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Integrated solid-state single photon emitters

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Why Solid-state Single Photon Emitters (SPEs) ?

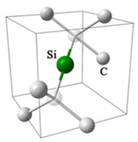
SPEs are building blocks for quantum applications :

- Quantum key distribution / quantum network
- Quantum metrology : $\frac{\sigma}{\sqrt{N}}$ (classic) → $\frac{\sigma}{N}$ (quantum)
- Optical quantum computing

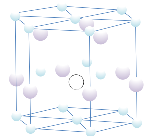
σ, N : standard deviation, # of measurements

Solid-state SPEs based on defect center

- Promising single photon generation platform
- Good scalability and easy integration with phonic devices



SiV defect in diamond
Aharonovich et. al., Rep. Prog. Phys. (2011)



Vacancy defect in GaN, AlN wide-bandgap semiconductors

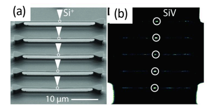
Goals : Develop suitable SPEs for QIS application

1. Improve low yield of current SiV SPEs
   - Exact yield estimation with counted ion implant and SPEs verification
2. Find out next-generation SPEs
   - Deterministic creation of optically active defects in GaN/AlN semiconductors
   - Monolithic integration with GaN/AlN photonic strucuture

Established Capabilities

Focused ion beam implantation (IBL) : deterministic SPEs creation

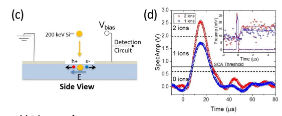
Ion position accuracy



(a) Precise placement of Si in 1D diamond photonic crystal nano-beam cavity.
(b) PL from SiV created in the 1D photonic cavity.

A. Sipahigil et al., Science (2016)

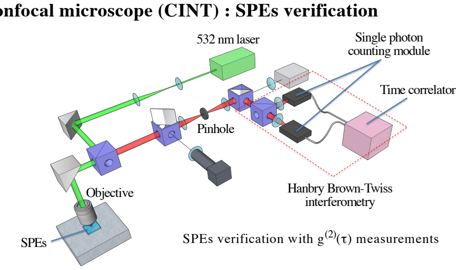
Ion number accuracy



(c) Schematic of in-situ ion counting setup.
(d) Detected pulse signals corresponding to 0, 1, 2 ions.

Michael Titze, 2021 CINT Annual Meeting

Confocal microscope (CINT) : SPEs verification



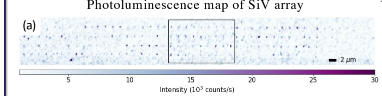
SPEs verification with $g^{(2)}(\tau)$ measurements

Precise SiV SPEs Yield Estimation

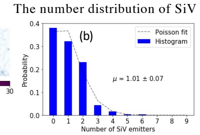
Difficulty in SiV SPEs yield estimation

- Origin : stochastic nature of ion implantation & Si-to-SiV conversion.
- Accurate yield estimation of SiV SPEs was achieved with improved ion number accuracy (in-situ ion counting) and SPE verification ($g^{(2)}$ measure).
- SiV SPEs yield was estimated to be ~2.98 %, mainly due to low conversion efficiency.

Photoluminescence map of SiV array



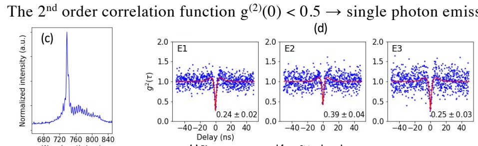
The number distribution of SiV



(a) Each dark spot corresponds to 2 μm pitch SiV array created by average ~30.8 ions counted implantation. Intensity distribution from site to site arises from different number of created SiV per site.
(b) Probability distribution of SiV emitters at each spot, obtained from total 320 implant locations (blue bar). Poisson fitting (dashed-line) gives average 1.01 SiV / site and ~2.98 % average yield of SiV SPEs.

Verification of SiV SPEs

- Zero phonon line (ZPL) at 738 nm → PL from SiV center
- The 2[nd] order correlation function $g^{(2)}(0) < 0.5$ → single photon emission



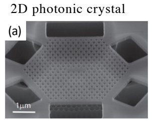
(c) PL spectrum measured from Si implanted area.
(d) $g^{(2)}(\tau)$ measurements from 3 dimmest spots in (a)

Developing Diamond Patterning Technologies

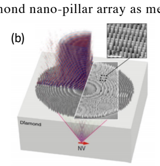
Why diamond fab is necessary?

- Optical cavity, resonator : enhanced ZPL emission
- Waveguides, metalens : improved light collection

[1]Diamond suspended 2D photonic crystal



[2]Diamond nano-pillar array as metalens



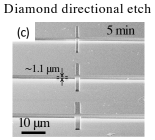
[1] Sara et. al. APL 2017
[2] Huang et. al. Nat. Commun. 2019

(a) 70 times enhanced ZPL (637 nm) emission from NV center inside the 2D photonic cavity.
(b) Diamond metalens composed of nano-pillar array. NA > 1 was achieved with this design.

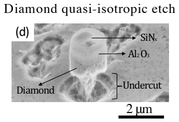
Current progress

- Anisotropic and quasi-isotropic diamond etching process
- Side-wall protection process toward suspended structure

Diamond directional etch



Diamond quasi-isotropic etch



(c) Patterned diamond by O_2 ICP etch with SiN_x hard-mask. Fast etch rate (230 nm/min) is achieved.
(d) Diamond undercut demonstration by combining a side-wall coverage with 20nm Al_2O_3 and O2 ICP etch without forward bias at high temperature (quasi-isotropic).

Next-generation SPEs based on AlN semiconductor

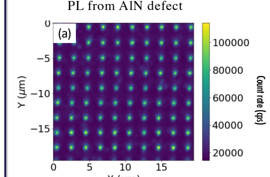
Why AlN ?

- SPEs at RT (defect in wide-bandgap 6.015 eV)
- High-performance scalable photonic integrated circuits (PICs)
- Strong nonlinearity and piezoelectricity
- AlN SPEs + AlN PICs : promising integrated quantum photonic platform with industrial scalability

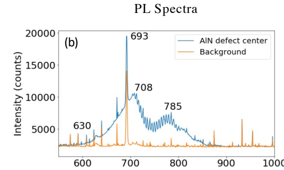
Current progress

- Deterministic creation of optically active defect in AlN
- Method : Li focused ion beam implantation in AlN and post-annealing

PL from AlN defect



PL Spectra



(a) 2 μm pitch Li implanted array spots show strong PL, demonstrating optically active AlN defect.
(b) PL spectra from AlN defect (blue) and background PL (orange). Sharp peak at 693 nm originates from Cr in sapphire substrate. Three broad peaks at 630, 708, and 785 nm are observed from AlN defect.

Conclusion and Outlook

Conclusion

- We have a long history of strong ion implantation capabilities at CINT.
- Now we are developing fabrication capabilities to enhance SPE properties for QIS applications.
- Have developed measurement capabilities to detect the quantum properties of SPEs.
- We are discovering new SPEs in wide-bandgap semiconductors for the next generation of SPE for QIS.
- Diamond etching and side-wall protection process we setup, which is applicable to various diamond photonic structure fabrication.
- Diamond photonic cavity fabrication process → enhanced photon emission rate for quantum entanglement.

Outlook

- Diamond photonic cavity fabrication → SPEs creation in this cavity
- Deterministic creation of AlN SPEs → Integration with AlN photonic structure

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