. Isochronal annealing of Re(g_m) at 1 kHz. The measured temperature is 293°K. For the purpose of the comparison of n- and p-type silicon, the unannealed fractions of Re(g_m) for both n- and p-channel JEET's are shown. The unannealed fraction for the p-channel JEET was calculated from the data of Fig. 9 of Ref. 16. Isochronal annealing of the light-sensitive defects reported by Stein (Fig. 4 of Ref. 2) is also shown.

300℃ anneal decrease rapidly with the annealing temperature compared with that up to the 210℃ anneal, which represents the character in the electron case rather than that in the neutron case.(5),(16) This result suggests that defect clusters recover with annealing temperature below 300℃, which coincides with the previously reported results.(2),(3),(25),(26)

4. Summary and Conclusion

Annealing behavior of neutron–produced defects in n–type silicon was studied in the temperature range 60–390℃ by measuring the phase angle θ of the small–signal transconductance of n–channel JFET's. In order to pursue the annealing behavior for each defect, K was calculated from θ_{max} in the characteristic of θ versus temperature at 1 kHz at each annealing temperature. It was found that the N–1, N–2 and N–3 levels annealed gradually and annealed out around 360, 330 and 270℃, respectively. The formation of two deep levels (N–4 and N–5 levels) during annealing was observed. For the N–4 and N–5 levels, θ was mesured as a function of frequency to obtain the time constant. From the temperature dependence of the time constant, assuming that capture cross sections are independent of temperature, the energy levels of the N–4 and N–5 levels were estimated to be E_c-0.34 and E_c-0.48 eV, respectively. The calculated electron capture cross sections of these levels were 7×10^{-15} and 5.7×10^{-14} cm^2, respectively.

Comparison of n– and p–type silicon was also made. It was found that defect clusters annealed with the recovery of defects introduced by irradiation. It seemed that defects introduced by irradiation were present within the defect clusters. Furthermore, it was found that the formation of defects during annealing occurred near 300℃ in both n–and p–type silicon. These defects were formed with the recovery of defect clusters. It was considered that vacancies liberated from defect clusters during annealing played an important role in the formation of defects. Comparing with other published data, it seemed that defects formed during annealing corresponded to the high-orber vacancy defects. Furthermore, some of these defects might be associated with oxygen.

Acknowledgments

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