

Progress of Si nanostructures used for the Si-based light sources

Yingcai PENG^{1,2*}, Xinwei ZHAO³, Guangsheng FU⁴

1. College of Electronic and Informational Engineering, Hebei University, Baoding 071002, P. R. China

2. Key Laboratory of Semiconductor Material Science, Institute of Semiconductor, Chinese Academy of Science, Beijing 100083, China

3. Department of Physics, Tokyo University of Science, 1–3 Kagurazaka, Shinjuku-ku, Tokyo 162–8601, Japan

4. College of Physical Science and Technology, Hebei University, Baoding 071002, P. R. China

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Abstract Si-based photonic devices have recently attracted much attention owing to their potential applications in the optical communication fields. The achievement of Si light sources such as Si light emitting diode (LED) and Si laser is the most challenging task in the Si-based photonic integration. The key of the study is how to achieve efficient light emission, optical gain and stimulated emission in various Si nanostructures. In this paper, the applications and progress of Si nanostructures in the Si-based light sources are reviewed.

Keywords: Si nanostructures, light sources, integrated optoelectronics, optical communications

1 Introduction

Optical communications have been greatly developed in the past decade because it can solve most of the problems related to interconnection bottlenecks and speed limitations of electronics, offering very large bandwidth, high noise immunity, reduced power dissipation and crosstalk^[1]. So far, optoelectronic devices used for optical communications are mainly III–V compound semiconductor with direct band-gap structures, such as GaAs, InP and other III–V alloys. However, the realization of optoelectronic integrated circuits on Si substrate is very difficult because of larger lattice mismatch and different thermal expansion coefficients between GaAs and Si, and their technological incompatibility.

Recently, Si-photonics has attracted great interest as it can allow integration of optical devices with conventional Si technology. This is the technology associated with signal generation, processing, transmission and detection where the signal is carried by photons. Principal optical devices are light emitting diodes, lasers, waveguides, modulators, detectors, and optical fibers. This paper will mainly focus

attention on the present status of Si nanostructures used for Si-based light sources, *i.e.* Si LED and laser.

2 Achievement of Si-based light emitting diodes

It is well known that Si is an indirect band-gap semiconductor, thus, the probability of spontaneous emission is very low for Si. Alternatively, the spontaneous emission or radiative lifetime in Si is very long while in direct band-gap GaAs it is very short. Because of the long radiative lifetime, non-radiative recombinations are dominant which in turn causes the very low luminescence efficiency.

New modern devices require new structural materials. In order to overcome the indirect band-gap limitations in light emission from Si, since the intense room temperature visible luminescence in porous silicon was discovered by Canham at the beginning of 1990, several strategies have been deeply studied to increase light emission from various Si nanostructures, such as Si nanocrystals (Si-nc) embedded in an SiO_x matrix, SiO₂/Si superlattices, rare earth-doped nanocrystal Si, self-organized Si or Ge quantum dots, and Si-based quantum cascade structures, *etc* ^[2–5]. At present, high efficient Si LEDs have been fabricated by using these nanostructural Si materials.

*Corresponding author.

Tel: +86-312-4101-595; E-mail:ycpeng2002@163.com

2.1 Nanocrystal Si–LED

By confining the electron and the hole in a small volume which is free of defects, it is possible to enhance the quantum efficiency of the optical transitions. The most common way to achieve such a confinement is to use small Si nanocrystals. When the size of the nanocrystals drops below the Bohr diameter of excitons, the quantum confinement effect increases the values of the band–gap energy and the electron–hole wave function overlap, resulting in increased light emission efficiency, and shifts of the emission peaks to higher energy. In addition, the probability of finding a non–radiative recombination center in these Si nanocrystals decreases rapidly with decreasing the size of Si nanocrystals. Such small nanocrystals are also called quantum dots (Si–QD).

Si–nc or Si–QD has been widely used to make LEDs [6–7]. For example, the electroluminescence (EL) properties of Si–nc embedded within a metal–oxide–semiconductor device were investigated. The overall quantum efficiency of the electrical pumping was estimated to be two orders of magnitude higher than the reported values in all studied temperature ranges. Moreover, this efficient emission can be reached at voltages as low as 4 V, even at room temperature [8–9]. Highly efficient Si–LED containing Si–nc has also been fabricated; the yield of the radiative emission of the device was as high as 19% [10]. Except for SiO_x matrix, the luminescent properties of Si–nc in SiN_x matrix were also studied. Cho *et al* [11] reported the high efficiency visible EL properties of Si–LED with Si–nc embedded in silicon nitride using a transparent doping layer, and the estimated external quantum efficiency of the devices was greater than 1.6%. Excitation occurs when the tunneling of electrically injected carriers into Si–nc and subsequently radiative recombination of electron–hole pairs appears. These results are very promising for the applications of Si–nc as light emitting source integrated within a silicon–based system.

The surface passivation can improve the light extraction efficiency. The ability of surface passivation to enhance the photoluminescence (PL) efficiency of Si–nc in SiO₂ films has been investigated. The enhancement of the light emission is directly related to the decrease of non–radiative recombination centers at the Si–nc/SiO₂ interface by

thermal annealing process. PL property of Si–QD in silicon nitride grown by using ammonia and silane gases was reported, the enhancement of PL intensity was attributed to the hydrogen passivation of dangling bonds related to silicon and nitrogen at the interface of Si–QD and silicon nitride [12].

The light emission properties of Si–nc can be further improved by constructing a microcavity structure, in which an active layer is put into two distributed Bragg reflectors (DBRs). When a photon is confined in a microcavity in resonance with the emission of the active medium, the light emission becomes spectrally sharp and is strongly enhanced in the direction of confinement. Toshikiyo *et al.* [13] studied the light emission of Si_{0.9}Ge_{0.1}–nc and Si–nc in an optical microcavity; the PL spectra were narrowed down to 17 meV for Si–nc, and 16 meV for Si_{0.9}Ge_{0.1}–nc, by microcavity structure formation. Furthermore, PL intensity was enhanced by a factor of about 20. In particular, light emission of a microcavity containing Si–nc with sizes ranging between 1.5 nm and 7 nm was reported by Amans *et al*, the PL spectrum showed a sharp emission peak at 674 nm and bandwidth (FWHM) of 13 nm [14].

A critical challenge to realize high efficient light emission of Si–nc embedded in Si dioxides is how to achieve efficient electrical carrier injection. Walters *et al.* proposed a field–effect EL mechanism. In this excitation process, electrons and holes are both injected from the same semiconductor channel across a tunneling barrier in a sequential programming process, in contrast to simultaneous carrier injection in conventional pn–junction light emitting diode structures. Field–effect–induced carrier injection may enable the problems associated with impact ionization excitation to be circumvented through controlling Fowler–Nordheim tunneling. The test devices has so far been observed to be stable over than $\sim 5 \times 10^9$ cycles [15].

2.2 Rare earth–doped nanocrystal Si–LED

Er is an important rare–earth luminescent candidate in various hosts, has been used as a light source at optical wavelength of 1.54 μm . Er related emission at this wavelength is due to intra–center transition between level $^4I_{13/2}$ and $^4I_{15/2}$. The radiative lifetime is long ($\sim \text{ms}$) and the oscillator strength of the transition is weak. Recently, Er–doping of Si–nc has been recognized as a hybrid approach

combining the promising feature of both quantum confinement and impurity doping. It has been demonstrated that Si-nc with presence of Er act as efficient sensitizers for Er light emission, enhancing the Er excitation cross section by more than two orders of magnitude due to a quasi-resonant energy transfer process. The transfer efficiency is related to Si-nc site, the distance between Er^{3+} and Si-nc, and excitation power. In fact, the observation of enhanced Er emission cross section in Er-doped Si-nc sensitized waveguides, and the demonstration of efficient room temperature EL from Er-doped Si-nc devices have opened the route towards the future fabrication of Si-CMOS compatible Er-based devices with efficient electron injection [16-17].

Iacona *et al* [18] studied the EL properties of Er-doped Si-nc embedded in MOS-devices. Due to the presence of Si-nc dispersed in the SiO_2 matrix, an efficient carrier injection occurs and Er is excited, so that producing an intense $1.54 \mu\text{m}$ room temperature EL. The estimated excitation cross section for Er under electrical pumping of $\sim 1 \times 10^{-14} \text{ cm}^2$, and the quantum efficiency of $\sim 1\%$ are obtained at room temperature in these devices. Furthermore, the room temperature PL spectrum of the Er-doped Si-nc films within the microcavity is compared with that of Er-doped Si-nc outside the microcavity. The PL spectrum is much sharper when Er is embedded in the microcavity, the emission peak is at $1.54 \mu\text{m}$ and the FWHM is 5 nm. The extremely efficient Si-based light sources have been fabricated by using MOS structures with Er-implanted in the thin gate oxide. The devices exhibit strong $1.54 \mu\text{m}$ EL at 300 K with a 10% external quantum efficiency. Excepting this, the MOS structures with Tb and Yb-doped SiO_2 films have also prepared, which show room temperature EL at 540 nm (Tb) and 980 nm (Yb) with an external quantum efficiency of a 10% and 0.1%, respectively. The light emission for Tb-doped MOS devices is due to the recombination by $^5\text{D}_4$ to $^7\text{F}_5$ level, while the light emission in Yb-doped MOS devices by $^5\text{F}_{5/2}$ to $^2\text{F}_{7/2}$ [19]. Very recently, optical activation of Si nanowires (Si-NWs) using sol-gel derived Er-doped silica was investigated. Such Er-doped silica/Si-NW nanocomposites are found to combine the advantages of crystalline Si and silica to simultaneously achieve both high carrier excitation efficiency and high Er^{3+} luminescence efficiency which at the same time pro-

vide high density of Er^{3+} and easy current injection, indicating the possibility of developing Si-based photonic devices [20]. Additionally, Er^{3+} -doped micro lasers on a silicon chip were fabricated from Er^{3+} -doped sol-gel layers by varying the erbium concentration of the starting sol-gel material. Continuous lasing with a threshold of 660 nW for erbium-doped micro laser was also obtained [21].

3 Approach to Si-based lasers

The conception and design of Si lasers is one of the most challenging tasks in the Si-based optoelectronic integrated circuits. To produce a Si laser, three key ingredients are required: 1. An active material that should give light emission in the region of interest and that should also be able to amplify the light; 2. An optical cavity in which the active material is placed to provide the positive optical feedback; 3. A suitable and efficient pumping scheme to achieve and sustain the laser action, preferably via electrical injection. In order to achieve a Si laser as a Si-based light source, to date, many studies have been made by scientists. In the following sections, we outline some new approaches to designing and producing Si laser.

3.1 Optical gain of small sized Si-nc

As mentioned above, a key problem to fabricate Si laser is that how to realize the optical gain of Si-based dimensional materials, which is one of the fundamental feature of laser emission. As an optical gain medium, Si-based nanostructures are promising materials. The first observation of optical gain in the Si-based low-dimensional structures has been demonstrated by Pavesi *et al* [22]. The Si-nc produced by negative ion implantation into ultra-pure quartz substrates or into thermally grown silicon dioxide layers on Si substrates, and then followed by high-temperature thermal annealing. The measured peak net modal gain is about 100 cm^{-1} for power density of about $5 \text{ KW} \cdot \text{cm}^{-2}$, owing to the much higher area density of Si nanocrystals embedded silicon oxides. Optical gain in Si/ SiO_2 lattice has also been observed. The experimental results show that a short lifetime of the population inversion allows a generation of short amplified light pulses [23]. The estimation for optical gain in the samples is 6 cm^{-1} at 720 nm. In addition, Negro and Luterova *et al* also reported the optical gain properties of Si-nc in the SiO_x films, the

values of net modal gain are 50 cm^{-1} and 25 cm^{-1} at excited power density of 3 kW and $1.1 \text{ W} \cdot \text{cm}^{-2}$, respectively [24–25].

Two nanoscale Si lasers have been designed by photonic crystal architecture that optical active Si-nc are used as the gain medium [26]. In the first design the Si-nc is encapsulated in a SiO_2 membrane, while in the second design Si-nc are embedded in a distributed-feedback laser cavity formed in the top region of bulk SiO_2 . These designs for a nanoscale silicon laser offer some significant advantages, such as excellent optical confinement, high area density of nanocrystals, high optical gain and high Q values, etc. Stimulated emission dynamics in Si-nc samples has been studied by time-resolved luminescence, and shows the presence of fast recombination dynamics related to population inversion leads to net optical gain [27].

3.2 Stimulated emission of Si nanostructures

The successful achievement of stimulated emission and light amplification is a necessary condition for the realization of a Si-based semiconductor laser. Theoretical considerations of laser operation in Si-nc, as well as experimental observation of high efficient luminescence in quantum-confined silicon system have appeared in the related literatures. An important feature of stimulated emission is the superlinear dependence of light output on pumping power density.

The first report of stimulated emission at $1.54 \mu\text{m}$ from an Er-doped nanocrystalline Si waveguide was presented by ZHAO *et al* [28]. A clear threshold excitation intensity at $\sim 1 \text{ MW} \cdot \text{cm}^{-2}$ was observed. The nanometer sizing of Si and the high doping density of Er enhance the $1.54 \mu\text{m}$ PL intensity at room temperature. The similar results were also obtained by Bresler *et al* [29]. The PL intensity is linear in the pumping power at low pumping rates, and then increases superlinearly at the pumping rate above $100 \text{ kW} \cdot \text{cm}^{-2}$.

Stimulated emission of Si-nc with ultrasmall size is very important for the achievement of Si-based laser. The observation of stimulated blue emission and laser oscillation in reconstructed films of ultrasmall silicon nanoparticles showed the strong blue band at 390 nm under excitation with 355 nm UV radiation [30–31]. For low intensity, the emission is finite, but at $\sim 1 \text{ MW} \cdot \text{cm}^{-2}$, it exhibits a sharp

threshold, rising by several orders of magnitude. Next, stimulated blue emission of Si^+ -implanted SiO_2 films was also investigated by picosecond UV excitation [32]. Room temperature PL spectra consists of a single blue band peak at about 440 nm ($\sim 2.8 \text{ eV}$), above a threshold of $\sim 50 \text{ MW} \cdot \text{cm}^{-2}$, it rises superlinearly, and the estimated power dependence factor is about $3 \sim 3.5$. Moreover, stimulated THz emission has been obtained from intra-center donor transition in silicon monocrystals doped by arsenic. Two emission lines at 6.03 and 6.36 THz corresponding the $2p_{\pm} \rightarrow 1s$ (E) and $2p_{\pm} \rightarrow 1s$ (T_2) intra-center arsenic transition [33]. The population inversion is formed due to fast $2s_{\pm} \rightarrow 1s$ (A_1) electron relaxation assisted by intervalley longitudinal acoustic f-phonon emission.

The described stimulated emission above is realized through optical excitation. For a real Si-based laser, however, electrical excitation is necessary. Recently, the first stimulated emission at bandgap energy of 1.1 eV was observed in a silicon nanostructured p-n junction diode using current injection at room temperature [34]. Because the carriers are spatially localized in a sufficiently small region in silicon nanostructures, so that optical gain and stimulated emission are enhanced, the corresponding external quantum efficiency increased rapidly when a threshold injected current is beyond 315 mA . If the injected current is increased further to 600 mA , the entire spontaneous spectrum is suppressed and two very large and sharp peaks with 3 nm half-width appear at 1214 nm and 1217 nm .

3.3 Intersubband transition in Si-based quantum cascade structures

Quantum cascade (QC) laser has established themselves as the leading tunable coherent semiconductor source in the mid- and far-infrared regions of the electromagnetic spectrum. Their uniqueness comes from the use of an intraband optical transition between quantized conduction band states or valence band states of a suitably designed multi-quantum well structure. One promising route to overcome the fundamental limitation of the indirect band-gap silicon is the use of intraband transition in the Si based QC system. However, SiGe/Si QC laser uses radiative transition between valence subbands mainly because the valence-band offsets in SiGe/Si quantum wells are generally larger than the conduction band offsets, this dif-

fers from QC laser based on III – V semiconductors that employ electron cascade structures. The possibility of monolithic integration of Si-based optoelectronic components is a strong incentive for this research.

Strain –compensated Si/Si_{0.2}Ge_{0.8} QC structures on Si_{0.5}Ge_{0.5} pseudo–substrates have been successfully grown by molecular beam epitaxy. Intersubband transition EL properties between heavy hole states were observed at 80 K for all device structures. The EL spectra exhibit pronounced peak at about 175 meV close to the designed transition energy^[35]. Electrically pumped quantum staircase intersubband p–i–p SiGe/Si strain–blanced superlattice lasers were reported, which can be operated at 77 K or higher. The wavelength of laser emission would be in the THz range. Two designs utilizing inverted hole effective mass produced by strong subband coupling of different type are investigated. One involving inverted light–hole mass uses the intersubband transition between the ground–state light–hole (LH1) to heavy–hole (HH1) in SiGe/Si SLs which allows surface emitting. The other, uses HH2 to HH1 transition with inverted heavy–hole mass enabling edge emission. Optical gain on the order of a few 100 cm^{–1} can be achieved for both lasers^[36–37].

To increase the operated temperatures of Si–based QC laser, new quantum well structures with much thinner barriers were designed. The reduction of the Si barrier thickness increases the current through the devices owing to increasing the tunneling of holes between active quantum wells, and the addition of doping in the active quantum wells also increases the current through the samples. The Si/SiGe QC lasers can be operated at 3.2 THz and at temperatures up to 150 K^[38].

4 Outlook

The design of Si LED and laser will need ordered Si–nc with small size (3~1 nm) and high density (10¹²~10¹³ cm^{–2}), because the small Si–nc can achieve the strongly quantum confinement effect. Thus efficient light–emission, optical gain and stimulated emission can be obtained. This is very important for Si–based light source applications. Two self–assembling growth methods for the fabrication of these materials were proposed: first, controlling the orderliness of preferential nucleated sites on solid–state surface;

and second, controlling the orderliness of nucleated process during self –assembled growth. Various ordered nanostructured Si have been fabricated by these methods, such as nanoquantum dots, nanocrystallites, nanoclusters and nanoscale films.

Although the QC concept works well for III – V semiconductors, the Si/Ge system has a fundamental limit based on the number of periods of successive cascades which is given by the critical thickness for the formation of misfit dislocations. Hence, even though these devices show interesting EL properties for developing the Si–based laser, high evolved cascade structures must still be realized. As the gain per single element is low, due to the nature of the intraband transition, a large number of cascading structures will be needed to accumulate a macroscopic gain. In fact, no stimulated emission in SiGe QC structures has been reported to date.

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