Optical studies of silicon color centers and CC-LEDs for consideration as telecom quantum light sources

Nikki Ebadollahi[1,2], Pradeep N. Namboodiri[1], Vijin V. Kizhake[1,3], Marcelo I. Davanco[1], Kartik A. Srinivasan[1], Aaron M. Katzenmeyer[1], Matthew Pelton[3], and Joshua M. Pomeroy[1]

[1]National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, Maryland 20899 USA
[2]University of Maryland (College Park), 4500 Campus Drive, College Park, Maryland 20742 USA
[3]University of Maryland (Baltimore County), 620 W Lexington Street, Baltimore, Maryland 21201 USA
nikki.ebadollahi@nist.gov

Abstract: We synthesized and studied color centers on silicon-on-insulator wafers with photoluminescence mapping and spectroscopy, and fabricated silicon W- and G- color center LEDs towards electrically-pumped single photon sources.

1. Introduction

Color centers (CCs) are point defects in silicon that were historically a bottleneck for the advancement of silicon-based microelectronics in the 1980s. Improvements in material processing eliminated them, but their optically emissive properties are now attractive for consideration as light sources in the telecommunications band [1]. Different chemical and structural configurations of CCs exist within silicon; here we focus on G-centers and W-centers. G-centers are complexes of two substitutional carbon atoms and an interstitial silicon atom, while W-centers are comprised of a vacancy and three silicon self-interstitials [2].

Photoluminescence (PL) of CCs uses a laser energy well above the silicon bandgap to excite electrons that radiatively recombine. G-center PL reveals a prominent zero-phonon line (ZPL) around 1269 nm [3], while W-centers emits at 1218 nm [4]. Compact integration of color centers into hybrid electronic-photonic systems motivates studying electroluminescence (EL), which eliminates the use of a laser and reduces the total amount of energy in the bath. P-I-N junctions in silicon can be used as light-emitting diodes (LEDs) and we have synthesized CCs in P-I-N junctions to facilitate CC EL, similar to prior work [5]. Here, we present our P-I-N devices as we work to drive CCs as on-chip light sources, which increases the efficiency and scalability of silicon-based optoelectronics.

2. Design and Fabrication

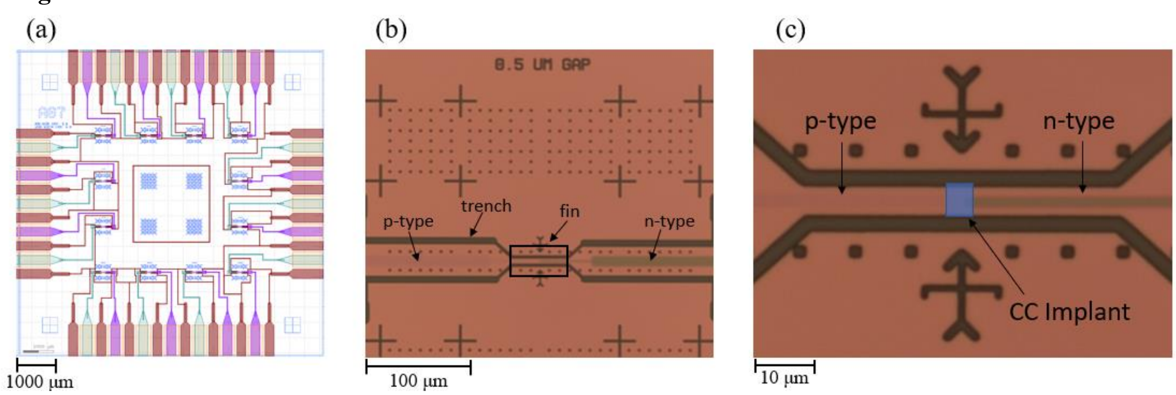

Fig 1. LEDs on silicon-on-insulator with CCs integrated. (a) Chip level view of a die with 12 p-i-n diodes composed of p-doped (red), n-doped (purple), and intrinsic regions isolated by trenches (green). (b) Optical image of the silicon fin with post-fabrication with p-type (left) and n-type (right) implants. (c) Zoom-in on the junction region showing a small gap between the p- and n-doped regions containing the color center implant.

Figure 1 shows the chip-scale layout and device-scale images of color center LEDs for G- and W-centers. A single die depicted in Figure 1(a) contains 12 p-i-n diodes with various junction parameters similar to the one shown in Figure 1(b). The devices were made by first etching global alignment marks and trench isolation through the entire 220 nm silicon layer of the silicon-on-insulator (SOI) wafer, then n-type ion-implantation, and then p-type ion-implantation. Both wafers used boron for p-type doping and phosphorous for n-type doping. An anneal to activate the dopants was performed prior to the color center implants. Carbon ions were implanted at 35 keV with a 5×10^{12} ions/cm^2 dose for the G-center wafer and silicon ions were implanted at 65 keV with a 5×10^{12} ions/cm^2 dose for the W-center wafer. However, from the CC implant step and onward the two CC types required differences in the ion used, the anneal activation steps and the final contact metallization, which are currently being tested and refined.

Each device on a die has a different separation between the p- and n-doped regions. The separation values range from a 3 μm gap to a 3 μm overlap. The CC implants are contained within the blue boxed region in Figure 1(c) at the intersection of the p- and n-doped implants. The wire width (2 μm, 3 μm, or 5 μm) and color center implant box areas vary across dies with all devices on the same die having the same wire width and implant areas. Variations in the wire width, implant area, and separation between p- and n-doped regions are used to optimize diode characteristics, which can impact CC photon emission.

3. Results

Since EL requires the use of CC and LEDs together, we must be able to successfully fabricate both within silicon. We verified CC synthesis using PL measurements on the implanted regions of the samples without LEDs to determine if CCs are present. The sample is cooled to <10 K in an optical cryostat and a laser is used to excite a spot on the implanted region. The emission is collected and sent to a spectrometer, or through a 900 nm long pass filter (LPF) for mapping. G-centers exhibit a zero-phonon line (ZPL) at 1269 nm, whereas W-centers have a ZPL at around 1218 nm [3,4]. Figure 2(a) shows a PL spatial map along the boundary of an implanted region indicating CC synthesis inside but not outside. The bright region is dominated by CC emission and is used for the spectral measurements shown. Figures 2(b) and 2(c) show peaks at a wavelength near 1218 nm for the sample implanted with silicon and 1280 nm for the implant with carbon, corresponding to W- and G-centers, respectively.

We have fabricated LED devices as shown in Figure 1 and performed I-V measurements at room temperature to verify diode behavior and low resistivity implants and contacts. We are currently setting up to measure the emitted light characteristics when driving them electrically at low temperatures. Future work will optimize our design for efficiency from the LED and compare EL and PL emission.

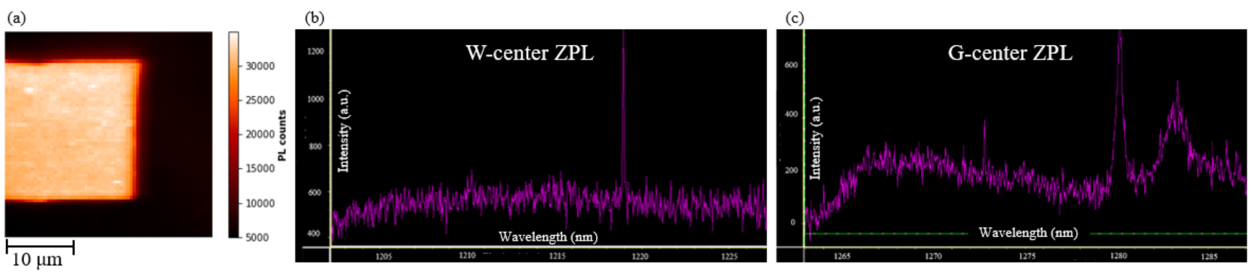

Fig 2. PL measurements of CC implanted regions. (a) PL map of a W-center implant region using a 900 nm LPF. (b) Intensity (a.u.) as a function of wavelength (nm) for one collection spot of Si implant region for W-centers and (c) carbon implant region for G-centers.

4. Conclusions

We designed and fabricated wafers containing LEDs and CCs to enable EL. Separately, we successfully fabricated W- and G-centers as shown in our PL measurements. We will show updated results on the EL samples we have fabricated containing LEDs by the time of the talk. This research will allow for a way to utilize the advantageous monolithic properties of silicon to further CC-based optoelectronics.

5. References

[1] Redjem, W., Zhiyenbayev, Y., Qarony, W. *et al.* All-silicon quantum light source by embedding an atomic emissive center in a nanophotonic cavity. *Nat Commun* 14, 3321 (2023). https://doi.org/10.1038/s41467-023-38559-6

[2] Hollenbach, M., Klingner, N., Jagtap, N.S. *et al.* Wafer-scale nanofabrication of telecom single-photon emitters in silicon. *Nat Commun* 13, 7683 (2022). https://doi.org/10.1038/s41467-022-35051-5

[3] 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

[4] Sonia M. Buckley, Alexander N. Tait, Galan Moody, Bryce Primavera, Stephen Olson, Joshua Herman, Kevin L. Silverman, Satyavolu Papa Rao, Sae Woo Nam, Richard P. Mirin, and Jeffrey M. Shainline, "Optimization of photoluminescence from W centers in silicon-on-insulator," Opt. Express 28, 16057-16072 (2020)

[5] Sonia Buckley, Jeffrey Chiles, Adam N. McCaughan, Galan Moody, Kevin L. Silverman, Martin J. Stevens, Richard P. Mirin, Sae Woo Nam, Jeffrey M. Shainline; All-silicon light-emitting diodes waveguide-integrated with superconducting single-photon detectors. *Appl. Phys. Lett.* 2 October 2017; 111 (14): 141101. https://doi.org/10.1063/1.4994692