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Stimulated photoluminescence emission and trap states in Si/SiO_2 interface formed by irradiation of laser*

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Stimulated photoluminescence (PL) emission has been observed from an oxide structure of silicon when optically excited by a radiation of 514nm laser. Sharp twin peaks at 694 and 692nm are dominated by stimulated emission, which can be demonstrated by its threshold behaviour and linear transition of emission intensity as a function of pump power. The oxide structure is formed by laser irradiation on silicon and its annealing treatment. A model for explaining the stimulated emission is proposed, in which the trap states of the interface between an oxide of silicon and porous nanocrystal play an important role.

Keywords: interface states, stimulated emission, oxide structure of silicon, laser irradiation
PACC: 4255R, 4270Q

1. Introduction

Recently, a significant progress has been made towards silicon based lasers. Silicon is an indirect band gap semiconductor. Therefore, it is difficult to realize an efficient process for light amplification. Many strategies have been developed to improve silicon's light emission efficiency, such as band gap engineering and quantum confinement[1] in nanocrystals. The porous silicon and silicon nanocrystals in SiO_2 layer are being investigated actively as some means of improving the light-emission properties of silicon.[2,3] Furthermore, the first silicon lasers operating at 1540 and 1675μm based on stimulated Raman scattering have been reported in Refs.[4, 5]. In this type of laser, the interaction between phonons and electrons is essential.

In our recent work, the stimulated emission is attributed to a phononless direct recombination between trapped electrons and free holes. In the paper, we report on two sharp peaks respectively at 694 and 692nm from an oxide structure of silicon when optically excited by a radiation of 514nm laser. The spectrum of the emission pulse has a Lorentzian shape with a full width at half maximum (FWHM) of 0.5–0.6nm. This is a kind of stimulated emission, which can be demonstrated by its threshold behaviour and linear transition of emission intensity in region of pump power over threshold. The special oxide structure is formed by laser irradiation on silicon and its annealing treatment. Only through annealing at 1000°C for 20 min after laser irradiating, can we observe the intensive stimulated emission from the silicon. A model for explaining the stimulated emission is proposed in which the trap states of the interface between an oxide of silicon and porous nanocrystal play an important role.

2. Experiment

We took some Si of P-type (100) oriented wafers with a 10–20Ω·cm as a silicon sample. It was cleaned in a Summa cleaner for 20 min. For ablation experiment, we used the radiation of a pulsed YAG laser with a wavelength of 1064nm, a pulse duration of 8ns FWHM, and a repetition rate of 800Hz, which was normally focused onto the silicon sample in air. The radiation intensity was about 5×10^8W·cm^{-2} with a 30μm diameter irradiation spot on silicon, which was sufficient to produce the laser plasma in air. After

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irradiation, the silicon sample was loaded into an oxidation furnace at 1000°C for 20 min.

Scanning electron microscopy (SEM: EPMA-1600) was used to observe the sample surface. The photoluminescence (PL) spectra of the sample under the excitation at 514nm were measured by using the RENISHAW Raman System, in which the diameter of laser spot on silicon for exciting reaches 1μm.

While a pulse laser irradiated the silicon, a kind of hole-net structure of silicon formed at the inside of the hole drilled by laser. This hole-net structure probably originated from a vibration of the plasma generated at high temperatures during laser irradiation. An intensive PL band (centred at 706nm) was produced due to the hole-net structure.[6,7]

Annealing the sample led to dramatic changes in structure and in PL spectrum. It was shown in Fig.1 that a new kind of porous structure occurred while the hole-net structure disappeared after annealing. In Fig.2, the size of nanocrystal silicon (nc-Si) can be calculated to be about 5 nm from D^2=88.34×10^{-7} ($\lambda^2/\Delta\lambda$) nm^2, where is the Raman peak wavelength of TO phonon, $\Delta\lambda$ is the wavelength deviation from the nc-Si peak to the bulk Si peak in Raman spectra.[8] The deeper oxidation in annealing produced the sharp PL peaks at 694 and 692nm, with the PL band disappearing.

The evolution of the PL peaks at 694 and 692nm is very intensive and very sharp which has a Lorentzian shape with an FWHM of 0.5–0.6nm (Figs.3 and 4). The intensity change of the 694-nm-peak evolution with the increase of the incident continuous-wave pump-power is shown in Fig.5 and 6 which indicates a kind of threshold behaviour and linear transition in a region of pump power over threshold.

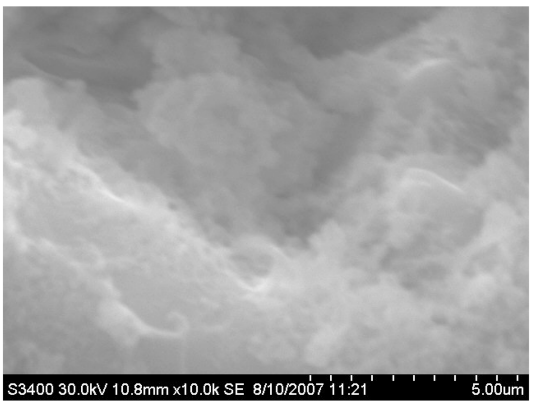


Fig.1. SEM image of a new kind of porous structure occurring while the hole-net structure disappearing after annealing.

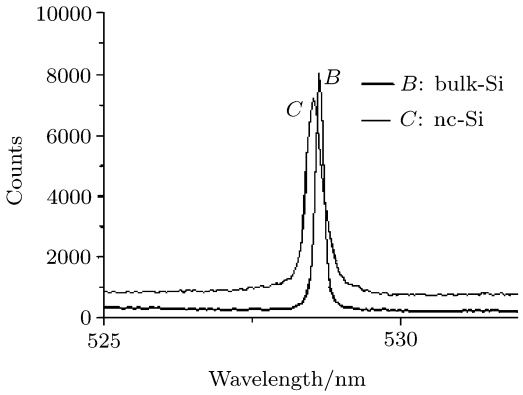


Fig.2. Wavelength deviation from the bulk Si peak to the nc-Si peak in Raman spectra.

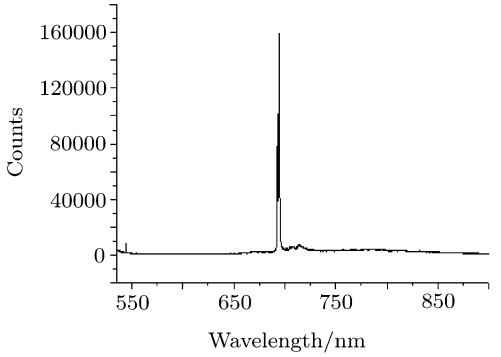


Fig.3. Sharp PL peaks at 694 and 692nm produced on silicon with annealing and irradiation treatment.

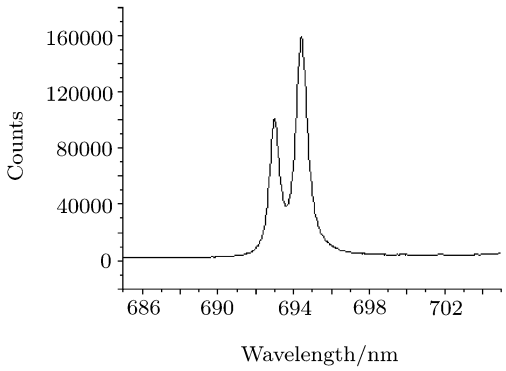


Fig.4. Evolution of the PL peaks at 694 and 692nm which has a Lorentzian shape with an FWHM of 0.5–0.6nm.

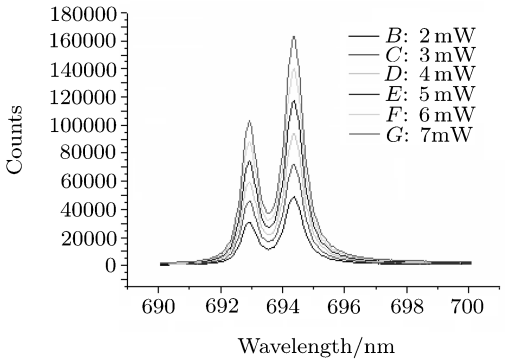


Fig.5. Intensity change of the 694-nm-peak evolution with incident continuous-wave pump power increasing.

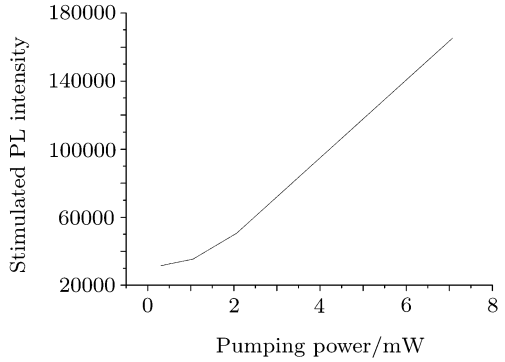


Fig.6. A kind of linear transition in a large range, which is the same as that widely observed in semiconductor lasers.

3. Discussion

The intensive stimulated emission occurs only when deeper oxidation takes place in annealing at 1000°C for 20 min. The mechanism of the stimulated emission in the porous and special oxide structure of silicon can be explained by the quantum confinement effect in a quantum well of nanocrystal in porous silicon and the trap states in the interface between the special oxide and the silicon nanocrystal.[9,10]

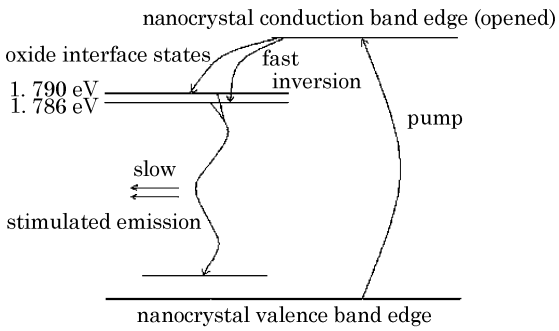


Fig.7. A model of four-level system associated with the crystal–oxide interface states for interpreting the stimulated emission peaks at 694 and 692nm from silicon.

As shown in Fig.7, a model of four-level system has been proposed to be associated with the nanocrystal–oxide interface states for interpreting the stimulated emission peaks at 694 and 692nm from silicon.

An injected photon excites an electron on the top of valence band to jump into the bottom of the conduction band. The gap between the valence band and the conductor band opens because of the quantum confinement effect of porous nanocrystal. The quantum confinement gap can be calculated from the formula[11−13]

$$E_{\text{confined gap}} = E_{\text{bulk gap}} + (3h^2/8)(1/L^2)(2/(m_c + m_v)),$$

where L is the diameter (about 5nm) of porous nanocrystal of silicon; m_c is the effective mass beneath the valley of the conduction band; m_v is the effective mass on the top of the valence band; h is the Planck constant. Then the electrons are rapidly caught into the interface states located in the region below the conduction band. These trap states have two narrow distributions near 1.786 and 1.790eV energy levels respectively. The electronic states in the valley of the conduction band opened should be located at higher levels (over 1.80eV) than the trap states. This is a necessary condition for electrons to be captured into the trap states. The electrons have a sufficiently long lifetime in such trapped states, population-inversion conditions can be established in this four-level system.

We think that it is the most important to select some oxidation conditions for forming discrete trap states in Si/SiO_2 interface from which a four level system can be built to produce a stimulated emission.

4. Conclusion

With annealing for 20 min at 1000°C after laser irradiation, the deeper oxidation produces a kind of special oxide structure of silicon which generates the sharp stimulated emission peaks at 694 and 692nm. We think that the stimulated emission probably comes from the establishing of population-inversion due to a sufficiently long electronic lifetime in the trap states in interface between porous nanocrystal and oxide of silicon. The results should be an important step towards silicon based lasers.

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