Active planar optical waveguide made from luminescent silicon nanocrystals

J. Valenta
Department of Chemical Physics and Optics, Faculty of Mathematics and Physics, Charles University,
Ke Karlova 3, CZ-121 16 Prague 2, Czech Republic

I. Pelant and K. Lutervá
Institute of Physics, Academy of Sciences of the Czech Republic, Cukrovarnická 10, CZ-162 53 Prague 6,
Czech Republic

R. Tomasianas
Institute of Materials Science and Applied Research, Vilnius University, 2054 Vilnius, Lithuania

S. Cheylan and R. G. Elliman
Electronic Materials Engineering Department, Research School of Physical Sciences and Engineering,
Australian National University, Canberra, ACT 0200, Australia

J. Linnros
Department of Microelectronics and Information Technology, Royal Institute of Technology, Electrum 229,
S-164 40 Kista-Stockholm, Sweden

B. Hönerlage
IPCMS, Groupe d’Optique Nonlinéaire et d’Optoélectronique, UMR 7504 CNRS-ULP, 23, rue du Loess,
67037 Strasbourg Cedex, France

(Received 2 July 2002; accepted 17 December 2002)

We show experimentally that a layer of silicon nanocrystals, prepared by the Si-ion implantation (with the energy of 400 keV) into a synthetic silica slab and exhibiting room-temperature red photoluminescence, can serve simultaneously as a single-mode planar optical waveguide. The waveguide is shown to self-select guided transverse electric and transverse magnetic modes from the broad photoluminescence emission of the nanocrystals resulting in a substantially narrower emission spectrum for these modes. We further report on an investigation of optical gain in a sample implanted to a dose of $4 \times 10^{17}$ $\text{cm}^{-2}$. Despite the occurrence of strong waveguiding, results of the variable stripe length method turned out not to be able to give unambiguous evidence for optical gain. © 2003 American Institute of Physics. [DOI: 10.1063/1.1544433]

The ongoing interest in Si-based optoelectronic devices has recently been further stimulated by reports of optical gain and stimulated emission in layers containing silicon nanocrystals (Si-NCs). This research is motivated by the technological prospect of making a silicon-based laser and by questions of fundamental importance, such as whether or not it is possible to overcome the constraints imposed by an indirect band gap by exploiting the properties of nanoscale material structures. Studies have largely concentrated on the properties of ensembles of Si-NCs embedded in a SiO₂ matrix. For example, waveguiding structures fabricated from erbium-doped Si-NCs embedded in a SiO₂ matrix have recently been shown to exhibit amplification of an externally coupled signal near 1.5 $\mu$m under optical pumping. The prospect of exploiting the waveguiding properties of nc-containing layers is particularly interesting since such guiding could enhance optical gain in such layers by eliminating losses as well as provide a useful basis for the fabrication of other Si-based optoelectronic devices and structures. In this letter the waveguiding properties of undoped Si-NCs containing layers are examined in detail. We further discuss the application of the variable stripe length (VSL) method for investigating the occurrence of gain near 750 nm in our waveguide structure.

Samples used in this study were prepared by implantation of $\text{Si}^+$ ions into synthetic silica slabs (Infrasil) with dimensions of $10 \times 5 \times 1 \text{ mm}^3$ and with optically polished faces. The implantation energy was 400 keV and ion doses were varied in the range $1 \sim 6 \times 10^{17}$ $\text{cm}^{-2}$. This resulted in slightly skewed implant distributions with a mean project range of $\sim 630$ nm and peak excess concentration of up to 26 at. % Si. The implanted samples were submitted to a postimplantation anneal at 1100 °C in a $\text{N}_2$ ambient for 1 h to form Si-NCs. To enhance the photoluminescence (PL) intensity from NCs owing to hydrogen passivation, an additional 1 h anneal was performed in a forming gas (95% $\text{N}_2$/5% $\text{H}_2$) ambient at 500 °C. The presence of Si-NCs was evidenced by Raman spectra that exhibited typical shift and line broadening consistent with a mean NC size of $\sim 3$ nm. Based on the implanted Si distribution an estimated peak density of NCs varies in the range $1 \sim 2 \times 10^{19}$ $\text{cm}^{-3}$. PL was studied using two independent setups. The first one (Royal Institute of Technology, Stockholm) used a continuous wave (cw) He–Cd laser (325 nm) as the excitation source and an imaging spectrograph with a CCD camera for detection. In the

aElectronic mail: pelant@fzu.cz
second PL setup (Institut de Physique et Chimie des Matériaux de Strasbourg). PL was excited with a pulsed XeCl excimer laser (308 nm, pulse duration ~18 ns) and analyzed in a scanning monochromator equipped with a GaAs photomultiplier and a boxcar integrator. This apparatus was also used to investigate optical gain via the VSL method in the temperature range from 8 to 292 K using a gas-flow optical cryostat.

The waveguiding properties of some of the investigated layers manifest themselves clearly as striking differences in PL spectra detected from the surface or from the facet of the sample, as demonstrated in Fig. 1 for samples with different implantation fluences. While for fluences of $1 \times 10^{17}$ cm$^{-2}$ (not shown) and $3 \times 10^{17}$ cm$^{-2}$ the emission spectra for both directions of detection correspond to the broad, structureless emission characteristic of nanometer-sized Si-NCs, the spectrum collected from the facet of the $4 \times 10^{17}$ cm$^{-2}$ sample differs significantly. It is much narrower and exhibits two distinct peaks. (The spectral position of the peaks is slightly different for different batches of samples [compare Figs. 1(b) and 2(a)] but the general shape is reproducible.) Similar behavior is evident also in the sample implanted to a dose $6 \times 10^{17}$ cm$^{-2}$.

We interpret this effect as being due to waveguiding of the red PL emission in the luminescent layer composed of Si-NCs. Due to the relatively high implantation energy, the resulting layer composed of Si-NCs is buried in the SiO$_2$ matrix providing the refractive index contrast indispensable for waveguiding: It possesses an increased refractive index (up to $n_1 \approx 1.73$) compared with the surrounding matrix ($n_2 \approx 1.455$) and is relatively thin (thickness $t$ is about 310 nm). In the first approximation we can model the layer as a symmetric planar waveguide (with a rectangular refractive index profile). Then, the condition for single mode guiding, $\frac{\lambda}{2} < n_1 t < \frac{\lambda}{2}$, is fulfilled for wavelengths $\lambda = 2 \pi c / \omega$ longer than $\sim 590$ nm. Indeed, investigation of the PL polarization revealed that the two peaks are clearly polarization resolved TE and TM modes [Fig. 2(a)].

It is worth stressing that in these experiments the PL generated by the layer itself serves as the test beam probing the waveguide properties, without the necessity of any external coupler. The waveguide obviously self-selects the discrete guided modes from the broad PL spectrum. Such behavior, also recently reported in Ref. 2, is quite interesting and possibly results from a “microcavity” effect in which the NC emission is modulated by the available optical density-of-states. This, coupled with the modified refractive index profile resulting from the different implant conditions, may also explain the observed spectral shift of the modes compared to the emission from the surface [a blue-shift for a dose of $4 \times 10^{17}$ cm$^{-2}$—see Fig. 1(b)]—and a red one for $6 \times 10^{17}$ cm$^{-2}$, Fig. 1(c)].

The waveguide properties together with the corresponding strong directionality of the spectral features are further demonstrated in Fig. 2(b). By collecting PL under various angles $\alpha$ with respect to the layer, the structure of guided emission is shown to be a sensitive function of detection angle—the clearly resolved peaks corresponding to TE and TM modes are observable over a narrow range of $\alpha$ only. When the guided PL is detected at angles greater than $\alpha = 5^\circ$, the spectrum becomes broad and structureless, indicating strong directionality of the spectral features. The solid line represents unpolarized PL, while the curves B represent PL collected from the facet of the samples (~ two distinct peaks). Emission spectra of the sample differ significantly. It is much narrower and exhibits two distinct peaks. (The spectral position of the peaks is slightly different for different batches of samples [compare Figs. 1(b) and 2(a)] but the general shape is reproducible.)

Similar behavior is evident also in the sample implanted to a dose $6 \times 10^{17}$ cm$^{-2}$.

When the guided PL is detected at angles greater than $\alpha = 5^\circ$, the spectrum becomes broad and structureless, indicating strong directionality of the spectral features. The solid line represents unpolarized PL, while the curves B represent PL collected from the facet of the samples (~ two distinct peaks). Emission spectra of the sample differ significantly. It is much narrower and exhibits two distinct peaks. (The spectral position of the peaks is slightly different for different batches of samples [compare Figs. 1(b) and 2(a)] but the general shape is reproducible.)

Similar behavior is evident also in the sample implanted to a dose $6 \times 10^{17}$ cm$^{-2}$.

When the guided PL is detected at angles greater than $\alpha = 5^\circ$, the spectrum becomes broad and structureless, indicating strong directionality of the spectral features. The solid line represents unpolarized PL, while the curves B represent PL collected from the facet of the samples (~ two distinct peaks). Emission spectra of the sample differ significantly. It is much narrower and exhibits two distinct peaks. (The spectral position of the peaks is slightly different for different batches of samples [compare Figs. 1(b) and 2(a)] but the general shape is reproducible.)

Similar behavior is evident also in the sample implanted to a dose $6 \times 10^{17}$ cm$^{-2}$.

When the guided PL is detected at angles greater than $\alpha = 5^\circ$, the spectrum becomes broad and structureless, indicating strong directionality of the spectral features. The solid line represents unpolarized PL, while the curves B represent PL collected from the facet of the samples (~ two distinct peaks). Emission spectra of the sample differ significantly. It is much narrower and exhibits two distinct peaks. (The spectral position of the peaks is slightly different for different batches of samples [compare Figs. 1(b) and 2(a)] but the general shape is reproducible.)

Similar behavior is evident also in the sample implanted to a dose $6 \times 10^{17}$ cm$^{-2}$.
In conclusion, we have presented experimental data demonstrating the waveguiding properties of a layer composed of Si nanocrystals embedded in a silica slab. Room temperature guided emission in the red spectral region, originating from the luminescent nanocrystals, was shown to contain polarization distinguished TE and TM peaks, the structure of which was a sensitive function of observation angle. However, the application of the VSL method, either with a cw 325 nm or a nanosecond 308 nm pumping, did not give conclusive evidence for optical gain in the waveguide.

This work was supported by Project Nos. A1010809 and AVOZ 1010914 of GAACR, Project 202/01/D030 of GACR, by NATO (PST.CLG.978100), and by the Royal Swedish Academy of Sciences. One of the authors (R.T.) appreciates the financial support from the Lithuanian State Foundation for Science and Studies. We would like to thank to Dr. P. Gilliot, Dr. O. Cregeut, and Dr. V. Vorlicek for experimental assistance.