

## 1.54 $\mu\text{m}$ Electroluminescence by Electron Impact Excitation of Er Atoms Doped in InP

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### Abstract

The Er-related 1.54  $\mu\text{m}$  electroluminescence (EL) could be observed by impact exciting Er-atoms implanted into InP in the temperature range from 77K to 360K. The L-V (emission intensity - applied voltage) characteristics exhibited a threshold voltage of about 4V and a saturation of the emission intensity at high voltages. No shifts in the peak wavelength of 1.543  $\mu\text{m}$  were observed in the voltage range from 4V to 15V and in the temperature range from 77K to 360K. The EL emission at room temperature was strong, about one half that at 77K. The temperature dependence of the quantum efficiency of the EL emission was discussed in comparison with that of the PL emission.

### 1. INTRODUCTION

Sharp luminescence peaks from rare-earth atoms doped in semiconductors have been attracting increasing attention<sup>1)-4)</sup>, especially the 1.54 $\mu\text{m}$  luminescence peak from erbium atoms due to the possibility of realizing light emitting diodes (LED's) or lasers as light sources of optical fiber communication systems<sup>5)6)7)</sup>. Recently, the room temperature emission of the 1.54 $\mu\text{m}$  peak has been demonstrated in Er-doped GaAs and AlGaAs LED's fabricated by molecular beam epitaxy (MBE)<sup>6)</sup> and metalorganic chemical vapor deposition (MOCVD)<sup>7)</sup>. The quantum efficiency and emission power have been discussed in view of device applications. This paper deals with the first observation of the Er-related 1.54 $\mu\text{m}$  electroluminescence from Er-doped InP by direct impact excitation of erbium atoms with energetic electrons. The excitation mechanisms will be discussed in comparison with the photoluminescence emission of the same peaks from the same sample.

### 2. EXPERIMENT

Undoped LEC n-type (100) InP ( $n = 5 \times 10^{15}/\text{cm}^3$ ) was implanted with 150 KeV Er ions to a dose of  $7 \times 10^{14}/\text{cm}^2$  at room temperature. Thereafter, the samples were put in an evacuated quartz ampule together with phosphorus powder and annealed at 600°C for

20 hours. Due to this phosphorus overpressure, the mirror-like surface was kept undamaged. The carrier type remained n-type after the annealing. Secondary ion mass spectroscopy (SIMS) showed nearly the same Er profiles for both as-implanted and annealed samples. The maximum Er density was  $3 \times 10^{20}/\text{cm}^3$  at a depth of 40nm.

The schematic structure of samples for the electroluminescence measurements is shown in Fig.1. Au/Sn ohmic contacts were deposited on the substrate surface at 250°C. The electrode spacing and the width were 100 $\mu\text{m}$  and 5mm, respectively. The current vs. voltage characteristics of the samples were nearly linear and symmetrical in both directions. The resistance between the electrodes was about 150 $\Omega$  at 300K. This value was much higher than the resistance of the original InP substrate and, therefore, was attributed to the resistance of the Er-implanted layer. The samples were excited by applying dc voltage between the electrodes, and the electroluminescence (EL) emission was monitored by a cooled germanium p-i-n photodiode. The photoluminescence (PL) measurements of the same samples with an argon laser at 514.5 nm as an excitation source was also carried out for the comparison.

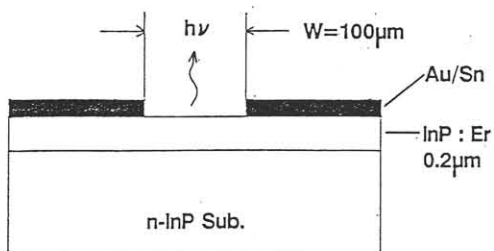


Fig.1. The schematic structure of samples for the EL measurements.

### 3. RESULTS

The Er-related EL emission at  $1.543\mu\text{m}$  could be observed by applying voltages between the electrodes in the temperature range from 77 K to 360 K. Fig.2 shows the EL emission intensity (L) at  $1.543\mu\text{m}$  versus applied voltage (V) at 300K. The L-V characteristics exhibited a threshold voltage of about 4 V. Assuming that the voltage is applied vertically to the Er-implanted high resistive layer alone, the electric field in this region is estimated to be about 100 KV/cm at the threshold, which may be large enough for the electron impact excitation of Er atoms to occur. The emission spectra at different voltages are also shown in the inset of Fig.2. Neither the shift in the dominant peak wavelength at  $1.543\mu\text{m}$  nor the emission of other Er-related peaks around  $1.54\mu\text{m}$  was observed in the voltage range from 4 V to 15 V. We could not observe any emission bands relating to the recombination of electron-hole pairs in the wavelength range from  $0.8\mu\text{m}$  to  $1.7\mu\text{m}$ <sup>8)</sup>. The L-V curve

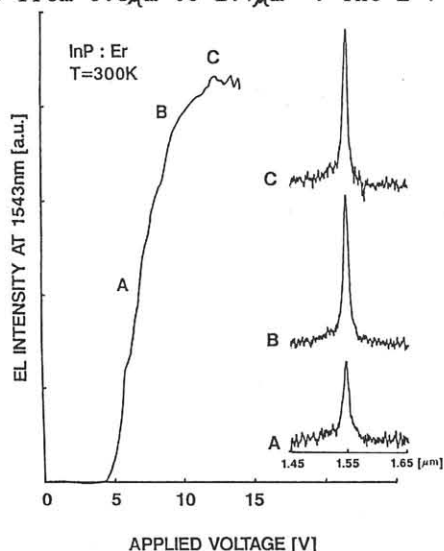


Fig.2. The Er related EL emission intensity vs applied voltage at 300K.

showed a saturation tendency at high voltages. This will be discussed in the next section.

Fig.3 shows the Er-related  $1.54\mu\text{m}$  EL spectra at 300K and 360K. The EL spectra showed only one peak at  $1.543\mu\text{m}$  with a linewidth of 4.9 nm ( $\Delta E=2.6\text{meV}$ ) at 300K. As in the case of voltage dependence, neither the shift of the peak wavelength nor other Er-related peaks was observed in the temperature range from 77K to 360K. In contrast to the EL emission, the PL spectrum of the same sample at 77K showed two Er-related peaks, a dominant peak at  $1.541\mu\text{m}$  and a small peak at  $1.548\mu\text{m}$ <sup>8)</sup>. Note that these PL peaks were observed only below 230K.

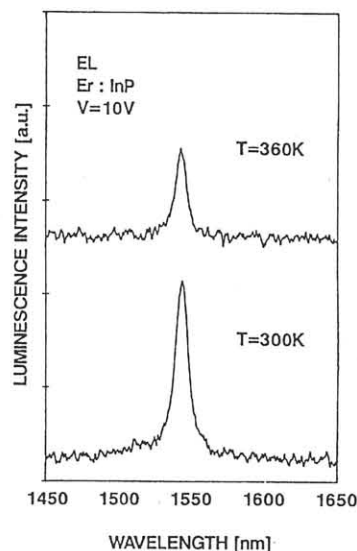


Fig.3. The Er-related EL spectra at 300K and 360K.

### 4. DISCUSSION

Although the emission spectra of rare-earth atoms doped in semiconductors are almost insensitive to temperature<sup>7)</sup>, the intensity or the quantum efficiency of these emissions in PL or LED decreases rapidly with increasing temperatures<sup>5)9)</sup>. Our EL emission, on the other hand, showed a strong emission intensity even above room temperature.

We measured the emission intensity (L) of the erbium-related EL emission at  $1.54\mu\text{m}$  as a function of the current (I) in the temperature range from 77K to 360K. Fig.4 shows the I-L characteristic at 300K. The emission intensity above the threshold increased linearly with current, and then saturated at high injection currents. We

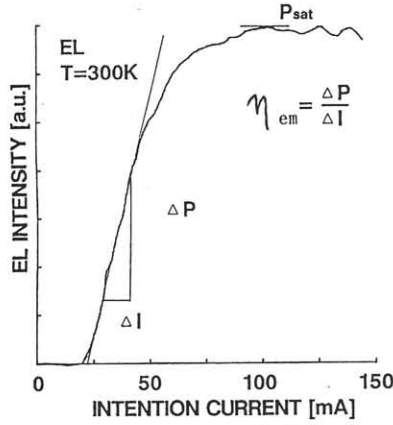


Fig.4. The Er-related EL emission intensity vs injection current at 300K.

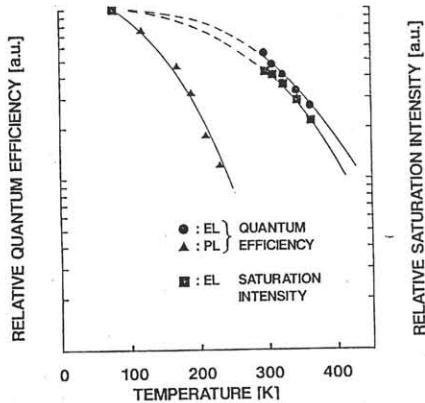


Fig.5. The temperature dependences of the EL and PL quantum efficiencies and of the EL saturation intensity.

evaluated the EL external quantum emission efficiency from a derivative ( $dP/dI$ ) of the linear part of the I-L characteristics. In Fig. 5 are shown the temperature dependencies of the EL external quantum efficiency evaluated as above and also of the PL intensity from the same sample, both as referred to the values at 77K. The temperature dependence of the PL intensity in Fig.5 is consistent with the result reported by P. N. Favennec et al.<sup>9)</sup>. It is interesting to note that the EL efficiency decreases more slowly with increasing temperature than the PL intensity does.

The EL and PL quantum efficiencies of the Er emission  $\eta_{em}$  can be written as <sup>6)</sup>

$$\eta_{em}^{EL} = \eta_{ET}^{EL} \cdot \eta_F \quad (1),$$

$$\eta_{em}^{PL} = \eta_{ET}^{PL} \cdot \eta_F \quad (2),$$

where  $\eta_{ET}$  is the energy transfer efficiency of the excitation energy to the erbium atoms and  $\eta_F$  the fluorescence emission efficiency

of the excited erbium atoms from  $^4I_{13/2}$  to  $^4I_{15/2}$ . The superscripts EL and PL in  $\eta_{ET}$  are for the EL and PL emission, respectively. We assume that the fluorescence emission mechanism is the same for both PL and EL, and use the same fluorescence emission efficiency in the equations. Then, the difference between PL and EL in Fig.5 is attributable to the difference of the temperature dependence between  $\eta_{ET}^{EL}$  and  $\eta_{ET}^{PL}$ . We also plotted the maximum EL intensity at the saturation as a function of temperature, and it showed surprisingly the same temperature dependence as the EL differential quantum efficiency. The appearance of saturation in the EL emission intensity means that all the erbium atoms available are excited at this excitation level. (Note that the temperature increase of the samples is marginal and that the saturation is not related to the temperature increase of the samples.) Then, the energy transfer efficiency is not involved in the saturation intensity, and the temperature dependence of the saturation intensity reflects directly that of the fluorescence emission efficiency;

$$P_s \propto \eta_F \quad (3).$$

The agreement of the temperature dependence of the EL emission efficiency  $\eta_{em}^{EL}$  with that of the saturation intensity  $P_{sat}$  in Fig.5 indicates that the energy transfer efficiency in the EL emission  $\eta_{ET}^{EL}$  is almost independent of temperature, and that the temperature dependence of  $\eta_{em}^{EL}$  also reflects the fluorescence emission efficiency  $\eta_F$  or fluorescence lifetime of excited erbium atoms.

The fluorescence emission efficiency  $\eta_F$  is proportional to the fluorescence lifetime as in the followings <sup>10)</sup>;

$$\eta_F = \tau_F / \tau_R \quad (4)$$

$$1/\tau_F = 1/\tau_R + 1/\tau_{NR} \quad (5),$$

where  $\tau_F$ ,  $\tau_R$  and  $\tau_{NR}$  are the fluorescence lifetime, the radiative lifetime and the non-radiative lifetime, respectively. The fluorescence lifetime  $\tau_F$  is, in general, shorter than the radiative lifetime  $\tau_R$  because of the presence of non-radiative

decay processes other than the main radiative one for the fluorescent state. These decay processes may consist of phonon-assisted (vibronic) emission and other radiationless transitions, for example, auger quenching<sup>(3)</sup>. As the radiative lifetime is almost independent of temperature, the non-radiative processes are mainly responsible for the thermal shortening of the fluorescence lifetime. The decrease in the EL emission efficiency in Fig.5 is, therefore, due to the increase in the phonon-assisted non-radiative process in the fluorescence state and this non-radiative process is negligible below 77K. This may be confirmed by a similar temperature dependence of the fluorescence lifetime of  $\text{Eu}^{3+}:\text{Y}_2\text{O}_3$  in ref.(11) .

The rapid decrease in the PL intensity compared with the EL emission efficiency can, therefore, be ascribed to the temperature dependence of the energy transfer efficiency in the PL emission. Though the energy transfer mechanism of the erbium emission in PL is not clear at present, the increase in the nonradiative recombination of the excited electron-hole pairs with increasing temperature may be responsible for the rapid decrease in the PL emission quantum efficiency.

A further study of the Er-related emission characteristics of both PL and EL may lead to a better understanding of the energy transfer mechanism for the excitation of rare earth atoms in semiconductors.

## 5. CONCLUSION

We have observed for the first time the Er-related  $1.54\mu\text{m}$  electroluminescence due to impact-excitation of Er atoms in the temperature range from 77K to 360K. The EL spectrum showed only one sharp peak at  $1.543\mu\text{m}$  with the linewidth narrower than 2.6meV at 300K, and this emission exhibited no shift of the emission energy against temperature and excitation voltage. The EL emission efficiency turned out less dependent on temperature than the PL emission. It is due to the temperature-independent energy transfer mechanism in the EL emission. The EL efficiency at room temperature was only 50% that at 77K. It is highly expected that light sources with a stable and sharp spectrum can

be realized at room temperature by impact excitation of rare earth atoms doped in semiconductors.

## ACKNOWLEDGMENTS

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