Temperature dependence and quenching processes of the intra-4f luminescence of Er in crystalline Si

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The luminescence quenching of Er in crystalline Si at temperatures between 77 and 300 K is investigated. Samples were prepared by solid-phase epitaxy of Er-implanted amorphous Si layers with or without O codoping. After epitaxial regrowth at 620 °C, thermal annealing at 900 °C for 30 sec was performed in order to eliminate residual defects in the regrown layer and electrically and optically activate the Er ions. Measurements of photoluminescence intensity and time decay were performed as a function of temperature and pump power. By increasing the temperature from 77 K to room temperature the luminescence intensity decreases by $\sim$ three orders of magnitude in the Er-doped sample without O codoping, but only by a factor of 30 in the O-doped sample. In this sample room-temperature photoluminescence and electroluminescence have been observed. Time-decay curves show a fast initial decay ($\sim$100 μsec) followed by a slow decay ($\sim$1 msec), with the relative intensity of these two components depending on temperature, pump power, and O codoping. The decay curves can be fitted by a sum of two exponential functions revealing the existence, in both samples, of two different classes of optically active Er sites. The concentration of excitable sites belonging to the slow-decaying class is similar for the samples with or without O codoping and rapidly decreases when temperature is increased. At temperatures above 150 K the Er luminescence is dominated by the fast-decaying centers the concentration of which is greatly increased by the presence of O. It is found that in the absence of oxygen room-temperature luminescence is hampered by the limited amount of excitable Er ions. In contrast, in O-doped samples the nonradiative decay of excited Er is the main quenching mechanism. The main factors determining the temperature quenching of Er luminescence and the crucial role of oxygen are discussed.

I. INTRODUCTION

The optical behavior of rare-earth atoms in semiconductors is a field of current interest in view of the potential applications to optoelectronic devices.[1,2] Rare-earth ions in their 3+state show luminescence from intra-4f-shell transitions the wavelength of which is almost independent of the host matrix. Er^{3+} ions produce light emission from the $^4I_{13/2} \rightarrow ^4I_{15/2}$ transition at around 1.54 μm, which is a particularly interesting wavelength since it falls in a window of maximum transmission for optical fibers. Silicon is the semiconductor with the most mature processing technology, but light emission from this material is hampered by its indirect-energy gap. The introduction of Er ions in silicon has therefore been recognized as a promising and interesting approach to obtain electrically induced light emission from this important material.[3-6]

Extensive studies have been performed on the Si:Er system both from theoretical[7] and experimental[8-16]

points of view, and several major problems limiting the Er luminescence in silicon have been solved. For instance, using nonequilibrium solid-phase epitaxy it has been demonstrated that it is possible to obtain Er incorporation in Si at concentrations as high as $1 \times 10^{20}/cm^3$ (Refs. 8, 9, and 15) without the formation of precipitates. Furthermore, evidence has been found for a strong interaction between oxygen and the implanted Er.[9-13] Oxygen coimplantation also enhances both the Er luminescence intensity in Si (Refs. 3, 9, and 11) and the Er donor concentration, which is found to increase by several orders of magnitude.[4,9,12] These similarities suggest that electrical and optical activations of Er in Si are correlated, i.e., the Er donor behavior might be associated with the optically active Er^{3+} state.

In spite of the large amount of experimental data, the strong temperature dependence of the luminescence,[3,6] resulting in a decrease as large as three orders of magnitude on going from 77 to 300 K, has not yet been understood. This temperature quenching is at the moment the

major limiting factor to the achievement of intense room-temperature luminescence. This decrease for increased temperatures can be the result of (i) a reduced pumping efficiency, (ii) a reduced number of excitable optically active sites, (iii) an increased efficiency of nonradiative deexcitation processes, or a combination of these three cases. In order to discriminate among these different mechanisms, detailed measurements of the excitation and nonradiative deexcitation of optically active Er^{3+} ions are required.

In this paper we present a study of the temperature and pump power dependence of the 1.54-μm luminescence intensity and time decay of Er-doped Si. We demonstrate that temperature quenching can be caused by the onset of nonradiative relaxation of excited Er, and by a decrease in the concentration of excitable sites as the temperature is increased. In addition, it is shown that oxygen strongly reduces the effect of temperature quenching. As a result, room-temperature photoluminescence and electroluminescence have been achieved in Er-doped Si codoped with oxygen. These data are presented and discussed.

II. EXPERIMENT

Samples of n-type Czochralski (CZ) Si, (100) oriented, were implanted with Er at 77 K using several different ion energies (ranging from 0.5 to 5 MeV) in order to obtain an approximately constant Er concentration of 1×10^{19}/cm^3 between 0.3 and 2 μm below the surface. In addition to Er, the samples were coimplanted with oxygen at several different energies in the range 0.15–1.4 MeV to produce an almost constant O concentration of 1×10^{20}/cm^3 in the Er-doped region. These implants produce a continuous amorphous layer extending from the surface to a depth of 2.3 μm. Similar implants were also performed on a Si p^+-n diode having an area of 0.25 cm^2, and the resulting device was used for electroluminescence measurements.

After implantation the samples were annealed in vacuum at 620 °C for 3 h, resulting in epitaxial recrystallization of the amorphous layer, as confirmed by transmission electron microscopy analyses. Additional annealing was performed in a rapid thermal anneal furnace under nitrogen flux at 900 °C for 30 sec in order to activate, both optically and electrically, the implanted Er. It has been shown that the Er segregation,[8] usually occurring at the moving crystal-amorphous interface, is inhibited in presence of oxygen[9,13,15] and, as a result, all of the Er is completely trapped in the regrowing crystal. Spreading resistance measurements[9] have demonstrated that 50% of the incorporated Er is electrically active. Therefore the previous recipe results in the formation of a ~2-μm-thick good quality single-crystalline layer containing almost constant concentrations of 1×10^{19} Er/cm^3 and 1×10^{20} O/cm^3. This sample will hereafter be referred to as O doped.

Er was also implanted in CZ-Si (containing ~1×10^{18} O/cm^3) without O coimplantation. In the absence of intentionally implanted oxygen, Er segregation occurs during the regrowth and, above a critical Er concentration,

interface instabilities take place inhibiting the regrowth of thick layers.[8,9,15] In thinner layers (~160 nm), however, complete regrowth can occur with the incorporation of ~1×10^{20} Er/cm^3.[8] We have therefore incorporated Er in a ~80-nm-thick layer at a concentration of ~1×10^{20}/cm^3 in order to have a similar total amount of implanted Er as in the O-doped sample. This sample was implanted with 9×10^{14} Er/cm^2 at 250 keV, and recrystallized at 600 °C for 15 min in vacuum, and activated by further heating under nitrogen flux at 900 °C for 15 sec. Spreading resistance analyses on this sample showed that only ~0.5% of the incorporated Er is electrically active. This sample will hereafter be referred to as undoped.

Photoluminescence spectroscopy was carried out using the 514.5-nm line of an Ar$^+$ laser as a pump source. The pump power in the ~1-mm-diameter spot was varied between 10 and 500 mW, and the pump beam was mechanically chopped at 55 Hz. The luminescence signal was analyzed with a spectrometer and detected with a liquid-nitrogen-cooled Ge detector. Spectra were recorded using a lock-in amplifier with the chopper frequency as a reference. Luminescence lifetime measurements were performed by monitoring the decay of the luminescence after pumping to steady state and mechanically switching off the light source. The overall time resolution of the system was 30 μsec. The decay curves were recorded and averaged using a digitizing oscilloscope system. Low-temperature measurements were performed using a liquid-nitrogen-cooled cryostat with the samples kept in vacuum. Electroluminescence measurements were carried out by biasing the diode with a square pulse at 55 Hz.

III. RESULTS

In Fig. 1, measurements of photoluminescence (PL) intensity at 1.538 μm as a function of the reciprocal temperature are reported. The data are taken for both undoped and O-doped samples at a constant pump power of
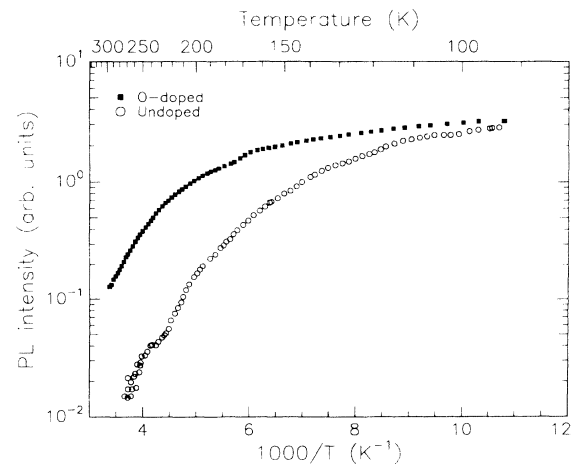

FIG. 1. Temperature dependence of the photoluminescence intensity at 1.538 μm for both the undoped (circles) and O-doped (squares) samples. Data are taken at a constant pump power of 200 mW.

200 mW. The PL intensity in the undoped layer decreases with increasing temperature with a behavior similar to that reported in the literature,[3,6] and shows two distinct regions. At low temperatures the decrease is quite gentle, and can be described by an apparent activation energy of only ~ 20 meV. On the other hand, at higher temperatures, a more dramatic decrease in the PL intensity is observed. This process is characterized by an apparent activation energy of ~ 150 meV and is responsible for the large thermal quenching of the Er luminescence in Si. In fact, no room-temperature luminescence is observed from this sample.

The temperature dependence of the O-doped sample also shows two distinct regions with apparent activation energies of ~ 20 and ~ 150 meV. However, the process responsible for the high-temperature quenching is clearly less efficient in this sample, and starts dominating at higher temperatures with respect to the undoped sample. Therefore, in spite of the fact that at 77 K the luminescence intensity is almost similar in the two cases, for higher temperatures, a much higher intensity is observed for the O-doped sample than for the undoped one. In fact, room-temperature luminescence is observed in this sample. This is shown in Fig. 2(a), where the PL spectra are shown for two different pump powers. It is interesting to note that the yield does not saturate with increasing pump power.

Photoluminescence excitation spectroscopy has been performed on the O-doped sample using six different lines from the Ar$^+$ laser in the wavelength range 476.5–514.5 nm. It has been found that the PL intensity is independent of pump wavelength within 10%. This indicates
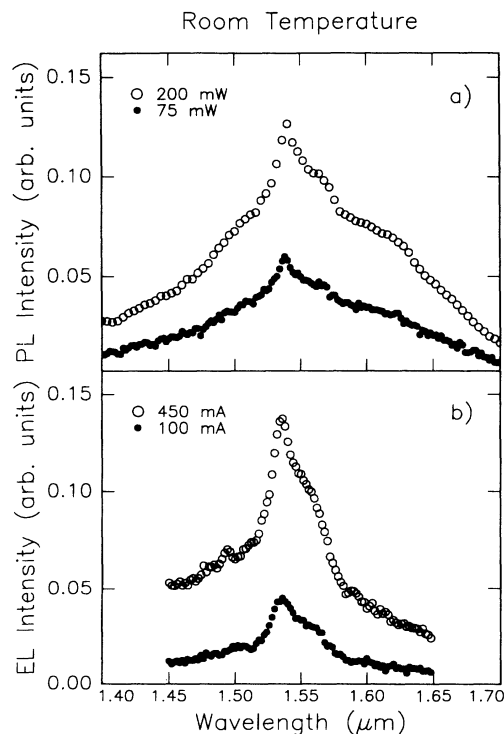
that Er is excited not by direct absorption but by a photocarrier-mediated process. Further evidence for this electrical excitation is provided by the fact that room-temperature electroluminescence (EL) also can be obtained from this sample when Er and O codoping is realized in the active region of a p^+-n diode. Our room-temperature EL spectra are shown in Fig. 2(b) for two different currents through the device. EL of Er in Si has been reported previously up to 230 K,[3] and only very recently a report was made for room-temperature EL.[17] The achievement of room-temperature EL therefore demonstrates that the fabrication of Er-doped layers by solid-phase epitaxy and oxygen codoping is a very promising approach.

PL time-decay measurements provide important information about the processes leading to quenching luminescence. We have therefore measured the time decay of the PL intensity at 1.538 μm in both O-doped and undoped samples at different temperatures. The results are shown in Fig. 3 for the O-doped sample and for a fixed pump power of 200 mW. The PL intensities are normalized to the initial value after the pump pulse was shut off at $t = 0$. At each temperature the time decay is characterized by an initial fast decay ($\tau \sim 100$ μsec) followed by a slow decay ($\tau \sim 900$ μsec). As the temperature is increased the contribution of the fast-decay component increases in magnitude. Eventually at 180 K the PL decay is nearly entirely determined by the fast component.

Previous studies[9] have shown that the dependence of the PL intensity on the pump power at a fixed temperature provides important information about the Er excitation process. Here we have also performed PL intensity measurements in combination with time-decay measurements also as a function of pump power. As an example, in Fig. 4 the PL decay for the O-doped sample is shown at a fixed temperature of 77 K and at different pump powers. All decay curves are normalized to the intensity at $t = 0$. Again, the decay curves are characterized by fast and slow components. Interestingly, the time evolution of the PL intensity, after the excitation pulse is turned
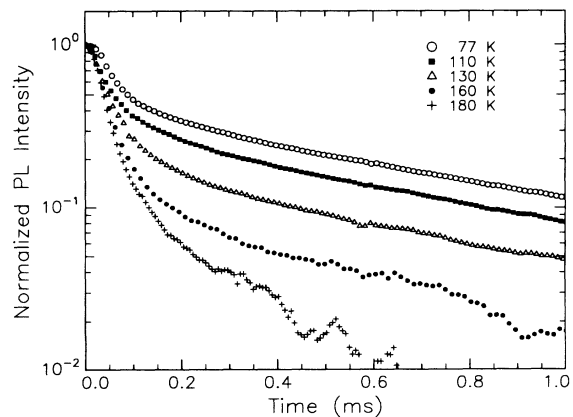

FIG. 2. Room-temperature photoluminescence (a) and electroluminescence (b) spectra for the O-doped sample.

FIG. 3. Time decay of the 1.54-μm luminescence in the O-doped sample at different temperatures. Data are taken after shutting off a 200-mW pump pulse and are normalized to the initial value.
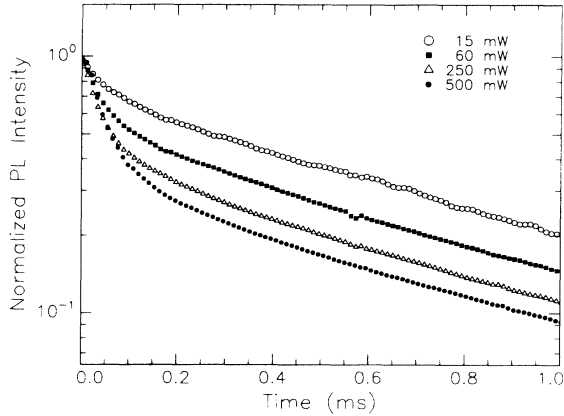
FIG. 4. Time decay of the 1.54-μm luminescence in the O-doped sample after excitation using different pump powers. Data are taken at a constant temperature of 77 K and are normalized to the initial value.
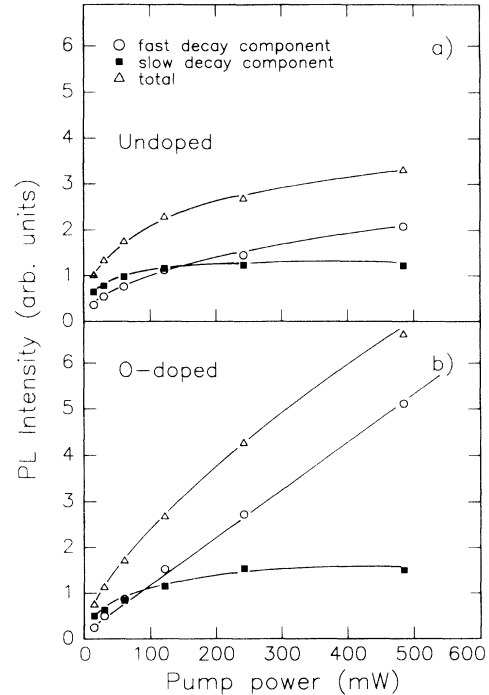

FIG. 5. PL intensity as a function of pump power for the undoped (a) and O-doped (b) samples at a temperature of 77 K. The total intensity (triangles) and the fast- (circles) and slow-decay (squares) components, as obtained from an analysis of the time-decay data, are shown.

off, is strongly dependent on pump power, and the fast-decay component dominates at high pump powers.

The time-decay data for the undoped sample (not shown) present similar features to those reported above as a function of both temperature and pump power.

All the time-decay curves can be fitted by the sum of two exponentially decaying components. This suggests that two different classes of Er^{3+} ions, having different nonradiative decay routes, are present in both samples. Under this assumption, it is possible to obtain from the fits the relative amounts and the lifetimes of the excited Er atoms belonging to the two classes under the different conditions of temperature and pump power.

We first discuss the decomposition of the pump power dependence data. At a fixed temperature, the fits of the time-decay data (see Fig. 4) give constant lifetimes for the two decay components regardless of the pump power, with only the relative intensities changing with power. This further supports the idea of the existence of two classes of Er ions with different decay routes. In Fig. 5 the PL intensity at 77 K is shown as a function of the pump power. The total intensity is reported together with the intensities of the fast- and slow-decay components as obtained from the decomposition of the experimental time-decay curves into the two classes. Data are shown for both undoped [Fig. 5(a)] and O-doped [Fig. 5(b)] samples. The total intensity shows a sublinear increase with pump power, as reported before.[9] A decomposition of the total yield demonstrates that in the undoped layers both slow- and fast-decay components saturate as the power is increased. In contrast, in the O-doped sample only the slow-decay component saturates, while the fast component increases linearly with pump power. These data suggest that the two different luminescent Er configurations exist at different concentrations in each sample. The one having a long lifetime is present in both samples in a very limited amount, and its excited-state population is already saturated at low pump powers. The other one, with a small lifetime, is also present in limited quantity in the undoped layers (where it also saturates). In the O-doped sample, instead, its amount is

greatly increased and hence the PL intensity originating from this center continuously increases with increasing pump power.

The temperature dependence data of the PL intensity in Fig. 1 has also been decomposed into two different components by analyzing the time-decay curves at different temperatures. The results of this analysis are shown in Fig. 6(a) for both undoped (closed symbols) and O-doped samples (open symbols). As a comparison the temperature dependence of the lifetime for both samples and for the two different components is reported in Fig. 6(b). The PL intensity of the slow-decaying component [circles in Fig. 6(a)] strongly decreases with increasing temperature in a similar fashion for both samples. For instance, on increasing the temperature from 77 to 200 K the intensity decreases by nearly two orders of magnitude. Also, the lifetime of the slow-decay component [circles in Fig. 6(b)] is identical in both samples, but its decrease on going from 77 to 200 K is only by a factor of 3 (from 900 to 300 μsec). The strong decrease in intensity shown in Fig. 6(a) for the slow component, therefore, cannot be explained by a change in the lifetime.

The PL intensity of the fast-decaying component [triangles in Fig. 6(a)] also decreases with increasing temperature. However, its decrease is more gentle and, in contrast to the slow-decay component, is different for the two samples. In fact, while in the undoped sample the yield decreases by about a factor of 8 on going from 77 to 200 K, in the O-doped one the decrease is only by a factor of 3. The lifetime of the fast-decaying component [see Fig. 6(b)], in agreement with the intensity data, changes
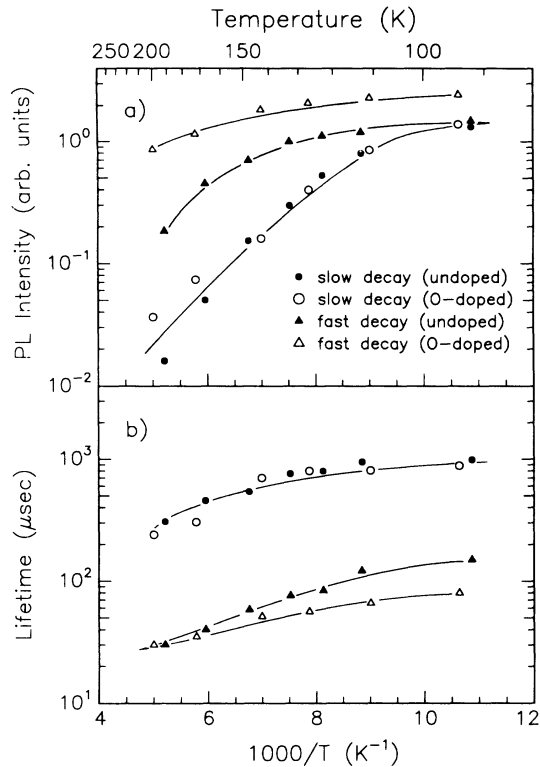
FIG. 6. Temperature dependence of the PL intensity (a) and the lifetime (b) for both the slow (circles) and fast (triangles) decay components. Data are shown for both the undoped (closed symbols) and O-doped (open symbols) samples.

more rapidly in the undoped sample than in the O doped. In fact, while this lifetime is a factor of 2 higher in the undoped sample at 77 K, at 180 K the lifetimes of the two samples are equal (40 μsec). This suggests that some correlation might exist between the temperature dependence of the intensity and of the lifetime for this component.

These data have several implications for our understanding of the mechanisms of Er luminescence in Si. A more detailed analysis, and a plausible excitation and deexcitation scenario, are reported in Sec. IV.

IV. DISCUSSION

On the basis of the experimental data reported so far, the following picture can be proposed. Two different classes of optically active Er^{3+} sites exist in Si. One of these is present in limited amount and decays with a long lifetime (~ 1 msec). When the temperature is increased, the contribution of this site vanishes.

The other optically active Er^{3+} site decays with a fast process (~ 100 μsec), and its concentration can be largely increased by the presence of O. Since O also enhances the Er donor behavior,[9,12] it seems plausible that this fast-decaying center is associated with a donor level in the Si band gap. When temperature is increased, quenching also occurs for this class. In particular, since at temperatures above 150 K the total PL intensity is dominated by this fast component [see Fig. 6(a)], the quenching

process with an activation energy of 0.15 eV (see Fig. 1) has to be attributed to phenomena occurring at this fast-decaying center.

The question arises: what is the process that quenches the luminescence at high temperatures? In order to answer this question, the processes determining the luminescence yield should be analyzed in more detail. The luminescence intensity I of Er in Si is, in general, given by

$$I \propto N_{Er}^{*} W_{rad} \ , \tag{1}$$

where N_{Er}^{*} is the number of excited Er atoms, and W_{rad} is the spontaneous emission rate. N_{Er}^{*} is determined by excitation and deexcitation processes. If the number of excitable Er atoms N_{Er} is large (or the pump power is low), and assuming that recombination at Er is the main carrier recombination route, then

$$\frac{dN_{Er}^{*}}{dt} = KR - \frac{N_{Er}^{*}}{\tau_d} \ , \tag{2}$$

with R the carrier generation rate, which is proportional to the pump power, K the total probability of excitation (through electron-hole-mediated processes), and τ_d the deexcitation lifetime accounting for both radiative and nonradiative processes. In steady state, $dN_{Er}^{*}/dt = 0$, so that

$$N_{Er}^{*} = KR\tau_d \ . \tag{3}$$

If, on the other hand, N_{Er} is small (or the pump power is large), all of the excitable atoms will be excited, so that

$$N_{Er}^{*} \simeq N_{Er} \ . \tag{4}$$

Therefore, for a fixed pump power, if N_{Er} is large, the PL intensity is controlled by the lifetime, while if N_{Er} is small the PL intensity is limited by the density of optically active sites.

The PL intensity for the slow component is always saturated at pump powers of ~ 200 mW at all temperatures explored and for both the undoped and O-doped samples. This implies that all of the excitable Er atoms belonging to this component are excited. Therefore, according to Eqs. (4) and (1), the strong decrease in the PL intensity for this component [data in Fig. 6(a)] cannot be caused by a reduction in lifetime, but it has to be associated with a decrease in the concentration of excitable Er centers (neglecting a temperature dependence of W_{rad}). We can speculate that the slow-decaying site is a very shallow donor, and soon ionizes when the temperature is increased. If excitation occurs, as previously proposed,[9] through the nonradiative recombination of an exciton bound to a neutral Er donor, ionization will inhibit the excitation of this site, as observed experimentally.

A similar argument can be made for the fast-decaying centers in the undoped sample, since these sites are also all excited at pump powers of ~ 200 mW. Therefore the temperature quenching of this component also has to be attributed to a reduction in the number of excitable centers. Since at temperatures > 150 K only the fast-decaying centers are present, this reduction is responsible

for the three orders of magnitude temperature quenching observed for the undoped sample, and typically reported in literature.[3,6] Once more, we speculate that this decrease might be associated with the ionization of the optically active sites.

A different picture emerges for the fast-decaying class in the O-doped sample. In this case we have observed that the pump power dependence is always linear at all temperatures investigated, demonstrating that only a fraction of the excitable atoms are excited. According to Eqs. (3) and (1), the temperature quenching of the luminescence is not associated with the reduction in the number of excitable atoms (since enough excitable centers are present even at room temperature) but is due to a reduction in the decay lifetime τ_d. Indeed in the temperature range measured, the fast-decay lifetime and the relative PL intensity have an identical temperature dependence (in the O-doped sample). This is particularly clear when these two quantities are compared on the same plot and on a linear scale, as in Fig. 7. Due to the time resolution of our system, we have no measurements at temperatures higher than 200 K, but it seems plausible that this correlation continues to hold at higher temperatures.

A temperature quenching in the luminescence resulting from a decrease in the lifetime is not unique for Er in Si, but has also been reported, for instance, for Yb in InP.[18,19] In that system it has been proposed[18,19] that quenching is due to a back-transfer process of the energy. We think that these two systems present several similarities, and that the quenching mechanism also might be similar. This process can be explained schematically as follows. It is known from deep-level transient spectroscopy measurements[4,20] that Er introduces several levels, one of which lies at ~0.15 eV below the conduction band.[4,20] An exciton can be bound to this level and excite the Er^{3+} ion by a nonradiative energy transfer.[9,21] The energy of the excited Er (0.8 eV) can be transferred back by exciting an electron from the Si valence band to this donor level. To do that, extra energy of 0.15 eV is required.

This energy is equal to the experimentally observed activation energy of the quenching.

A few more comments should be made. An estimate of the number of emitting centers can be made by comparing the PL intensity in our samples with that of an Er-doped SiO_2 sample measured under the same experimental conditions. The SiO_2 sample was implanted at an Er fluence of $1 \times 10^{15}/cm^2$, and the measurements were performed at a pump power of 500 mW. The measured PL intensity, both for Er-doped Si and for Er-doped SiO_2, is in general given by

$$I = \gamma \eta_t N^*_{Er} W_{rad} \qquad (5)$$

γ being a constant taking into account all parameters related to the photoluminescence apparatus (transmission through the monochromator, detection efficiency, etc.) used, and η_t the fraction of emitted photons that are collected in the apparatus. By comparing the PL intensities in the two samples (and taking into account that γ is a constant dependent only on the experimental setup) the number of excited atoms in the Si sample ($N^*_{Er}(Si)$) can be derived as

$$N^*_{Er}(Si) = \frac{I(Si)}{I(SiO_2)} \frac{\eta_t^{SiO_2}}{\eta_t^{Si}} \frac{W_{rad}(SiO_2)}{W_{rad}(Si)} N^*_{Er}(SiO_2) . \qquad (6)$$

The ratio $\eta_t^{SiO_2}/\eta_t^{Si}$ can be calculated taking into account that, due to the different refractive indexes in Si and SiO_2, for a constant solid angle of collection a different solid angle of emission is explored inside the sample. In Eq. (6) the intensities are experimentally measured under identical conditions, the ratio $\eta_t^{SiO_2}/\eta_t^{Si}$ is calculated as explained above, the radiative lifetimes are assumed to be 1 and 15 msec for Er in Si and in SiO_2, respectively, and $N^*_{Er}(SiO_2)$ is estimated from the following expression:

$$N^*_{Er}(SiO_2) = N_{Er} \sigma \phi_{in} , \qquad (7)$$

σ being the cross section for the direct excitation of Er in SiO_2 that, according to the literature, we assume to be ~8×10^{-21} cm^2,[22] and ϕ_{in} the incident photon flux. According to this calculation, we find that in the undoped layer at 77 K and in the saturation region [see Fig. 5(a)] the areal density of excited Er atoms is ~$4 \times 10^{12}/cm^2$. This is a very small number when compared with the total amount of incorporated Er (~$10^{15}/cm^2$). It is interesting to note that the areal density of excited Er atoms is similar to that of the electrically active dose as measured by spreading resistance (~$5 \times 10^{12}/cm^2$). Though this argument is still controversial,[4,12,20] this observation strengthens the suggestion that only electrically active Er is excitable.

In the O-doped sample at 77 K and 500 mW, the areal density of excited Er atoms is $8 \times 10^{12}/cm^2$, of which $2.1 \times 10^{12}/cm^2$ belongs to the slow-decaying component, and $5.9 \times 10^{12}/cm^2$ to the fast-decaying component. Since the yield of the fast-decaying component in this sample never saturates for all the pump powers explored, this last number represents only a fraction of the total number of the excitable centers.

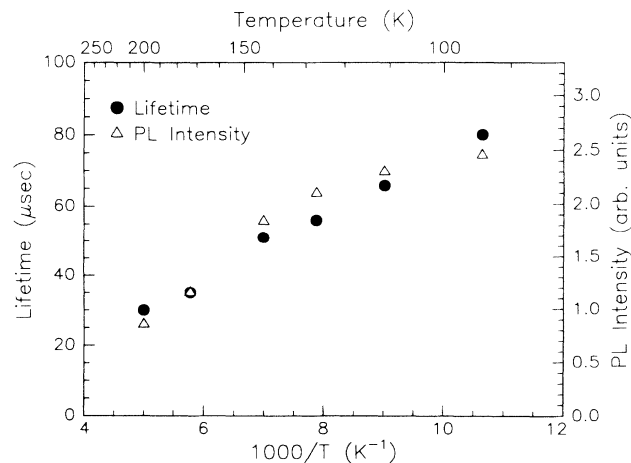Therefore, O codoping produces an increase in the

FIG. 7. Temperature dependence of the lifetime (circles) and of the PL intensity (triangles) of the fast decaying component. Data refer to the O-doped sample.

number of optically active sites larger than the factor of 3 observed experimentally at 77 K and at a pump power of 500 mW [see Fig. 5(b)]. The exact number of active sites in the O-doped sample cannot be estimated since the pumping efficiency does not allow us to reach saturation, but it is expected to be quite large on the basis of the possible correlation between optical activity and donor behavior. In fact, an electrically active dose of $1 \times 10^{15}/cm^2$ is obtained by spreading resistance measurements on this sample.

The results reported so far demonstrate that the role of impurities on Er luminescence cannot be explored fully by only comparing the luminescence intensity at a fixed temperature and pump power. In fact, as shown, the crucial role of oxygen only emerges when the temperature dependence is measured and the pump power dependence taken into account. The data clearly indicate that the major limitation to the achievement of intense room-temperature luminescence is not the limited number of excitable sites. Indeed, codoping with O produces a large increase in the number of excitable sites. On the other hand, nonradiative deexcitation processes are now limiting the pumping efficiency and maintaining the number of excited Er atoms at a low level. Most future work will be aimed at reducing or inhibiting the nonradiative process which dominates above 150 K, to enhancing the efficiency of pumping in order to excite all of the optically active sites, and/or to controlling the radiative emission processes as recently done for Er in SiO_2.[23,24]

V. CONCLUSIONS

In conclusion, we have investigated the temperature dependence of the luminescence intensity and lifetime in Er-doped crystalline Si. We have shown that the dramatic decrease in PL intensity with increasing temperature is noticeably reduced in the presence of O codoping, and that this permits the observation of both photolumines-cence and electroluminescence at room temperature. Lifetime measurements have proved the existence of two classes of optically active Er sites having slow (~ 1 msec) and fast (~ 100 μsec) decaying times at 77 K. Luminescence at temperatures above 150 K is given solely by the fast-decaying centers, and is limited by two major factors. The first is a reduction in the number of excitable Er atoms with increasing temperature. This phenomenon might be correlated with the ionization of the Er donor levels, and is the limiting factor in samples having small concentrations of optically active Er. The second is a decrease in the lifetime as a result of nonradiative relaxation of excited Er. This effect dominates when the number of excitable Er atoms is sufficiently high (as in O-doped samples). Therefore, the limiting step to the achievement of intense room-temperature luminescence from Er in Si is not the small number of the optically active Er atoms but the reduction of the nonradiative processes which are dominant above 150 K, as well as the efficient pumping of all excitable Er sites.

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