Design and optical response of a thin film structure enhancing the photoluminescence of an embedded single layer of Er^{3+} ions

Johann Toudert, Javier Martin Sánchez, Rosalia Serna
Instituto de Óptica, CSIC
Madrid, Spain
johann.toudert@gmail.com

***Abstract*— This paper presents a thin film structure designed for optimizing the excitation efficiency of a single layer of luminescent Er^{3+} ions embedded in a solid host medium. In this structure, the Er^{3+} ions are located on top of a single layer of amorphous Si nanoparticles acting as sensitizers for the rare-earth excitation. This a-Si/Er active layer is sandwiched between two amorphous Al_2O_3 thin layers, the thickness of which is chosen so that the excitation electric field is maximized at the Si nanoparticles. Optical characterization of a thin film with such a structure grown by pulsed laser deposition shows the presence of a bandgap absorption (due to electron confinement in nanostructures a few nm in size), measurable Er^{3+} photoluminescence (in contrast with a single layer of Er^{3+} ions embedded in amorphous Al_2O_3) and evidence of a sensitization mechanism involving the Si nanostructures.**

Keywords: Er, photoluminescence enhancement, a-Si

I. INTRODUCTION

Due to their luminescence properties, Er^{3+} ions are of interest in photonics. For applications in this field, it is generally desirable to embed the rare-earth ions into stable matrices and to maximize their luminescence efficiency (for functional and economical reasons). In such a context, it was shown that the photoluminescence (PL) efficiency of Er^{3+} ions in an amorphous Al_2O_3 (a-Al_2O_3) matrix can be improved if the ions are distributed in separated single layers, rather than randomly in the matrix [1]. Further improvement of the PL efficiency was obtained by depositing the Er on top of a single layer of amorphous Si (a-Si) nanoparticles, acting as sensitizers for the Er excitation [2], thus forming an a-Si/Er active layer. These studies were nevertheless limited to the case of multilayered systems containing several active layers evenly spaced. In this work, we focus on a system based on just a single a-Si/Er active layer embedded in a simple photonic structure designed for maximizing the excitation electric field at the active layer.

II. DESIGN AND PREPARATION OF THE STRUCTURE

A. Definition and optimization of the structure

Figure 1a shows the thin film structures of interest in this paper. A buffer a-Al_2O_3 layer (of thickness t_{buffer}) separates the a-Si/Er active layer (thickness t_{active} of a few nm) from the Si substrate. A second a-Al_2O_3 layer of thickness t_{cap} caps the active layer. For comparison, a similar structure with only a single layer of Er^{3+} ions - called hereafter "Er active layer"- instead of the a-Si/Er active layer will also be considered.

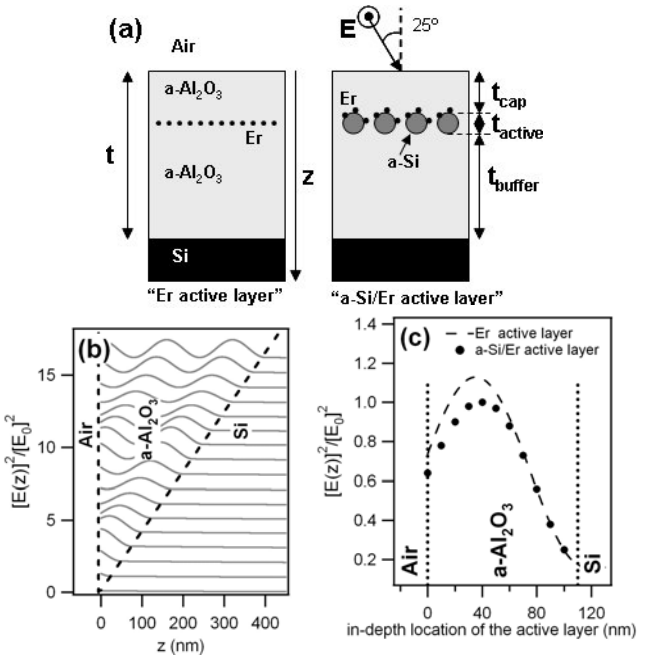

Figure 1: (a) Schematic representation of the film structures studied in this paper, (b) square module of the excitation electric field as a function of the depth **z** in a-Al_2O_3 thin films of various thicknesses (the different curves are displayed with a vertical offset for the sake of clarity, (c) square module of the excitation electric field at an Er or a-Si/Er active layer as a function of its in-depth location inside a 110 nm-thick a-Al_2O_3 film. The incident field incomes from above, with a 25º angle and a S-polarization, as shown in (a) and a 514.5 nm wavelength.

Figure 1b shows a simulation of the square module of the electric field as a function of the depth **z** in a-Al_2O_3 films of different thicknesses t, standing on a bulk Si substrate, assuming a 25º incidence angle, a S-polarization and a 514.5 nm wavelength for the incoming field. The coherent matrix formalism was used for the calculations; the refractive index of a-Al_2O_3 layers was fixed at 1.65. Since a single layer of Er^{3+} ions induces no significant changes to the in-depth complex refractive index of the film, the calculated profiles also hold for thin films of a-Al_2O_3 with an embedded Er active layer (figure 1a, left), located at any depth in the film. It can be seen that

stationary waves develop in the structure with maxima at depths whose value depend on the film thickness t. Thus, an Er active layer should be located at one of these maxima in order to optimize its excitation. Figure 1c presents the evolution of the square module of the excitation electric field at an Er active layer (dashed line; structure depicted on fig. 1a, left) and at an a-Si:Er active layer (dots; structure depicted on fig. 1a, right) as a function of its in-depth location in a 110 nm-thick a-Al_2O_3 film standing on a bulk Si substrate. In the latter case, calculations were performed assuming a trilayer structure for the film, the central layer of thickness t_{active}=5 nm being considered as an effective medium of refractive index and extinction coefficient n_{active}= 2.5 and k_{active}=0.1, respectively. Such values are typical of granular layers of a-Si embedded in a-Al_2O_3. The field profiles are very similar in both cases, with a slight perturbation due to the presence of Si in the a-Si:Er case, and it is seen that the highest values for the excitation field at the active layer are obtained at a depth between 20 and 60 nm.

B. Pulsed laser deposition of the structures

Alternate pulsed laser deposition of Er, Si and Al_2O_3 in vacuum and at room temperature [2] was thus performed to grow a thin film with the structure shown in figure 1a (right), the a-Si:Er active layer consisting of Er^{3+} ions deposited on top of the a-Si material, as required for efficient sensitization of the Er by a-Si nanostructures [2]. Deposition was performed onto transparent fused silica and opaque Si substrates. The Er target was ablated using only one laser pulse, thus depositing a very low amount of material (areal density in the 10^{-13} ions/cm^2 range). Nominal values of 85 nm, 20 nm were used for t_{buffer} and t_{cap}, respectively. The Si amount was chosen so that a-Si nanoparticles a few nm in size form [2]. In these conditions, the active layer is located at a depth of around 20 nm in an almost 110 nm-thick film, thus providing a quasi-maximized excitation field at the active layer in the pumping conditions considered above. A film with the same structure but with only Er doping for the active layer (figure 1a - left), was prepared as reference.

III. OPTICAL RESPONSE

The optical response in the 300-900 nm range of both films was studied by optical transmittance at normal incidence and spectroscopic ellipsometry (65º, 70º and 75º). Room temperature IR PL measurements were performed under visible excitation with an argon laser (25º incidence angle, S-polarization), using standard lock-in techniques. PL was collected at normal incidence through lenses, and detected by a NIR PMT through a single monochromator. The substrates considered for each type of measurements were fused silica and Si, respectively. The transmittance spectrum of the reference film is typical of a transparent dielectric, whereas that of the a-Si/Er active layer-based film presents a bandgap absorption noticeable in the UV and blue regions. This absorption is attributed to electron confinement in Si nanostructures of a few nm in size. A fast analysis of ellipsometry spectra (not shown) confirmed the value of the overall thickness of the films, close to 110 nm. Figure 2b presents the PL spectra of both films: the 1.54 μm PL band characteristic of Er^{3+} ions is observed only for the a-Si/Er active layer-based film. Its excitation spectrum, presented in the right inset of figure 2b, shows a slowly decreasing linear evolution of the 1.54 μm PL as a function of the excitation wavelength, which is typical of a pumping of the Er^{3+} ions through a-Si. The excitation spectrum of directly pumped Er^{3+} ions through direct excitation (measured on a thick and annealed Er-only doped sample) is also shown for comparison.

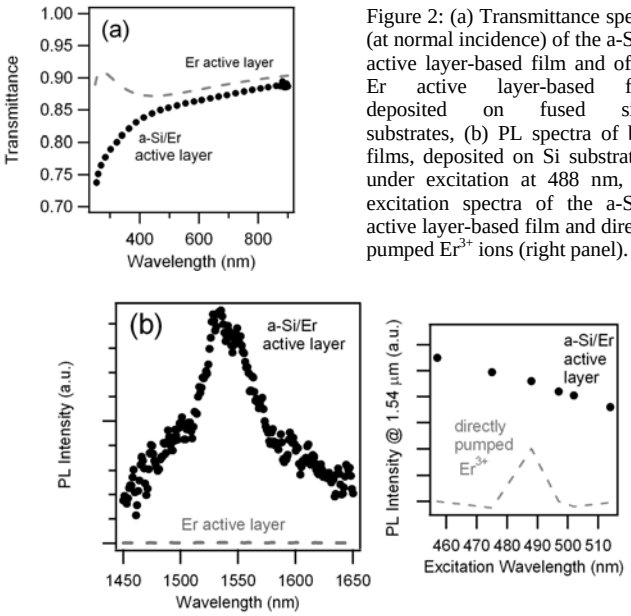

Figure 2: (a) Transmittance spectra (at normal incidence) of the a-Si:Er active layer-based film and of the Er active layer-based film, deposited on fused silica substrates, (b) PL spectra of both films, deposited on Si substrates , under excitation at 488 nm, and excitation spectra of the a-Si:Er active layer-based film and directly pumped Er^{3+} ions (right panel).

IV. CONCLUSIONS

In this paper, we propose a strategy for improving the excitation of a single layer of Er^{3+} ions embedded in a solid host medium. Two aspects are investigated: i) the design and preparation of a 1D photonic structure maximizing the excitation field at the active layer, ii) the contact-sensitization by a-Si nanostructures. The film presenting the pre-defined photonic structure shows a measurable PL at room temperature, in contrast with a film with a comparable structure but without Si nanostructures. Future works should deal with experimental studies to optimize the a-Si nanostructure, the photonic enhancement of the PL excitation, and light extraction.

ACKNOWLEDGEMENTS

The authors thank Pablo Roque and Francisco Valle Brozas for their valuable support during the films elaboration. J.T. acknowledges financial support from the Spanish ministry for Science and Innovation (Juan de la Cierva Grant Nº JCI-2009 – 05098).

REFERENCES

[1] R. Serna, M.J. de Castro, J.A. Chaos, C.N. Afonso and I. Vickridge, "The role of Er^{3+}-Er^{3+} separation on the luminescence of Er-doped Al2O3 films prepared by pulsed laser deposition" Appl. Phys. Lett., vol. 75, pp. 4073-4075, 1999.

[2] S. Núñez-Sánchez, P.M. Roque, R. Serna and A.K. Petford-Long, "Si-nanoparticle Er^{3+} coupling through contact in as-deposited nanostructured thin films", Appl. Phys. Lett., vol 98, pp.151109, 2011.