

# Efficiency Analysis of Electrically-Driven Silicon Color Centers for Photonic Integration

Nikki Ebadollahi<sup>1,2</sup>, Christian Pederson<sup>1,2</sup>, Saumya Choudhary<sup>1</sup>, Marcelo I. Davanco<sup>1</sup>, Pradeep N. Namboodiri<sup>1</sup>, Kartik A. Srinivasan<sup>1</sup>, Aaron M. Katzenmeyer<sup>1</sup>, Joshua M. Pomeroy<sup>1</sup>

<sup>1</sup>National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, Maryland 20899 USA

<sup>2</sup>University of Maryland (College Park), 4500 Campus Drive, College Park, Maryland 20742 USA  
nikki.ebadollahi@nist.gov

**Abstract:** By engineering silicon color center (CC) embedded p-i-n junctions, we achieve telecom-band electroluminescence and identify optimal device geometries. We aim to integrate CCs with photonic cavities toward efficient, electrically-driven single-photon sources for silicon-based spin-qubit readout.

## 1. Introduction

To bridge silicon electronics and photonics together and ultimately enable coupling to spin qubits in silicon, we integrate silicon p-i-n junctions with W- and G-type color centers, which emit in the telecom band with zero-phonon lines at 1218 nm [1] and 1279 nm [2], respectively. These silicon CCs are promising candidates for quantum light sources and for optical spin-to-charge conversion. Their Stark-tunable optical transitions enable electrically assisted qubit readout and, when integrated with photonic devices, can potentially support on-chip quantum information processing.

While our broader objective is optical spin readout, our present work focuses on achieving efficient single-photon emission from CC-LEDs (ie: CC-embedded p-i-n devices). By systematically varying CC-LED geometry, we identify parameter combinations that maximize electro-optic efficiency, defined as the ratio of CC optical output power to electrical input power. We report on results of this efficiency analysis, progress toward single-photon detection, and our strategy for integrating these CC-LEDs with photonic structures.

## 2. CC-LED Design and Efficiency

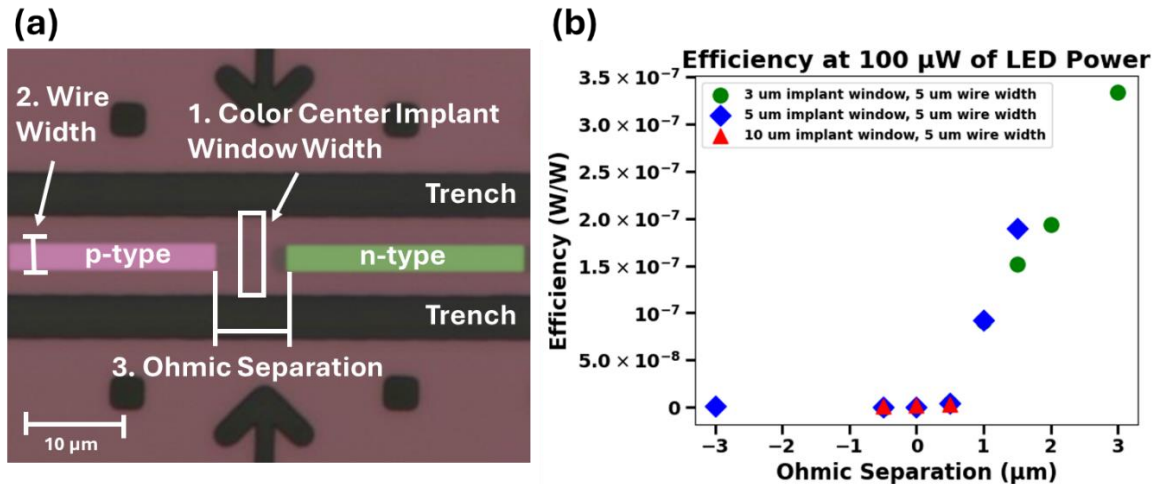


Fig 1. (a) Labeled micrograph of a CC-LED with the 3 varied design parameters. (b) The electro-optic efficiency for three CC-LEDs of different implant window widths and wire widths as a function of the Ohmic separation parameter.

Figure 1(a) illustrates a CC-embedded p-i-n device with the three geometric design parameters varied in this study: the width of the CC implantation window, the width of the Ohmic dopant wires, and the lateral separation between the p- and n-type wires. The CC-LEDs were cooled to 4 K in a cryocooler system. The CCs exhibit measurable emission below ~40 K [3]. Under applied bias, carrier recombination at the CCs generates photons, which are collected by an InGaAs photodiode positioned above the device. Utilizing the electrical current injected through the CC-LED and the emitted photocurrent, we calculate the electrical and optical powers, respectively. We then defined the electro-optic efficiency as the ratio of the collected optical power to the injected electrical power.

Upon comparing this efficiency for CC-LEDs of various geometric designs, we identify that the p–n wire separation produces the most significant variation in efficiency. As shown in Fig. 1(b), W-center CC-LEDs with larger p–n separations exhibit higher electro-optic efficiency. Identifying the most efficient CC-LED geometries provides a critical foundation for selecting prospects for optimal collection efficiencies upon integration with photonic structures for eventual spin qubit readout.

### 3. Spectroscopy and Photonics

Electrical excitation of the CC region can be evaluated both electrically—through photocurrent and electro-optic efficiency—and optically through spectroscopic measurements. Figure 2(a) presents a confocal scan taken with a 635 nm filter of a W-center CC-LED, revealing CC emission localized between the p- and n-type lead. While this confirms light generation, it does not identify its origin. Figure 2(b) shows the corresponding emission spectrum collected from the bright CC region, exhibiting the W-center zero-phonon line (ZPL) at 1218 nm and verifying CC-mediated emission.

Figure 2(c) displays one of our fabricated photonic crystal cavities, which guides light in the lateral direction and has compatible geometry with our CC p–i–n device fabrication process. This crystal cavity will improve the photon collection from our devices. These cavities will enable Purcell enhancement [6] and facilitate seamless integration of electrical, optical, and photonic functionalities in silicon—ultimately supporting coupling to quantum dots for spin readout.

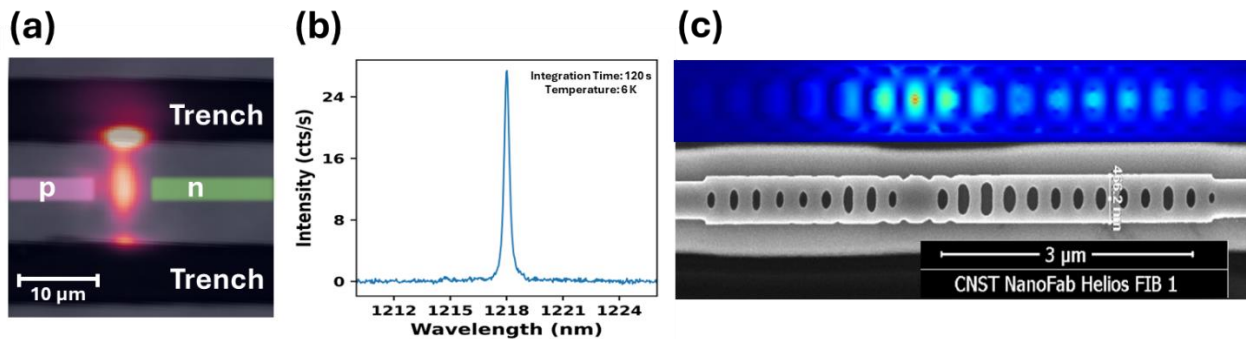


Fig 2. (a) Confocal image of the emission taken from the CC implanted region with a 635 nm filter overlaid on a micrograph of the CC-LED. (b) Intensity as a function of wavelength for a collection spot from a W-center CC-LED showing a ZPL at 1218 nm confirming successful electroluminescence. (c) SEM image of an inversely designed crystal cavity (bottom) and the intensity of the cavity mode field profile (top).

### 4. Conclusions

We demonstrate electrically driven telecom-band emission from W- and G-type silicon color centers and identify device geometries that exhibit higher electro-optic efficiency. Our spectroscopic analysis confirms CC-mediated emission, and the integration of these emitters with photonic crystal cavities is in progress and can provide a clear path toward Purcell-enhanced, on-chip single-photon sources. These results advance the development of electrically addressable silicon-based quantum light sources compatible with spin-readout architectures for quantum dots.

### 5. References

- [1] Buckley, S.M., Tait, A.N., Moody, G., *et al.* Optimization of photoluminescence from W centers in silicon-on-insulator. *Opt. Express* **28**, 16057-16072 (2020).
- [2] Durand, A., Baron, Y., Redjem, W. *et al.* Broad diversity of near-infrared single-photon emitters in silicon. *Phys. Rev. Lett.* **126**, 083602 (2021). <https://doi.org/10.1103/PhysRevLett.126.083602>
- [3] Baron, Y., Durand, A., Udvarhelyi, P., *et al.* Detection of Single W-Centers in Silicon. *ACS Photonics* **2022** 9 (7), 2337-2345 DOI: 10.1021/acsp Photonics.2c00336.
- [4] Brown, R., Twiss, R. Correlation between Photons in two Coherent Beams of Light. *Nature* **177**, 27–29 (1956). <https://doi.org/10.1038/177027a0>.
- [5] P. Michler, *et al.* A Quantum Dot Single-Photon Turnstile Device. *Science* **290**, 2282-2285 (2000). DOI: [10.1126/science.290.5500.2282](https://doi.org/10.1126/science.290.5500.2282)
- [6] Kizhake V.V., Song, J., Nambodiri, P.N., *et al.* Enhanced zero-phonon line emission from an ensemble of W centers in circular and bowtie Bragg grating cavities. *Nanophotonics*, 2024. <https://doi.org/10.1515/nanoph-2024-0485>