Light emission from Ge quantum dots in silicon microcavities

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Self-assembled quantum dots embedded in microcavities show strong room-temperature photoluminescence.

Silicon (Si) is the dominant material of the integrated circuit (IC) industry. Consistent with Moore’s law, Si transistors continue to become smaller and smaller, seriously testing fabrication technology. Moreover, the performance of traditional transistors is expected to reach theoretical limits in the near future. In addressing these challenges, scientists have made numerous efforts to extend the Si platform. Integrating photonic and electronic circuits on Si is one solution, since light provides higher bandwidth and flexibility than electronics alone. Diverse photonic devices have been reported for possible use in Si-based optoelectronic integrated circuits (Si-OEICs).

Among these alternatives, Si-based light-emitting devices are critical for Si-OEICs. Unfortunately, Si has an indirect bandgap, which leads to very low light-emission efficiency. Silicon nanocrystals, erbium-doped Si, and dislocation engineering represent just some of the approaches to improving efficiency based on quantum effects. But most proposals are hampered by problems of instability, high current injection, and incompatibility with standard IC technology. We have developed a promising Si-based light-emitting device that uses self-assembled germanium (Ge) quantum dots in Si microcavities as the active medium.

These quantum dots are attractive due to their ease of fabrication, full compatibility with current IC technology, and potential as light sources around 1.5 μm. Their drawbacks include poor spectral purity and low luminescence yield at room temperature. In principle, optical microcavity resonators can solve these problems.

At the resonant wavelengths of optical microcavities, the spontaneous emission rate is significantly enhanced by modifying the distribution of the electromagnetic field. Compared with other designs, these structures offer advantages such as wavelength selectivity, better directionality, and enhanced optical yield. In our research, we boost the light emission from self-assembled Ge quantum dots by embedding them in two-dimensional photonic crystal (PhC) microcavities.

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The devices were made using standard fabrication techniques. First, three layers of the quantum dots were grown on Si-on-insulator (SOI) wafers in Stranski-Krastanov mode using gas-source molecular-beam epitaxy at 600°C. Electron-beam lithography, reactive-ion etching, and wet etching were used to pattern optical microcavity structures.

Figure 1 shows schematically the two-dimensional PhC microcavity, with Ge dots as internal light sources. Figure 2 shows a scanning electron microscope image of a triangular microcavity designated T6. The cavity was formed by removing the center air holes from a hexagonal PhC lattice whose optical bandgap of the PhC was designed to cover the 1.3–1.6µm emission range of the Ge dots.

These devices were characterized at room temperature using confocal microscope photoluminescence (µPL). The vertically incident 514.5nm argon-ion pump laser was focused into a 1µm spot by an objective lens. The µPL signal was collected by the same lens and detected by a liquid-nitrogen-cooled indium-gallium-arsenide detector array.

Figure 3. The room-temperature microscope photoluminescence (µPL) of Ge quantum dots shows strongly enhanced peaks at the T6 microcavity (blue) compared to a PhC-pattern-free region (red). The lattice constant of the PhC, a, is 460nm and the diameter, 2r, of the air holes is 322nm. Representative quality factors (Q) are indicated. The wavelengths of peaks P1 and P2 are plotted in Figure 4.

Figure 4. Dependence of the resonant peak wavelengths, denoted P1 and P2 in Figure 3, on the lattice constant of the photonic crystal.

Figure 3 shows the room-temperature µPL spectrum of the PhC cavity. Strong light emission is observed in the range from 1.3 to 1.6µm. No signal is observed in a pattern-free region under the same conditions, which indicates that optical resonance in the cavity causes significantly increased photoluminescence. Multiple, sharp peaks dominate the luminescence spectrum, while no obvious off-resonant luminescence is observed. The quality factors (Q) of these resonant peaks are in the range of 300–600. We also investigated how the luminescence wavelengths vary as the PhC lattice constant increases (see Figure 4). The plot shows the wavelengths of the peaks denoted P1 and P2 in Figure 3. Tuning the lattice constant of the structure is thus one possible way to control the emission wavelength.

Silicon-based light-emitting devices are highly desired for Si-OEICs to make the Si platform more powerful. Embedding self-assembled Ge quantum dots in optical microcavities is a promising direction that is fully compatible with the IC industry. Our results show that strong room-temperature photoluminescence with controlled wavelength is obtainable from such structures. The next step in our research is to develop current-injected Si-based Ge-dot microcavity light emitters with single-wavelength output at 1.5µm, which is closer to practical applications.
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References