

# Effect of germanium doping on the formation kinetics of vacancy-dioxygen complexes in high dose neutron irradiated crystalline silicon

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The effect of germanium (Ge) doping on the formation kinetics of vacancy-dioxygen (VO<sub>2</sub>) complexes in high dose neutron irradiated crystalline silicon (c-Si) has been quantitatively investigated using infrared spectroscopy at 10 K. It is observed that Ge doping of  $10^{19} \text{ cm}^{-3}$  enhances the formation of vacancy-oxygen (VO) complexes by  $\sim 15\%$  during neutron irradiation and slightly suppresses the conversion of VO into VO<sub>2</sub> complexes. By studying the generation kinetics of VO<sub>2</sub> complexes in the temperature range of 300–345 °C, it is found that the activation energies of VO<sub>2</sub> generation are determined to be 1.52 and 1.71 eV in the reference and Ge-doped c-Si, respectively. According to the theory for diffusion limited reactions, it is suggested that Ge doping can retard the VO diffusion in c-Si and therefore reduce the capture probability of O<sub>i</sub> for VO complexes. This may be attributed to the temporary trapping of vacancies by Ge atoms. Hence, the formation of VO<sub>2</sub> complexes in c-Si is slightly suppressed by Ge doping. Published by AIP Publishing. [<http://dx.doi.org/10.1063/1.5001139>]

## I. INTRODUCTION

Germanium (Ge) doped crystalline silicon (c-Si) is of potential interest for applications in microelectronics and photovoltaic industries.<sup>1–3</sup> Being electrically inactive in c-Si, the presence of Ge impurity does not affect its electrical properties. Ge atoms give rise to compressive elastic strains in the Si lattice, which can affect the reactions among vacancies, self-interstitials, and impurities. Thus, it could affect the formation of secondary defects in the course of irradiation and annealing. It has been found that an appropriate Ge-doping suppresses the formation of oxygen-related thermal donors and large-sized crystal originated particles (COPs).<sup>4,5</sup> It also enhances the mechanical properties of c-Si wafers and mitigates the light-induced degradation of minority carrier lifetime of c-Si used for solar cells as well as enhances the oxygen precipitation, therefore improving the internal gettering capability of metallic contamination for devices.<sup>6–9</sup>

Recently, Londos and Chreneos *et al.* have performed an extensive study of the influence of Ge doping on the behavior of oxygen and carbon impurity related complexes in electron irradiated c-Si, showing the potential application of Ge doped c-Si substrates in radiation-hardened microelectronics.<sup>2,10–15</sup> They found that an appropriate Ge doping in c-Si crystals can effectively reduce the introduction rate of vacancy-oxygen (VO) complexes, which are generated by the pairing of oxygen atoms with mobile vacancies induced by irradiation.<sup>10,16,17</sup> The VO complexes produce an acceptor level at  $E_C - 0.17 \text{ eV}$  in the energy gap of Si and give rise to a well-known infrared (IR) band at  $830 \text{ cm}^{-1}$ .<sup>18,19</sup> Acting as an important recombination center in Si, the VO complex

plays a critical role in the lifetime control of relative electronic devices. Upon thermal annealing above 300 °C, VO complexes can be transformed into VO<sub>2</sub> complexes by combining with interstitial oxygen (O<sub>i</sub>). This gives rise to an IR band at  $888 \text{ cm}^{-1}$  at room temperature. Although the VO<sub>2</sub> complex is electrically inactive, it may act as a nucleation center for oxygen aggregation processes. Therefore, VO<sub>2</sub> complexes are important for the development of oxygen precipitates.<sup>20,21</sup> Londos *et al.* found that the conversion ratio of VO into VO<sub>2</sub> complexes decreased with the increase of Ge concentration in electron irradiated c-Si. This phenomenon is attributed to the elastic strains in the lattice induced by the Ge presence, which can affect the balance between two reactions, i.e.,  $\text{VO} + \text{O}_i \rightarrow \text{VO}_2$ ,  $\text{VO} + \text{Si}_i \rightarrow \text{O}_i$ .<sup>12,13,22</sup> However, to the best of our knowledge, a detailed quantitative study on the effect of Ge-doping on the formation kinetics of VO<sub>2</sub> complexes has been little undertaken, including its generation rate and activation energy. Therefore, this study is very important for the physical picture of  $\text{VO} \rightarrow \text{VO}_2$  transformation in Ge-doped c-Si.

In this paper, new light is shed on the role of Ge impurity atoms on the formation kinetics of VO<sub>2</sub> complexes in neutron irradiated c-Si with the help of Fourier transformed infrared absorption spectroscopy (FTIR). Compared with electrons, neutron irradiation mainly causes displacement damage in silicon bulk and therefore avoids the influence of ionization damage on the formation of point defects arising from displacement damage. It is found that Ge doping can lead to the increase of energy barrier for VO diffusion and thus slow down the formation of VO<sub>2</sub> complexes. These results give the deep understanding of the reaction among vacancy, interstitial oxygen, and Ge impurity atoms, which is necessary for the defect engineering of c-Si.

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## II. EXPERIMENTAL DETAILS

In this study, two gallium-doped p-type Czochralski-grown Si crystals having 200 mm-diameter and  $\langle 100 \rangle$ -orientation were investigated. One of the Si crystals was co-doped with  $\sim 10^{19} \text{ cm}^{-3}$  Ge (GCz) and the other one was free from Ge (Cz). The both crystals were grown under the same pulling conditions, thus having similar thermal histories, resistivity, and interstitial oxygen contents. The concentrations of gallium and oxygen in both substrates were estimated to be  $1.0 \times 10^{16}$  and  $10.4 \times 10^{17} \text{ cm}^{-3}$ , respectively. The carbon concentration was below the detection limit of infrared spectrometer ( $1 \times 10^{16} \text{ cm}^{-3}$ ). It is to mention that the gallium concentration was derived from the resistivity measurement by the four probe method. The oxygen ( $1106 \text{ cm}^{-1}$ ) and carbon ( $604 \text{ cm}^{-1}$ ) concentrations were determined by an FTIR spectrometer (IFS 66 V/S) at room temperature with the calibration coefficients of  $3.14 \times 10^{17}$  and  $1.0 \times 10^{17} \text{ cm}^{-2}$ , respectively. All the samples were mechanically polished with a thickness of  $\sim 2 \text{ mm}$ . Thereafter, they were subjected to neutron irradiation with a dose of  $5 \times 10^{17} \text{ cm}^{-2}$  at room temperature. Subsequently, the samples were annealed from 300 to 345 °C with a step of 15 °C. Afterwards, the samples were dipped in the diluted HF solution to remove the surface oxide films. Finally, the VO and VO<sub>2</sub> complexes in all annealed samples were investigated using the FTIR spectroscopy by monitoring the relevant 836 and 896  $\text{cm}^{-1}$  bands of IR spectra at 10 K. Herein, the absorption coefficient of VO complexes was determined by integrating the IR peak after separating the overlapped peaks by means of Lorentzian profile fitting.

## III. RESULTS AND DISCUSSION

Figure 1 shows segments of the absorption spectra at 10 K for the neutron irradiated samples before and after isochronal anneals from 250 to 400 °C, in steps of  $\Delta T = 50$  °C and  $\Delta t = 30$  min. The depicted bands at 836, 896, 924, 830, and 843  $\text{cm}^{-1}$  have already been reported and assigned to VO, VO<sub>2</sub>, [VO + O<sub>i</sub>], V<sub>2</sub>O, and V<sub>3</sub>O complexes, respectively.<sup>23–25</sup> All the IR bands at 10 K originating from these defects show a slightly blue shift of 6–8  $\text{cm}^{-1}$  as compared to those at room temperature. The concentrations of O<sub>i</sub> before and after irradiation and the respective VO production in Cz and GCz silicon are illustrated in Table I. Upon irradiation, a large amount of the vacancies that survive annihilation with self-interstitials are captured by oxygen atoms to form VO pairs, since interstitial oxygen moves much slower than vacancy and therefore can be regarded as practically immobile compared with vacancy.<sup>26,27</sup> This in turn results in the decrease of O<sub>i</sub> concentration depicted in Table I, which is in agreement with the previous report.<sup>16</sup> With the calibration coefficient of  $6.25 \times 10^{16} \text{ cm}^{-2}$ , the concentrations of VO complexes in Cz and GCz Si are determined to be  $4.7 \times 10^{16}$  and  $5.4 \times 10^{16} \text{ cm}^{-3}$ , respectively. The Ge-doping with a concentration of  $\sim 10^{19} \text{ cm}^{-3}$  weakly enhances the VO production during high dose neutron irradiation, which is consistent with the previous reports by Londos and Chroneos *et al.*<sup>10,16,17</sup> The enhanced VO production can be ascribed to the Ge atoms which act as the temporary traps for vacancies and thus reduce the recombination rate of Frenkel

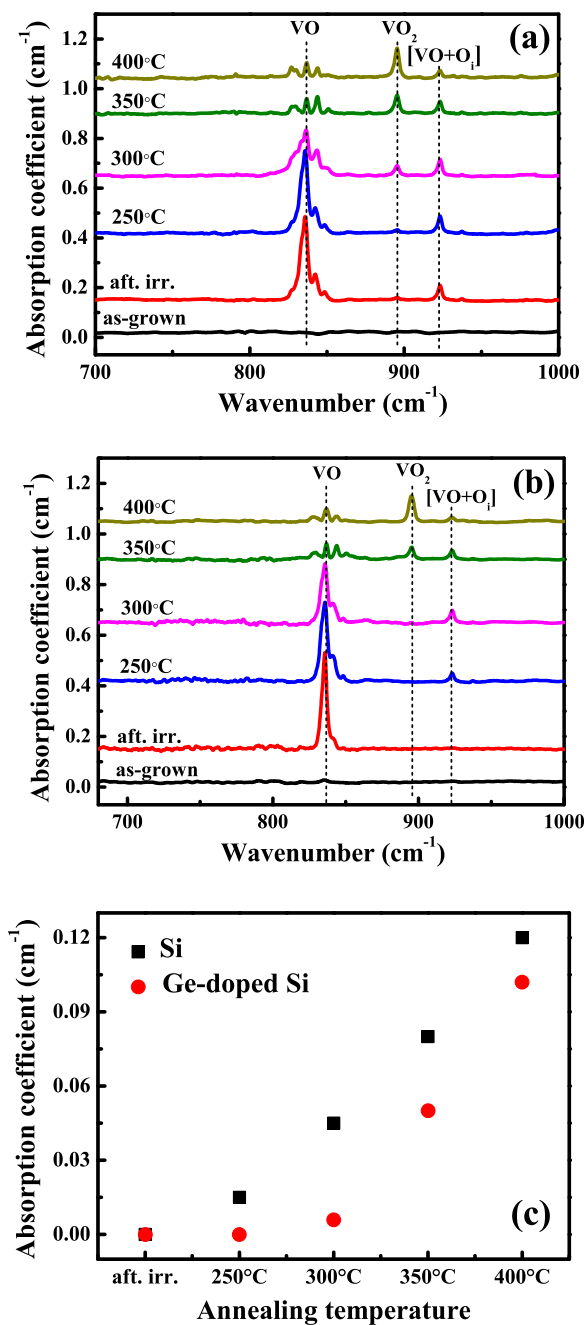


FIG. 1. Segments of the absorption spectra at 10 K for the irradiated Cz (a) and GCz Si (b) before and after isochronal anneals from 250 to 400 °C, in steps of  $\Delta T = 50$  °C and  $\Delta t = 30$  min. (c) The production of VO<sub>2</sub> complexes in Cz and GCz Si.

pairs. With an increase of annealing temperature, the VO<sub>2</sub> related band at 896  $\text{cm}^{-1}$  obviously grows at temperatures above 300 °C [as depicted in Fig. 1(c)], whereas the absorption coefficient of 836  $\text{cm}^{-1}$  band from VO complexes decreases

TABLE I. The concentrations of O<sub>i</sub> before and after irradiation ([O<sub>i</sub>]<sub>0</sub> and [O<sub>i</sub>]<sub>a.i.</sub>) and VO production ([VO]) in Cz and GCz silicon.

|        | [Ge]<br>$\times 10^{19} \text{ cm}^{-3}$ | [O <sub>i</sub> ] <sub>0</sub><br>$\times 10^{17} \text{ cm}^{-3}$ | [O <sub>i</sub> ] <sub>a.i.</sub><br>$\times 10^{17} \text{ cm}^{-3}$ | [VO]<br>$\times 10^{16} \text{ cm}^{-3}$ |
|--------|--|--|---|--|
| Cz Si  | 0  | 10.4   | 9.5   | 4.7                                      |
| GCz Si | 1.0                                      | 10.4   | 9.3   | 5.4                                      |

simultaneously. Therefore, it is inferred that the  $\text{VO}_2$  formation can be ascribed to the capture of mobile VO complexes by  $\text{O}_i$ . It can be seen from Fig. 1(c) that  $\text{VO}_2$  production is slightly suppressed in GCz Si than Cz Si during the isochronal anneals from 250 to 400 °C. Besides, the  $924\text{ cm}^{-1}$  band from  $[\text{VO} + \text{O}_i]$  complexes appears in the IR spectrum of Cz Si,<sup>25,29</sup> whereas is absent in GCz Si with no annealing. This might be attributed to the suppression of Ge doping on the reaction between VO and  $\text{O}_i$  during irradiation at room temperature. The  $924\text{ cm}^{-1}$  band from  $[\text{VO} + \text{O}_i]$  complexes becomes more prominent after the subsequent annealing at 250 °C, but it begins to anneal out at a temperature above 300 °C, along with the appearance of  $896\text{ cm}^{-1}$  band from stable  $\text{VO}_2$  complexes. This suggests that the  $[\text{VO} + \text{O}_i]$  complex is an intermediate structure for the conversion of VO into the  $\text{VO}_2$  complex.<sup>25,29</sup> Additionally, the IR bands at  $830\text{ cm}^{-1}$  and  $843\text{ cm}^{-1}$  from  $\text{V}_2\text{O}$  and  $\text{V}_3\text{O}$  complexes, respectively, are gradually annealed out in the temperature range of 350–400 °C. This might be associated with the dissociation of  $\text{V}_2\text{O}$  and  $\text{V}_3\text{O}$  complexes into vacancies and  $\text{O}_i$ .

Figure 2 shows the concentrations of  $\text{VO}_2$  complexes as a function of annealing time in the temperature range of 300–345 °C. These are deduced from the peak amplitudes of the associated IR band at  $896\text{ cm}^{-1}$  with the calibration coefficient of  $4.25 \times 10^{16}\text{ cm}^{-2}$ .<sup>30</sup> The concentration of  $\text{VO}_2$  complexes

increases quickly at the early stage of annealing and then gradually reaches a saturation value after several hours. It can be seen that  $\text{VO}_2$  complexes are relatively more difficult to generate in GCz Si than Cz Si. On the other hand, the concentration of VO complexes decreases with annealing time and accompanied by the growth of  $\text{O}_i$  concentration (as depicted in Fig. 3). After the complete annealing sequence, the decrease and increase of VO and  $\text{O}_i$  concentration, respectively, are slightly higher in GCz Si than Cz Si. The physical process behind this phenomenon will be discussed later.

The concentration of  $\text{VO}_2$  complexes exhibits an exponential increase with time, and its formation rate can be expressed as

$$[\text{VO}_2](t, T) = [\text{VO}_2]_{\text{sat.}} [1 - \exp(-R(T)t)], \quad (1)$$

where  $T$  is the absolute temperature,  $t$  is the annealing time,  $[\text{VO}_2]$  is the concentration of  $\text{VO}_2$  complexes, and  $R(T)$  is a temperature dependent rate constant. This relation holds for all annealing temperatures in both Cz and GCz Si.

The conversion ratios of VO into  $\text{VO}_2$  complexes in Cz and GCz Si at different temperatures are depicted in Fig. 4, where  $[\text{VO}]_{t=0}$  is the concentration of VO complexes in as-irradiated Si, and  $[\text{VO}_2]_{\text{sat.}}$  is the saturation value for  $\text{VO}_2$  concentration and derived from Fig. 2 at the temperature

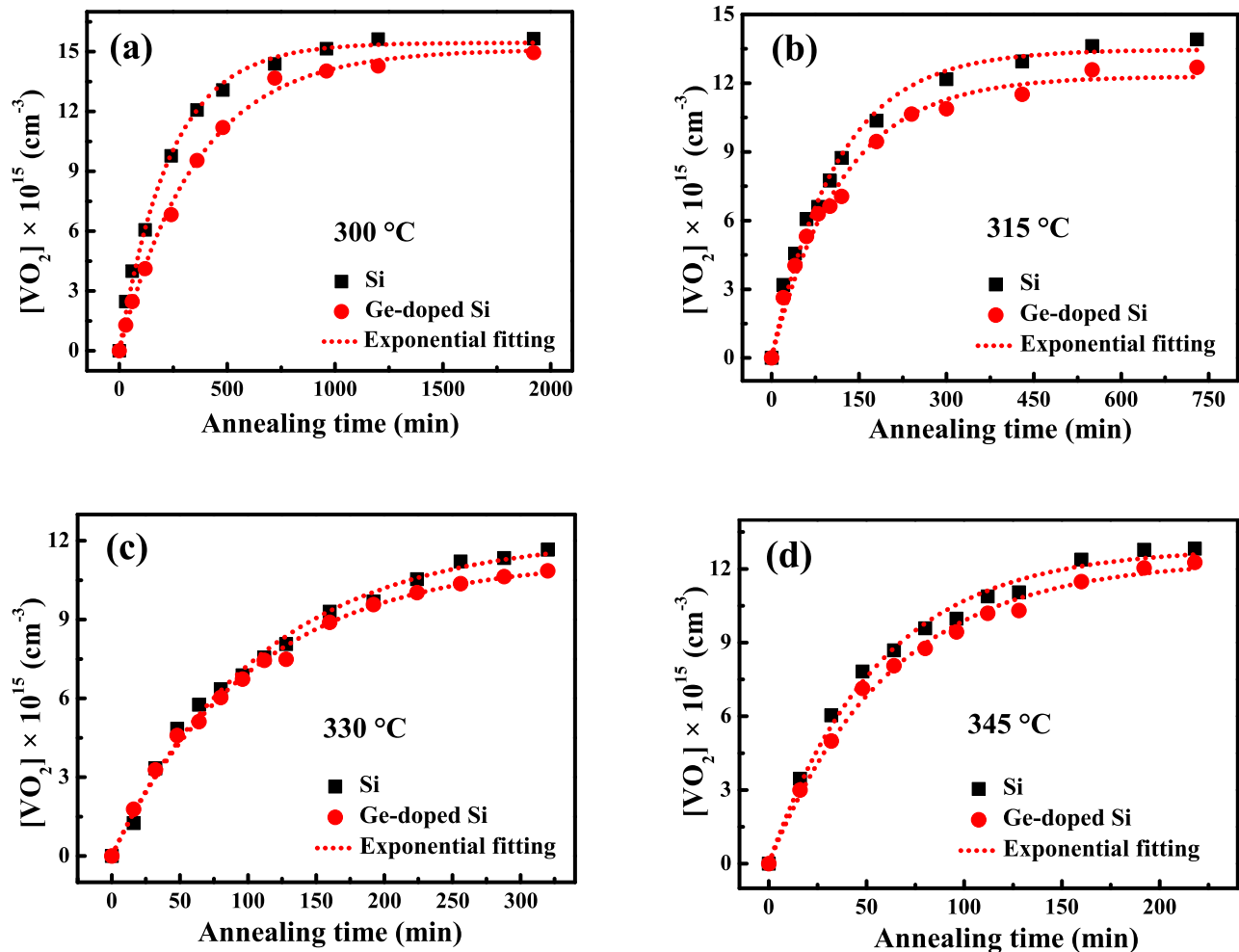


FIG. 2. The concentration of  $\text{VO}_2$  complexes during isothermal annealing at (a) 300, (b) 315, (c) 330, and (d) 345 °C in irradiated Cz and GCz Si.

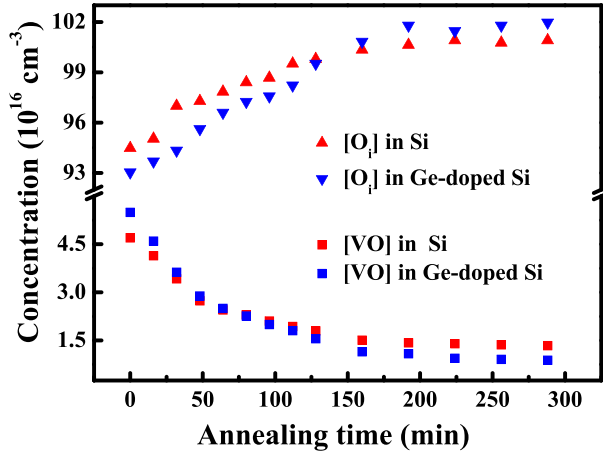


FIG. 3. The concentrations of  $O_i$  and VO complexes as a function of post-annealing times at 330 °C in Cz and GCz Si.

range of 300–345 °C. The  $[VO_2]_{\text{sat}}$  values at 370 °C are derived from the IR spectra of Cz and GCz silicon annealed at 370 °C for 1 h, which is considered as the saturation state for  $VO_2$  generation. It can be seen that about 20%–35% of VO complexes are transformed into  $VO_2$  complexes. At the same time, the other two reactions are supposed to be involved in VO elimination, i.e.,  $VO + Si_i \rightarrow O_i$ ,  $VO \rightarrow V + O_i$ . Moreover, at all annealing temperatures, the conversion ratios of  $[VO]_{t=0}$  to  $[VO_2]_{t \rightarrow \infty}$  are lower in GCz Si as compared to Cz Si. Londos *et al.* have also found the similar changing trend.<sup>12,13</sup> Apparently, the conversion reaction  $VO + O_i \rightarrow VO_2$  is directly proportional to the oxygen concentration in Si. The higher the oxygen concentration, the stronger will be the conversion of VO into  $VO_2$  complexes. However, there is no essential difference of oxygen concentrations between Cz and GCz Si. Therefore, it is suggested that Ge doping should be responsible for the suppressed transformation of VO into  $VO_2$  complexes in c-Si. Generally, the interstitial silicon atoms ( $Si_i$ ) induced by high dose of neutron irradiation tend to form cluster in heavily irradiated Cz Si. The compressive strain in crystalline lattice induced by Ge doping probably suppress the clustering of  $Si_i$ . Therefore, it is suggested that more free  $Si_i$  existing in GCz Si promotes the reaction  $VO + Si_i \rightarrow O_i$ , which in turn

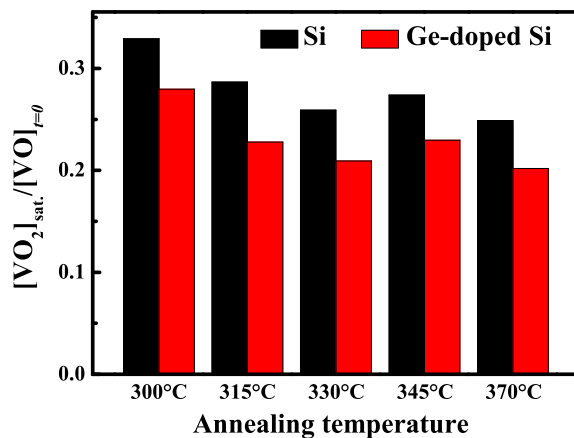


FIG. 4. The conversion ratios of VO to  $VO_2$  complexes as a function of annealing temperatures in Cz and GCz Si.

suppresses the conversion reaction  $VO + O_i \rightarrow VO_2$ . This can be indirectly verified by the slightly enhanced VO loss and  $O_i$  generation after the annealing sequences in Ge-doped silicon (as illustrated in Fig. 3).

Figure 5 depicts the generation rate constant of  $VO_2$  complexes as a function of temperatures in Cz and GCz Si. The formation rates of  $VO_2$  complexes are relatively smaller in GCz Si as compared to Cz Si, which indicates that Ge doping slows the  $VO_2$  formation in c-Si. For a singly activated process, an Arrhenius behavior is expected,

$$R_{VO_2} = \kappa_0 \exp\left(-\frac{\Delta E}{k_B T}\right), \quad (2)$$

where  $k_B$  is the Boltzmann's constant,  $\Delta E$  is the activation energy, and  $\kappa_0$  is the pre-exponential factor. From the slope of  $\ln R \sim 1/T$ , the activation energies for the  $VO_2$  formation are determined to be 1.52 and 1.71 eV in Cz and GCz Si, respectively. The formation of  $VO_2$  complexes can be expressed by the reaction  $VO + O_i \rightarrow VO_2$ . According to the theory for diffusion limited reactions,<sup>31</sup> the reaction rate is proportional to  $D_{VO} + D_{O_i}$ , where  $D_{VO}$  and  $D_{O_i}$  represent the diffusivity of VO and  $O_i$ , respectively. However, according to the reported diffusion coefficients for interstitial oxygen and VO complexes,<sup>27,32</sup> the diffusion rate of  $O_i$  at 330 °C is estimated to be  $\sim 1.0 \times 10^{-22}$  cm<sup>2</sup>/s and is far below that of VO complexes ( $5.6 \times 10^{-15}$  cm<sup>2</sup>/s). Hence, interstitial oxygen can be regarded as practically immobile at temperatures of 300–345 °C. Therefore, the formation of  $VO_2$  complexes can be ascribed to a process of VO complexes diffusing towards  $O_i$ . And the diffusion energy barriers of VO complexes are 1.52 and 1.71 eV in Cz and GCz Si, respectively. These are close to the previously reported values of 1.7–1.8 eV extracted from FTIR and deep-level transient spectroscopy (DLTS) studies.<sup>32,33</sup> It is suggested that a larger energy barrier in Ge-doped Si leads to the decrease of VO diffusivity, which in turn slows down the capture of VO by  $O_i$  and therefore retards the  $VO_2$  formation in c-Si.

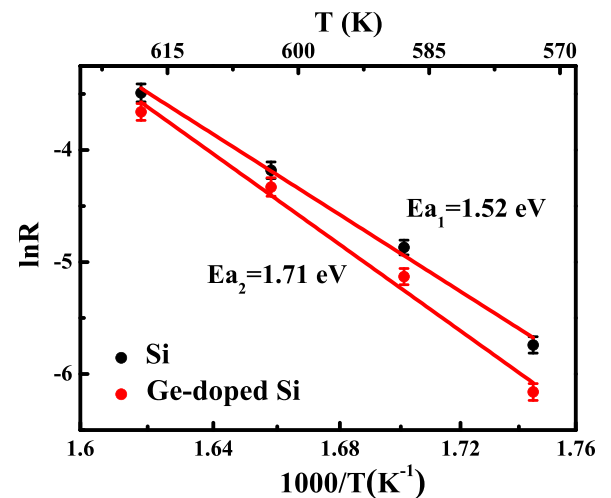


FIG. 5. The generation rates of  $VO_2$  complexes as a function of temperatures in neutron irradiated Cz and GCz Si. The solid lines are obtained by a linear fit of experimental points.



It is proposed by Furuhashi and Taniguchi that vacancy migration is involved in the diffusion of VO complexes.<sup>34</sup> They have suggested that the VO complex first transforms into a bond-center structure, in which a vacancy is the nearest neighbor to Si–O–Si. Thereafter, the vacancy migrates on each Si site step by step along a six-member ring and becomes the nearest neighbor to the Si–O–Si structure again. Finally, the bond-center structure newly forms VO after the vacancy jumps into the Si site nearest to the oxygen, and therefore completes an atomic step of VO diffusion.<sup>34</sup> It is speculated that the suppressed VO diffusion in GCz Si might be related to the vacancy migration along a six-member ring. The energy diagram for VO diffusion in GCz silicon is shown in Fig. 6. Hybrid density functional theory calculations show that the binding energy of GeVO complexes is 0.21–0.23 eV larger than the counterpart of VO complexes, indicating that the system gains more energy by the formation of GeVO complexes as compared to VO complexes.<sup>35</sup> These GeVO complexes have been found by deep level transient spectroscopy in electron irradiated Cz-grown Si<sub>1-x</sub>Ge<sub>x</sub> crystals. However, in the present study, the Ge-doping concentration is not high enough to cause a visible shift of the 836 cm<sup>-1</sup> band in IR spectra. In view of the above-mentioned analysis, it is inferred that VO complexes are more inclined to form at the neighboring site of Ge atoms. The vacancy migration involved in VO diffusion may be affected by its neighboring Ge atom. During vacancy migration, the neighboring Ge atom serves as a temporary sink for a vacancy and gives rise to the metastable GeV pair with the binding energy of 0.25–0.27 eV.<sup>35,36</sup> The captured vacancy has to overcome the additional binding energy to escape from the neighboring Ge atom (from A to B in Fig. 6). Coincidentally, the reported binding energy of GeV pair (0.25–0.27 eV) is close to the energy barrier difference of VO diffusion (0.19 eV) between Cz and GCz Si. Therefore, the retarded VO diffusion in Ge-doped Si is tentatively ascribed to the temporary trapping of a vacancy by the Ge atom associated with the formation of GeV pair. However, the physical picture for the VO diffusion in Ge-doped Si is complicated and further investigations are required to clarify the issue.

#### IV. CONCLUSIONS

FTIR measurements have been performed to quantitatively study the formation kinetics and mechanism of VO<sub>2</sub>

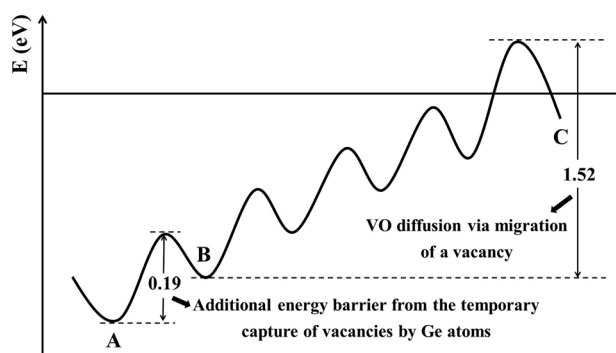


FIG. 6. The schematic illustration for the suppressed VO diffusion in GCz silicon.

complexes in neutron irradiated Ge-doped Si. It is found that Ge-doping with a concentration of  $\sim 10^{19}/\text{cm}^3$  slightly enhances the VO formation in c-Si and suppresses the transformation of VO into VO<sub>2</sub> complexes, which might originate from the high concentration of self-interstitial Si atoms in GCz Si, thus promoting the reaction of  $\text{VO} + \text{Si}_i \rightarrow \text{O}_i$ . Besides, the activation energies for VO<sub>2</sub> formation are determined to be 1.52 and 1.71 eV in Cz and GCz Si, respectively, which corresponds to the energy barriers of VO diffusion according to the theory for diffusion limited reactions. The larger energy barrier of VO diffusion in GCz Si suppresses the diffusion of VO complexes, thus, slows down the capture of VO complexes by O<sub>i</sub> and retards the VO<sub>2</sub> formation. Furthermore, it is found that the increase in energy barrier of VO diffusion by Ge-doping coincides with the binding energy of GeV pairs. This led us to assume that the retarding effect of VO diffusion in GCz Si might be due to the temporary trapping of a vacancy by its neighboring Ge atom, that is, the formation of GeV pair.

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- <sup>1</sup>X. Yu, J. Chen, X. Ma, and D. Yang, *Mater. Sci. Eng., R* **74**, 1 (2013).
- <sup>2</sup>A. Chroneos, E. N. Sgourou, C. A. Londos, and U. Schwingschlögl, *Appl. Phys. Rev.* **2**, 021306 (2015).
- <sup>3</sup>J. Vanhellemont, J. Chen, J. Lauwaert, H. Vrielinck, W. Xu, D. Yang, J. Rafi, H. Ohyama, and E. Simoen, *J. Cryst. Growth* **317**, 8 (2011).
- <sup>4</sup>D. Yang, X. Yu, X. Ma, J. Xu, L. Li, and D. Que, *J. Cryst. Growth* **243**, 371 (2002).
- <sup>5</sup>J. Vanhellemont, X. Zhang, W. Xu, J. Chen, X. Ma, and D. Yang, *J. Appl. Phys.* **108**, 123501 (2010).
- <sup>6</sup>P. Wang, X. Yu, Z. Li, and D. Yang, *J. Cryst. Growth* **318**, 230 (2011).
- <sup>7</sup>P. Wang, X. Yu, P. Chen, X. Li, D. Yang, X. Chen, and Z. Huang, *Sol. Energy Mater. Sol. Cells* **95**, 2466 (2011).
- <sup>8</sup>J. Chen, D. Yang, H. Li, X. Ma, and D. Que, *J. Appl. Phys.* **99**, 073509 (2006).
- <sup>9</sup>H. Li, D. Yang, X. Ma, X. Yu, and D. Que, *J. Appl. Phys.* **96**, 4161 (2004).
- <sup>10</sup>C. A. Londos, A. Andrianakis, V. Emtsev, and H. Ohyama, *J. Appl. Phys.* **105**, 123508 (2009).
- <sup>11</sup>A. Chroneos and C. A. Londos, *J. Appl. Phys.* **107**, 093518 (2010).
- <sup>12</sup>C. A. Londos, A. Andrianakis, E. N. Sgourou, V. V. Emtsev, and H. Ohyama, *J. Appl. Phys.* **109**, 033508 (2011).
- <sup>13</sup>C. A. Londos, E. N. Sgourou, and A. Chroneos, *J. Appl. Phys.* **112**, 123517 (2012).
- <sup>14</sup>C. A. Londos, E. N. Sgourou, D. Hall, and A. Chroneos, *J. Mater. Sci.: Mater. Electron.* **25**, 2395 (2014).
- <sup>15</sup>C. A. Londos, T. Angeletos, E. N. Sgourou, and A. Chroneos, *J. Mater. Sci.: Mater. Electron.* **26**, 2248 (2015).
- <sup>16</sup>C. A. Londos, A. Andrianakis, V. V. Emtsev, and H. Ohyama, *Semicond. Sci. Technol.* **24**, 075002 (2009).
- <sup>17</sup>E. N. Sgourou, A. Andrianakis, C. A. Londos, and A. Chroneos, *J. Appl. Phys.* **113**, 113507 (2013).
- <sup>18</sup>L. C. Kimerling, *Inst. Phys. Conf. Ser.* **31**, 221 (1977).
- <sup>19</sup>G. D. Watkins and J. W. Corbett, *Phys. Rev.* **121**, 1001 (1961).
- <sup>20</sup>V. Voronkov and R. Falster, *J. Electrochem. Soc.* **149**, G167 (2002).
- <sup>21</sup>G. Kissinger, J. Dabrowski, A. Sattler, C. Seuring, T. Mueller, H. Richter, and W. von Ammon, *J. Electrochem. Soc.* **154**, H454 (2007).
- <sup>22</sup>E. N. Sgourou, C. A. Londos, and A. Chroneos, *J. Appl. Phys.* **116**, 133502 (2014).
- <sup>23</sup>J. L. Lindstrom, L. I. Murin, V. P. Markevich, T. Hallberg, and B. G. Svensson, *Physica B* **273–274**, 291 (1999).
- <sup>24</sup>L. I. Murin, B. G. Svensson, J. L. Lindstrom, V. P. Markevich, and C. A. Londos, *Solid State Phenom.* **156–158**, 129 (2010).

- <sup>25</sup>C. A. Londos, G. I. Georgiou, L. G. Fytros, and K. Papastergiou, *Phys. Rev. B* **50**, 11531 (1994).
- <sup>26</sup>V. V. Voronkov and R. Falster, *Mater. Sci. Eng. B* **134**, 227 (2006).
- <sup>27</sup>A. Borghesi, B. Pivac, A. Sassella, and A. Stella, *J. Appl. Phys.* **77**, 4169 (1995).
- <sup>28</sup>G. Davies, E. C. Lightowlers, R. C. Newman, and A. S. Oates, *Semicond. Sci. Technol.* **2**, 524 (1987).
- <sup>29</sup>C. A. Londos, N. Sarlis, L. G. Fytros, and K. Papastergiou, *Phys. Rev. B* **53**, 6900 (1996).
- <sup>30</sup>V. Quemener, B. Raeissi, F. Herklotz, L. I. Murin, E. V. Monakhov, and B. G. Svensson, *J. Appl. Phys.* **118**, 135703 (2015).
- <sup>31</sup>T. R. Waite, *Phys. Rev.* **107**, 463 (1957).
- <sup>32</sup>P. Pellegrino, P. Lévêque, J. Lalita, A. Hallén, C. Jagadish, and B. G. Svensson, *Phys. Rev. B* **64**, 195211 (2001).
- <sup>33</sup>B. G. Svensson, J. L. Lindström, and J. W. Corbett, *Appl. Phys. Lett.* **47**, 841 (1985).
- <sup>34</sup>M. Furuhashi and K. Taniguchi, *Appl. Phys. Lett.* **86**, 142107 (2005).
- <sup>35</sup>H. Wang, A. Chroneos, C. A. Londos, E. N. Sgourou, and U. Schwingenschlogl, *Phys. Chem. Chem. Phys.* **16**, 8487 (2014).
- <sup>36</sup>K. Sueoka, E. Kamiyama, and J. Vanhellefont, *J. Appl. Phys.* **114**, 153510 (2013).