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Magneto-optical study of Er^{+3}-related center in selectively doped Si:Er

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Abstract

Photoluminescence at $\lambda = 1.54$ μm from an Er^{3+}-related center dominant in a sublimation MBE-grown multi-layer Si/Si:Er structure is investigated in magnetic fields up to 6 T. The magnetic-field-induced splitting is observed for all the main lines of the Er-related photoluminescence spectrum. For the most intense emission line, angular dependence of the splitting is measured in the (011) crystallographic plane of the sample. The effective *g*-tensor, corresponding to the difference between individual *g*-tensors of the lowest multiplets of the ground and the first excited states, is experimentally determined. In this way the symmetry of the Er-related optically active center dominant in the structure is found to be orthorhombic I (C_{2v}). From temperature dependence of the intensity of the magnetic field split components, individual *g*-tensors of the ground and the excited states are separated. No influence of the growth direction on the symmetry of Er-related center was found.

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1. Introduction

Erbium-doped silicon attracts attention because the $^4I_{13/2}$–$^4I_{15/2}$ transition of Er^{3+} occurs at the technologically important wavelength of 1.54 μm. This wavelength matches the absorption minimum of silica-based optical fibers and is thus important for telecommunication. However, understanding of several basic aspects of Er luminescence in silicon is far from being complete. In particular, until now there is only limited information regarding the microstructure of the optically active Er-related center in silicon.

Several papers have dealt with the sites of Er in Si host and the presence of oxygen in its immediate surrounding [1,2]. Channeling experiments [2] indicated that an isolated Er atom occupies a tetrahedral interstitial site, but these experiments could not distinguish between optically active and non-active Er-related centers. Electron paramagnetic resonance (EPR) which is a direct method to identify atomic structure and symmetry of point defects failed to detect optically active Er in silicon [3]. Application of EPR to RE-doped semiconductors, however, is not simple, because RE atoms are generally incorporated in several different atomic configurations.

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Direct information on microscopic structure of the Er-related emitting center would be best provided by a magneto-optical study.

2. Experimental

The sample used in this investigation was grown by sublimation MBE method as described in Refs. [4,5]. For the Zeeman experiment, we used a photoluminescence (PL) setup consisting of a cw Ar^{+}-ion laser operating at 514.5 nm for excitation and a superconducting magnet with split-coil configuration (Oxford Instruments Spectromag 4), providing magnetic fields up to 6 T. The emerging luminescence was dispersed by a high-resolution 1.5 m F/12 monochromator (Jobin Yvon THR-1500 equipped with a 600 grooves/mm grating blazed at 1.5 μm) and detected with a liquid-nitrogen cooled Ge detector (Edinburgh Instruments). The experimental configuration permitted observation of the luminescence along and perpendicular to the field direction.

3. Results and discussion

When erbium is incorporated into silicon it takes the Er^{3+} charge state with the electron configuration $4f^{11}$. The interactions within the 4f shell give rise to a $^4I_{15/2}$ ground state and a first excited state $^4I_{13/2}$. The surrounding ligands cause an additional weak splitting of the levels. In a crystal field of cubic symmetry, i.e., T_d, the ground state $^4I_{15/2}$ is split into $3 \times \Gamma_8$, Γ_7, and Γ_6 and the excited state into $2 \times \Gamma_8$, Γ_7, and $2 \times \Gamma_6$. For an Er^{3+} center with cubic symmetry, one would expect five lines (resulting from transitions from the first excited state) in the PL spectrum at a low temperature. If there is a lower symmetry distortion of the lattice, the ground and excited states will split into 8 and 7 Kramer's doublets, respectively; so in such a case each PL line would correspond to a transition between effective spin doublets and up to eight lines will appear in PL spectrum at low temperature.

A typical PL spectrum of Si:Er prepared by ion implantation is characterized by rather broad bands of several milli-electron volts. Fig. 1 compares the PL spectra of an implanted sample and the sample prepared by MBE. The implanted sample exhibits a spectrum with a multiplicity of lines centered at 1.54 μm which suggests that this sample may contain several types of Er^{3+}-related complexes. Due to the inhomogeneous character of PL bands, upon application of magnetic field, that splits individual lines into several components, the whole band becomes broader and vanishes.

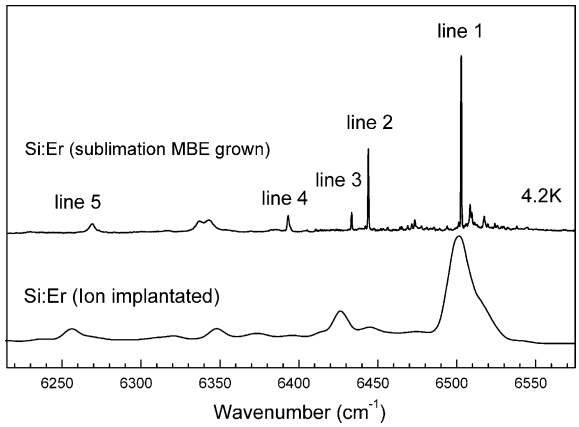

Fig. 1. PL spectra of the implanted sample and the sample prepared by MBE used in this study.

With a sample grown by the sublimation MBE technique, the Zeeman effect was observed. The main line (marked 1 in the spectrum depicted in Fig. 1) at $B = 0$ appears to split into three components for $B \| \langle 1\,0\,0 \rangle$ and seven components for $B \| \langle 0\,1\,1 \rangle$ [5,6]. The number of lines and their relative intensities indicate the C_{2v} symmetry of the center responsible for PL. The position of one of the lines in both field orientations almost does not change upon increase of the magnetic field.

Fig. 2 shows the splitting for $B \| \langle 1\,1\,1 \rangle$. Also, in this configuration the position of the middle line does not change with magnetic field. Therefore, for this line, the effective g factors of the upper and lower state must be almost equal. We note that the components with index 1 decrease in intensity with increasing magnetic field, while components with index 4 increase. As can be seen from Fig. 2, more intense lines occur at higher energies, which gives us an additional information that $|\mathbf{G}| < |\mathbf{g}|$, where $\mathbf{G}$ and $\mathbf{g}$ correspond to the spectroscopic g factors of the lowest excited and ground state multiples, respectively.

A closer inspection of Fig. 2 reveals that the splitting towards higher and lower emission energies is not

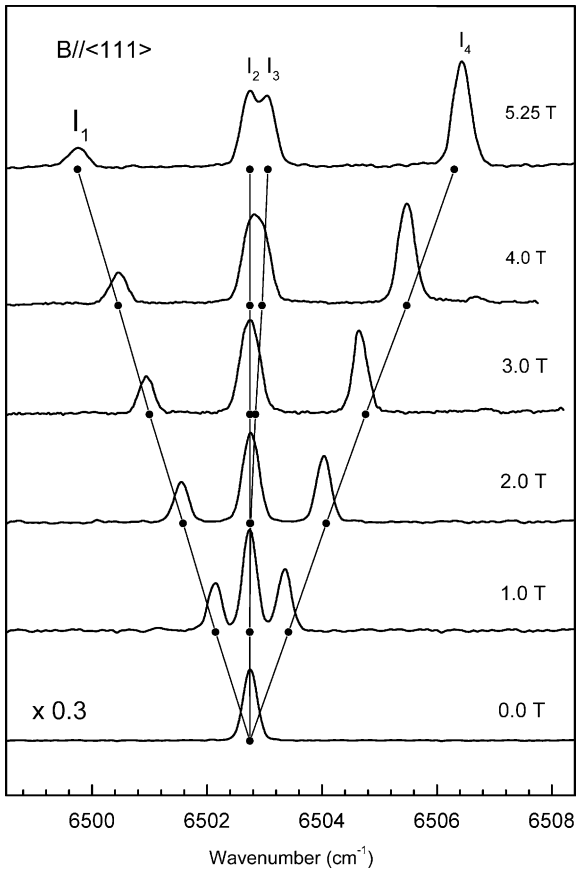

Fig. 2. Magnetic-field-induced splitting of the main PL line at $T = 4.2$ K for $B\|\langle 111\rangle$.

symmetric. This is due to the fact that at high magnetic fields the magnitude of the Zeeman splitting becomes comparable with the crystal field effect and, therefore, mixing between individual sublevels in the $J = 15/2$ and 13/2 manifolds appears.

Assuming full thermalization, the individual g-tensor of the excited state doublet **G** can be estimated from the temperature dependence of the intensity ratio of the high- and low-energy components at a high field. The intensity ratio of these components follows Boltzmann's distribution, with the activation energy equal to the splitting within the upper doublet.

The intensity ratio of two middle components I_2 and I_3 does not change with temperature, indicating $\Delta G \cong 0$ (at $B\|\langle 1\,1\,1\rangle$). Also, the intensity ratio of components related to $\Delta G_x(B\|\langle 1\,0\,0\rangle)$ ΔG_y $(B\|\langle 0\,1\,1\rangle)$ is independent of temperature (not shown). This indicates that both $|G_x|$ and $|G_y|$ are very small, so $|G_\perp|$ value for the excited state is close to zero. We have a particular situation where $|g_\perp|$ is close to zero for both ground state and excited state doublets. This provides an important clue as to why the Er^{3+}-related optically active centers in crystalline silicon were not detected by magnetic resonance [6,7].

4. Conclusions

Based on the Zeeman effect data, we have provided direct microscopic information on the structure of a prominent optically active Er-related center in silicon. The symmetry of the emitting center is identified as orthorhombic I (C_{2v}) with $g_\perp$ of both excited and ground states close to zero. We note that this symmetry type is also found recently by total energy calculation for the most stable Er-related center in crystalline silicon host [8].

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