Quantum Efficiency, Electron Spin Polarization and Lifetime Study on GaAs Based Truncated Nanocone Array Photocathodes

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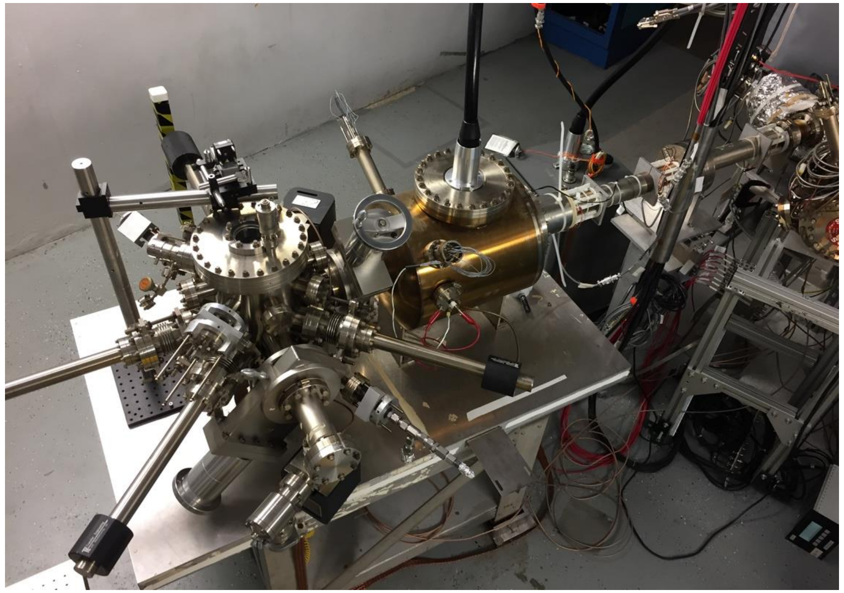
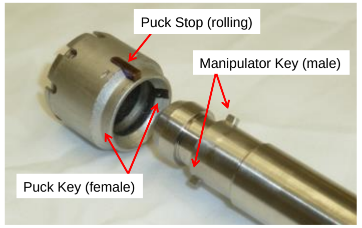
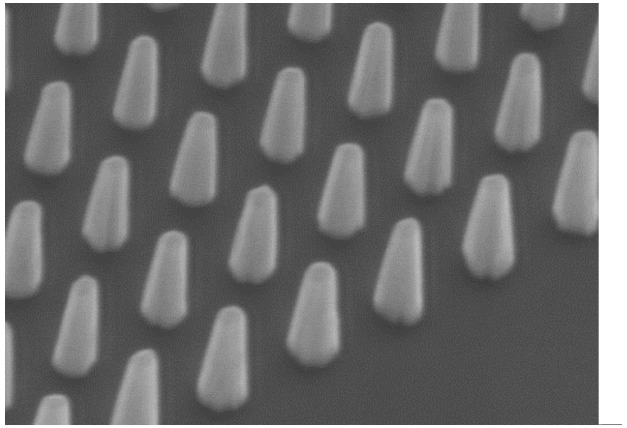






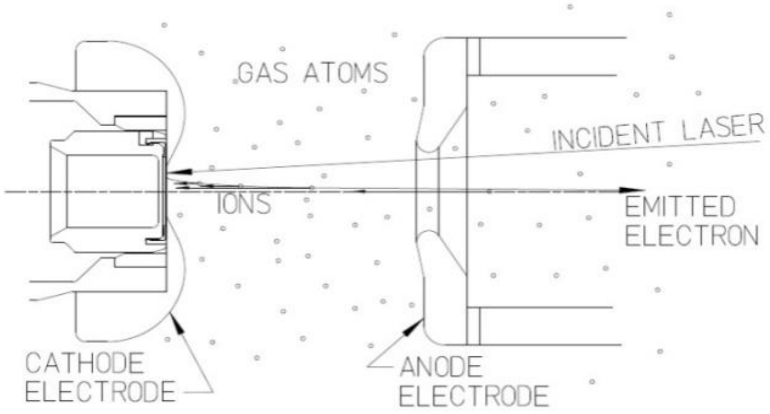
Outline

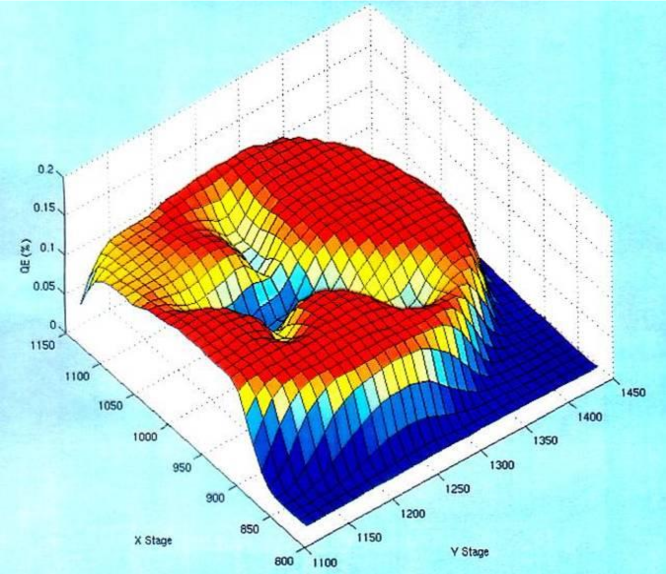
- Introduction
- Truncated Nanocone Array (TNCA) Fabrication
- Sample Preparation & Experimental System
- Results
- Summary

Introduction

GaAs as a Photoemission Electron Source:

- Direct band-gap photocathode (E_g= 1.42 eV).
- Valence band maximum (VBM) is doubly degenerate, Max. electron spin polarization (ESP) ~35-40%.
- Strained-superlattice (SSL) removes the VBM degeneracy, ESP ~85-90%, with QE of ~1% at 780 nm.
- Requires UHV: Lifetime ~200 C with ~200 µA beam current.
- Ion-back bombardment degrades the lifetime.
- Improvement in charge lifetime required for JLAB polarized positron source program: 1mA-10mA beam current for 2 weeks ~ 10^3-10^4C.





Ion back-bombardment significantly damage QE from laser spot to electrostatic center for flat wafers.

Introduction

Nanostructured GaAs:

Mie resonance enhanced absorption:

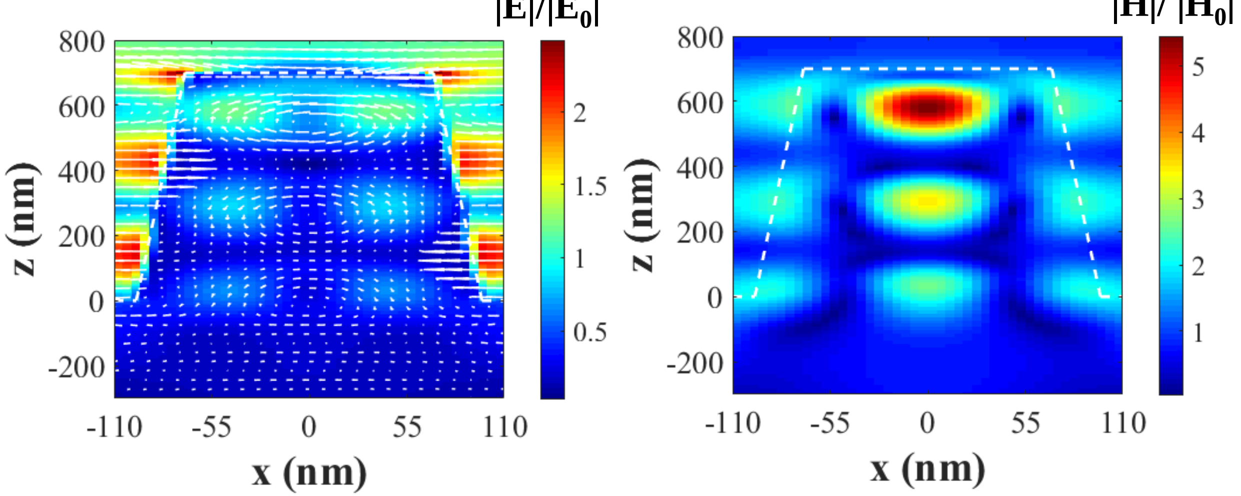
- Optical field enhancement within subwavelength scale nanostructure due to dipole / higher order mode excitations
- $\frac{nD}{\lambda} = 1\ (dipole), 2\ (quadrupole), \ldots$ [a]
- Results in enhanced absorption

Shorter electron travel path towards emission surface.

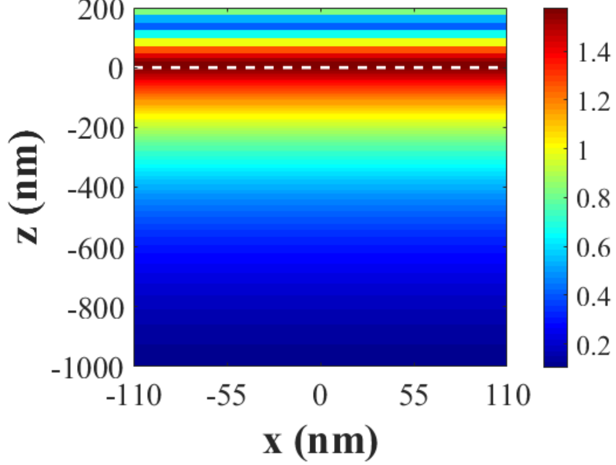
- Shorter travel path = Less scattering/ Energy loss
- For p-type GaAs (~10^{19}cm^{-3}): momentum relaxation length ~100 nm, thermalization length ~ 300 nm

Truncated nanocone structure has enhanced surface area

- Enhancement in active region area leads to longer lifetime



Truncated Nanocone:



Bulk (without the nanocone):

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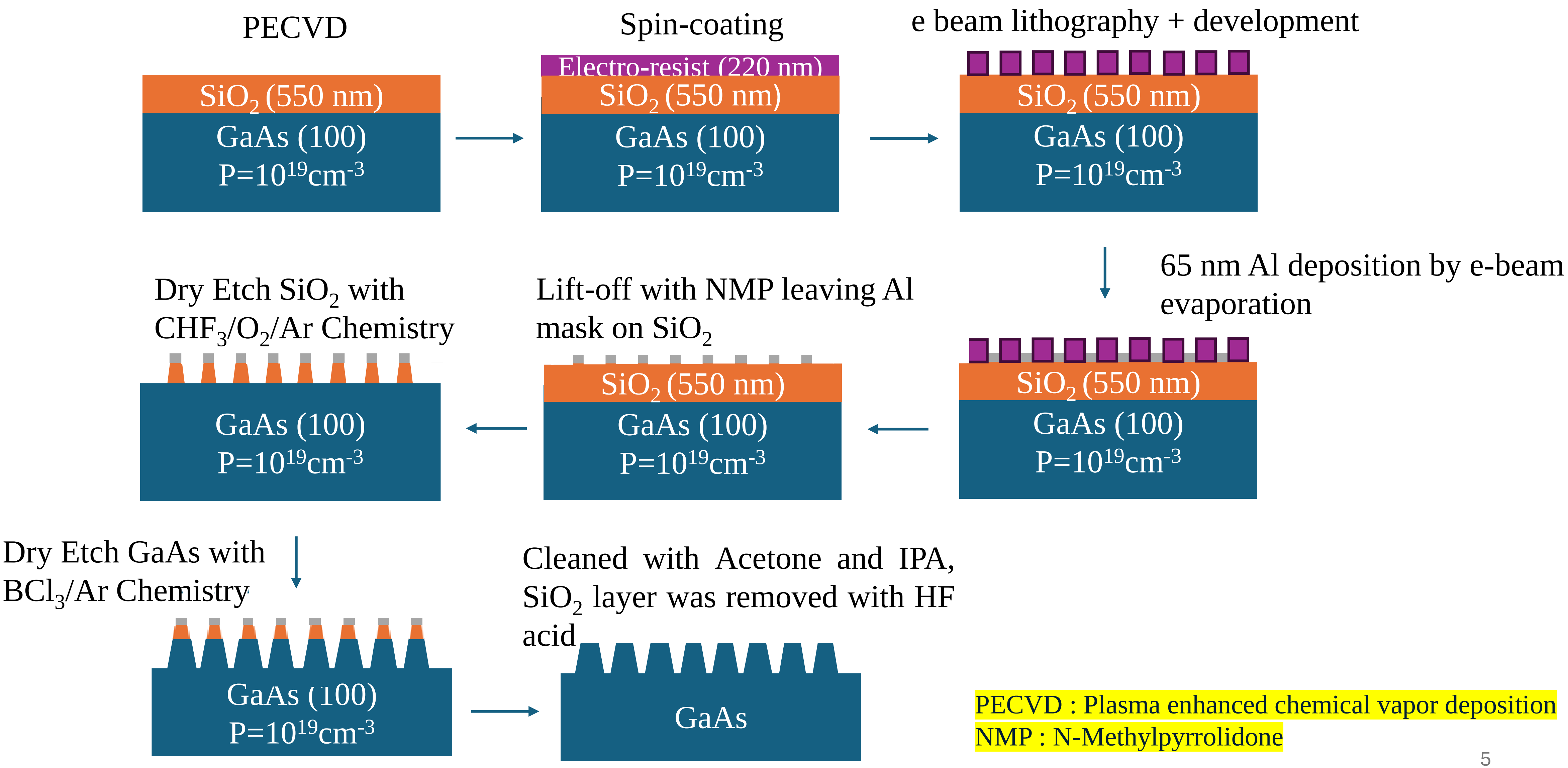
* [a] A. I. Kuznetsov et al., "Optically resonant dielectric nanostructures," Science **354**(6314), aag2472 (2016).

Truncated Nanocone Array (TNCA) Fabrication:



PECVD

Spin-coating

e beam lithography + development

65 nm Al deposition by e-beam evaporation

Lift-off with NMP leaving Al mask on SiO_2

Dry Etch SiO_2 with $CHF_3/O_2/Ar$ Chemistry

Dry Etch GaAs with BCl_3/Ar Chemistry

Cleaned with Acetone and IPA, SiO_2 layer was removed with HF acid

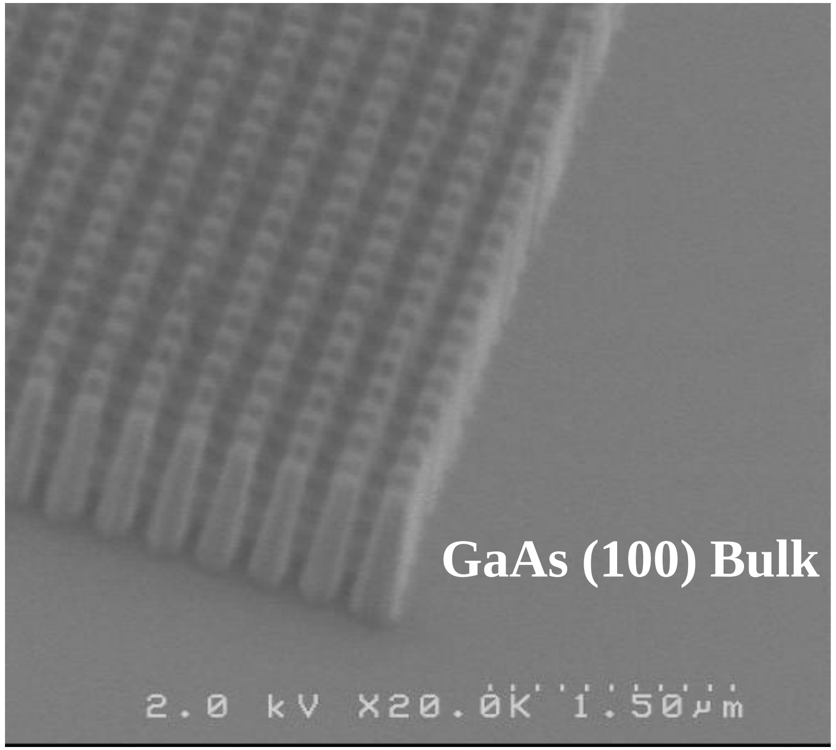
PECVD : Plasma enhanced chemical vapor deposition

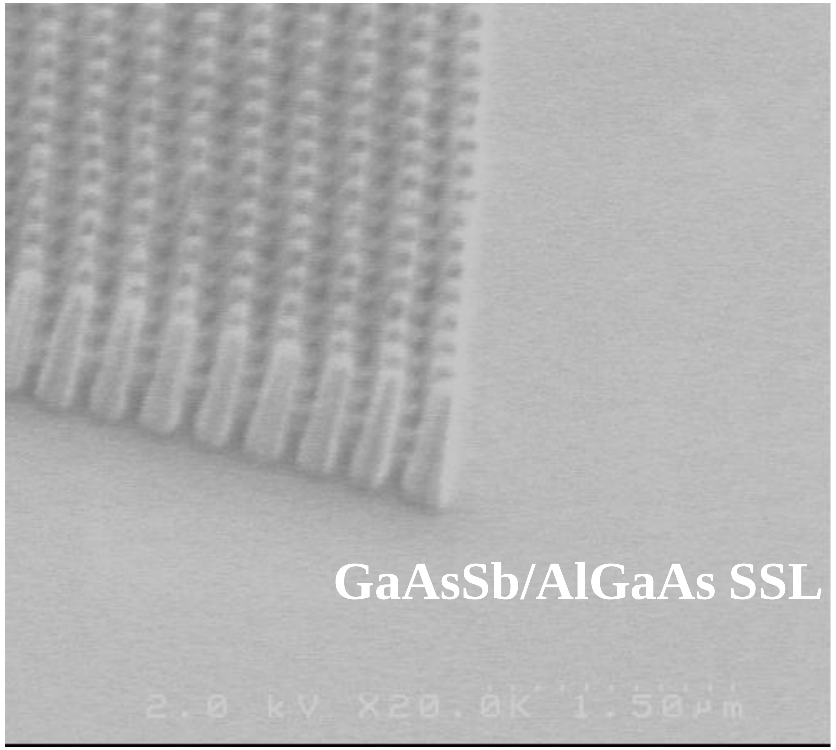
NMP : N-Methylpyrrolidone

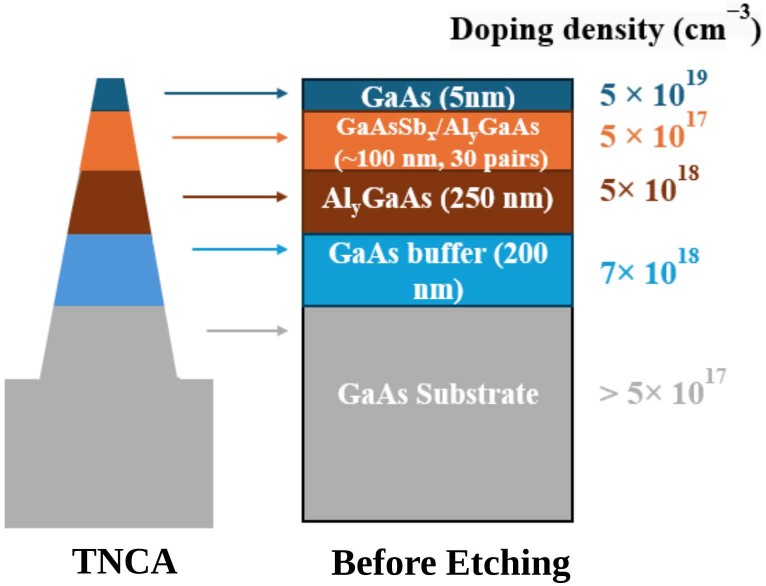
* The sample was fabricated by SRI International, Princeton, New Jersey

Truncated Nanocone Array (TNCA) Fabrication:

Top Diameter (nm)	Bottom Diameter (nm)	Height (nm)	Pitch (nm)
~139	~195	~700	~318
~135	~198	~700	~321







Doping density (cm^{-3})

Before Etching	Doping density (cm^{-3})
GaAs (5nm)	5×10^{19}
$GaAsSb_x/Al_yGaAs$ (~100 nm, 30 pairs)	5×10^{17}
Al_yGaAs (250 nm)	5×10^{18}
GaAs buffer (200 nm)	7×10^{18}
GaAs Substrate	$> 5\times 10^{17}$

TNCA

Before Etching

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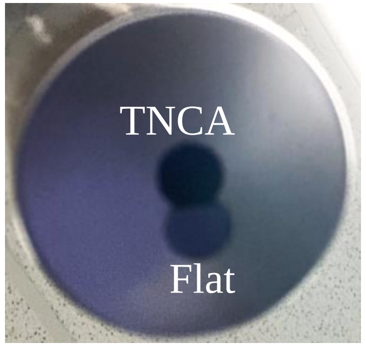
* The sample was fabricated by SRI International, Princeton, New Jersey

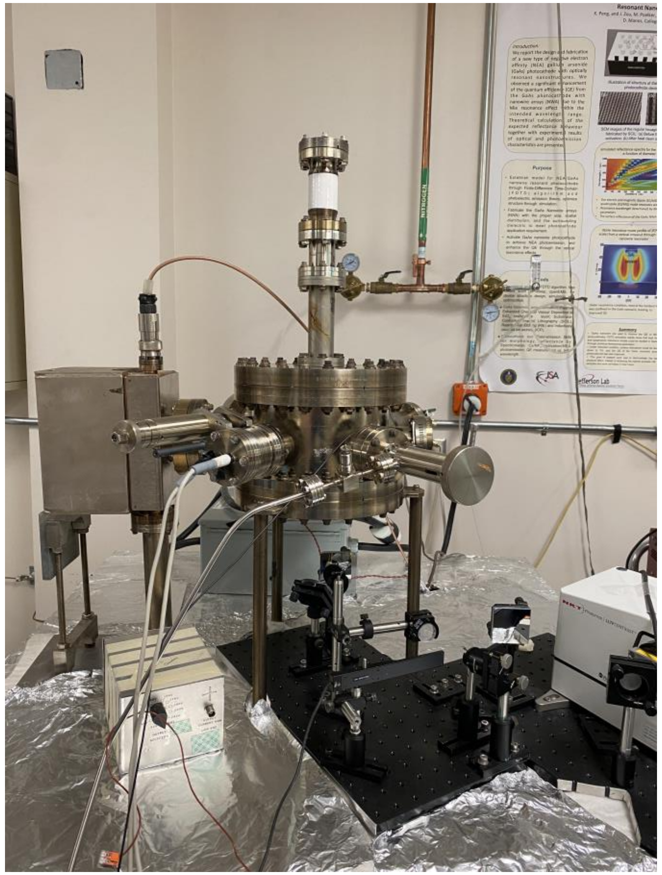
Sample Preparation & Experimental System:

Sample Preparation:

- Sample is cleaned with $HCl:H_2O$ (1:10) solution.
- Sample loaded in the chamber and the chamber is vacuum-baked for 30 hours at ~200°C.
- Sample is heat cleaned at 550°C for ~2 hours.
- NEA activation using Cs and NF_3.



We have two regions in our photocathode: Truncated Nanocone Array (TNCA) and Flat GaAs.



Test Chamber

Mott Polarimeter

Result

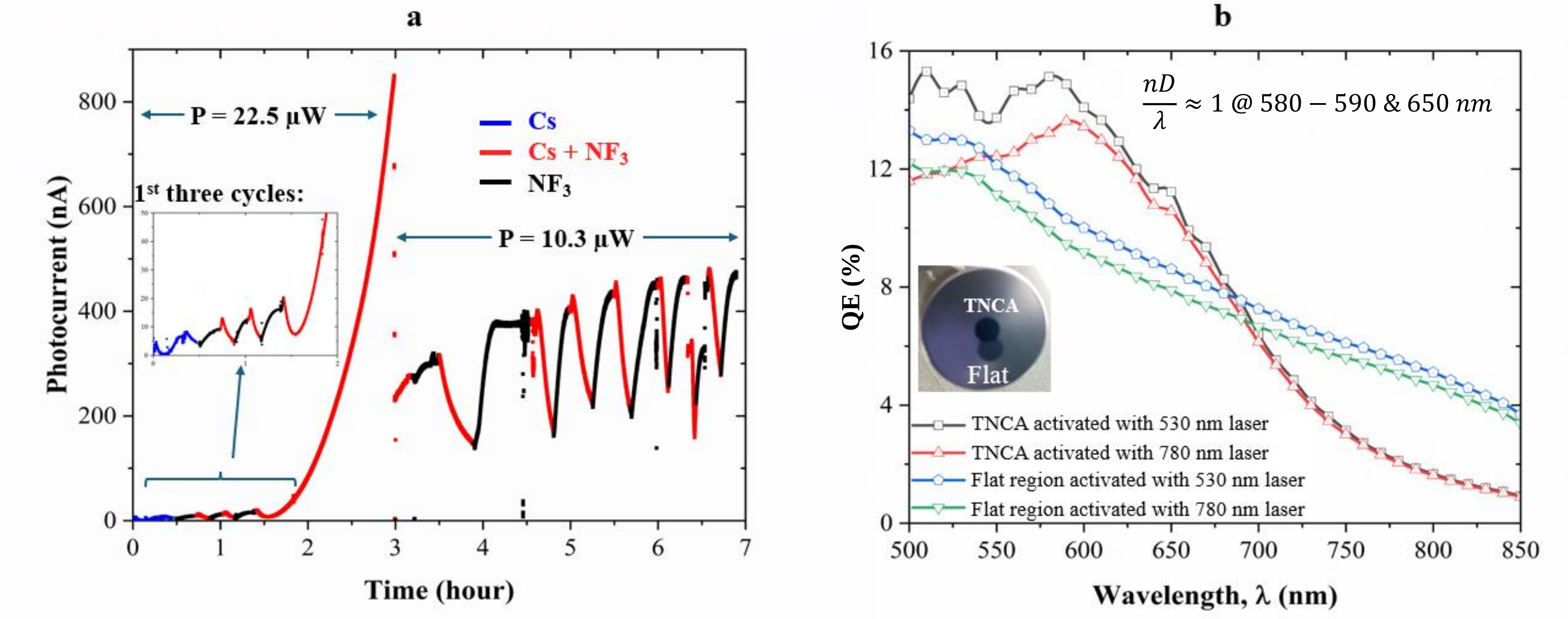


Figure: (a) GaAs truncated nanocone array (TNCA) activation by modified co-deposition, (b) Spectral response comparison between GaAs TNCA and GaAs flat wafer.

Result

Spectral Scan at Different Activation Temperature:

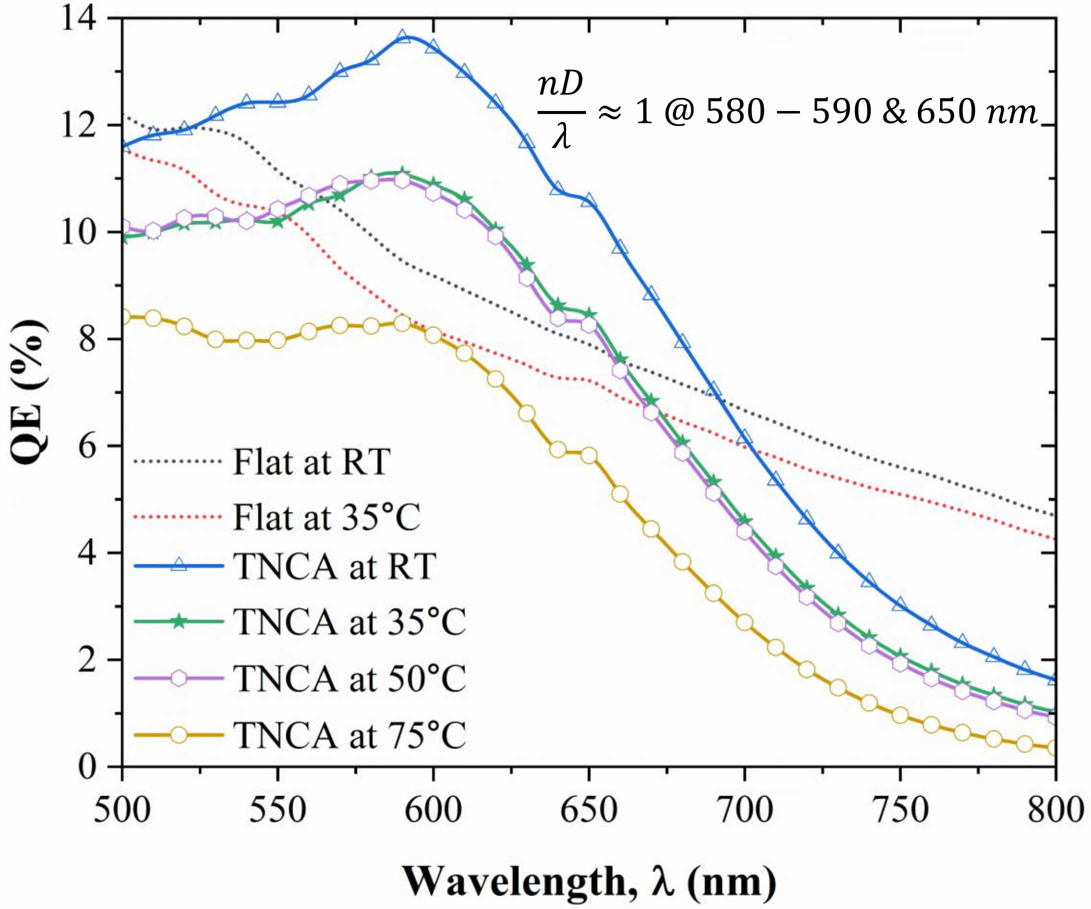


Figure: Spectral response comparison between GaAs truncated nanocone array (TNCA) and flat photocathodes.

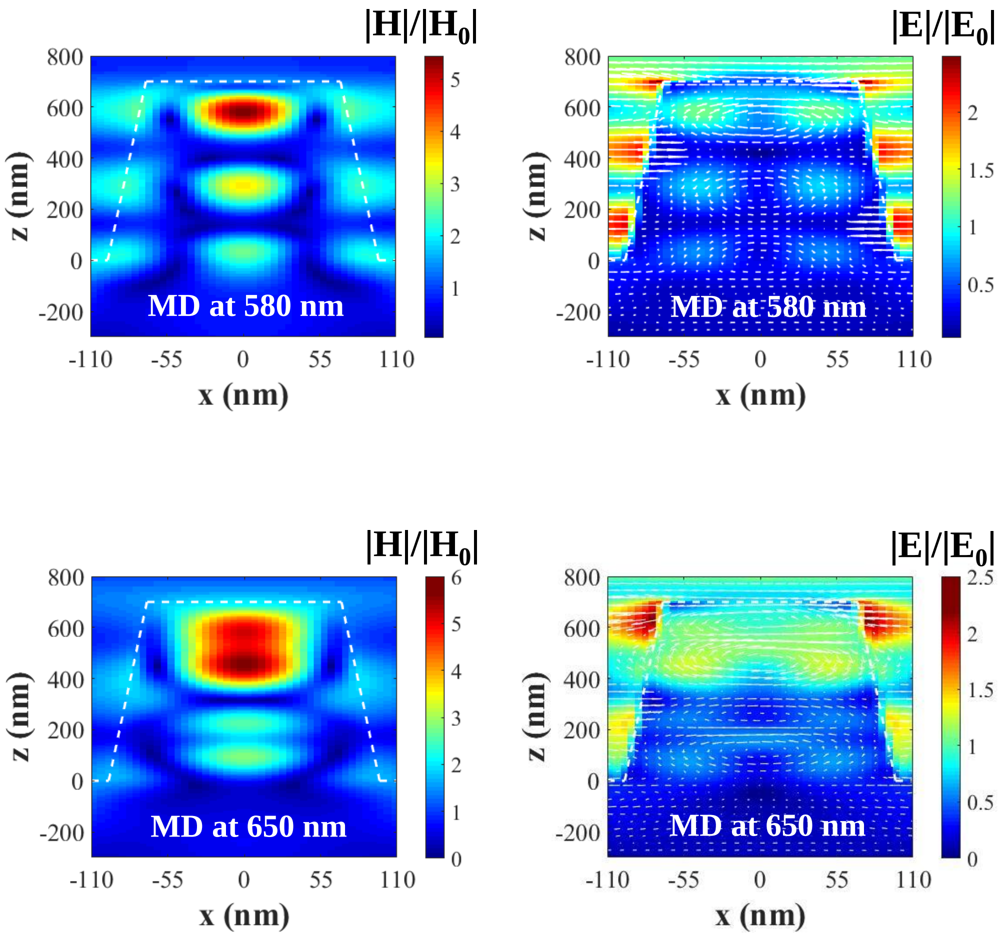
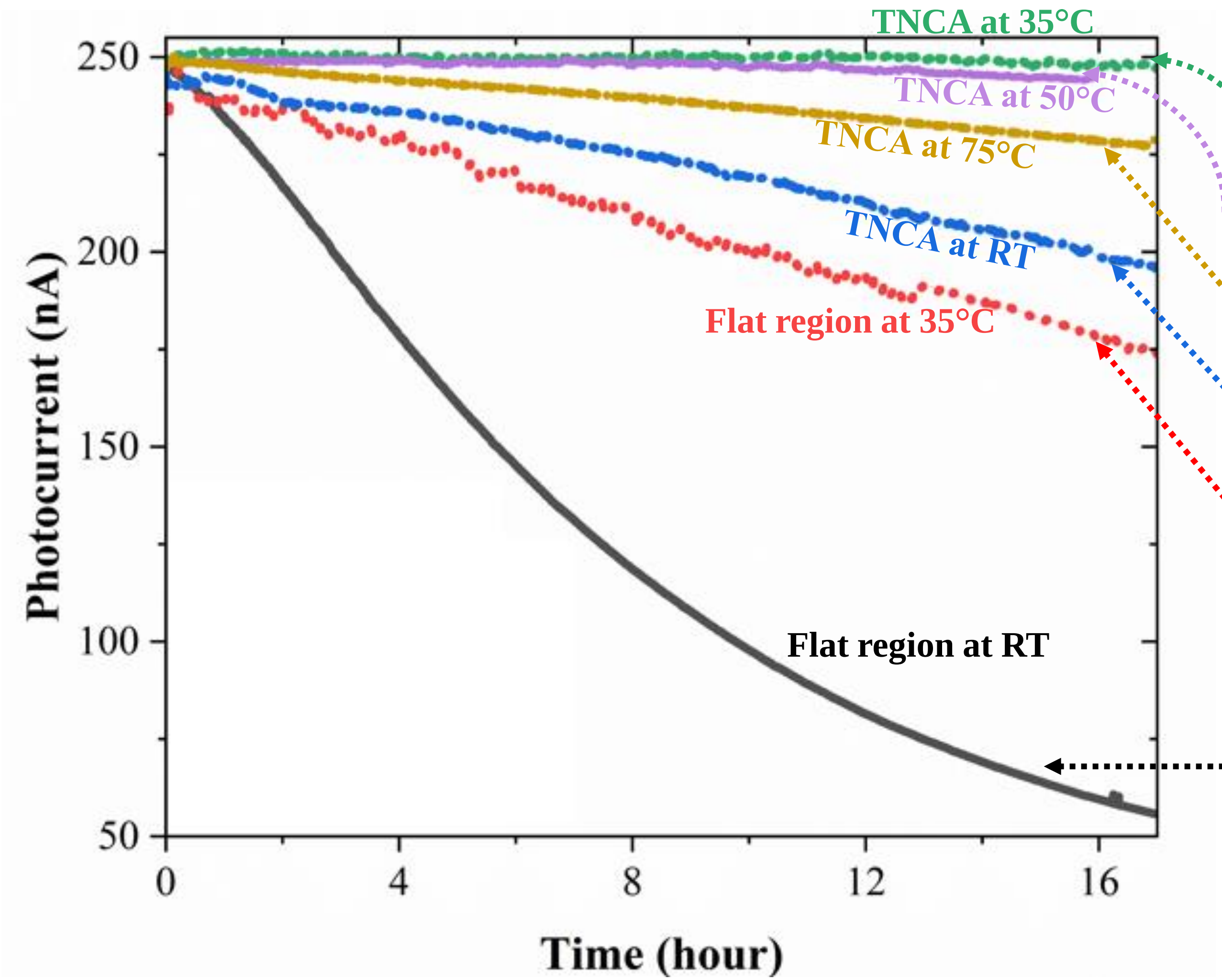


Figure: Optical field enhancement at 580 nm (top) and 650 nm (bottom).

Result

Comparison of Lifetime with Temperature:



Sample with Activation Temperature	Laser Power (µW)	1/e lifetime (hr.), EF	Charge lifetime (mC), EF
TNCA at 35°C	~30	411.4, ~43.9	220.7, ~41.2
TNCA at 50°C	~33	405.3, ~42.2	218.9, ~40.9
TNCA at 75°C	~78	141.9, ~14.7	76, ~14.2
TNCA at RT	~17.7	71.9, ~7.5	29.75, ~5.6
Flat region at 35°C	~8.6	42.6, ~4.4	22.7, ~4.2
Flat region at RT	7.85	9.6, 1	5.35, 1

***RT: Room Temperature ~ 21°C**

**** EF: Enhancement Factor relative to Flat region at room temperature**

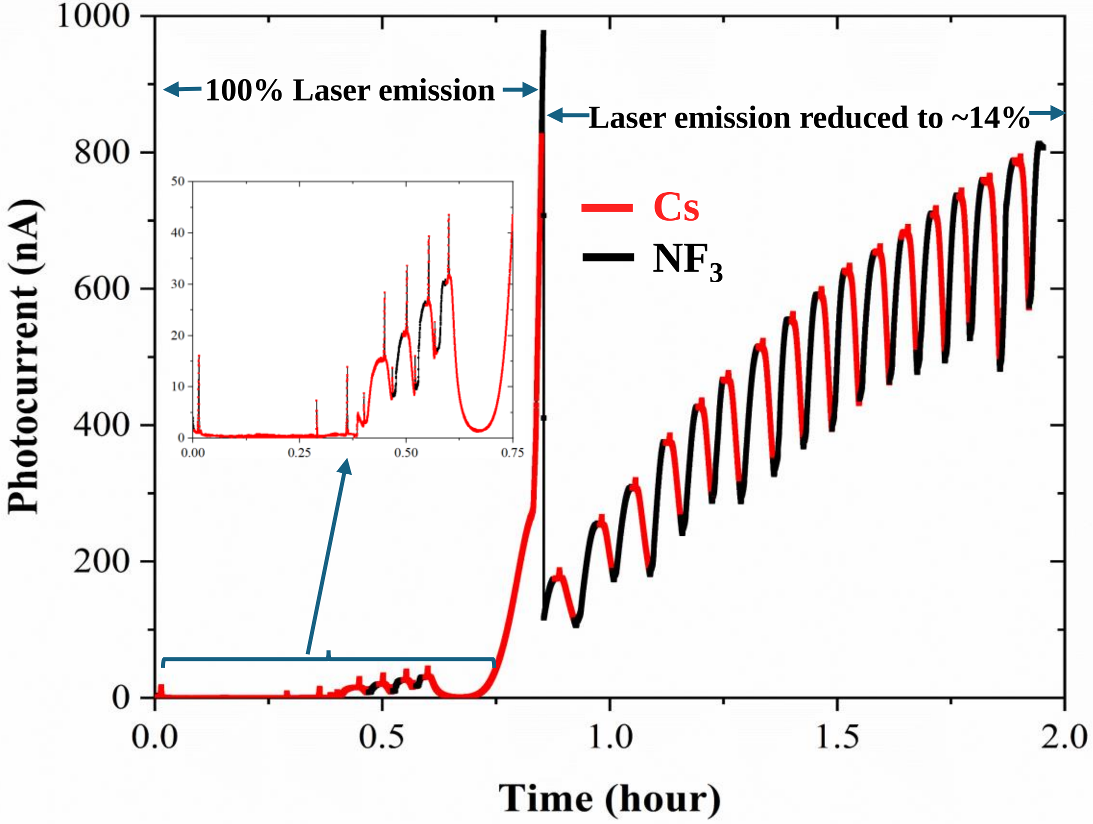
Figure: Lifetime measurement for truncated nanocone array (TCNA) and flat GaAs photocathode under continuous illumination of 780 nm laser light and comparable vacuum pressure (~10^{-11} Torr).

Result

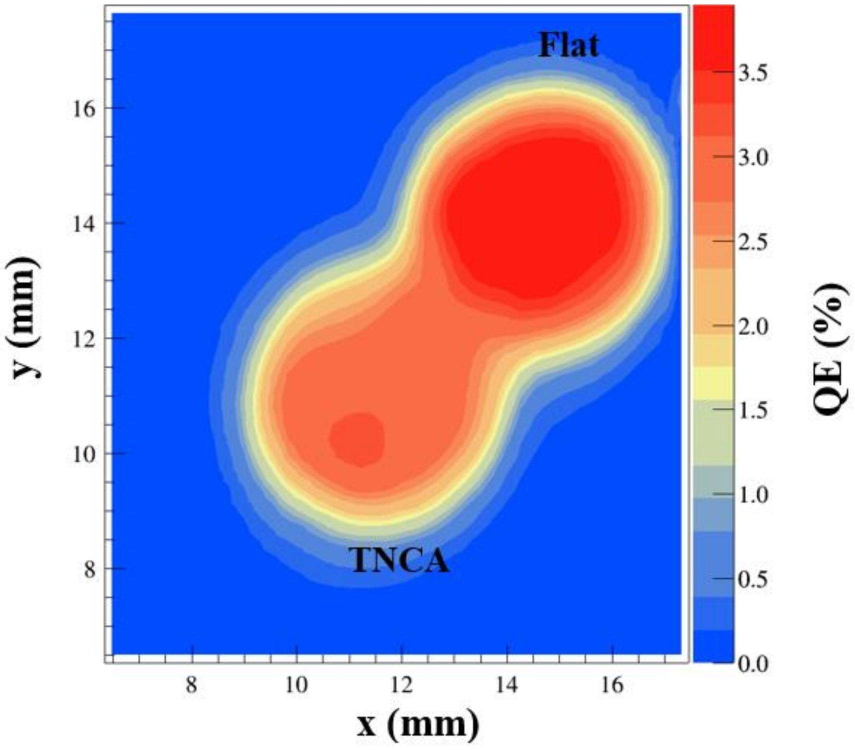
GaAsSb/AlGaAs SSL TNCA Activation:

- **The activation was reproduced in the Micromott deposition chamber.**
- **Uniform QE distribution in both Flat (GaAs bulk) and TNCA region.**

Modified yo-yo activation



QE Map using 660 nm laser



Result

GaAsSb/AlGaAs SSL TNCA vs. Flat wafer:

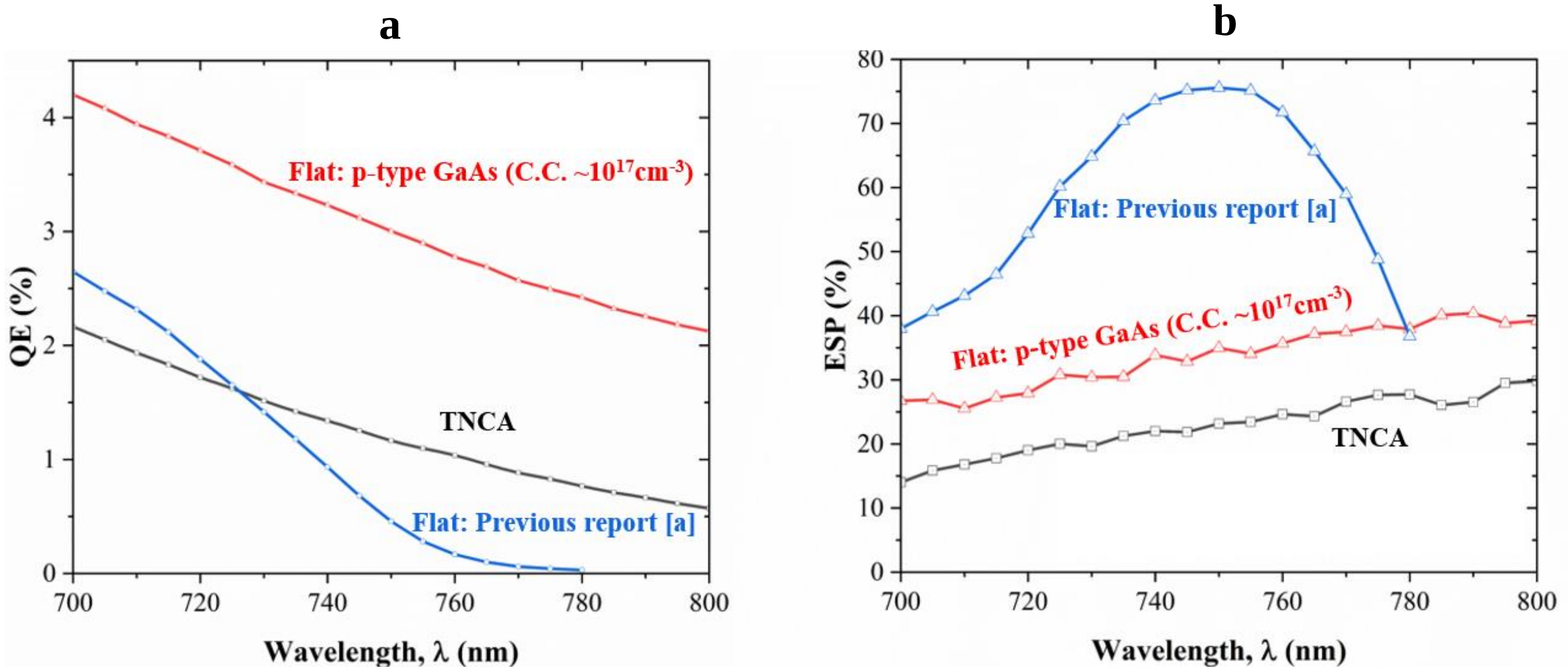
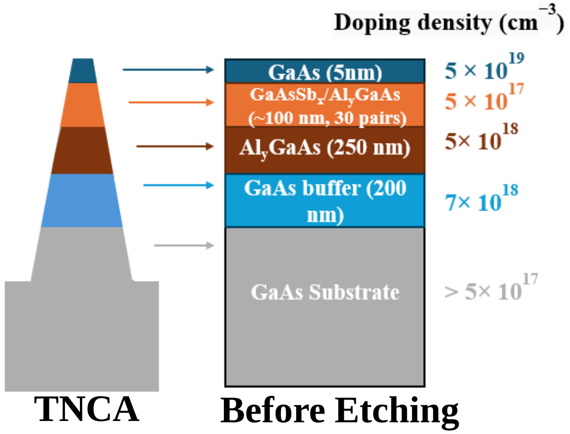
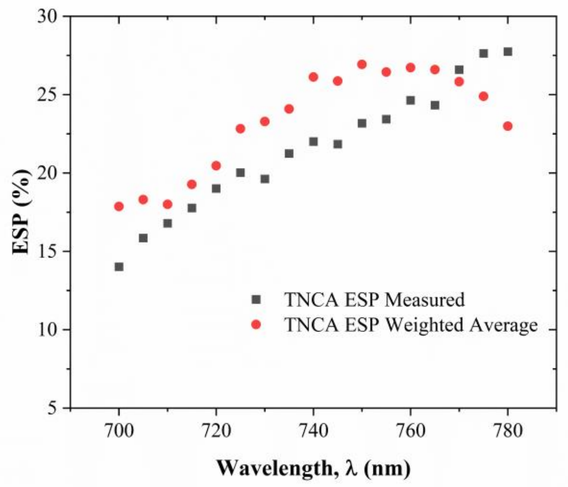


Figure: (a) QE, and (b) Electron Spin Polarization (ESP) comparison between truncated nanocone array (TNCA) and flat GaAsSb/AlGaAs SSL photocathodes.



ESP estimated for TNCA by different emission region contribution:



* [a] *AIP Advances* 8, 075308 (2018)

Summary

- **Observed QE enhancement in 500-680 nm waveband at room temperature activation. Peak near 580 nm due to magnetic dipole (MD) excitation mode.**

- **Lifetime enhancement by a factor of 7.5 (1/e) and 5.6 (charge) respectively, compared to the flat GaAs at room temperature.**

- **At higher activation temperature, QE decreased while operational lifetime (both 1/e and charge) is significantly increased (~ 42 times at 35° C).**

- **~20-30% ESP of TNCA GaAsSb/AlGaAs SSL in 750-800 nm wavelength region.**
  - **ESP can be improved by having SSL pairs deposited both on top and lateral surfaces of truncated nanocones.**

- **Test of emittance and lifetime performance in high voltage gun in near future.**

Acknowledgement

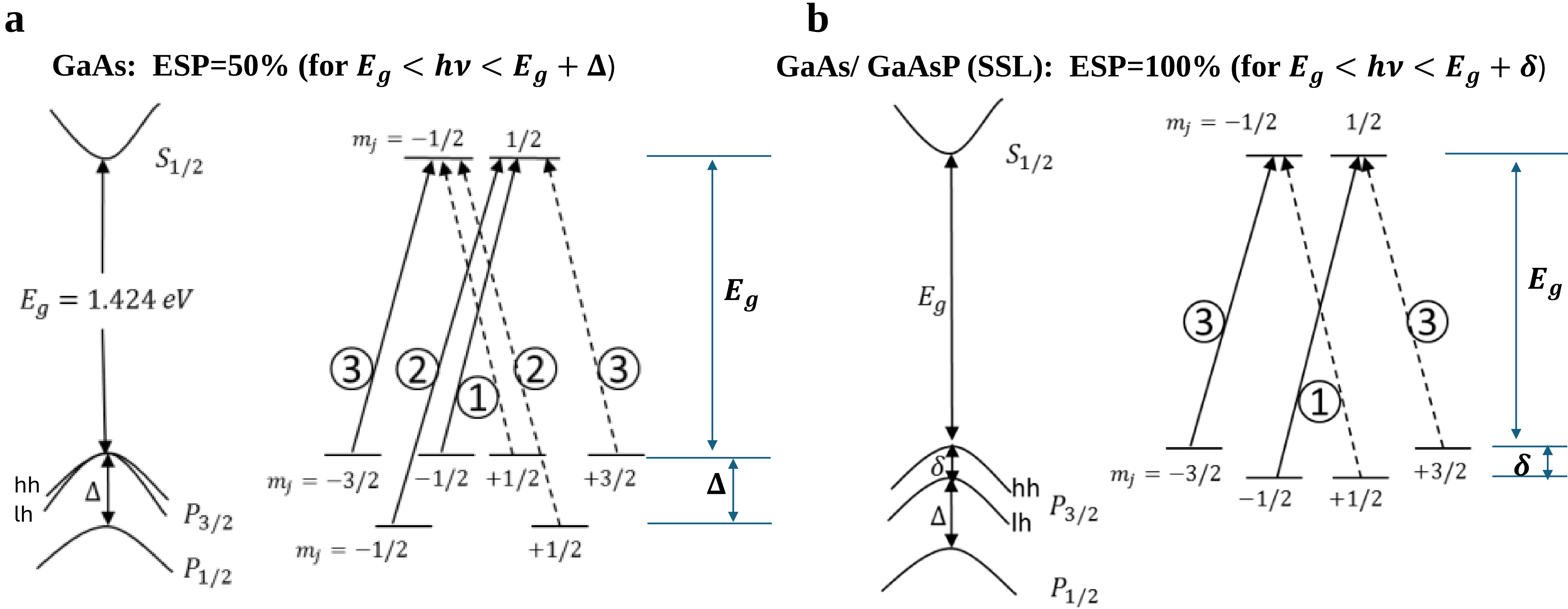
We would like to thank the JLAB CIS group for the essential support, in particular M. Stutzman, J. Grames, and A. Kachwala.

Thanks For Your Attention!

Backup Slides

GaAs Vs. GaAs/GaAsP Strained-Superlattice (SSL):

$$\text{Electron spin polarization , ESP} = \frac{P_{+1/2} - P_{-1/2}}{P_{+1/2} + P_{-1/2}}$$



a

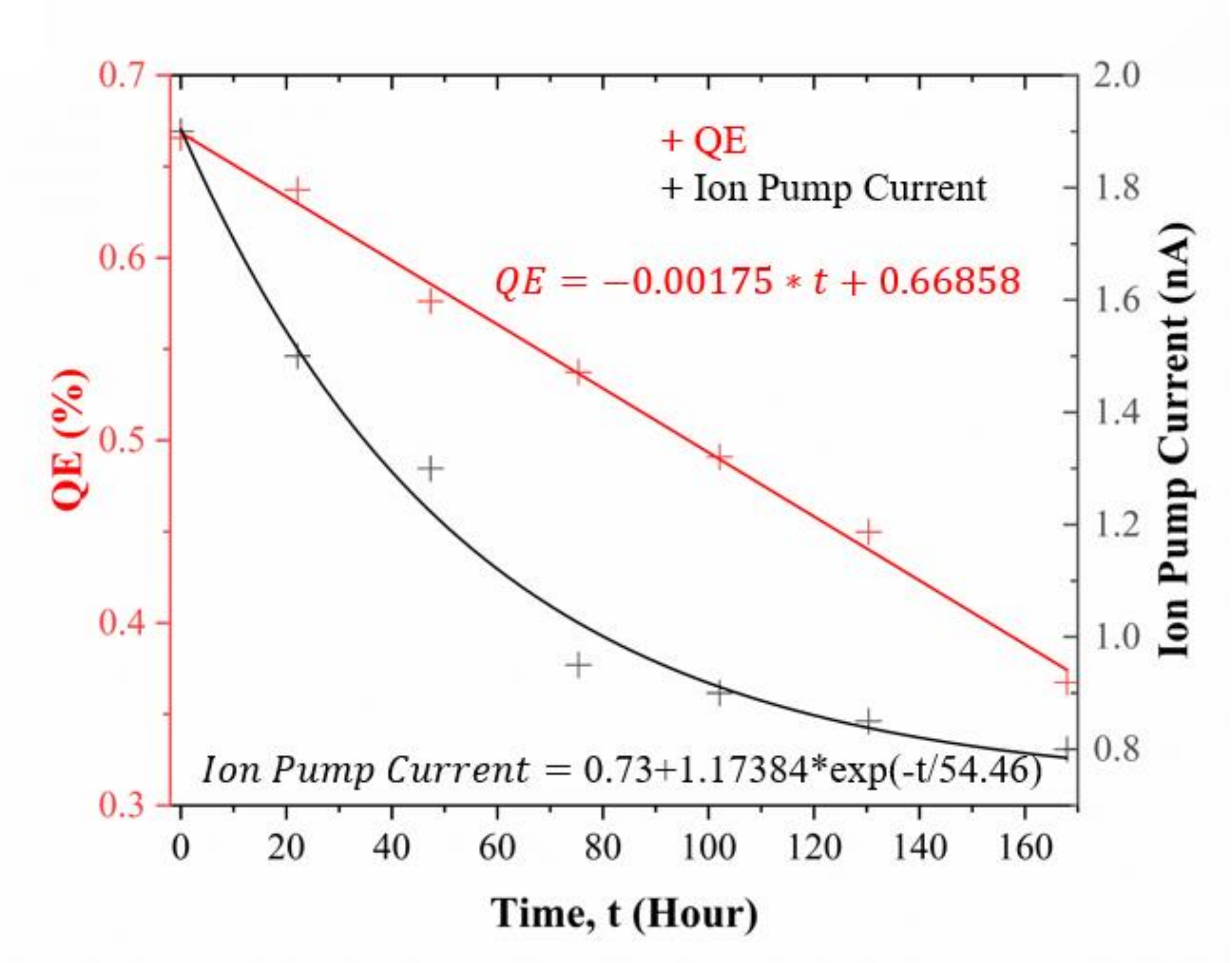
GaAs: ESP=50% (for $E_g < h\nu < E_g + \Delta$)

b

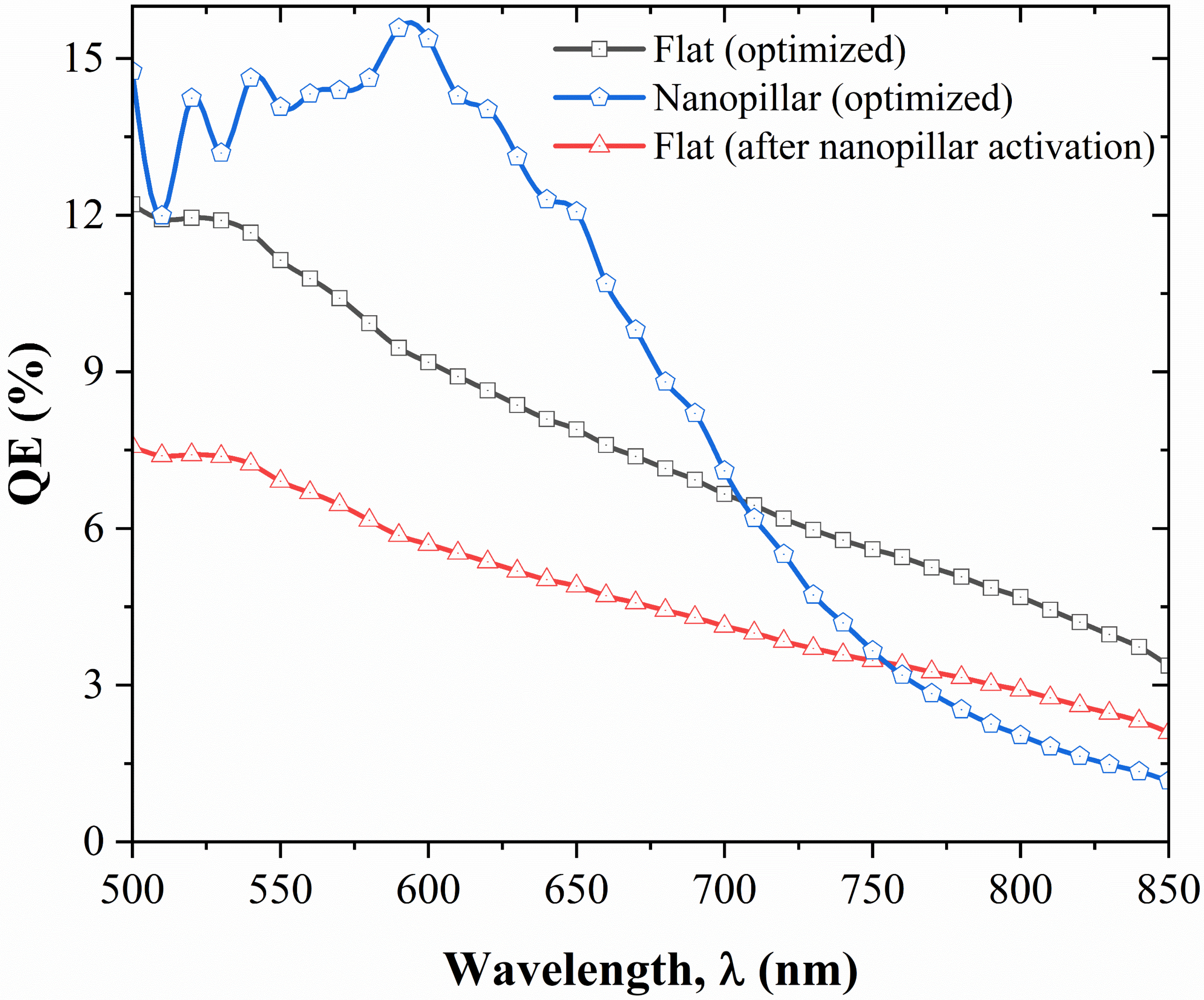
GaAs/ GaAsP (SSL): ESP=100% (for $E_g < h\nu < E_g + \delta$)

Figure: Energy bands diagram of (a) GaAs and (b) GaAs/GaAsP SSL. Solid lines reflect the possible transition due to right circularly polarized light and the dashed lines represents the possible transitions due to left circularly polarized light.

Dark Lifetime of TNCA at Room Temperature Activation:

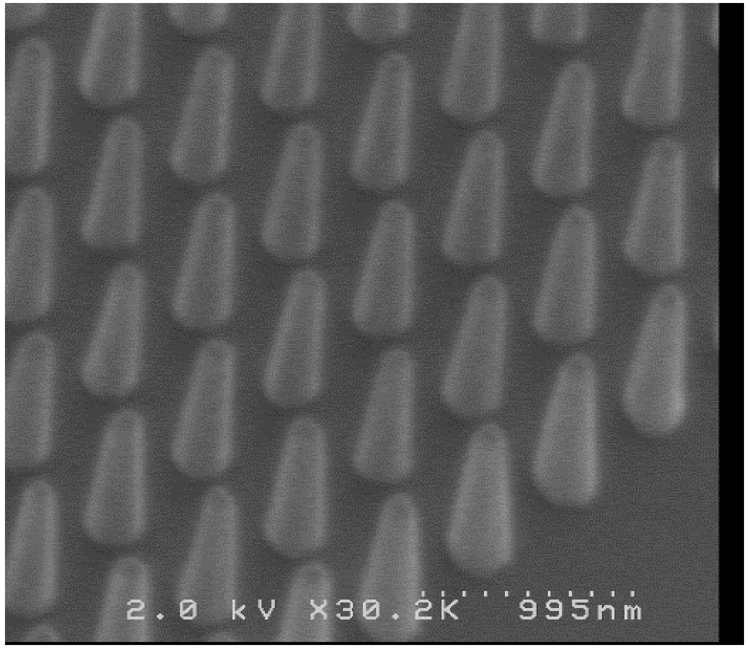


Optimizing the Activation Layer

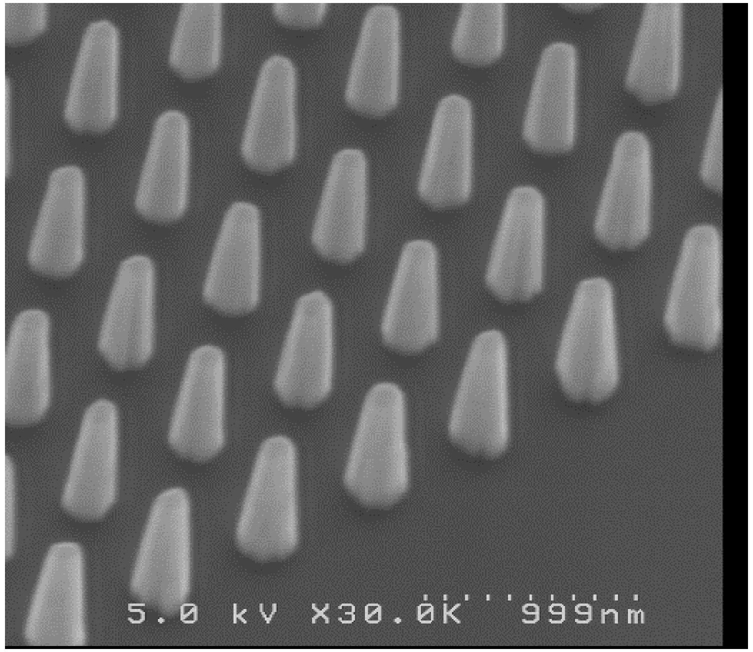


- Firstly, the flat side of GaAs wafer was activated (black curve).
- The nanopillar region was barely showing any QE (not shown in the figure).
- Activation was carried out on nanopillar region and optimized on the nanopillar side (blue curve).
- After optimizing the activation layer on nanopillar region the QE was found to be significantly dropped on flat side (red curve).
- Physically it is impossible to have optimized activation layer in every emission surface.

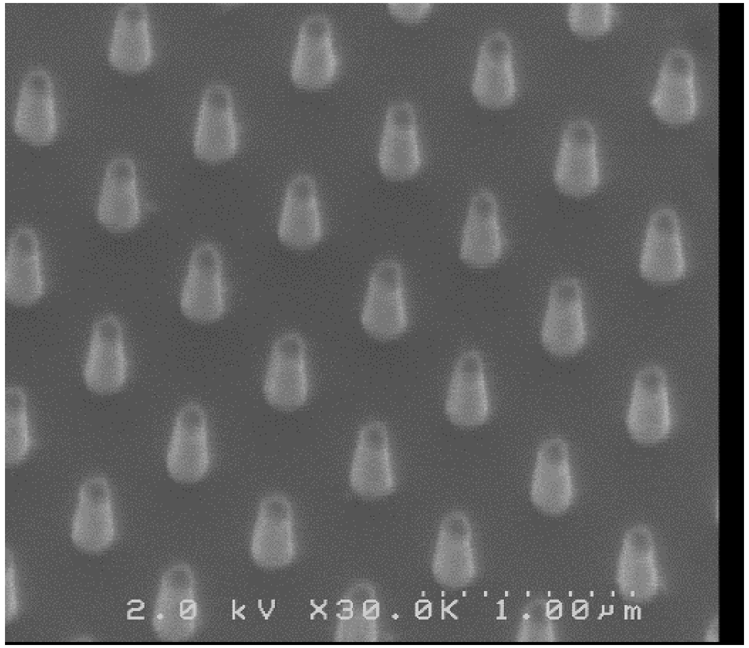
Height = 1000 nm, Period = 600 nm



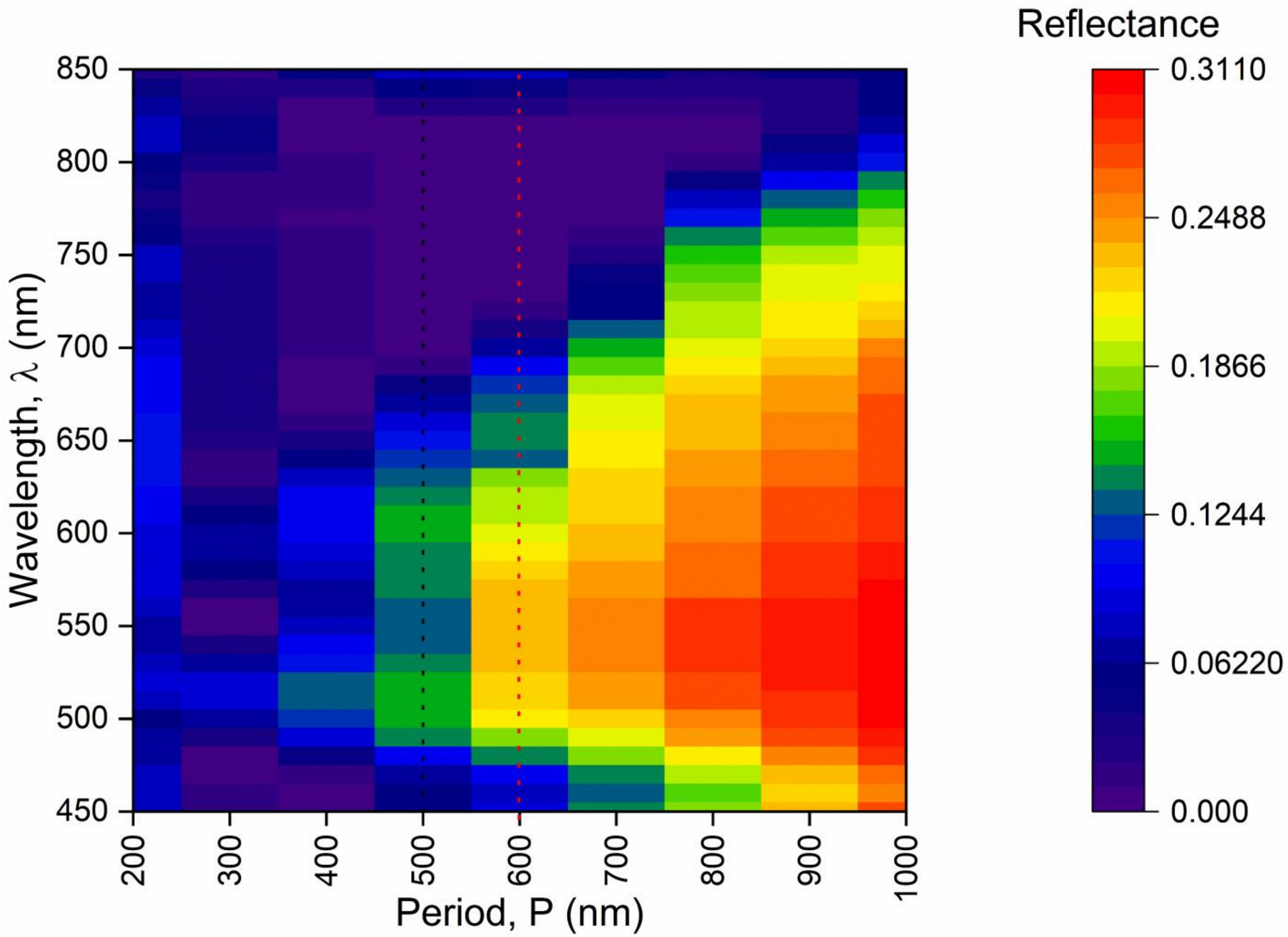
Height = 700 nm, Period = 600 nm

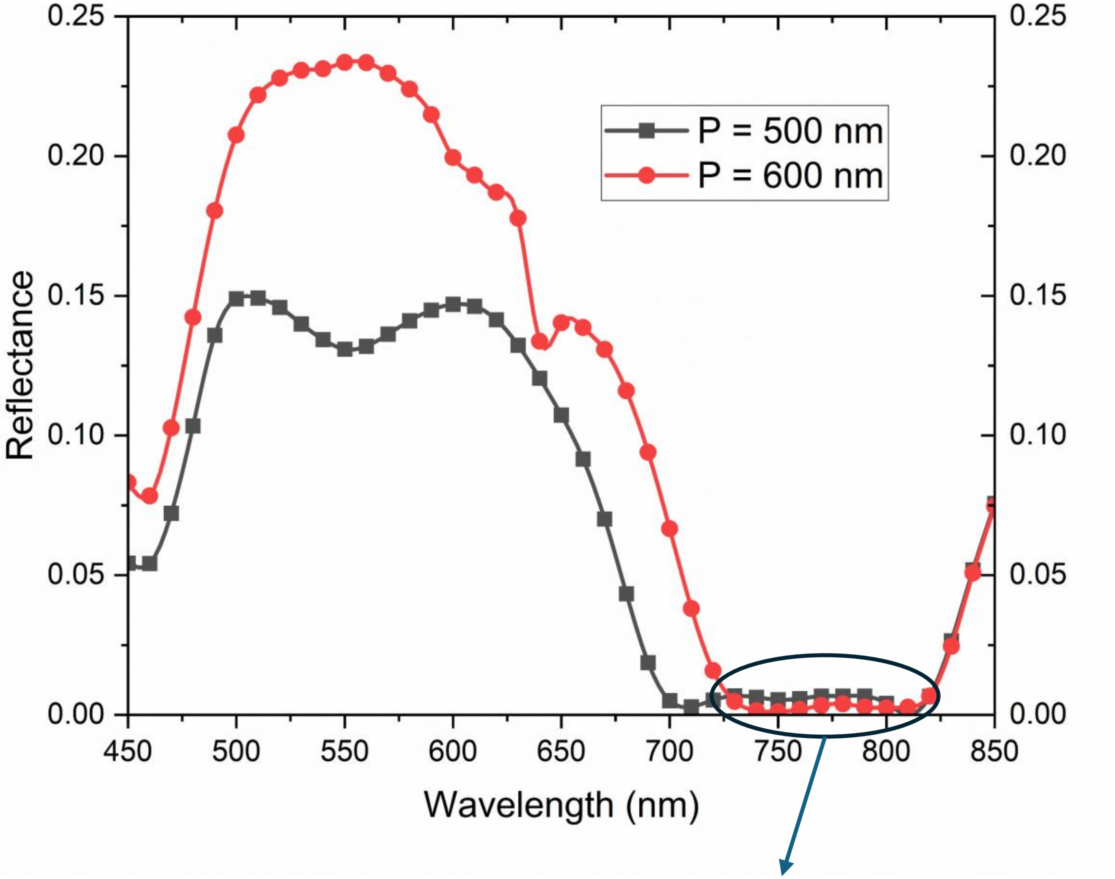


Height = 400 nm, Period = 600 nm



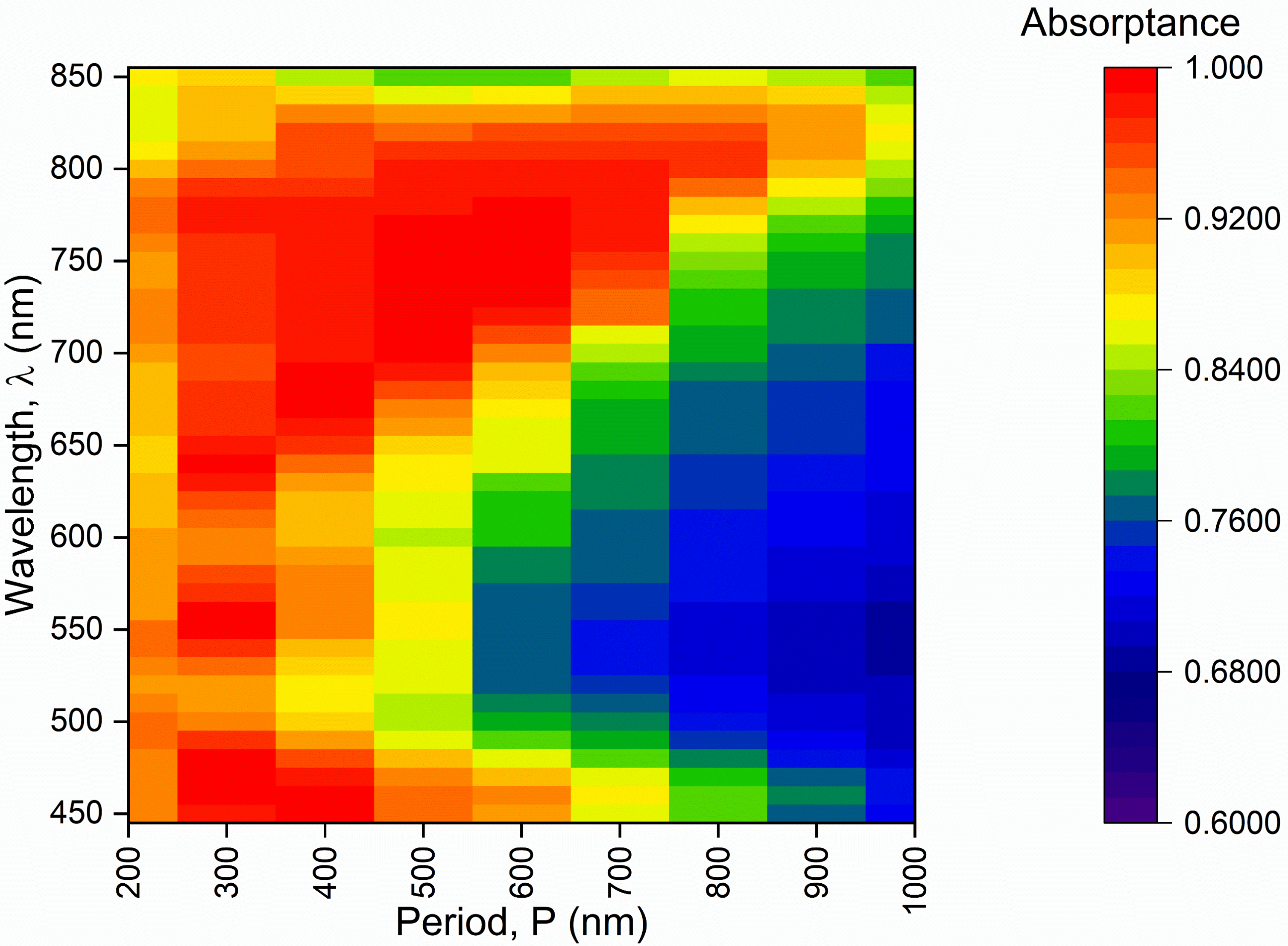
Reflectance at different period for D1,D2 = 137, 169 nm, H = 1000 nm





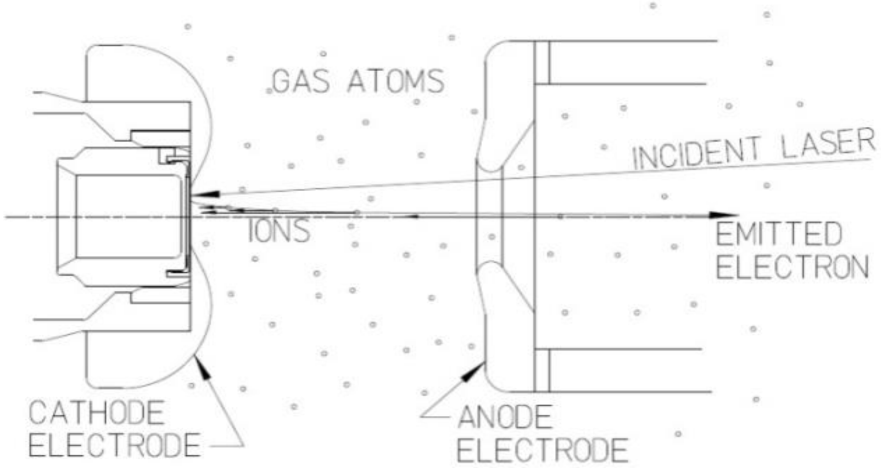
Backscattering is almost suppressed,
We expect the circular polarization of
light should be intact in this region,
Particularly at 750 nm

Absorption at different period for D1,D2 = 137, 169 nm, H = 1000 nm



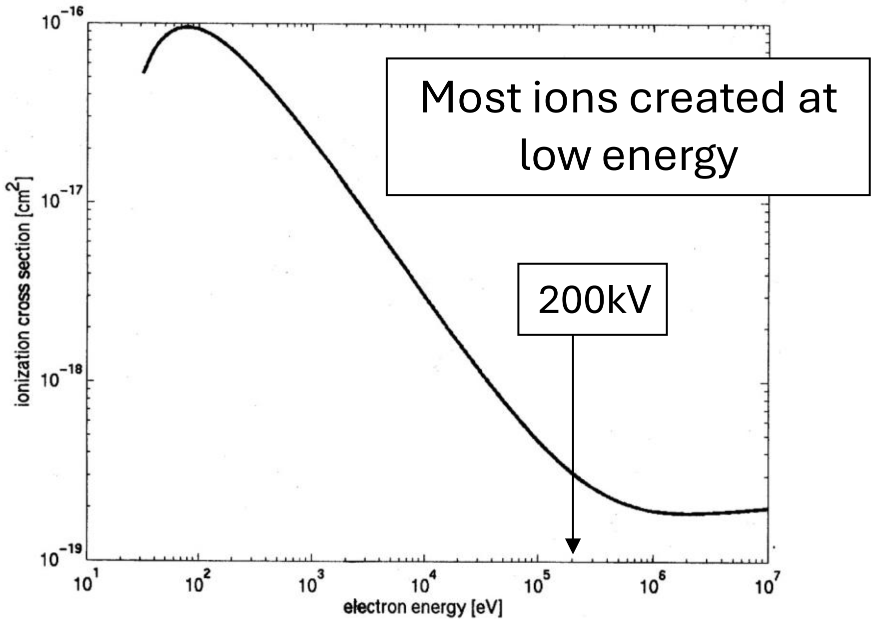
We expect the 1000 nm high nanopillar with Period of 600 nm should give wide bandwidth for suppressed back-scattering (725-820 nm) and ~99.5% absorption at 750 nm, which is expected to be optimized for both QE and spin polarization.

Imperfect Vacuum = Finite Lifetime



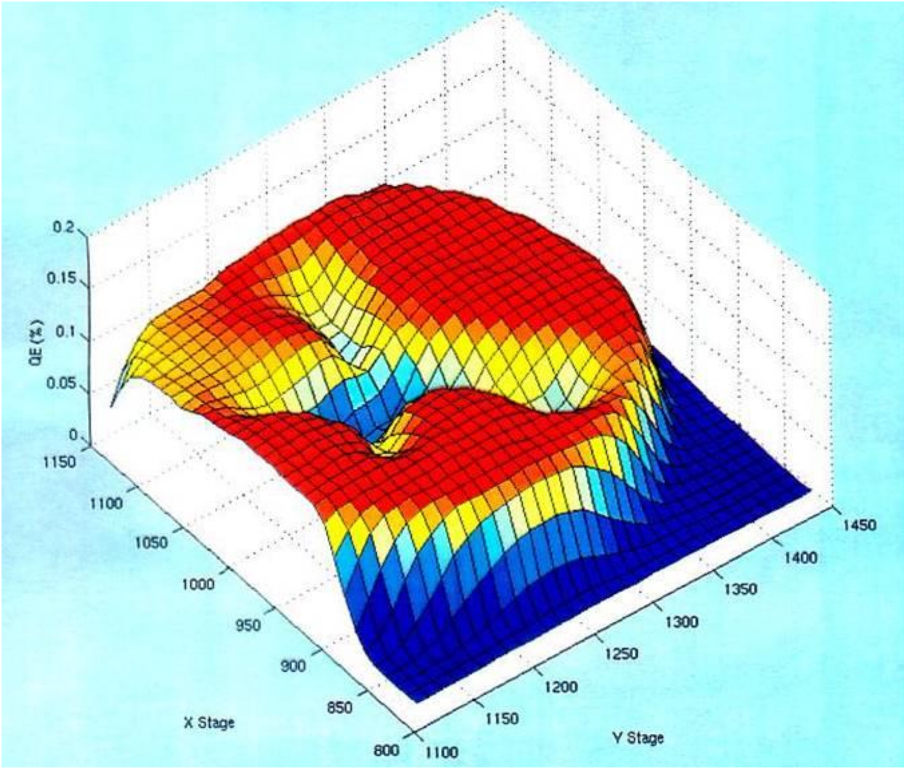
Ion bombardment -
notice characteristic “trench” from laser spot to electrostatic center of photocathode

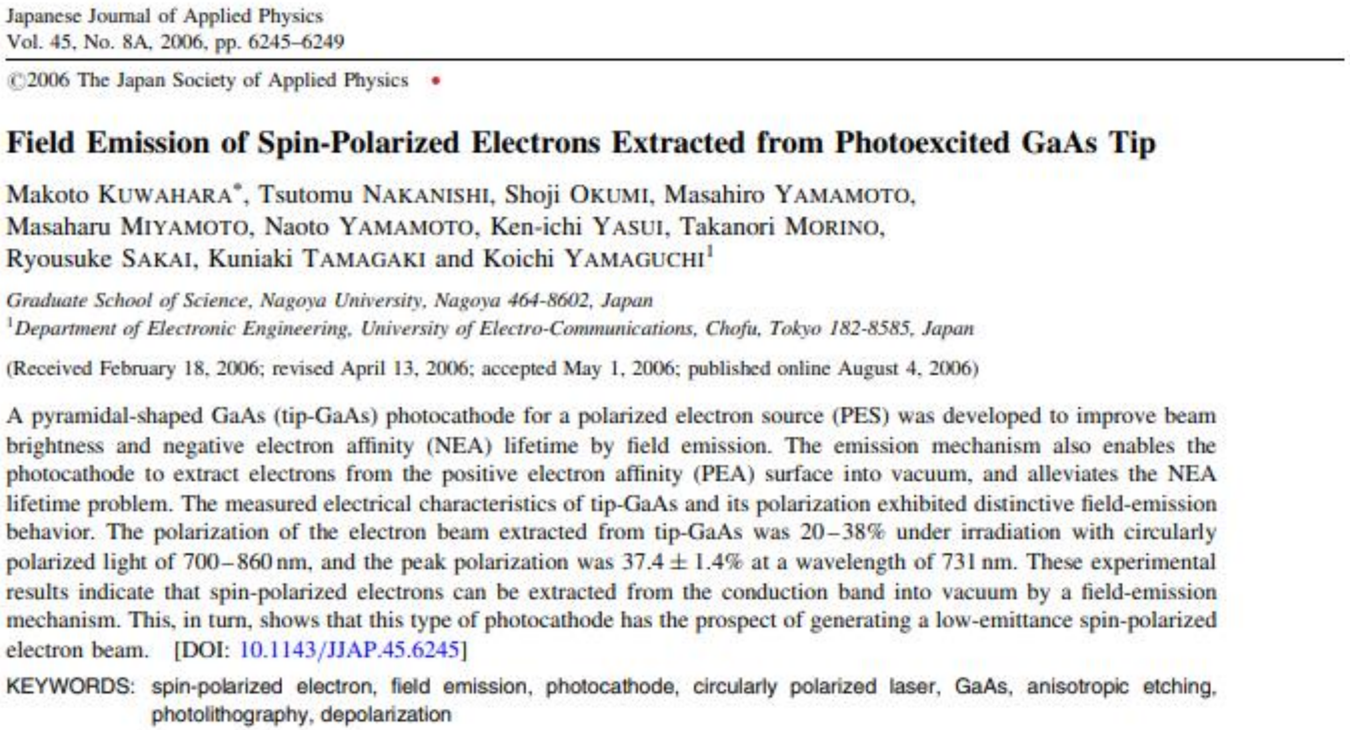
Ionization cross-section for



Most ions created at low energy

200kV





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Field Emission of Spin-Polarized Electrons Extracted from Photoexcited GaAs Tip

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A pyramidal-shaped GaAs (tip-GaAs) photocathode for a polarized electron source (PES) was developed to improve beam brightness and negative electron affinity (NEA) lifetime by field emission. The emission mechanism also enables the photocathode to extract electrons from the positive electron affinity (PEA) surface into vacuum, and alleviates the NEA lifetime problem. The measured electrical characteristics of tip-GaAs and its polarization exhibited distinctive field-emission behavior. The polarization of the electron beam extracted from tip-GaAs was 20–38% under irradiation with circularly polarized light of 700–860 nm, and the peak polarization was 37.4 ± 1.4% at a wavelength of 731 nm. These experimental results indicate that spin-polarized electrons can be extracted from the conduction band into vacuum by a field-emission mechanism. This, in turn, shows that this type of photocathode has the prospect of generating a low-emittance spin-polarized electron beam. [DOI: 10.1143/JJAP.45.6245]

KEYWORDS: spin-polarized electron, field emission, photocathode, circularly polarized laser, GaAs, anisotropic etching, photolithography, depolarization

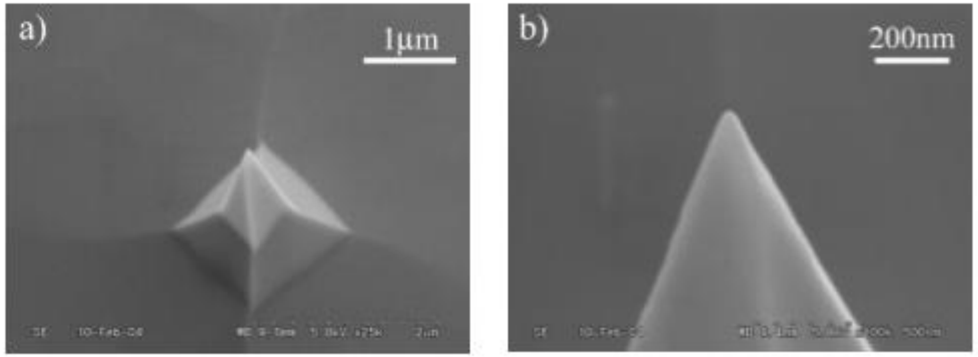

Fig. 1. SEM images of tip-GaAs fabricated by anisotropic wet etching: (a) overview of pyramidal-shaped GaAs (tip-GaAs) and (b) magnified image of pointed tip.

* Didn’t observe any field emission below 4.8 MV/m field strength.

We can deposit SSL layers on lateral and top surfaces just like the Ge NP solar cell with multiple junction.

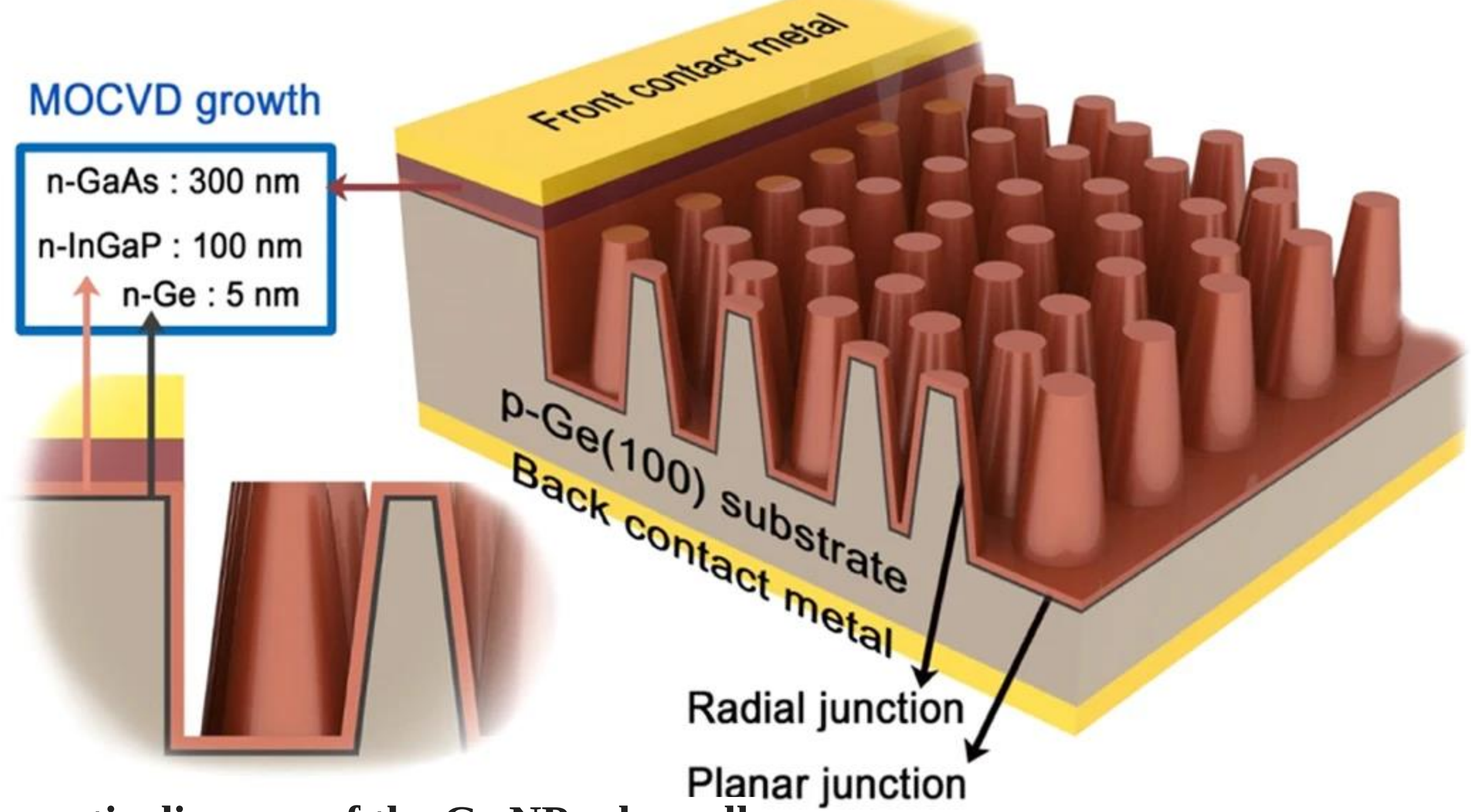

Figure : A schematic diagram of the Ge NP solar cell.

The Ge NP solar cell consists of three parts including metal contact area, radial junction area, and planar junction area. An n-type Ge emitter layer (5 nm), an n-type InGaP window layer (100 nm), and an n-type GaAs ohmic layer (300 nm) are grown by MOCVD on the p-type Ge NP templates. The ohmic layer on the junction area is selectively removed during the device fabrication process.

Kim, Y., Lam, N., Kim, K. *et al.* Ge nanopillar solar cells epitaxially grown by metalorganic chemical vapor deposition. *Sci Rep* **7**, 42693 (2017). https://doi.org/10.1038/srep42693