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Sandia National Laboratories

Deterministic creation of optically active defects in AlN towards integrated single photon emitters

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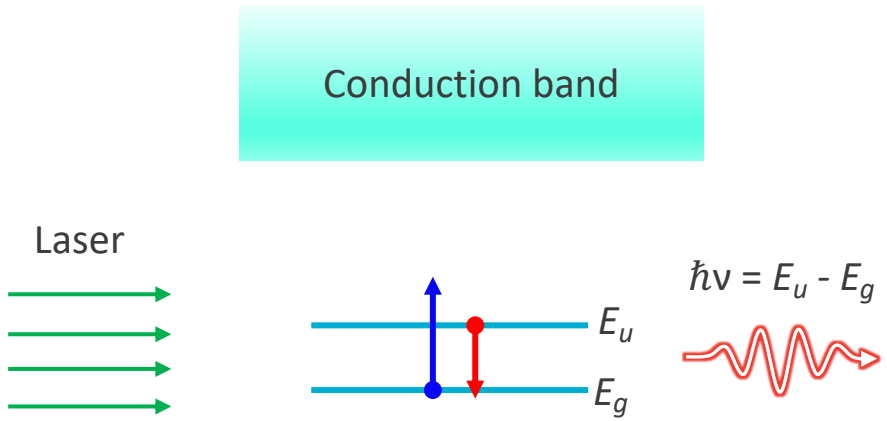
Solid-state single photon emitters (SPEs)

SPEs = building blocks for quantum applications

- Optical quantum computing
- Quantum key distribution / quantum network
- Quantum metrology : smaller error, $\frac{\sigma}{\sqrt{N}}(\text{classic}) \rightarrow \frac{\sigma}{N}(\text{quantum})$

σ, N : *standard deviation, # of measurements*



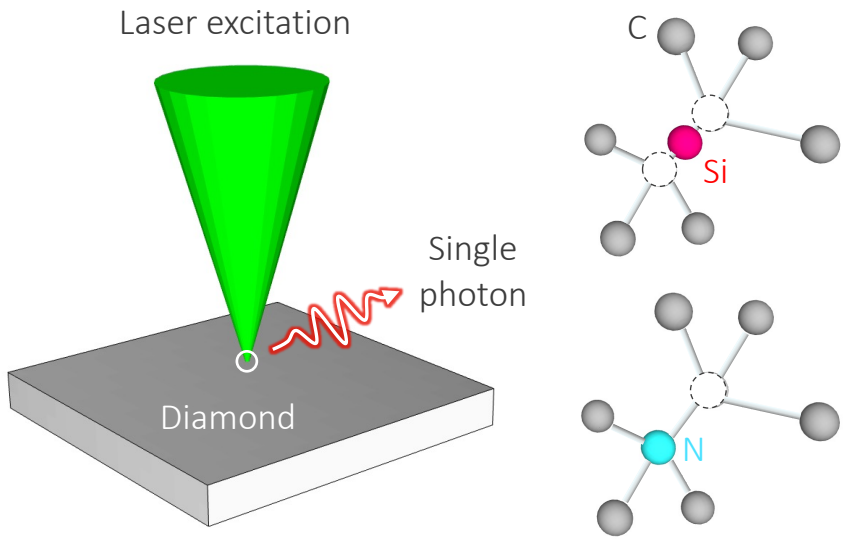
Solid-state SPEs based on defect center

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

Atom-like defect within bandgap

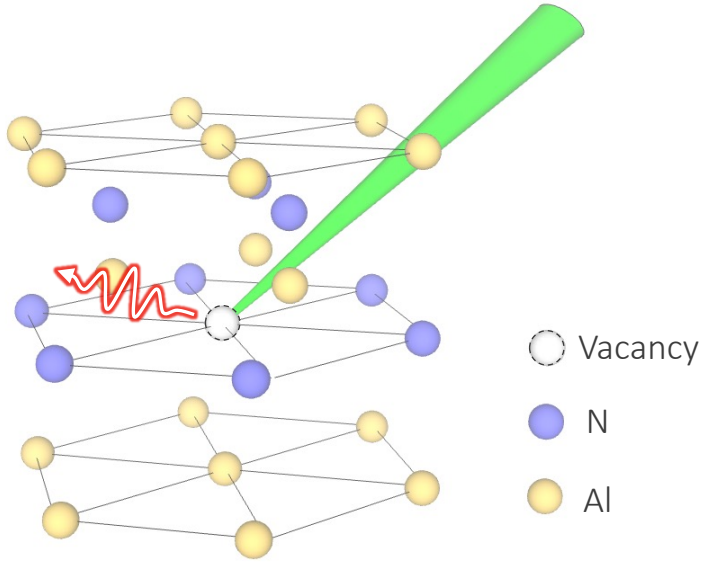
SPEs in AlN

Color center in diamond



- Most studied & well-known system
- Most advanced demonstration in QIS[1] application
- *high material cost, poor scalability, and challenging fab*

Optical defect in AlN wide-bandgap semiconductor (next-generation SPE platform)



- Defect within large bandgap (6.015 eV) → SPEs at room-temperature
- High-performance scalable photonic integrated circuits (PICs)
- Strong nonlinearity and piezoelectricity

→ Goal : deterministic creation of SPEs in AlN PICs towards integrated quantum photonic platform with industrial scalability

[1] QIS : quantum information science

Motivation

Direct integration of AlN SPEs in AlN PICs (Dirk Englund group) [1]

- Demonstration of potential for AlN-based integrated quantum photonic platform
- Generation of AlN SPEs by He ion broad-beam implant → position of SPEs is *NOT* controllable

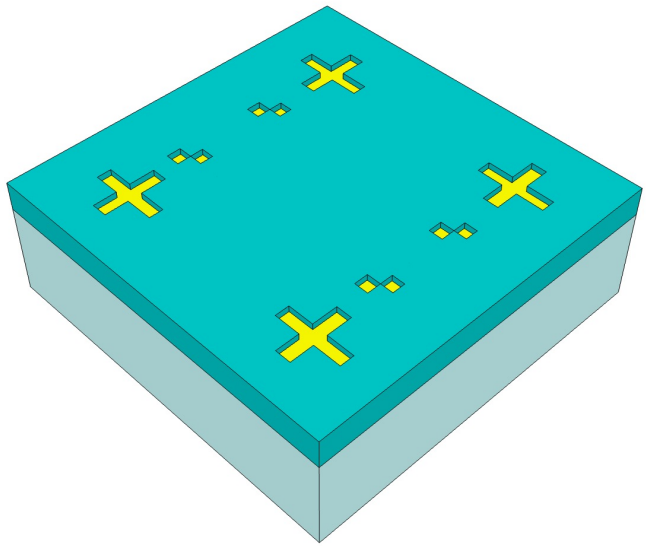
Deterministic creation of AlN SPEs is a key requirement for practical application

- Placing AlN SPEs to desired location allows for optimal operation of AlN-based quantum photonic platform
- We have a strong localized ion implantation capabilities at Sandia National Lab (position accuracy ≤ 50 nm)
- We're developing a deterministic method of SPEs creation in AlN using a localized ion implantation

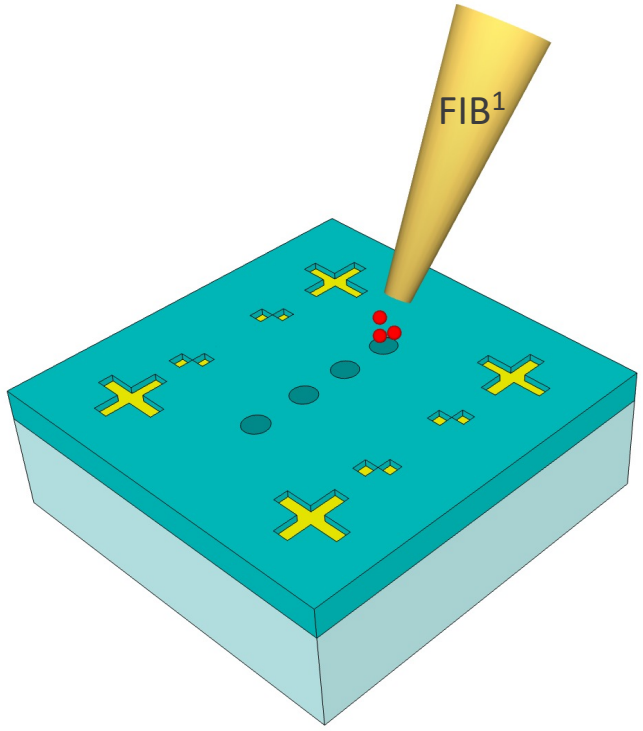
[1] *Lu, Tsung-Ju, et al. ACS Photonics 7.10 (2020)*

Deterministic defect creation in AlN

Device fabrication

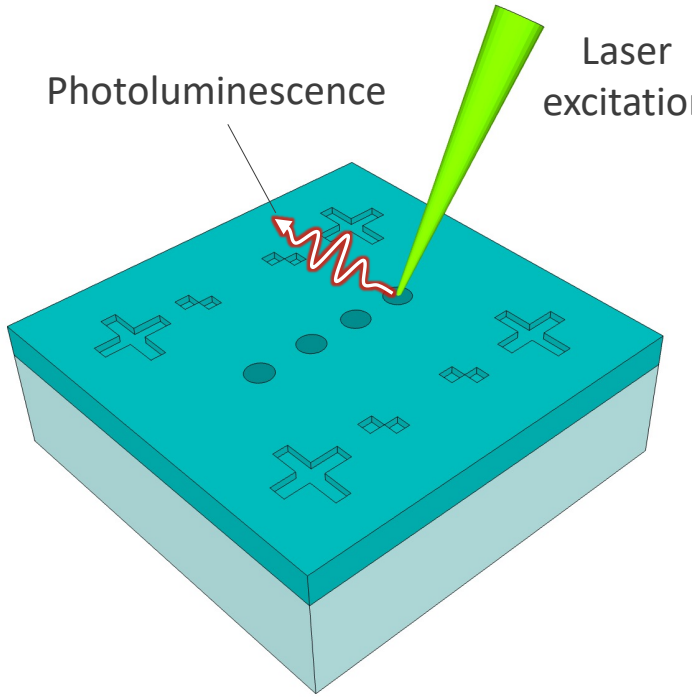


Localized ion implantation



[1] FIB : Focused Ion Beam

Post-anneal (optional) & measurement



: Sapphire substrate : 200 nm AlN film (c-plane)

: Ti 5 nm / Au 20 nm (align marker)

: ion implant region

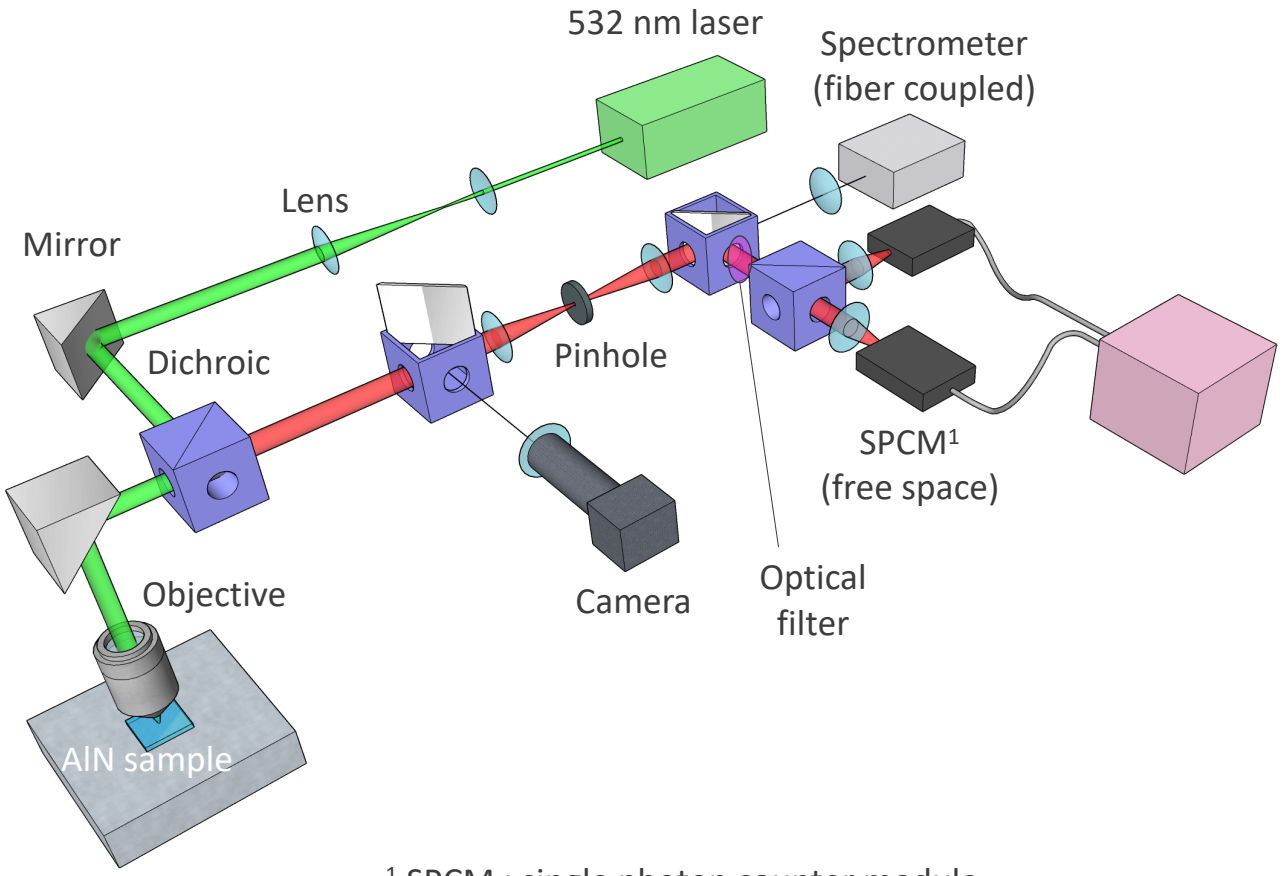
: 300 keV He or 35 keV Li ion

Anneal condition : 950 °C 30 min (Ar ambient)

Optical defect created by ion implant

Experimental setup

Confocal microscope



[1] SPCM : single photon counter module

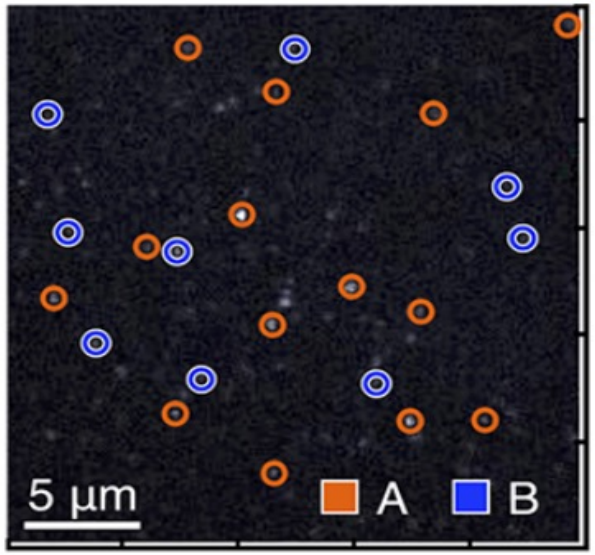
Details

- Objective : oil (60x, NA=1.4) or dry (100x, NA=0.9)
- Laser : 532 nm @ 4mW
- Dichroic : Cut-on wavelength 550 nm
- Filter : 700 nm long pass
- Pinhole : 50 µm diameter
- Stepper motor + piezo stage

Photoluminescence of defects in AlN (1)

He broad-beam ion implant (MIT) [1]

→ Random occurrence of SPEs in AlN

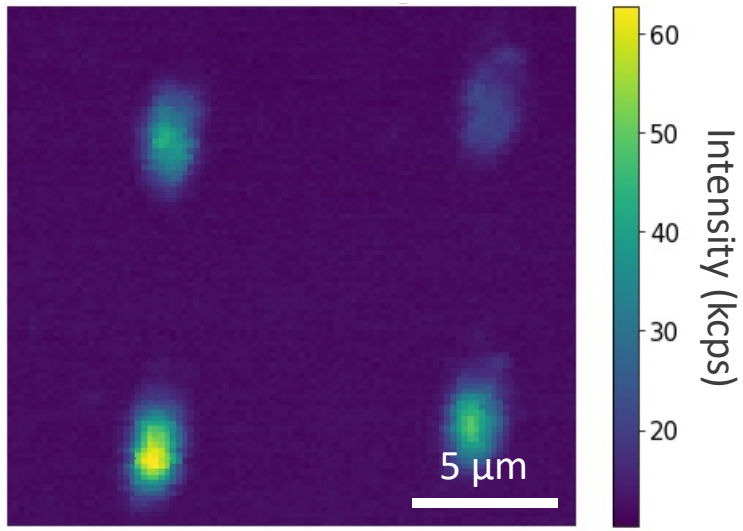


: SPEs

1x10^{15} ions/cm^2 (dose), 35 keV (ion energy)

He localized ion implant (Sandia)

→ Deterministic defect creation in AlN (bright region)



3x10^{13} ions/cm^2 (dose), 300 keV (ion energy)

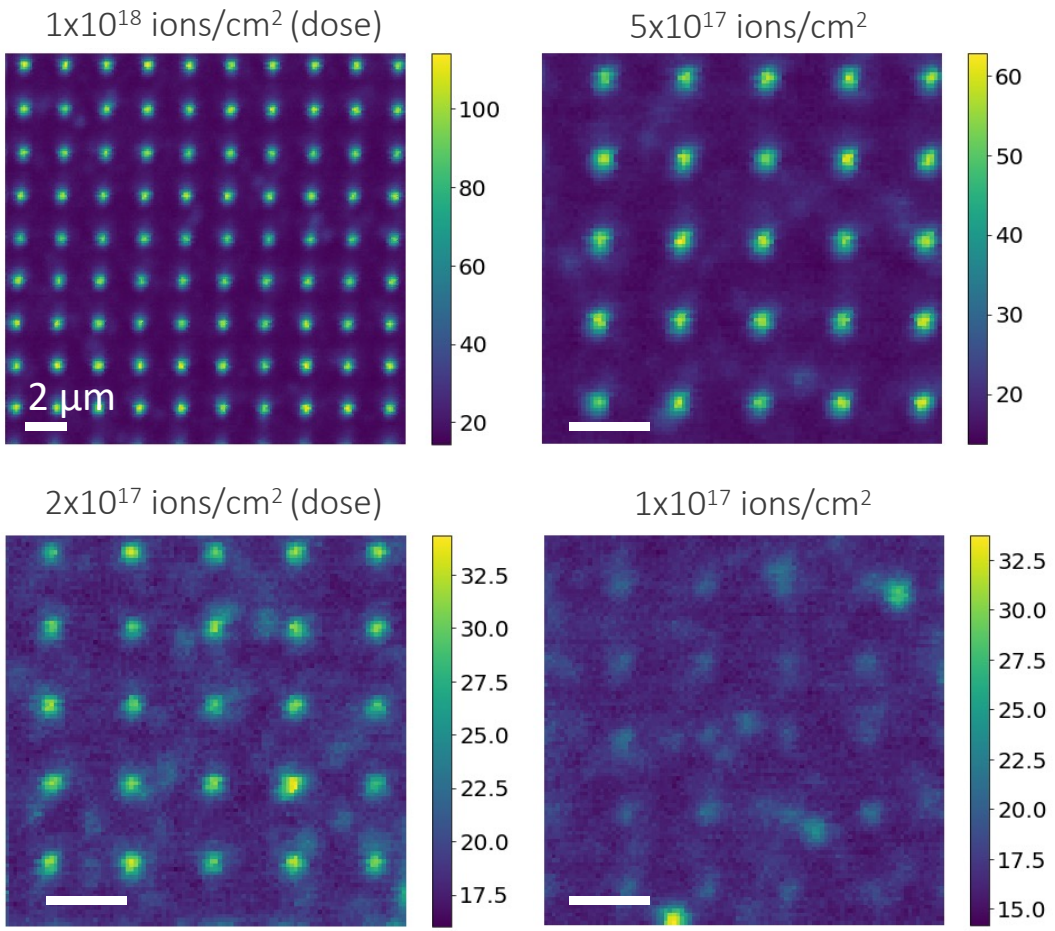
- He localized ion implantation enables deterministic creation of optical defects in AlN
- To achieve SPE level, we plan to decrease He implant spot size (few micron → 50 nm) and ion energy (300 keV → ~30 keV)

[1] *Lu, Tsung-Ju, et al. ACS Photonics 7.10 (2020)*

Photoluminescence of defects in AlN (2)

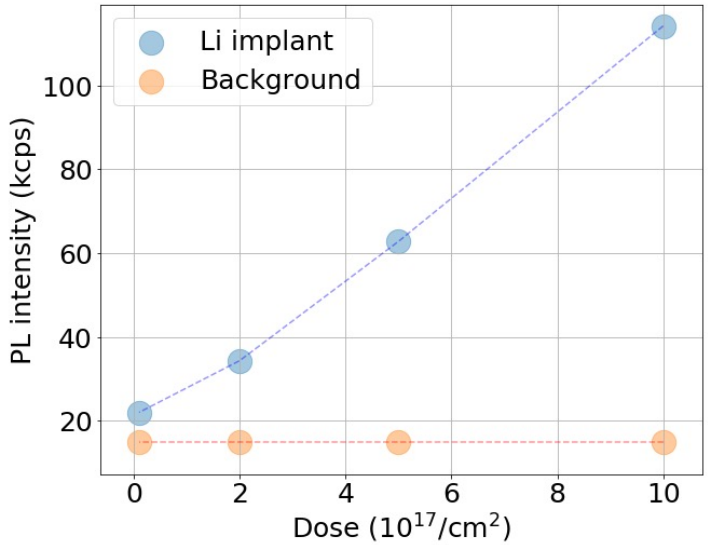
Li ion array implant with different dose

→ Bright spots = deterministically created defects



Color bar : intensity (kcps) Li ion energy : 35 keV

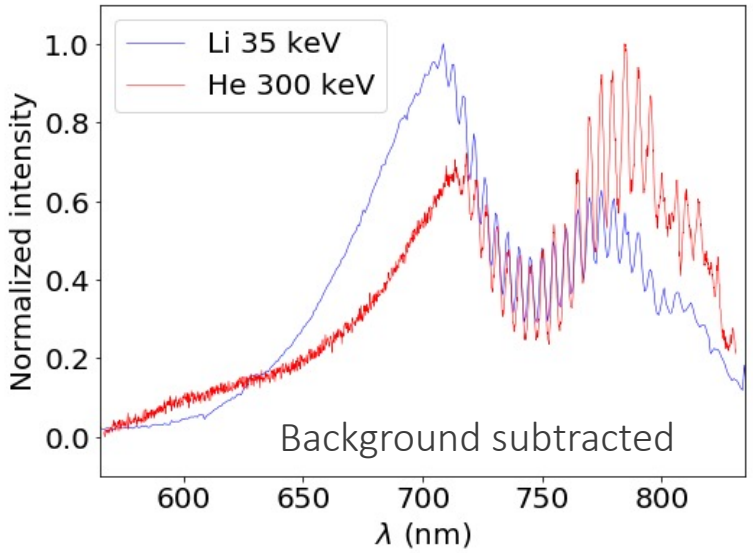
PL intensity vs dose



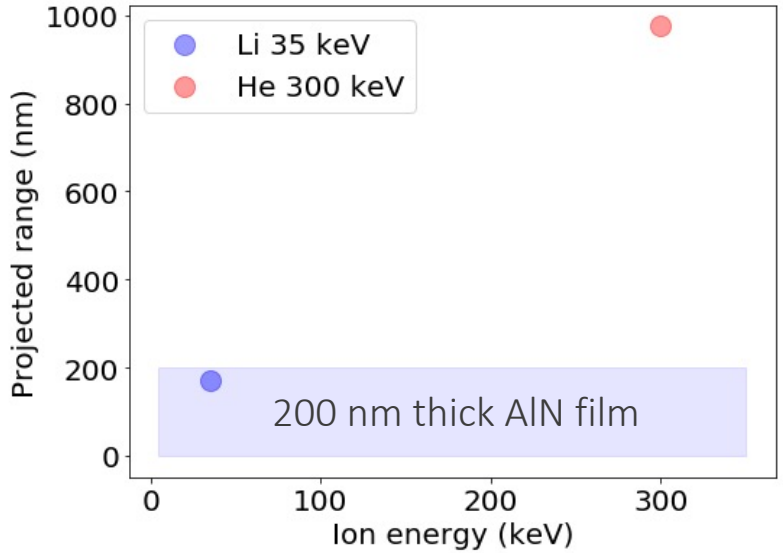
- PL intensity of defect array is proportional to dose
- For dose < 1x10^{17}/cm^2, optical defect is *NOT* resolvable
- No dark spot in the array → *NOT* SPE level
- Need to improve $\frac{\text{Defect PL}}{\text{Background PL}}$ to detect defects at lower dose

Emission spectrum of defects in AlN

Room-temperature PL spectra of defects created by localized ion implant



Average penetration depth of implanted ions (SRIM[1] calculation)



- Similar PL spectra for both Li and He implant : two broad peaks around ~710 and ~780 nm
- No He species inside AlN film (SRIM calculation) → optical defects might be associated with vacancy for both case
- DFT prediction[2] : anti-site nitrogen vacancy complex ($N_{Al}V_N$) – 713 nm (matched), di-vacancy complex ($V_{AL}V_N$) – 867 nm
- Fringe pattern around 750 nm due to multiple reflections inside a Si layer of the CCD camera

[1] *Stopping and Range of Ions in Matter*

[2] *Xue, Yongzhou, et al. The Journal of Physical Chemistry Letters 11.7 (2020)*

Conclusion

1. Using localized ion implant, we demonstrated deterministic creation of optical defect in AlN for the first time

   → *Open door to accurate positioning of AlN SPEs for optimal operation of the AlN-based quantum photonic platform*

2. Emission peaks of defects in AlN are located around 710 and 780 nm at room temperature

3. SRIM calculation and DFT theory predict that the origin of the defect can be vacancy complex in AlN

What will we do next ?

1. Systematic study of annealing for better defect activation

2. Low-temperature spectrum analysis to figure out zero phonon line (ZPL)