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Excitation cross section of erbium in semiconductor matrices under optical pumping

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Based on a detailed consideration of excitation mechanisms of erbium in crystalline and amorphous matrix we present an analysis of the physical meaning of the Auger excitation cross section of Er^{3+} ions in semiconductor. It is demonstrated that large values of Auger excitation cross sections under optical pumping in semiconductor matrices are due to large values of band-to-band absorption coefficient exceeding by several orders of magnitude the absorption coefficient of erbium in dielectric SiO_2 and $\mathrm{Al}_2\mathrm{O}_3$ matrix. The Auger excitation cross section of Er^{3+} in semiconductor matrices is roughly given by the ratio of the matrix absorption coefficient to concentration of Er^{3+} ions. While the analysis of the excitation cross section is carried out for Er-doped crystalline and amorphous silicon, the results are expected to be applicable to the other rare-earth doped semiconductors. Based on low-temperature experimental results for crystalline silicon we get the Auger excitation coefficient of $c_A^{\mathrm{cryst}} \approx 7\times10^{-10}\ \mathrm{cm}^3\mathrm{s}^{-1}$ and the effective excitation cross section $\sigma_{\mathrm{eff}}^{\mathrm{cryst}} = (2-8)\times10^{-12}\ \mathrm{cm}^2$. For amorphous silicon at 100 K we obtain $\sigma_{\mathrm{eff}}^{\mathrm{amorph}} \approx 1.4\times10^{-14}\ \mathrm{cm}^2$.

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I. INTRODUCTION

Semiconductor matrices doped with rare earth ions are of great interest for optoelectronics. A special attention is drawn at present to erbium since the wavelength of intrashell radiative transition from the first excited $^4I_{13/2}$ to the ground $^4I_{15/2}$ state of the $4f$ shell of the Er^{3+} ion coincides with the minimum of optical absorption losses in silica glass optical fiber communication lines. The efficiency of erbium excitation (excitation rate) is determined by the excitation cross section of erbium. It is an important characteristic needed for fabrication of laser and amplifier based on erbium-doped semiconductor matrices, controlling the pump power necessary to achieve population inversion.

The efficiency of erbium excitation under direct optical absorption in the dielectric matrix, for example, such as SiO_2 and $\mathrm{Al}_2\mathrm{O}_3$, is determined by the excitation cross section of erbium σ, which enters the rate equation

$$\frac{dN_{\mathrm{Er}}^*}{dt} = \sigma\Phi(N_{\mathrm{Er}} - N_{\mathrm{Er}}^*) - \frac{N_{\mathrm{Er}}^*}{\tau}, \tag{1}$$

where Φ is the photon flux, N_{Er} and N_{Er}^* are total concentrations of erbium ions and of excited erbium ions, respectively, and τ is the lifetime of erbium in the excited state. This equation describes the processes of excitation and deexcitation of erbium in a two-level scheme and σ is a real cross section of photon absorption by an erbium ion. The same equation can be used also for three-level excitation scheme that involves the second excited $^4I_{11/2}$ state, because the excitation relaxes fast to the $^4I_{3/2}$ state by nonradiative way. In this case σ is a real cross section of photon absorption by an erbium ion for transition from $^4I_{15/2}$ to $^4I_{11/2}$.

Experimental value of the excitation cross section may be deduced from the power dependence of the rise time of erbium photoluminescence (PL) intensity after switch-on of a rectangular pulse of optical pumping. Indeed, from Eq. (1) the rise time of the erbium luminescence intensity τ_{on} is determined as

$$\frac{1}{\tau_{\mathrm{on}}} = \frac{1}{\tau} + \sigma\Phi. \tag{2}$$

The excitation cross section can be also obtained from the experimental power dependence of erbium luminescence intensity. From the stationary solution of Eq. (1) the dependence of erbium luminescence intensity on photon flux should depend on the excitation cross section σ

$$I_{\mathrm{Er}} \propto N_{\mathrm{Er}}^* = \frac{\sigma\tau\Phi}{\sigma\tau\Phi+1} N_{\mathrm{Er}}. \tag{3}$$

For erbium in SiO_2 the experimentally determined value of σ is $8\times10^{-21}\ \mathrm{cm}^2$.[1]

In the same manner the excitation cross section is determined in the case of optical excitation of erbium in semiconductor matrix under band-to-band optical pumping. According to experimental data the erbium excitation cross section in crystalline silicon is by several orders of magnitude higher than that for direct absorption of photons in the dielectric SiO_2 and $\mathrm{Al}_2\mathrm{O}_3$ matrices.[2,3]

However, in semiconductor matrices excitation of erbium ions occurs mainly by free charge carriers in an Auger process[4] or via impact excitation by hot electrons in the case of electroluminescence from reversely biased *p-n* junctions.[5] In this case the excitation cross section of erbium σ entering in Eq. (1) and, therefore the formulas (2) and (3), should have another physical meaning. In contrast to dielectric matrices in which σ is nearly independent of matrix, in semiconductors σ should depend on the efficiency of the energy

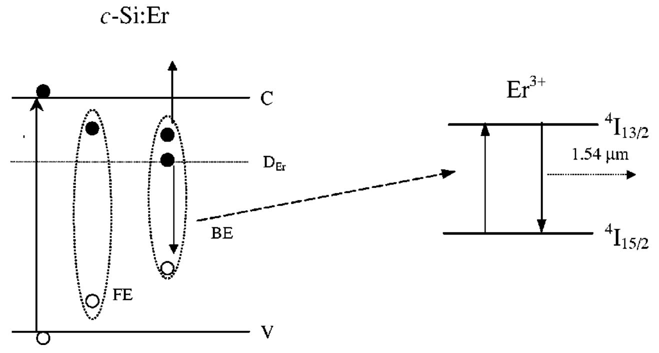

FIG. 1. Model of exciton mechanism of Er^{3+} excitation in crystalline Si.

transfer from photons to erbium ions via free carriers, i.e., should depend on characteristics of the semiconductor matrix doped with RE.

We present here an analysis of the physical meaning of the excitation cross section of erbium ions in semiconductor matrices, based on detailed consideration of excitation mechanisms under optical pumping in crystalline and amorphous silicon. We demonstrate that large values of excitation cross sections in crystalline *c*-Si and amorphous hydrogenated *a*-Si:H semiconductor matrices are due to a large band-to-band absorption coefficient exceeding by several orders of magnitude the absorption coefficient of erbium in the dielectric SiO_2 and Al_2O_3 matrices. The excitation cross section in semiconductor matrices is determined by the ratio of the matrix absorption coefficient to concentration of optical active erbium, which should be multiplied by a factor that depends on the ratio of the intensity of the channel transferring absorbed energy to the erbium ions to that of all the loss channels. The experimental results on excitation cross section of Er^{3+} ions in crystalline and amorphous silicon are presented and discussed.

II. CRYSTALLINE SILICON

A. Theoretical considerations

At low temperatures, the most probable excitation mechanism of Er^{3+} ions in crystalline silicon under optical pumping is by exciton recombination. In the case of band-to-band absorption in the matrix free excitons are formed. Neutral (at low temperatures) donors introduced by erbium and/or erbium-oxygen complexes easily capture them. Excitation of an erbium ion occurs via an Auger recombination of excitons in which the recombination energy is transferred by Coulomb interaction to an electron of $4f$ shell of the erbium ion. Alternatively the Auger process could take place at collisions of free excitons with donors associated with erbium ions. The presence of a donor electron favors the energy conservation in the Auger process.[6] This excitation mechanism is schematically illustrated in Fig. 1.

In order to describe the excitation process, we consider first the rate equations governing concentrations of free electrons and holes. We note that at low temperatures nonradiative recombination via deep centers is suppressed, and the recombination via shallow donor and acceptor centers is negligible. Though the capture cross section of electrons and holes by shallow Coulomb centers is sufficiently large, the interimpurity recombination rate is low, and shallow centers are instantly filled by charge carriers blocking this recombination channel. For this reason binding of free carriers into free excitons dominates at low temperatures and at fairly high pumping levels. Under these conditions rate equations for electrons and holes will have the form

$$\frac{dn}{dt}=\frac{dp}{dt}=\alpha\Phi-\gamma np, \tag{4}$$

where Φ is the flux of pumping photons, and α is absorption coefficient of silicon, n and p are the concentrations of nonequilibrium electrons and holes, respectively, and γ is the coefficient of the exciton binding process. The rate equation for free excitons can be written as follows:

$$\frac{dn_{\mathrm{ex}}}{dt}=\gamma np-\frac{n_{\mathrm{ex}}}{\tau_{\mathrm{ex}}}, \tag{5}$$

where τ_{ex} is the exciton lifetime.

We assume that the exciton lifetime is controlled mainly by nonradiative Auger processes associated with neutral Er-related donors or other impurities,

$$\frac{1}{\tau_{\mathrm{ex}}}\cong c_{\mathrm{im}}N_{\mathrm{im}}+c_{\mathrm{Er}}N_{\mathrm{Er}}+c_A(N_{\mathrm{Er}}-N_{\mathrm{Er}}^*), \tag{6}$$

where N_{Er} is a total concentration of optical active erbium, N_{Er}^* is the concentration of excited erbium, N_{im} is the concentration of other impurities, c_{im}, c_{Er}, and c_A are the capture coefficients of free excitons by impurities (including also optically nonactive erbium), erbium-related donor centers without erbium excitation and with erbium excitation, respectively. In Eq. (6) we took into account possible saturation of excited erbium, which leads to blocking of Er excitation process.

The rate equation, which describes excitation of erbium ions, has the form

$$\frac{dN_{\mathrm{Er}}^*}{dt}=c_An_{\mathrm{ex}}(N_{\mathrm{Er}}-N_{\mathrm{Er}}^*)-\frac{N_{\mathrm{Er}}^*}{\tau}, \tag{7}$$

where τ is the erbium lifetime in the excited state due to both radiative and nonradiative recombinations.

In order to analyze the rate equations (4)–(7), we shall separate our physical system into two subsystems. One of them (fast) has the relaxation times of all the processes involved not exceeding several microseconds: capture of free excitons by donors induced by erbium or some other impurities. The other one (slow) is characterized by a lifetime by two orders of magnitude larger: the lifetime of erbium ions in the excited state. Therefore we can regard the ‘‘fast’’ subsystem to be in a quasistationary state and get

$$n_{\mathrm{ex}}=\alpha\Phi\,\tau_{\mathrm{ex}}. \tag{8}$$

In this approximation, we can represent Eq. (7) as

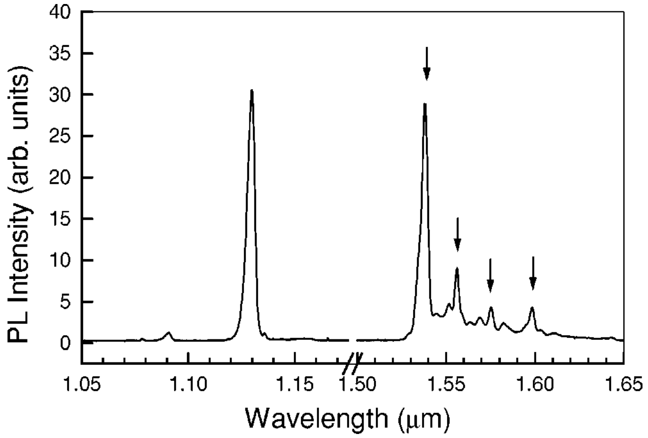

FIG. 2. Photoluminescence spectrum of Er-doped crystalline silicon under Ar laser excitation. Arrows indicate PL lines usually assigned to Er^{3+}-related optically active center of cubic symmetry.

$$\frac{dN^*_{\mathrm{Er}}}{dt}=\sigma_{\mathrm{eff}}\Phi(N_{\mathrm{Er}}-N^*_{\mathrm{Er}})-\frac{N^*_{\mathrm{Er}}}{\tau}, \tag{9}$$

where we have introduced the effective cross section of erbium excitation σ_{eff}:

$$\sigma_{\mathrm{eff}}=\alpha c_A \tau_{\mathrm{ex}}. \tag{10}$$

It is convenient for the analysis to present the effective cross section as a product of two factors:

$$\sigma_{\mathrm{eff}}=\frac{\alpha}{N_{\mathrm{Er}}}\,\frac{c_A N_{\mathrm{Er}}}{c_{\mathrm{im}}N_{\mathrm{im}}+c_{\mathrm{Er}}N_{\mathrm{Er}}+c_A(N_{\mathrm{Er}}-N^*_{\mathrm{Er}})}. \tag{11}$$

As can be seen from the formula (11), the excitation cross section of erbium is roughly determined by the first term and is inversely proportional to the concentration of optically active erbium. The excitation cross section depends not only on the absolute value of the capture coefficient c_A, but on the ratio of capture probability of free excitons by erbium-related centers with excitation of erbium ion and total probability of all the capture processes, as given by the second term in Eq. (11).

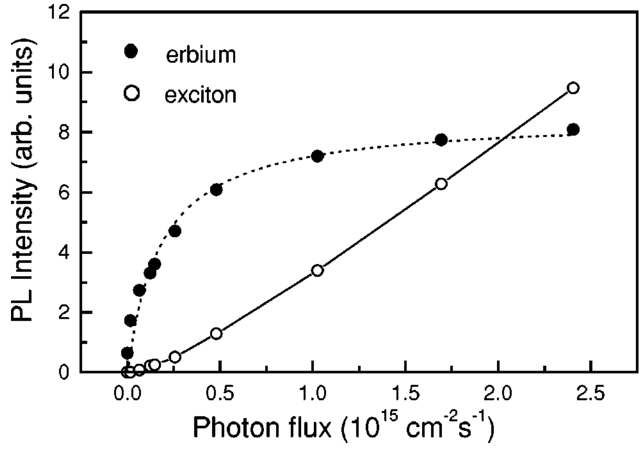

FIG. 3. Intensity of erbium and exciton photoluminescence as a function of pumping photon flux (Ar laser excitation). Dotted line is a fitting curve to Eq. (15) with $\sigma_{\mathrm{eff}}\tau=5.4\times10^{-15}$ cm^2 s, solid line is a guide for eye.

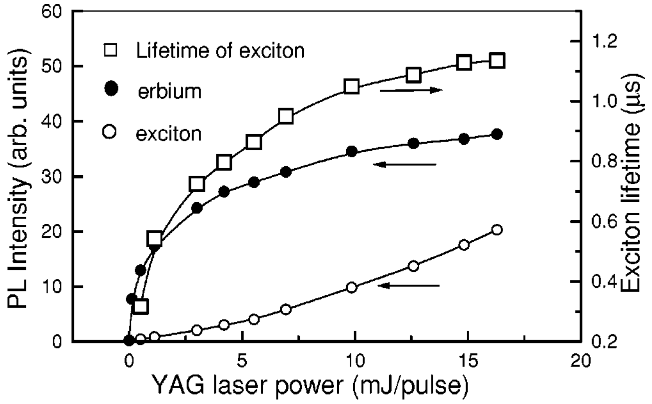

FIG. 4. Intensity of erbium and exciton photoluminescence and exciton lifetime as a function of power of pulsed Nd:YAG laser.

B. Experimental results

We have measured the effective excitation cross section of erbium in the crystalline silicon. A single-crystal $\langle 111\rangle$-oriented, *p*-type (B-doped) Czochralski-grown silicon wafer was implanted with Er ions at room temperature to a total dose of 3×10^{12} cm^{-2} with an energy of 300 keV. Oxygen was coimplanted at 40 keV to a total dose of 3×10^{13} cm^{-2}. The sample was annealed in N_2 for 30 min at 900 °C to recrystallize the implanted layer. The concentration of erbium in the implanted layer measured by SIMS method was 5×10^{17} cm^{-3}. Photoluminescence measurements were performed using the 514.5 nm line of an Ar laser. The PL signal was passed through a Jobin-Yvon THR 1500 grating monochromator, and detected with liquid nitrogen cooled Ge detector using standard lock-in techniques. The sample was placed on a cold finger of a closed cycle helium cryostat. All measurements were done at 20 K. Figure 2 shows a PL spectrum of the *c*-Si:Er sample in the 1–1.7 μm range. The luminescence peaks designated by arrows in the region of 1.54–1.6 μm correspond to the radiative transitions from the first excited state $^4I_{13/2}$ to the ground state $^4I_{15/2}$ of Er^{3+} ion. The observation of the several sharp lines is due to splitting of the $^4I_{15/2}$ ground state. The depicted spectrum is typical for erbium implanted in silicon. Phonon-assisted free exciton PL is observed at 1.13 μm. Figure 3 shows intensities of erbium (main peak at 1.54 μm) and exciton PL as a function of the photon flux (quasistationary conditions). As can be seen, the intensity of the exciton PL is very weak until the intensity of the erbium PL saturates.

Decay time measurements of erbium and exciton PL were performed using the $\lambda=532$ nm second harmonic of a Nd:YAG laser of nanosecond pulse duration. In this case we used a digitizing oscilloscope in combination with an InP/InGaAs nitrogen-cooled photomultiplier tube Hamamatsu R5509-72. The system response time was 0.1 μs. All measurements were done at 20 K. Figure 4 demonstrates dependences of decay time of exciton and intensities of exciton and erbium luminescence on power of the Nd:YAG laser, under pulsed excitation conditions. As can be seen, the exciton lifetime is approximately 0.3 μs at low pumping and saturates at a level close to 1.1 μs for the high pumping regime, following saturation of Er PL intensity. From the same figure we note also that the intensity of the exciton PL increases faster with excitation power when the intensity of Er PL reaches saturation. We have found that the erbium lifetime of approximately 1.3 ms is practically independent of the pump power over the whole investigated range.

C. Discussion

We have observed a strong correlation between exciton and erbium PL intensity as a function of laser power. This correlation has been observed both for continuous and pulsed excitation. As one can see from Figs. 3 and 4, the PL intensities of exciton are very weak before the PL intensity of erbium saturates. This fact indicates that the main recombination channel of free excitons is the capture by erbium-related centers, assisted by excitation of erbium. This conclusion is also supported by the dependence of exciton lifetime on laser power. The lifetime of exciton is shown to increase as saturation of erbium luminescence sets in. As the concentration of optically active Er ions is much less than total concentration of Er and other impurities, $N_{\mathrm{im}} \gg N_{\mathrm{Er}}$, we conclude that

$$c_A \gg c_{\mathrm{im}}, c_{\mathrm{Er}}. \tag{12}$$

The inequality (12) takes place in our opinion because the normal bound exciton Auger recombination involving loosely bound carriers is suppressed by the selection rules associated with the laws of conservation of the angular momentum and of the momentum in Si.[7] It is natural to suggest that $c_{\mathrm{Er}} \approx c_{\mathrm{im}}$. In this case we can neglect the second term in the right side of Eq. (6) and similarly simplify Eq. (11). From the experimental data as given in Fig. 4 we find the exciton lifetime in saturation regime ($N_{\mathrm{Er}} \approx N_{\mathrm{Er}}^*$) $\tau_{\mathrm{ex}}^{\mathrm{sat}} \approx 1.1$ μs, which leads to $c_{\mathrm{im}} N_{\mathrm{im}} \approx 0.9 \times 10^6$ s^{-1}. For low excitation $\tau_{\mathrm{ex}}^{\mathrm{low}} \approx 0.3$ μs resulting in $c_{\mathrm{im}} N_{\mathrm{im}} + c_A N_{\mathrm{Er}} = 3.3 \times 10^6$ s^{-1}, which gives $c_A N_{\mathrm{Er}} \approx 2.4 \times 10^6$ s^{-1}.

By using Eq. (11), we get for the effective cross section in the case of low excitation pumping ($N_{\mathrm{Er}}^* \ll N_{\mathrm{Er}}$):

$$\sigma_{\mathrm{eff}}^{\mathrm{min}} \approx 0.73 \frac{\alpha}{N_{\mathrm{Er}}}, \tag{13}$$

and for the maximum excitation cross section of erbium in the saturation range

$$\sigma_{\mathrm{eff}}^{\mathrm{max}} \approx 2.67 \frac{\alpha}{N_{\mathrm{Er}}}. \tag{14}$$

Thus the effective cross section should rise with the increase of the pumping intensity by a factor of approximately 4.

However, we shall consider the effective excitation cross section σ_{eff} as a constant and try to estimate its value from the intensity dependence of the erbium PL on photon flux. In quasistationary conditions this is given by

$$I_{\mathrm{Er}} = \frac{\sigma_{\mathrm{eff}} \tau \Phi}{\sigma_{\mathrm{eff}} \tau \Phi + 1} \frac{N_{\mathrm{Er}}}{\tau_{\mathrm{rad}}}, \tag{15}$$

where τ_{rad} is the radiative lifetime of erbium in the excited state. This relation can be obtained as a stationary solution for N_{Er}^* from Eq. (7). The fitting curve with $\sigma_{\mathrm{eff}} \tau \approx 5.4 \times 10^{-15}$ cm^2 s is presented in Fig. 3 (dotted line). Taking the lifetime of erbium 1.3 ms we have obtained $\sigma_{\mathrm{eff}} \approx 4 \times 10^{-12}$ cm^2. This value should be considered as an average one. The real cross section should be in the range $\sigma_{\mathrm{eff}} \approx (2-8) \times 10^{-12}$ cm^2.

Now we can calculate the concentration of optically active erbium from Eq. (13) corresponding to the obtained value σ_{eff}. Taking the value of absorption coefficient equal to 1×10^4 cm^{-1} at 515 nm,[8] we find $N_{\mathrm{Er}} = (2-5) \times 10^{15}$ cm^{-3}. As expected, this value is lower than the concentration of implanted erbium 5×10^{17} cm^{-3}. Thus only approximately 1% from total concentration of erbium is in the optically active state. This result coincides with the well known fact that concentration of optically active erbium in crystalline silicon doped by ion implantation does not exceed several percents.

In this section we have introduced the simplest model that includes only one type of optically active erbium center and a single excitation mechanism. However, it should be noted that total concentration of optically active erbium is determined by the preparation technology of the sample. Because of different configurations of the immediate Er^{3+} ion environment, erbium may be in several different optically active states. In this case the fraction of the total concentration of optically active erbium ions, which is excitable, may depend on the excitation mechanism.

We conclude by the estimation of the value of the Auger excitation coefficient $c_A = 7 \times 10^{-10}$ cm^3 s^{-1} from Eq. (10). This excitation coefficient is the object for theoretical calculation.

III. AMORPHOUS SILICON

Promising results were obtained in the case of optical excitation of erbium inserted into the matrix of amorphous hydrogenated silicon. Simple method of introduction of large concentration of erbium into amorphous matrix and the fact that the intensity of erbium emission at 1.54 μm is nearly independent of temperature from liquid helium to room temperature attracted special attention of the researchers. There is evidence that the radiative lifetime of erbium ion in the excited state in this matrix is several times smaller than that in the crystalline silicon.[9]

Introduction of erbium into the matrix of amorphous hydrogenated silicon leads to generation of ruptured bonds (dangling bond defects) which can have one electron (defect in a neutral D^0 state) or two electrons (negatively charged defect in a D^- state). These states induce defect levels approximately in the midgap of the matrix. They are separated by correlation energy of 0.1–0.2 eV. The energy position of the $4f$ term of the erbium ion is situated by 8–10 eV below the edge of the matrix valence band, therefore excitation of the $4f$ shell of the erbium ion can occur only via Coulomb

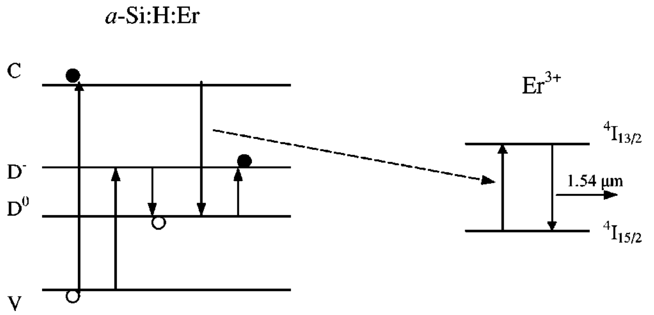

FIG. 5. Model of defect-related Auger mechanism of Er^{3+} excitation in *a*-Si:H:Er.

interaction with the charge carriers of the matrix (an Auger process).

It is well known[10,11] that doping of crystalline silicon with erbium and oxygen leads to formation of erbium-oxygen complexes which have energy levels with a bonding energy of 0.1–0.25 eV. We assume here that similar doping of amorphous silicon will be also accompanied by an appearance of donor states. This assumption is confirmed by *n*-type of electric conduction of erbium- and oxygen-doped amorphous silicon. The measurements of temperature dependence of electrical conductivity performed for a number of our samples gave the position of the Fermi level by 0.5 eV below the mobility edge of the conduction band. Since concentration of erbium and oxygen in typical samples is $[\mathrm{Er}] \approx 10^{20}\ \mathrm{cm}^{-3}$, while concentration of D^- defects does not exceed 10^{18}–$10^{19}\ \mathrm{cm}^{-3}$,[12,13] all the D defects in erbium-doped amorphous silicon exist in equilibrium in a D^- state.

Scheme of defect-related Auger mechanism of Er^{3+} excitation in *a*-Si:H:Er is presented in Fig. 5. In the case of band-to-band excitation geminate radiative recombination of electron-hole pairs is efficient only in the samples with low concentration of defects and at low temperatures (and under high excitation density). Therefore we can expect that in the samples containing large concentration of D^- defects[13] recombination occurs mainly nonradiatively via D defects. This assumption is corroborated by the absence in the spectra of erbium-doped amorphous hydrogenated silicon both band-to-band radiative transitions and defect luminescence. Since concentrations of electrons, holes and D^0 centers are negligible in equilibrium, while the concentration of D centers is practically equal to the total concentration of D^- defects, $N_D^- \approx N_D$, in the first stage of the recombination process holes are captured by D^- centers transforming them into D^0 defects. This process is described by the rate equation

$$\frac{dp}{dt} = \alpha\Phi - cpN^a_{D^-} - cpN^n_{D^-}, \tag{16}$$

where Φ is the photon flux, α the absorption coefficient of the pumping radiation, p is the concentration of free holes, c the capture coefficient of holes by D^- centers, $N^a_{D^-}$ and $N^n_{D^-}$ are concentrations of D^- centers for optically active and optically nonactive erbium ions, respectively.

In the second stage of the recombination process the electrons undergo transitions from the tail states of the conduction band to D^0 centers transforming them in D^- centers. The concentration of free electrons is controlled by the equation

$$\frac{dn}{dt} = \alpha\Phi - c_a nN^a_{D^0} - c_n nN^n_{D^0}, \tag{17}$$

where n is the concentration of free electrons, c_a total capture coefficient of electrons by D^0 centers active in excitation of erbium ions and it is a sum of contributions from two competing processes: capture of an electron with excitation of an erbium ion via an Auger process and multiphonon nonradiative capture: $c_a = c_A + c_{\mathrm{imp}}$.[13,14] Coefficient c_n is the capture coefficient of D^0 centers which do not participate in excitation of erbium ions (nonactive).

It should be noted that in our case D^0 centers are formed only due to capture of holes by D^- centers under optical pumping. Their concentration can be found from the equations

$$\frac{dN^a_{D^0}}{dt} = cpN^a_{D^-} - c_a nN^a_{D^0}, \tag{18}$$

$$\frac{dN^n_{D^0}}{dt} = cpN^n_{D^-} - c_n nN^n_{D^0}. \tag{19}$$

In the stationary state we have from Eqs. (18) and (19)

$$c_n N^n_{D^0} = c_a N^a_{D^0} \frac{N^n_{D^-}}{N^a_{D^-}}. \tag{20}$$

The rate equations system should be supplemented by the neutrality condition:

$$n = p + N^0_D. \tag{21}$$

Excitation of erbium ions in the amorphous silicon matrix is produced by the Auger process whose probability is proportional to the product of concentration of free electrons and concentration of D^0 centers. Thus, the concentration of excited erbium ions is determined by the rate equation

$$\frac{dN^*_{\mathrm{Er}}}{dt} = c_A nN^a_{D^0}\left(1 - \frac{N^*_{\mathrm{Er}}}{N_{\mathrm{Er}}}\right) - \frac{N^*_{\mathrm{Er}}}{\tau}. \tag{22}$$

When analyzing the system (16)–(20), we can use again the possibility to separate the physical system consisting of matrix and erbium ions into two subsystems: a fast one (the matrix) with relaxation time of all the electronic processes (recombination, capture of free charge carriers by D centers) not exceeding tens of microseconds, and a slow one (erbium ions) in which the characteristic lifetime (the lifetime of erbium ions in the excited state) equals one millisecond by the order of magnitude. Therefore, when we consider the evolution of the system under the pumping mechanism switched on, we can treat the subsystem of free carriers and defects as being in a stationary state. In this case using Eq. (20) we can get from Eq. (17)

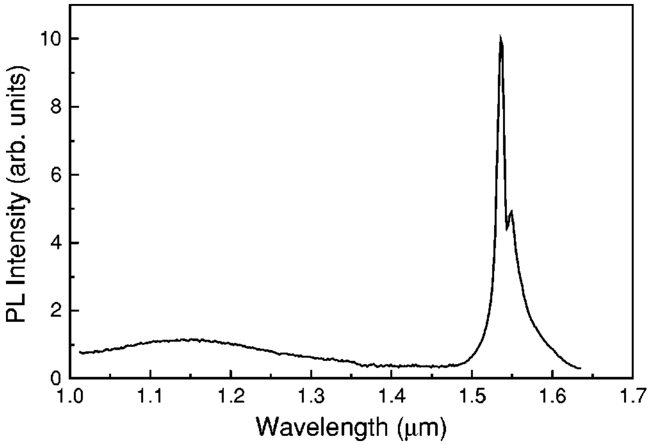

FIG. 6. Photoluminescence spectrum of Er-doped *a*-Si:H.

$$nN^{a}_{D^0}=\frac{\alpha\Phi}{c_a\left(1+\frac{N^n_{D^-}}{N^a_{D^-}}\right)}. \tag{23}$$

Then Eq. (22) can be represented in the form

$$\frac{dN^*_{\mathrm{Er}}}{dt}=\sigma_{\mathrm{eff}}\Phi(N_{\mathrm{Er}}-N^*_{\mathrm{Er}})-\frac{N^*_{\mathrm{Er}}}{\tau}, \tag{24}$$

where

$$\sigma_{\mathrm{eff}}=\frac{\alpha}{N_{\mathrm{Er}}}\frac{c_A N^a_{D^-}}{c_a(N^a_{D^-}+N^n_{D^-})}. \tag{25}$$

It should be noted that the ratio $N^n_{D^-}/N^a_{D^-}$ does not depend on the pumping rate in the conditions of our work since the concentration of D centers practically does not change for small illumination density: the concentration of arising D^0 centers makes only a small fraction of total concentration of D defects.

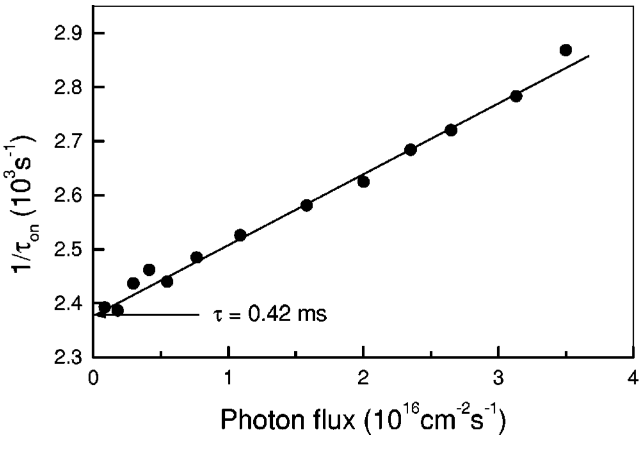

FIG. 7. Dependence of the reciprocal rise time $1/\tau_{\mathrm{on}}$ of erbium luminescence intensity in amorphous silicon on the pumping photon flux.

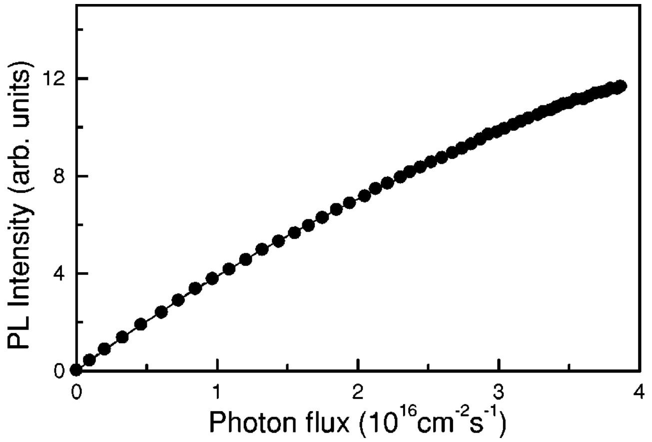

FIG. 8. Intensity of Er luminescence in Er-doped amorphous silicon as a function of pumping power.

In Eqs. (22), (24), and (25) the notation N_{Er} refers actually not to the total concentration of erbium ions but only to that of optically active ions, which is considerably lower.

From Eq. (23) it follows that in the case of optical pumping of erbium in the amorphous silicon matrix the maximum possible cross section of erbium excitation is

$$\sigma^{\max}_{\mathrm{eff}}=\frac{\alpha}{N_{\mathrm{Er}}}. \tag{26}$$

This result follows from the same reason as in the case of crystalline matrix: the band-to-band absorption coefficient of the semiconductor matrix of amorphous silicon for the pumping radiation is independent of the concentration of erbium ions.

We have measured the effective excitation cross section of erbium for the sample of amorphous hydrogenated silicon doped by erbium (*a*-Si:H:Er). The sample *a*-Si:H:Er was grown by magnetron sputtering of metal erbium onto the silicon substrate in the atmosphere of silane, argon, and oxygen. The concentrations of erbium and oxygen in the obtained film measured by SIMS method were 3.5×10^{19} cm^{-3} and 2×10^{20} cm^{-3}, respectively. It should be noted that the presence of oxygen increases the intensity of erbium PL.

Photoluminescence spectra were measured using a light emitting diode (LED) with maximum radiation at 0.64 μm as excitation source. The emitted light was passed through a monochromator and detected by cooled Ge detector using lock-in techniques. Photoluminescence raise traces of erbium PL were recorded using a digitizing oscilloscope in combination with the Ge detector. The system response time was 5 μs. All measurements were done at 100 K. Figure 6 shows a PL spectrum of *a*-Si:H:Er film in the 1–1.7 μm range. A luminescence peak at the wavelength of 1.54 μm corresponds to the radiative transition from the first excited state $^4I_{13/2}$ to the ground state $^4I_{15/2}$ of Er^{3+}. A weak maximum around 1.3 μm (defect luminescence) is due to the transition of electrons from conduction band to D^0 defect level.

From the solution of the rate Eq. (24) it follows that a reciprocal rising time τ_{on} of erbium intensity after switch-on of a rectangular pulse is

$$\frac{1}{\tau_{\mathrm{on}}}=\frac{1}{\tau}+\sigma_{\mathrm{eff}}\Phi. \tag{27}$$

Figure 7 shows the experimental data on the reciprocal rise time as a function of photon flux (dots) and the calculated dependence fitted to the experimental data using the formula (27). The obtained value of the excitation cross section σ_{eff} is 1.4×10^{-14} cm^2, and the erbium lifetime τ is 420 μs. The obtained values σ_{eff} and τ may be checked from the dependence of the PL erbium intensity on photon flux using Eq. (15). Figure 8 shows the dependence of experimental data on pumping power and calculated fitting curve of PL erbium intensity (with σ_{eff} and τ obtained above).

Now we can calculate the concentration of optically active erbium from Eq. (13) corresponding to the obtained value σ_{eff}. Taking the value of absorption coefficient of amorphous silicon equal to 1×10^4 cm^{-1} at 514.5 nm, we find $N_{\mathrm{Er}}\approx0.7\times10^{18}$ cm^{-3}. This value is lower than the concentration of implanted erbium 3.5×10^{19} cm^{-3}. Thus only about one percent of the total concentration of erbium embedded in amorphous matrix is optically active.

IV. CONCLUSIONS

A detailed consideration of excitation mechanisms of erbium in crystalline and amorphous silicon is carried out and physical meaning of excitation cross section of erbium in semiconductor matrices under optical pumping is revealed. It is demonstrated that large values of excitation cross section of erbium in semiconductor matrices are due to the fact that the absorption coefficient of the matrix for pumping radiation exceeds the direct absorption of erbium by several orders of magnitude. The Auger excitation cross section of erbium in semiconductor matrices is roughly determined by a ratio of the absorption coefficient of pumping light to the concentration of optically active erbium, irrespective of the excitation mechanism. It should be noted that concentration of optically active erbium ions may depend on a particular excitation mechanism. On the other hand, if we have several optically active erbium centers with different concentrations we may have several different effective excitation cross sections with a single excitation mechanism.

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