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Spectroscopic characterization of Er-1 center in selectively doped silicon

N.Q. Vinh [a,*], M. Klik [a], B.A. Andreev [b], T. Gregorkiewicz [a]

[a] *Van der Waals–Zeeman Institute, University of Amsterdam, Valckenierstraat 65, NL-1018 XE Amsterdam, The Netherlands*
[b] *Institute for Physics of Microstructures, Russian Academy of Sciences, GSP-105, 603600 Nizhny Novgorod, Russia*

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Abstract

We report on investigation of Er-related optically excited emission from selectively doped Si/Si:Er nanolayer structures grown by sublimation MBE method. Results of high-resolution photoluminescence (PL) and magneto-optical spectroscopy are presented. We show that annealing of such samples results if a preferential formation a single type of optically active Er-related centers. This is concluded from a successful observation of the Zeeman effect of magnetic field induced splitting of the photoluminescence spectrum, labeled Er-1, associated with this center. We further show that the Er-1 spectrum is characterized by an ultra narrow bandwidth of less than 10 μeV, consistent with an assignment to a single type of centers. Consequences of this new development for future photonic applications of Si:Er are pointed out.

Keywords: Photoluminescence; Rare earths; Zeeman effect

1. Introduction

Optical doping introducing efficient radiative recombination centers is commonly used to improve optical properties of solids. In case of silicon, erbium has become the optical dopant of choice, in view of the fact that its emission wavelength of ∼1.5 μm is suitable for telecommunication applications. At the moment, Er-doped silicon and silicon oxide are at the forefront of silicon photonics. Fundamental understanding of physical processes taking place in these structures is still rather poor, in sharp contrast to impressive advances toward development of practical devices.

In the past decade, Si:Er has been intensively investigated for emission optimization [1]. The research revealed several disadvantages of this system, which could not be fully eliminated: a strong emission reduction at higher temperatures, and a high diversity and low percentage of optically active Er-related centers.

The major obstacle on the way towards efficient room temperature emission from Si:Er is posed by the so-called back-transfer (BT) process of nonradiative de-excitation. The microscopic mechanism behind the BT is that of a direct reversal of the last step of the indirect excitation process, in which the energy of the 4f-electron core is used to recreate an electron–hole pair at an Er-related level in Si bandgap. In contrast to the well understood case of InP:Yb [2], spectroscopic investigation of the BT process for Si:Er is hindered by the afore mentioned multiplicity of Er-related optical centers. Formation of many different centers with very long radiative decay time, and therefore with, at most, only partially overlapping emission spectra, will also prevent realization of stimulated emission in Si:Er.

Thermal quenching is absent for photoluminescence (PL) of Er ions embedded in a SiO_2 matrix, but this system, in turn, is characterized by a very small cross-section of (direct) excitation. In view of that, a non-homogenous dispersion of Si nanocrystals (nc-Si) in a SiO_2 matrix is recently investigated as an alternative medium for Er doping. In this case, the large bandgap of SiO_2 provides thermal stability for the Er emission, while Si nanocrystals allow efficient excitation. Following this approach, development of RT-operating

* Corresponding author. Tel.: +31-20-525-5644; fax: +31-20-525-5788.
E-mail address: nguyen@science.uva.nl (N.Q. Vinh).

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LEDs was proven to be possible. However, recent results indicate that population inversion cannot be reached in this system [3].

2. Selectively doped Si/Si:Er structures

As is evident from the preceding section, it would be beneficial if only a limited number of different types of Er centers would be present in the investigated material. Therefore, realization of preferential formation of a single type of an optically active Er-related center is decisive for the future of Si:Er as photonic material. This is not possible in standard Si:Er materials prepared by ion implantation, where a large variety of Er-related optically active centers are simultaneously generated [4]. The situation is different in MBE grown multilayer structures of alternating Si and Si:Er layers [5], where both conditions necessary for realization of efficient PL, i.e., high Er^{3+} ions concentration and efficient exciton generation, can be met simultaneously. This is achieved in a sandwich structure of interchanged Si/Si:Er nanolayers. Upon illumination with a laser beam, excitons generated in undoped Si spacer regions diffuse into doped layers and provide excitation of Er^{3+} ions.

Fig. 1 compares the 1.5 μm Er-related emission band from a multilayer structure (trace B) with that observed in a "standard" sample prepared by ion implantation (trace A). The measurements were taken at 4.2 K under 514 nm excitation with an Ar^{+} laser. The sample used in the experiment has been grown by sublimation MBE and consists of 400 Si:Er layers of 2.7 nm thickness separated by 1.7 nm spacers of undoped Si. Er concentration in the layers was [Er] = $5 \times 10^{18}\,cm^{-3}$. The structure is schematically depicted in the inset to Fig. 1. Detailed investigations reveal that the intensity of the Er-related PL from the multilayer sample is at least by an order of magnitude higher than from a single Si:Er layer with the volume equal to that of all the Si:Er nanolayers of the multistructure [6]. Since the decay time remains in the millisecond range, this result indicates a considerably higher percentage of optically active Er ions. The PL spectrum of the sublimation MBE grown sample shows multiple sharp features superimposed on a relatively broad band. The advantageous optical properties of the multilayer structure are evident.

Annealing considerably alters PL characteristics of the multilayer structure (see trace C in Fig. 1). While the total intensity of emission changes only slightly, the spectrum undergoes an important transformation: the broad band disappears and a small number of sharp and intense lines (the Er-1 PL spectrum) remain. Fig. 2 shows a high-resolution scan of the main feature of the Er-1 spectrum. As can be seen, the real width of this PL band is measured to be $\Delta E \leq 10\,\mu eV$. To our best knowledge, this is the smallest bandwidth ever measured for any emission band in a semiconductor matrix.

The ultra narrow width of the Er-1 spectrum suggests that it originates from a single kind of Er-related optically active center. This issue has been further investigated in magneto-optical studies. The inset to Fig. 2 illustrates a successful observation of the Zeeman effect for the main spectral feature of the Er-1 spectrum. Detailed analysis of the magnetic field induced splitting [7] indeed confirmed that the Er-1 PL emission is related to a particular type of Er center dominant in the studied structure, and established its microscopic symmetry as orthorhombic-I. Also, the g-tensor of the ground state has been determined.

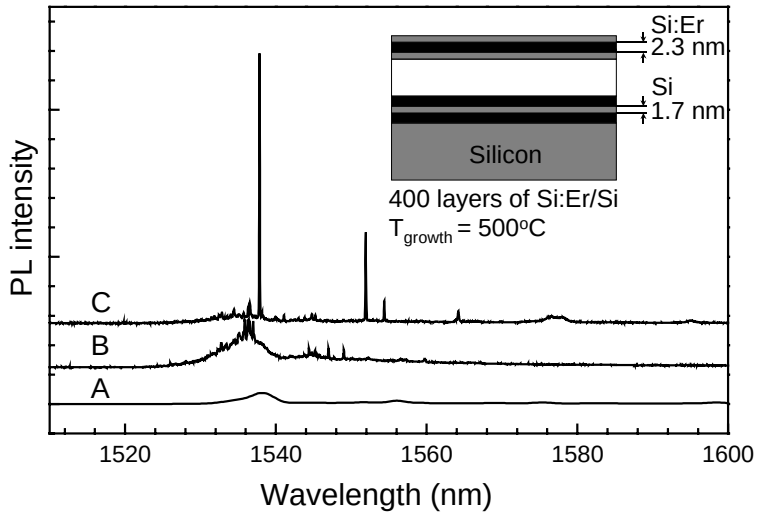

Fig. 1. PL spectra of Si:Er prepared by ion implantation (A), sublimation MBE as grown (B) and following a short annealing (C). All the spectra have been recorded at LHe temperature under Ar^{+}-ion laser excitation. In the inset, the multilayer structure of the sublimation MBE grown sample is schematically illustrated.

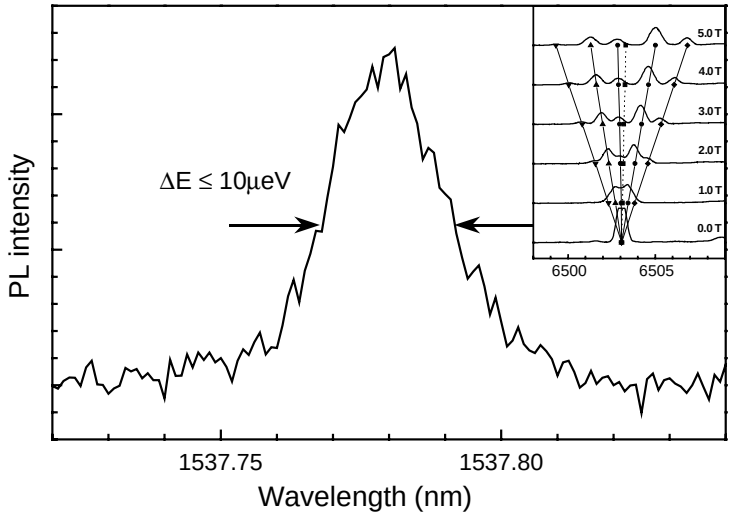

Fig. 2. High-resolution scan of the most intense line of the Er-1 spectrum observed in the multilayer Si/Si:Er structure grown by sublimation MBE. In the inset, the Zeeman effect observed for this particular line in magnetic fields up to 6 T is illustrated for B‖⟨0 1 1⟩.

3. Conclusions

The possibility of preferential generation of a single type of optically active Er-related center, which is realized by an appropriate annealing of the sublimation MBE grown Si:Er/Si multinanolayer structure, is a major step forward toward Si photonics based on Er doping. In particular, it will enable spectroscopy of the BT effect of nonradiative recombination of excited Er^{3+} ions. Thorough understanding and control over physical mechanisms governing BT will possibly allow to eliminate this deleterious effect, thus paving the way to versatile room temperature photonics based on Si:Er. On the other hand, availability of a single type of Er-related optical center opens new hopes for realization of stimulated emission in Si:Er.

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