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Si-Based Light Emission at 1530 nm with Optical Gain Using Mixture of Er_2O_3, P_2O_5, Yb_2O_3 Nanoparticles and Spin-on Glass

Kuo-Jui Sun, Ping-Hung Shih, Yi-Shin Su, Eih-Zhe Liang, and Ching-Fuh Lin[+]

Graduate institute of Electro-Optical Engineering, National Taiwan University,
No.1, Sec. 4, Roosevelt Road, Taipei, 106, Taiwan, R.O.C
[+]also with Graduate institute of Electronics Engineering, and Dept. of Electrical Engineering

***Abstract* — We explore a new way of light emission at 1530 nm. The light-emitting layer contains the mixture of Er_2O_3 nanoparticles and spin-on glass. It is deposited on silicon wafers. This layer is very thin, but exhibits optical gain. We can also improve the emission efficiency by introducing P_2O_5 and Yb_2O_3 nanoparticles.**

***Index Terms* — Nanotechnology, optical communication, optical pumping, rare earth compounds.**

I. Introduction

The amount of data transmission continues to grow, so the advantage of high transmission capability of optical fiber is of great worth. In order to transmit signals over long distances, the first generation of optical systems used periodic electrical repeaters which detected, regenerated and re-transmitted the optical channel. The link was thus composed of small optical transmission segments of several tens of km length. The main constraint in terms of cost, capacity and flexibility was therefore due to the electrical regenerators. Indeed, if such regenerators could process signals with relatively high modulation speed (100 MHz–10 GHz), their cost dramatically increases with the signal bit-rate. In addition, the bit-rate, the modulation format and the data protocol are fixed for the whole system lifetime (e.g., 15–25 years). In-line regeneration by optical amplification was introduced to avoid such expensive electrical regeneration. Optical amplification also brought the potential of regenerating several WDM channels at once. Thus, the Er-doped optical fiber amplifier becomes the core technique of modern optical communication systems [1]-[4].

However, Er-doped optical fiber has several disadvantages. For example, it requires a quite long distance to acquire optical gain and has expensive fabricating cost. Thus it is not good for chip-scale applications and is difficult to monolithically integrate with electronics. Thus, we introduce a new manufacturing technique to create a light emitting layer on Si wafer. It emits light at 1530 nm and furthermore it has optical gain. The fabrication process is very simple and with very low cost, compared with the ion implantation technique. Ordinary erbium-doped optical fiber requires a quite long distance to acquire significant light emission from Er^{3+} ions. Relatively, our emitting layer is able to show the signals only within several millimeters due to the higher concentration of Er^{3+} and surface effect of nano-particles. In addition, it can be possibly integrated with mature IC manufacturing process widely used today for the realization of monolithic integration. Therefore, we can extend the applications of Si such as taking the Si optoelectronic integrated circuits (OEIC) for optical communication systems.

II. Experiment

Er_2O_3, P_2O_5, and Yb_2O_3 nanoparticles are mixed into spin-on glass (SOG). The SOG is taken as the host material. The nanoparticles are uniformly distributed in the solution by means of the ultrasonic agitation. This solution was then deposited onto the Si substrate.

The detail steps are schematically shown in Fig.1. A piece of silicon wafer is cleaned with standard procedure [5]. Then, we deposit the solution on the silicon wafer and soft bake it at 80°C for 1 minute to remove the solvent. This step is repeated a few times to obtain a thick enough emitting layer. The thickness of emitting layer will affect the photoluminescence intensity. P_2O_5 sublimes at 358°C. Therefore, heating the specimens in 300°C for 30 minutes could prevent P_2O_5 from sublimation and let the mixed nanoparticle layer with SOG become phosphate glass. Finally, The specimen is heated at 1000°C for 90 minutes in order to make the Er_2O_3 release Er^{3+} and react with SOG. The heating temperature has to be 880°C or above so that Er_2O_3 would be reactive [2]. The heat treatment is an important experimental parameter. The final heating step significantly dominates the light emission efficiency of emitting layers. In our experiments, it has been investigated that specimens without the final step of high-temperature heat treatment could not emit light at 1530 nm because no Er^{3+} was released from Er_2O_3 nanoparticles.

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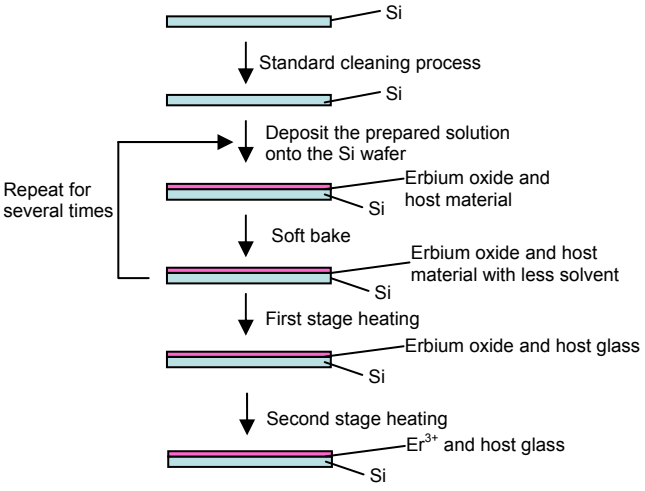

Fig. 1. Sample manufacturing process.

III. Results

A. P_2O_5 Nanoparticles Transform into Phorphare Glass

A large Er^{3+} concentration in silica glass results in concentration quenching caused by ion clusters. Phosphate and silicate glasses are superior to silica glass for the realization of high concentration erbium-doped optical amplifiers. Due to the high solubility of rare-earth ions without cluster formation, phosphate glasses are of great interest as a gain medium for compact erbium-doped optical amplifiers [3], [6]-[8]. Therefore, we add P_2O_5 nanoparticles to the solution of light emitting layer to reduce cluster formation.

Current Er^{3+} doped fiber amplifiers typically utilizes approximately 20 m of silica fiber doped with a few hundred ppm weight Er^{3+} ions. A larger Er^{3+} doping concentration in silica glass results in concentration quenching caused by ion clusters. However, an Er^{3+} doping concentration greater than 2 wt% is required to decrease the length of the active fiber to a few centimeters for integrated devices. This is achievable with phosphate and silicate glasses, which are superior to silica glass for the realization of high concentration erbium-doped optical amplifiers [3].

In these sets, P_2O_5 nanoparticles are added to the solution of emitting layer, and then applied to the Si substrate, as illustrated in Fig. 1. The composition is listed in TABLE I.

It can be seen that the signal to background level ratio has been greatly improved due to lowering the Er^{3+} cluster formation. Comparing the photoluminescence results of Set A1 and Set A2, peak intensity of Set A2 is about 2.5 times of that for Set A1 (TABLE I). This means that the phosphate host, which comes from P_2O_5 nanoparticles, can influence the emission efficiency like ordinary phosphate host does.

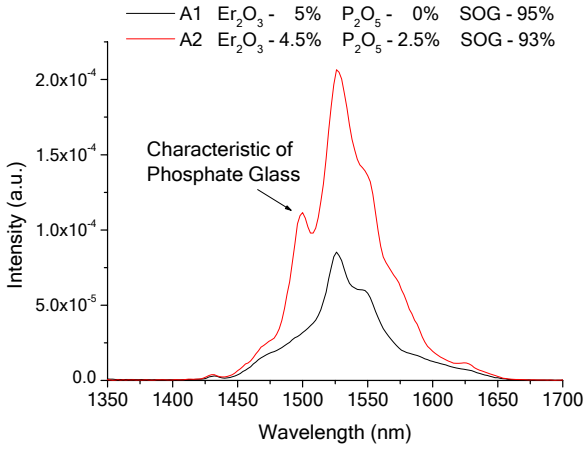

Fig. 2. Fine structure of photoluminescence spectra of Er_2O_3 and P_2O_5 nanoparticles doped samples.

TABLE I
SUMMARY OF COMPOSITIONS AND SIGNAL TO BACKGROUND RATIO

Set	Compositions (Weight Percentage)				Signal to Background Ratio		
	Er_2O_3	P_2O_5	Yb_2O_3	SOG	Peak Signal Values (a.u.)	Background Level (a.u.)	Peak to Background Ratio (dB)
A1	5			95	8.53×10^{-5}	4×10^{-7}	23.3
A2	4.5	2.5		93	2.07×10^{-4}	4×10^{-7}	27.1
B1	3.5	3	25	68.5	2.9×10^{-5}	2.6×10^{-7}	20.5
B2	6	5.5		88.5	9.1×10^{-7}	6×10^{-8}	11.8
C1	18	10		72	1.7×10^{-6}	5×10^{-8}	15.3
C2	14	8		78	3.1×10^{-6}	5×10^{-8}	17.9

With better resolution of monochromator, the fine structures of photoluminescence spectra can be resolved. The peak around 1500 nm is the fingerprint of Er-doped phosphate glass [4]. Thus, Fig. 2 gives a cue that the P_2O_5 nanoparticles indeed transform into phosphate glass. By mixing P_2O_5 nanoparticles and SOG, we can gain the benefit of higher rare-earth solubility due to the formation of phosphate glass.

B. Spin-on Glass Mixed with Er_2O_3 and Yb_2O_3

It has been known that ytterbium-sensitization offers a way to accommodate the needs of broad absorption. With ytterbium-sensitization, the optical pump excites the Er^{3+} ions indirectly, via energy transfer from Yb^{3+} ions. In contrast to Er^{3+}, the Yb^{3+} ion offers a broad absorption band from 800 to 1100 nm, with a particularly high peak absorption cross section. Moreover, ytterbium is less prone to concentration quenching than erbium, and an ytterbium-sensitization erbium-doped fiber has peak absorption typically two orders of magnitude larger than a nonsensitized one [9]. Fig.3 shows that Yb_2O_3 nanoparticles could also improve the emission around 1530 nm by nearly one order of magnitude (TABLE I). This result is similar to the benefit of ytterbium-sensitization erbium-doped fiber.

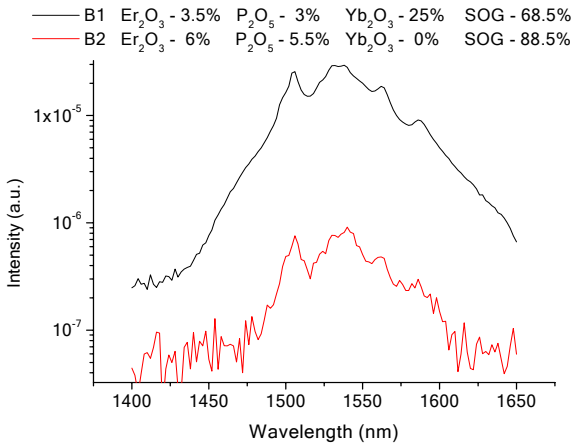

Fig. 3. Photoluminescence spectra of samples with/without Yb_2O_3 nanoparticles doped.

C. Exhibition of Optical Gain

The photoluminescence spectra of specimen are shown in Fig. 4. The spectrum has a peak at 1530 nm. The signal at 1530 nm is observed to super-linearly proportional to the pumping length, while the pumping power is linearly proportional to the pumping length, as show in Fig. 5. This is evidence that the emitting layer exhibits optical gain.

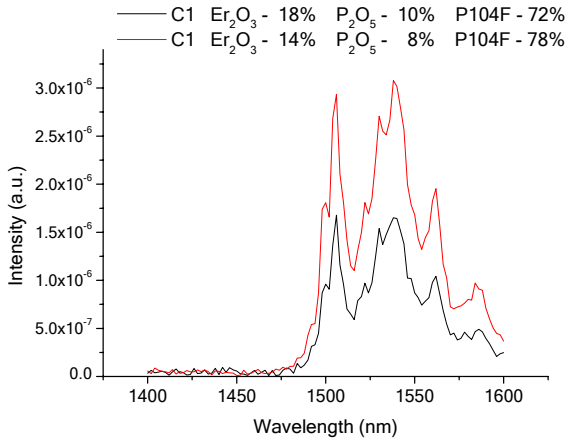

Fig. 4. Photoluminescence spectra of samples used in investigation of optical gain.

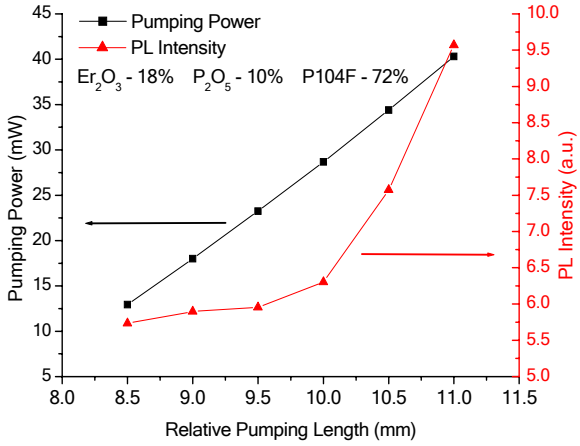

Fig. 5. The pumping power at 980 nm and the optical signal at 1530 nm vs. pumping length.

IV. Conclusion

Emitting 1530 nm light on Si wafer is very useful because 1530nm is an important band in optical fiber communication. We demonstrated a simple process to form light-emitting layer on Si. This emitting layer can also provide optical gain around 1530 nm. The properties of samples can be varied through controlling the composition. A very valuable part of the process is that it can be possibly integrated with IC manufacturing process. In the future, building electrical and optical systems together on Si is expected.

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