

Integrating Nearly-Indistinguishable Quantum Emitters onto a Photonic Interposer

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Abstract: Current challenges for quantum repeaters using solid-state emitters include incorporating (1) multiple nearly-indistinguishable emitters (2) into an interposer with photonic processing capabilities. We develop a process flow that targets both of these tasks. © 2023 The Author(s)

1. Introduction

Quantum repeaters that feature solid-state defects as quantum memories [1, 2] are an important component of memory-based quantum networking. These devices can store and swap entanglement among quantum bits to circumvent lossy transmission of quantum signals through optical fibers as well as synchronous limits on linear optics-based quantum networking [3]. However, state-of-the-art implementations of defect-based network nodes—which feature single nanophotonic crystals coupled to adiabatically tapered fiber—face scaling difficulties in incorporating multiple emitters at a single node. This leads to two central challenges for future iterations on solid-state defect-based quantum repeaters: (C1) incorporating multiple nearly-indistinguishable quantum emitters at a single quantum network node and (C2) coupling and multiplexing these emitters to single-mode fiber. Indistinguishability in the emission frequency of emitters is necessary for many protocols for generating quantum entanglement. The qualifier of ‘nearly’ refers to targeting emission frequencies which are sufficiently close to fine tune via active methods, such as Stark tuning, strain tuning, or electrooptic frequency shifting. The criterion C2 is a critical for scaling systems to large numbers of qubits, especially in cases with cryostats without free-space access.

Here, we present an architecture for heterogeneous integration of pre-selected nearly-indistinguishable quantum emitters in a quantum microchiplet (QMC) onto a photonic integrated circuit (PIC). First, we characterize individual microchiplets with implanted tin-vacancy (SnV^-) centers by measuring emitter frequencies across the SnV^- inhomogeneous distribution, with the goal of finding candidate emitters within a target ~ 5 GHz range across microchiplet channels. Then, we demonstrate a pick-and-stamp transfer technique to transfer these QMCs with high reliability. Following the transfer process, we re-characterize the inhomogeneous distribution to post-select quantum emitters in different channels that remain within a ~ 5 GHz range of each other. The pick-and-stamp process with pre- and post-transfer characterization of quantum emitters addresses C2 and C1, respectively. This demonstration represents a repeatable, scalable, high-success-rate process flow that can be used for picking-and-stamping hybrid quantum sources onto photonic interposers.

2. Pre- & Post- Characterization

The process flow of emitter integration begins with pre-characterization of QMCs fabricated in bulk electronic-grade (EG) diamond from Element Six implanted by Innovion with tin ions and annealed to form SnV^- centers. Fabrication of QMCs follows the protocol detailed in [4]. Characterization of emitters is completed using wide-field photoluminescence excitation (PLE) [5] of SnV^- centers in the QMC in 30 GHz increments across the inhomogeneous distribution in a Montana cryostat at 4.3 K.

Following the pick-and-stamp process, the transferred QMC is re-characterized at 4.3 K to map pre-characterized emitters to post-characterized frequency locations. The post-characterization process allows us to deterministically track emitters from QMC fabrication until PIC integration to identify shifts in emitter frequency that may result from the transfer process, induced strain caused by the heterogeneous integration, or other phenomena.

3. Hybrid Pick & Stamp

We developed a hybrid pick-and-stamp technique to integrate QMCs into a PIC [6]. This procedure first utilizes a tungsten probe to break QMCs out of a bulk diamond chiplet, followed by placement of the QMC via the probe

onto a PDMS stamp (X-Celeprint). Finally, the stamp is used to transfer-print the QMC onto an interposer PIC by peeling the stamp off of the QMC in a shear motion. This PIC features a silicon nitride waveguide array, where alignment is accomplished by imaging through the transparent stamp. The PIC provides multi-channel optical access to the QMC, and is equipped with electrodes for tuning nearly-indistinguishable emitters onto resonance.

This hybrid approach combines the best features from both stamp-only and probe-only approaches. Stamping is simple and easy. Moreover, re-positioning of QMCs on a PIC can be easily accomplished by re-stamping the QMC. However, the fabrication process for the QMC results in an uneven and rough bottom surface, in contrast to the near-atomically-smooth top surface. A procedure involving only a single stamping step from parent diamond to PIC would result in the rough QMC side down, and insufficient contact between waveguide and QMC. Probe-only methods work well for breaking the QMC away from the parent diamond. However, these probe-based methods suffer from the challenge of manipulating, flipping, and aligning the QMC, to the point that the attrition rate is costly in terms of time required for additional pre-characterization and placement. In contrast, the hybrid approach is immediately compatible with placing the smooth side of the diamond onto the PIC waveguides without additional process complexity, and avoids the challenge of probe-based placement.

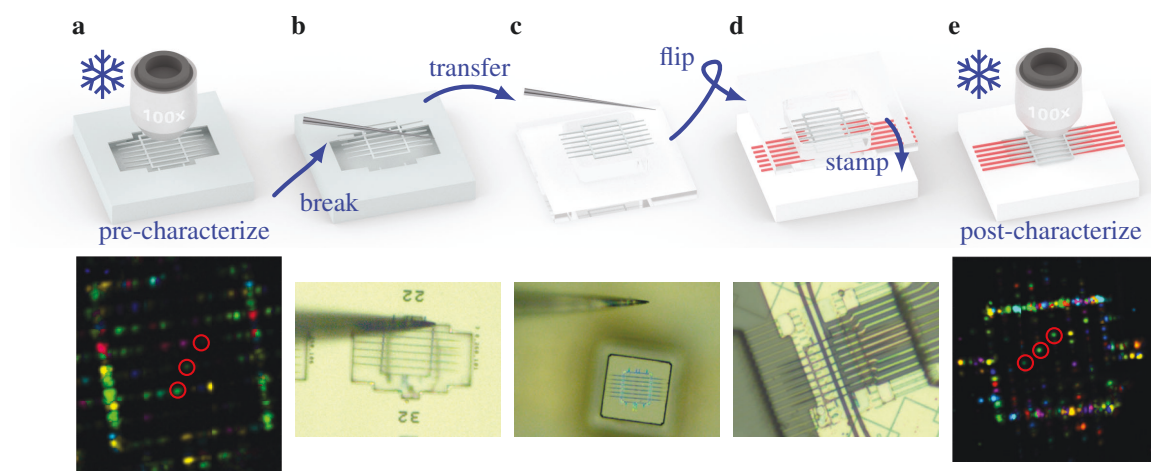


Fig. 1. **a** Cryogenic pre-characterization of emitters in widefield. The hue of the lower plot (also in **e**) corresponds to emitter frequency over a 30 GHz bandwidth, while the value corresponds to the measured intensity. **b** Desired devices are removed from the parent diamond via probe and **c** transferred to a stamp with minimal finesse or complexity required. **d** The QMC is transfer-printed by flipping the stamp onto the target PIC. **e** Cryogenic post-characterization of emitters after transfer. Three emitters within 20 GHz of each other are circled in the pre- and post-characterization plots.

4. Conclusion

We developed a high-success-rate process flow featuring pre- and post-characterization and an updated pick-and-stamp process targeting reliable integration of nearly-indistinguishable quantum emitters in a PIC interposer. This process flow and platform demonstrate strides toward a new generation of integrated quantum repeaters.

References

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