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Selecting of modes in nano-laser of silicon quantum dots

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ABSTRACT

In a nano-laser of Si quantum dots (QD), the smaller QD fabricated by nanosecond pulse laser can form the pumping level tuned by the quantum confinement (QC) effect. Coupling between the active centers formed by localized states of surface bonds and the two-dimensional (2D) photonic crystal used to select model can produce a sharp peak at 2.076 eV in the nano-laser. It is interesting to make a comparison between the localized electronic states in gap due to defect formed by surface bonds and the localized photonic states in gap of photonic band due to defect of 2D photonic crystal.

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Replacing electrical interconnects with optical interconnects is a new way to increase the integration density and operating frequency in chip. In optical interconnects there is no distance related loss or distortion of the signal, no deleterious fringing effect and no heat dissipation in the interconnect itself. In future it will be easy to realize three dimensional connecting on chip in optical interconnects. Silicon can already be used for most of the elements of a complete interconnect system which includes detector, switch and modulator. However, due to the poor efficiency of silicon based light emitters there are no appropriate silicon light sources. Recently, good progress has been made in light emission and amplification of silicon. In 2000, evidence for optical gain was presented in silicon nanocrystals produced by implanting silicon in silicon dioxide layers grown on silicon wafers [1]. In 2005, light amplification and stimulated emission were clearly observed in periodic nanopatterned crystalline silicon [2]. In 2008, a sharp peak of stimulated emission (with a full width half maximum of 0.5 nm) was demonstrated in oxidized quantum dots of silicon prepared by pulse laser [3]. Another approach towards realizing active functionalities in silicon is to make use of Raman scattering [4].

In a nano-laser of Si quantum dots (QD) prepared by second pulse laser, the state in the conduction band opened due to quantum confinement (QC) effect forms a pumping level from which the electron is trapped into the localized state of surface bonds in band gap. The inverse population can occur between the localized state in gap and the top state of the valence band. The active centers formed by localized states of surface bonds such as Si≡O bonds, Si—O—Si bonds, Si—N bonds and Si—(ON) are very important [5,6]. Generally speaking, various experiments show the wide PL intensity in the range of wavelength of 500–800 nm which includes some stimulated emission and amplification spontaneous emission in Si QD prepared in oxygen, nitrogen or air [7,8]. In our work, it is a goal to make a narrow range in size of Si QD and get a sharp distribution of the localized states to form active centers to improve stimulated emission. It is good way that Si QD is prepared by nanosecond pulse laser in oxygen, nitrogen or air. Especially, it is easy to form Si—N and Si—(ON) bonds on surface of Si QD in plasma generated by interaction between silicon and pulse laser. It is very important to combine both suitable annealing and irradiation of pulse laser by which we can get an active material of nano-laser.

In a general laser, a pair of flat mirrors is used to form a feedback cavity so that a mode of laser can be selected and an intensive beam can be obtained. But no mirror in nano-laser, instead of a Purcell cavity and 2D photonic crystal are built in it [9,10]. We use a pulse laser to make Purcell cavity and 2D photonic crystal. Here the effect of enhancing and selecting mode can be generated from both coupling regime of cavity quantum electrodynamics and coupling band of photonic crystal.

It is noticed that the localized electronic states in band gap come from the defect formed by some surface bonds on Si QD, and similarly the localized photonic states in gap of photonic band come from the defect of 2D photonic crystal in which their coupling is very important to produce a coherent beam in nano-laser. This kind of the coupling has a selecting effect for emission of single quantum dot remarked by its size and its localized state which is available to the quantum communication, the quantum information process and the quantum computing scheme in future.

We prepared the Si QD by using a pulse laser. The quantum dots were fabricated by plasma produced from interaction between silicon and nanosecond pulse of laser [3,6,7]. We used the pulse laser (wavelength: 1064 nm, pulse width (FWHM): 60–80 ns, repetition rate: 1000–3000/s) in preparing process, which was normally focused

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onto the silicon sample placed in oxygen, air or nitrogen atmosphere. The intensity of the laser pulse was about 5×10^8 W cm^{-2} with an irradiation spot (diameter: ~5 μm) on silicon, which was sufficient to produce the plasma on sample. A P-type silicon wafer with room temperature resistivity of 20 Ω cm was used as starting material which was cleaned in a Summa cleaner for 20 min. After irradiation, many silicon quantum dots are prepared by plasma. They distribute on the wall of the cavity hit by laser beam. In plasma, the dangling bonds are formed on surface of Si QD. Passivation of the dangling bonds on surface could be obtained by different gas atoms in different atmosphere. Some kind of the surface bonds may not provide a good passivation in small crystallites so that some defect states remain. Therefore there are more surface dangling bonds and defect states before annealing. Then the samples selected for comparing were loaded into an oxidation furnace at 1000 °C for 5–30 min. After annealing the range of QD sizes becomes narrower and the defect states decrease. The combination of both suitable annealing and irradiation of pulse laser is a good way to produce the active material of laser.

We designed and made a kind of nano-laser in which the silicon quantum dots oxidized can be as active material of laser, and a 2D photonic crystal as a feedback device can be used to select a longitudinal mode of laser. We use a pulse laser to fabricate the 2D photonic crystal. Fig. 1 shows the structure of the nano-laser in which the 2D photonic crystal with an array of cavities is built on silicon wafer and the active material of laser is set in every cavity as shown in Fig. 1(a). Fig. 1(b) shows a SEM image of the 2D photonic crystal and demonstrates the measured output spectrum of the nano-laser for pump wavelength of 532 nm.

Under TEM, we can observe the quantum dots structure embedded in silicon oxide (the concentration of QD is about 10^{12}/cm^2) as shown in Fig. 2(a), which was fabricated by nanosecond pulse laser in oxygen and then treated with annealing at 1000 °C for 20 min. As shown in Fig. 2(b), B curve describes the quantum confinement (QC) effect of Si QD, C and E curve relate to the localized states in gap due to Si O and Si—O—Si bond, respectively, and D curve is due to Si—N bond on surface of QD.

Room-temperature PL measurements on samples were performed by exciting with the 514 nm line of Ar$^+$ laser whose power was 0.2–20 mW. The PL signal was analyzed in Renishaw micro-Raman

systems. Fig. 3 shows the peaks of stimulated emission at 1.78 and 2.03 eV originating from the active centers due to Si≡O and Si—O—Si bond on surface of QD.

Figure 4 shows two photonic bands related to period of 100 μm and 200 μm in 2D photonic crystal in which we use a pumping laser with wavelength of 532 nm and power of 20 mW. The external angle of incidence is about 20°. It is interesting to make a comparison between Fig. 2 which shows electronic defect states on QD surface and Fig. 4 which shows photonic defect states in 2D photonic crystal whose coupling produces a sharp peak at 2.076 eV while the peak of the mode at 1.78 eV disappears.

We fabricated an electroluminescent (EL) device containing a sputtering Au film covered on the Si QD oxidized to form a Schottky junction. The EL emission in wavelength range of 600 nm–700 nm was observed when the injection current is 25 mA with applied voltage of 20 V.

Figure 3 shows a physical process of nano-laser that at first the electrons are pumped to the states of the conduction band opened by QC effect as shown in right diagram, and then in smaller QD ($d < 3$ nm) the electrons can tunnel into the localized states in band gap which form active centers due to Si≡O or Si—O—Si on surface of QD where the population inversion can be formed as shown in left diagram. In Fig. 2(b), it is clear that Si—H bonds have a good passivation on QD surface so that the change of the energy states depending on the sizes of QD does an agreement with the QC effect (B curve) which provides a pumping level. But some localized states due to Si≡O, Si—O—Si or Si—N bonds on surface will go into band gap of small crystallites (C, E and D curve) which provide some active centers of nano-laser. Figure 2(b) also shows that the Si—N bond on surface forms the localized state in gap on smaller Si QD ($d < 2$ nm) than others. These localized states have a lower level than the bottom states (pumping level) of the conduction band in smaller QD, such as the pumping level of 1.82 eV in the QD of 3 nm is higher than the localized state of 1.78 eV and the pumping level of 2.33 eV in the QD of 2 nm is higher than the localized state of 2.03 eV. The peaks of stimulated emission at about 700 nm or 600 nm for the 514 nm excitation at 300 K can be observed obviously in Fig. 3 where the QD sizes are concentrated to a narrower range near 3 nm or 2 nm respectively after suitable treatment of annealing. Using the VSL method, we
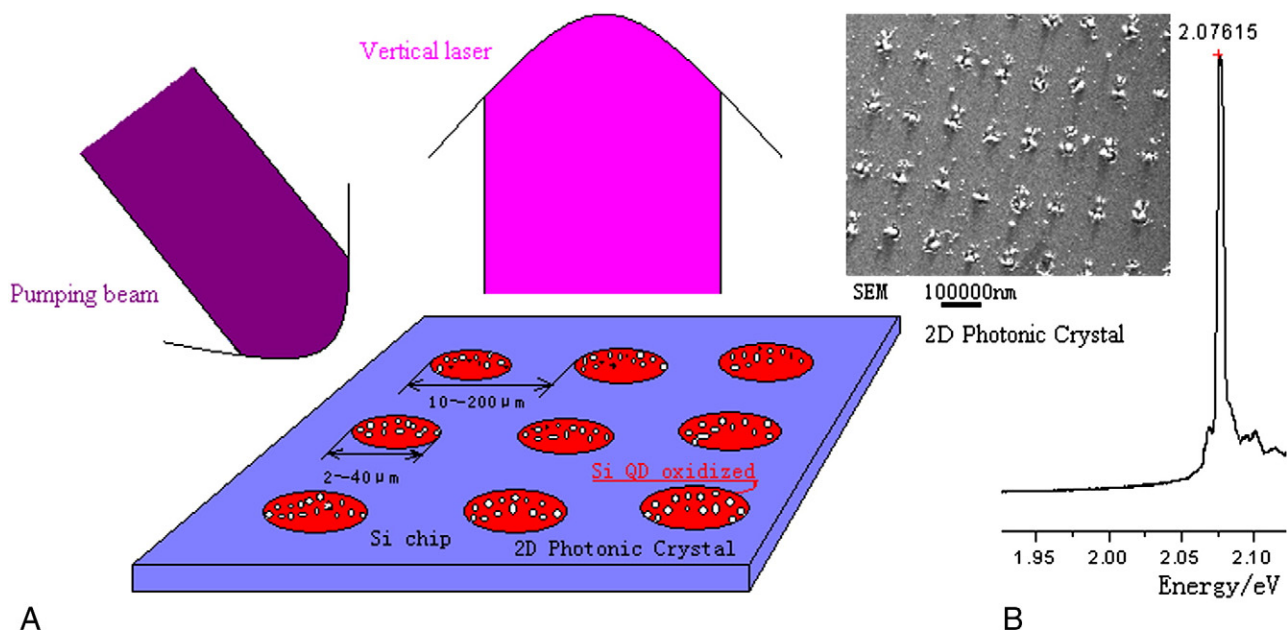

Fig. 1. (A). Nano-laser structure in all-silicon including three main components: 2D photonic crystal with an array of cavities, active material (active QD set in every cavity) and pumping beam.(B). SEM image of the 2D photonic crystal and output spectrum of the nano-laser for pump wavelength of 532 nm.
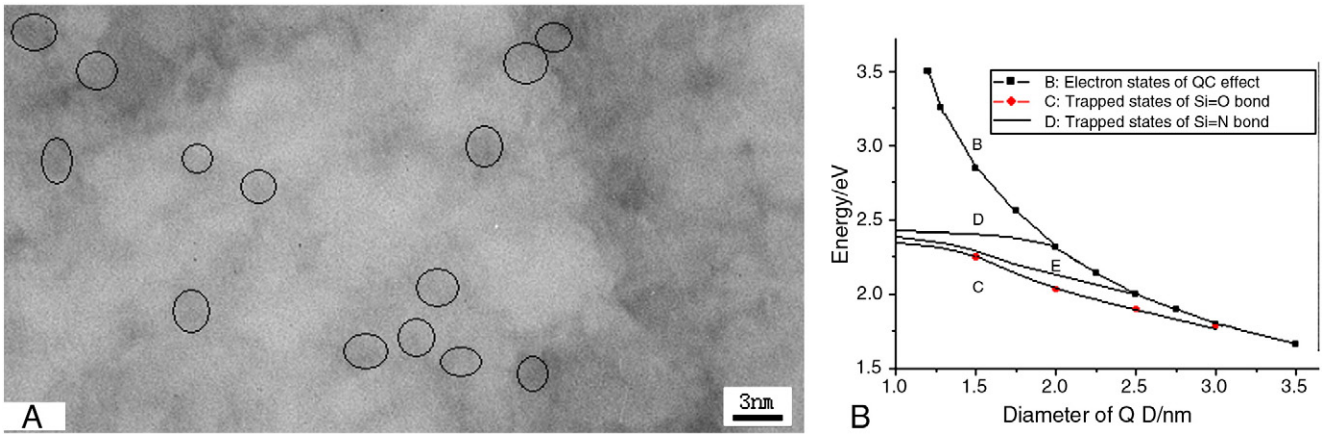
Fig. 2. (A). TEM image of quantum dots structure embedded in silicon oxide.(B). Electronic states with changing sizes of Si QD.Curve B: the relation between the energy of band gap opened and the sizes of QD.Curve C: the evolution of the localized level due to a Si=O on surface.Curve E: the evolution of the localized level due to a Si—O—Si on surface.Curve D: the evolution of the localized level due to a Si—N on surface.

measured the gain coefficient from the evolution of the peak-emission intensity as a function of the optically pumped sample length whose gain coefficient is larger than 60/cm [9].

For the structures of Si QD prepared in different atmosphere, we have chosen some model in order to simulate the experiment process. The electronic behavior is investigated in the work by an ab initio
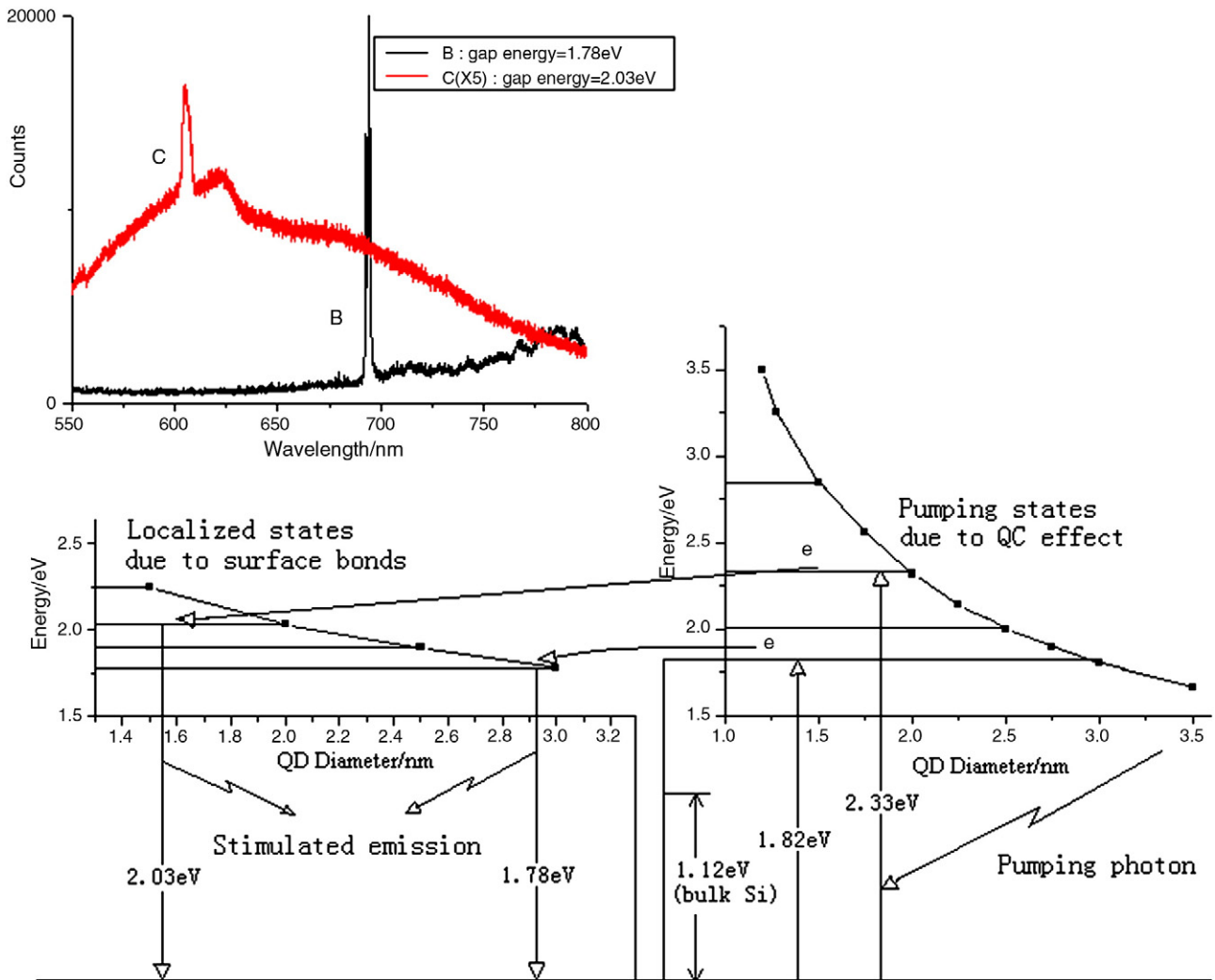

Fig. 3. Physical process of nano-laser that at first the electrons are pumped on the states of the conduction band opened by QC effect (on the right side), and then in smaller QD, the electrons can tunnel into the localized states on surface of QD where the population inversion forms (on the left side) in which the peaks of stimulated emission are observed at about 600 nm and 700 nm.
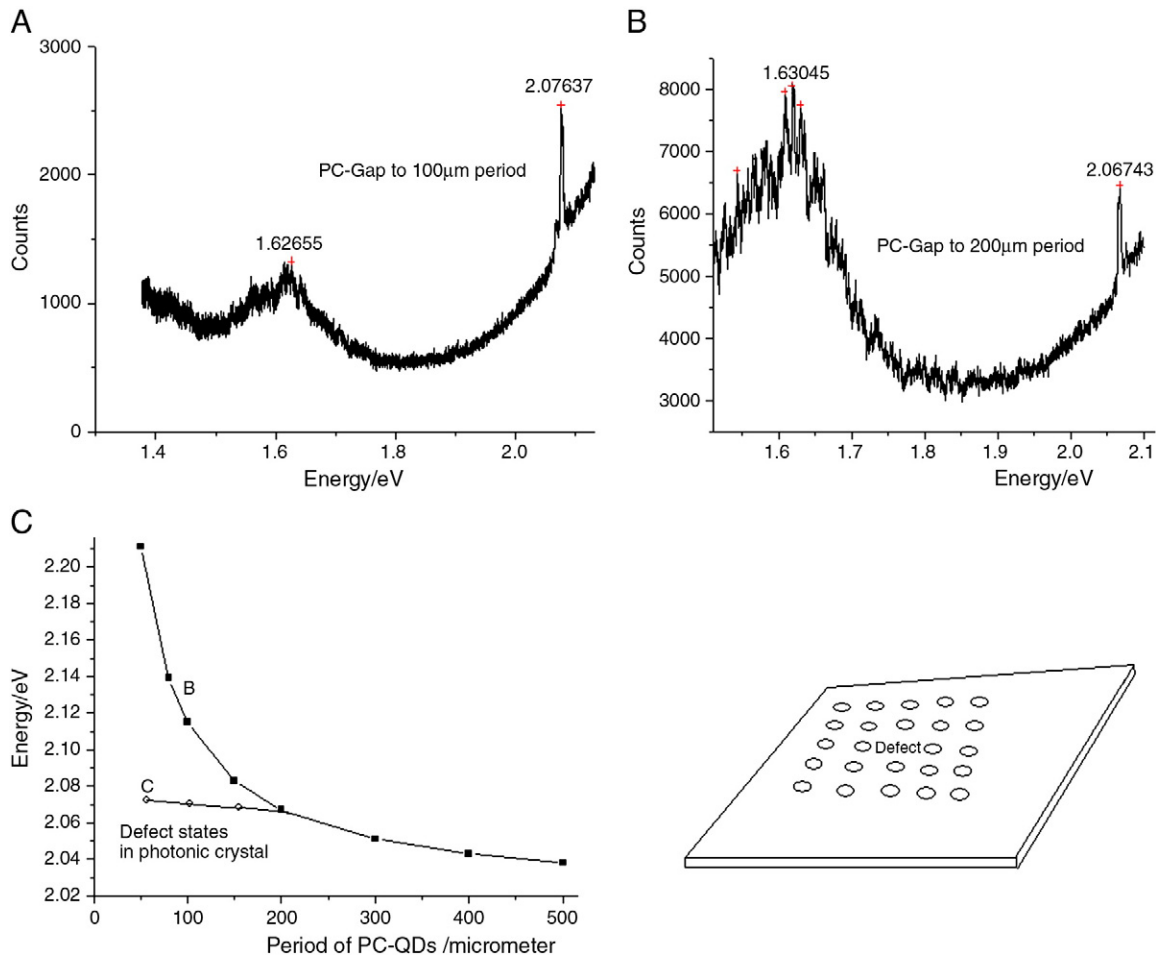
Fig. 4. Two photonic bands related to period of 100 μm (A) and 200 μm (B) in 2D photonic crystal in which we use a pumping laser with wavelength of 532 nm and power of 20 mW; the defect states in photonic crystal are shown (C).

non-relativistic quantum mechanical analysis. The DFT calculation was carried out by using the local density approximation (LDA) and non-local gradient-corrected exchange-correlation functional (GGA) for the self-consistent total energy calculation. It is considered that both LDA and GGA underestimate the band gap for semiconductors and insulators. A four-level system of nano-laser can be constructed which involves the localized states from electrons of p-state mainly in band gap opened, respectively at the levels below the conduction band and up the valence band.

It is found that the effect of annealing is very important to improve the stimulated emission where the QD sizes concentrate at about 2 nm to form a pumping level of about 2.30 eV and electron tunnel to go into the active level of about 2.03 eV to form the inverse population. The peak of the stimulated emission is sharper after annealing for 20 min than that for 10 min.

The two-dimensional photonic crystal with an array of Purcell cavity can select some modes and enhance its emission by coupling regime of cavity quantum electrodynamics and coupling band of photonic crystal. Figure(a) and (b) show the construction of photonic band with period of 100 μm and 200 μm in 2D photonic crystal. It is very important that the photonic states due to the defect of photonic crystal localize at the position of 2.06–2.08 eV in gap of photonic band as shown in Fig. 4(c).

The photonic localized states are near the electronic localized state of 2.03 eV at which the coupling between them occurs. In contrast with it the peak of stimulated emission at 1.78 eV in gap middle of photonic band is uncoupled to disappear at all which is far from the electronic localized state of 2.03 eV. Generally speaking, the

calculation indicates that a large blue-shift of beam takes place with decreasing period of the perfect 2D photonic crystal which is agreement with B curve in Fig. 4(c). But it is interesting that less blue-shift of beam occurs under coupling of the 2D photonic crystal with defect when the period of 2D photonic crystal decreases from 200 μm to 100 μm which can be described in C curve of Fig. 4(c). After taking a comparison between the localized electronic states in band gap due to no having good passivation on QD surface and the localized photonic states in photonic band gap due to defect of photonic crystal, we could understand their coupling deeply. Here, we can remark a Si QD with its size and passivation bond of surface as the single QD. Then the emission of the single QD can be selected by coupling of the localized photonic states to it with adjusting defect of photonic crystal.

In the physical process of nano-laser, several new effects are important: (1) the active centers with different emitting wavelength can be obtained by different surface bonds on smaller QD; (2) the electrons pumped can tunnel out smaller QD into the localized trap states to form population inversion; (3) by controlling plasma formed by pulse laser and suitable annealing, we can decrease the range of QD sizes and the defect to improve the stimulated emission; (4) the blue-shift of the localized photonic states from the photonic defects is much less than that of the photonic states from the perfect photonic crystal with decreasing period of photonic crystal; (5) generally speaking, by coupling both the localized electronic states due to surface bonds and the localized photonic states due to defect of 2D photonic crystal, we can select emission modes and enhance beam of nano-laser.

Taken together, we discussed the mechanism of a nano-laser including several main components: quantum dots on all-silicon, active centers due to surface bonds and 2D photonic crystal with an array of Purcell micro-cavity. We fabricated the main structures of nano-laser by using a nanosecond pulse laser. It is very important that evidences of the coupling between the electronic trapped states of surface bonds and the photonic localized states due to the defect of 2D photonic crystal in nano-laser were clearly observed on samples. On other hand, this kind of the coupling has a switch effect to emission of an active center in single quantum dot remarked by its size and its localized state which is available to the quantum communication, the quantum information process and the quantum computing scheme in future.

We hope the report will help generate broad interest.

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