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# Time-resolved study on the impact excitation and quenching processes of the 1.54 $\mu\text{m}$ electroluminescence emission of Er ions in InP

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Time-resolved impact excitation and de-excitation processes of the 1.54  $\mu\text{m}$  electroluminescence (EL) emission of  $\text{Er}^{3+}$ -doped InP are investigated. Samples are impact excited by applying electrical pulses and the time response of the EL emission is measured in the temperature range from 77 K to 330 K. The decay of the emission proves almost exponential in all the temperature ranges and shows little thermal quenching with the decay time decreasing from 2 ms at 77 K to only 1 ms at 330 K. This result contrasts with the large thermal quenching and nonexponential characteristics of the photoluminescence (PL) time decay at high temperatures in the same sample, suggesting different excited  $\text{Er}^{3+}$  centers between EL and PL. Also measured is the emission rise time as a function of excitation pulse current, giving us the impact cross section of  $9 \times 10^{-16} \text{ cm}^2$  for  $\text{Er}^{3+}$  ions in InP. The excitation and quenching processes as well as the efficiency of Er emission are analyzed. A model taking into consideration the presence of different Er centers explains the different behaviors in the time responses between EL and PL.

## I. INTRODUCTION

Sharp and thermally stable photoluminescence emissions of rare-earth (RE) doped semiconductors have been attracting much attention with an expectation of realizing electrically excited light emitting diodes. Improvement in the emission efficiency is one of the great concerns, and the energy transfer mechanisms from the  $e$ - $h$  pairs of host materials to the  $4f$  electrons of RE ions and the energy backflow mechanisms in the de-excitation processes have been studied extensively. It has been shown that Er ions in InP can be impact excited and emit light at 1.54  $\mu\text{m}$ .<sup>1,2</sup> This electroluminescence (EL) emission is characterized especially by little thermal quenching of the emission intensity as well as a fine emission structure different from that of photoluminescence (PL) emission from the same sample.<sup>2,3</sup> It has been suggested that  $\text{Er}^{3+}$  ions located on different lattice sites are excited between EL and PL. Different fine luminescent structures between PL and EL have also been presented recently by using Er-doped metalorganic chemical vapor deposition (MOCVD) GaAs  $pn$  junction diodes,<sup>4</sup> and the above result may, therefore, be a general characteristic peculiar to the EL emission of rare-earth ion doped III-V compounds. It is expected that the analysis of the excitation and de-excitation processes of the RE emissions by comparing EL and PL emissions will give us some indications to physical key factors related to the emission efficiency of rare-earth ions in III-V semiconductors.

This paper deals with the time-resolved characteristics of the 1.54  $\mu\text{m}$  EL excitation. The temperature dependence of the time decay is measured and the de-excitation mechanisms of the excited  $4f$ -electron states are discussed in comparison with PL time decay, assuming the presence of differ-

ent Er emission centers. The rise time is measured as a function of excitation current. By analyzing the data theoretically, the impact excitation cross section of  $\text{Er}^{3+}$   $4f$  electrons for the emission at 1.54  $\mu\text{m}$  is deduced. Also the EL emission efficiency of the  $\text{Er}^{3+}$  ions in InP is estimated. Finally, the excitation and de-excitation processes as well as the efficiency of Er emission are discussed.

## II. EXPERIMENT

Samples used in the present experiment were Er ion implanted  $n$ -type ( $n \sim 5 \times 10^{15} / \text{cm}^3$ ) InP with an Er ion dose of  $7 \times 10^{14} / \text{cm}^2$  at 150 keV. Then, they were annealed at 600  $^\circ\text{C}$  for 20 h in a quartz ampoule with As over pressure. Au/Sn ohmic contacts were evaporated and alloyed on both surfaces. Electrical pulses of 2–4 ms on-time and 6 ms off-time durations were applied to the samples, and the time-resolved light emission at 1.54  $\mu\text{m}$  due to impact excitation of  $\text{Er}^{3+}$  was detected with a cooled germanium detector. The emission at 1.54  $\mu\text{m}$  was selected using an interference filter ( $< -40$  dB attenuation between 1.1  $\mu\text{m}$  and 1.4  $\mu\text{m}$  and 0 dB attenuation between 1.45  $\mu\text{m}$  and 1.6  $\mu\text{m}$ ) and an Si wafer between the samples and the detector, which cut off emissions other than at 1.54  $\mu\text{m}$ . The time response of the detecting system was  $< 70 \mu\text{s}$ . The rise and decay processes of the 1.54  $\mu\text{m}$  emission were measured in the temperature range from 77 K to 330 K.

## III. RESULTS AND DISCUSSION

### A. EL decay

Figure 1 shows the time response of the EL emission to applied electrical pulses of different peak currents at 300 K. The decay process is nearly exponential and its decay time is independent of the excitation current. Figure 2 shows decay curves at different temperatures between 77 K and 330 K.

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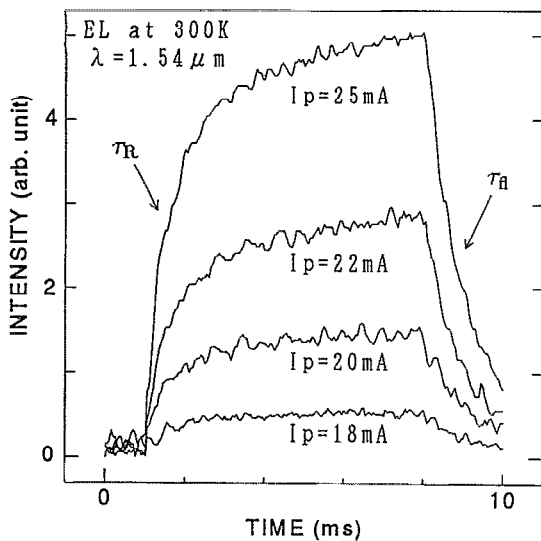


FIG. 1. Time response of the impact excitation electroluminescence of  $\text{Er}^{3+}$  ions in InP at  $1.54 \mu\text{m}$  as a function of excitation current. The input pulses are 2–4 ms on-time and 6 ms off-time in duration. The time response of the detecting system is  $<70 \mu\text{s}$ .

The decay process is again exponential in all the measured temperature ranges. The EL decay time is then defined and plotted as a function of temperature in Fig. 3.

At 77 K, the EL decay time ( $\sim 2$  ms) is nearly of the same magnitude as that of PL ( $\sim 1$  ms) (Ref. 5) and that of Er ions in glass or dielectric crystal (several ms).<sup>6</sup> With increasing temperatures, the EL decay time decreases very slowly (little thermal quenching) to 1 ms at 330 K. The PL decay of Er ions in InP or in GaAs which is nearly exponential at 77

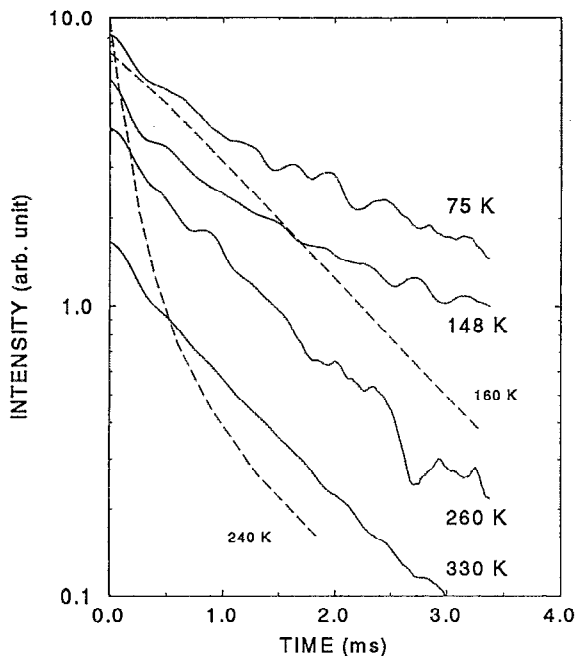


FIG. 2. Electroluminescence decay curves of the  $\text{Er}^{3+}$   $1.54 \mu\text{m}$  peak at different temperatures (solid lines). Photoluminescence decay curves of  $\text{Er}^{3+}$  ions in GaAs (Ref. 5) are also plotted for comparison (dashed lines).

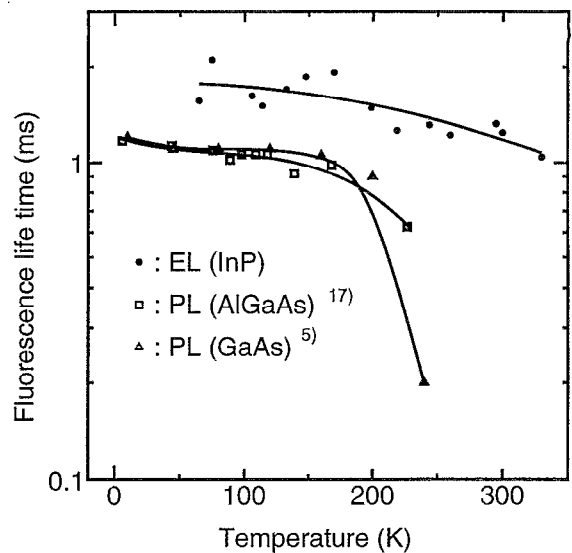


FIG. 3. Temperature dependence of the EL decay time as a function of temperature ( $\bullet$ ). The PL decay times reported in the literature (Ref. 5) ( $\Delta$ ), (Ref. 17) ( $\square$ ) are also plotted for comparison.

K becomes nonexponential and the initial decay becomes very fast at high temperatures, but is followed by a slow decay. The PL decay time in the initial stage reported in the literature<sup>5</sup> is also plotted for comparison.

In the PL emission,  $\text{Er}^{3+}$  ions are excited by the energy stored in the electron-hole pairs or excitons. It has been proposed that, in the case of Yb-doped InP, the energy transfer from the electron-hole pairs to  $\text{Yb}^{3+}$  ions is effectively carried out via Yb-related electron traps (RE traps). Though the presence of such traps has not been confirmed in Er-doped InP or GaAs, the energy transfer from the electron-hole pairs to Er ions will take place much more efficiently when Er ions form such traps. In the EL emission, however, Er ions are considered to be excited directly by energetic electrons through collision from the ground state ( $^4I_{15/2}$ ) to the first ( $^4I_{13/2}$ ) or upper excited states.<sup>2</sup> (At high voltages, however, the impact ionization occurs and the formed electron-hole pairs excite Er ions, too.) It is considered that Er ions on any sites may be almost equally impact excited when they meet electrons with sufficient energy irrespective of whether they form RE traps or not. As shown in Fig. 2, the EL decay curves are exponential in all the measured time and temperature ranges, in contrast with the nonexponential PL decay at high temperatures.<sup>7</sup> This result suggests that coupling of Er ions with host materials may affect strongly the nonradiative relaxation process of excited  $4f$  electrons at high temperatures.

Various mechanisms for the thermal quenching of the PL emission have been proposed in relation to the energy transfer process, for example, of InP:Yb.<sup>7,8</sup> The photoluminescence excitation spectroscopy (PLE) has revealed that the generation of electron-hole pairs is necessary to excite  $4f$  electrons.<sup>9</sup> The energy released through recombination of electrons and holes is transferred very inefficiently to  $4f$  electrons, but more efficiently if RE traps are involved in the

energy transfer. These RE traps are considered to be created if Er ions are on certain special lattice sites. These traps, however, help the relaxation energy of 4f electrons back-transfer nonradiatively to electrons in the host semiconductors. This is a kind of Auger process via intermediates. With increasing temperatures, this nonradiative transition increases because the increase in the energy of thermal phonons help the energy back transfer. The higher the temperature, the shorter the fluorescence lifetime and the lower the PL emission efficiency. Another reason for the low efficiency of the PL emission is that only a small fraction of Er ions are on those special lattice sites and form traps that relate 4f electrons of Er ions to the host semiconductors.<sup>10</sup>

Taking into consideration the above results and reports, we analyzed the excitation and de-excitation processes in the presence of two different Er emission centers. We limit the transition only between the ground and the first excited states for simplicity. The rate equation for a center is given by

$$\frac{dN_2}{dt} = R N_1 - \frac{N_2}{\tau_{\text{fl}}} = R N - \left( R + \frac{1}{\tau_{\text{fl}}} \right) N_2, \quad (1)$$

$$\frac{1}{\tau_{\text{fl}}} = \frac{1}{\tau_{\text{rad}}} + \frac{1}{\tau_{\text{nrad}}}, \quad (2)$$

where  $R$  is the excitation rate,  $N_1$  and  $N_2$  are the densities of the ground and excited states, respectively,  $N = N_1 + N_2$ ,  $\tau_{\text{rad}}$ , and  $\tau_{\text{nrad}}$  are the radiative and nonradiative lifetimes, respectively, and  $\tau_{\text{fl}}$  is the fluorescence lifetime. The radiative lifetime is considered constant independent of the kind of Er centers and temperatures. The nonradiative lifetime is, however, related to the mechanism for the energy backflow to electrons and/or phonons in the host semiconductor and therefore depends greatly on the lattice sites of Er ions and on temperatures. The solution of Eq. (2) for a step excitation at  $t=0$  is given by

$$N_2(t) = \frac{R N}{R + (1/\tau_{\text{fl}})} \left[ 1 - \exp\left(-\frac{t}{\tau_R}\right) \right], \quad (3)$$

where  $\tau_R$  is

$$\frac{1}{\tau_R} = R + \frac{1}{\tau_{\text{fl}}}, \quad (4)$$

and  $N_2(0) = 0$  is assumed. At steady state,

$$N_{2,\text{steady}} = \frac{R}{R + (1/\tau_{\text{fl}})} N = \frac{R \tau_{\text{fl}}}{1 + R \tau_{\text{fl}}} N. \quad (5)$$

In the decay process ( $R=0$  and  $N_2 = N_{2,\text{steady}}$  at  $t=0$ ),

$$N_2(t) = N_{2,\text{steady}} \exp\left(-\frac{t}{\tau_{\text{fl}}}\right). \quad (6)$$

In case there are various kinds of Er centers relating to different energy backflow processes and therefore different non-radiative lifetimes, the emission intensity  $L(t)$  is given by

$$L(t) = \hbar \omega \eta_{\text{ex}} S w \sum_i N_{2,i}(t) / \tau_{R,i}, \quad (7)$$

where  $\hbar \omega$  is the photon energy,  $\eta_{\text{ex}}$  is the external efficiency,  $S$  is the current flowing area, and  $w$  is the effective thickness of the Er<sup>+</sup> implanted region.

To simplify the discussion, we consider only two kinds of centers whose properties are quite different. One (named the  $P$  center) has an RE trap and the other (named the  $E$  center) does not have such a center. In the PL excitation, the former is effectively excited as the energy stored in the electron-hole pairs is effectively transferred to the 4f electrons via this trap; however, the latter is hardly excited. In the EL excitation, both centers are equally and effectively excited, as the impact excitation does not need such traps to excite 4f electrons. The nonradiative lifetime of a center as a function of temperature is expressed by

$$\tau_{\text{nrad}} = \tau_{\text{nrad}}(T \rightarrow \infty) \exp(E_a/kT), \quad (8)$$

where  $E_a$  is the activation energy for the backflow. The radiative lifetime  $\tau_{\text{rad}}$  is independent of temperature. Then, the fluorescent lifetime  $\tau_{\text{fl}}(T)$  is given by

$$\tau_{\text{fl}}(T) = \frac{\tau_{\text{rad}}}{1 + [\tau_{\text{rad}}/\tau_{\text{nrad}}(T \rightarrow \infty)] \exp(-E_a/kT)}. \quad (9)$$

When the densities of  $P$  and  $E$  centers are  $N_P$  and  $N_E$ , respectively, the dc emission intensity  $L(T)$  is given by

$$L_{\text{dc}}(T) = \hbar \omega \eta_{\text{ex}} S w \left( \frac{R \eta_{f,P}(T)}{1 + R \tau_{\text{fl},P}(T)} N_P + \frac{R \eta_{f,E}(T)}{1 + R \tau_{\text{fl},E}(T)} k_E N_E \right), \quad (10)$$

where  $\eta_f(T) = \tau_{\text{fl}}/\tau_R$  is the fluorescence efficiency and  $k_E$  is the portion of the  $E$  centers that are excited. The subscripts  $P$  and  $E$  are for  $P$  and  $E$  centers, respectively. We assume that  $k_E = 1$  in EL and  $k_E \ll 1$  in PL. Recent backscattering measurements on the site of rare earth ions in semiconductor lattices<sup>11</sup> and a comparative study on the direct optical excitation of RE ions and the indirect excitation through electron-hole recombination<sup>10</sup> can make us assume that the number of  $P$ -centers  $N_P$  is much smaller than the number of  $E$ -centers  $N_E$ . Here, we assume also that both centers are excited effectively in EL ( $k_E \sim 1$  and  $N_E \gg N_P$ ), whereas  $P$  centers are effectively excited and  $E$  centers are very ineffectively excited in PL ( $k_E \ll 1$  and  $N_P \gg k_E N_E$ ). The fluorescence decay of the emission intensity is given by

$$L_{\text{decay}}(t, T) = \hbar \omega \eta_{\text{ex}} S w \left[ \frac{R \eta_{f,P}(T)}{1 + R \tau_{\text{fl},P}(T)} N_P \times \exp\left(-\frac{t}{\tau_{\text{fl},P}(T)}\right) + \frac{R \eta_{f,E}(T)}{1 + R \tau_{\text{fl},E}(T)} k_E N_E \times \exp\left(-\frac{t}{\tau_{\text{fl},E}(T)}\right) \right]. \quad (11)$$

The dc emission intensity  $L_{\text{dc}}(T)$  and the decay  $L_{\text{decay}}(t, T)$  are calculated for various values of  $k_E$  from 1 down to  $1 \times 10^{-8}$  and are shown in Fig. 4. The reported activation energy in Eq. (8) of the PL intensity of Er<sup>3+</sup> ions is

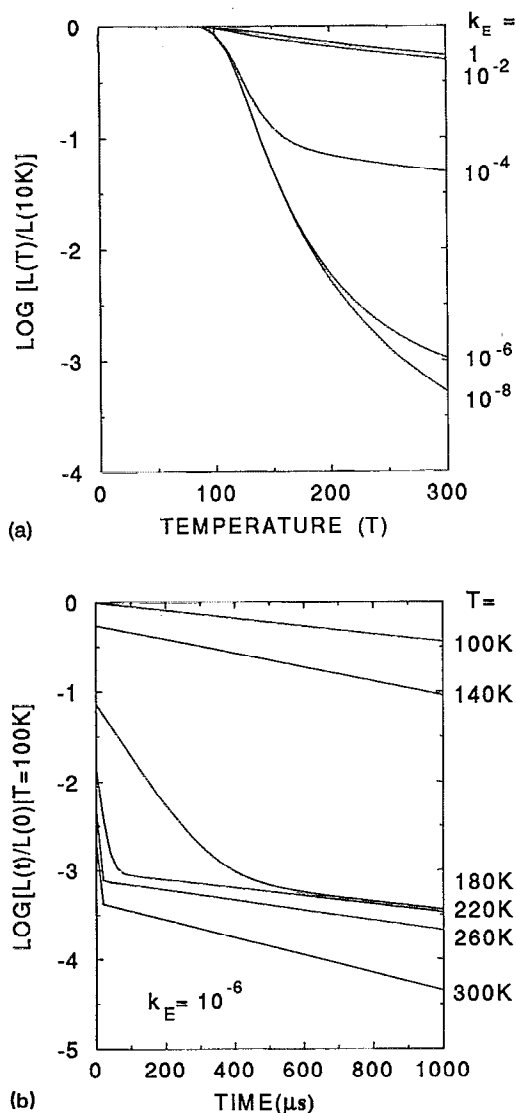


FIG. 4. Simulated luminescence decay curves in the presence of two different  $\text{Er}^{3+}$  centers ( $P$  and  $E$  centers) at a ratio of  $1:k_E$ . (a) Steady state intensity vs temperature for different  $k_E$  values from 1 to  $10^{-8}$ . The difference in the temperature dependence of PL and EL decay curves is simulated using different  $k_E$  values (EL for  $k_E = 1, 10^{-2}$  and PL for  $k_E = 10^{-6}, 10^{-8}$ ). (b) Decay curves at different temperatures for  $k_E = 10^{-6}$ . They reproduce the temperature dependence of the PL decay semiquantitatively. The following are assumed as for the lifetime. Both centers have the same temperature independent radiative lifetime  $\tau_{\text{rad}}$  of 1 ms. The nonradiative lifetime of  $P$ -center  $\tau_{\text{nr},P}$  has a smaller activation energy (0.15 eV) and is expressed by  $\tau_{\text{nr},P} = 5 \times 10^{-9} \exp(0.15 \text{ eV}/kT)$  (s), whereas that of  $E$ -center  $\tau_{\text{nr},E}$  has a larger activation energy (0.25 eV) and is expressed by  $\tau_{\text{nr},E} = 5 \times 10^{-8} \exp(0.25 \text{ eV}/kT)$  (s). The above nonradiative lifetimes for  $P$  and  $E$  centers are taken as an example set, but they reproduce well the tendency of the temperature dependence of the PL and EL emission intensity by the use of different  $k_E$  values.

dependent on the energy gap of the host semiconductor. For example, it varies from 150 meV for InP (which agrees with our result<sup>12</sup>) to 410 meV for  $\text{In}_{0.69}\text{Ga}_{0.31}\text{P}$ .<sup>13</sup>

We took here 0.15 eV for  $E_{a,P}$  of Er in InP. On the other hand, the present result as well as the temperature dependence of the EL emission intensity<sup>14</sup> suggest a higher value for  $E_{a,E}$  which is difficult to estimate exactly from data be-

low room temperature. Here, we assume a value of 0.25 eV for  $E_{a,E}$ .

In Fig. 4,  $k_E = 1$  shows the case where both  $E$  and  $P$  centers are excited (EL excitation:  $N_E \gg N_P$ ). Both the steady state emission and the decay curve are characteristics of  $E$  centers. For  $k_E \ll 10^{-4}$  but not too small ( $k_E N_E \ll N_P$ ), the calculated results reproduce both the steady state emission which shows a thermal quenching as well as a nonlinear decay at around  $T = 200$  K which is characteristic of PL decay. It is a combination of  $P$  and  $E$  center characteristics, where a very small fraction of  $E$  centers compared to  $P$  centers are excited (PL excitation). The nonlinear decay is a manifestation of a large fast initial decay of  $P$  centers followed by a slow decay of  $E$  centers. It should be noted that such nonexponential decay is not obtained in the case of one type of luminescent center unless a nonlinear excitation dependent relaxation process is involved. A possible example might be the energy transfer between Er centers which is sometimes observed in the case of high Er doping (i.e., concentration quenching). However, the nonlinear decay is experimentally observed even in the case of low Er densities. The interaction between Er ions and host semiconductors is considered much faster than the decay time of Er emissions and this may not be the case either.

The above simple analysis together with experimental results leads to the following important remarks. In case of impact excitation emissions, the dominant excited Er centers are those that do not form Er-related traps in semiconductors and therefore the energy backflow related to the nonradiative transition processes is small. The fluorescence lifetime is, therefore, almost determined by the temperature independent radiative transition lifetime. However, in the photoluminescence, the energy released through recombination of electron-hole pairs can excite mainly Er centers that form traps and thereby couple strongly with the host semiconductor in the excitation process. These Er centers, however, couple strongly with the host semiconductor in the relaxation process as well, leading to a large nonradiative transition at high temperatures, and a slow decay of  $E$  centers appears after the fast decay of the emission from  $P$  centers if a small fraction of  $E$  centers, even if it is very small, is excited. The assumption that different types of Er centers are excited between EL and PL is supported also by recent reports that show that the fine structure of the emission spectrum is different between PL and EL for Er:InP (Refs. 2 and 3) and for Er:GaAs (Ref. 4).

## B. EL excitation rate and impact cross section

As shown in Eq. (4), the excitation rate  $R$  is related with the rise time  $\tau_R$  and the fluorescent decay time  $\tau_f$ . From the results shown in Fig. 1,  $R$  is obtained as a function of current. The results are shown in Table I and in Fig. 5. As is characteristic of the impact excitation, the emission is observed above a critical applied field (or current), and the increment of the excitation rate  $\Delta R$  is almost linear to the increment of the input current  $\Delta I_p$  above the threshold. The relation between the increments of the excitation rate  $\Delta R$  and current  $\Delta I_p$  is expressed by the following equation,

TABLE I. Excitation rate  $R$  deduced from the rise ( $\tau_R$ ) and fall ( $\tau_f$ ) times using the relation of Eq. (4).

$I_p$ (mA)	$\tau_R$ (ms)	$\tau_f$ (ms)	$R$ (1/ms)
18		1.5	
20	0.44	1.4	1.6
22	0.26	1.1	2.9
25	0.19	1.1	4.3

$$\Delta R = \frac{(\Delta I_p/q)}{S} \sigma_0, \quad (12)$$

where  $\sigma_0$  is the average impact cross section of  $\text{Er}^{3+}$  ions which is here assumed to be constant above the threshold, and  $q$  is the unit charge. From the gradient of the linear part in Fig. 5, the impact cross section of Er ions is experimentally obtained. The estimated value of  $\sigma_0$  is about  $9 \times 10^{-16} \text{ cm}^2$ , which is of the same order as that of  $\text{Er}^{3+}$  ions in ZnS ( $2 \times 10^{-16} \text{ cm}^2$ ) (Ref. 15) for the impact excitation from  $^4I_{15/2}$  to  $^2H_{11/2}$ . In Fig. 5 also shown is the dc luminescence intensity  $L_{dc}$ , and it behaves in the same manner as  $R$ . This is consistent with the theoretical prediction given by Eq. (10) in case of  $R \tau_{fl,E} \ll 1$ .

The dc EL emission intensity given by Eq. (10) is rewritten to

$$\begin{aligned} L_{dc} &= \hbar \omega \eta_{ex} S w N_E \frac{R \eta_{f,E}}{1 + R \tau_{fl,E}} \\ &= \hbar \omega \eta_{ex} \eta_f S \gamma N_{dose} \frac{R}{1 + R \tau_{fl,E}}, \end{aligned} \quad (13)$$

where  $N_{dose}$  is the total implant dose and  $\gamma = N_E w / N_{dose}$  is the fraction of the  $\text{Er}^{3+}$  ions which are excited by impact excitation to the total Er atoms in InP. We make a rough estimate of  $\gamma$  at room temperature in the following. First, we assume that  $\eta_{f,E} = 0.5$  at room temperature, since  $\tau_{fl,E}$  at room temperature is about half that at low temperatures<sup>2</sup>

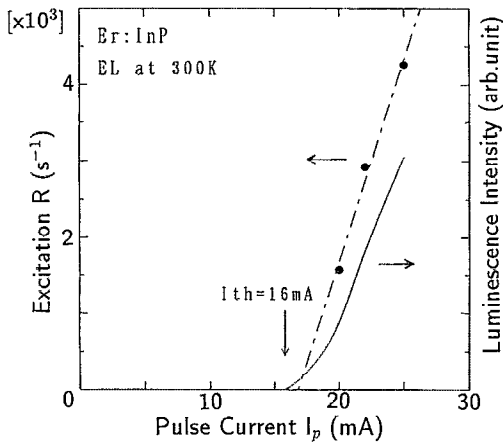


FIG. 5. The relation between excitation rate  $R$  and input pulse current  $I_p$ . From the gradient of the linear part, the impact cross section is obtained. Also shown is the dc luminescence intensity  $L_{dc}$  which behaves in the same manner as  $R$ .

where  $\tau_{fl,E}$  is considered nearly equal to the radiative decay time ( $\eta_{f,E} = 1$ ). The measured emission intensity is about  $10^{-8} \text{ W}$  at 100 mA/10 V input at room temperature and with a rough estimate of  $\eta_{ex} \sim 0.01$  due to the geometrical structure, we obtain  $2.2 \times 10^{-3}$  for  $\gamma$ . This estimate shows that about 0.2% of the total implanted Er atoms is excited by impact excitation at room temperature in our samples.

The following are considered as possible causes for low  $\gamma$ . First, the assumption of a constant impact cross section above the threshold current is too rough. The energy of the accelerated electrons has a distribution and only a small fraction of the accelerated electrons can excite Er 4f electrons when the energy of the electrons matches the energy difference between the excited and the ground states. This fraction will decrease when Er ions are as highly incorporated as in our samples ( $10^{20}/\text{cm}^3$  at the peak), since the mean distance between each Er ion becomes shorter and the electrons cannot gain sufficient energy between collisions. Second, the implanted Er ions are not uniformly distributed in our samples. Then, the sample resistivity at the tail is low and the electric field there may be too low to excite Er ions.

Finally, we estimate the theoretically expectable maximum EL power efficiency using the above obtained impact cross section and the fluorescence efficiency at room temperature. We assume a simple resistive sample structure like ours. The excitation rate  $R(F)$  which is a function of the electric field  $F$  is given by<sup>2</sup>

$$\begin{aligned} R(F) &= n \int_0^\infty \sigma(E) v(E) f(E) dE \\ &= n \sigma_0 \int_{E_0}^\infty v(E) f(E) dE = n \sigma_0 g_{E_0}(F), \end{aligned} \quad (14)$$

where  $n$  is the electron density,  $E$  is the kinetic energy of electrons,  $\sigma(E)$  is the impact cross section of erbium luminescent centers,  $v(E)$  is the velocity of electrons,  $f(E)$  is the energy distribution function of electrons, and  $\sigma_0$  is the average impact cross section above the threshold energy  $E_0$  for the impact excitation to occur. The current flowing through the sample is given by

$$I = qnS \int_0^\infty v(E) f(E) dE = qnSg_0(F). \quad (15)$$

The input power is

$$P_{in} = nqSg_0(F)V, \quad (16)$$

where  $V$  is the voltage across the Er-doped layer. The output emission power is given by

$$P_{out} = \hbar \omega \eta_{ex} \eta_f S w [n \sigma_0 g_{E_0}(F)] \gamma N, \quad (17)$$

where  $N$  is the total Er concentration and  $R \tau_{fl,E} \ll 1$  is assumed. Then the power efficiency is given by

$$\eta_{\text{power}} = \frac{\hbar\omega}{q} \eta_{\text{ex}} \eta_f \gamma N \sigma_0 \frac{w}{V} \frac{g_{E_0}}{g_0}. \quad (18)$$

Here, we consider the case where  $\eta_{\text{ex}}$  is assumed to be unity and all the  $\text{Er}^{3+}$  ions can be excited if they meet electrons with energy higher than  $E_0$  ( $\gamma=1$ ). With  $\hbar\omega/q=0.8$  V,  $\eta_f=0.5$ ,  $V/w=10^6$  V/cm (the threshold electric field above which we observe the EL emission),  $\sigma_0=9\times 10^{-16}$  cm<sup>2</sup>, and  $N=10^{20}$ /cm<sup>3</sup> (Er concentration of our sample), and with a rough estimation of  $g_{E_0}/g_0=0.1$  for such a simple sample structure as we used in the present experiment, we obtain  $\eta_{\text{power}}=3.6\times 10^{-3}$ . If we can devise a sample structure such that the energy distribution of electrons is like a  $\delta$  function using, for instance, a heterobarrier,<sup>16</sup> we can make  $g_{E_0}/g_0$  approach unity, and a power efficiency higher than 1% can be expected.

#### IV. CONCLUSION

The time dependence of the EL emission of  $\text{Er}^{3+}$  ions in InP has been measured for the first time. The decay is almost exponential. The decay time at 77 K is about 2 ms, nearly the same order as that of the PL decay time, and it shows little thermal quenching with increasing temperatures up to 330 K, in contrast to the large thermal quenching of the PL decay time. These different behaviors are explained in terms of different Er centers that are involved in EL and PL. The impact cross section of  $\text{Er}^{3+}$  ions for excitation from  $^4I_{15/2}$  to  $^4I_{13/2}$  is also evaluated by analyzing the rate equation using the above data. The impact cross section obtained is  $\sim 9\times 10^{-16}$  cm<sup>2</sup>. Though the EL power efficiency of our samples is only  $\sim 10^{-8}$  with our present samples, a value larger than 1% may be expected with an improved sample structure and the optimization of the Er doping.

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