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# Hybrid integration of quantum/classical light sources on Si using transfer printing

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**Abstract**

**We discuss a novel approach for hybrid integration of various photonic elements on silicon photonics platforms. We employ transfer printing, which is based on a pick-and-place assembly technique and enables the transfer of structured photonic elements on silicon with high positioning accuracy. With this method, we realized quantum dot nanolasers and single-photon sources integrated on CMOS-processed silicon photonics chips.**

## 1. Introduction

Silicon photonics has been a landmark of photonic integration toward low-cost, highly-functional photonic circuits [1]. While silicon photonics leverages the power of large-scale monolithic integration using complementary metal-oxide semiconductor (CMOS) technology, this integration approach itself sometimes limits the capability of the circuits. A major limitation arises from poor accessibility to diverse materials which may not be compatible with CMOS processes, despite the fact that silicon as material can only provide limited performances and functionalities for photonic elements. Furthermore, the introduction of a new material with conventional hybrid integration techniques may require large modifications in the matured CMOS process flow, which will pose a huge burden on CMOS manufacturers.

In this context, hybrid integration methods that do not violate well-established CMOS processes could become imperative. Among such approaches [2], we have been investigating transfer printing [3,4]. This technique is based on a pick-and-place assembly operation using a transparent rubber stamp manipulated under an optical microscope. Material coupons or structured photonic elements can be transferred on a completed photonic circuits, hence allowing for avoiding altering the flow of silicon chip fabrication. The adhesion of the transferred structure on the circuit is mediated by van der Waals force, thus making the technique compatible with various materials. The positioning accuracy of printed elements has been demonstrated to be superior than a few μm for massive parallel transfer [5]. The value can be improved to be better than 100 nm when locating a single element [4], which is sufficient for faithfully integrating some kinds of photonic elements.

In this correspondence, we discuss our recent progress on the application of transfer printing, in particular for the integration of quantum/classical light sources on silicon. We demonstrate an InAs/GaAs quantum dot (QD) single photon source integrated on a CMOS-processed photonic waveguide [6]. Our approach provides further advantages for the integration of such solid quantum elements, which inherently possess randomness in their properties, despite the fact that dominant quantum protocols require the integration of exactly-identical elements. Meanwhile, with pre-characterization, transfer printing enables selective assembly of quantum elements with desired properties on desired positions of the circuits, providing a path for overcoming the randomness issue. The separation of fabrication processes for silicon and quantum elements is highly helpful for realizing highest-quality sample fabrication, which is required for quantum photonic circuit applications. We also demonstrate on-silicon quantum dot nanolasers [7], which constitutes the first quantum dot nanolaser integrated on a CMOS processed silicon chip. The technique can be applied to larger-size QD lasers for higher power output. We believe that the transfer-printing-based approach will enable agile development of various material-hybridized photonic chips, and will eventually allow for the hybrid integration of arbitrary materials on silicon photonics platforms.

## 2. Transfer process and experimental results

Figure 1 shows the flow of transfer printing process for integrating an InAs/GaAs QD single photon source on a CMOS-processed silicon chip. First, we prepare airbridge QD sources on a GaAs chip using standard nanofabrication techniques. The QDs are enclosed in photonic crystal nanobeam cavities, which facilitate efficient coupling of QD emission into the underlying silicon waveguide. In the meantime, we obtain silicon chips from a CMOS process foundry, which fabricates the optical circuits as we designed. The silicon waveguide is covered by a silica clad, the thickness of which is important to control the QD-waveguide coupling. Then, we pick-up a QD source by attaching and quickly laminating a soft stamp off. Subsequently, the lifted source is placed on the target silicon waveguide and released by slowly peeling the stamp off. The transfer processes are manipulated under optical microscope and can achieve position accuracy better than 100 nm with our home-made apparatus.

Figure 2(a) shows a fabricated sample based on the procedure described above. We examined optical properties of the device using low-temperature microphotoluminescence spectroscopy (μPL). Figure 2(b) shows a measured PL spectrum radiated from an output grating port under 808-nm laser pumping of the QD. We observed a sharp QD emission peak

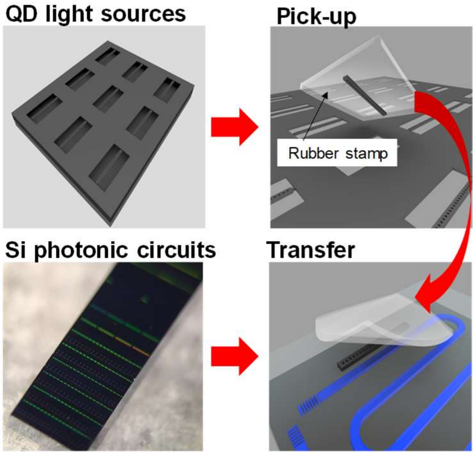

Fig. 1. Investigated transfer printing method

together with a cavity emission peak, verifying the optical coupling of QD radiation into the waveguide. Based on time resolved PL measurements and measured Q factors, we estimated the coupling efficiency of 70% of the QD radiation into the waveguide (not shown). Finally, we investigated quantum correlation of the QD radiation using a Hanbury-Brown-Twiss interferometer, as plotted in Fig. 2(c). We confirmed an anti-bunching with a time zero value of the second order coherence function of $g^{(2)}(0) = 0.3$, demonstration single photon generation on chip. Using a similar platform but with an increased cavity Q factor, we have also succeeded in QD-cavity QED experiments on a silicon photonic circuit [8].

Next, we applied the technique to integrating QD nanolasers on a CMOS-processed chip [7]. Figure 3(a) shows a fabricated structure. We evaluated the emission from the nanobeam cavity again using μPL experiments. Figure 3(b) shows measured PL intensities and spectral linewidths of the cavity signal as a function of pump power. A nonlinear intensity rise with a threshold, together with a concomitant linewidth narrowing, is clearly observed, elucidating lasing from the structure. Figure 3(c) shows a PL spectrum above the threshold measured at an output port, showing predominant cavity contribution. These results demonstrate the integrated QD nanolaser on silicon using transfer printing.

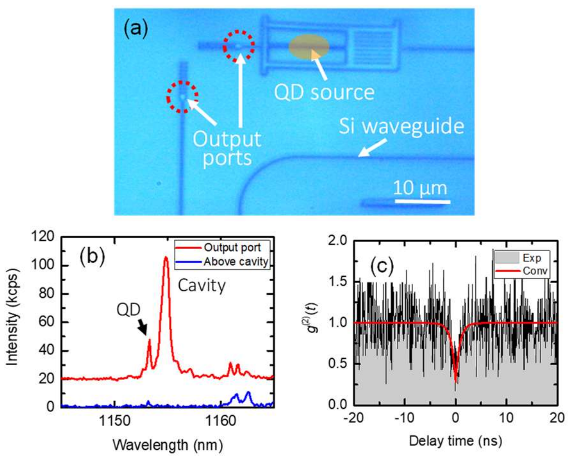

Fig. 2. Fabricated QD single photon source on silicon

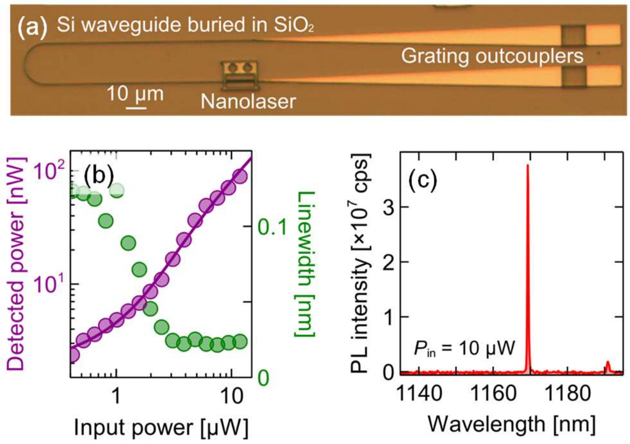

Fig. 3. Fabricated QD single photon source on silicon

## 3. Conclusions

We discuss a transfer printing technique as a powerful mean to perform hybrid integration on silicon photonics circuits. With this approach, we demonstrated the integration of an InAs/GaAs QD single photon source on a CMOS-processed photonic chip. We also applied the technique to integrating QD nanolasers on silicon in a similar manner. We foresee huge potential of this approach as a promoter of material-unlimited hybrid integration in silicon photonics and in other fields of nanophotonics as well.


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