

論文の内容の要旨

Study on quantum-dot single-photon sources
hybrid integrated on optical circuits

(光回路上にハイブリッド集積された
量子ドット単一光子源に関する研究)

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Single photons are very promising candidates of carriers for quantum information processing. A powerful approach for future scalable quantum photonic devices is integrated quantum photonics by leveraging the strength of mature modern photonic integrated circuits (PICs) technologies. For future quantum applications based on single photons, however, it is vital to introduce single-photon sources (SPSs) which are able to deterministically operate with pure and indistinguishable single-photon generation. Among the various SPSs, the use of semiconductor quantum dots (QDs) is highly promising because they have been shown to fulfill these stringent requirements imposed on SPSs. In this context, the development of QD-based SPSs on PICs is attractive for constructing large-scale integrated quantum optical circuits. Several techniques have been developed for the hybrid integration of QD SPSs onto PICs based on various material platforms, including silicon photonics, and silicon nitride photonics.

However, there remain lots of challenges in the hybrid integrated QD SPSs. One of the most significant issues is the low coupling efficiency of single photons into the photonic waveguide. Toward the scalable operation of quantum optical circuits, it is essential to realize highly efficient coupling of single photons into the optical circuits. Efficient use of waveguide-coupled single photons is also crucial. In addition, the efficient interface of integrated quantum optical circuits with optical fibers is of great importance to realize fiber-based long-distance quantum photonic networks.

Another significant issue is the compatibility of hybrid integration technology with current mature PIC platforms. Particularly, silicon photonics is a powerful platform for large-scale PICs using advanced complementary-metal-oxide-semiconductor (CMOS) technology. Silicon photonics also provides various well-developed nanophotonic elements that allow us to construct highly functional and robust integrated quantum optical circuits. However, the hybrid integration of QDs is inherently difficult and often lacks compatibility with current CMOS technology.

Spectral and spatial randomness inherent in QDs is also the challenge. For the practical quantum applications, the integration of multiple identical SPSs is important to perform two-photon interference using them on chip. However, the QD's random emission property hinders the implementation of desirable QD SPSs on preferred locations of a PIC.

To overcome these major challenges in QD SPSs, this thesis presents original research works on QD SPSs hybrid integrated on optical circuits toward scalable and advanced integrated quantum photonics. To solve the issues mentioned above, a deep investigation of transfer printing technology has been done. This technique is based on the pick-and-place manner using an adhesive and transparent rubber stamp.

Firstly, the theoretical work for an efficient QD SPS structure is presented. Since transfer printing allows the individual fabrication of each optical component, it is possible to design on-chip SPS structure flexibly. The numerical simulations show that our SPS structure's design enables the coupling of single-photon emission from QDs into the waveguide over 99%. Notably, this near-unity efficiency can be maintained even under the position misalignment of transfer printing or even under the material change.

Secondly, the hybrid integration technique based on transfer printing is presented. To perform hybrid integration of QD SPSs with high position accuracy at high yield, lots of efforts are paid to develop transfer printing technology. Experimentally, the device exhibits efficient coupling of single photons with coupling efficiency over 70%. Our transfer printing approach further makes it possible to integrate two SPSs into a single photonic waveguide. Details of the nanofabrication technique required for this whole study are also introduced.

Thirdly, hybrid integration of a QD SPS on a silicon PIC processed by a CMOS foundry is studied. Since the integration of photonic devices is based on van der Waals adhesion, transfer printing enables us to assemble QD SPSs after the completion of the entire CMOS process. To unveil a method to integrate QD SPSs on a silicon CMOS chip, QD SPSs are transfer-printed onto a dry-etched glass surface of a CMOS chip. It is confirmed that integrated QDs are cooled down even on a

foundry-processed silicon chip. Intensity correlation measurement also verifies single-photon generation from an integrated QD on silicon with $g^{(2)}(0) = 0.30$. Its efficient waveguiding in the CMOS-processed photonic chip with the coupling efficiency of $\sim 70\%$ is also confirmed in experiment.

Fourthly, in-situ fine wavelength tuning of QD SPSs on a CMOS-processed silicon PIC is demonstrated. Optically-driven heater pads are utilized to tune the emission wavelengths of integrated QDs thermally. Transfer printing enables us to integrate these functional components as well as QD SPSs in a simple pick-and-place manner. The obtained maximum possible tuning range of QD emission wavelength is 0.9 nm. Furthermore, this approach is leveraged for the spectral matching of two dissimilar integrated QD sources on the same silicon CMOS chip, which is a significant step toward on-chip two-photon interference with dissimilar QD-based SPSs.

Fifthly, the efficient output of QD SPSs hybrid integrated on a silicon waveguide terminated with a PhC mirror is examined. The numerical calculation reveals that our designed SPS structure can support the QD-to-waveguide coupling efficiency over 99% with unidirectional output. By employing a subwavelength grating structure as a waveguide, the SPS structure can maintain near-unity output efficiency in the waveguide, even considering the finite positioning accuracy accompanied by transfer printing. Experimentally, the overall output efficiency of the QD emission in the waveguide is estimated to be $\sim 74\%$. Observation of single-photon generation from an integrated QD is also performed with $g^{(2)}[0]$ value of 0.28.

Sixthly, fiber-pigtailed QD SPSs hybrid integrated on a silicon CMOS chip is presented. To achieve the efficient fiber output of single photons, a telecom QD SPS is integrated on a fiber-pigtailed silicon CMOS chip using transfer printing, which enables us to take full advantage of mature silicon photonics components. Observation of Purcell-enhanced QD emission through the optical fiber is demonstrated with the single-photon generation in the fabricated device. Fabrication technique of InP-based photonic crystal nanobeam cavities is also introduced.

Finally, the conclusion of this thesis is presented. An outlook for prospects is also discussed.