High-Q states in the emission spectra of linear periodic chains of Si nanodisks with embedded GeSi quantum dots

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In this work the luminescent properties of structures with linear periodic chains of Si nanodisks with embedded GeSi quantum dots were studied. It was found that the formation of linear chains of resonators leads to a change in the intensity and directivity of quantum dots emission. Narrow high-Q peaks that are associated with collective modes in linear chains appear in the spectrum. A theoretical analysis of the dependence of the mode quality factor on the parameters of linear chains has shown that, under certain parameters, states that are close in nature to symmetry-protected bound states in the continuum can be realized.

Keywords: luminescence, quantum dots, silicon, germanium, nanodisks, linear chains, collective modes.

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1. Introduction

Today there are a lot of finding indicating that modification of the optical properties of materials using various types of micro- and resonators can be successfully applied to create efficient sources of photonic radiation [1,2]. Among the promising options are the structures with arrays of ordered sub-wavelength dielectric particles that support collective Mie resonances, allowing effective control of the interaction of light with matter [3,4]. The amplification of the radiation intensity in such structures is achieved by increasing the probability of optical transitions when the emitters are placed at the maxima of the electric field inside the resonator (Purcell effect [5,6]). In this study, it was shown that linear periodic chains of Si nano-disks with embedded GeSi quantum dots (QDs) can be used to control the intensity and direction of QDs radiation.

2. Experimental methods

For fabrication of linear chains of disk resonators with embedded GeSi QDs the silicon-on-insulator (SOI) substrate with upper layer of Si 180 nm thick and sublayer SiO_2 3 μm thick was used. During the first stage a method of molecular-beam epitaxy was used at 500°C with a rate of 0.6 Å/s to grow a buffer layer of Si with a thickness of 110 nm. During the next stage at a temperature of 600°C 10 layers of GeSi QDs were grown interlaid with silicon layers 15 nm thick. Each QD layer was formed by deposition of 7 monolayers of Ge with a growth rate of 0.05 Å/s. At the final stage the structure was covered with a Si layer 15 nm thick. Si-spacers and upper layer were grown with a rate of 1 Å/s. Total thickness of the multilayer structure was 440 nm. At the second stage, linear periodic chains of disk resonators (Figure 1) of various geometry were formed using electron-beam lithography and plasma-chemical etching through a metal mask on the surface of the layer SiO_2. Diameter of resonators in various chains varied from 660 to 770 nm, and period — from 1 to 3 μm. The luminescence properties of structures were examined using the micro-photoluminescence (micro-PL) technique. The micro-PL signal was excited by a continuous-wave laser emitting at a wavelength of 532 nm. Laser emitted-radiation was focused into a $\sim 2\,\mu$m spot on the sample through Mitutoyo M Plan APO 50x objective (numerical aperture NA $= 0.42$). The excitation power was 5 mW: The spectra ofmicro-PL were measured with a resolution of 4 cm^{-1}. Measurements were made at temperature of 77 K. The

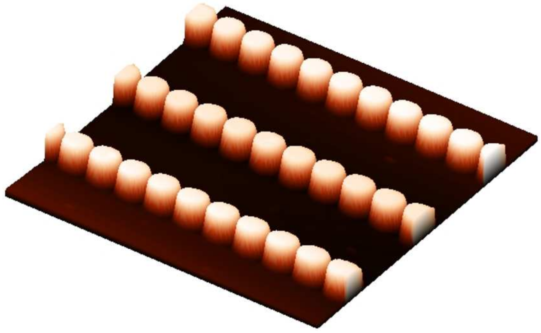

Figure 1. AFM-image of the surface structure with linear periodic chains of silicon disk resonators with embedded GeSi QD. Scan area was $10 \times 10\,\mu\text{m}^2$ in size. Diameter of disks — 770 nm, height — 440 nm, period — $1\,\mu$m, inter-chain distance — $3\,\mu$m. (A color version of the figure is provided in the online version of the paper).

distributions of the components of the near and far fields, as well as the dispersion dependences of the eigen modes, were numerically calculated using COMSOL Multiphysics software.

3. Results and discussion

The study by micro-PL method demonstrated that the formation of linear chains of Si-disks with embedded GeSi QDs results in modification of micro-PL spectra compared to the initial, non-treated area of the structure. The most significant changes were observed for chains with a period of $1\,\mu$m and a disk diameter of 770 nm. In this case, in PL spectra there were observed two narrow peaks at ≈ 827 and ≈ 849 meV (Figure 2). While at transitions of $\geq 2\,\mu$m, there were observed wide PL peaks with positions of maxima independent from the disk diameter. It was found that narrow peaks are present in the PL spectra even for very short chains, for example, with the number of disk resonators in the chain $N = 2$. With the increase of N these peaks become narrower and more intense. With maximal length of chain ($N = 51$) the Q-factor of peaks was $Q \approx 190$ (peak at 827 meV) and $Q \approx 340$ (peak at 849 meV). These values were obtained based on the approximation of the micro-PL spectrum by a set of Lorentz functions (Figure 2). In order to understand the nature of the observed narrow peaks, the electric fields and dispersion dependences of eigen modes for model structures corresponding to experimental ones were analyzed. The modeling demonstrated that for a single resonator 770 nm in diameter in 790–870 meV region there exists a double-degenerated high-Q mode with an azimuthal number $m = 3$ (magnetic octupole). At $N = 2$ already the degeneracy of this mode is removed and two collective modes are formed with different direction of electrical field relative to the chain line. One of the modes, with a larger amplitude of the electric field in the gap between the disks, shifts down the energy scale, and the other moves up. Further, we will call the first mode with a predominant propagation of the electric field along the chain — „longitudinal“ (see the upper box in Figure 3), and the second mode with the predominant propagation of the electric field across the chain — „transverse“ (see the lower insert in Figure 3). According to calculation, for a infinite length chain the „longitudinal“ mode had an energy of ≈ 827 meV, while the energy level of the „transverse“ mode was ≈ 847 meV, which is quite consistent with position of two narrow peaks observed in the spectra micro-PL (Figure 2). It was found that the Q-factor of the „transverse“ mode increases with the growth of chain length, while the Q-factor of the „longitudinal“ mode tends to stabilize at 200 after initial growth. For the „transverse“ mode the rated Q-factor reaches ~ 2900 at $N = 51$.

For an infinite chain of disk resonators, the theoretical values of Q-factor were calculated for the „longitudinal“ (Figure 3, curve *1*) and „transverse“ (Figure 3, curve *2*) collective modes depending on the wave numbers $k_x a/\pi$, where k_x — projection of the wave vector onto the axis x directed along the chain and passing through the centers of the disks at their half-height, a — chain period. It follows from the obtained dependencies that the „transverse“ mode behaves like a symmetrically protected bound state in the continuum (BIC) [7], since the Q-factor of this mode reaches its maximum ($\sim 10^4$) at zero value of the wave vector ($k_x = 0$). Whereas the „longitudinal“ mode turned out to be similar to another type of BIC, namely the parametric BIC [8], because Q-factor of this mode reaches its maximum at a non-zero value of the wave vector. However, it should be noted that these collective modes cannot be fully attributed to BIC, since they, even in the

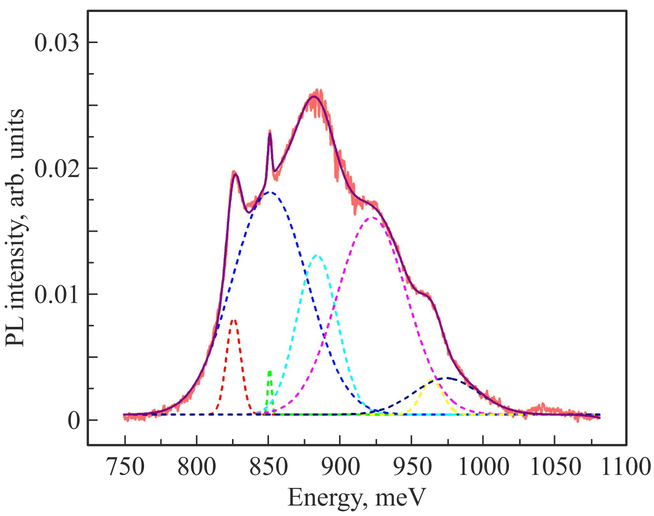

Figure 2. micro-PL spectra measured at 77 K on a sample with linear chains of disk resonators with embedded GeSi QD in them. Diameter of disks — 770 nm and period — $1\,\mu$m, number of disks in the chain $N = 51$. The dotted lines show the approximation of the micro-PL spectrum by a set of Lorentz functions, which were used to determine the experimental values of the Q-factor of the observed PL peaks.

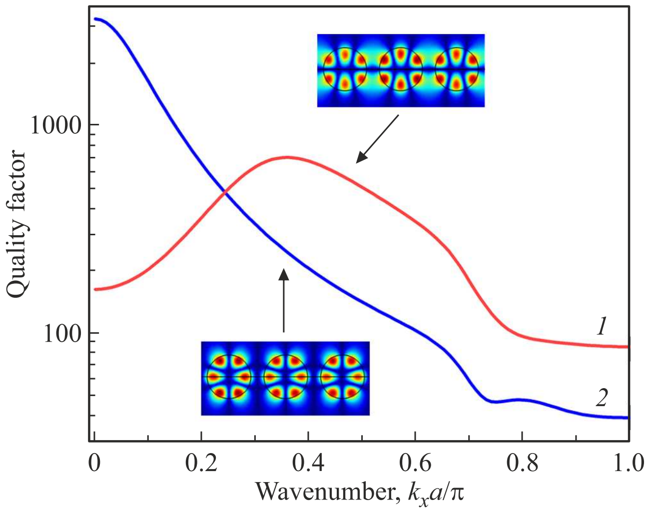

Figure 3. Q-factor versus wavevector k_x (along the chain line) calculated for „longitudinal“ mode (curve *1*) and „transverse“ mode (curve *2*) for a infinite Si-nano-disk chain. The radius of disks was 385 nm, period — 1 μm. Calculations were carried out without taking into account the substrate, and the refractive index of the environment was assumed to be 1. Refractive index and extinction coefficient of Si were taken according to paper [9]. The upper insert of the figure shows the characteristic distribution of the electric field for the „longitudinal“ collective mode, the lower insert — for the „transverse“ mode.

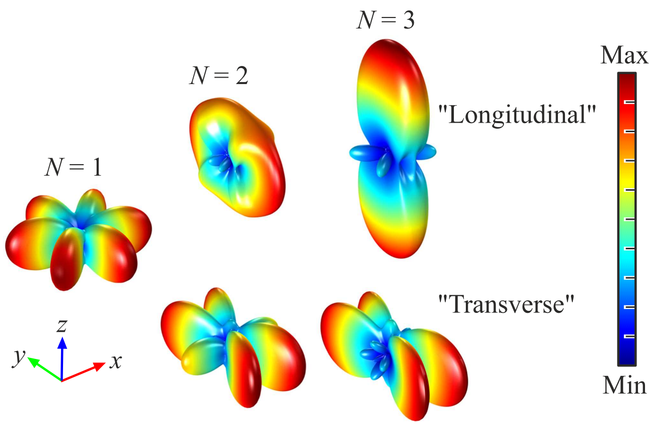

Figure 4. Distribution of radiation into long-range field for a chain of two ($N = 2$) and three ($N = 3$) disks. The paintings in the upper part of the figure correspond to the „longitudinal“ collective fashion, in the lower part of the figure — „transverse“ fashion. The distribution with $N = 1$ corresponds to the case of a single isolated disk (main mode — magnetic octupole).

absence of medium losses, have a large but finite Q-factor in special points. By varying the parameters of the resonator chains, it was found that the Q-factor value can increase by several orders of magnitude compared to the experimental ones. In particular for a disk with diameter of 632 nm and period of 804 nm the value of Q-factor may reach $\sim 10^7$. It should be noted that in this case, the collective mode in an infinite chain is close in field configuration to the magnetic quadrupole ($m = 2$).

The change in the pattern of radiation in the long-range field with an increase in the length of the chain is a theoretical study finding that is worth noting. For both modes, it was found that the fraction of radiation directed upwards (normal to the surface of the structure) increases markedly with an increase of N (Figure 4). Whereas for $N = 1$ there is practically no upward radiation, which is consistent with the results of measurements using the micro-PL method.

4. Conclusion

The results obtained demonstrated that linear periodic chains of disk resonators with integrated GeSi QDs can be used to control the intensity and directivity of the QDs radiation. Theoretical analysis has shown that under certain parameters of the structure, high quality states can be implemented, which are close in nature to symmetrically protected bound states in the continuum.

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Conflict of interest

The authors declare that they have no conflict of interest.

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