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Building blocks for quantum information processing with color centers in silicon

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Abstract: Color centers in silicon are leading qubits for scalable quantum information processing. We will discuss recent developments towards a technological platform including the formation of waveguide-integrated color centers, their spectral control, and on-chip single-photon detection. © 2025 The Author(s)

1. Main text

Color centers are atomic defects in a solid-state crystals characterized by absorption and emission of photons. For some color centers, this photon emission is coupled to a spin degree of freedom, resulting in a system that can be operated as a controllable and optically-interfaced spin qubit. Their long spin coherence with photon-mediated spin entanglement in the solid state makes color centers promising qubits for quantum communications, computing, and sensing [1].

A color center quantum information processor requires the combination of several optical and electrical components (Fig. 1a), including the color center qubits, optical switching and filtering, detection, and excitation lasers, all controlled via electronics and software. Recently, silicon has emerged as a promising material to build such a system. This is due to the recent demonstration of long spin coherence and optical emission in the telecom O-band from color centers in silicon [2], and the viable path towards scalability enabled by the already advanced silicon nanofabrication and optoelectronic integration.

Challenges to build a quantum information processor with color centers include 1) the integration of all required building blocks including waveguide-coupled color centers with spin control, optical switching, filtering, and single-photon detection with the rates and fidelities required by a given application; 2) the deterministic localized formation of color centers with high optical and spin coherence; 3) their coupling to high Q/V cavities to enhance light-matter interaction and compensate their below unity quantum efficiency; and 4) their spectral tuning to enable entanglement generation mediated by two-photon interference.

Here we describe some of our work tackling these challenges.

Challenge 1) is partially addressed by demonstrating single G-centers embedded in silicon photonic waveguides (Fig. 1b) [3], and via the hybrid integration of superconducting single-photon detectors onto foundry silicon photonics operating in the telecom O-band emission spectra of silicon G- and T-centers (Fig. 1d) [4].

For 2) and 3) we will discuss recent results that demonstrate color center generation on pre-fabricated nanophotonic cavities via laser annealing [5], as well as the demonstration of high Q/V cavity coupling of single G-centers [6].

We also demonstrate two avenues tackling 4) through in-waveguide spectral tuning of single G-centers via laser irradiation (Fig. 1c) [3] and microelectromechanically-induced strain [7].

These demonstrations show that silicon offers a viable path towards the integration of the key components required for quantum information processing with color centers.

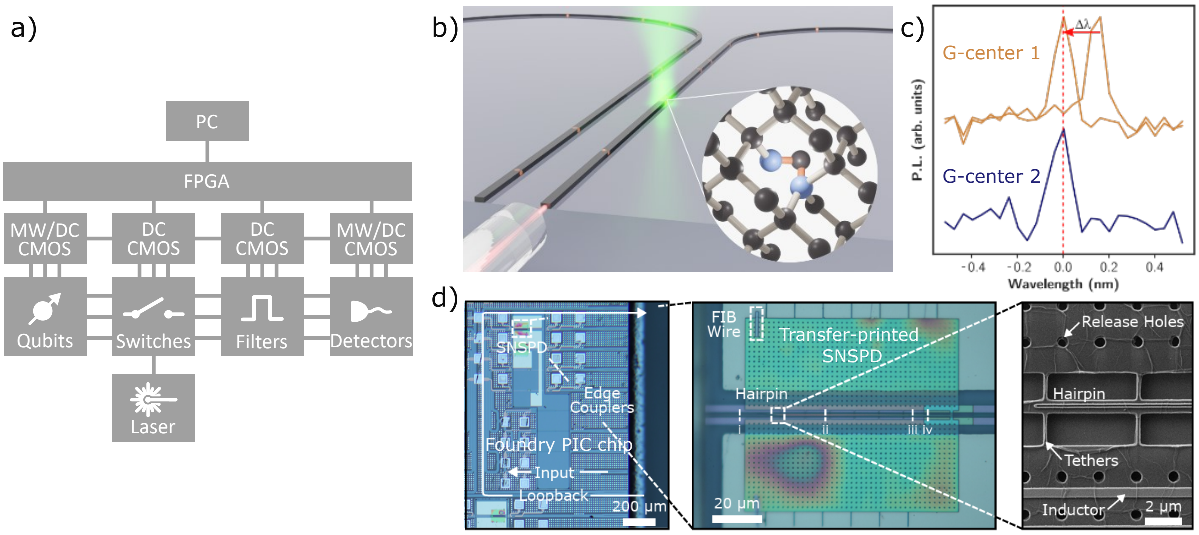

Fig. 1. a) Schematic showing the components required for a color center quantum information processor. b) Schematic showing waveguide-integrated G-centers [3]. c) Spectral tuning of individual G-centers along a silicon waveguide via laser irradiation [3], d) Hybrid-integrated superconducting single-photon detectors on a foundry silicon chip operating at the telecom O-band [4].

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