Erbium Doped Al2O3 Films For Integrated III-V Photonics

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***Abstract*—We describe the fabrication optimization of Er-doped Al2O3 films for III-V integrated photonics. Smooth and thick films, with high refractive index and Erbium emission in the C-band spectrum (1530 nm to 1565 nm) are obtained using the co-sputtering technique. Thermal annealing at 850 ^{0}C is shown to provide the highest Photoluminescence intensity of the films. However, the onset of crystallization leads to large fluctuation in refractive index. We also show that the annealing at temperatures larger than 600 ^{0}C causes well intermixing in the laser structure. Therefore, local annealing and/or a reduction in annealing temperature may be required. Alumina waveguides are fabricated by the same technique, but the process have to be improved, as optical losses are very high.**

Keywords—III-V; integrated photonics; alumina; erbium; waveguide; optical amplifier

I. INTRODUCTION

Erbium doped films are of great interest for integrated optoelectronics, since erbium has transitions involving wavelengths of interest for telecommunications. Alumina has a high refractive index (1.7) and is known to have higher Er solubility; its concentration can be 100 times higher than in SiO_2 before degrading performance, making it one of the best choices for compact optical devices [1]. One possibility of integrated optical device is an Erbium-Doped Waveguide Amplifier (EDWA). This planar device can potentially replace conventional Erbium Doped Fiber Amplifiers (EDFA's) for drastic footprint and power consumption reduction. The optical amplification (at 1550 nm) is caused by stimulated emission from excited Er ions, which need to be optically pumped at 980 nm. The need for an external laser and the critical alignment necessary to obtain optimal pumping makes the concept of an integrated waveguide amplifier very attractive. Moreover, the integration of the waveguide amplifier with the pumping laser can provide extreme miniaturization of the device. Commonly, 980 nm lasers are obtained using epitaxial structures based on $In_XGa_{1-X}As$ strained quantum wells grown on GaAs substrate. Two major challenges exist with the development of such device: (a) Coupling light between the laser and the waveguides; (b) A possible incompatibility between the amplifier post fabrication process and the laser epitaxial structure integrity.

Two approaches may be considered for coupling: One using folded cavity devices where the laser light uses an integrated Bragg mirror and uses a dry etched 45° mirror to send light towards the substrate [2]. In this case, the amplifiers can be fabricated on the bottom side of the substrate. A second approach is to fabricate the amplifiers on the same side as the lasers. Although the first method save epitaxial layer real state, it reduces the complexity of the epitaxial layer fabrication. In both cases, non cleaved facets will be required. Lasers with dry etched facets or focused ion beam milled facets have been fabricated where passivation techniques were used to reduce damages [3, 4]. Therefore, coupling should be accomplished with a combination with the above techniques.

The second challenge depends critically upon the post fabrication steps required for the Er doped alumina films. This work describes the optimization of the Er doped alumina films considering its integration with laser epitaxial material. Initially, we describe the deposition optimization process. Subsequently, we investigate a thermal annealing process to improve the activation of the Er atoms, based on photoluminescence. In order to investigate a fundamental incompatibility between this process and the laser structure performance, we investigated the effects of the temperature annealing on the laser quantum well emission. Finally, we have fabricated waveguides with the alumina films for a first assessment of guiding losses.

II. FILM DEPOSITION

The Al_2O_3 films were deposited via sputtering, where Argon atoms (plasma) are accelerated to collide with a target, of the same material as the thin film we want to create. This collision ejects molecules of the target, which are eventually deposited on the sample.

To create erbium-doped films, we used an alumina target (99.9%), with Erbium pieces (99.9%) on top of it. This inexpensive technique, very useful for quick depositions of doped films, is called co-sputtering. Inside the vacuum chamber, the base pressure was $2x10^{-6}$ mbar, which was then filled with a $6x10^{-3}$ mbar Argon atmosphere.

Using the sputtering system described above, we optimized the film deposition parameters, shown in Table I, to suit our needs: relatively high thickness, uniformity/low rugosity, and high index of refraction.

The sample temperature can be controlled, and we found that high temperatures has a negative effect on film thickness, but a positive effect on film uniformity, roughness, and refractive index, so 300ºC was found to be the optimal value. Increasing the bias voltage resulted in an increase of deposition rate with little influence on roughness. We chose 1000 V to be the standard voltage.

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TABLE I. Al_2O_3 SPUTTERING PARAMETERS AND RESULTS

#	Bias (V)	Time (h)	O_2 %	Temp (°C)	Thickness (nm)	Refr. Index
1	150	2	10	200	55	1.61
2	650	2	10	200	125	1.61
3	1000	2	10	200	275	1.61
4	1000	4	10	200	480	1.61
5	1000	6	10	200	620	1.61
6	1000	4	5	200	500	1.61
7	1000	4	1	200	650	1.61
8	1000	4	1	250	630	1.63
9	1000	4	1	300	580	1.66

The control of the O_2 concentration in the chamber. We found that a small concentration is beneficial to the film roughness, but a high concentration has the opposite effect. It also decreases deposition rates, so we settled with 1% of the chamber total pressure, $6x10^{-5}$ mbar.

After the optimizationm we have obtained a reliable sputtering process, resulting, after 4 hours of deposition, in smooth films with thickness of 600 nm and refractive index of 1.66.

III. THERMAL ANNEALING

Various samples containing Er-doped Al_2O_3 films were submitted to thermal annealing procedures at temperatures ranging from 400°C to 1000°C in a quartz tube oven under an 99.99% N_2 atmosphere for 30 min. After this, the photoluminescence spectrum was measured for each sample, for a 532 nm incident laser. The results are shown in Fig. 1.

If only the emission power is considered, the optimal temperature is 850°C, which increased the 1535 nm peak emission by 24 times. If the sample stays at this temperature for 30 more minutes, only a small increase of 3% is observed. Changing the atmosphere inside the chamber also affects the emission: using O_2 we achieved a further increase of 11%.

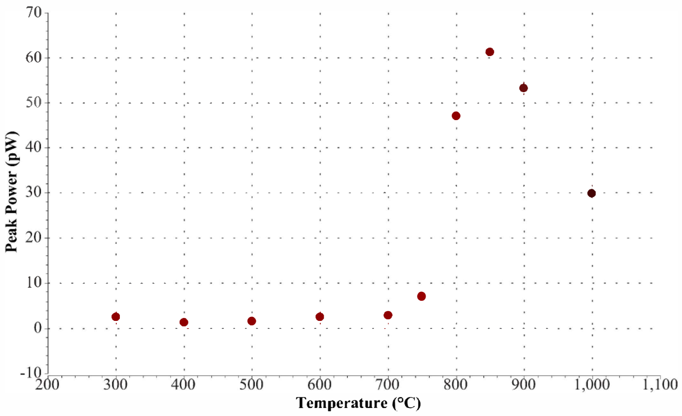

Fig. 1. Peak emission power in function of the annealing temperature.

Measuring the index of refraction, we immediately notice a problem at the optimal temperature: its value, of aproximately 1.8, varies along sample surface, shown in Fig. 2. This happens because the Al_2O_3 the film is beginning to form microcrystalline structures, at the same time when impurities are removed from the sample and Er ions are activated [5, 6]. A trade-off between refractive index uniformity and emission enhancement has to be studied.

IV. INTEGRATION

We are able to obtain Er-doped films with high emission in the C-Band, but if we intend to integrate these films with other III-V optical devices on the same chip, we have one important issue to worry about. Since the optimal temperature for the thermal annealing is 850°C, we have to study the possible damages to other dielectric films commonly used, and to the III-V epitaxial structure. To characterize these effects, we have deposited SiO_2 films on top of non-processed 980 nm laser samples (GaAs substrate, InGaAs quantum well), which were submitted to the same annealing process previously described, in steps of 200°C. No visible damages were observed on the film up to 800°C, but at 1000°C, the film was destroyed.

The photoluminescence spectra of these same samples were then measured, and the results show no peak emission shift for temperatures lower than 600°C. At 800°C, however, the emission is slightly blue-shifted, from 970nm to 960 nm, seen in Fig. 3. This is an indication of intermixing between well and barriers. This may represent a problem, since we have to give up some Erbium emission efficiency to avoid this kind of damage to other devices on the same chip, if this method of annealing is used. To address this issue, we may have to either reduce the annealing temperature or we may need to use a localized optical annealing, using high-power CO_2 laser pulses [7]. This very promising procedure is currently being investigated. A second assessment of the incompatibility that needs to be investigated is related to the electrical properties of the junction. This work is ongoing.

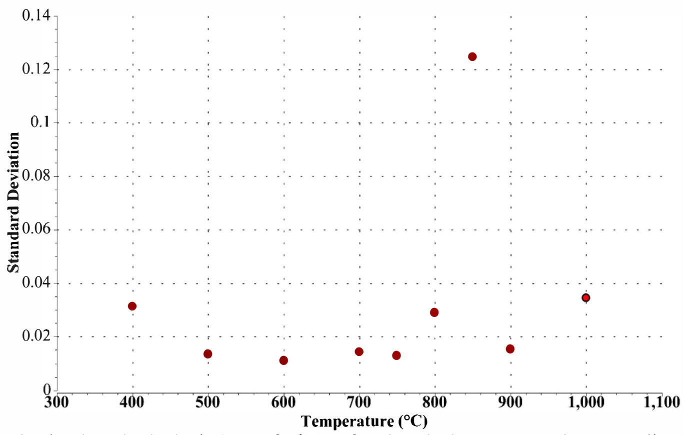

Fig. 2. Standard deviation of the refractive index versus the annealing temperature.

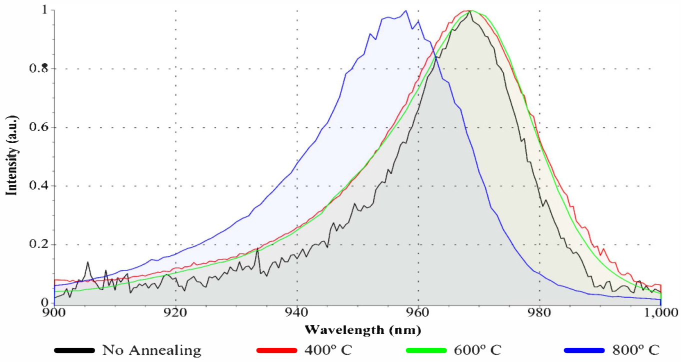

Fig. 3. Photoluminescence spectra of uprocessed 980 nm laser samples, for various annealing temperatures.

We now proceed to perform our first evaluation of the optical guiding properties of the alumina films. Since the 980 nm pump laser and the erbium-doped waveguides are two completely different devices, and we pursue integration on the same chip, the fabrication process can be tricky, but it is possible to obtain good results using conventional photolithography to define the geometries, well known wet etches for III-V materials removal, and RIE (Reactive Ion Etching) for Al_2O_3. The waveguide cladding can be created using SiO_2 deposition before and after the alumina layer is done. In the following, we describe our first fabrication of alumina wave guides.

Starting with a Silicon substrate having a 4 µm SiO_2 film on top, we deposited a 600 nm layer of undoped Al_2O_3, using the system and procedures described above. Using a photolitographic mask, we recorded a pattern of 7 µm wide straigh lines in AZ3312 photoresist, in the entire sample. After revelation, the sample went through a RIE plasma process for 60 minutes, under 30 mTorr of $SiCl_4$ and Ar, with flow rates of 10 sccm and 5 sccm, respectively. This etched the alumina layer, creating straight waveguides, with air as the top cladding layer (no film was deposited on top).

The sample was cleaved perpendicularly to the waveguides and we obtained bars with various waveguides on it, with varying length, from 500 µm to 2 mm.

We aligned both ends of the waveguides to a microlens in one end of an optical fiber. One of these was connected to a tunable laser source, and the other to an optical power meter, so we could guide the light from the laser in the waveguide, and measure the output power. Varying the laser wavelength, we could measure the transmission spectrum, shown in Fig. 4. The oscillation observed is due to the Fabry-Perot cavity, and using (1) we can obtain the attenuation coefficient [8]:

$$\alpha = \frac{-1}{L} \ln\left[\frac{1}{R}\left(\frac{\sqrt{\xi}-1}{\sqrt{\xi}-1}\right)\right], \xi = \frac{I_{max}}{I_{min}} \qquad (1)$$

Here, I_{max} and I_{min} are the normalized intensity of the Fabry-Perot peaks and valleys, respectively, L is the waveguide length, and R is the reflectivity between the air/alumina interface. The average attenuation of these waveguides was 15 dB/cm, a very high value. This may be caused by the top air cladding interface and high scattering on the sidewalls. It is important to note that this extrapolated insertion loss value may be strongly increased in the presence of many transversal modes. Therefore, we need to fabricate a single transverse mode for the correct evaluation. This work is ongoing, and more reliable results are expected at the time of the conference. Nevertheless, there is a need for improvement in the processes. Improved lithography using Electron-beam or Laser lithography as well as an optimized etching procedure may improve the performance.

We are also able to fabricate 980 nm lasers with a threshold current of 23 mA and 40 mW emission at 100 mA, so the next step after improvement of current results is the fabrication of these two devices, shown in Fig. 5., on the same chip. Basic simulations show that our design for this optical amplifier should be able to achieve a total gain of 1.55 dB/cm, close to values found in the literature [9].

V. CONCLUSION

We described the optimization of Erbium-doped Al_2O_3 films development for integrated III-V photonics applications.

A reliable process of co-sputtering deposition have been obtained, and it was possible to improve the photoluminescence emission of these films 28 times at 1535 nm with the optimized thermal annealing, although further investigation of the effects of this procedure on the refractive index is necessary. It was shown that the developed films can be used in an integrated Erbium-doped Waveguide Amplifier, able to achieve a gain of 1.55 dB/cm.

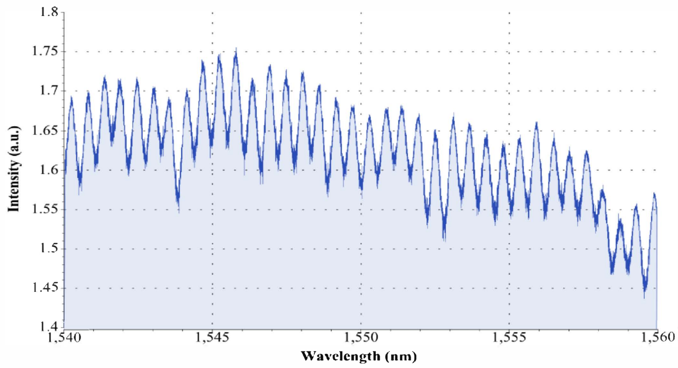

Fig. 4. Typical transmission spectrum of the alumina waveguides.

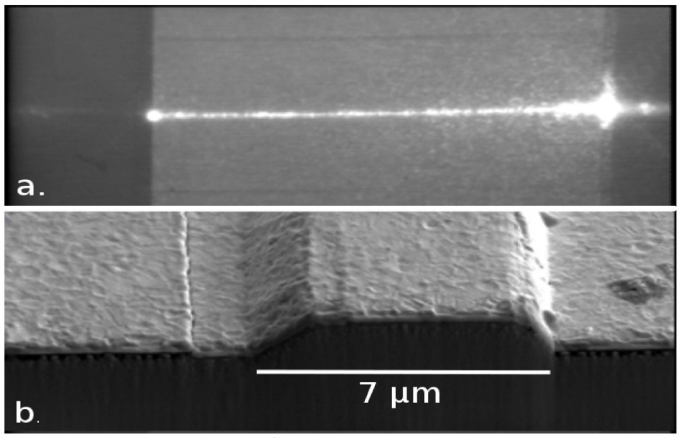

Fig. 5. Fabricated devices. Infrared light (1550 nm) is guided in an 1.1 mm long Al_2O_3 waveguide (a). 980 nm laser mirror polished by FIB (b).

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