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Time-Resolved Study on the Impact-Excited 1.54 μm Emission of Er^{3+} Ions in InP and Its Excitation and Quenching Mechanisms

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The EL (electroluminescence) time-decay of the 1.54μm emission of Er^{3+} doped in InP was investigated between 77K and 330K. The major decay was almost exponential and the decay time showed little thermal quenching, decreasing from 2ms at 77K to 1ms at 330K. This result contrasts with the large thermal quenching of the PL (photo-luminescence) time-decay, suggesting different excited Er^{3+} centers between EL and PL. The results are analyzed and the excitation and quenching mechanisms are discussed.

1. INTRODUCTION

In our previous papers[1,2], we showed that the 4f-electrons of Er^{3+} ions implanted into InP were excited by energetic free electrons in the conduction band (EL: electroluminescence by impact excitation) and that sharp emission peaks at 1.54μm and 0.99μm were observed. The fine structure of the 1.54μm EL emission peak and the temperature dependence of the emission intensity differed from those of photoluminescence (PL) emission peak where the 4f-electrons were excited with the energy released through recombination of electron-hole pairs. It was speculated that the different Er^{3+} centers related with different lattice sites were excited depending on the energy transfer mechanisms.

The purpose of this study is to measure time-resolved characteristics of 1.54μm EL emission as functions of temperature and to discuss the excitation and quenching mechanisms of the 4f-electron-related emission of Er^{3+} ions in comparison with the reported data of PL emission.

2. EXPERIMENTAL

Er ions were implanted into n-type InP at 150 keV to a dose of 7×10^{14} cm^{-2} and thereafter annealed at 600°C for 20 hrs in a quartz ampule with As overpressure. Au/Sn ohmic contacts were evaporated and alloyed on both of the surfaces. Electrical pulses of 2-4ms on-time and 6ms off-time durations were applied to the samples. The EL emission at 1.54μm was detected with a liquid-nitrogen cooled germanium detector. Emissions other than the 1.54μm emission were cut off using an interference filter and an Si wafer. The time-response of the detecting system was <70μs. The EL time decay of the 1.54μm emission peak after the electrical pulse excitation was measured as a function of temperature from 77 K to 330 K.

3. RESULTS AND DISCUSSION

Time decay of the 1.54μm EL emission (fluorescence decay time τ_{FL} due to the transition from $^4I_{13/2}$ to $^4I_{15/2}$ of 4f-electrons) measured at various temperatures between 77K and 330K is shown in Fig.1. The decay is nearly exponential. The EL exponential decay time is plotted versus temperature (T) in Fig.2 together with PL decay time reported in the literature. The EL decay-time at 77K (~2ms) agrees nearly with those of PL (~1ms) obtained by means of optical excita-

tion of Er^{3+} ions doped in III-V semiconductors.

The EL decay time showed, however, little thermal quenching, decreasing from 2ms at 77K to 1ms at 330K. This result contrasts very much with the large thermal quenching above 200K of the PL decay-time of Er^{3+} ions doped in InP or GaAs[3)]

A similar difference in the temperature dependence has already been reported in the emission intensity between EL and PL[2)]. The PL intensity decreased very rapidly with increasing temperatures and was hardly observable at room temperature. The EL intensity, in contrast, shows little thermal quenching and the intensity at room temperature amounted still to a half of the value at 77K. Moreover, the fine structure of the 1.54μm emission spectra was also found different between EL and PL. The above results lead us to a confidence that the efficient EL Er centers are different from PL ones.

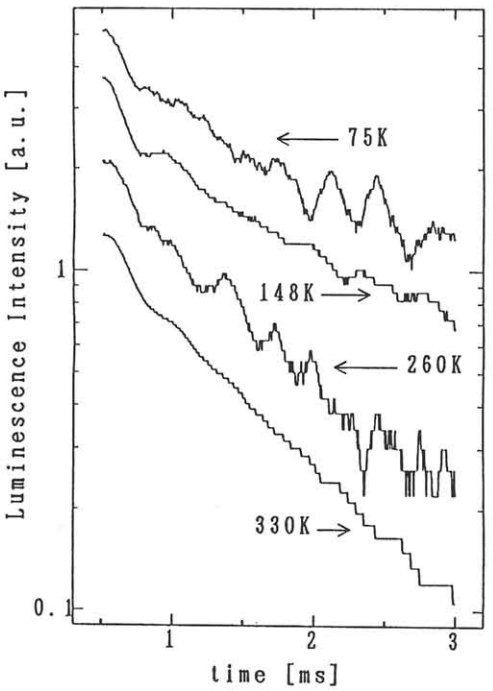

Fig.1 Electroluminescence time decay of the Er^{3+} 1.54μm peak after short electrical pulse excitation at different temperatures. Photoluminescence time decay in the literature[3,4)] is also plotted for comparison.

The PL Er centers are excited through the energy released by the recombination of electrons and holes or excitons which are excited by the above band-gap light illumination, and therefore it is more efficient if they are coupled with the host semiconductor via, for example, some traps which are related to doped rare-earth ions[5)]. This coupling may, in turn, lead to a strong de-excitation of the Er^{3+} ions at high temperatures, due to non-radiative energy backflow from excited 4f-electrons to the host material[5)].

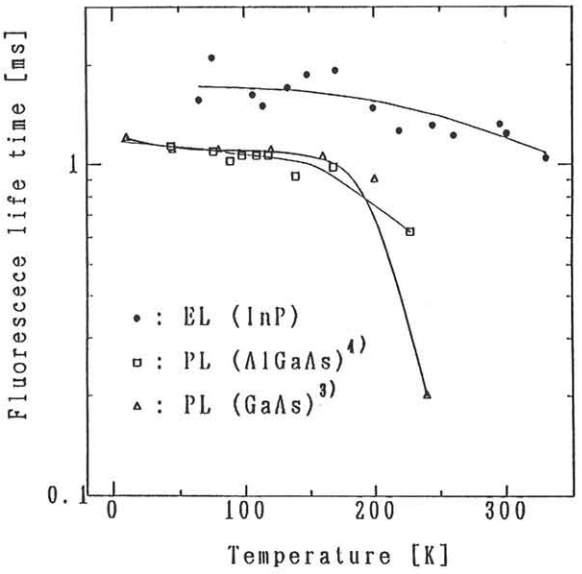

Fig.2 Temperature dependence of the EL and PL decay time constants.

The EL Er centers, however, are directly impact excited with energetic electrons and do not need intermediated centers coupled with the host semiconductor for the excitation. This direct excitation is similar to the direct optical excitation of rare earth ions doped in glass fibers where large thermal quenching of both the intensity and decay time is not observed. As a result, it is considered that Er^{3+} centers which are efficiently excited may be different between PL and EL, leading to different time decay vs temperature relations or quenching mechanisms.

The PL decay curves of Er^{3+} ions in GaAs reported by Takahei[3)] is exponential at low temperatures with a single time constant of about 1ms which is nearly equal to that of EL decay time (2ms). At high temperatures, however, it becomes nonexponential and shows a much shorter decay time in the initial stage followed by a slow decrease.

In the EL emission at low temperatures, we observed two dominant emission lines relating to

two different Er^{3+} centers, one which is mainly excited by impact excitation (EL line) and the other excited by recombination of electron-hole pairs produced through impact ionization (PL line). As is expected from the large thermal quenching of the PL emission, the PL line of the EL emission was not observed at high temperatures.

Though not clearly shown in Fig.1, there seems to be an initial fast decay in the EL intensity at low temperatures at a rate < 1ms followed by the main decay at a decay time of 2ms. At high temperatures, however, the initial fast decay is not seen and the decay is exponential in the intensity range studied here. We speculate that the fast small decay observed at low temperatures may be due to the PL line which may have a smaller time constant than that of the EL line. More precise spectral- and time-resolved measurements are necessary to confirm the present speculation.

In our previous paper[2], we measured only the temperature dependence of EL and PL intensities, and in analyzing the energy transfer and fluorescence efficiencies of PL and EL, we assumed that the fluorescence efficiency was the same for both PL and EL. But the present results show that this assumption is valid only at low temperatures.

The emission efficiency (η_{EM}) is expressed as a product of the energy transfer efficiency (η_{ET}) and fluorescence efficiency (η_{FL}), that is,

$$\eta_{EM} = \eta_{ET} \times \eta_{FL}$$

η_{EM} and η_{Fl} are proportional to the emission intensity and the fluorescence life time τ_f, respectively.

With the present results of $\eta_{FL}(T)$ for EL combined with $\eta_{EM}(T)$, the temperature dependence of the EL energy transfer efficiency $\eta_{ET}(T)$ was derived and is shown in Fig. 3. As shown in the figure, the EL energy transfer efficiency is almost independent of temperature up to 230K with a slight decrease at higher temperatures (up to 330K), probably due to the increased phonon scattering. The EL fluorescence efficiency is also a slowly decreasing function of temperature. Similar results for the PL energy transfer efficiency and the fluorescence efficiency are also plotted in the figure using the results by Takahei et al. [3]. The PL energy transfer efficiency is also nearly constant up to the observed limit of 240K and the thermal quenching of the PL emission intensity is ascribed solely to the thermal quenching of the fluorescence efficiency in the reported temperature range.

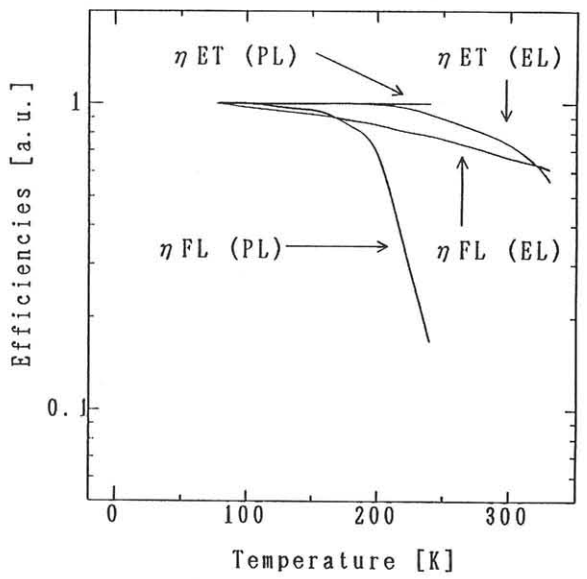

Fig.3 Temperature dependence of the energy transfer (η_{ET}) and fluorescence (η_{FL}) efficiencies of EL and PL.

4. CONCLUSION

The time decay of the EL emission of Er^{3+} ions doped in InP has been measured for the first time. The decay was almost exponential. The decay time at 77K was about 2ms, nearly the same order as that of the PL decay time, but it showed little thermal quenching with increasing temperatures up to 330K, which contrasts with the large thermal quenching of the PL decay time. This difference is ascribed to different Er centers which are efficiently excited between EL and PL.

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