Development of new-type 1.5 µm light-emitting devices based on Er,O-codoped GaAs

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Abstract. We have fabricated two types of 1.5 µm light-emitting devices based on Er,O-codoped GaAs (GaAs:Er,O) using organometallic vapor phase epitaxy (OMVPE). In a device exhibiting a room-temperature lasing at the GaAs band-edge, the threshold current density increased with Er concentration. The Er intensity rose up steeply and then decreased gradually in the spontaneous emission region. In the stimulated emission region, it remained almost constant, reflecting ultrafast energy transfer to Er ions. In a device exhibiting a room-temperature lasing from strained GaInAs quantum wells (QWs) embedded in GaAs:Er,O, on the other hand, the lasing wavelength was designed to tune to the energy separation between the second excited states $^4I_{11/2}$ and the ground state $^4I_{15/2}$ of Er$^{3+}$ ions. The Er intensity revealed initially steep increase with injected current density in the region for spontaneous emission from the GaInAs QWs. In the stimulated QW emission region, however, the intensity continued to increase with the current density.

1. Introduction

Rare-earth (RE)-doped semiconductors are a new class of materials with various promising potentials. RE ions doped in semiconductors exhibit a characteristic emission due to intra-4f shell transitions of RE ions. The emission shows sharp spectrum, temperature-stable wavelength and host-independent wavelength. Significant attention has been paid to Er-doped semiconductors because it can emit 1.5µm light. The wavelength is quite important for present silica-based optical communication.

We have succeeded in atomically-controlled doping of Er to various III-V semiconductors such as GaAs and InP by organometallic vapor phase epitaxy (OMVPE) [1]. In Er,O-codoped GaAs (GaAs:Er,O), one kind of Er center was formed selectively as an Er atom located at the Ga sublattice with two adjacent O atoms (hereafter referred as Er-2O) together with two As atoms, resulting in drastic enhancement in intensity of Er-related luminescence due to intra-4f shell transitions of Er$^{3+}$ ions [2,3]. We have fabricated GaInP/GaAs:Er,O/GaInP double-heterostructure (DH) light-emitting diodes (LEDs), aiming at realizing the stimulated emission at the Er center under current injection. Radiant Er-2O electroluminescence (EL) has been successfully observed at around 1.54 µm at room temperature under forward bias [4]. Extremely large Er excitation cross section of $10^{15}$ cm$^2$ was obtained under current injection, which is five orders larger than optical excitation cross section in the conventional Er-doped fiber amplifiers ($10^{20}$–$10^{21}$ cm$^2$) [5]. For the improvement in the device performance, we have investigated quantitatively the mechanism of excitation and relaxation of Er ions by means of a pump-probe reflection technique, and found that there is a characteristic ultrafast...
trapping process for nonequilibrium carriers in GaAs:Er,O [6,7].

The excitation mechanism of Er ions doped in the LEDs is shown in figure 1(a). Current injection introduces a free electron and a free hole. If we assume a trap as a donor-like hole trap, the injected hole is captured by the trap. The positively charged trap attracts the injected electron to create an electron-hole pair. The electron-hole pair recombines and part of the recombination energy is transferred to Er ions for 4f-shell excitation. Therefore, this excitation mechanism can be called indirect excitation. Now, we consider direct excitation with a lasing in the host material as shown in figure 1(b). If the wavelength is well matched to the energy separation of 4f-shell transitions, we can expect resonant direct excitation. In this case, the indirect excitation can be also expected. Therefore, the intensity of the Er luminescence should be enhanced under double excitation.

In this article, we report on fabrication and EL properties of two types of GaAs:Er,O-based laser diodes (LDs). One is a GaInP/GaAs:Er,O/GaInP LD exhibiting a lasing at the GaAs band-edge. The other is a LD with strained GaInAs quantum wells (QWs) embedded in the GaAs:Er,O, exhibiting a lasing from the QWs. The lasing wavelength was designed to tune to the energy separation between the second excited states \( ^{4}I_{15/2} \) and the ground state \( ^{4}I_{15/2} \) of Er\(^{3+}\) ions. The two LDs showed a quite different behavior of the Er intensity against the injected current density in the region for the stimulated emission from the GaAs band-edge and the GaInAs QWs.

2. OMVPE growth

The LDs were grown on (001)-oriented Si-doped \( n \)-GaAs and Zn-doped \( p \)-GaAs substrates at 545 °C by a low-pressure OMVPE system with a horizontal reactor. The reactor pressure was 76 Torr. Triethylgallium (TEGa), trimethylindium (TMIn), tertiarybutylarsine (TBAs) and tertiarybutylphosphine (TBP) were used as sources. H\(_2\)S and diethylzinc (DEZn) were also used for \( p \)-and \( n \)-type doping sources, respectively. Er was doped using Er(DPM)\(_3\) \([\text{C}_{11}\text{H}_{19}\text{O}_{2}]\text{Er}\) which contains six O atoms bonded to one Er atom in one molecule. The Er source was maintained at 80 °C and introduced into the reactor by a \( H_2 \) flow through the Er source cylinder (hereafter referred as Er flow). Er concentration of GaAs:Er,O layers was below the detection limit of secondary ion mass spectroscopy (SIMS) measurements (<10\(^{17}\) cm\(^{-3}\)). \(^{18}\)O\(_2\) of 49.9 ppm in Ar was used as an O\(_2\) source in the growth of GaAs:Er,O. The O\(_2\) content in growth ambient was set at 0.6 ppm.

3. LD exhibiting a lasing at the GaAs band-edge

The schematic drawing of the device structure is shown in figure 2. The growth sequence was initiated on a \( n \)-GaAs substrate by a 0.2-μm-thick, \( n \)-GaAs (1 x 10\(^{18}\) cm\(^{-3}\)) buffer layer, which was followed by a 1.0-μm-thick \( n \)-GaInP (3 x 10\(^{17}\) cm\(^{-3}\)) cladding layer and a 0.2 μm GaAs:Er,O active layer. A \( p \)-GaInP (6 x 10\(^{17}\) cm\(^{-3}\)) cladding layer was also 1.0 μm thick and a 0.1-μm-thick \( p \)-GaAs (1 x
A 10^{19} \text{ cm}^{-3} \) contact layer was grown on top of the \( p \)-type cladding layer. Broad-stripe laser tips of the Fabry-Perot type were fabricated by a standard photolithography process.

In figure 3, the output of GaAs band-edge light (\( \lambda = 889 \text{ nm} \)) for the GaInP/GaAs:Er,O/GaInP DH LDs is shown as a function of forward current density (\( I-L \)). The result in a LD with an undoped GaAs active layer is also shown for comparison. All the Er-doped LDs show a lasing at the GaAs band-edge at room temperature. The threshold current density (\( J_{th} \)) is also found to increase with the Er flow rate, suggesting that an energy-transfer from GaAs host to the 4f-shell of Er ions increases with the Er concentration.

The \( J_{th} \) has been analyzed as a function of reciprocal cavity length (\( 1/L \)) [8]. The LDs showed a linear relationship between the \( J_{th} \) and \( 1/L \). Furthermore, the coefficient of the \( J_{th} \) against \( 1/L \) also increased with the Er flow. It is well known that the \( J_{th} \) is simply expressed by the following equation [9],

\[
J_{th} = \frac{d}{\beta \Gamma} \left( \alpha_{fc} + \frac{\ln \left( \frac{1}{R} \right)}{L} \right) + dJ_0.
\]

Here, \( d \) is the active layer thickness, \( \beta \) is gain factor, \( \alpha_{fc} \) is internal loss due to free carrier absorption, \( \Gamma \) is the optical confinement factor, \( R \) is the reflectance and \( J_0 \) is the nominal current density at which the gain vanishes. As seen in the equation, the coefficient of the \( J_{th} \) against \( 1/L \) depends only on \( 1/\beta \) because \( d, \Gamma \) and \( R \) are the same in all the LDs. Therefore, the large coefficient in the Er-doped LDs indicates that a gain factor becomes small by the Er doping.

Pump and probe reflectance spectroscopy for GaAs:Er,O with Er concentration of \( 10^{18} \text{ to } 10^{19} \text{ cm}^{-3} \) revealed that the hole capturing and the electron-hole pair formation take place within 1 ps and 3-30 ps, respectively. Furthermore, the formation time is shorter in the sample with higher Er concentration [6,7]. In GaAs:Er,O with extremely low Er concentration (the Er flow rate: 1500 sccm), the fast decrease in \( dR/R \) was also observed, indicating that the fast hole capturing and the electron-hole pair formation are achieved at such low Er concentration. In the Er-doped LDs, the reduced gain factor was observed. The behaviour is quantitatively understood by the ultrafast carrier-capturing as follows. In high-gain region of \( g > 30 \text{ cm}^{-1} \), the gain factor \( \beta \) is approximately written by \( \beta = a \tau / q \), where \( a \) is
constant, \( \tau_n \) is lifetime of photoexcited carriers and \( q \) is elementary charge [10]. Therefore, the reduced gain factor indicates that the lifetime of photoexcited carriers becomes short with increasing Er flow.

In order to confirm the ultrafast carrier-capturing in the Er-doped LD prepared with the Er flow rate of 1500 sccm, the intra-4f shell emission due to Er\(^{3+}\) ions at 1.54 \( \mu \)m was measured at 4.2 K under forward bias. Figure 4 shows EL intensity of the GaAs band-edge emission (\( \lambda = 831 \text{ nm} \)) (a) and the Er-related emission (\( \lambda = 1539 \text{ nm} \)) (b) as a function of current density. The LD on an \( n \)-GaAs substrate shows the stimulated emission at the GaAs band-edge with \( J_{th} = 9.5 \text{ kA/cm}^2 \) at 4.2 K. The EL intensity of the Er-related emission saturates at 2 kA/cm\(^2\) and decreases gradually at higher current density. The decrease is due to the Auger effect, energy transfer from excited Er ions to injected carriers. In the stimulated emission region, on the other hand, the EL intensity becomes almost constant. The constant EL intensity is closely related to saturated concentration of injected carriers during laser action. In GaAs, carrier lifetime varies from \( \tau \approx 1 \text{ ns} \) at spontaneous recombination to \( \tau \approx 200 \text{ ps} \) at stimulated recombination [11,12]. The observation of both the band-edge stimulated emission and the Er-related spontaneous emission in the stimulated emission region is a clear evidence that the carrier-capturing time at the bound state produced by Er-doping is quite shorter than the lifetime of the band-edge stimulated emission. Similar results were also obtained on a \( p \)-GaAs substrate. Furthermore, the lasing wavelength of the LDs was 831 nm, whose energy is smaller than the reported energy separation between the third excited states \( ^4I_{9/2} \) and the ground states \( ^4I_{9/2} \) of Er\(^{3+}\) ions. Therefore, the resonant direct excitation by the band-edge lasing could never be expected in the LDs.

### 4. LD exhibiting a lasing from GaInAs QWs

The device structure is schematically shown in figure 5, which is a well-known separated confinement heterostructure (SCH-structure) [13]. A 0.2-\( \mu \)m-thick, \( p \)-GaAs (2 \( \times \) 10\(^{19} \) cm\(^{-3} \)) buffer layer and a 1.0-\( \mu \)m-thick \( p \)-GaInP (1 \( \times \) 10\(^{18} \) cm\(^{-3} \)) cladding layer were subsequently grown on a \( p \)-GaAs substrate. Two 8-\( \text{nm} \)-thick Ga\(_{0.76}\)In\(_{0.24}\)As QWs with a 20-\( \text{nm} \)-thick GaAs:Er,O layer as a barrier were embedded in the center of a GaAs:Er,O waveguide layer with thickness of 200 nm. A \( n \)-GaInP (6 \( \times \) 10\(^{11} \) cm\(^{-3} \)) cladding layer

![Figure 4. EL intensity of the (a) GaAs band-edge emission (\( \lambda = 831 \text{ nm} \)) and (b) Er-related emission (\( \lambda = 1539 \text{ nm} \)) as a function of current density in the LD prepared with 1500 sccm.](image)

| Layer                  | Thickness |
|------------------------|-----------|
| \( n \)-GaAs buffer layer | 200 nm    |
| \( n \)-GaInP cladding layer | 1000 nm  |
| GaAs:Er,O             | 100 nm    |
| GaAs:Er,O             | 20 nm     |
| GaAs:Er,O             | 100 nm    |
| \( p \)-GaInP cladding layer | 1000 nm  |
| \( p \)-GaAs buffer layer | 200 nm    |
| \( p \)-GaAs substrate |           |

![Figure 5. Device structure of a LD with two GaInAs QWs embedded in GaAs:Er,O.](image)
was also 1.0 μm thick and a 0.2-μm-thick $n$-GaAs ($8 \times 10^{17}$ cm$^{-3}$) contact layer was grown on top of the $n$-type cladding layer. In the growth of GaAs:Er,O, the Er flow rate was fixed at 1500 sccm.

Figure 6 shows the output of GaInAs QW emission ($\lambda = 1033$ nm) in the LD as a function of forward current density ($I_L$) at room temperature, which is compared with the result for a GaInAs QW-LD with undoped GaAs instead of GaAs:Er,O. Clear laser action can be observed in both the LDs. The $J_{th}$ in the LD with GaAs:Er,O as a waveguide layer is seven times larger than that in the LD with an undoped GaAs waveguide layer. The increase in the $J_{th}$ also reflects the ultrafast carrier capture by an Er-related trap in GaAs:Er,O.

What wavelength is required for the direct excitation of Er$^{3+}$ ions? Hogg et al. reported a spectroscopic study on GaAs:Er,O with excitation in the near-band-edge region [14]. They observed two extremely sharp signals, attributed to $^4I_{15/2} \rightarrow ^4I_{11/2}$ intra-4f-shell transitions of Er$^{3+}$ ions in the Er-2O center, at 981.4 nm and 984.1 nm on a broad background due to indirect excitation by way of defect levels. In this study, therefore, the lasing wavelength of the LD was changed by the device temperature to tune the objective wavelengths. The Er intensity ($\lambda = 1539$ nm) at 110 K is shown in figure 7 as a function of the current density. The $I-L$ characteristics for the GaInAs QW emission are also shown in the figure. The $J_{th}$ at the temperature is 0.84 kA/cm$^2$ and the lasing wavelength is 981 nm. In the region for the spontaneous emission from the GaInAs QWs, the Er intensity increases steeply with the current density and then starts to saturate. In the region of the stimulated QW emission, on the other hand, the intensity continues to increase. This behavior is quite different from the behavior in the GaInP/GaAs:Er,O/GaInP DH LDs exhibiting a lasing at the band-edge of GaAs. The disappearance of the Auger effect in the GaInAs QW-LD is attributed to spatial separation between QWs and Er ions. The gradual increase in Er intensity under the QW lasing might be due to the resonant direct excitation of Er$^{3+}$ ions. Further study on the increase of the intensity is now in progress.
5. Conclusions
Two types of GaAs:Er,O-based LD were fabricated by OMVPE and effects of the lasing on the Er luminescence was investigated. In the LD exhibiting a lasing at the GaAs band-edge at room temperature, the $J_{th}$ increased with the Er flow rate during the growth and its reciprocal cavity length dependence indicated the effective gain factor of the LDs decreased by the codoping of Er and O, which is due to ultrafast capturing of injected carriers at an Er-related trap. The fast capturing process allowed us to observe both the spontaneous intra-4f-shell emission due to Er$^{3+}$ ions at 1.54 μm and the stimulated emission at the GaAs band-edge in the Er-doped LDs. In the LD with GaInAs QWs embedded in the GaAs:Er,O, the lasing wavelength was designed to tune to the energy separation between $^4I_{15/2} - ^4I_{11/2}$ intra-4f-shell transitions of Er$^{3+}$ ions. The $J_{th}$ for the lasing at room temperature was seven times larger than that of a GaInAs QW-LD with an undoped GaAs waveguide layer. The increase in the $J_{th}$ also reflected the ultrafast carrier capture by an Er-related trap in GaAs:Er,O. In the region for spontaneous emission from the GaInAs QWs, the Er intensity revealed initially steep increase with injected current density, which was followed by a saturation. In the stimulated QW emission region, the intensity continued to increase with the current density, indicating a feasibility of the resonant direct excitation of Er$^{3+}$ ions.

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