Photoluminescence spectroscopy on erbium-doped and porous silicon
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Chapter 3

Photoluminescence of erbium-doped silicon: excitation power dependence

Abstract
Photoluminescence measurements have been performed on float-zoned and Czochralski-grown silicon samples which were doped with erbium by ion implantation with and without oxygen co-implantation. An erbium-doped sample grown by a molecular beam epitaxy method and an amorphous silicon sample were included in the experiments as well. The characteristic luminescence spectra in the wavelength range between 1.5 and 1.6 μm were observed. Differences in the multiple line structure of the spectra indicated that the active luminescent centers have different symmetries and atomic structures. The dependence of the luminescence intensity on the laser excitation power was measured. Experimental observations are analyzed on the basis of a physical model which includes the formation of free excitons, the binding of excitons to erbium ions, the excitation of 4f-inner-shell electrons of erbium ions and their subsequent decay by light emission. To obtain a quantitative agreement between model analysis and experimental data the consideration of Auger processes by which erbium-bound excitons and erbium ions in excited state can decay by dissipating...
energy to conduction band electrons appears to be required. The luminescent properties of the erbium-doped samples of the different types of crystalline silicon are remarkably similar. A good quantitative agreement can be obtained for suitable values of the model parameters.

3.1 Introduction

In recent years a great research activity has been devoted to rare-earth impurities in silicon and semiconductor compounds with the objective of investigating basic physical properties and developing related electro-optical applications [1]. Erbium-doped silicon is intensively investigated since the luminescence of erbium occurs in the wavelength region of minimum loss and dispersion of glass fibers.

The characteristic luminescence of erbium is due to electronic transitions within the $4f$ shell between states of which energy differences are primarily determined by spin-orbit coupling. For an isolated erbium ion electric dipole transitions between such states are not allowed. In a silicon crystal the transitions become possible if due to the presence of a ligand field the local symmetry is lowered and states of opposite parity become mixed. It has been found that erbium ions can be incorporated in silicon on sites of different symmetries [2, 3, 4] and have a strong propensity to form complexes with other impurities [5]. This gives rise to structurally different erbium-related centers which are characterized by individual luminescence spectra [6]. For the formation of complexes the presence of oxygen appears to be especially important [7, 8, 9]. It has been reported that the photoluminescence intensity of Er- and Er,O-doped Czochralski silicon (Cz-Si) is always higher than that observed in float-zoned silicon (Fz-Si) [10, 11]. The particular role of oxygen as a co-dopant in the enhancement of erbium-related photoluminescence is, however, not established in sufficient detail. In an extended X-ray absorption fine structure (EXAFS) study, Adler et al. [12] found that the first neighbor shell of the erbium ion in Cz-Si comprises four to six oxygen atoms which are responsible for the optical activity of the complex. In Fz-Si an erbium ion is surrounded by twelve silicon atoms yielding an optically inactive complex. Based on these findings they concluded that the higher intensity in
Cz-Si is due to the formation of erbium-oxygen complexes. Przybylińska et al. [13, 14] identified more than 100 distinct lines in photoluminescence spectra of erbium-implanted silicon and ascribed them to different types of erbium centers: isolated erbium ions at cubic and non-cubic symmetry sites, erbium-oxygen complexes and centers related to clusters of erbium with residual radiation defects. All these results underline the relevance of oxygen in the formation of optically active erbium centers and the enhancement of the photoluminescence yield.

Valuable information on the excitation and de-excitation mechanisms can be deduced from the dependence of the photoluminescence intensity on the excitation power and the temperature. A comprehensive theoretical treatment of the energy transfer in the Er-in-Si system, also accounting for temperature effects, was developed by Bresler et al. [15]. Recently, Palm et al. [16] proposed a set of rate equations to describe the photoluminescence of erbium in silicon and pointed out the importance of nonradiative energy transfer processes involving conduction band electrons.

In this chapter photoluminescence measurements on both float-zoned, oxygen lean, and Czochralski-grown, oxygen rich, silicon samples doped with erbium are presented. The same experiments were performed on a sample grown by a molecular beam epitaxy method as well. Some contrasting results obtained on an amorphous sample are also reported. By the multiple component structure in the spectra the existence of erbium-related centers of different symmetry, cubic and non-cubic, is confirmed. The laser power dependence was measured and is described by an excitation mechanism involving free and bound exciton intermediate states. Results are analyzed on the basis of a physical model with the aim of verifying the quantitative agreement.

### 3.2 Experiment

In the experiments the following five kinds of materials were used.

1. Float-zoned, n-type phosphorus-doped, <100>-oriented silicon wafers, labeled Fz-Si:Er. The room-temperature resistivity of this material was 0.7—0.9 Ωcm. The samples were implanted with erbium ions at an energy of 1.1 MeV to total doses in the range of $1 \times 10^{12}$ to $5 \times 10^{15}$ cm$^{-2}$. 


Implantations were performed at 500°C. No additional heat treatment has been applied [17].

2. A p-type Czochralski-grown silicon sample with oxygen concentration of $2 \times 10^{18}$ cm$^{-3}$. The sample was implanted with erbium ions at an energy of 320 keV, to an erbium peak concentration of $5 \times 10^{17}$ cm$^{-3}$. The sample is designated as Cz-Si:Er.

3. Other p-type Cz-Si material with room-temperature resistivity of 1 to 10 Ω cm. Wafers were implanted with erbium ions, at an energy of 1.2 MeV, to a dose of $10^{13}$ cm$^{-2}$, and co-implanted with oxygen ions of energy 0.17 MeV to a dose of $10^{14}$ cm$^{-2}$. Such samples are labeled as Cz-Si:Er,O. To optimize the luminescence output the samples were subsequently annealed for 0.5 hour at the temperature of 900°C in a chlorine-containing atmosphere [18, 19].

4. An erbium-doped crystalline silicon layer of about 2 μm thickness grown by a molecular beam epitaxy (MBE) method. This sample is labeled as MBE-Si:Er. The growth process was performed in a vacuum of $2 \times 10^{-7}$ mbar at temperature 600°C. The sample was subsequently annealed in a vacuum chamber at 700°C for 30 minutes. It exhibited n-type conductivity with erbium concentration of $5 \times 10^{18}$ cm$^{-3}$, as characterized by secondary ion mass spectroscopy (SIMS) [20].

5. An amorphous silicon sample designated as a-Si:Er. This sample was prepared by magnetron-assisted silane decomposition technique, whereby mixtures of Ar, SiH$_4$ and H$_2$ are used as sputtering gas. The silicon targets were partially covered by small metallic platelets of erbium. A film of 1 μm was deposited on a fused silica substrate. The erbium concentration measured by Rutherford back scattering was $1 \times 10^{20}$ cm$^{-3}$ [21].

The photoluminescence was excited by the 514.5 nm line of an Ar$^+$-ion laser (Spectra-Physics Stabilite 2016-05s). The laser power could be varied from 0.1 to 1000 mW. This corresponded to an excitation power in the spot of about 1 mm diameter measured in front of the sample in the range from 1 μW to 10 mW. The emitted light was dispersed by a high-resolution 1.5 m F/12 grating monochromator (Jobin-Yvon THR 1500) and detected by a liquid-nitrogen cooled North-Coast EO-817 germanium detector. Variation of the photoluminescence yield as a function of excitation power was measured with the sample immersed in
Figure 3.1: Photoluminescence spectra measured at 4.2 K for (a) sample of Cz-Si:Er,O, (b) sample of MBE-Si:Er, (c) sample of Fz-Si:Er and (d) sample of a-Si:Er. The arrows [c] indicate the spectral components due to emission of the cubic center, mainly present in the Czochralski-grown samples; the arrows [o] relate to the erbium-oxygen complexes which are enhanced in MBE-silicon samples, the arrows [nc] label the structural components belonging to a center of lower symmetry prevailing in the float-zoned samples. In the amorphous silicon samples the erbium-related PL line is designated by the arrow [a-Er].
liquid helium, at 4.2 K.

3.3 Experimental results

In Fig. 3.1 the erbium-related photoluminescence (PL) spectra measured for the Cz-Si:Er, O (a), MBE-Si:Er (b), Fz-Si:Er (c) and a-Si:Er (d) samples at the temperature of 4.2 K are shown. The data were obtained with laser power set to 100 mW, corresponding to power incident on the sample of about 1 mW. For the float-zoned material the spectrum was taken for a sample implanted to a dose of $1 \times 10^{13} \text{cm}^{-2}$. This particular sample was chosen for the more detailed studies as reported here following an investigation of the PL intensity dependence on erbium-implantation dose, as presented in Fig. 3.2. In these preceding measurements, it was observed that the PL intensity increases with implantation dose from $10^{12}$ to $10^{13} \text{cm}^{-2}$, corresponding to erbium peak concentrations of approximately $4 \times 10^{16} \text{cm}^{-3}$ and $4 \times 10^{17} \text{cm}^{-3}$, respectively, as revealed by Rutherford back-scattering (RBS) and secondary ion mass spectroscopy [17, 22]. For higher doses the PL intensity stabilized and then decreased.

Previous studies of the erbium-related photoluminescence revealed that the spectrum measured at liquid-helium temperature consists of a high-intensity peak around the wavelength $\lambda = 1.54 \mu\text{m}$, possibly having some nearly coincident components, and several lines with smaller intensity on the lower energy side of the main feature [2, 6, 7, 8, 9]. In oxygen-lean material usually a weaker photoluminescence spectrum than in Czochralski material is observed. From high-resolution PL studies on a wide range of erbium-implanted silicon samples Jantsch et al. [9] and Przybilińska et al. [14] reported that two high-intensity lines with the wavenumbers $\sigma = 6507.5 \text{cm}^{-1} (\lambda = 1536.7 \text{nm})$ and $\sigma = 6508.5 \text{cm}^{-1} (\lambda = 1536.5 \text{nm})$ were observed in Cz-Si but not in Fz-Si, while other non-cubic centers could be detected in both materials. They suggested to ascribe these emissions to erbium-oxygen complexes. In Fig. 3.1(a) the four PL lines at wavelengths $\lambda = 1538 \text{nm} (\text{wavenumber} \sigma = 6502 \text{cm}^{-1})$, 1556 nm (6427 cm$^{-1}$), 1575 nm (6349 cm$^{-1}$), 1598 nm (6257 cm$^{-1}$), respectively, marked by arrows [c], which are commonly assigned to an erbium-related center of cubic symmetry, are more prominently present in implanted Cz-Si samples. For the MBE-Si:Er sample, Fig. 3.1(b),
Figure 3.2: Integrated photoluminescence intensity versus implantation dose measured for the float-zoned silicon sample doped with erbium by ion implantation, Fz-Si:Er. Temperature $T = 4.2 \text{ K}$.

The PL spectrum consists of six main lines at wavelengths $\lambda = 1536.5 \text{ nm} \ (\sigma = 6508.5 \text{ cm}^{-1})$, $1545 \text{ nm} \ (6472.5 \text{ cm}^{-1})$, $1567 \text{ nm} \ (6382 \text{ cm}^{-1})$, $1583.5 \text{ nm} \ (6315 \text{ cm}^{-1})$, $1605 \text{ nm} \ (6230 \text{ cm}^{-1})$ and $1620 \text{ nm} \ (6173 \text{ cm}^{-1})$. These PL lines are assigned to erbium-oxygen complexes and are marked by arrows [o]. In the case of Fz-Si:Er, the set of eight lines marked by arrows [nc] is most probably related to erbium luminescent centers of lower symmetry, Fig. 3.1(c). These lines are located at wavelengths $\lambda = 1539.5 \text{ nm} \ (6495.5 \text{ cm}^{-1})$, $1548 \text{ nm} \ (6460 \text{ cm}^{-1})$, $1550 \text{ nm} \ (6451 \text{ cm}^{-1})$, $1559 \text{ nm} \ (6415 \text{ cm}^{-1})$, $1576.2 \text{ nm} \ (6344.3 \text{ cm}^{-1})$, $1586 \text{ nm} \ (6305 \text{ cm}^{-1})$, $1595.3 \text{ nm} \ (6268.4 \text{ cm}^{-1})$ and $1614.2 \text{ nm} \ (6195 \text{ cm}^{-1})$. At last, in Fig. 3.1(d) the prominent photoluminescence emission for a-Si:Er at $\lambda = 1539 \text{ nm} \ (\sigma = 6498 \text{ cm}^{-1})$ is close to the first PL line of the Fz-Si. This erbium-related emission in amorphous silicon material is designated by the [a-Er] arrow.

Following the generally adopted interpretation, we can conclude that in the materials used in the present experiments spectra originating from cubic, non-cubic centers and a center related to oxygen-erbium complexes were observed. For the Cz-Si:Er,O sample the emission at 1538 nm of
the cubic center dominates the spectrum. For the MBE-Si:Er sample emissions from lower-symmetry oxygen-erbium complexes are enhanced in the photoluminescence spectrum. In the spectra obtained for the Fz-Si and the amorphous materials the non-cubic centers seem to prevail.

The excitation power dependence of the photoluminescence intensity was measured for all five kinds of samples. Results are presented in Figs 3.3(a) to 3.3(e) for a sample temperature of 4.2 K obtained by immersing samples in liquid helium. Power dependencies are plotted in terms of normalized luminescence intensity $I$ as a function of normalized excitation power $P$, as will be discussed in the next section. Results were fitted by the formula

$$I(P) = \frac{P}{1 + \beta \sqrt{P} + P}, \quad (3.1)$$

where $\beta$ is an adjustable parameter representing the physical elements of the luminescence process. The solid curves in Fig. 3.3(a) for Fz-Si:Er, Fig. 3.3(b) for Cz-Si:Er, Fig. 3.3(c) for Cz-Si:Er,O, Fig. 3.3(d) for MBE-Si:Er and Fig. 3.3(e) for a-Si:Er correspond to the computer fits by above expression with $\beta = 2.63, 2.73, 2.25, 3.3$ and $-0.25$, respectively. In these five cases a normalized power $P = 1$ corresponds to laser set powers of 36, 14, 3, 155 and 420 mW, respectively. For the Cz-Si doped with both erbium and oxygen by implantation the saturation level is approached most closely for lower excitation power; the MBE silicon sample needs more excitation power and the amorphous silicon sample is most difficult to saturate. In all cases the saturation level is substantially reduced for higher temperatures, but no systematic quantitative observations were made for this effect.

3.4 Discussion

3.4.1 Mechanism of the photoluminescence

To understand the dependence of the erbium-related photoluminescence on excitation power, as well as on temperature, the overall process of energy transfer in the erbium-doped silicon crystal must be considered
Figure 3.3: Photoluminescence intensity, measured at 4.2 K, in normalized units \( I \), as a function of excitation power, both in units mW of laser power and in normalized units \( P \) for (a) Fz-Si:Er, (b) Cz-Si:Er, (c) Cz-Si:Er,O, (d) MBE-Si:Er and (e) a-Si:Er. Experimental data points (*) and theoretical curves according to formula 3.1 with fitting parameters \( \beta = 2.63, 2.73, 2.25, 3.3 \text{ and } -0.25 \), respectively.
in detail. In the currently commonly accepted physical model this is the multi-step process schematically illustrated in Fig. 3.4. The participating species are free electrons and holes with concentration \( n \), free excitons with concentration \( n_x \), erbium-bound excitons with concentration \( n_{xb} \) and erbium ions in an excited state with concentration \( n_{Er}^* \). The forward process of energy transfer leading to photoluminescence starts with the generation of free electrons and holes, to equal concentrations, at the rate \( G \) by the incident laser light. These free carriers can combine into free excitons following a second-order process with the rate \( \gamma_x n^2 \). Trapping of the free excitons at free erbium sites will be proportional to both the concentration of the free excitons and the concentration of available free erbium sites. This latter concentration is written as the total erbium concentration \( n_{Er} \), multiplied by the fraction of free sites \( [(n_{Er} - n_{xb})/n_{Er}] \). Erbium-bound excitons can transfer their energies in an impurity Auger process to the \( 4f \) electrons in the inner core of the erbium ion with a transfer time \( \tau^* \). At the same time a hot carrier accepting the excess energy \( E_A \) is formed. This process can only happen for erbium ions still in their ground state, i.e., to the fraction \( [(n_{Er} - n_{Er}^*)/n_{Er}] \). At high excitation power the fractions given between the square brackets tend to zero and counteract further energy transfer. The exhaustion of the available erbium centers results in saturation of the luminescence output. In the last step, the luminescence follows from decay of excited erbium ions \( n_{Er}^* \) with the time constant \( \tau_d \). The photoluminescence as measured in the experiments is proportional to the decay rate \( n_{Er}^*/\tau_d \). This decay, from an erbium \( ^4I_{13/2} \) excited to the \( ^4I_{15/2} \) ground state, is an internal atomic transition and is expected to have a temperature-independent time constant.

Reverse processes are indicated in Fig. 3.4 by the arrows pointing in the left direction. They include the dissociation of free excitons into free electrons and holes, \( fn_x \), the release of excitons from their erbium trapping sites, \( cf_{xb}n_{xb}N_x \), and a back-transfer process in which an erbium-bound exciton is recreated starting from an excited erbium ion, \( n_{Er}^* f_1/\tau^* \). In those reverse processes the energy increases and they are therefore thermally activated by energies characteristic for the distinct processes, which are in the 10 to 100 meV range. Reverse processes are suppressed at the lowest temperatures. They reduce the luminescence output, although
Excitation power dependence of photoluminescence intensity

Figure 3.4: Two-stream model for the photo-excitation of erbium luminescence showing generation and loss of free electrons $n$, free excitons $n_x$, erbium-bound excitons $n_{xb}$ and erbium ions in excited state $n_{Er}^*$. Notation $\eta_1 = (n_{Er} - n_{xb})/n_{Er}$, $\eta_2 = (n_{Er} - n_{Er}^*)/n_{Er}$.

they do not remove energy from the luminescence path. The coefficients of forward and reverse processes, as indicated in Fig. 3.4, are linked by considerations of detailed balancing.

In addition to the energy transfer in the chain leading to luminescence, the full analysis of the luminescence mechanism must also include processes which act in competition, and remove energy irreversibly from the proper path. Processes in this category are indicated in Fig. 3.4 by the arrows pointing downwards. They include the loss of free electrons and holes via recombination centers other than the optically active erbium centers, with the rate $\gamma n^2$, e.g., due to deep levels existing as the
result of implantation damage and deciding on the lifetime of the carriers. The direct recombination of free excitons or via alternative centers, with the rate \( n_x/\tau_x \), also leads to loss of excitation energy. In Fig. 3.4 also two Auger processes which will irreversibly remove energy from the luminescence path are indicated. In the first one erbium-bound excitons dissipate their energy in an Auger process with the involvement of a free electron in a conduction band state. In the other process, erbium ions in the excited state loose their energy by imparting it to a free electron. Both processes are thus assumed to be proportional to the free-electron concentration and proceed with rate constants \( c_{Ax} \) and \( c_{AEr} \) as indicated in Fig. 3.4.

In a recent paper a model as discussed above, but not including the two Auger processes, has been put on a mathematical basis by Bresler and co-workers [15]. In a steady state the concentrations are described by balance equations: Eq. 3.2 for free electrons, Eq. 3.3 for free excitons, Eq. 3.4 for bound excitons and Eq. 3.5 for excited erbium ions. Following the model of Bresler et al. these are

\[
G + f n_x = \gamma n^2 + \gamma_x n_x^2, \tag{3.2}
\]

\[
\gamma_x n_x^2 + c f_{xb} n_{xb} N_x = c n_x n_{Er} \frac{n_{Er} - n_{xb}}{n_{Er}} + f n_x + \frac{n_x}{\tau_x}, \tag{3.3}
\]

\[
c n_x n_{Er} \frac{n_{Er} - n_{xb}}{n_{Er}} + n_{Er}^* f_1 \frac{1}{\tau^*} = n_{xb} n_{Er} \frac{n_{Er} - n_{Er}^*}{n_{Er}} \frac{1}{\tau^*} + c f_{xb} n_{xb} N_x \tag{3.4}
\]

and

\[
n_{xb} n_{Er} \frac{n_{Er} - n_{Er}^*}{n_{Er}} \frac{1}{\tau^*} = n_{Er}^* \frac{1}{\tau_d} + n_{Er}^* f_1 \frac{1}{\tau^*}. \tag{3.5}
\]

Generation terms are given on the left hand sides of these equations; loss terms appear in each case on the right hand sides. Relations between the coefficients of forward and reverse processes are, as mentioned, based on detailed balancing of the separate steps. Such considerations lead to
Excitation power dependence of photoluminescence intensity

\[ f = \gamma_x \frac{N_c N_v}{N_x} e^{-E_x/kT}, \]  

(3.6)

\[ f_{xb} = e^{-E_{xb}/kT} \frac{N_x e^{-E_{xb}/kT}}{N_x e^{-E_{xb}/kT} + n_{Er}} \]  

(3.7)

and

\[ f_1 = e^{-E_A/kT}. \]  

(3.8)

Characteristic energies involved in these process steps appear in the equations by \( E_x \), the binding energy of electron and hole in an exciton, \( E_{xb} \), the energy of binding of an exciton to a neutral erbium center and \( E_A \), the energy dissipated in the creation of an excited erbium ion from the bound exciton situation. Densities of states in conduction, valence and exciton bands are found from the standard relations

\[ N_c = 2 \left( \frac{2\pi m_e kT}{\hbar^2} \right)^{3/2}, \]  

(3.9)

\[ N_v = 2 \left( \frac{2\pi m_h kT}{\hbar^2} \right)^{3/2}, \]  

(3.10)

\[ N_x = 2 \left( \frac{2\pi m_x kT}{\hbar^2} \right)^{3/2}, \]  

(3.11)

with the relevant effective masses. An exact solution of the balance equations, in the form of a quadratic equation for \( n_{Er}^*/n_{Er} \), is presented by Bresler et al. [15]

### 3.4.2 Energy transfer without Auger processes

Measurements of the power dependence of the luminescence intensity as reported in this chapter were performed at liquid-helium temperature,
4.2 K. At this low temperature the balance equations are reduced to more simple forms since the reverse processes, all requiring thermal activation, are suppressed. Expressed in mathematical form this means \( f = f_{xb} = f_1 = 0 \).

For the balance equations valid at low temperature one obtains

\[
G = \gamma n^2 + \gamma_x n^2, \quad (3.12)
\]

\[
\gamma_x n^2 = c n_x n_{Er} \frac{n_{Er} - n_{xb}}{n_{Er}} + \frac{n_x}{\tau_x}, \quad (3.13)
\]

\[
c n_x n_{Er} \frac{n_{Er} - n_{xb}}{n_{Er}} = n_{xb} \frac{n_{Er} - n^*_{Er}}{n_{Er}} \frac{1}{\tau^*} \quad (3.14)
\]

and

\[
n_{xb} \frac{n_{Er} - n^*_{Er}}{n_{Er}} \frac{1}{\tau^*} = \frac{n^*_{Er}}{\tau_d}. \quad (3.15)
\]

The concentration of excited erbium ions \( n^*_{Er} \) is found as the solution of

\[
a_0 \left(\frac{n^*_{Er}}{n_{Er}}\right)^2 - (b_0 + b_2 G)\left(\frac{n^*_{Er}}{n_{Er}}\right) + c_2 G = 0 \quad (3.16)
\]

with the coefficients

\[
a_0 = 1 + c n_{Er} \tau_x (1 + \frac{\tau^*}{\tau_d}), \quad (3.17)
\]

\[
b_0 = 1 + c n_{Er} \tau_x, \quad (3.18)
\]

\[
b_2 = \gamma_x \tau_x c \tau_d (1 + \frac{\tau^*}{\tau_d}) \frac{1}{\gamma_x + \gamma} \quad (3.19)
\]
Excitation power dependence of photoluminescence intensity

and

\[ c_2 = \gamma_x T_x C_T d \frac{1}{\gamma_x + \gamma}. \]  (3.20)

In its general form, the equation 3.16 predicts saturation of \( n_{Er}^*/n_{Er} \) for high excitation power \( G \) at the level \( n_{Er}^*/n_{Er} = c_2/b_2 \). For low power a linear relationship \( n_{Er}^*/n_{Er} = (c_2/b_0)G \) is expected. When comparing predictions of the model equations with experimental data one must be aware that neither generation power nor the luminescence output are easily known in absolute numbers to good accuracy. For instance, the doping of the sample may be spatially non-uniform and the volume in which excitation takes place is not well defined. The fraction of optically active erbium centers may be much less than one, which is still a matter of investigation. Such uncertain factors are likely to change from sample to sample. For such reasons it is of advantage to eliminate these factors by resorting to relative units. As regards the luminescence intensity the most natural unit at hand for normalization is the saturation value \( c_2/b_2 \). A dimensionless normalized intensity is therefore introduced as \( I \equiv (n_{Er}^*/n_{Er})/(c_2/b_2) \). For the excitation power a unit \( G_1 \) is obtained as the value at which the extrapolated linear increase at low power crosses the saturation level. This will be for \( G_1 = b_0/b_2 \). Also the normalized power \( P \equiv G/G_1 \) is a dimensionless quantity. In terms of normalized units Eq. 3.16 acquires the simple form

\[ I^2 - \alpha(1 + P)I + \alpha P = 0, \]  (3.21)

with

\[ \alpha \equiv \frac{b_0b_2}{a_0c_2}. \]  (3.22)

It thus appears that the dependence of the intensity \( I \) on the generation power \( P \) is governed by one parameter \( \alpha \), through which all aspects of the luminescence process are represented. However, from Eq. 3.21 it is easily concluded that for low power \( I = P \), and for high power \( I = 1 \), irrespective the value of the parameter \( \alpha \). This implies that, when
Figure 3.5: Dependence of normalized luminescence output $I$ on normalized laser input power $P$ as predicted by the model equations without Auger processes for lowest and highest values of parameter $\alpha$. Experimental data points ($\times$) for five samples of type $Fz$-$Si$:Er, $Cz$-$Si$:Er, $Cz$-$Si$:Er, O, MBE-$Si$:Er and $a$-$Si$:Er are given for unit power $P = 1$.

Considered in normalized form, the parameters $a_0, b_0, b_2$ and $c_2$, or the more basic physical coefficients $\gamma, \gamma_x, c, f, f_x, f_1, \tau_x, \tau^*$ and $\tau_d$, have no effect on the power dependence in the low- and high-power regions. Only at intermediate power, i.e., $P \approx 1$, the results will depend on $\alpha$. Only in the transition region between linear increase and saturation the observed luminescence does reveal insight into the luminescence process. The most typical value to study the luminescence mechanism is therefore at power $P = 1$. At this excitation level the luminescence intensity is given by

$$I = \alpha - \sqrt{\alpha^2 - \alpha}.$$  \hspace{1cm} (3.23)

From the equality $\alpha = b_0b_2/a_0c_2$ and the parameters as given by Eqs 3.17-3.20 one concludes that $1 \leq \alpha \leq \infty$. For such values of $\alpha$ always solutions from Eq. 3.23 do exist. For $\alpha = 1$ one obtains $I_{P=1} = 1$ and for $\alpha = \infty$
Excitation power dependence of photoluminescence intensity

one has $I_{P=1} = 0.5$. The range of possible luminescence intensities at unit power $P = 1$ consistent with Eq. 3.21 is restricted between 0.5 and 1. For these limiting values the intensity versus power curves for an extended range are drawn in Fig. 3.5.

In Fig. 3.5 also experimental data are included. They result from measurements at liquid-helium temperature on the five samples with different specifications as given in section 3.2. In all cases the luminescence intensity was followed as a function of excitation power over the maximum accessible range. Experimental data are plotted for normalized power $P = 1$ at observed values $I = 0.216$ for Fz-Si:Er, $I = 0.212$ for Cz-Si:Er, $I = 0.235$ for Cz-Si:Er,O and $I = 0.18$ for MBE-Si:Er. Obviously, these are all outside the range of results that can described by the model. For the a-Si:Er material, on the other hand, the observed $I = 0.57$, corresponding to $\alpha = 2.32$ represents a possible solution. Further interpretation of this result, using Eq. 3.22 and Eqs 3.17-3.20, leads to the requirement that both conditions $\tau^*/\tau_d > 1.32$ and $1/c_{nE_r} \tau_x > 1.32$ must hold. As this is not likely to be the case, the validity of the model also for the a-Si is doubtful.

3.4.3 Energy transfer with Auger processes

One has to conclude that the presented model is not able to provide the quantitative description of the luminescence process. In order to improve the model energy losses through Auger processes involving conduction band electrons may be considered, as has been suggested before by Palm, et al. [16]. Erbium-bound excitons can dissipate their energy in an Auger process with involvement of free electrons. Similarly, erbium ions in excited state can decay in an Auger process, also with conduction band electrons. The two processes are indicated in Fig. 3.4. In the balance equations 3.14 and 3.15 they are implemented by including on the loss side the Auger rates $c_A n_{xb}$ and $c_{A_E r} n_{E_r}$. The extended balance equations for bound excitons and excited erbium ions become, respectively,

$$
-c_{nE_r} \frac{n_{E_r} - n_{xb}}{n_{E_r}} = n_{xb} \frac{n_{E_r} - n_{E_r}^*}{n_{E_r}} \frac{1}{\tau^*} + c_A n_{xn_{xb}} \quad (3.24)
$$
and

\[ \frac{n_{xb}^{n_{Er}} - n_{Er}^{*}}{n_{Er}} \tau^* = \frac{n_{Er}^{*}}{\tau_d} + c_{AEr}nn_{Er}^{*}. \]  

(3.25)

In order to solve the new set of equations 3.12, 3.13, 3.24 and 3.25 it is helpful to introduce appropriate simplifications. Considering numerical values one may assume that the loss of free electrons and holes is dominated by their recombination via traps with rate \( \gamma n^2 \). The loss via exciton formation \( \gamma_x n^2 \) is comparatively much less. Under such conditions the energy transfer model can be broken up into two parts. In stream I the balance of electrons is considered separately by Eq. 3.12. The loss of electrons through exciton formation is ignored in this main stream. At low temperature this leads to

\[ G = (\gamma_x + \gamma)n^2 \]  

(3.26)

and

\[ n = \sqrt{\frac{G}{\gamma_x + \gamma}}. \]  

(3.27)

The electron concentration obtained via this solution is used to describe the Auger processes. Typical numbers are \( G = 10^{22} \text{ cm}^{-3}\text{s}^{-1}, \gamma_x = 10^{-12} \text{ cm}^3\text{s}^{-1}, \gamma = 10^{-10} \text{ cm}^3\text{s}^{-1} \) and \( n = 10^{16} \text{ cm}^{-3} \), corresponding to an electron lifetime of 1 \( \mu \text{s} \).

In energy stream II the balance of free excitons, bound excitons and excited erbium ions is separately considered. Solution of the equations leads to a cubic equation in \( n_{Er}^{*} / n_{Er} \):

\[ A\left(\frac{n_{Er}^{*}}{n_{Er}}\right)^3 - B\left(\frac{n_{Er}^{*}}{n_{Er}}\right)^2 + C\left(\frac{n_{Er}^{*}}{n_{Er}}\right) - D = 0 \]  

(3.28)

with

\[ A = (1 + cn_{Er}\tau_x)(1 + c_{AEr}n\tau_d) + cn_{Er}\tau_x\frac{\tau^*}{\tau_d}(1 + c_{AEr}n\tau_d)^2, \]  

(3.29)
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\[ B = (1 + c n_{Er} \tau_x) (1 + c_{AEr} n \tau_d) + \]
\[ c n_{Er} \tau_x \frac{\tau^*}{\tau_d} (1 + c_{AEr} n \tau_d)^2 (1 + c_{Ax} n \tau^*) + \]
\[ (1 + c n_{Er} \tau_x) (1 + c_{AEr} n \tau_d) (1 + c_{Ax} n \tau^*) + \]
\[ \gamma_z n \tau_x c n \tau_d + \gamma_z n \tau_x c n \tau_d (1 + c_{AEr} n \tau_d) \frac{\tau^*}{\tau_d}, \quad (3.30) \]

\[ C = (1 + c n_{Er} \tau_x) (1 + c_{AEr} n \tau_d) (1 + c_{Ax} n \tau^*) + \]
\[ 2 \gamma_z n \tau_x c n \tau_d + \gamma_z n \tau_x c n \tau_d (1 + c_{AEr} n \tau_d) \frac{\tau^*}{\tau_d} \quad (3.31) \]

and

\[ D = \gamma_z n \tau_x c n \tau_d. \quad (3.32) \]

Neglecting the term \( c_{Ax} n \tau^* c n_{Er} \tau_x \tau_d \frac{\tau^*}{\tau_d} (1 + c_{AEr} n \tau_d)^2 \) in coefficient B, on the basis of a consideration of numerical values of \( c, n, n_{Er}, c_{AEr}, \tau_x, \tau^*, \tau_d \), the Eq. 3.28 can be written as

\[ A \left( \frac{n^{*}_{Er}}{n_{Er}} \right)^3 - (A + B_1) \left( \frac{n^{*}_{Er}}{n_{Er}} \right)^2 + (B_1 + D) \left( \frac{n^{*}_{Er}}{n_{Er}} \right) - D = 0, \quad (3.33) \]

with

\[ B_1 = (1 + c n_{Er} \tau_x) (1 + c_{AEr} n \tau_d) (1 + c_{Ax} n \tau^*) + \]
\[ \gamma_z n \tau_x c n \tau_d [1 + (1 + c_{AEr} n \tau_d) \frac{\tau^*}{\tau_d}]. \quad (3.34) \]

Eq. 3.33 can be factorized as

\[ [A \left( \frac{n^{*}_{Er}}{n_{Er}} \right)^2 - B_1 \left( \frac{n^{*}_{Er}}{n_{Er}} \right) + D] [\left( \frac{n^{*}_{Er}}{n_{Er}} \right) - 1] = 0. \quad (3.35) \]

Using the expression 3.27 for the electron concentration, the dependence of luminescence output \( n^{*}_{Er}/n_{Er} \) on power \( G \) follows from
(a_0 + a_1 \sqrt{G} + a_2 G) \left( \frac{n^*_E}{n_{Er}} \right)^2 - \\
(b_0 + b_1 \sqrt{G} + b_2 G + b_3 \sqrt{G^3}) \left( \frac{n^*_E}{n_{Er}} \right) + c_2 G = 0, \quad (3.36)

with

\begin{align*}
a_0 &= 1 + cn_{Er} \tau_x \left( 1 + \frac{\tau^*}{\tau_d} \right), \quad (3.37) \\
a_1 &= c_{AEr} \tau_d \left[ 1 + cn_{Er} \tau_x \left( 1 + 2 \frac{\tau^*}{\tau_d} \right) \right] \frac{1}{\sqrt{\gamma_x + \gamma}}, \quad (3.38) \\
a_2 &= cn_{Er} \tau_x \frac{\tau^*}{\tau_d} \left( c_{AEr} \tau_d \right)^2 \frac{1}{\gamma_x + \gamma}, \quad (3.39) \\
b_0 &= 1 + cn_{Er} \tau_x, \quad (3.40) \\
b_1 &= (1 + cn_{Er} \tau_x) \left( c_{AEr} \tau_d + c_{Az} \tau^* \right) \frac{1}{\sqrt{\gamma_x + \gamma}}, \quad (3.41) \\
b_2 &= [(1 + cn_{Er} \tau_x) c_{AEr} \tau_d c_{Az} \tau^* + \gamma_x \tau_x c_{T_d} (1 + \frac{\tau^*}{\tau_d})] \frac{1}{\gamma_x + \gamma}, \quad (3.42) \\
b_3 &= \gamma_x \tau_x c_{T_d} c_{AEr} \frac{\tau^*}{\tau_d} \frac{1}{\sqrt{(\gamma_x + \gamma)^3}} \quad (3.43)
\end{align*}

and

\begin{align*}
c_2 &= \gamma_x \tau_x c_{T_d} \frac{1}{\gamma_x + \gamma}. \quad (3.44)
\end{align*}

At low power the model equations reflect the linear increase \( n^*_E/n_{Er} = \)
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\[(c_2/b_0)G,\] just as before. At high power, however, the consistent solution
\[n_{Er}^*/n_{Er} = (c_2/b_0)\sqrt{G} \] predicts decreasing luminescence intensity upon increase of the excitation level \(G\). Such a behavior is to be expected as in the present case two independent saturation mechanisms are active. In the first one the concentration of erbium-bound excitons, \(n_{xb}\), is driven towards the concentration of available erbium ions but is limited to stay below or become equal to this concentration. The second saturation mechanism is the combined action of the two Auger processes. At high power, and hence high concentration of free electrons, the Auger mechanism removing excited erbium ions nonradiatively becomes very effective. This will result in a reduction of \(n_{Er}^*\), which becomes proportional to \(1/n\) or \(1/\sqrt{G}\). Such a decrease has not been observed in the present experiments; it has also not been reported in the literature. Inspection of the equations shows that one should expect the decrease to set in at excitation values where \(c_{AEr}\tau_d(\tau^*/\tau_d)\sqrt{G} > 1\). Considering numerical values \((c_{AEr} \approx 10^{-12} \text{ cm}^3\text{s}^{-1}, \tau^* \approx 4 \times 10^{-6} \text{ s})\) this corresponds to high values of \(G\), near and above \(10^{26} \text{ cm}^{-3}\text{s}^{-1}\), which are not reached in actual experiments. This can be attributed to the small value of \((\tau^*/\tau_d)\), as \(\tau^*\) is in the range of microseconds and \(\tau_d\) is of order milliseconds. Introducing the approximation \(\tau^*/\tau_d \approx 0\), Eq. 3.36 reduces in many respects to Eq. 3.16. In particular the term \(b_3\sqrt{G^3}\) in Eq. 3.36 is lost and the equation predicts saturation at \(c_2/b_2\). Both for low and for high power an approximate solution of Eq. 3.36 will be

\[
\frac{n_{Er}^*}{n_{Er}} = \frac{c_2G}{b_0 + b_1\sqrt{G} + b_2G}. \tag{3.45}
\]

This result will also be valid for intermediate power if the Auger processes are strong \((c_{AEr}n\tau_d > 1, c_{Az}n\tau^* > 1)\). Following solution 3.45 for this special case one has saturation at \(c_2/b_2\), linear increase at low power with \((c_2/b_0)G\), and \(G_1 = b_0/b_2\). Expressing Eq. 3.45 in terms of normalized units, as before, the result will read

\[
I = \frac{P}{1 + \beta\sqrt{P} + P}. \tag{3.46}
\]
with

\[ \beta = \frac{b_1}{\sqrt{b_0 b_2}} \]  

(3.47)

or

\[ \beta = \frac{c_{AEr} T_d + c_{Ax} T^*}{\sqrt{c_{AEr} T_d c_{Ax} T^* + \gamma_{Ax} T_x c_r T_d / (1 + c_{AEr} T_x)}}. \]  

(3.48)

Under the assumed condition of strong Auger effect this reduces to

\[ \beta = \frac{c_{AEr} T_d + c_{Ax} T^*}{\sqrt{c_{AEr} T_d c_{Ax} T^*}}, \]  

(3.49)

or

\[ \beta = \sqrt{\frac{c_{AEr} T_d}{c_{Ax} T^*}} + \sqrt{\frac{c_{Ax} T^*}{c_{AEr} T_d}}. \]  

(3.50)

As usual, the power dependence of the luminescence has its linear increase at low power with \( I = P \) and saturates at high power at \( I = 1 \). Features of the luminescence process are only revealed at intermediate power, e.g., at \( P = 1 \), where \( I = 1/(2 + \beta) \). For a general case, parameter \( \beta \) will be positive following Eq. 3.48; for the case of strong Auger effect \( \beta \geq 2 \), as follows from Eq. 3.49 or Eq. 3.50. Fig. 3.6 illustrates the curves as obtained from Eq. 3.46 for \( \beta = 0 \) and \( \beta = 2 \). Curves for \( \alpha = \infty \) in Fig. 3.5 and \( \beta = 0 \) in Fig. 3.6 are identical, both representing \( I = P/(1 + P) \). Compared to the previous case, without Auger effect, the transition region between linear behavior and saturation is broader. This is due to the appearance of the \( \beta \sqrt{P} \) term, which in this model is a fingerprint of the Auger effect.

Considering again the experiment, the measured data for the luminescence power dependence of the five different types of samples are plotted in Figs 3.3. The solid curves are the best fits to the experimental data using Eq. 3.46 with parameter \( \beta = 2.63 \) for Fz-Si:Er, \( \beta = 2.73 \) for Cz-Si:Er and \( \beta = 2.25 \) for Cz-Si:Er, O [23]. For the MBE-Si:Er sample the result gives a value of \( \beta = 3.3 \). The data points for the four samples for \( P = 1 \) and \( I = 1/(2 + \beta) \) are also plotted in Fig. 3.6. The results for the three crystalline silicon samples doped with erbium by implantation
Figure 3.6: Dependence of normalized luminescence output $I$ on normalized laser power input $P$ for the model including strong Auger decay processes for process parameter $\beta = 0$ and $\beta = 2$. The transition region in which the term $\beta \sqrt{P}$ dominates in the denominator of Eq. 3.46 is indicated for $\beta = 2$. Experimental data points (×) for the five samples of type Fz-Si:Er, Cz-Si:Er, Cz-Si:Er, O, MBE-Si:Er and α-Si:Er are given for unit power $P = 1$.

are quite similar with $\beta = 2.5 \pm 0.25$. With Eq. 3.50 the result is converted to $(c_{AEr} \tau_d / c_{Ax} \tau^*)_\pm^1 \approx 4 \pm 1$. This compares favorably with data as published in the literature, e.g., $c_{AEr} = 10^{-12} \text{cm}^3\text{s}^{-1}$, $\tau_d = 10^{-3} \text{s}$, $c_{Ax} = 10^{-10} \text{cm}^3\text{s}^{-1}$ and $\tau^* = 4\times10^{-6} \text{s}$ [16]. From the present analysis one can only conclude that $c_{AEr} \tau_d / c_{Ax} \tau^*$ is very similar in these three kinds of erbium-doped crystalline silicon materials. This can be due to an accidental combination of parameters, but one is tempted to believe that all process parameters, i.e., $c_{AEr}, \tau_d, c_{Ax}$ and $\tau^*$, have similar values. In such a case the probable difference in structure of the luminescent centers in these three materials has little influence on the later steps in the photoluminescence process as depicted in Fig. 3.4. For the sample prepared by the MBE method the slightly different value of $\beta = 3.3$ giving $(c_{AEr} \tau_d / c_{Ax} \tau^*)_\pm^1 \approx 9$, might be due to a larger ratio $\tau_d / \tau^*$ in this material. In particular, any special role of oxygen in the formation of suitable
luminescent centers is not borne out by these results. The conclusion
of similar luminescence properties of the erbium-doped crystalline silicon
samples, as reported here, is entirely a result of the introduction of the
normalized units. Considered in terms of direct experimental units for ex-
citation and yield, as is common practice, the results would have looked
rather different. A conclusion of different behavior of the luminescent
centers in these materials is then easily, but erroneously, made.

The result for the a-Si sample is different. To fit the experimentally
observed power dependence with expression 3.46, parameter $\beta$ has to be
given the negative value $\beta = -0.25$, incompatible with Eq. 3.48. One
can conclude that the assumption of strong Auger effect leading to the
solution 3.46 is not valid in the case of amorphous silicon.

Returning to absolute units, the laser excitation power correspond-
ing to the unit of normalized power, $P = 1$, is different for the five
samples. The values, which can be taken from the co-ordinate axes in
Figs 3.3(a,b,c,d,e), are 36 mW for Fz-Si:Er, 14 mW for Cz-Si:Er, 3 mW
for Cz-Si:Er,O, 155 mW for MBE-Si:Er and 422 mW for the a-Si samples.
In terms of the model equations unit power $G_1$ is given by

$$G_1 = \frac{b_0}{b_2},$$

which can be approximated by

$$G_1 \approx \frac{\gamma}{c_{AEr} \tau_d c_{Az} \tau^*}.$$  

In view of this result, the different values for the unit of excitation
power can easily be related to specific sample conditions, even for equal
values of parameters $c_{AEr}, \tau_d, c_{Az}$ and $\tau^*$. The parameter $\gamma$ is influenced
by the presence of recombination centers in and near the excited volume,
and therefore related to implantation damage and annealing treatments.
Impurities, such as oxygen, either from the crystal growth or from implan-
tation, will have their effects. Considering this factor, one may expect
that in the a-Si the free-electron and -hole lifetime is shorter due to a
higher recombination rate $\gamma$. A lower steady state electron concentration
will make the luminescence excitation less probable and more excitation
energy will be required to reach the saturation region. Lower electron
concentration will also reduce the reaction rate of the Auger processes, in agreement with the earlier conclusion. As such parameters are not under precise control, the results, which are not vastly different for the crystalline samples, will not be subjected to further quantitative analysis.

For an order-of-magnitude evaluation of Eq. 3.52 the conditions of the experiment have to be considered in more detail. In the experimental set-up a power set to 10 mW on the laser unit, the typical unit power for the crystalline samples, resulted in about 100 μW of light power incident on the sample. Given the wavelength 514.5 nm of the Ar⁺ laser light, with associated photon energy of 2.4 eV, and assuming a 100% quantum efficiency, this light energy will yield an electron-hole generation rate of around $2.5 \times 10^{14} \text{s}^{-1}$. Assuming a penetration depth of 1 μm of the light in the sample and a spot size of 1 mm², the volume in which the excitation takes place is very roughly estimated at $10^{-6} \text{cm}^3$. The generation parameter $G_1$ for a 10 mW excitation will then be $G_1 = 2.5 \times 10^{20} \text{cm}^{-3}\text{s}^{-1}$. An evaluation of the right hand side of Eq. 3.52 will give, with $\gamma = 10^{-10} \text{cm}^3\text{s}^{-1}$ and parameters $c_{AEr}, \tau_d, c_{Ax}$ and $\tau^*$ as before, precisely this number. Under these generation-recombination conditions the electron and hole concentrations will be $n = 1.6 \times 10^{15} \text{cm}^{-3}$ and their lifetime 6 μs. Corresponding values for the a-Si sample are $G_1 = 10^{22} \text{cm}^{-3}\text{s}^{-1}$, $\gamma = 4 \times 10^{-8} \text{cm}^3\text{s}^{-1}$, $n = 1.6 \times 10^{15} \text{cm}^{-3}$ and the shorter lifetime 0.15 μs confirming expectations.

### 3.5 Conclusions

The dependence of the photoluminescence intensity of erbium-doped silicon in the 1.54 μm spectrum on excitation power has been experimentally measured and analyzed. For the analysis a physical model was used in which the incident light energy is transferred via the intermediate stages of free electrons and holes, free excitons, and erbium-bound excitons to the intra-4f-shell excited erbium ions. The experiments showed that the transition from linear behavior at low power towards saturation at high power proceeds quite gradually. In order to explain the power dependence, it was found to be necessary to include Auger processes, by which erbium-bound excitons and excited erbium ions decay nonradiatively, into the model. A remarkable similarity was found for erbium-doped crys-
talline implanted samples of float-zoned and Czochralski origin. In these materials the probable structural difference in the luminescent centers appears to have no strong effect on the basic process of luminescence. This conclusion was revealed by the consistent use of normalized units for both excitation power and luminescence intensity. Typical medium electron-hole excitation rates in the experiments are estimated at $10^{22}$ cm$^{-3}$s$^{-1}$. A consistent analysis of experimental results for power dependence was carried out with parameter values $\gamma_x = 10^{-12}$ cm$^3$s$^{-1}$, $\gamma = 10^{-10}$ cm$^3$s$^{-1}$, $c = 5\times10^{-10}$ cm$^3$s$^{-1}$, $c_{Ax} = 10^{-10}$ cm$^3$s$^{-1}$, $c_{AEr} = 10^{-12}$ cm$^3$s$^{-1}$, $\tau_x = 5\times10^{-6}$ s, $\tau^* = 4\times10^{-6}$ s and $\tau_d = 10^{-3}$ s.

References


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