Optical properties of Er-doped Si-based media

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Summary

This thesis entitled "Optical properties of Er-doped Si-based media" describes research performed on silicon (Si) based materials doped with erbium (Er). In particular optical properties of these media have been investigated in detail, using a wide range of optical techniques both in situ, at the laboratory in the Van der Waals-Zeeman Institute in Amsterdam and at the free electron laser facility (FELIX) in Rijnhuizen.

The thesis begins by introducing briefly basic concepts on microelectronics, its capital importance in modern society and the limitations that the discipline is facing both from a basic physics and a technological point of view.

Further on, in the same introductive chapter, different ways of overcoming the major drawbacks are presented and shortly discussed. Firstly, the issue of optical doping of silicon with Er\textsuperscript{3+} ions is addressed. Because of the inefficiency of Er light emission in bulk silicon, two distinct ways of structural manipulation of the system are considered: fabrication of stacked Er-doped and undoped nanolayers of silicon and creation of Si nanocrystals in Si dioxide matrix. In the first case, efficiency of luminescence is enhanced with respect to a layer of silicon because of the spatial separation of the created excitons and their subsequent excitation of Er\textsuperscript{3+} ions. Moreover, those systems have been shown to have peculiar optical properties such as the narrowest emission spectra ever recorded from Er-doped materials. The Er and Si nanocrystals codoped SiO\textsubscript{2} couples in the same system the possibility of using the high excitation cross section of Si with the thermal stability of emission of Er that is placed in the insulating matrix rather than in the semiconductor host.

The first chapter is divided in two parts: the first one concerns the samples and the second one the experimental techniques used in the research that is subject of this thesis.

All the samples, namely the two different kinds of nanolayers, Si/Si:Er and Si/Si\textsubscript{1-x}Ge\textsubscript{x}, the Er and Si nanocrystals codoped SiO\textsubscript{2} and Er-doped amorphous Si are presented, both concerning fabrication procedure and parameters, and structural characterization.

The second section describes the experimental techniques employed for the
realization of the measurements on the above mentioned samples.

Subject of Chapt. 2 is the issue of optical activity of Er$^{3+}$ ions in Si/Si:Er and Si/Si$_{1-x}$Ge$_x$. Optical activity is defined as the ability of the centers to luminesce once being excited. For all the investigated nanolayers, a percentage of optically active Er$^{3+}$ in respect to the total amount is determined. In order to establish this, the nanolayers have to be compared with a sample whose optical activity is known; in our case this role is taken by an optimized Er-doped SiO$_2$ sample. After few corrections, concerning differences in characteristics of the compared samples, a value for the optical activity of the nanolayers is obtained. Optical activity in all samples is of the order of a few percent, with a maximum of 10% in the best one. This value is high when compared to the ones reported in literature, but still low in order to attain optical amplification in such structures.

Chapt. 3 is closely related to the previous one, since a direct link between the optical activity of the Er$^{3+}$ ions and the presence of oxygen in their surrounding is established. In order to prove that, two different experiments have been performed, both employing a free electron laser at the FELIX facility in Rijnhuizen.

The first one, a two-color experiment, makes use of two laser beams: an Nd:YAG emitting at 532 nm, that induce band-to-band excitation of the Si matrix and eventually of the Er$^{3+}$ ions, and an IR beam tuned to the energy of the vibrational modes of the Si-O-Si “molecule”. The Nd:YAG laser brings the Er$^{3+}$ ions to the excited state, after which the IR laser is fired with an adjustable delay respect to the first beam.

Due to the the fact that emission spectrum of Er$^{3+}$ ions in Si/Si:Er presents few and very narrow lines, it is possible to reconstruct a detailed scheme of the ground and first excited state of the intra-4f shell Er$^{3+}$ ions. In particular, transitions within the ground state $^4I_{15/2}$ lay in the THz range. Chapt. 4 is devoted to probe possible transitions in such a range. In fact, presence of THz transitions is tested by using two distinct pump-probe techniques, in a transient-grating and in a pump-probe-reference configuration. In both cases, a transition is detected at the wavelength of 43 µm, with a decay time of the order of 50 ps. This short decay time is a fingerprint of a non-radiative phonon-assisted decay channel, since theoretical calculations for the radiative transition give a decay time of the order of seconds. The value of radiative rate is much too small in comparison to the non-radiative ones, for the radiative processes to take place.

The last two chapters describe different systems than Si nanolayers, previously discussed. In particular, Chapt. 5 focuses on the optical activity of a series of samples composed of SiO$_2$ co-doped with Er$^{3+}$ ions and Si nanocrys-
tals. To fabricate the samples, two Er and three Si contents, and three distinct annealing temperature have been used, with a total of 18 different samples produced. Optical activity of Er$^{3+}$ ions excited via nanocrystals is of the order of a few percent with a maximum of 8%. In case of direct excitation of Er$^{3+}$, the optical activity spans a much wider range, from a maximum of 51% to a practically negligible value.

Chapt. 6 is concerned with optical characterization of hydrogenated amorphous silicon doped with erbium. The material shows peculiar and unexplained properties. In fact, intrinsic luminescence of the a-Si, as well as Er-related PL, can be found for different excitation flux regimes. At low excitation flux only Er-related PL is detected, but when excitation reaches a threshold value a broad and intense luminescence appears. This luminescence, due to recombination from various transitions in the amorphous matrix, especially defects, depends exponentially on the excitation flux. This exponential increase of the PL is related to creation of defects (dangling bonds) that grow exponentially as function of temperature, while the temperature of the sample grows linearly with the excitation flux.