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Annealing behaviour of structure and morphology and its effects on the optical gain of Er^{3+}/Yb^{3+} co-doped Al_2O_3 planar waveguide amplifier*

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Using transmission electron microscopy (TEM) and x-ray diffraction analysis, we have studied the structural and morphological evolution of highly Er/Yb co-doped Al_2O_3 films in the temperature range from 600 °C–900 °C. By comparison with TEM observation, the annealing behaviours of photoluminescence (PL) emission and optical loss were found to have relation to the structure and morphology. The increase of PL intensity and optical loss above 800 °C might result from the crystallization of amorphous Al_2O_3 films. Based on the study on the structure and morphology, a rate equation propagation model of a multilevel system was used to calculate the optical gains of Er-doped Al_2O_3 planar waveguide amplifiers involving the variation of PL efficiency and optical loss with annealing temperature. It was found that the amplifiers had an optimized optical gain at the temperature corresponding to the minimum of optical loss, rather than at the temperature corresponding to the maximum of PL efficiency, suggesting that the optical loss is a key factor for determining the optical gain of an Er-doped Al_2O_3 planar waveguide amplifier.

Keywords: Er-doped waveguide amplifier, annealing behaviour, structural characterization, optical gain

PACC: 7855, 6170T, 6860

1. Introduction

Er-doped planar waveguide amplifiers (EDWAs) have attracted much attention because of their potential applications in the field of integrated optics to compensate for signal losses by absorption, scattering, splitting, coupling, etc.[1−4] In order to fabricate and optimize EDWA, it is necessary to study the basic material issues such as photoluminescence (PL) spectra, lifetime, upconversion effects, and concentration dependence as well as annealing behaviour for Er-doped films.[4−8] Al_2O_3 is a material of interest because Al^{3+} ions have the same valency as Er^{3+} and Yb^{3+} ions, which may enable Er^{3+} ions to be optically activated effectively. Van den Hoven *et al* found the PL lifetime of Er^{3+} ions in Al_2O_3 films to be about 6–10 ms, even for the film doped with ∼1 at.% Er.[9] A 2.3 dB net optical gain at 1.53 μm has been successfully obtained with a 4 cm long Er-doped Al_2O_3 spiral waveguide amplifier pumped with 9 mW light at 1.48 μm from a laser diode.[10]

To improve the optical gain of Er-doped Al_2O_3 waveguide amplifier, a lot of work focusing on the PL behaviour of Er-doped Al_2O_3 films were done in the past decade. However, few reports paid attention to the optical loss and the variation in phase transition and morphology of the films during annealing process. Furthermore, there is still a lack of a report on the Er-doped Al_2O_3 waveguide amplifier with a net optical gain higher than 2.3 dB though nearly 20 dB can be expected in the theoretical predication.[10] In fact, the optical gain of an EDWA is determined not only by the PL efficiency but also by the optical loss. The PL characteristics of Er-doped materials are related to the local environment of Er^{3+} ions, which is dominated by the phase structure of the host materials, while the optical loss is related to the densities of defects and the uniformity of the films. Both of the PL characteristics and the optical loss can be changed during annealing process. It is necessary to study the variation of the structure and morphology during annealing, and hence to reveal the influence of annealing temperature on the optical gain by considering the

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variation of PL efficiency and optical loss in the optimization of an EDWA.

In the present study, we report the structural and morphological evolution of highly Er/Yb co-doped Al_2O_3 films with annealing temperature in the temperature range of 600 °C–900 °C. By comparing with the transmission electron microscopy (TEM) observation, the annealing behaviours of PL efficiency and optical loss were found to have relation to the structure and morphology of Er-doped Al_2O_3 films annealed at different temperatures. By considering the variation of PL efficiency and optical loss, the dependence of optical gain on annealing temperature was discussed for an Er-doped Al_2O_3 waveguide amplifier with a rate equation propagation model of a multilevel system.[8] It was found that the amplifiers has an optimized optical gain at the temperature corresponding to the minimum of optical loss, rather than at the temperature corresponding to the maximum of PL efficiency. Our results suggest that the optical loss is a key factor for determining the optical gain of an Er-doped Al_2O_3 planar waveguide amplifier.

2. Experimental procedures

The highly Er/Yb co-doped Al_2O_3 films were deposited on n-type Si (100) wafers by radio-frequency (RF) reactive magnetron sputtering from a 99.9% Al metal target of 60 mm diameter. Er/Yb codopants were incorporated into the films during the deposition with the co-sputtering method. Metal Er and Yb were made into rods of 2 mm diameter and embedded in the Al target. Using Rutherford backscattering spectrometry (RBS), we confirmed the films to be stoichiometric Al_2O_3 films with a thickness of $\sim$ 600 nm. The concentrations of Er and Yb were determined to be 1.0 at.% and 4.0 at.%, respectively, by fitting the RBS data. The film deposition was carried out at 1.0 Pa in an ambient mixture of 90% Ar and 10% O_2 and the substrates were heated to 400 °C during the deposition. The films were then annealed at temperatures ranging from 600°C to 1200 °C in air for 2 h. TEM and x-ray diffraction (XRD) were used to characterize the phase structure and morphology for the films annealed at various temperatures. PL measurements were carried out on a spectrum analyser with a grating monochromator and a semiconductor detector at room temperature. The pumping light was from a 980 nm semiconductor laser and was directed onto the sample with a fibre of 0.6 mm diameter.

3. Results and discussions

Figure 1 is the TEM micrographs for Er/Yb co-doped Al_2O_3 films annealed at given temperatures. The as-deposited film is confirmed to be typically amorphous with XRD and selected area electron diffraction (SAD) analysis. TEM micrographs and SAD patterns reveal that the film is amorphous up to 750 °C without crystallization. Figures 1(a) and 1(b) show the similarity in structure and morphology between the as-deposited film and the film annealed at 750 °C. The difference in morphology can be interpreted as having different defect densities and the film densities between the as-deposited film and the film annealed at 750 °C. It can be seen that the as-deposited film has many more micro-dots than the film annealed at 750 °C. These micro-dots may be caused by the aggregation of residual gases, such as Ar or O_2 in the film. The TEM observations suggest that the annealed film below 750 °C may have an optical loss less than the as-deposited one. In other words, the annealing treatment can reduce the optical loss of an Er-doped waveguide with the increase of annealing temperature up to 750 °C.

For the films annealed at 800 and 900 °C, however, TEM micrographs and SAD patterns show that γ-Al_2O_3 and amorphous phases co-exist in the films, as shown in Figs.1(c) and 1(d). It can be seen that the films have the morphology quite different from those annealed at temperatures below 750 °C. The TEM micrographs suggest that the film has many more defects and a worse uniform density distribution above 800 °C than those below 750 °C, and the uniformity of the films goes worse with the increase of annealing temperature thereafter. The TEM observation indicates that crystallization may result in the increase of the optical loss for an Er-doped Al_2O_3 waveguide amplifier. Because the phase transition is an intrinsic property of a material, our results mean that a minimum in optical loss should be at a temperature around 750 °C, corresponding to the temperature of phase transition from amorphous Al_2O_3 to γ-Al_2O_3, and will be varied in a certain temperature range with the different fabrication methods.

Our TEM observation coincides with Smit *et al*'s[11] measurements of optical loss in the Al_2O_3 waveguides fabricated by RF magnetron sputtering. Their results showed that the optical loss decreased with the increase of annealing temperature up to 800 °C and increased sharply thereafter. All sput-

tering processes yield qualitatively similar annealing curves, showing a minimum in optical loss at a temperature around 800 °C and dependent on the deposition process or the annealing duration and history. Hoven *et al*[5] also reported that the optical loss could be minimized to 0.35dB/cm by thermal annealing at 825 °C or 775 °C for the Er-doped Al_2O_3 films deposited by RF magnetron sputtering. Based on the facts of optical loss measurements above and our TEM observation, we believe that Er-doped Al_2O_3 waveguide might have a similar annealing behaviour of optical loss.

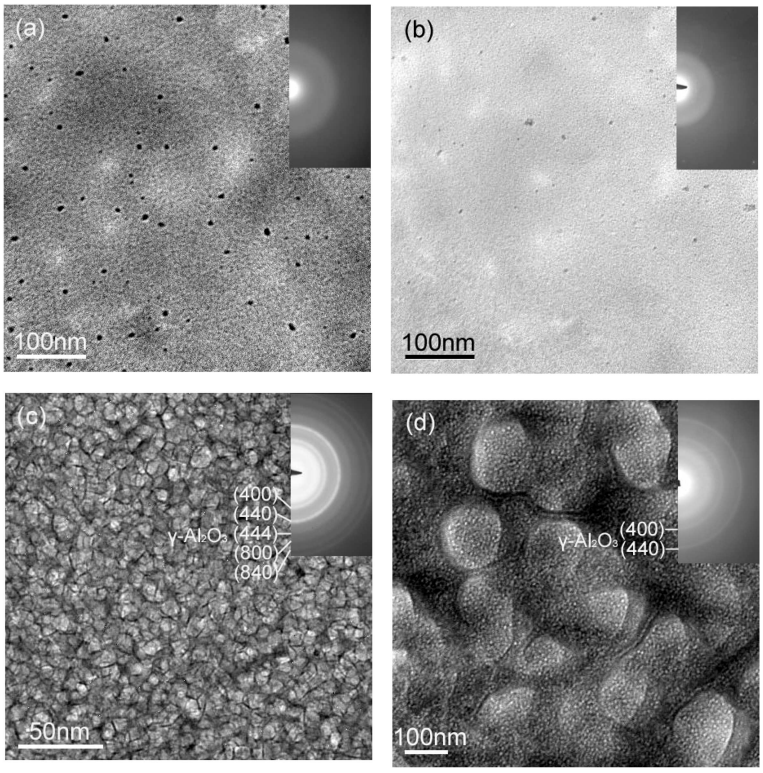


Fig.1. TEM micrographs and SAD patterns of (a) the as-deposited film and Er/Yb co-doped Al_2O_3 films annealed at (b) 750 °C, (c) 800 °C and (d) 900 °C.

On the other hand, we found Er-doped Al_2O_3 films having a similar annealing behaviour of PL characteristics. The annealing behaviour of PL characteristics can also be attributed to evolution in structure with annealing temperature.[12] Figure 2 shows the dependence of PL intensity on annealing temperature reported by different authors[2,6,9] and in this work, where the data are normalized with their respective maxima. We can see that all PL intensities have annealing behaviours quite similar in the given temperature range, though the films were fabricated by different methods and the concentration of dopants ranged from 0.13 at.% to 5.0 at.%. A critical temperature (T_c) can be taken to be the point where the intensity increases dramatically around 750 °C. The PL intensities have much higher growing rates above T_c than below it. The optimized temperature is 900 °C or 950 °C.

According to the above analysis, we can conclude that the PL efficiency has an optimized temperature different from the optical loss for an Er-doped Al_2O_3 waveguide amplifier and both of them are related to the structure and morphology of the Er-doped Al_2O_3 films. As a result, the optical gain of an Er-doped Al_2O_3 waveguide amplifier has to be optimized at a temperature involving both the PL efficiency and the optical loss. According to Strohhofer and Polman,[8] the population rate equations of a multilevel system

are

$$\frac{\mathrm{d}N_\mathrm{b}}{\mathrm{d}t} = \sigma_\mathrm{ab}\Phi_\mathrm{p}N_\mathrm{a} - \sigma_\mathrm{ba}\Phi_\mathrm{p}N_\mathrm{b} - W_\mathrm{b}N_\mathrm{b} - C_\mathrm{b0}N_\mathrm{b}N_0 + C_\mathrm{2a}N_\mathrm{a}N_2 - C_\mathrm{b2}N_\mathrm{b}N_2\,, \quad (1)$$

$$N_\mathrm{Yb} = N_\mathrm{a} + N_\mathrm{b}\,, \quad (2)$$

$$\frac{\mathrm{d}N_1}{\mathrm{d}t} = \sigma_{01}\Phi_\mathrm{s}N_0 - \sigma_{10}\Phi_\mathrm{s}N_1 - \sigma_{12}\Phi_\mathrm{s}N_1 + W_{21}N_2 - W_1N_1 - 2C_{11}N_1^2\,, \quad (3)$$

$$\frac{\mathrm{d}N_2}{\mathrm{d}t} = \sigma_{02}\Phi_\mathrm{p}N_0 - \sigma_{20}\Phi_\mathrm{p}N_2 + \sigma_{12}\Phi_\mathrm{s}N_1 - \sigma_{23}\Phi_\mathrm{p}N_2 - W_2N_2 + C_{11}N_1^2 - 2C_{22}N_2^2 + C_\mathrm{b0}N_\mathrm{b}N_0 - C_\mathrm{2a}N_\mathrm{a}N_2 - C_\mathrm{b2}N_\mathrm{b}N_2 - W_{21}N_2\,, \quad (4)$$

$$\frac{\mathrm{d}N_3}{\mathrm{d}t} = \sigma_{23}\Phi_\mathrm{p}N_2 - W_3N_3 + C_{22}N_2^2 + C_\mathrm{b2}N_\mathrm{b}N_2\,, \quad (5)$$

$$N_\mathrm{Er} = N_0 + N_1 + N_2 + N_3\,, \quad (6)$$

where N_i represents the population density of the energy level marked i (i = a, b, 0, 1, 2, 3) in Fig.3, which is the energy level diagram of a multilevel system co-doped with Er^{3+} and Yb^{3+} ions under consideration. Φ_p and Φ_s are the photon flux densities of the pump and signal lights, respectively. Absorption and stimulated emission processes are characterized by their respective cross sections σ_{ij}, where i and j indicate the initial and final energy level of the process. Spontaneous decay is identified by its rate W_{ij}. If no final level j is given, the corresponding decay rate W_i signifies the sum of all individual decay rates from level i to lower lying states. Energy transfer between Yb^{3+} and Er^{3+} or between two excited Er^{3+} ions are characterized by their energy transfer rate constants C_{ij}. Here the subscripts i and j denote the energy levels populated prior to energy transfer. N_Er and N_Yb is the doping concentration of Er^{3+} and Yb^{3+} ions respectively. These equations can be solved with the given radiation parameters for steady state at a given pumping power density and negligible signal photon flux.

For a ridge waveguide, the development of the power in pump and signal mode over the length of the waveguide is governed by the light propagating equations with co-propagating mode.[8] The optical gain can be obtained by integrating the power in pump (P_pump) and signal (P_signal) with the light propagating equations over a given length of the waveguide. The optical gain is defined as

$$\mathrm{Gain} = 10 \times \log_{10}(P_\mathrm{signal}^\mathrm{output}/P_\mathrm{signal}^\mathrm{input})\,, \quad (7)$$

where $P_\mathrm{signal}^\mathrm{output}$ and $P_\mathrm{signal}^\mathrm{input}$ are the output and input powers in signal, respectively.

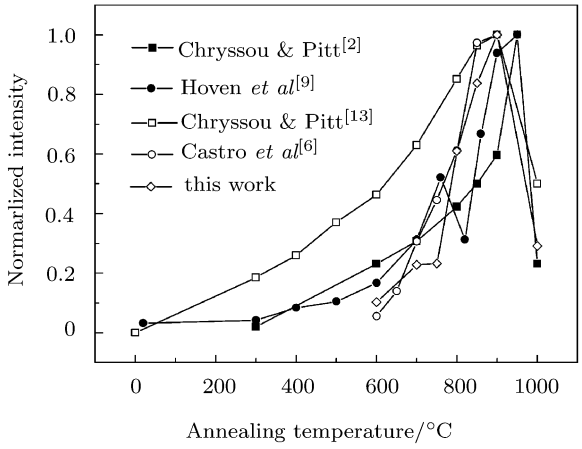


Fig.2. Normalized PL intensities as a function of annealing temperature from different authors.

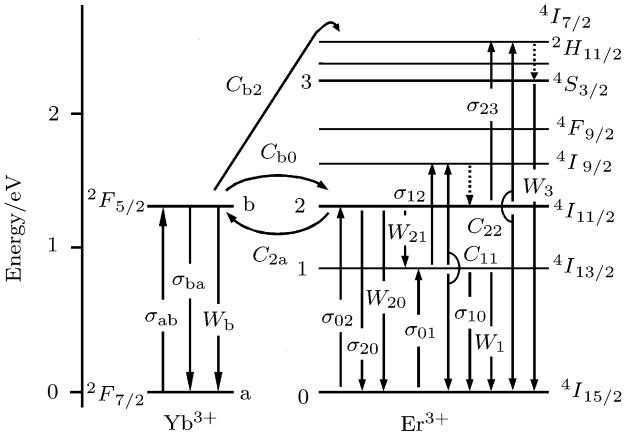


Fig.3. Energy level diagram of a multilevel system co-doped with Er^{3+} and Yb^{3+} ions. The arrows represent the transition process included in the population rate equations.

Suppose that the EDWAs have an optical loss (α) function vs annealing temperature similar to Smit *et al*'s[11] measurements with different minimums (α_min) and the variation of PL efficiency can be approximated to two linear functions of annealing temperature with different slopes, as shown in Fig.4. The dependence of optical gain on annealing temperature has been calculated with the radiation parameters suggested by Strohhofer and Polman[8] for an Er/Yb co-doped waveguide amplifier with a rectangular cross section of 2 μm $\times$ 0.5 μm and 4 cm in length. The calculation was performed with an optimized Er and Yb concentrations of 3.6 $\times 10^{20}$ and 8.0×10^{20} cm^{-2}, respectively, at the

given pumping power (20 mW).

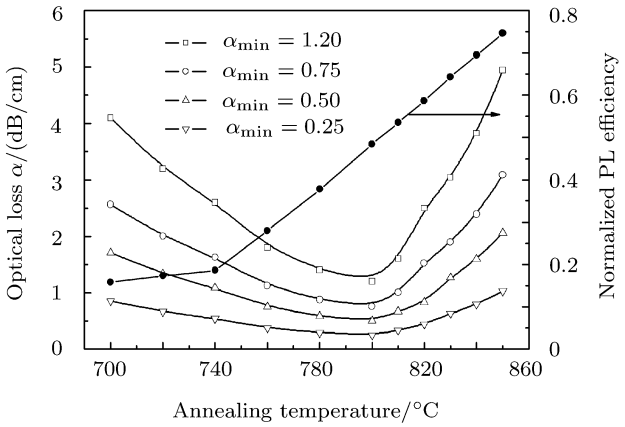


Fig.4. Dependence of optical loss and normalized PL efficiency on annealing temperature.

Figure 5 is the dependence of optical gain on annealing temperature for the Er/Yb co-doped Al_2O_3 waveguide amplifiers with 4 cm in length and pumped by a 980 laser at an effective coupling power of 20 mW, where the EDWAs have similar annealing behaviour but different minimums of optical loss. As can be seen in the figure, the maxima of optical gain appear at 800 °C, corresponding to the minimums of optical loss, though the optimized temperature of PL efficiency is about 900 °C. With the decrease of optical loss level, the maximum of optical gain increases and the range of net optical gain goes wide. The results suggest that the optical loss plays a role of determining optical gain more important than the PL efficiency for the Er-doped Al_2O_3 waveguide amplifier due to its annealing behaviour in structure and morphology. In other words, the increase of PL efficiency annealed at a higher temperature cannot compensate the increase of optical loss in the EDWA.

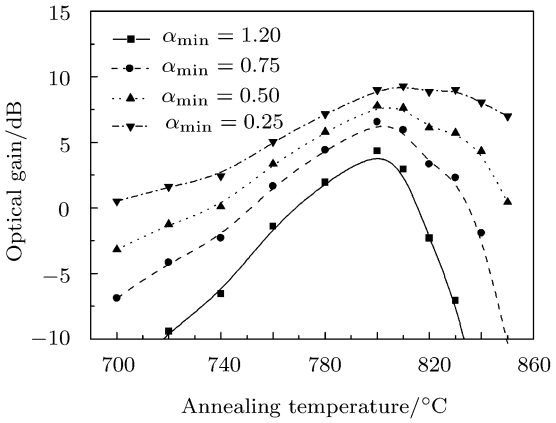


Fig.5. Dependence of optical gain on annealing temperature for the Er/Yb co-doped Al_2O_3 waveguide amplifiers with different optical loss function.

4. Conclusion

In summary, we have studied the structure and morphology of Er/Yb co-doped Al_2O_3 films annealed at different temperatures. It was found that the PL efficiency and the optical loss are related to the structure and morphology of the Er-doped Al_2O_3 films. With the rate equation propagation model of a multilevel system, we conclude that the Er-doped Al_2O_3 waveguide amplifier has a maximum of optical gain at the temperature corresponding to the minimum of optical loss, but not at the temperature corresponding to the optimized PL efficiency. Our results suggest that the optical loss plays an important role in determining the optical gain for an Er-doped Al_2O_3 waveguide amplifier and the crystallization is responsible for the sharp increase of optical loss.

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