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Photoluminescence mechanism of rare-earth erbium in silicon: Influence of defect specifics and shallow centers

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The 1.54 μm luminescence emitted from erbium-doped semiconductors has generated much interest due to its potential application in optoelectronics. In this report we discuss excitation and de-excitation mechanisms of erbium doped into silicon that is influenced by shallow centers of the silicon host and erbium-related defect specifics. An enhancement of photoluminescence when the temperature is raised from 4 to 25 K was observed. In the same temperature range there was also a transition from excitons bound to shallow impurities to free excitons. The effect was explained by thermally induced energy transfer from impurity traps to erbium-related centers. Time response of photoluminescence intensity was recorded and analysed. Variation of the luminescence decay time is related to the presence of several centers simultaneously contributing to the luminescence of erbium in silicon.

1. Introduction

Photoluminescence (PL) related to erbium impurity in silicon proceeds along a complex chain of processes by which excitation energy imparted to the crystal is transferred to the final step of light emission by the $^4I_{13/2}$ to $^4I_{15/2}$ transition of erbium 4f inner-shell electrons. Full understanding of these processes presents a challenging topic in semiconductor physics, in which currently intensive research activity is displayed. The present paper reports a discussion on the influence of impurity traps of the silicon host on the photoluminescence of erbium. Photoluminescence decay time of erbium is measured and analysed on the basic of the excitonic model.

2. Results and discussion

2.1 Erbium photoluminescence

For the experiment two kinds of float-zone and Czochralski-grown silicon samples doped with erbium by ion implantation method were used. The erbium peak concentration of these samples is in the order of 10^{17} cm^{-3} as revealed by secondary ion mass spectroscopy. The samples are labeled as Fz-Si:Er and Cz-Si:Er, respectively. The samples were excited by an Ar^{+}-ion laser line of 514.5 nm with a laser power of 10 mW. The samples exhibited the characteristic luminescence related to Er^{3+} ion in the wavelength range 1.5 to 1.7 μm. The emitted light was dispersed by a Jobin-Yvon THR 1500 monochromator. Illustrations of the emissions are plotted in Fig.1

Erbium luminescence follows from the radiative $^4I_{13/2}$ to $^4I_{15/2}$ transition with the emission of a photon of energy around 800 meV. Such an electric-dipole transition is parity forbidden in the spherical potential of a free atom. For an erbium ion embedded in a silicon crystal the transition will become allowed due to the lower symmetry of the crystal-field potential, which will be tetrahedral or lower depending on the specific structure of the luminescent centers. Crystal-field induced effects are directly manifested in the multiple-line structure of the optical spectrum. Previous studies of the erbium-related PL revealed that for the oxygen-rich sample, Cz-Si-Er, the cubic center and oxygen-erbium complexes dominate the spectrum. In the spectra obtained for the Fz-Si:Er the non-cubic center seems to prevail [1]. For the centers in the investigated samples this is shown in Fig. 1.

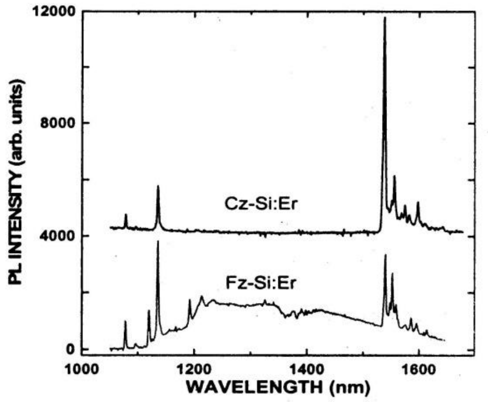

Fig. 1: Photoluminescence spectra observed for erbium doped Fz-Si and Cz-Si samples. The spectra revealed non-cubic center in Fz-Si:Er and cubic center in Cz-Si:Er, respectively.

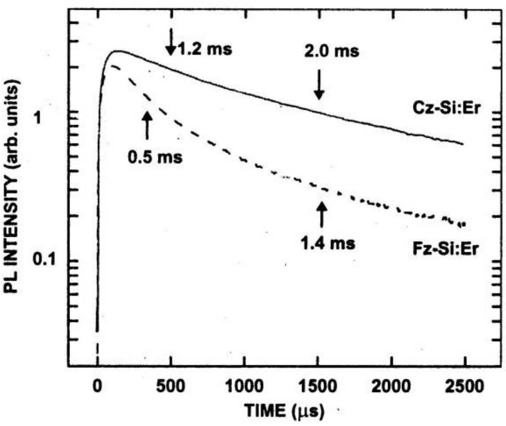

Fig. 2: Time dependence of Er PL intensity observed for erbium doped silicon samples.

2.2 Time dependence of erbium photoluminescence intensity

Fig. 2 illustrates the results of time response of erbium photoluminescence of the two samples. In the experiment, the samples were excited by a short pulse of a frequency-double Nd:YAG laser delivering a power of 800 W during 5 ns at the wavelength $\lambda = 532$ nm. The photoluminescence generated by these pulses was measured as a function of time (with sample temperatures varied over the range 10 - 80 K). The Er PL intensity first increases, achieves a maximum and then gradually decreases. The rise time of several tens microseconds and the decay time in order of millisecond were obtained.

Erbium-related photoluminescence was analysed by an excitonic model [1]. In this model the incident laser line generates free electrons and holes which will combine into free excitons. Then the excitons are quickly bound to impurity of silicon or to erbium-related traps. In the rise region Er PL was determined by the time constant τ^*, by which energy can be transferred from an impurity of the host to the 4f electrons in the inner core of the erbium ion via an Auger process. For this time constant, several groups reported large values, such as 100 μs by Przybylinska *et al.* [2], 30 μs by Shin *et al.* [3], 4 μs by Palm *et al.* [4] or very short of a few tens of nanoseconds [5] depending on the detection system time response. The rise time derived from our result for both kinds of samples is about 30 μs which is within the range of reported data in literature. Full understanding of the origin of rise time is still under debate.

Erbium luminescence is a result of decay of excited erbium ions with a time constant τ_d. As a consequence of the multi-structural behavior of erbium PL, one should therefore expect the decay time constant to depend on the defect structure. Hartung *et al.* report lifetimes of 870 and 1060 μs, respectively, for different optically active centers in their research [6], similar to a value of 1200 μs given by Taguchi *et al.* [5]. Palm *et al.* give a somewhat larger time constant of 1300 μs [4] and Priolo *et al.* [7] find lifetime in the range 800-2000 μs. The results for our samples match well with data known from the literature. Decay times between 500 and 2000 μs are derived. In the time dependence spectra of the Er PL intensity the decay curves deviate from exponential form and they are better described by two time constants for both the samples. For the sample Fz-Si:Er two decay times of 500 μs and 1400 μs are obtained. The two of Cz-Si:Er sample are 1200 μs and 2000 μs. The results indicate that Er PL predominantly originates from different types of luminescence centers; the lifetime is defect specific. Such a behavior was also in agreement with the complex structure of the luminescence spectra as shown in Fig. 1.

2.3 Influence of impurity traps on photoluminescence of erbium

In the excitonic model explaining the excitation mechanism of erbium, the formation of the intermediate state related to shallow impurities of the silicon host or erbium-related weakly bound state is considered. Both states are formed in the fabrication of silicon crystals or when erbium ions were introduced into the silicon host. Through these states excitation energy can be transferred to excite erbium ions. Influence of impurity traps on photoluminescence of erbium is observed on both Fz-Si:Er and Cz-Si:Er samples and can be described by the following.

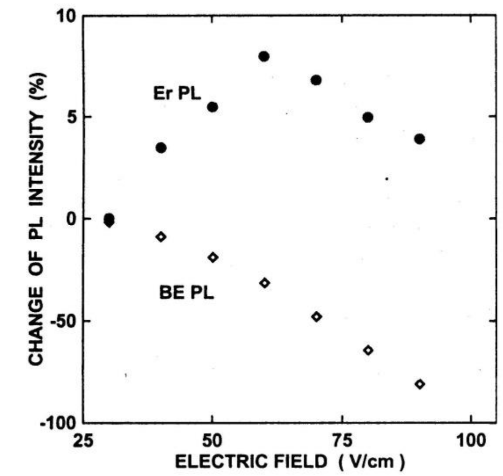

Fig. 3: Change of bound-exciton and Er PL intensities upon electric field for sample Fz-Si:Er.

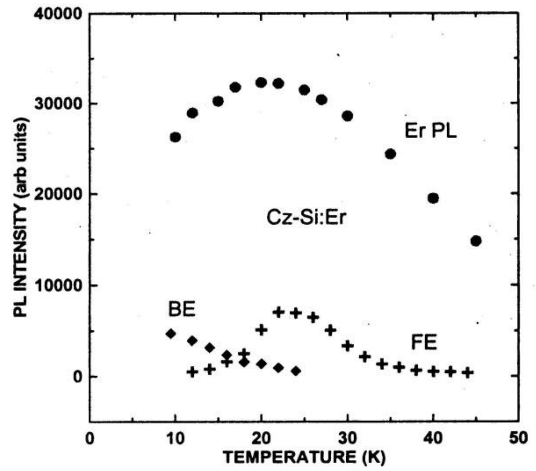

Fig. 4: Temperature dependence of PL intensities of free excitons (FE), bound-excitons (BE) and erbium; sample Cz-Si:Er.

Fig. 3 illustrates the PL intensities of erbium and phosphorus-bound exciton in Fz-Si:Er upon application of a DC electric field. As the field increases, shallow-impurity phosphorus-bound exciton in this sample is dissociated. This results in free carriers that then promote recombination via deeper erbium-related levels. As can be seen, erbium PL increases at the same value of the field for which phosphorus-bound exciton line quenches. For higher fields also the erbium photoluminescence intensity decreases. It can be concluded that the exciton binding energy is bigger for Er-related trap suggesting larger ionization energy than that for phosphorus-bound exciton trap.

Influence of impurity traps on the photoluminescence of erbium is also manifest in the temperature dependence of Er PL intensity of Cz-Si:Er sample in the temperature range from 10-50 K, as shown in Fig. 4. At low excitation level, excitons bound to shallow impurity start to decrease when temperature raised resulting in enhancement of free excitons that reaches maximum value at 25 K. The freed excitons tend to be captured by deeper excitonic traps in the band gap of silicon. In this case they are possibly erbium-related traps. Energy will be transferred to excite erbium ions into excited states $^4I_{13/2}$. As can be seen in Fig.4 Er PL intensity has an enhancement below temperature of 30 K. At higher temperatures erbium-related traps are also dissociated. As a consequence of this Er PL starts quenching with the activation energy of around 15 meV [1]. Free excitons still remain at temperature of 100 K and at high excitation level.

3. Conclusion

The defect specifics in silicon doped with rare-earth erbium have been deduced from the photoluminescence structure and the time dependence analyses of Er PL intensity. A relation between exciton-related shallow impurity of silicon host and PL intensity of erbium is observed. Through this channel energy transferred to excite erbium ions increases the PL intensity.

Acknowledgements

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