Photonic waveguide engineering using pulsed lasers – A novel approach for non-clean room fabrication!

A Jha[1*], G Jose[1], M Murray[1], M Irranejad[1], Z Zhao[1], T T Fernandez[1], R A Hogg[2], Z Y Zhang[2], N Bamiedakis[3], R V Plenty[3], I H White[3]

*[,1] *Institute for Materials Research, Houldsworth Building,Clarendon Road, University of Leeds, Leeds LS2 9JT.*

[2]*School of Electronics and Electrical Engineering, University of Sheffield, Sheffield S1 3JD, UK.*

[3] Electrical Engineering Division, 9 JJ Thomson Avenue, University of Cambridge, Cambridge, CB3 0FA, UK.

Tel: +44 113 343 2342 Fax: +44 113 343 2384, e-mail: a.jha@leeds.ac.uk

ABSTRACT

Over the last 25 years has seen an unprecedented increase in the growth of phonic components based on semiconductor and solid-state lasers, glass and polymer based optical fibres, and organic LEDs. Emerging technology for component engineering must embed dissimilar materials based devices into an integrated form which is more efficient. In this article, we demonstrate techniques for overcoming the materials related limitations by adopting thin-film deposition techniques based on nano- and femto-second pulsed laser deposition. Three examples of thin-film fabrication for near-IR devices using Er^{3+}-ion doped glass-on-GaAs, Er^{3+}-ion doped glass-polydimethyl silane (PDMS) polymer, and Tm^{3+}-doped nano-silicon thin films and gain medium waveguides are discussed.

The modelling tools are used *a priori* for waveguide engineering for ascertaining the extent to which the structural incompatibility due to mismatch strain can be minimized. The structure and spectroscopic properties of Er^{3+}- ion doped thin films on silica, polymer, and semiconductor GaAs substrates were examined in detail and are reported. We demonstrate the formation of glass-polymer superlattice structures for waveguide fabrication for overcoming the solubility limits of Er^{3+}-ions in PDMS polymers. For inscribing waveguides in superlattice structures and nano silicon structures, the ablation machining using fs-pulsed Ti-sapphire laser was used, and the resulting spectroscopic properties of waveguides are discussed.

Keywords: Er^{3+}-doped waveguides, thin films, glass-semiconductor integration, nano silicon, glass-polymer waveguides, waveguide amplification

1. INTRODUCTION

Recently in Optics and Photonics News, the predictions for demand in data were reported to increase up to 10^7 Tb per month [1,2] by 2016, which is attributed to an increase in the demand for internet TV, online gaming, and enterprise data exchange . At the user level this demand is also reflected by the download/upload data speeds in personnel computers, connected with the current gigabit Ethernet services. However, modern PCs do not operate in an all-optical regime, which implies that there is a need to upgrade the backplanes of PCs to cope and support the higher speeds of signal processing. A similar situation is confronted in any network pre-amplifiers which are operating within the limited bandwidth at the optical transition ($^4I_{13/2} \rightarrow {}^4I_{15/2}$) wavelength of Er^{3+} ion doped fibre amplifiers (EDFA). In an EDFA preamplifier, the pump laser is the most expensive component which is not utilized effectively due to poor gain per unit length (dB m^{-1}) in Er^{3+}-doped fibre, when compared with dB.mm^{-1} gain in semiconductor devices. Although all-optical semiconductor amplifiers have been known for the 1300-1600 nm wavelength region of the optical communication, each optical amplifier is significantly limited in bandwidth when compared to a rare-earth ion doped glass fibre amplifiers, making them unaffordable. For PC network-to-fibre interface and for large area networks (metro and local), besides EDFA, the alternatives are still at research stage using the nonlinear optical amplifiers based on parametric processes. However, this approach also suffers from a major limitation which is low gain per unit length when compared with the large parametric gain in semiconductor devices, which are efficiently electrically pumped.

One of the approaches discussed in this invited paper is based on a materials approach, allowing improved optical integration of different materials (glass, polymer, semiconductors) in planar geometries, especially used for enhanced gain per unit length when compared with a standard EDFA. In this materials approach our aim is also to reduce the insertion loss wherever possible by minimizing the refractive-index difference between two media. In the context of engineering planar gain media, three different materials processing approaches are discussed for engineering waveguide gain media and these are the Er^{3+}-doped phosphate modified tellurite glass film on GaAs semiconductor, Er^{3+}-doped glass-polydimethyl silane (PDMS) nano-scale composite, and a Tm^{3+}-doped nano-Si waveguide approach. For dissimilar optical materials integration for gain medium, not only the spectroscopic properties of materials fabricated need to be controlled and maximized for a specific application,

but also the thermal and stress mismatch must be controlled for long term structural stability of a device in service.

2. EXPERIMENTAL DETAILS

In the context of thin film fabrication, both the standard excimer at 193nm and 800nm Ti-sapphire lasers, pulsed in nano and femto second regimes, respectively were used [3-5]. The pulse width and repetition rates of excimer and Ti-sapphire lasers were in sub μs and 1-20Hz and 100fs and 250-1KHz, respectively. For Er^{3+}-ion doping, the composition of a phosphate modified tellurite glass in mol% was with $50TeO_2$, $20P_2O_5$, 20 Na_2O, $10ZnF_2$. In this glass, the total rare-earth ion concentration can be several weight percent which for the pulsed laser deposition conditions were optimized at 1.1mol% Er_2O_3, 1.5mol% Yb_2O_3, and 0.9 mol% CeO_2. The details of thin film deposition and characterization using excimer laser is described elsewhere [5,6]. For PDMS materials preparation and thin film deposition on silica substrate was attempted by controlling the cracks due to thermal mismatch [4], and then optimized by forming nanometer scale amorphous superlattice structures of PDMS with Er^{3+}-ion doped phosphate modified tellurite glass [7].

In an attempt to control the rare-earth thulium (Tm) element solubility in silicon matrix for engineering mid-IR waveguide gain medium [8], we adopted an approach which is predominantly based on metastable thermodynamic solubility of rare-earth elements in Si. The solubility limit of rare-earth elements in silicon matrix is less than 1000 ppm, which is undesirable for waveguide gain medium engineering. This limit is overcome in the femto-second pulsed laser regime, as a result more than 10,000 ppm of Tm-element, for example, may be solubilized in nano- and amorphous silicon [8,9].

3. RESULTS AND DISCUSSION

3.1 Glass-semiconductor integration

For phosphate modified tellurite glass integration on GaAs substrate, first of all it was essential to analyze and model the thermal stress and mode confinement. For thermal stress management during deposition due to mismatched expansion coefficients and elastic constants between the GaAs substrate and Er^{3+}-doped glass, the Stoney's equation was adopted for computing the thermally induced residual stress (σ_r^f) in thin films [4]:

$$\pm_r^f = \frac{E_s.t^2{}_s}{6.(1-{}^3{}_s).t_f}\left(\frac{1}{R}-\frac{1}{R_o}\right) \qquad (1)$$

where the symbols "*s* and *f* " in subscripts/superscripts describe the substrate and thin films, respectively. E, t, and υ are the Young's modulus, thickness of the film in micrometer, and Poisson's ratio, respectively. In this model, a thin buffer layer of silica was also considered for minimizing the overall residual stress, which can be established from the data summarized in *Table 1* below using the equation (1). The resultant radius of curvature of each type of deposited thin film on GaAs was computed and found to be dominated by a small magnitude of tensile stress, yielding a positive (convex) radius of curvature of 22.82 metres, as shown in *Table 1*. In the context of engineering waveguide gain medium over a Q-dot structure bearing GaAs pump source at 980 nm, it is essential that the PLD deposition of glass films at and above 100°C on GaAs does not adversely affect the pump laser performance which is dependent on the Q-dot structure. This hypothesis was tested by heating GaAs with Q-dot structures under the deposition conditions in the PLD chamber at selected temperatures for several hours, after which the threshold pump current performance was determined for each annealing condition. The results are summarized in *Fig. 1*, from which it is apparent that the threshold current performance is only marginally affected by the heat treatment.

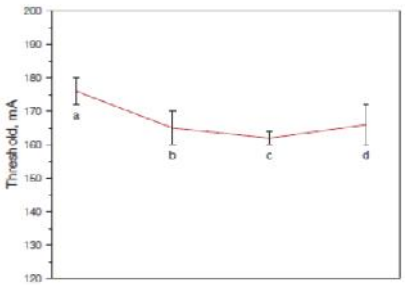
Table 1. Thicknesses (μm) of substrates and films leading to a change in radius of curvature

GaAs, μm	Silica, μm	Glass film, μm	PLD Temperature, °C	Radius of curvature, m
390	1	0	-	-8.09
390	1	1.50	100	22.82
555	0	1.12	100	54.22

The final design requirement was to determine the leaky modes between the glass layer and the GaAs semiconductor pump, considering that the silica buffer layer may be essential for reducing the residual deposition stress. The 2D model of mode confinement is summarized in *Fig. 2*. The effective mode index supported by the Er^{3+}-doped phosphate modified tellurite glass deposited on silica layer is 1.600385 [4]. The elliptical mode dimensions in micrometers are represented on the X- and Y-axes. Based on the materials and waveguide engineering considerations, discussed in Table 1 and Figs. 1 and 2, the optimized Er^{3+}-doped glass films on silica

buffer layer machine-etched with an 800 nm fs-laser for inscribing the waveguide structure, which was then tested for signal amplification in the C and L bands, shown in *Fig. 3*. Since the insertion loss was not determined for this waveguide, in this figure only positive internal gain (black squares) was reported between 1547nm and 1580 nm. The maximum gain of 2.2dB in a centimeter long waveguide was observed when pumping with an external source.

Figure 1. Threshold currents for pump lasers fabricated on GaAs Q-dot structures used for PLD under different



temperatures and deposition times: a) reference sample, b) 3 hours at 100°C, c) 8 hours at 200°C and d) 7 hours at 400°C.

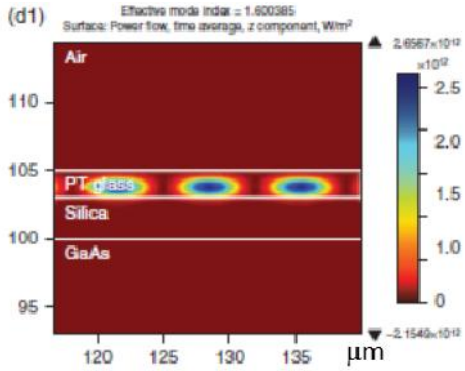


Figure 2: A 2D model of confined elliptical modes in an Er^{3+}-doped phosphate modified tellurite glass waveguide over silica buffer layer on GaAs with Q-dot structures for pumping.

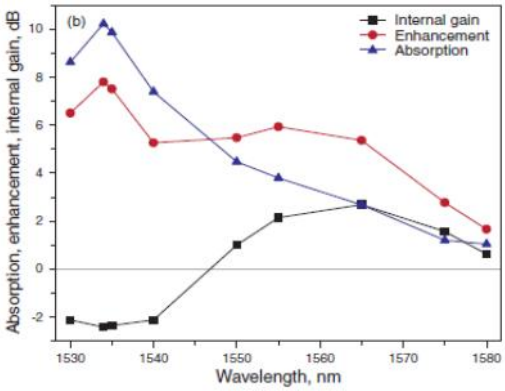


Figure 3: A comparison of 980 nm pump absorption, signal enhancement and internal gain in an Er^{3+}-doped phosphate modified tellurite waveguide.

3.2 Er^{3+} doped Glass-optical polymer waveguide fabrication

Optical polymers such as PDMS depict worse rare-earth ion solubility characteristics than silica and silicate inorganic glass hosts, consequently and it is impossible to design efficient Er^{3+}-doped polymer waveguides for engineering lossless splitters, which can then potentially open the opportunity for engineering seamless and complex photon carrier circuits for the backplane of PCs. In an earlier approach [7], investigations into whether the deposition of a large expansion coefficient glass on a PDMS substrate might be feasible for engineering a suitable gain medium. However it was soon realized that the apparent large mismatch between the coefficients of thermal expansion and elastic constants of an Er^{3+}- phosphate modified tellurite glass and PDMS were the two main barriers for film growth. It is for this reason a nano-scale glass-polymer superlattice approach was proposed using excimer PLD [4,6], in which a multilayer structure of these two dissimilar materials were sequentially deposited to grow 100s of nanometer thick layers for waveguide engineering. An exemplar microstructure of PDMS-glass superlattice, grown using sequential deposition of these two materials is shown in *Fig. 4*, which was characterized for spectroscopic properties, including the lifetime of 1-2 ms in the film and waveguide structures. Note that although the PDMS is possible to process using standard cleanroom techniques, the nano-composite materials are impossible to etch or selectively ion-beam mill. For this reason, the 100fs pulsed laser was used for waveguide inscription and fluorescence characterization [7]. Preliminary data from waveguide engineering is sufficiently encouraging to advance this technique of sequential deposition to the next level for gain characterization in future.

3.3 Tm^{3+} doped nano-silicon thin film deposited waveguide

As explained above, the solubility of rare-earth ions in silicon is extremely small, which results in poor spectroscopic properties due to clustering and an inherent energy back-transfer mechanism [8,9]. Recently it was demonstrated that Tm^{3+}-doping may be possible in crystalline silicon using ion-implantation, which showed PL under sub-ambient condition, requiring extensive cooling of the material at liquid nitrogen temperature.

By considering the importance of silicon for CMOS and mid-IR, in our investigation we deposited Tm^{3+}-dopant in nano-Si (n-Si) using fs-laser at 800 nm inside a PLD chamber. The room temperature PL properties of films deposited and that of the waveguide are summarized in Fig. 5. The measured lifetime of Tm^{3+} at $^3F_4$ level is more than 300μs, compared to more than 1000 μs in silicates, 5000 μs in a ZBLAN glass and 2300 μs in tellurite glass. Neither of the latter two hosts can surpass the 8 μm cut-off edge of silicon, which is highly relevant for applications in mid-IR. It was noticeable from the PL data that the peak position of Tm^{3+}:$^3F_4 \rightarrow {}^3H_6$ transition was red-shifted, thereby allowing a proportionally larger access to spectral range near 2 μm for signal amplification, generation and nonlinear optics.

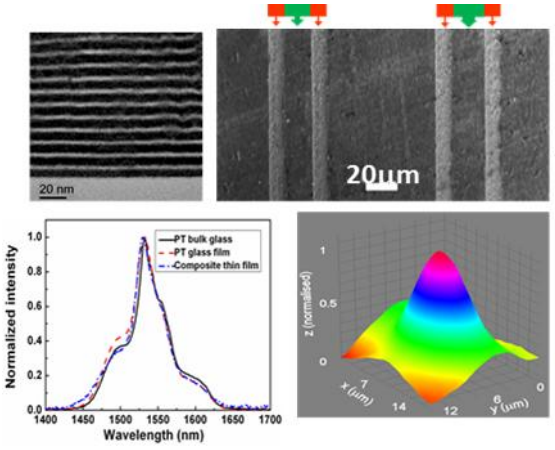


Figure 4: Top left- Superlattice layers of glass (dark) and PDMS (bright). Top right -The laser inscribed waveguides showing simulated Er^{3+} emission (bottom right) and the measured PL which is compared with bulk glass, thin films and superlattice composites

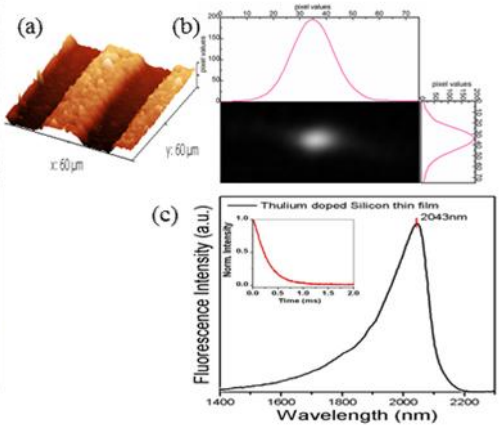


Figure 5: (a): (in colour) 3D-AFM image of a waveguide, measuring 15 μm across (z-axis reads 1 μm/div). (b): (in colour online) 1550 nm propagated mode through the waveguide. (c) (in colour online) Emission spectrum of Tm^{3+} doped silicon thin film at room temperature using an 808 nm laser diode. Inset shows the fluorescence decay curve.

4. CONCLUSIONS

i) Using modelling for thermal mismatch and mode confinement and pulsed laser deposition, an Er^{3+}-doped phosphate modified tellurite glass waveguide was engineered on a silica buffered Q-dot containing GaAs substrate, showing an internal gain of 2.25 $dB.cm^{-1}$ gain at 1565 nm, when externally pumped.

ii) The PLD technique alleviated the limited solubility of RE-ions in PDMS and thermal mismatch, by allowing the control of polymer and Er^{3+}-doped glass layers in nm scale superlattice geometry. The superlattice structure was etched with a fs-laser for waveguide engineering, showing 1534 nm emission at RT.

iii) The limited solubility of RE- ions in silicon was overcome by fs-PLD technique for engineering a mid-IR light waveguide by doping with thulium ions (Tm^{3+}). At RT, the PL at 2000 nm was observed.

5. ACKNOWLEDGEMENTS

The authors acknowledge the financial support from RCUK Basic Technology project (EP/D048692/1).

REFERENCES

[1] B. Jalali and M S Asghari: *Big Data:The Anamorphic Stretch Transform.* OPN Feb, p.9, 2014.
[2] V.C. Coffey: *Sea Change: The challenges facing submarine optical communications,* OPN Mar p.12, 2014.
[3] Z. Zhao et al: *Tellurite glass thin films on silica and polymer using UV PLD,* J Phys D: App Phys 44 (9), 095501, 2011.
[4] M Irannejad et al: *Active glass waveguide amplifier on GaAs by UV-PLD,* Laser Phys Letts 9 (5) 329, 2012.
[5] T Kakkar et al: *Glass–polymer superlattice for integrated optics,* Optical Engg, 53(7), P.071818, 2014.
[6] M Irannejad et al: *A parametric study of Er^{3+}-doped phospho-tellurite glass thin films by pulsed laser deposition,* Optical Materials, 33 (2), 215-219, 2010.
[7] Z Zhao et al: *Active glass–polymer superlattice structure for photonic integration*, Nanotechnology 23 (22), 225302, 2014.
[8] M Murray et al: *Tm^{3+} doped silicon thin film and waveguides for mid-infrared sources,* Appl. Phys. Letts, 101 (14), 141107, 2012.
[9] M Murray et al: *Femtosecond pulsed laser deposition of silicon thin films,* Nanoscale Res Letts 8 (1), 1, 2013.