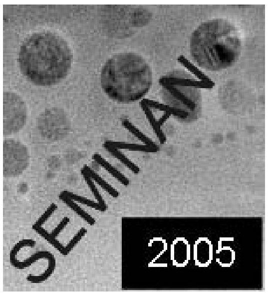
SEMICONDUCTOR NANOCRYSTALS
Volume 2

Proceedings of the First International
Workshop on Semiconductor Nanocrystals,
SEMINANO2005

September 10-12, 2005
Budapest, Hungary



Editors:
B. Pődör, Zs. J. Horváth, P. Basa

Felelős kiadó: Magyar Tudományos Akadémia
Műszaki Fizikai és Anyagtudományi Kutató Intézet, Budapest
Készült a Budapesti Műszaki Főiskola Nyomdájában
Munkaszám: 144/2005
ISBN 963 7371 20 6, ISBN 963 7371 18 4
Műszaki vezető: Bélteky István

First International Workshop on Semiconductor Nanocrystals,
SEMINANO2005, September 10-12, 2005, Budapest, Hungary

Silicon nanostructures for photonics applications

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Low dimensional silicon is used to improve the optical properties of silicon and enable silicon photonics: few recent developments in the fields are here described.

1. Introduction

Having light to transmit, handle and manipulate signals on an electronic chip is a fascinating opportunity which can help in solving many of the present problems in the microelectronic evolution, e.g. power dissipation, interconnect bottleneck, I/O of the chip to optical communication channels, signal bandwidth, etc. Unfortunately, the material used to manufacture electronic chip, silicon, is not a good photonic material: it has very poor light emission efficiency and negligible electro-optic effect. Silicon photonics is born [1] aiming to improve the physical properties of silicon and turn it into a photonic material where full convergence between electronics and photonics is possible. In my group we are using nano-sized silicon to improve the optical properties of silicon.

2. Silicon amplifiers

Silicon is an inefficient light emitter due to its indirect band gap which renders very improbable radiative transitions with respect to non-radiative ones. To beat this inefficiency, one can reduce its size to few nanometers to obtain quantum confinement of the excited carriers. As a consequence, strong visible luminescence at room temperatures is emitted from Si nanocrystals (Si-nc). This is the first necessary condition to get lasing in silicon. The second is to obtain stimulated emission, i.e. light amplification. Positive optical gain in silicon nanocrystals has been demonstrated in Si-nc formed in a SiO_2 matrix [2]. Evidences of light amplification have been obtained by measuring the amplified spontaneous emission which exponentially grows in a planar waveguide with a core layer rich of Si-nc when the optically pumped volume is increased (Figs. 1A and B). In addition, time resolved measurements show that a critical balance exists between stimulated emission and non-radiative recombination processes, such as Auger recombination or confined carrier absorption (Fig. 1C). Population inversion in Si-nc is modeled by a four level model based on the existence of silanone-like (Si=O) localized states which form at the interface between the Si-nc and the surrounding silica matrix (Fig. 1D). Such observations have been confirmed by other authors on different Si-nc systems [1]. Hopes to produce a Si-nc laser are thus born.

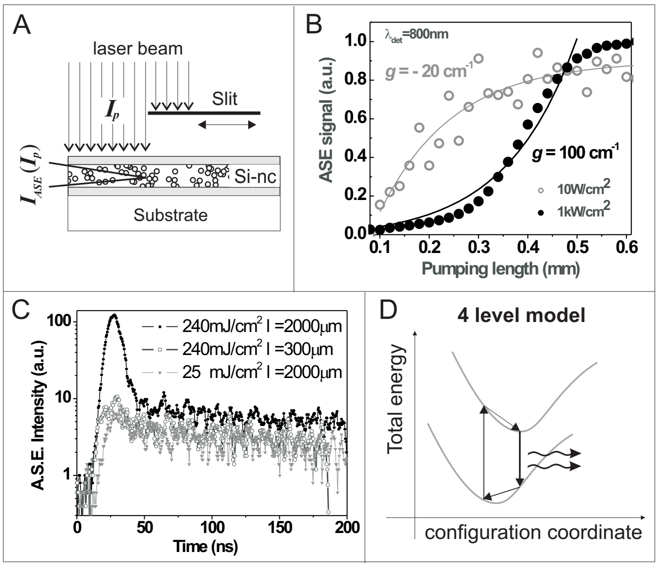

Fig. 1. The variable length stripe technique (A) allows to measure the optical gain in Si-nc formed in a SiO_2 matrix. The amplified spontaneous emission intensity, which is collected from the edge of the waveguide containing Si-nc, grows exponentially upon increasing the pumped volume at high pumping rate, while it saturates at low pumping rate (B). Time-resolved measurements at various pumping rates and excited stripe lengths l (C) evidence the critical interplay between the radiative and non-radiative recombination processes. A four level model (D) describes the inversion in Si-nc.

3. Er-coupled silicon nanocrystals amplifiers

To develop on-chip optical amplifier, Er^{3+}-doped planar glass optical amplifier operating at 1.5 μm are actively looked for. Compact amplifiers at 1535 nm with gain value of about 2-4 dB/cm have been demonstrated. However, these systems have both intrinsic limits, e. g. cooperative up-conversion and excited state absorption, and extrinsic limit, e. g. the need of expensive 980 nm or 1480 nm pump lasers. The use of suitable Er^{3+} sensitizers could overcome these limitations [3]. Si nanoclusters (Si-nc) in SiO_2 are good candidates because of their broad and continuous absorption band in the visible and of the possibility of electrical excitation. Excitation is transferred from the Si-nc to the Er^{3+} ions via a fast (~1μs), very efficient (>70%) and with a large excitation cross section (~10^{-16} cm^2 at 488 nm) process. Pump and probe experiments on Er^{3+} ions coupled to Si nanoclusters have been performed in rib-loaded waveguides to investigate optical amplification at 1.54 μm. Rib-loaded waveguides were obtained by photolithographic and reactive ion etching of Er-doped silica layers containing Si nanoclusters grown by reactive sputtering. Insertion losses measurements in the infrared erbium absorption region allowed to gauge an Er^{3+} absorption cross-section of about 5×10^{-21} cm^2 at 1534 nm. Signal transmission under optical pumping at 1310 nm shows confined carrier absorption of the Si nanoclusters. Amplification experiments at 1535 nm evidence two pump power regimes: losses due to confined carrier absorption in the Si nanoclusters at low pump powers and signal enhancement at high pump powers. For strong optical pumping, signal enhancement of about 1.2 dB/cm was obtained [4].

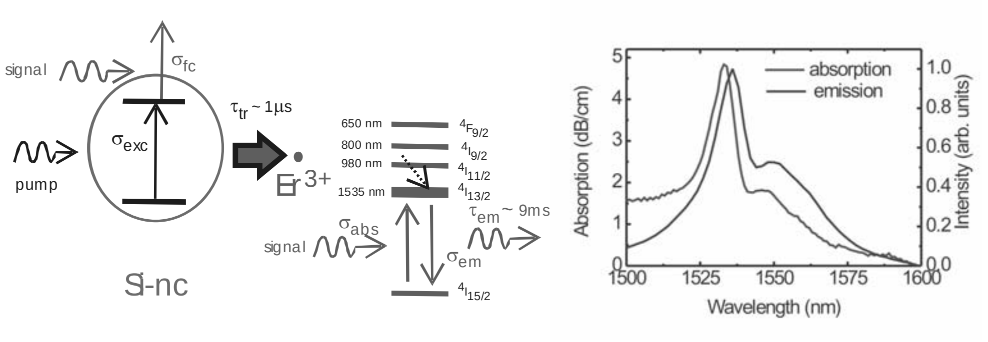

Fig. 2. (left) Diagram of the excitation process of Er^{3+} ions via a Si-nc, with the main related cross sections. On the right the main internal energy levels of the Er^{3+} are shown. (right) Absorption and luminescence spectra of an Er^{3+} coupled Si-nc waveguide.

4. Silicon based complex dielectric structures

Nanostructured silicon can also be forged to produce complex photonic structures, such as 1D-optical superlattices. Exploiting the analogy between electrons and photons and being able to mimic the action of an external bias via a controlled change in the optical path inside the optical superlattice, we have recently observed the optical analogues of time-resolved electronic Bloch oscillations [5] and resonant Zener tunnelling [6]. Optical superlattices have been grown by using electrochemical etching of silicon, i.e. porous silicon formation. Porous multilayers can be formed by varying the current during the etch (Fig. 3A). If an optical path gradient is formed during the growth, the photonic bands inside the structure tilt (Fig. 3B). In analogy to what happens in an electronic superlattice when a constant electric field is applied, we observed that the flat optical miniband transforms into an optical Wannier Stark ladder of equidistant and localized photonic states. A photon pulse coupled into the Wannier Stark ladder experiences multiple reflections yielding oscillating transmission behaviour (Fig. 3C). When two optical minibands are formed in the optical superlattice and an optical path gradient is applied, resonant photon tunneling between the two minibands can be observed. This is the optical analogue of the resonant Zener tunneling for electrons. High transmission intensity and damping of the Bloch oscillations are observed due to the presence of a resonant tunneling channel in the middle of the photonic gap. The transition from low to high transmission is extremely sensitive to the variation of optical path gradient, therefore Zener tunneling light valve can be foreseen (Fig. 3D). These fascinating analogies between electrons and photons show the potentiality of these complex photonic structures to study fundamental problems and add new functionalities to silicon.

4. Conclusion

These three short descriptions of recent achievements indicate that nanostructured silicon has the potentiality to yield a true convergence between photonics and electronics and thus promise new interesting fundamental and applied breakthroughs in the near future.

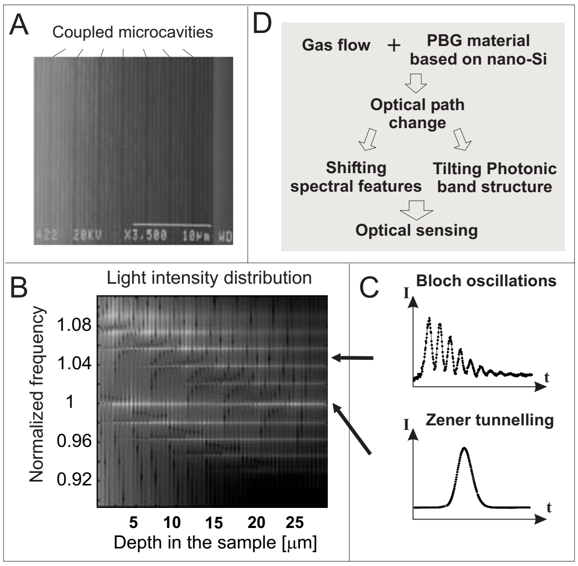

Fig. 3. All-silicon 1D-optical superlattices build up by coupled microcavities with nanometer thick layers are grown electrochemically and shown in a SEM image (A). A controlled optical path gradient allows to tilt the photonic minibands (B) and hence to observe time-resolved photon Bloch oscillations (C, upper graph) and resonant Zener tunnelling of light waves (C, lower graph) in such systems. The coupling between optical Wannier-Stark states turns to be extremely sensitive to slight changes in the optical path gradient, which predicts enhanced optical sensing mechanism (D) and possibility to build a new type of optical valve.

Acknowledgement

The research described here has been supported by EC through the SEMINANO, SINERGIA and PHOLOGIC projects and by MIUR through the FIRB and COFIN projects.

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