Study on the defect-related emissions in the light self-ion-implanted Si films by a silicon-on-insulator structure*

Wang Chong(王 茺)[a)†], Yang Yu(杨 宇)[a)b)‡], Yang Rui-Dong(杨瑞东)[a)c)], Li Liang(李 亮)[a)], Xiong Fei(熊 飞)[a)], and Bao Ji-Ming[b)]

[a)] *Institute of Optoelectronic Information Materials, Yunnan University, Kunming* 650091, *China*

[b)] *Department of Electrical and Computer Engineering, University of Houston, Houston, Texas* 77204, *USA*

[c)] *Department of Physics, Honghe University, Mengzi* 661100, *Yunnan Province, China*

(Received 20 April 2010; revised manuscript received 31 July 2010)

This paper reports that the Si^+ self-ion-implantation are conducted on the silicon-on-insulator wafers with the $^{28}Si^+$ doses of 7×10^{12}, 1×10^{13}, 4×10^{13}, and 3×10^{14} cm^{-2}, respectively. After the suitable annealing, these samples are characterized by using the photoluminescence technique at different recorded temperatures. Plentiful emission peaks are observed in these implanted silicon-on-insulator samples, including the unwonted intense P' band which exhibits a great potential in the optoelectronic application. These results indicate that severe transformation of the interstitial clusters can be manipulated by the implanting dose at suitable annealing temperatures. The high critical temperatures for the photoluminescence intensity growth of the two signatures are well discussed based on the thermal ionization model of free exciton.

Keywords: self-ion-implantation, photoluminescence, interstitial cluster, silicon-on-insulator

PACS: 68.35.Dv, 78.67.–n, 78.55.Ap **DOI:** 10.1088/1674-1056/20/2/026802

1. Introduction

Due to the indirect-band-gap property of silicon, the direct optical transition and radiation recombination from band-to-band are rare in the Si-based semiconductors. This limits the applications of silicon a lot in the optoelectronics.[1] However, considerable arts have been made in the two past decades toward the goals of the so-called "defect engineering" and the "full silicon integration of optoelectronics and microelectronics" in those Si-based materials.[2−8] Ion-implantation is one of those attractive techniques which can effectively introduce the "intermedial state" into the forbidden band of silicon, and then endues the Si-based materials with some novel physical properties, such as the zero-phonon optical transition.[9,10]

As the two typical emission peaks of the ion-implanted silicon, the zero-phonon "*G*" and "*W*" lines which locate at 0.969 eV and 1.018 eV, respectively, had been utilized to fabricate the sub-band light-emitting-diodes (LEDs). These devices exhibit high optical efficiency, but the working temperatures of them are still relatively low ($<$ 100 K).[11−13] The desired light emitter should not only exhibit high luminescence efficiency, but emit at about 1.55 μm or 1.3 μm and work at room temperature. Most recently, it was demonstrated that the intense and sharp D_1 line can be detected clearly in an Si^+ self-ion-implanted (SII) silicon bulk at temperature as high as 280 K, moreover, the photoluminescence (PL) intensity of this feature does not show evident temperature dependence.[14] This reinforces the conception that SII silicon can be an important candidate material for fabricating the optoelectronic device operating at the desired wavelength of 1.55 μm and temperature of $\sim$300 K.

Some experimental and theoretical works had revealed the presence, evolution, and complexity of interstitial clusters (ICs) in the Si bulk.[15−18] For example, it was argued earlier that the tri-interstitial cluster (I_3C) could account for many fundamental properties of *W* centre. Later, the first principle calculations on vibration modes of I_3C cast doubts on the relation between I_3C and *W* centre.[19] Giri *et al.* pro-

*Project supported by the National Natural Science Foundation of China (Grant No. 10964016), the Key Project of the Chinese Ministry of Education (Grant No. 210207), and the Natural Science Foundation of Yunnan University (Grant No. 2009E27Q).

†Corresponding author. E-mail: cwang6@163.com

‡Corresponding author. E-mail: yuyang@ynu.edu.cn

© 2011 Chinese Physical Society and IOP Publishing Ltd

posed that the W line is more likely to originate from the small I_2C, and the X band at 1.040 eV originates from the larger I_4C which is formed at the cost of the W centres at higher annealing temperatures (ATs).[20] The R line at 0.901 eV was directly correlated with the rod-like {311} defects based on the observation of the transmission electron microscopy (TEM),[21] and the chain-like cluster was believed to be the precursor of R defect.[22] The multiple PL peaks labeled as I_n-bands in the range of 0.89–1.01 eV were ascribed roughly to the luminescence from the complex ICs,[23] but no satisfactory explanation exists for these interstitial defects.[20] In fact, these intermediate ICs are prone to evolve from one to the other with the change of implanting energy, dose, AT, annealing time, and ion species. Moreover, they are difficult to be detected by traditional electric and magnetic techniques. Theoretical investigations on the structure and dynamics of the ICs have accumulated a diverse results but in most of the case correlated with the experiments has been found to be very poor.[23] These open up challenges for the deeper understanding on the optical characteristic of the ICs in silicon. Hence, more PL experiments are needed to probe the nature of the ICs responsible for the emission properties as a function of AT and dose, because the studies on the luminescence are believed to better compare with the theoretically predicted behaviours of the ICs. Although the Si bulk implanted with heavy-dose ions has been extensively investigated by PL, TEM, deep level transient spectroscopy (DLTS),[15] and optical absorption techniques,[24] to our knowledge, little work was conducted with light ion dose ($\leq 10^{14}$ cm^{-2}) and the subsequent AT above 600 °C,[14] nothing of that operating on the silicon-on-insulator (SOI) wafer. Especially, the better performance of the sub-bandgap LED has been demonstrated most recently on the SOI structure other than on the Si bulk.[25] On the other hand, implanting heterogeneous ion (such as Ge^+, Al^+, B^+, P^+, and Er^+) into Si generally affects the optical properties of the Si matrix.[26,27] Those negative effects are mainly due to the implanted impurities which disturb the periodic potential and therefore act on the energy-band structure, consequently, on the optical properties of Si-based materials. To eliminate such chemical effects and purify the luminescence mechanism, in this paper, the $^{28}Si^+$ with different doses was self-implanted into the Czochralski (CZ) Si films on the SOI wafer. The plentiful emissions from the interstitial defects are well studied by the PL technique in a wide recorded temperature (RET) range.

2. Experiments

The SOI structures having a 100-nm-thick top CZ Si (high content of oxygen and carbon impurity) layer and a 1000-nm-thick buried oxide layer were fabricated on (100)-oriented, $\sim$ 10 $\Omega\cdot$cm Si substrates by the SIMOX method.[3] The CZ Si films on the SOI structure were implanted at room temperature with the energy of 300 keV and the $^{28}Si^+$ ion dose of 7×10^{12}, 1×10^{13}, 4×10^{13}, and 3×10^{14} cm^{-2}, respectively. The radius of the corresponding projected ion range (R_p) is about 450 nm. All the implantation experiments were conducted with an ion beam at an incident angle of 7° with respect to the normal of the Si film to avoid the channeling effects. After the ion-implantation finished, the SOI wafers were cut into several pieces, and then they were annealed in the N_2 atmosphere for 30 minutes at two typical annealing temperatures (ATs), 650 °C and 750 °C, where the self-interstitial defects transform tempestuously. Here, for the convenience of depiction, the five SOI samples processed at 650 °C, including the as-annealed (no implantation) SOI samples and the four SII ones implanted with the Si^+ dose of 7×10^{12}, 1×10^{13}, 4×10^{13}, and 3×10^{14} cm^{-2}, are named as samples A_{650}, B_{650}, C_{650}, D_{650}, and E_{650}, respectively. Correspondingly, the SOI samples annealed at 750 °C are named as samples A_{750}, B_{750}, C_{750}, D_{750}, and E_{750}, respectively.

The PL signatures were recorded by using a Syner JY spectrometer (Tria 550). The SOI samples were mounted on the cold-tip of a drip-feed liquid helium cryostat, and the RETs were changed from 6 K to 280 K during the optical measurements. An argon-ion laser with its wavelength of 458 nm was used as an irradiation source. In all the PL experiments, the excited power was monitored by a laser power-meter and well normalized. The spot diameter and the exciting power of the laser beam were 2.5 mm and 15 mW, respectively. Light emission from the samples was dispersed by using a monochromator and detected by a liquid-nitrogen refrigerated Ge detector. Standard lock-in technique was used to improve the ratio of luminescence signal to noise.

3. Results and discussion

Figure 1 shows a set of PL spectra of the SOI samples annealed at 650 °C. Each PL curve was well fitted by the Gaussian line-shape model.[14,28] In the PL spectroscopy of sample A_{650}, the intense "EHD^{TO}" peak at 1.09 eV and with a full maximum

at half height (FWHM) of 5 meV can be attributed to the condensate luminescence from the spatially localized electron and hole drop (EHD). This identification depends on the spectra line-shape fitting, which is viewed as an effective tool for the evidence of the formation of EHD luminescence.[29] Usually, the EHD^{TO} signature can be detected in an SOI wafer below a critical temperature, due to the recombination of high-density carrier confined in the superficial Si film by the SiO_2 layer which acts as a diffusion barrier of the photoexcited carriers. The observation of EHD^{TO} emission implies the good crystalline quality of the CZ Si films and the interface between CZ Si film and oxide layer. It also indicates that the EHD^{TO} peak can be excited by the blue laser, not necessarily by an ultraviolet (UV) one. This differs from the report in the literatures where the UV irradiation was proposed to be a major factor for activating the EHD^{TO} emission.[30,31] The other peaks in the PL curve of sample A_{650}, labeled as X, S_1, S_2, and P which locate at 1.035, 0.932, 0.885 and 0.767 eV respectively, can be attributed to the radiative combination from the I_4C, the small IC in the strained regions (for both S_1 and S_2), and such cluster with a carbon centre perturbed by a bi-oxygen atoms, respectively.[14] The rest broad-envelope labeled as "I band" at 0.965 eV may originate from the undefined ICs which are generally formed by heating the CZ Si at high temperatures.[31]

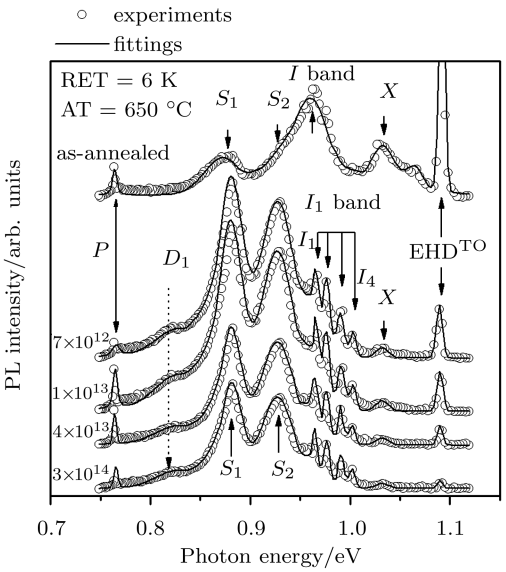


Fig. 1. The PL spectra of the SII SOI wafers with the ion doses of 0.0 (as-annealed), 7×10^{12}, 1×10^{13}, 4×10^{13}, and 3×10^{14} cm^{-2}, respectively, and annealed at 650 °C for 30 min. The RET in the PL experiments was 6 K. The Si^+ implantation energy in all the experiments was 300 keV.

With the implantation of Si^+into the SOI wafer, some interesting optical features are observed in those SII SOI samples annealed at 650 °C. The intensity of EHD^{TO} peak decreases with the increase of Si^+ implanting dose, and shows obvious dose dependence. Actually, the more the Si^+ dose is, the more the damage formation is, and the more the photoexcited EHD involved in non-radiative recombination is. A broad envelope D_1 with the FWHM of 47 meV is observed at 0.820 eV in those PL curves of samples B_{650}, C_{650}, D_{650}, and E_{650}. Whether the D_1 centres originate from the relaxed dislocation loops[32] or the point defects in between the dislocations[33] is still a controversy. In our recent study on the defect depth profile by the reactive ion etching technique, the PL intensity of D_1 band declines steeply before the dislocation loops are removed,[34] this seems to support the latter identification.

In the range of 0.950 eV–1.020 eV, several sharp $I_{l\ (l=1,2,3,4)}$ peaks (labeled as I_1–I_4, at 0.965, 0.976, 0.991, and 1.003 eV, shown with arrows, respectively) overlapping on the S_2 band are shown in the PL spectra of samples B_{650}, C_{650}, D_{650}, and E_{650}. The four I_l peaks disappear till the RET up to 60 K. This excludes the possibility that the I_l signatures originate from the noise introduced during the optical measurements. The peak position and the FWHM of I_1 line are very close to the G line whose luminescence centres are formed with an interstitial carbon atom trapped at a substitute carbon atom (C_iC_s) in silicon. However, most of the G centres are produced during the short-time annealing below 500 °C, and they transform to the other ICs at higher ATs (> 500 °C) or by prolonging the annealing time to hours in the low AT range of 250 °C–500 °C.[14,25] The FWHM and intensity of these I_l feature, do not exhibit apparent dose dependence, and these sharp peaks seem to be lying on the broad and asymmetrical S_2 band whose intensity decreases with the increase of Si^+ dose. It implies that the I_l centres can be formed even with the lowest dose of 7×10^{12} cm^{-2}, and the cluster configuration of the I_l centres keeps relatively stable in spite of further increasing the Si^+ dose.

Figure 2 shows another set of PL spectra of the SII SOI wafers with the corresponding Si^+ doses but the AT of 750 °C. The luminescence properties of these SII SOI samples exhibit a strong dependence of the dose. The PL curve of sample A_{750} only shows a single EHD^{TO} peak at 1.090 eV. Note that the EHD^{TO} intensity of sample A_{750} is about 70 times stronger than that of sample A_{650} with the same PL measurement

conditions. The peak at 0.901 eV can be attributed to the R-line which is observed usually in the damaged Si bulk annealed above 600 °C.

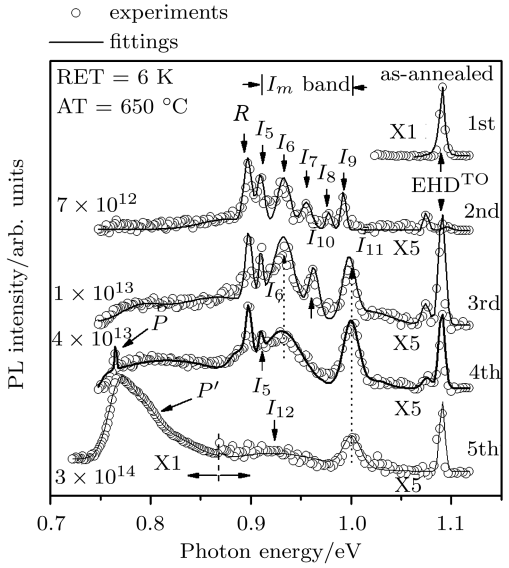


Fig. 2. The PL spectra of the SII SOI wafers with the different ion doses and the post-annealing temperature of 750 °C. The RET in the PL experiments was 6 K. The Si^+ implantation energy in all the experiments was 300 keV.

In the range of 0.91 eV–1.01 eV, several peaks labeled as $I_{m\ (m=5-12)}$ (at 0.910, 0.932, 0.956, 0.976, 0.992, 0.963, 0.998, and 0.922 eV, shown with arrows, respectively) are observed in these SII SOI samples annealed at 750 °C. The I_5 peak with an FWHM of 4 meV can be detected in samples B_{750}, C_{750}, and D_{750}. Although the I_6 feature also presents in the PL curves of the above three samples, the FWHMs of this signature increase from 15 to 24 and 42 meV with the increase of dose. Whereas, the I_7, I_8, and I_9 features can only be observed in sample B_{750}. The absence of I_7 peak in the PL curve of sample C_{750} probably results from the evolution of I_7 centre to I_6 defect with the increase of the interstitial. This may account for the broadening and strengthening of I_6 peak of sample C_{750} in comparison with those of sample B_{750}. A new I_{10} peak with different position and FWHM with those of I_7 and I_8 is shown in the PL spectroscopy of sample C_{750}. It suggests that the I_8 centre is likely to be the precursor of the I_{10} centre. Similar behaviour occurs on the I_{11} feature in the PL curve of sample C_{750}. The I_{11} centre possibly grows at the cost of the I_9 centre. With the evolution from I_9 centre to I_{11} one, the I_{11} signature undergoes a blue-shift of 6 meV and a broadening from 6 meV to 15 meV. Although the peak position of I_{11} feature superposes with that of the phonon replica W^{TA} of W-line, few W centres can be survived after the AT above 600 °C.[35–37]

Further increase the dose to 4×10^{13} cm^{-2}, the PL spectroscopy of sample D_{750} shows the P, R, I_5, I_6, and I_{11} peaks. The weak P-line begins to be detected till the dose up to 4×10^{13} cm^{-2}, while there are scarcely any changes occurred on the line shape of I_{11} feature with the increase of dose from 1×10^{13} to 4×10^{13} cm^{-2}. Considering the continuous broadening of I_6 peak, the absence of I_{10} peak in the PL curve of sample D_{750} probably implies that the I_{10} centre repeats the behaviour of I_7 centre, i.e., the I_{10} centre transforms to the I_6 centre with the incorporation of the more interstitials. Therefore, it can be concluded that the structural size of I_6 centre is larger than those of I_7, I_8, and I_{10} centres.

Great changes of the luminescence characteristic occur on sample E_{750}. Not only the I_5 and I_6 peaks, but the R line can no longer be detected in sample E_{750}. Instead, a weak and broad I_{12} band with its centre at 0.922 eV and an FWHM of 110 meV appears in the I_m band range. The I_{12} centres seem to grow at cost of the {311} rod-like defects (R centre), the I_5, and I_6 centres. In such structural transformation process, the large ICs, such as I_6 centres and {311} defects, may transform to the extended ICs which then greatly enhance the FWHM of I_{12} band.

Similar "I band" has also been observed in those ion-implanted Si bulk, and some rough structures have been proposed to describe the configurations of the ICs related to the I bands.[38] However, less the specific structures and explicit numbers in those complex ICs have been proposed yet, and none of that have been demonstrated directly in the experiments. So, the determination for the exact configuration of the ICs still remains an open question. Tsuji *et al.* attributed the I band to those defects which are the precursor of {311} rod-like defects. However, this identification was not well supported in the literature where the evolution of {311} rod-like defects did not occur even that the I band has been observed clearly.[37] After the annealing in the AT range of 600 °C–700 °C and beyond the processing time of ∼18 minutes, it was argued that half of the I_nCs in the damaged Si bulk have the clustered interstitial size of $n = 8$, the other half of that are ripened then have a broad size distribution in the range of $n = 10$–100.[39] Whereas, such larger I_nCs with wide distribution ($n = 10$–100) cannot account for the sharp multi-peak,[20] such as

the four I_l features shown in Fig. 1. Another possible mechanism for the multiple sharp-peaks is the optical transition from different excited states to the same ground state of large IC. For instance, NL51 signal in the electron-spin resonance spectra of electron-beam irradiated Si had been attributed to an excited state of the neutral I_4C.[40] The PL excitation spectra of diamond exhibit a series of similar undocumented PL peaks which are ascribed to be the radiative transitions from different excited states to the same ground state of the divacancy-related IC.[41] As a result, it is proposed in this paper that the four I_l peaks observed in those SII SOI samples annealed at 650 °C may originate from the radiative combination between different excited states and the same ground state of the I_8C. Another evidence supports this identification is that the four I_l peaks disappear simultaneously with increasing RET to 60 K. Moreover, the four features have almost the same deactivation energy of 23±1.8 meV, which were obtained by fitting the RET-dependent PL intensities with an Arrhenius form, i.e. $I(T) \sim I(I_0)\exp(E/k_BT)$, where k_B is the Boltzmann constant.[14] This suggests that the series of I_l peaks may originate the same interstitial defect. However, this mechanism cannot interpret the origin of those multiple I_m peaks observed in those 750 °C annealed samples, since the I_m centres are not stable and each of them is prone to transform to the other IC with the increase of Si interstitials. The sharp I_8 and I_9 features, which have the similar PL line profile, may originate from two different configurations of the I_8C, respectively. Note that even the small I_3C has possible multiple configurations.[18] As a result, the relatively stable I_{11} centre may be composed of the diploid I_8C, namely, $I_{16}C$. The I_7 and I_{10} centres are probably the large but compact I_nCs. The I_5 and I_6 centres may correspond to the chain-like defects which should not be attributed affirmatively to the precursor of the {311} rod-like defects. Although these I_m features are assigned, more experiments are needed to classify the specific configuration of these ICs.

An intense peak labeled as P' and with its centre at ∼0.773 eV (∼1.6 μm) is observed in the PL spectroscopy of sample E_{750}, as shown in Fig. 2. The intensity of P' band at 6 K is even stronger than that of the EHD^{TO} peak of sample A_{750}. Our original fitting experiments indicate that the line-shape of P' band is asymmetric, and this signature cannot be constructed by only one type of luminescence centre. Further fitting operations emphasize that the 0.767 eV line, 0.789 eV line, and the 0.820 eV band are actually the basic features for forming the intense P' peak, as shown in the inset of Fig. 3. The three features can be definitely attributed to the P, C_iO_i, and D_1 lines, respectively. Note that the C_iO_i line at 0.789 eV corresponds to the monoclinic interstitial centre involving carbon and oxygen atoms.[42] So, the observation of the intense P' band only in sample E_{750} probably can be ascribed to the increase of the P and D_1 centres and the new formation of the C_iO_i centre induced by further increasing the dose to 3×10^{14} cm^{-2} and the AT to 750 °C.

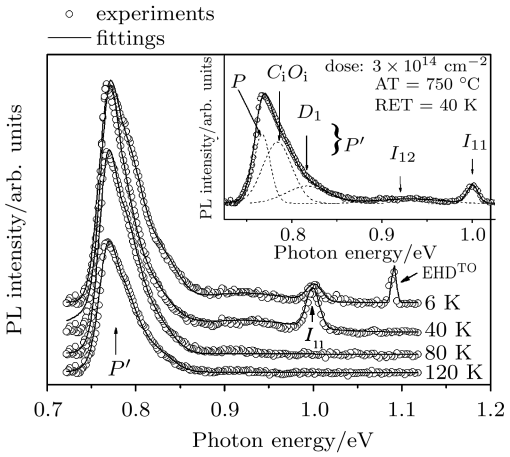


Fig. 3. The PL spectra of sample E_{750} at different RETs. Inset is the detailed fitting results for the 40 K PL spectroscopy.

Figure 3 shows the PL spectra of sample E_{750} at different RETs. The EHD^{TO} peak can still be observed in the 15-K PL curve, but disappears in the 20-K one. It supports the EHD phase diagram model in which the upper-limit temperature for the observation of EHD phenomena is below 20 K.[43] The I_{11} feature can only be detected below 80 K. However, the P' band can still be observed at 260 K. This is very promising for the optoelectronic application operating at room temperature.

The intensities of both I_{11} peak and P' band do not decrease monotonously with the increase of RET, as shown in Fig. 4. Actually, the zoro-phonon I_{11} line exhibits a maximal intensity at ∼40 K. The abnormal intensity growth below 40 K is similar to the increase of free exciton luminescence, and probably can be interpreted in terms of the competition for capturing the excitons between the optical centres and other traps. With the increase of temperature from 0 K, there is a rapid increase in the probability of thermal

ionization of the excitons, more excitons involved in the I_{11} emission then freed from the original traps become available for capture by other, deeper, exciton traps, including luminescence centres, increasing the probability of radiative combination. Consequently, a growth in PL intensity can be frequently expected. Beyond the critical temperatures (40 K for I_{11} feature), the PL intensity decreases due to the thermally scattering and dissociation of excitons. Same temperature dependences of the intensity of I_{11} feature have also been confirmed in sample C_{750} and D_{750}. It suggests that luminescence growth of I_{11} feature at low temperature is dose-independent.

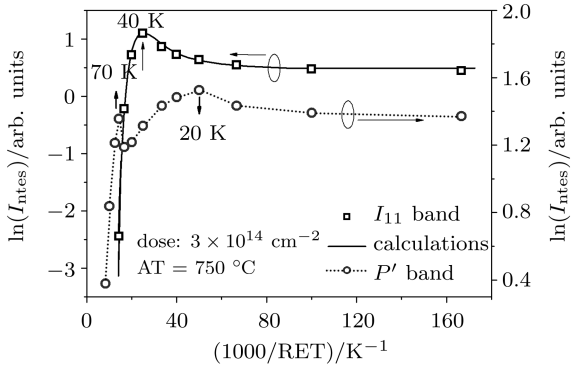


Fig. 4. The RET-dependent PL intensities [1000/RET vs. $\ln(I_{\rm ntes})$] of the I_{11} (□) and P' ($\cdots\circ\cdots$) signatures of sample E_{750}. The maximal PL intensities at different RETs had been normalized before plotting. The solid line is the theoretical result based on Eq. (2).

The P' band exhibits its maximal intensity ($I_{\rm ntes}$) at RET of 20 K, as shown in Fig. 4. Different from the expectation, RET-dependent PL intensity of the P' band exhibits another intensity growth near the liquid nitrogen temperature range (70 K). In order to understand the interesting behaviour, we have extracted RET-dependent PL intensities of the three features for forming the P' band, P, $C_{\rm i}O_{\rm i}$, and D_1 lines from the PL data, respectively, as shown in Fig. 5. Then, it can be concluded that the maximal intensity of P' band at ∼20 K are mainly dominated by the enhancement of P line in the corresponding temperature range, while the small growth of the PL intensity at ∼70 K is contributed by the abnormal growth of $C_{\rm i}O_{\rm i}$ line.

Within the frame of thermal ionization model of free exaction, taking into account that the binding energy of an exciton at a trap is $E_{\rm b}$, and assuming that all species of traps in a particular sample can be parametrized by traps of one effective $E_{\rm t}$, we can statistically describe a fraction of the traps (f) which are not ionized and can compete with the luminescence centres for the capture of excitons by using Eq. (1).[42] Therefore, the luminescence intensity at a certain temperature (T) can be expressed by Eq. (2)

$$f = [1 + bT^{3/2}\exp(-E_{\rm t}/k_{\rm B}T)]^{-1}, \quad (1)$$

$$I(T) = I(I_0)/[(1 + f')(1 + P)], \quad (2)$$

where $P = gT^{3/2}\exp(-E_{\rm b}/k_{\rm B}T)$, $gT^{3/2}$ is the effective density of band continuum states where ionization occurs, f' is equal to cf which includes the temperature-independent ratio of the trapping cross excitons at the luminescence centres and the competing traps, b and c are constants. The fitting results based on Eq. (2) are agreed with the RET-dependent data of I_{11} and $C_{\rm i}O_{\rm i}$ features well, as the solid lines shown in Figs. 4 and 5, respectively. The $E_{\rm t}$ values of the I_{11} and $C_{\rm i}O_{\rm i}$ features are ∼5.3 meV and ∼8.8 meV, which are the possible values for the exciton binding to the shallow-levels, respectively. Both values larger than that of P line (∼3 meV) derived by G. Davis in the damage CZ Si bulk.[42] This suggests that the higher binding energies are responsible for the higher critical temperatures, ∼40 K and ∼70 K, observed in Figs. 4 and 5, respectively. Combining with our recent work, we conclude that the exciton binding energy of some defects, such as D_1 and $C_{\rm i}O_{\rm i}$ centres, can be improved by the SII and its subsequent annealing process. This offers an alternative method to realize the high-efficiency luminescence at room temperature by using the silicon-based materials.

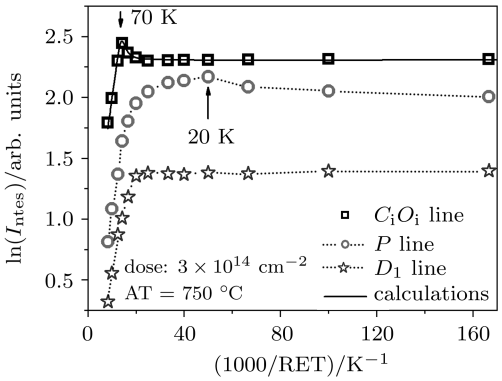


Fig. 5. The RET-dependent PL intensities [1000/RET vs. $\ln(I_{\rm ntes})$] of the $C_{\rm i}O_{\rm i}$ (□), P ($\cdots\circ\cdots$), and D_1 ($\cdots\star\cdots$) features of sample E_{750}. The maximal PL intensities at different RETs had been normalized before plotting. The solid line is the theoretical result based on Eq. (2).

4. Conclusions

Several new emission features have been detected in the Si^+ self-ion-implanted SOI wafers with differ-

ent Si^+ doses and subsequent ATs. The luminescence properties of the interstitial clusters formed at AT of 650 °C seem to be less dependent on the implanting dose. However, those defects formed at 750 °C are strongly dependent on the dose and undergo a severe transformation from one type of interstitial cluster to the other. An intense emission band, which is observed at ∼1.6 μm in the SOI wafer with the dose of 3×10^{14} cm^{-2} and the AT of 750 °C, shows great potential in the optoelectronic application. The abnormal intensity growth of this intense band is well discussed based on the thermal ionization model of free exaction. Although the emission related to the interstitial-clusters has been detected and identified in this study, more experimental and theoretical works are needed to clarify the concrete configurations of these interstitial-clusters, then to realize the manipulation on the luminescence of these defects in silicon for the purpose of the application.

Acknowledgement

The authors would like to thank Prof. Lu Wei (SITP, CAS) for the useful discussions. One of the authors (Yu Yang) thanks Prof. Aziz M J and Capasso F (Harvard University) and the program for studying at Harvard University launched by the government of Yunnan Province (China).

References

[1] Pavesi L 2003 *J. Phys.*: *Condens. Matter* **15** R1169
[2] Hirschman K D, Tsybeskov L, Duttagupta S P and Fauchet P M 1996 *Nature* **384** 338
[3] Yu X, Seifert W, Vyvenko O F, Wilhelm T and Reiche M 2008 *Appl. Phys. Lett.* **93** 041108
[4] Pavesi L, Negro L D, Mazzoleni C, Franzo G and Priolo F 2000 *Nature* **408** 440
[5] Geis M W, Spector S J, Grein M E, Schulein R T, Yoon J U and Lennon D M 2007 *IEEE Photon. Technol. Lett.* **19** 152
[6] Green M A, Zhao J, Wang A, Reece P J and Gal M 2001 *Nature* **412** 805
[7] Davies G, Hayama S, Murin L, Davia C and Karpenko A 2006 *Phys. Rev.* B **73** 165202
[8] Ding J N, Wu J X, Yuan N Y, Kan B and Chen X S 2010 *Chin. Phys.* B **19** 077103
[9] Huang W Q, Wang H X, Jin F and Qin C J 2008 *Chin. Phys.* B **17** 3753
[10] Liu H X, Zhang H M, Hu H Y and Song J X 2009 *Chin. Phys.* B **18** 734
[11] Cloutier S G, Kossyrev P A and Xu J M 2005 *Nature Mater.* **4** 887
[12] Rotem E, Shainline J M and Xu J M 2007 *Appl. Phys. Lett.* **91** 051127
[13] Recht D, Capasso F and Aziz M J 2009 *Appl. Phys. Lett.* **94** 251113
[14] Yang Y, Wang C, Yang R D, Li L, Xiong F and Bao J M 2009 *Chin. Phys.* B **18** 4906
[15] Libertino S, Coffa S and Benton J L 2001 *Phys. Rev.* B **63** 195206
[16] Bondi R J, Lee S and Hwang G S 2009 *Phys. Rev.* B **79** 104106
[17] Lee S and Hwang G S 2008 *Phys. Rev.* B **78** 045204
[18] Richie D A, Kim J, Barr S A, Hazzard K R and Wilkins J W 2004 *Phys. Rev. Lett.* **92** 045501
[19] Coomer B J, Goss J P, Jones R, Oberg S and Broddon P R 2001 *J. Phys.*: *Condens. Matter* **13** L1
[20] Giri P K 2005 *Semicond. Sci. Technol.* **20** 638
[21] Coffa S, Libertino S and Spinella C 2000 *Appl. Phys. Lett.* **76** 321
[22] Kim J, Kirchhoff F, Wilkins J W and Khan F S 2000 *Phys. Rev. Lett.* **84** 503
[23] Lopez G M and Fiorentini V 2004 *Phys. Rev.* B **69** 155206
[24] Yu C H, Zhang B, Li Y J, Lu W and Shen X C 2007 *Solid State Commun.* **142** 71
[25] Bao J M, Charnvanichborikarn S, Yang Y, Tabball M, Shin B, Williams J S, Aziz M J and Capasso F 2008 *Proc. SPIE* **6800** 68000T
[26] Vina L and Cardona M 1984 *Phys. Rev.* B **29** 6739
[27] Jellison G E, Withrow S P, McCamy J W and Godbole M J 1995 *Phys. Rev.* B **52** 14607
[28] Wang C, Li Z F, Chen X M, Liu J M, Liu Z L, Cui H Y, Yang Y and Lu W 2008 *Appl. Surf. Sci.* **254** 4626
[29] Ibuka S and Tajima M 2002 *J. Appl. Phys.* **91** 5035
[30] Tajima M and Ibuka S 1998 *J. Appl. Phys.* **84** 2224
[31] Minaev N S and Mudryi A V 1981 *Phys. Stat. Sol.* (a) **68** 501
[32] Tajima M, Gosele U, Weber J and Sauer R 1983 *Appl. Phys. Lett.* **43** 270
[33] Wijarankuia W 1991 *J. Appl. Phys.* **70** 3018
[34] Yang Y, Bao J M, Wang C and Aziz M J 2010 *J. Appl. Phys.* **107** 123109
[35] Giri P K, Coffa S and Rimini E 2001 *Appl. Phys. Lett.* **78** 291
[36] Burger N, Thonke K, Sauer R and Pensl G 1984 *Phys. Rev. Lett.* **52** 1645
[37] Nakamura M and Murakami S 2003 *J. Appl. Phys.* **94** 3075
[38] Libertino S, Coffa S and Benton J L 2001 *Phys. Rev.* B **63** 195206
[39] Cowern N E, Mannino G, Stolk P A, Claveri A and Jaraiz M 1999 *Phys. Rev. Lett.* **82** 4460
[40] Mechedlidze T, Yonenaga I and Suezawa M 2003 *Mater. Sci. Semicond. Process.* **6** 263
[41] Ikoubovskii K and Adriaenssens G J 2000 *Phys. Rev.* B **61** 10174
[42] Davis G 1989 *Phys. Rep.* **176** 83
[43] Shah J, Combescot M and Dayem A H 1977 *Phys. Rev. Lett.* **38** 1497