Optical properties of Er-doped Si-based media

Minissale, S.

Citation for published version (APA):
2 Optical activity of Er\(^{3+}\) ions in Si/Si:Er nanolayers

Yes, that is the artist’s job: takes mineral rock from dark silent earth, transforms it into shining light-reflecting form from sky.

Philip K. Dick

While crystalline silicon (c-Si) continues to dominate the mainstream integrated circuit device manufacturing, applications of this most important semiconductor material remain electronic rather than photonic. Due to the relatively small and indirect bandgap, silicon is a poor light emitter. Nevertheless, as the result of continued research effort, optical gain (Si nanocrystals)\(^\text{[36]}\) and Raman lasing (Si)\(^\text{[37,38]}\) have recently been demonstrated, and even intense room temperature emission\(^\text{[39]}\) from Si structures seems to be possible. The optical properties of silicon can be enhanced by Er doping but here the situation is still not settled. While room-temperature luminescence has been realized\(^\text{[40]}\), population inversion and optical gain have not been obtained and fundamental problems remain. Due to the long radiative lifetime of Er\(^{3+}\) in Si, a high doping concentration, in the range of \(10^{19} - 10^{20} \text{ cm}^{-3}\), is necessary for intense emission. Such high impurity levels exceed by far the solubility limit, and can only be realized by nonequilibrium methods. This readily leads to segregation of Er to the surface and in a form of metallic clusters. Although this effect can be suppressed by oxygen co-doping, only a minor part (\(\sim 0.1\% - 1\%\)) of the Er ions incorporated in the material take part in photon emission\(^\text{[41,42]}\). This low percentage of Er\(^{3+}\) ions which participate in the radiative recombination process practically precludes realization of optical gain in Si:Er.
It is generally recognized that for an efficient optical excitation of Er in Si, a high exciton concentration is necessary. This can be obtained in intrinsic material of high purity. Therefore the requirements of high Er concentration and efficient exciton generation cannot be met simultaneously. This leads to a situation that for heavily Er-doped layers excitons develop in the substrate rather than in the layer itself. Consequently, the intensity of Er-related photoluminescence (PL) does not increase above a certain thickness of the Si:Er layer. This limitation can be overcome when a “spacer” layer of undoped Si is inserted into the Si:Er layer. Whilst thermal stability of Er-related PL is not improved, it turns out that at cryogenic temperatures a sandwich structure of interchanged Si/Si:Er nanolayers features more intense emission at 1.5 µm \[^43\]. In addition, as evidenced by our previous studies, Si/Si:Er nanolayer structures offer a unique possibility of preferential formation of a particular type of optically active Er-related center, labelled Er-1 \[^13,14\]. Since the homogeneous emission bands of the Er-1 center are characterized at low temperature by ultra-small width of a few µeV, this indicates a potential increase of the gain coefficient by a factor of $10^3 \sim 10^4$ when compared to Si:Er materials used so far. Therefore Si/Si:Er nanolayers emerge as a promising medium for achieving population inversion and stimulated emission in a Si-based material; while in view of thermal quenching of PL emission this could possibly be obtained at cryogenic temperatures only (at this point), it would nevertheless represent a major advance, as realization of population inversion and optical gain is a long sought after goal of silicon science and technology. A necessary (although by itself insufficient) condition for that is a very high percentage of dopants which can participate in radiative recombination. In this chapter, we investigate the limits of optical activity of Er in Si/Si:Er nanolayer structures, \textit{i.e.}, the maximum concentration of Er dopants which contribute photons upon optical excitation.

### 2.1 Samples preparation and experiment

All the measurements presented in this chapter have been performed at cryogenic temperatures (4 - 15 K) on the samples described described in Chapt.\[^1\] specifically: the differently optimized Si/Si:Er nanolayer structures grown by SMBE at 560 °C and the three Si/Si$_{1-x}$Ge$_x$:Er nanolayers grown by SMBE at 500 °C. For reference, a SiO$_2$ sample, has been used and in order to validate the experimental method for determination of the percentage of optically active Er, an implanted Si:Er sample, called IMP, was used. The latter is representative for state-of-the-art Si:Er material which can be obtained by implantation.
The PL experiments were carried out in a continuous-flow cryostat (Oxford Instruments Optistat CF). The samples were excited using an Ar\textsuperscript{+}-ion laser or a tunable Optical Parametric Oscillator (OPO) producing pulses of 5 ns duration at 20 Hz repetition rate. The luminescence was resolved with a 1 m F/8 monochromator (Jobin-Yvon THR-1000) equipped with a 900 grooves/mm grating blazed at 1.5 \(\mu\)m and detected by an infrared photomultiplier with a 30 \(\mu\)s response time.

2.2 Experimental results and discussion

2.2.1 Si/Si:Er multinanolayers

Fig. 2.1 shows (normalized) PL spectra of the 4 samples used in the present study. These were obtained at \(T = 4.2\) K, outside the saturation range under continuous wave (cw) excitation with an Ar\textsuperscript{+}-ion laser operating at 488 nm.

![Figure 2.1: PL spectra of the four investigated samples.](image_url)

For sample NLA the characteristic ultra narrow lines of the Er-1 center can
easily be distinguished [14]. Some sharp lines can also be found in the broad spectrum of sample NLB. The integrated PL spectrum intensity ratio for all the samples, normalized to the same signal maximum, and thus reflecting only different spectral characteristics, is:

\[ I_{\text{NLA}} : I_{\text{NLB}} : I_{\text{IMP}} : I_{\text{STD}} = 1 : 5.6 : 2.5 : 4 \]  

(2.1)

The excitation power dependence of the PL intensity for samples NLA and NLB under cw excitation at \( \lambda_{\text{exc}} = 514.5 \) nm was measured at 4.2 K. The emission wavelengths selected for this experiment are indicated by arrows in Fig. 2.1 shows the power dependence of the PL intensity for the main line at \( \lambda = 1537.8 \) nm and at a wavelength of \( \lambda = 1525 \) nm for the “background” feature for sample NLA, and \( \lambda = 1536.3 \) nm for sample NLB.

![Graph showing the excitation power dependence of the PL intensity for samples NLA and NLB. The curve labelled “NLA background” refers to PL recorded away from the luminescence peaks, at the wavelength indicated by the left arrow in the “NLA” spectrum of Fig. 2.1.](image)

Figure 2.2: PL recorded at the maximum of emission, as function of the excitation power for the two multilayer samples NLA and NLB. The curve labelled “NLA background” refers to PL recorded away from the luminescence peaks, at the wavelength indicated by the left arrow in the “NLA” spectrum of Fig. 2.1.

As has been discussed previously [44][45], under cw excitation conditions,
power dependence of Si:Er PL intensity is well described with the formula:

\[ I_{PL} = \frac{A \sigma \tau \Phi}{1 + \beta \sqrt{\sigma \tau \Phi} + \sigma \tau \Phi}, \quad (2.2) \]

where \( \sigma \) is an effective excitation cross-section of Er\(^{3+} \), \( \tau \) is the effective lifetime of Er\(^{3+} \) in the excited state, and \( \Phi \) is the flux of photons. The appearance of the \( \beta \sqrt{\sigma \tau \Phi} \) term, with an adjustable parameter \( \beta \), is a fingerprint of the Auger effect hindering the luminescence. The solid curves in Fig. 2.2 represent the best fits to the experimental data using Eq. 2.2. For sample NLA we get \( \sigma_{cw}^{NLA} = 5 \pm 2 \times 10^{-15} \text{ cm}^2 \) for the Er-1 related lines and an order of magnitude smaller value of \( \sigma_{cw}^{bkg} = 7.5 \pm 2 \times 10^{-16} \text{ cm}^2 \) for the “background” emission, with the Auger process related parameter \( \beta = 2 \pm 0.1 \). For sample NLB the best fit is obtained for \( \sigma_{cw}^{NLB} = 2 \pm 1 \times 10^{-15} \text{ cm}^2 \) and \( \beta = 2 \pm 0.1 \). The values of \( \sigma \) are similar to those reported for Er-implanted silicon \[46\] and indicate a similar Er excitation mechanism.

Fig. 2.3 shows decay characteristics of Er-related PL at \( T = 4.2 \text{ K} \) under pulsed excitation with a wavelength of \( \lambda_{exc} = 520 \text{ nm} \). As can be seen, the decay kinetics is composed of a fast and a slow components. Fitting the profiles measured for sample NLA, we obtained two decay times of \( \tau_F = 0.16 \text{ ms} \) and \( \tau_S = 0.83 \text{ ms} \) contributing to the relaxation. The intensity ratio of the fast and slow components is found to be 3:2, the same for all the emission lines of this sample. For sample NLB, we have \( \tau_F = 0.19 \text{ ms} \) and \( \tau_S = 0.90 \text{ ms} \). These values are again similar to those commonly found in Si:Er structures prepared by implantation \[46\]. For IMP we get \( \tau_{IMP} = 1.9 \text{ ms} \), not shown, which is indicative for the dominance of radiative recombination.

As mentioned before, the percentage of Er dopants that can emit photons upon excitation is known to be notoriously low in Si \[47\], dispersions of Si nanocrystals in SiO\(_2\) \[48\] and also in other semiconductors matrices, like, e.g., GaN. Yet this parameter is crucially important for the application potential of Er-doped semiconductors and, in particular for Si:Er, since it determines the PL intensity and is decisive for (a possibility of achieving) population inversion. An estimate of the number of excitable centers can be made by comparing the intensity of the observed PL with that of the SiO\(_2\):Er “standard” STD sample measured under the same conditions. This is presented in Fig. 2.4 where flux dependencies of Er-related PL intensities are shown for samples NLA, NLB and STD.

The experiment has been performed under pulsed excitation with the OPO set to \( \lambda_{exc} = 520 \text{ nm} \). This particular wavelength corresponds to the \(^{4}I_{15/2} \rightarrow ^{2}H_{11/2}\) internal transition of Er\(^{3+} \) ion and therefore can be used for both indirect (Si) and direct (SiO\(_2\)) excitation of Er\(^{3+} \) ions. Since, in the experi-
2. Optical activity of Er\textsuperscript{3+} ions in Si/Si:Er nanolayers

![Graph showing decay kinetics for two samples NLA and NLB]

**Figure 2.3:** Decay kinetics for the two samples NLA and NLB. Solid curves are exponential fits to the experimental data with two decay time constants.

The PL signal is effectively integrated over time, and the PL intensity is proportional to $N_{\text{Er}}^*/\tau_{\text{rad}}$, the result of the experiment is given by $N_{\text{Er}}^*/\tau_{\text{rad}}$. Therefore, the ratio of the number of photons emitted from the two investigated samples after an excitation pulse is given by:

$$
\frac{I_{\text{Si:Er}}}{I_{\text{SiO}_2:\text{Er}}} = \frac{\eta_{\text{Si}}}{\eta_{\text{SiO}_2}} \frac{N_{\text{Er}^*/\text{Si:Er}}}{N_{\text{Er}^*/\text{SiO}_2:\text{Er}}} \times \left(\frac{\tau_1}{\tau_1^\text{rad}}\right) \times \left(\frac{\tau_2}{\tau_2^\text{rad}}\right),
$$

where $\tau_1$, $\tau_2$, $\tau_1^\text{rad}$, $\tau_2^\text{rad}$, $N_{\text{Er}(\text{Si:Er})}$, $N_{\text{Er}(\text{SiO}_2:\text{Er})}$, $\eta_{\text{out}}^\text{Si}$, $\eta_{\text{out}}^\text{SiO}_2$ correspond to the effective and radiative decay times, density of excited Er\textsuperscript{3+} ions, and the fraction of emitted photons that leave the sample (extraction efficiency), respectively, for the Si:Er and SiO\textsubscript{2}:Er materials. The ratio of the extraction efficiencies
2.2 Experimental results and discussion

Figure 2.4: Integrated PL intensity as function of the excitation power, for the samples NLA, NLB and STD. On the right axis, PL intensity has been re-scaled to obtain the density of activated Er ions in the samples.

can be calculated from the refractive indexes of Si and SiO$_2$:

$$\frac{\eta_{\text{Si}}}{\eta_{\text{SiO}_2}} \approx 0.175,$$

where $n_1$, $n_2$ are the reflective indexes of 3.49 and 1.46 at 1.5 μm emission for Si and SiO$_2$, respectively [12] (see Chapt. 7 for details).

In the present experiment, the duration of the OPO pulse ($\Delta t = 5$ ns) is much shorter than the characteristic lifetime $\tau$ of Er$^{3+}$ in the excited state: $\Delta t \ll \tau$. Consequently, we can assume that recombination does not take place during illumination, and the population $N_{\text{Er}}^*$ reaches the level of:

$$N_{\text{Er}}^*(t = \Delta t) = N_{\text{Er}}^{\text{act}}[1 - exp(-\sigma \Phi \Delta t)].$$

In this equation, $N_{\text{Er}}^{\text{act}}$ is the total concentration of excitable Er$^{3+}$ ions present in the sample. For low excitation density, when $\sigma \Phi \Delta t \ll 1$, this for-
mula gives a linear dependence on flux: \(N^*_\text{Er} = \sigma \Phi N^\text{act}_\text{Er} \Delta t\). When \(\sigma \Phi \Delta t \gg 1\), the saturation regime can be obtained: \(N^*_\text{Er} = N^\text{act}_\text{Er}\). From Fig. 2.4 we conclude that the intensity of emission from SiO\(_2\):Er sample shows a linear dependence over the whole investigated flux range. For the SiO\(_2\):Er system, the values of all parameters are known: \(\sigma_{520\text{ nm}}^\text{SiO}_2\text{:Er} = 2 \times 10^{-20} \text{ cm}^2\) \[^{11}\] and \(N^\text{act}_\text{Er} = 9.9 \times 10^{14} \text{ cm}^{-2}\), i.e., we assume that all the implanted ions participate in emission. We also take \(\tau/\tau_\text{rad} = 1\). In that way, the well-characterized SiO\(_2\):Er system can be used to attribute the measured PL intensity to a particular areal density (cm\(^{-2}\)) of excited Er\(^{3+}\) ions, as given by the right hand scale in Fig. 2.4.

For Si, the Er\(^{3+}\) excited state population should be corrected due to non-radiative contribution to the effective lifetime \[^{49}\]. If we assume the slow component in the decay kinetic to represent radiative recombination (which seems very reasonable in view of the published data on the radiative decay of Er in c-Si \[^{46}\]), the correction to the integrated PL intensities is given by:

\[
\frac{I_{\text{Si:Er}}}{I_{\text{Si:Er (total)}}} = \frac{N^*_\text{Er} \tau/\tau_\text{rad}}{N^*_\text{Er} \tau_\text{rad}/\tau_\text{rad}} = \frac{\tau}{\tau_\text{rad}} = \frac{A_F/\tau_F + A_S/\tau_S}{(A_F + A_S)\tau_S} = \frac{A_F/\tau_F + A_S/\tau_S}{(A_F/\tau_S + 1)\tau_S},
\]

(2.6)

where \(A_F\), \(A_S\), \(\tau_F\), \(\tau_S\) correspond to amplitudes and decay times of the fast and the slow components of the signal, respectively. At the saturation level of the sample NLA, \(A_F/A_S = 1.5\), \(\tau_F = 0.16 \text{ ms}\), \(\tau_S = 0.83 \text{ ms}\), and we get \(I_{\text{Si:Er}}/I_{\text{total}} = \tau/\tau_\text{rad} \approx 0.5\). Therefore, under the same excitation conditions, the excited state population in this sample has to be 2 times higher in order to give PL intensity equal to that of sample SiO\(_2\):Er. This is similar for the sample NLB, for which we get \(\tau/\tau_\text{rad} \approx 0.45\). Using data of Fig. 2.4 the maximum number of Er\(^{3+}\) ions emitting photons in the Si:Er samples can be derived from the saturation level of PL intensity, and taking into account the different spectral shape of the 1.5 \(\mu\text{m}\) band (Eq. 2.1), effective lifetime, and extraction loss. For sample NLA, we have \(N^\text{act}_\text{Er} \approx 1.4 \times 10^{12} \times (1/0.175) \times 2 \times (1/4) = 4.0 \times 10^{12} \text{ cm}^{-2}\). This implies that at saturation the percentage of Er dopants contributing to photon emission is \(P_{\text{NLA}} \approx 2 \pm 0.5\%\). For sample NLB, with a lower signal-to-noise ratio, we arrive at \(N^\text{act}_\text{Er} \approx 0.17 \times 10^{12} \times (1/0.175) \times (1/0.45) \times (5.6/4) = 3.0 \times 10^{12} \text{ cm}^{-2}\), and \(P_{\text{NLB}} \approx 15 \pm 5\%\).

To cross-check the methodology, we performed a comparative measurement using the implanted sample IMP. In Fig. 2.5 the power dependence of PL intensity is shown for samples NLA and IMP.

The experiment has been performed at low temperature under cw Ar laser excitation. As can be seen, the PL saturation intensity of sample NLA is about
2.2 Experimental results and discussion

25-30 times larger than that of IMP. Based on that, and taking into account the difference in effective decay time (×2) and spectral shape, we obtain in this case the percentage of radiatively recombining Er dopants as $P_{\text{IMP}} \approx 6.6 \pm 1\%$. This value is in reasonable agreement with the optical activation limit of state-of-the-art c-Si:Er co-doped with oxygen [50], and provides verification of the method and approximations used in this work.

We note that the percentage of photon-emitting Er dopants obtained for the Si/Si:Er multilayer structure NLA from PL saturation level is comparable to that achieved in the best Si:Er materials prepared by ion implantation. We point out, that in view of the relatively long radiative lifetime of Er in Si $\tau_{\text{rad}}$ used here for concentration evaluation, the estimated percentage should be seen as the lower limit.

Alternatively, the amount of Er$^{3+}$ ions participating in the radiative recombination can be estimated from the linear part of the excitation power dependence under pulsed excitation. Such an approach seems more appropriate, since the simple excitation model used here does not take into account
various cooperative processes which are important in the saturation regime. The linear part of integrated PL intensity, determined as the number of photons emitted after each laser pulse, is given by:

\[
I_{\text{Si:Er}} = \sigma_{\text{Si:Er}} \varepsilon \Phi_{\text{Si:Er}} N_{\text{Si:Er}}^{\text{act}} \Delta t \frac{\tau}{\tau_{\text{rad}}}, \quad \text{and} \\
I_{\text{SiO}_2:\text{Er}} = \sigma_{\text{SiO}_2:\text{Er}}^{520 \text{ nm}} \Phi_{\text{SiO}_2:\text{Er}} N_{\text{SiO}_2:\text{Er}}^{\text{act}} \Delta t \frac{\tau}{\tau_{\text{rad}}}
\]

(2.7)

for the Si:Er and SiO₂:Er samples, respectively. The correction factor ε indicates photon loss due to surface reflection of Si. For a Si-air interface at normal incidence, this can be estimated as ε = 70% \[12\]. Reflection loss for SiO₂ is negligible. The linear component for samples NLA and NLB is derived fitting the data depicted in Fig. 2.6.

Figure 2.6: Linear part of the PL dependence on the excitation power. The curves are taken from Fig. 2.4 but focusing on the linear region.

Those curves are the same as in Fig. 2.4 but taking into account only the initial linear part. The values are scaled with the linear dependence found.
for the SiO$_2$:Er “standard” sample STD. When corrected for the shape of individual spectra, the lifetime, and with the average excitation cross-section as determined earlier and now scaled for Si absorption at 520 nm, we can estimate the upper limit of the total concentration of excitable Er$^{3+}$ ions $[N_{\text{ex}}^\text{Er}]_{\text{MAX}}$. In that way, we get the $[N_{\text{ex}}^\text{Er}]_{\text{MAX}}$ values of $25 \pm 10\%$ and $48 \pm 20\%$ for samples NLA and NLB, respectively.

<table>
<thead>
<tr>
<th>Method</th>
<th>Sample</th>
<th>NLA</th>
<th>NLB</th>
<th>IMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturation</td>
<td>2±0.5</td>
<td>15±5</td>
<td>6.6±1</td>
<td></td>
</tr>
<tr>
<td>Linear</td>
<td>25±10</td>
<td>48±20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1: Percentage of optically active Er ions in the investigated set of samples.

It is important to point out that these values correspond to an idealization when no effects related to the increased concentration of Er in the excited state are taken into account. Nevertheless, they are of importance, indicating the upper limit of Er activation. The obtained optical activity of multinanolyer samples is summarized in Table 2.1. Also the saturation value for the IMP sample is shown for comparison.

2.2.2 Si/Si$_{1-x}$Ge$_x$:Er nanolayers

Following the same procedure as for Si/Si:Er multilayers, optical activity has been determined for the Si/Si$_{1-x}$Ge$_x$:Er structures described in Sec. 1.1.2.

PL spectra of the three samples (see Fig. 2.7) do not present significant differences in shape, only intensity of PL changes and it reaches maximum in the sample 168III, the one with the greatest concentration of defects. Er$^{3+}$ ions form similar centers in the samples as confirmed by the identity of spectral shapes. Intensity of PL, however, increases with the concentration of defects.

Also decay curves do not show any difference, therefore only the one obtained for sample 168II has been shown in Fig. 2.8 for sake of clarity. The fact that effective lifetime is the same for all samples means that non-radiative processes are similar, regardless on the concentration of defects. For all samples two lifetime components are obtained by a double exponential fit. Since they are very close to each other, $\sim 0.73$ and $\sim 1.3$ ms, and have comparable amplitudes, the decay dynamics can be well approximated by an average of 1 ms.

Fig. 2.9 shows the PLE spectrum of the sample 168III. In a PLE spectrum, PL is recorded in function of the excitation energy and Er$^{3+}$ ions are indirectly excited, therefore PLE is proportional to absorption of light in the medium; the
2. Optical activity of Er$^{3+}$ ions in Si/Si:Er nanolayers

Figure 2.7: PL spectra for the three Si/Si$_{1-x}$Ge$_x$:Er nanolayers. The spectra of structures 185II and 142II are multiplied by a factor 4.

The dependence in Fig. 2.9 can be interpreted as the absorption spectrum of the sample. Again, similar spectra have been obtained for all three investigated samples.

Usually, for Si, absorption is higher at high excitation energy, and decreases monotonically with decreasing photon energy approaching zero at the energy of the bandgap. The experimental dependence shown in Fig. 2.9 does not follow that behavior. In fact, absorption is lower at higher energy and a peak is detected when excitation energy is slightly above the band gap. We note that a similar feature (although much less intense and with a different shape) has been also reported in the Si:Er multinanolayers [51,52].

In that case, the appearance of this peak has been related to a resonant excitation mechanism of the Er$^{3+}$ ions. Er excitation proceeds, in case of over bandgap illumination, via four steps: creation of electron-hole pairs, formation of excitons, binding of excitons to the Er-related donor level, energy transfer to Er. The first two steps can be skipped by direct creation of excitons bound
Figure 2.8: Decay curve of PL for one of the samples, 168III. Two decay components have been identified. Curves for the other two samples are omitted since no substantial difference have been recorded.

to the Er-related donor center. In order to do that, the right amount of energy has to be provided to the system. The energy necessary for this direct creation of bound excitons is [52]:

\[ E_R = E_G - E_{FEX} + E_{LO} - E_{BE}, \]  \hspace{1cm} (2.8)

where \( E_R \) is the required energy for the process, \( E_G \) the band gap, \( E_{FEX} \) the exciton formation energy, \( E_{LO} \) the energy of the lattice phonon (necessary because of the indirect nature of the bandgap) and \( E_{BE} \) the exciton-donor binding energy. Taking values of these parameters for Si, namely \( E_G = 1.17 \) eV, \( E_{FEX} = 0.015 \) eV, \( E_{LO} = 0.063 \) eV and \( E_{BE} = 0.0218 \) eV, \( E_R \) assumes the value of 1.19 eV, exactly as measured in the PLE spectrum. This is strange since energies of the bandgap \( E_G \) and of the optical phonon \( E_{LO} \) actually

\[ \text{For effective-mass donors, } E_{BE} \approx 10\% E_D \text{ commonly. For Si, the Er-related donor level } E_D \text{ was determined to be equal to 218 meV.} \]
depend in $\text{Si}_{1-x}\text{Ge}_x$ alloy on the Ge content $x$ with in the following way (at 4 K and for $x < 0.85$ \cite{25,53,54}):

$$E_G = 1.17 - 0.43x + 0.206x^2 \text{ eV}, \quad \text{and} \quad E_{LO} = 63 - 8.7x \text{ meV},$$ \hspace{1cm} (2.9)

Therefore for the material used we get the values of $\sim 1.07 \text{ eV}$ and $\sim 60.6 \text{ meV}$ for $E_G$ and $E_{LO}$ respectively, and consequently the direct Er excitation should be obtained for $E_R \approx 1.09 \text{ eV}$. Moreover, the energy of the peak in the PLE spectra does not change for samples with different Ge contents. It follows that the energies of both band gap and optical phonons are not modified according to Eq. (2.9). This may be attributed to the fact that Er$^{3+}$ ions are positioned in Si rather than in the SiGe alloy, but, a final conclusions can not be made at this point.

In order to evaluate the optical activity of Er$^{3+}$ ions in SiGe alloy, Fig. 2.10
Figure 2.10: Power dependence of Er PL in sample 168III for the three different excitation energies marked in Fig. 2.9. For comparison, power dependence of the reference sample is shown (linear curve).

compares power dependencies of Er-related emission from the sample 168III for the three different excitation wavelengths indicated in Fig. 2.9 and from the SiO$_2$ reference sample. Analog as for Si:Er multinanolayers, a scale for the density of excited state is obtained and after the necessary corrections a value for the percentage of optical activity is determined for the three samples under investigation. For each sample, this percentage is calculated at the three excitation wavelengths as summarized by Table 2.2.

Highest percentage of optically active centers is achieved in all cases when excitation energy is set at 1.18 eV, namely at the peak in Fig. 2.9. The absolute maximum, found for sample 185II, of 4.2%, is comparable with the one determined in Si/Si:Er. We conclude that for Er in Si multinanolayer structures and in SiGe optical activity shows an intrinsic limit of a few percent.
2. Optical activity of Er$^{3+}$ ions in Si/Si:Er nanolayers

<table>
<thead>
<tr>
<th>Sample</th>
<th>Excitation Energy</th>
<th>1.18eV</th>
<th>1.38eV</th>
<th>2.42eV</th>
</tr>
</thead>
<tbody>
<tr>
<td>168III</td>
<td></td>
<td>2.4%</td>
<td>0.74%</td>
<td>0.56%</td>
</tr>
<tr>
<td>185II</td>
<td></td>
<td>4.2%</td>
<td>1.9%</td>
<td>0.97%</td>
</tr>
<tr>
<td>142II</td>
<td></td>
<td>1.6%</td>
<td>0.83%</td>
<td>0.83%</td>
</tr>
</tbody>
</table>

Table 2.2: Optical activity of the three investigated Si/Si$_{1-x}$Ge$_x$:Er nanolayers structure. The percentage of optical active centers has been determined for three excitation wavelengths to distinguish among different excitation mechanisms.

2.3 Conclusions

Based on the presented results, we conclude that the percentage of Er dopants undergoing radiative recombination and contributing to the 1.5 $\mu$m emission in SMBE-grown Si nanolayers is similar to that realized in the best Si:Er structures prepared by ion implantation. But, in contrast to the implanted material, all the Er emitters in the NLA structure are incorporated in a single type of optical center, resulting in the ultra narrow homogeneous linewidth of PL bands. Moreover, the already relatively high percentage of emitting Er$^{3+}$ ions as found for the Si/Si:Er nanolayer structure NLA can possibly be further improved. This prospect is justified by results obtained for sample NLB, for which our estimate gives the active Er fraction in excess of 10%, with the upper limit being comparable with the total Er contents. Future research will tell whether also for such a structure an appropriate thermal treatment can preferentially convert emitting centers into the Er-1, as was the case for NLA. We point out that the calculated high percentage of Er dopants which contribute to the 1.5 $\mu$m emission in Si/Si:Er nanostructures corresponds to the absolute concentration which is similar to the solid solubility limit of Er in crystalline Si [55]. The high percentage of emitting dopants combined with the ultra-narrow emission lines makes the Si/Si:Er multinanolayers materials interesting for silicon photonics. In particular, the Si/Si:Er nanolayer structures appear promising for realization of population inversion and, consequently, optical amplification at low temperature. The situation is similar in Si/Si$_{1-x}$Ge$_x$:Er nanolayers where also Er optical activity of a few percentage has been recorded.