

Energy transfer between shallow centers and rare-earth ion cores: Er^{3+} ion in silicon

T. Gregorkiewicz and D. T. X. Thao

Van der Waals–Zeeman Institute, University of Amsterdam, Valckenierstraat 65, NL-1018 XE Amsterdam, The Netherlands

J. M. Langer

Institute of Physics, Polish Academy of Sciences, Al. Lotników 32/46, PL-02-663 Warszawa, Poland

H. H. P. Th. Bekman

TNO Physics and Electronics Laboratory, Oude Waalsdorperweg 63, NL-2509 JG Den Haag, The Netherlands

M. S. Bresler

A.F. Ioffe Physicotechnical Institute, Russian Academy of Sciences, 194021 St. Petersburg, Russia

J. Michel and L. C. Kimerling

Department of Materials Science and Engineering, MIT, Cambridge, Massachusetts 02139

(Received 2 July 1999; revised manuscript received 8 October 1999)

Two-color optical spectroscopy is used to directly manipulate shallow levels available in Si:Er samples of different parameters. It is observed that the excitation energy provided by a laser operating in the visible can be temporarily stored by trapping photogenerated carriers at shallow centers available in the material. Subsequently, this energy can be transferred to the $4f$ -electron core of the Er^{3+} ion in a trap ionization process induced by a mid-infrared pulse from a free-electron laser. In that way, Er-related luminescence at $1.5 \mu\text{m}$ can be generated by an infrared pulse applied within several milliseconds after the band-to-band excitation pulse. By scanning the wavelength of the free-electron laser, ionization spectra of the shallow centers participating in the energy transfer are obtained, allowing for their identification. On that basis, the involvement of thermal donors is suggested. The results demonstrate that excitation of Er ions in Si is a multichannel energy transfer process where shallow centers play an important role.

I. INTRODUCTION

Properties of erbium-doped silicon receive much attention due to photonic potential of this material. However, in spite of extensive investigations, the available information on the energy-transfer processes taking place in Si:Er is mostly phenomenological and their understanding remains rather speculative. Yet only full control of the excitation and de-excitation paths available to the rare-earth (RE) ion Er imbedded in a semiconductor Si matrix will allow for optimization of emission intensity and its thermal stability. Consequently, it is these fundamental aspects which will be determinative to the event of versatile silicon photonics based on Er doping.

The current information on the specific excitation mechanism of Er ion in silicon has been almost exclusively gathered from investigations of the thermal behavior of photoluminescence (PL) intensity and lifetime. These nonspectroscopic experiments are rather indiscriminate and obtained information is not very specific, as different energy-transfer processes are simultaneously activated and their individual contributions entangled. The situation is further complicated by multiplicity of Er-related optical centers in Si,¹ which are very likely to differ also in details of their energetic coupling with the host material. This is in a striking contrast to another semiconductor:RE system InP:Yb. For generation of Si:Er luminescence different mechanisms have been put forward;² these include exciton binding,^{3,4} recombination of an electron bound at an Er-related donor center,⁵ and impact with hot electrons.⁶ Also a possibility of partici-

pation of the higher-lying Δ_2' conduction subband has been considered.⁷ None of the proposed mechanisms could be supported by spectroscopic data, however.

Recently, two-color spectroscopy with a tunable free-electron laser (FEL) operating in the mid-infrared (MIR) has been successfully applied to investigate the energy-transfer process between the $4f$ -electron shell of an Er^{3+} ion and silicon host. An intense MIR pulse of a chosen wavelength, power and timing is used to selectively address shallow levels available in the material. In that way levels participating in the Er-related energy-transfer path can be distinguished by the FEL-induced changes of the Er photoluminescence generated by band-to-band excitation with a second laser operating in the visible. The experiment showed that the excitation mechanism could be disrupted by the MIR pulse when applied shortly after the visible laser pulse. In that way an existence of a two-stage excitation mechanism for an Er^{3+} ion embedded in silicon host has been explicitly shown.⁸ Based on the quenching magnitude, lifetime of the state intermediating the energy transfer was estimated as approximately $100 \mu\text{s}$.⁸ We note that such a long value is not expected for states whose lifetimes are controlled by Auger recombinations; rather it seems typical for excitons bound to isoelectronic impurities. If Er excitation would proceed exclusively via the intermediate state, its lifetime should correspond to the transfer time determining the rise of PL signal intensity upon the excitation pulse. In experiments performed with a fast detector which reproduces the true time development of the PL signal, Taguchi *et al.* reported the rise time in the studied material to be much shorter.⁹ Moreover,

recent experiments show no MIR-induced quenching in oxygen-rich Si:Er samples containing exclusively *cubic Er* center. These different results can be reconciled if we assume that Er can be excited by a variety of ways, each characterized by different transfer rates. An important question therefore arises on the uniqueness of the Er excitation path and, in particular, whether participation of an intermediate state forms always a significant step in the excitation process.

In this contribution we present evidence that PL of Er in Si can be generated using energy stored at shallow centers available in the material and not necessary related to Er. In that way the multiplicity of the energy-transfer paths leading to excitation of an Er^{3+} ion in silicon is illustrated.

II. EXPERIMENTAL DETAILS

The experiments have been performed at the Free Electron Laser for Infrared eXperiments (FELIX) users facility at the FOM Institute for Plasma Physics ‘‘Rijnhuizen’’ in Nieuwegein, The Netherlands. MIR pulses of approximately 5- μs duration and up to approximately 5-mW power have been used. For spectroscopical measurements the wavelength λ_{FEL} was varied within 7.5–17- μm range. For band-to-band excitation the second harmonic of a pulsed Nd:YAG laser operating at $\lambda_{YAG}=532$ nm or a cw solid-state laser with $\lambda_{DIODE}=820$ nm were used. The signal was detected with a germanium detector (North Coast, $\tau\approx 75$ μs) through a narrow-band pass filter tuned to the Er-related emission at $\lambda_{Er}=1.54$ μm . All the reported experimental data were obtained for samples placed in a helium gas flow cryostat at cryogenic temperatures between 4 and 40 K. More details on the experimental setup for the two-color spectroscopy with FEL can be found in Ref. 8.

While the effect of the MIR-induced Er PL was found to be omnipresent in a large variety of differently prepared materials, two particular samples, representing two different classes of Si:Er materials, have been chosen for the present study. One sample was low-energy (320 keV) Er implanted oxygen-rich *p*-type Cz-Si. The sample was further coimplanted with oxygen and annealed at 650°C for 30 followed by 15 min at 900°C. The PL spectrum of the sample contained predominantly the cubic Er center. The second sample was prepared from FZ *n*-type ($[P]\approx 6\times 10^{15}$ cm^{-3}) oxygen-lean material by Er implantation (1100 keV) at an elevated temperature of 500°C. No coimplants have been used and no further heat treatment has been applied. Deep level transient spectroscopy (DLTS) measurements revealed presence of donor centers with ionization energy of approximately 280 meV. The PL spectrum was dominated by noncubic components. Several samples with different implantation doses were tested; a sample with the maximum PL intensity has been chosen for detailed investigations.

III. EXPERIMENTAL RESULTS

The current study is based on an observation that the MIR pulse applied with a considerable delay to the (visible laser) excitation pulse generates additional PL signal at the wavelength characteristic for Er emission. The effect is illustrated in Fig. 1. It was observed in all the investigated materials in 4–40-K temperature range. The lowest solid trace shows

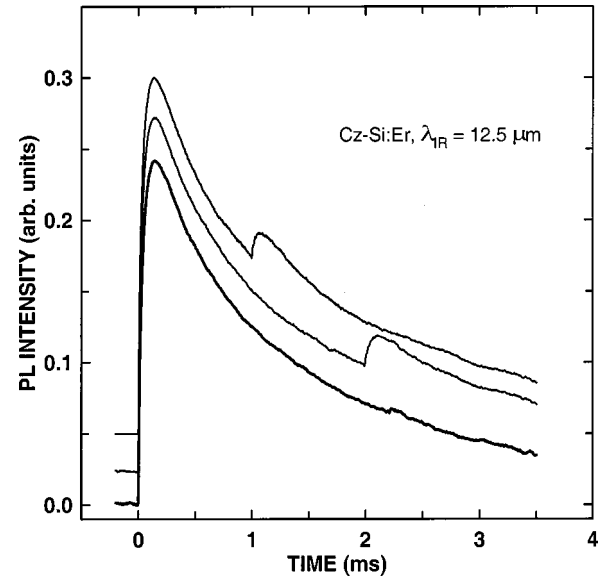


FIG. 1. Illustration of the MIR-induced Er PL generated with $\lambda_{FEL}=12.5$ μm in Cz-Si:Er for different delay times.

time development of the PL signal generated in the oxygen-rich sample by a nanosecond pulse of the visible light from a Nd:YAG laser. From the decay of the PL intensity lifetime of the ${}^4I_{13/2}$ excited state of Er^{3+} ion is determined as approximately 1.2 ms. The upshifted curves show PL responses when an MIR pulse ($\lambda_{FEL}=12.5$ μm) is also applied on the sample at different delays in respect to the band-to-band excitation pulse. As can be concluded, MIR light generates additional PL signal of considerable intensity. Within the experimental error the decay time of the MIR-induced PL is identical to that of the signal generated by the band-to-band excitation. This feature, in addition to the characteristic wavelength, identifies the MIR-induced PL as Er related. Consequently, we conclude that the MIR pulse from FEL leads to an increase of the excited Er concentration, and therefore activates Er excitation mechanism. The magnitude of the effect depends on the particularities of the sample: in the oxygen-lean sample it is considerably smaller than in Cz-Si. It also depends on delay time Δt between the visible and the MIR pulses; under the chosen experimental conditions the effect initially grows, attains a broad maximum for $\Delta t\approx 3\text{--}5$ ms, and gradually diminishes to zero for $\Delta t\geq 30$ ms. We note that the MIR-induced Er PL can be observed exclusively when the FEL pulse is preceded by the visible laser excitation: the MIR pulse applied prior to the band-to-band excitation does not generate any PL.

The experimentally obtained wavelength dependence of the magnitude of the MIR-induced Er-related PL, scaled for an identical number of photons per pulse at every wavelength, is shown in Figs. 2(a) and (b) for the oxygen-rich and oxygen-lean samples, respectively. A clear difference between the results for both samples is concluded. The effect of the MIR-induced PL has also been investigated under conditions of continuous band-to-band excitation with a solid-state laser; the wavelength characteristics obtained in that case is also included in Fig. 2(a). Comparing both data sets in Fig. 2(a) we conclude that the wavelength dependence remains identical regardless of the excitation regime, while the magnitude of the effect is larger under cw illumination.

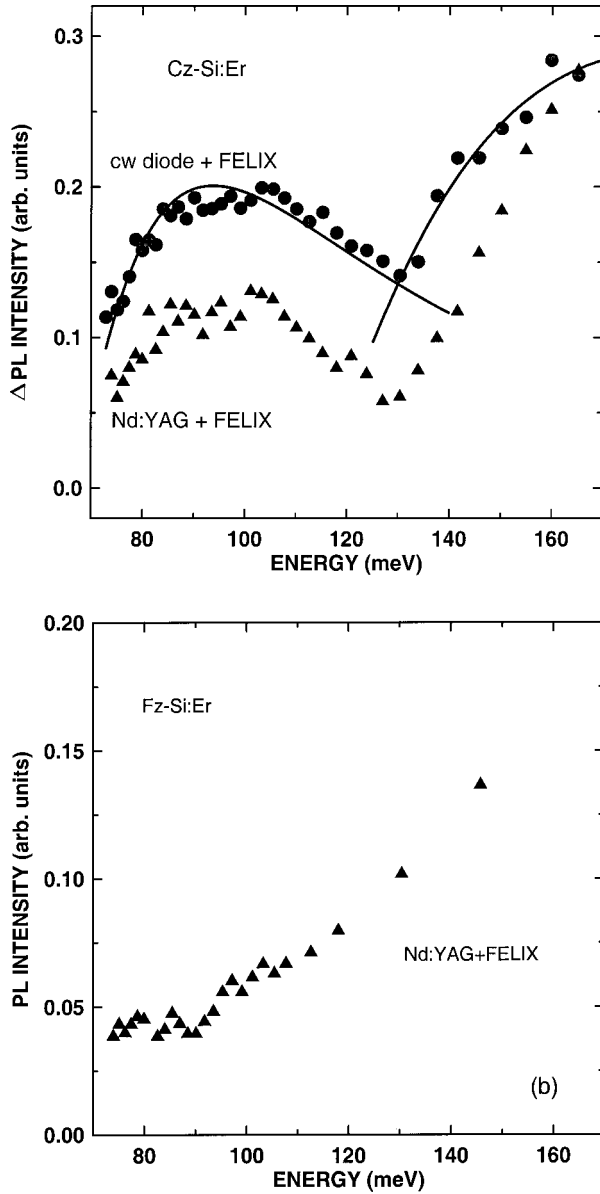


FIG. 2. Wavelength dependence of the magnitude of the MIR-induced PL for an oxygen-rich (a) and an oxygen-lean (b) sample. Solid lines represent numerical fits obtained with Eq. (1). See text for discussion.

Also the MIR power dependence of the additional Er excitation has been investigated and is illustrated for both samples in Fig. 3. It was found to be different for pulsed and cw excitation. Figure 3(a) presents data obtained for both samples under condition of pulsed band-to-band excitation; the effect is initially linear and saturation sets in for higher power values. Experimental data could be successfully fitted with a formula $I_{PL} = c_1 I_{FEL} / (1 + c_2 I_{FEL})$, where I_{FEL} is FEL power and c_1 and c_2 are fitting parameters. In contrast to that, the MIR-induced PL obtained for a cw band-to-band excitation—Fig. 3(b)—shows practically no saturation over four decades of FEL pulse power and is found to follow the square-root dependence $I_{PL} \sim \sqrt{I_{FEL}}$.

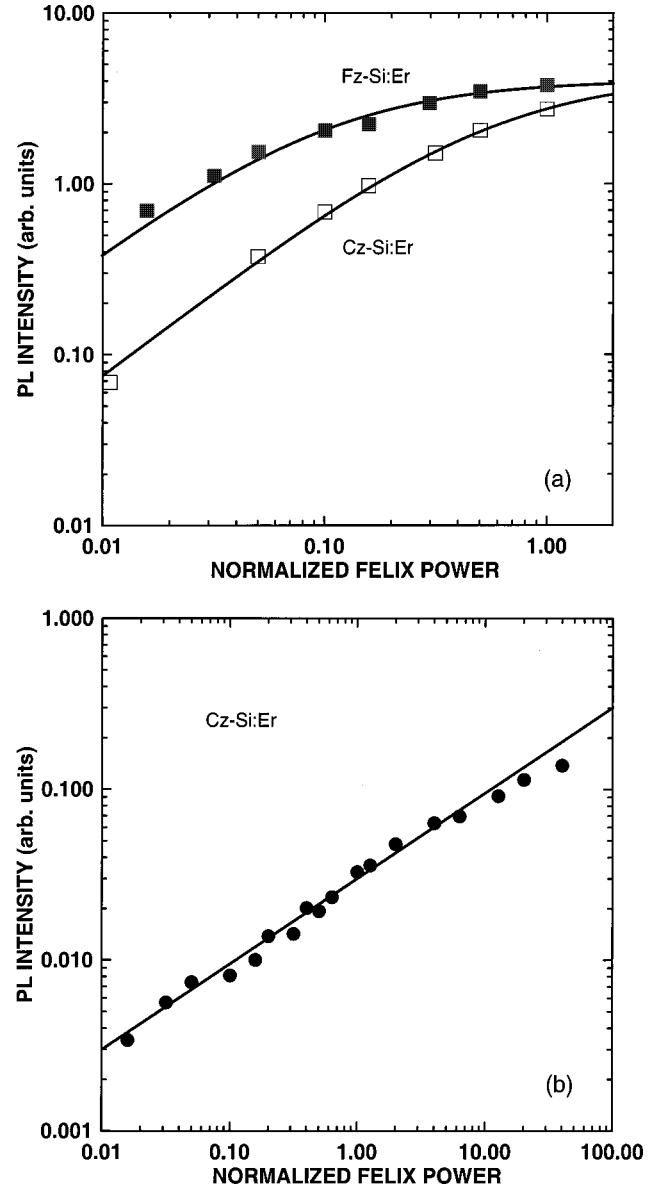


FIG. 3. Power dependence of the magnitude of the MIR-induced PL for the oxygen-rich (\square) and the oxygen-lean (\blacksquare) sample under conditions of (a) pulsed ($\lambda_{YAG} = 532$ nm) and (b) cw ($\lambda_{DIODE} = 820$ nm) band-to-band excitation. The experimental data are fitted with the formulas $I_{PL} = c_1 I_{FEL} / (1 + c_2 I_{FEL})$ and $I_{PL} = c \sqrt{I_{FEL}}$ for (a) and (b), respectively.

IV. DISCUSSION

A. Proposed mechanism of MIR-induced PL

From the experimental data obtained in the presented study we conclude that the Er related emission can be generated with a light pulse in the mid-infrared range. Since the smallest energy necessary for generation of the $^4I_{13/2}$ Er^{3+} state responsible for the luminescence is approximately 800 meV, and therefore much larger than the MIR quantum energy of 70–170 meV, it seems plausible to assign the effect to a multiple photon absorption. However, the experiments show that the band-to-band excitation proceeding the MIR

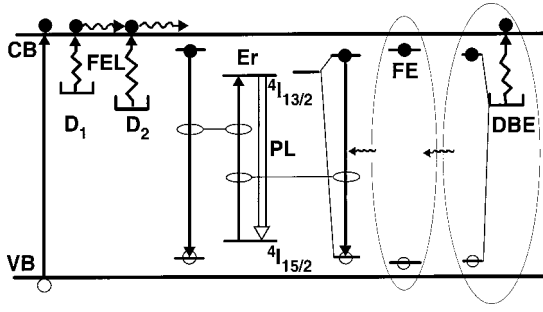


FIG. 4. Schematic illustration of the proposed mechanism responsible for the MIR-induced Er^{3+} excitation.

pulse constitutes a necessary condition for the effect to occur; the additional PL is not observed when the FEL pulse is applied prior to the Nd:YAG laser pulse. We can therefore exclude direct multiphoton absorption by Er^{3+} ions (or by Si matrix) as a possible excitation mechanism and conclude that the energy provided by the excitation in the visible is stored away for some time and is then transferred to Er ions upon application of the MIR pulse. The energy storage can be realized either by exciton localization or by carrier capture at shallow centers. In either case, these might then be released by a subsequent MIR pulse and become available for recombinations at the Er-related traps, leading to the Er core excitation. The localization energy must be sufficiently small, so that the process can be activated by the MIR. Such an effect is in its appearances similar to thermoluminescence, when carriers bound to various defects have a considerably long lifetime and can therefore be thermally reactivated to the band becoming thus available for radiative recombinations. Consequently, in order to account for the effect of the MIR-induced Er PL, we propose a similar mechanism, as depicted in Fig. 4. Free carriers excited by the visible light undergo various recombinations, some of which result in Er excitation, giving rise to luminescence. In strongly defected material, however, many carrier trapping centers will exist, the majority not being Er related and therefore not contributing to Er PL. These, on the contrary, provide alternative channels of (mostly) nonradiative recombinations. Some of them will serve as efficient recombination centers, while others may have longer lifetimes. The intense MIR pulse applied shortly after the excitation might ionize the long-living traps. The free carriers and/or excitons generated in that way might be recaptured at Er-related centers capable of Er^{3+} core excitation. Consequently, additional PL will appear, with its magnitude governed by the concentration, capture cross section, and lifetime of relevant traps.

B. Wavelength dependence

In contrast to the indiscriminate character of thermal excitation responsible for classical thermoluminescence, the monochromatic MIR beam allows for a selective and independent addressing of shallow traps available in the material. According to the proposed mechanism, the wavelength dependence of the magnitude of the effect—see Fig. 2—corresponds to the ionization spectrum of dominant traps contributing to the energy storage process. It has been shown¹⁰ that the photoionization cross section σ of a trap can be described as

$$\sigma = \text{const} \cdot \frac{(h\nu - E_D)^{3/2}}{(h\nu)^{3+2\gamma}}, \quad (1)$$

where $h\nu$ and E_D correspond to the energy of the ionizing beam and the ionization energy of the trap, respectively. γ parameter ($0 \leq \gamma \leq 1$) depends on the particular form of the binding potential and is $\gamma=0$ and $\gamma=1$ for the δ -like and Coulomb potentials, respectively. Equation (1) gives a rather broad and featureless wavelength dependence, with an onset corresponding to $h\nu = E_D$, and a maximum at $h\nu = \frac{10}{7} E_D$ and $h\nu = 2E_D$ for the delocalized and localized binding potentials, respectively. Comparing the wavelength dependencies obtained experimentally for the oxygen-rich and oxygen-lean samples we conclude that different traps are responsible for the MIR-induced excitation of Er in these materials. While for both samples PL intensity exhibits a similar growth for the largest energy quanta, the ionization spectrum in Cz-Si has also a broad maximum at a smaller energy, with an extrapolated onset at approximately 60 meV and a broad maximum around 90–100 meV. Following our interpretation we conclude that the trap responsible for the MIR-induced PL is in that case characterized by an extended binding potential and an ionization energy $E_{D1} \approx 60$ meV. This value falls well within the range of ionization energies of typical shallow effective-mass-theory centers in silicon. The observation of a shallow oxygen-related center participating in the energy-transfer processes pertinent to Er core excitation is spectroscopic evidence of influence of oxygen on the optical activity of Er in silicon. The experimentally measured ionization cross sections show a very pronounced increase for the largest energies of the MIR beam. We assign this feature to a deeper trap characterized by a binding energy $E_{D2} \approx 100$ –120 meV and, most probably, by a more localized potential. This trap is apparently identical in both investigated materials, and is likely to be introduced by the Er ion itself. Alternatively, it could represent an inherent feature of silicon matrix revealed here via its influence on Er excitation.

Finally, we note that although the MIR radiation penetrates the whole sample (and not only the thin subsurface implanted layer as is the case for the visible pulse), the detection of its effects proceeds only via Er-related emission. Therefore this particular form of ionization spectroscopy is exclusively sensitive to centers which are capable of transferring their energy to Er ions; this is likely to be easier for centers located in direct vicinity of Er ions, rather than in the bulk of the sample.

C. Power dependence

The integrated intensity of the additional PL signal is proportional to the number of Er^{3+} ions which attain the excited state following the MIR pulse. On the other hand, the operational power of FEL determines the actual number of photons contained in the MIR pulse. Therefore the linear power dependence of the MIR-induced PL intensity experimentally found in case of pulsed excitation implies that there exists also a proportionality between the number of MIR photons and number of additional recombinations leading to Er excitation. We conclude that the trap ionization due to MIR photon absorption leads to a release of an exciton (bound-to-free

exciton transition) or that the carrier (an electron or a hole) ionized from the trap can recombine with carriers of the opposite charge available in the material. In both cases the intensity of additional PL will increase linearly on MIR power until, at high densities of MIR photons, the saturation effect will set in, as the number of populated traps becomes exhausted. As evidenced by Fig. 3(a), this scenario is fully consistent with the experimental data obtained for both samples under conditions of band-to-band excitation with a pulsed laser operating in the visible.

The situation will be different under conditions of continuous illumination (cw) with the solid-state laser. In this case all the centers, related and unrelated to Er, attain equilibrium concentrations as excitation and recombination processes balance each other. Application of the MIR radiation under cw illumination will (temporarily) block recombination channels involving shallow impurities by ionizing them; at the same time other recombination paths will be promoted. Such an effect will be somewhat similar to that observed under application of the microwave field. In view of an evidently very long lifetime of centers involved in the mechanism investigated here, we might assume that these levels will be completely filled under conditions of continuous band-band excitation, thus resulting in carrier storage. Generation of extra carriers in the band by the FEL will resemble generation of electron-hole pairs across the band gap, with the recombination kinetics being bimolecular: $\delta n p_{imp} \sim I_{FEL}$ and $\delta n = p_{imp}$, where p_{imp} corresponds to concentration of empty traps, and δn is the ‘‘additional’’ concentration of free electrons generated to conduction band by MIR photon absorption (we have implicitly assumed here the traps to be donors). This is clearly different than in the previously considered situation under pulsed excitation, where we had $\delta n \ll p_{imp}$. If we now consider that the application of the MIR pulse is a small perturbation of the equilibrium situation determined by the cw laser, the additional MIR-induced Er PL will be proportional to the product $\delta n p$ (where p is the number of holes generated by the primary beam), and thus to $\sqrt{I_{FEL}}$, in agreement with the experiment.

We can more rigorously describe the equilibrium situation using the excitonic mechanism developed for Si:Er.¹¹ Since the experiment was done at a liquid-helium temperature, we shall assume that practically all electron-hole pairs excited by visible light are bound into free excitons and that concentrations of free electrons and holes are very low. Free excitons migrate and are captured by neutral donors induced by erbium complexes. We further assume that there exist two types of capture centers one of which does not activate erbium ions (we shall designate it as ‘‘nonactive’’) while the other produces excitation of erbium luminescence (‘‘active’’). Under stationary conditions of erbium pumping the equilibrium situation will be reached. The appropriate set of rate equations will read

$$\frac{dn_x}{dt} = 0 = G - \nu_{comb} n_x, \quad (2)$$

$$\frac{dn_{b_{xn}}}{dt} = 0 = \nu_{cn} n_x - \nu_L n_{b_{xn}}, \quad (3)$$

$$\frac{dn_{b_{xa}}}{dt} = 0 = \nu_{ca} n_x - \nu_{tr} n_{b_{xa}}, \quad (4)$$

$$\frac{dN^*}{dt} = 0 = \nu_{tr} n_{b_{xa}} - \nu N^*, \quad (5)$$

where n_x , $n_{b_{xn}}$, $n_{b_{xa}}$, and N^* are concentrations of free, bound nonactive, and bound active excitons and excited Er ions, respectively, G is the electron-hole generation rate by the cw operating laser diode, ν_{cn} and ν_{ca} are the capture coefficients of free excitons by nonactive and active donors, respectively, ν_{comb} is the total capture coefficient of free excitons ($\nu_{comb} = \nu_{cn} + \nu_{ca}$), ν_{tr} is an energy-transfer coefficient from active bound excitons to Er ions, ν_{tr}^{-1} is the lifetime of the active bound exciton relative to Auger excitation process, ν_L^{-1} is the lifetime of the nonactive centers, and ν^{-1} is the lifetime of an Er ion in the excited state. This set of rate equations yields

$$n_x = G \nu_{comb}^{-1}, \quad (6)$$

$$n_{b_{xn}} = G \nu_{comb}^{-1} \frac{\nu_{cn}}{\nu_L}, \quad (7)$$

$$n_{b_{xa}} = G \nu_{comb}^{-1} \frac{\nu_{ca}}{\nu_{tr}}, \quad (8)$$

$$N^* = G \nu_{comb}^{-1} \frac{\nu_{ca}}{\nu}, \quad (9)$$

with the intensity of erbium luminescence being given by $I_{PL} = N^* / \tau_R$, where τ_R is the radiative lifetime of the excited state of Er³⁺ ion.

If we apply a short pulse of a free-electron laser, a change of erbium luminescence intensity occurs. We assume that the only quantity which can be seriously influenced by the free-electron laser is the capture coefficient ν_{cn} , since ν_{tr} and ν cannot depend on the absorption of MIR light and ν_L is not connected in any way with excitation of Er. Guided by the experiment, we assume further that only nonactive centers are influenced by absorption of MIR light while its energy is too low to induce changes in the capture coefficient of active centers ν_{ca} .

In fact,

$$\nu_{cn} = \sigma_c N_0 V_T, \quad (10)$$

where σ_c is the capture cross section, N_0 is the concentration of neutral donors (nonactive centers), V_T is the thermal velocity of free excitons. Since the capture time of carriers at donor levels is short (\sim ns) in comparison to the duration of the FEL pulse, we assume that the equilibrium between free-electron and ionized donor concentrations is established. In that case, on application of the free-electron laser pulse the concentration of neutral donors changes according to a kinetic equation:

$$\begin{aligned} \frac{d\delta N_0}{dt} &= -I_{FEL} \delta(t-t_1) \sigma_{IR} N_0 + \gamma \delta n \delta N_0 \\ &= -I_{FEL} \delta(t-t_1) \sigma_{IR} N_0 + \gamma (\delta N_0)^2, \end{aligned} \quad (11)$$

where I_{FEL} is the intensity of a free-electron laser applied at t_1 , σ_{IR} is the cross section of MIR light absorption by neu-

tral donors, and δn and δN_0 are the FEL-induced changes of the conduction-band electrons and nonactive donors, respectively. Absorption of MIR light will decrease concentration of neutral donors and block the formation of bound excitons at nonactive centers. Assuming that the situation is quasistationary we can neglect the derivative and solve Eq. (11) to get

$$\delta N_0 \approx \sqrt{\frac{\sigma_{IR} N_0 I_{FEL} \Delta t}{\gamma}}, \quad (12)$$

where Δt is the duration of the MIR pulse. Now this sudden rise of the concentration of free excitons induces additional flow of excitons to active centers with a corresponding increase of erbium luminescence intensity. These effects can be described with the same set of Eqs. (2)–(5) (this time not in equilibrium, as a transient signal will be created) where the role of the excitation “source” is played by the term

$$\sigma_c V_T \sqrt{\frac{\sigma_{IR} N_0 I_{FEL} \Delta t}{\gamma}} G v_{comb}^{-1} v_L^{-1} \delta(t - t_1). \quad (13)$$

Under assumption $v_{tr} \gg v_{comb}$ we will get now

$$N^* = A \frac{v_{ca}}{v_{tr} - v_{comb}} \frac{v_{tr}}{v_{comb} - v} \times \{\exp[-v(t - t_1)] - \exp[-v_{comb}(t - t_1)]\}, \quad (14)$$

where

$$A = \sigma_c V_T \sqrt{\frac{\sigma_{IR} N_0 I_{FEL} \Delta t}{\gamma}} G v_{comb}^{-1} v_L^{-1}. \quad (15)$$

Such a dependence will produce an additional signal of Er PL whose magnitude will be proportional to the square root of the FEL set power. This is indeed confirmed by the experiment over four decades of FEL pulse energies, see Fig. 3(b), supporting the proposed model.

V. CONCLUSIONS

The presented study reveals that the excitation energy can be stored in a silicon crystal for an unexpectedly long time, and then transferred to erbium core upon application of the MIR pulse. This observation has important implications advancing our understanding of the energy transfer responsible for generation of Er-related PL. In this respect, the effect of the MIR-induced Er PL under conditions of pulsed Nd:YAG laser excitation is especially important. In this case the additional PL signal is generated by the MIR pulse applied with a considerable delay (up to tens of milliseconds) in respect to the initial excitation in the visible. Since the typically observed lifetimes of the excitonic centers in silicon are known to be significantly shorter, the MIR pulse is likely to generate carriers rather than to release excitons. In order to provide energy for Er excitation, the carriers ionized from shallow traps by the MIR pulse will have to recombine subsequently with carriers of the opposite charge, apparently available in

the material, with the recombination energy being transferred to the $4f$ -electron shell of Er^{3+} ion. Such an excitation is then somewhat different than the one usually considered, where the localization of an exciton at a (neutral) Er-related donor center is assumed to take place directly following the band-to-band excitation. At the same time, this scheme does not involve hot carrier injection as in electroluminescence.

Current results are also relevant for the issue of the well-documented but thus far unexplained special role of oxygen in the PL of Si:Er. As conclusively established from the wavelength dependence, oxygen provides shallow trapping centers active in temporal energy storage. At low temperatures carrier trapping at oxygen-related centers appears then to provide an alternative recombination path competing with Er excitation. However, since the total intensity of Er PL is found to be higher in oxygen-rich than in oxygen-lean material, we conclude that the oxygen-related recombination path apparently replaces other efficient channels of nonradiative recombination. Further, the current experiments show that the energy transfer from oxygen-related centers to Er is possible upon application of a MIR pulse. It is then plausible that a similar transfer can also be induced thermally, at an elevated temperature. In that case oxygen presence would effectively enhance the small excitation cross section of Er, the notorious fundamental problem of all semiconductor:RE systems. Recent experiments performed on Cz-Si:Er samples additionally implanted with oxygen revealed that the magnitude of the MIR-induced signal comparable to the “original” PL generated with visible laser pulse could be achieved. This result illustrates efficiency of the shallow trap related excitation mechanism revealed in the current study.

While the available data do not allow for a conclusive microscopic identification of the shallow oxygen-related level participating in the proposed energy transfer, it is certainly tempting to suggest the involvement of thermal donors (TD's) which are known to be formed by practically any heat treatment of oxygen-rich silicon, and whose (multispecies) first ionization donor level appears at approximately 50 meV below the bottom of the conduction band. Since generation kinetics of thermal donors is proportional to the fourth power of oxygen concentration, it is possible that TD's concentration in direct surrounding of Er^{3+} ions is significantly increased.

ACKNOWLEDGMENTS

We gratefully acknowledge the support by the Stichting voor Fundamenteel Onderzoek der Materie (FOM) in providing the required beam time on FELIX and highly appreciate the skillful assistance by the FELIX staff, in particular, Dr. A. F. G. van der Meer and Dr. Ir. H. P. M. Pellemans. This work was supported in part by the TMR program of the European Community and by Linkage Grant No. HTEC.LG 972032. One of us (J.M.L.) is grateful for the financial support of the Polish State Committee for Scientific Research (Grant No. 2P 03B 103 15). M.S.B. acknowledges hospitality during his stay at the Van der Waals–Zeeman Institute in Amsterdam.

- ¹H. Przybylińska, W. Jantsch, Yu. Suprun-Belevitch, M. Stepikhova, L. Palmethofer, G. Hendorfer, A. Kozanecki, R.J. Wilson, and B.J. Sealy, *Phys. Rev. B* **54**, 2532 (1996).
- ²M.S. Bresler, T. Gregorkiewicz, O.B. Gusev, N.A. Sobolev, E.I. Terukov, I.N. Yassievich, and B.P. Zakharchenya, *Fiz. Tverd. Tela* **41**, 97 (1999) [*Phys. Solid State* **41**, 770 (1999)].
- ³S. Coffa, F. Priolo, G. Franzò, V. Bellani, A. Carnera, and C. Spinella, *Phys. Rev. B* **48**, 11 782 (1993).
- ⁴J. Palm, F. Gan, B. Zheng, J. Michel, and L.C. Kimerling, *Phys. Rev. B* **54**, 17 603 (1996).
- ⁵F. Priolo, G. Franzò, S. Coffa, A. Polman, S. Libertino, R. Barklie, and D. Carey, *J. Appl. Phys.* **78**, 3874 (1995).
- ⁶G. Franzò, F. Priolo, S. Coffa, A. Polman, and A. Carnera, *Appl. Phys. Lett.* **64**, 2235 (1994).
- ⁷I.N. Yassievich and L.C. Kimerling, *Semicond. Sci. Technol.* **8**, 718 (1993).
- ⁸I. Tsimperidis, T. Gregorkiewicz, H.H.P.Th. Bekman, and C.J.G.M. Langerak, *Phys. Rev. Lett.* **81**, 4748 (1998).
- ⁹A. Taguchi, K. Takahei, M. Matsuoka, and S. Tohno, *J. Appl. Phys.* **84**, 4471 (1998).
- ¹⁰J.M. Langer, T. Langer, G.L. Pearson, B. Krukowska-Fulde, and U. Piekara, *Phys. Status Solidi B* **66**, 537 (1974).
- ¹¹M.S. Bresler, O.B. Gusev, B.P. Zakharchenya, and I.N. Yassievich, *Fiz. Tverd. Tela* **38**, 1474 (1996) [*Phys. Solid State* **38**, 813 (1996)].