

Broad-band and flashlamp pumping of 1.53 μm emission from erbium-doped silicon nanocrystals

A.J. Kenyon ^{a,*}, C.E. Chryssou ^a, C.W. Pitt ^a, T. Shimizu-Iwayama ^b, D.E. Hole ^c,
N. Sharma ^d, C.J. Humphreys ^d

^a Department of Electronic and Electrical Engineering, University College London, Torrington Place, London WC1E 7JE, UK

^b Department of Materials Science, Aichi University of Education, Igaya-cho, Kariya-shi, Aichi 448-8542, Japan

^c School of Engineering, University of Sussex, Falmer, Brighton BN1 9QH, UK

^d Department of Materials Science and Metallurgy, University of Cambridge, Pembroke St, Cambridge CB2 3QZ, UK

Abstract

We report recent results showing broad-band excitation of erbium ions implanted into thin films of silica containing silicon nanocrystals. Evidence for the existence of nanocrystals is presented in the form of HR-TEM images of crystalline regions of the thin films. Indirect excitation of the rare-earth ions is mediated by the nanocrystals, which are either grown in during plasma enhanced CVD of the films, or are formed by implantation of thermally grown SiO_2 layers with Si^+ ions. We demonstrate efficient flashlamp pumping of the erbium 1.535 μm PL band and discuss the device implications of this material. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Erbium; Silicon nanoclusters; Luminescence; Excitation

1. Introduction

A number of studies have shown that the coupling between semiconductor nanocrystals and luminescent rare-earth ions [1–5] can yield a considerable enhancement of the rare-earth absorption cross-section [2,4]. In the case of Er^{3+} in ‘silicon-rich silica’ (silica containing silicon nanocrystals) this enhancement can be up to four orders of magnitude relative to a stoichiometric silica host [4]. Potentially, this coupling mechanism may relax the limitations on pump wavelength for erbium-doped optoelectronics, leading to the production of broad-band pumpable optical amplifiers at the important telecommunications wavelengths around 1.55 μm . In this paper we report the results of a study into the feasibility of achieving broad-band and flashlamp pumping of erbium via silicon nanocrystals.

2. Experimental

Erbium-doped silicon-rich silica thin film samples were prepared by both Plasma Enhanced Chemical Vapour Deposition onto silicon wafers and ion implantation of Si^+ and Er^{3+} into high quality thermally grown oxide layers on silicon. Each sample was implanted with the same peak concentration of erbium (0.5 at.%), but the peak excess silicon concentration varied from 5 to 15 at.%. Samples were annealed at 1100°C for 90 min in flowing argon and the presence of ~ 3 nm diameter silicon crystals was confirmed using high resolution transmission electron microscopy (TEM).

Photoluminescence experiments were conducted using a standard tungsten-halogen bulb to excite the samples, care being taken to eliminate any 1.5 μm output from the bulb using a low-pass filter. A band-pass filter inserted between the source and sample left only a narrow range of pump wavelengths between 560 and 640 nm. In this way, only indirect excitation channels were selected.

* Corresponding author. Tel.: +44-020-7679-3270; fax: +44-020-7387-4350.

E-mail address: t.kenyon@ee.ucl.ac.uk (A.J. Kenyon).

Flashlamp pumping experiments were carried out using a standard camera flashgun (Chinon Auto S-280) which produced a peak output power density at the sample of 88 mW cm^{-2} in a $250 \mu\text{s}$ pulse. The infra-red portion of the flashgun output was filtered out. The output from the thin films was measured at 1535, 1450 and 1350 nm in order to confirm that the measured luminescence was due to Er^{3+} emission at $1.53 \mu\text{m}$.

3. Results

Fig. 1 demonstrates the presence of silicon nanoclusters in our sample: Fig. 1a is a plasmon loss cross-sectional TEM image showing the distribution of nanoclusters (dark areas) in the silica matrix. Fig. 1b is the cluster size distribution determined from this image. The mean cluster size is 3.6 nm, which increased slightly on annealing.

Fig. 2 illustrates the effect of pumping our sample with a broad-band source from which wavelengths corresponding to erbium absorption lines have been re-

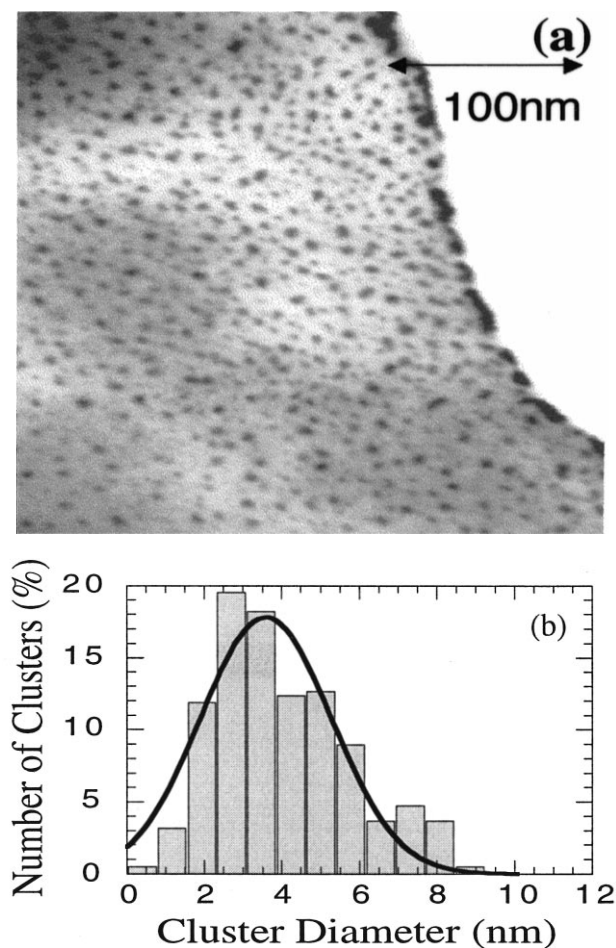


Fig. 1. (a) A plasmon-loss TEM picture of a PECVD-grown sample; (b) the distribution of cluster diameters from Fig. 1(a). The data have been fitted with a normal distribution function.

moved. The dotted line in Fig. 2a is the spectral distribution of the filtered source: this clearly falls between the Er absorption lines around 520 and 650 nm illustrated by the solid trace (Er absorption spectrum from an erbium doped silica fibre). Fig. 2b is the emission spectrum of the sample pumped using the filtered broad-band source. It should be noted that the intensity of emission increased by a factor of around 3.5 when the filtering was removed, allowing direct pumping to the 520 and 650 nm bands.

Fig. 3 shows the time response of the 1535 nm emission from the sample pumped using a camera flashgun. It should be noted that no signal could be seen at 1400 or 1650 nm, confirming that the emission was from erbium. The time resolution of the system was of the order of $15 \mu\text{s}$ and the decay time of the erbium luminescence (approximately 3 ms in the case of the 10% sample) matches that measured using laser excitation. The power efficiency of the excitation process was estimated using the method detailed in reference [6] to be 0.1%. The oscillations evident on the 10 and 15% traces are artefacts of the detection electronics.

4. Discussion

The observation of clear erbium luminescence spectra in these samples using such low excitation levels away from erbium absorption lines suggests a very efficient excitation exchange mechanism. We postulate absorption via the silicon nanoclusters, excitation transfer to erbium ions, and consequent $1.5 \mu\text{m}$ emission. In our samples, the efficiency of this process is around 0.1% for resonant laser excitation; the observation that this efficiency is preserved for flashlamp pumping indicates that the predominant route for excitation of the optically active erbium is indirect and supports the contention that the cross-section for indirect excitation of erbium is much greater than that for direct optical absorption.

For the implanted samples, in the case both of laser and flashgun excitation there is a striking trend in photoluminescence output; the highest being from the sample containing 10% excess silicon, the lowest from that with 5 and the 15% sample being intermediate. There are also significant differences in the photoluminescence lifetimes observed in these samples. The 15% excess silicon film exhibits a much shorter lifetime than either of the others. Our contention in an earlier publication [7] was that the change from 5 to 10% excess silicon represented an increase in both number density and size of silicon nanoclusters (TEM studies support this) and consequently, the mean separation between erbium ions and silicon nanoclusters reduces at higher silicon concentrations. However, there is an

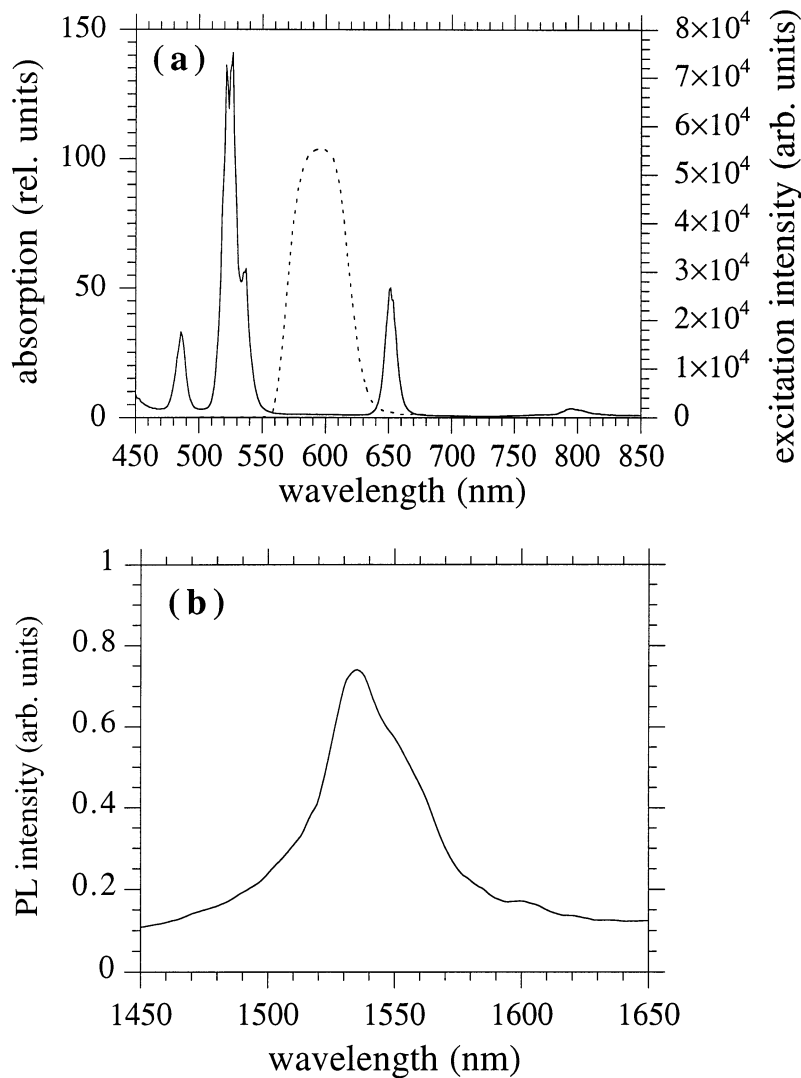


Fig. 2. (a) Absorption spectrum of stoichiometric erbium-doped silica fibre (solid line). The dotted line in (a) is the emission spectrum of the filtered white light source; (b) PL spectrum of the CVD erbium-doped sample pumped using the filtered white light source.

associated increased probability that the erbium sits within the silicon nanoclusters, rather than in the surrounding silica. Coordination with oxygen is a prerequisite for efficient emission from Er^{3+} and it is well known that the presence of strong non-radiative de-excitation pathways make erbium-doped silicon a very inefficient emitter at $1.5 \mu\text{m}$. The results for the 15% excess silicon sample can, therefore, be explained by assuming that at this concentration a significant proportion of the erbium lies within the silicon nanoclusters and hence the luminescence intensity is quenched with respect to that from the 10% sample. The lifetime data may be explained similarly, as erbium in bulk silicon shows a much shorter luminescence lifetime (typically around $100 \mu\text{s}$) than that in silica ($2\text{--}10 \text{ms}$, depending on the degree of rare-earth ion clustering) [8].

5. Conclusion

Even with wavelengths corresponding to erbium absorption bands removed from our white-light pump source, emission from the thin film samples was strong enough to yield a clear spectrum. We have estimated the power efficiency of this indirect excitation to be 0.1% and we postulate an efficient excitation exchange mechanism between silicon nanoclusters and erbium ions. It is possible that the mechanism may be carrier-mediated or take the form of a resonant dipole-dipole interaction: the exact nature of the transfer is unclear and work is underway within this group to investigate it more closely. However, we have used this effect to pump erbium-doped SiO_x samples using a low power, low cost source, a standard SLR camera flashgun. The efficiency of this process suggests that flashlamp

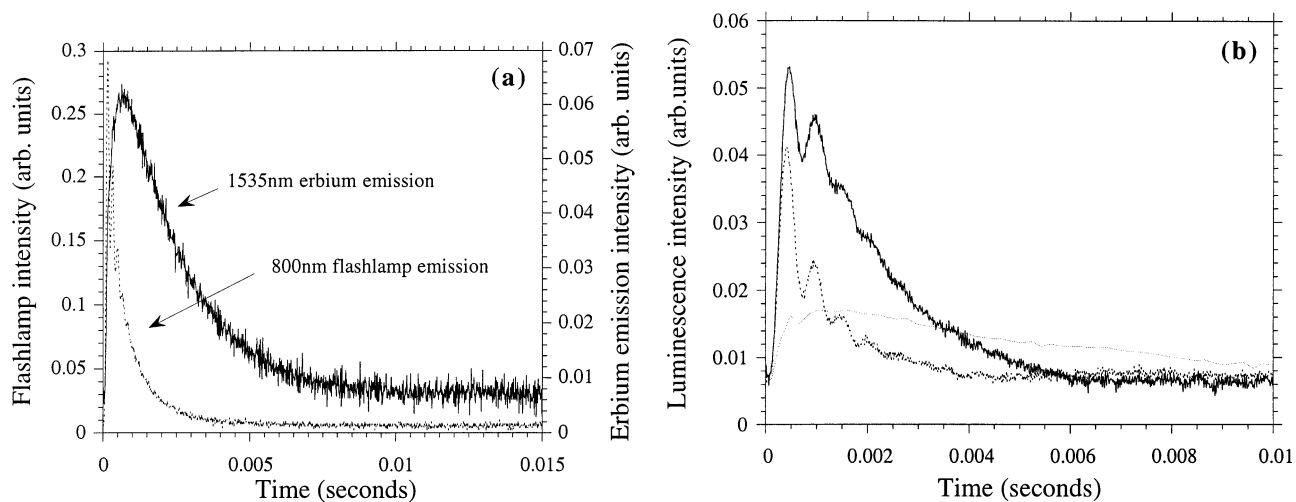


Fig. 3. (a) Time evolution of the 1.5 μm signal from the same sample pumped using a flashgun (solid line) also shown is the flash output at 800 nm (dotted line); (b) time evolution of flashgun-pumped 1.53 μm output from three samples produced by ion implantation containing 5, 10, and 15% excess silicon.

pumped erbium-doped optoelectronic components are feasible. This is particularly attractive for use in local networks and integrated systems, in which the cost of the pump source is an important design factor.

References

[1] A.J. Kenyon, P.F. Trwoga, M. Federighi, C.W. Pitt, *J. Phys.: Condens. Matter* 6 (1994) L319.

[2] M. Fujii, M. Yoshida, Y. Kanzawa, S. Hayashi, K. Yamamoto, *Appl. Phys. Lett.* 71 (1997) 1198.

[3] J.H. Shin, M. Kim, S. Seo, C. Lee, *Appl. Phys. Lett.* 72 (1998) 1092.

[4] G. Franzò, V. Vinciguerra, F. Priolo, *Appl. Phys. A* 69 (1999) 3.

[5] P.G. Kik, M.L. Brongersma, A. Polman, *Appl. Phys. Lett.* 76 (2000) 2325.

[6] A.J. Kenyon, P.F. Trwoga, C.W. Pitt, G. Rehm, *Appl. Phys. Lett.* 73 (1998) 523.

[7] C.E. Chryssou, A.J. Kenyon, T.S. Iwayama, D.E. Hole, C.W. Pitt, *Appl. Phys. Lett.* 75 (1999) 2011.

[8] A. Polman, *J. Appl. Phys.* 82 (1997) 1.