Study of Quantum Efficiency Enhancement in Different Mie-type Nanostructured NEA GaAs Photocathodes

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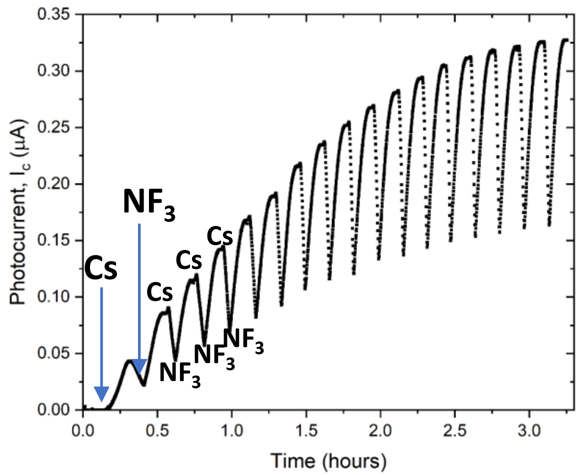
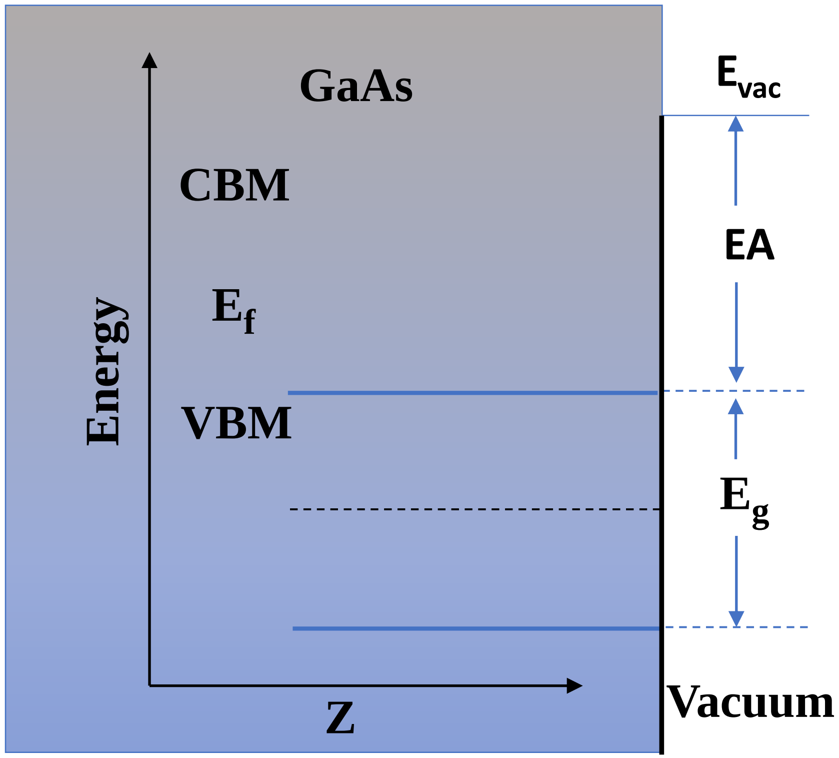
GaAs Negative Electron Affinity (NEA) Photocathode

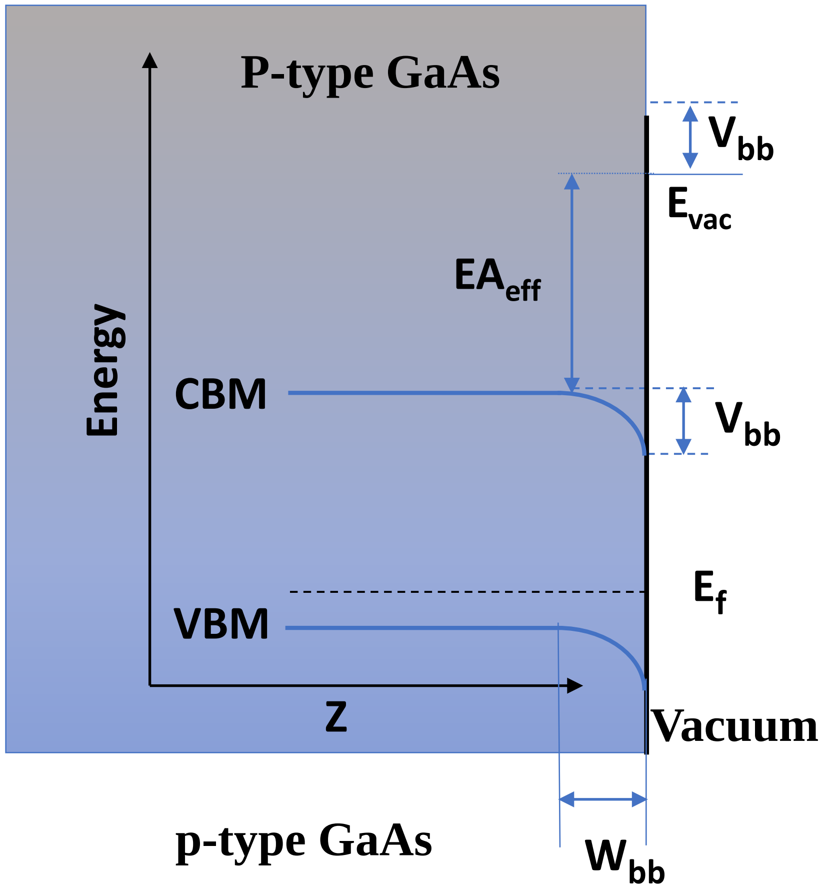


E_g = 1.42 eV (~873 nm)

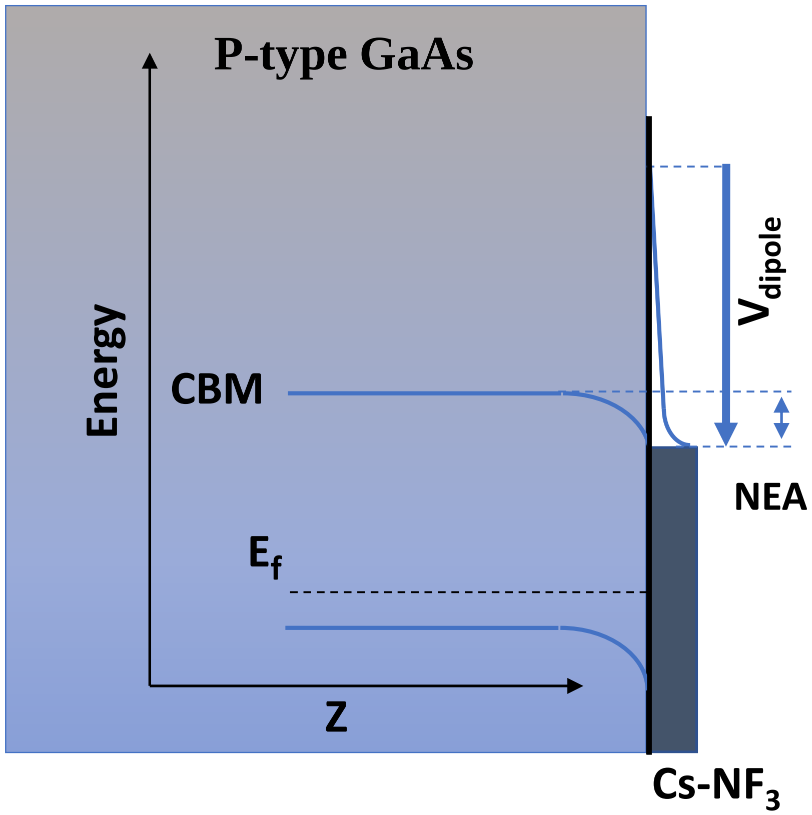
EA ~ 4.0 eV



Intrinsic GaAs

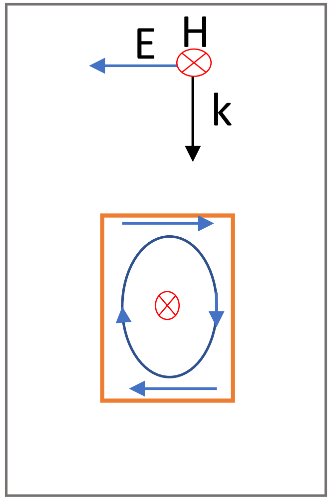


p-type GaAs



NEA p-type GaAs

Mie-type Nanostructures:



- Subwavelength sized nanostructures of dielectric material with higher refractive index. Example: GaAs, Silicon nanopillar array (NPA).

- Size: Diameter, D≈ $\frac{\lambda}{n}$ (where n is refractive index of material)

- Mie resonance theory [a],
  $$\frac{nD}{\lambda} = 1\ (dipole), 2\ (quadrupole), \ldots$$

H= 1200 nm, L= 142 nm, $\lambda = 780\ nm$

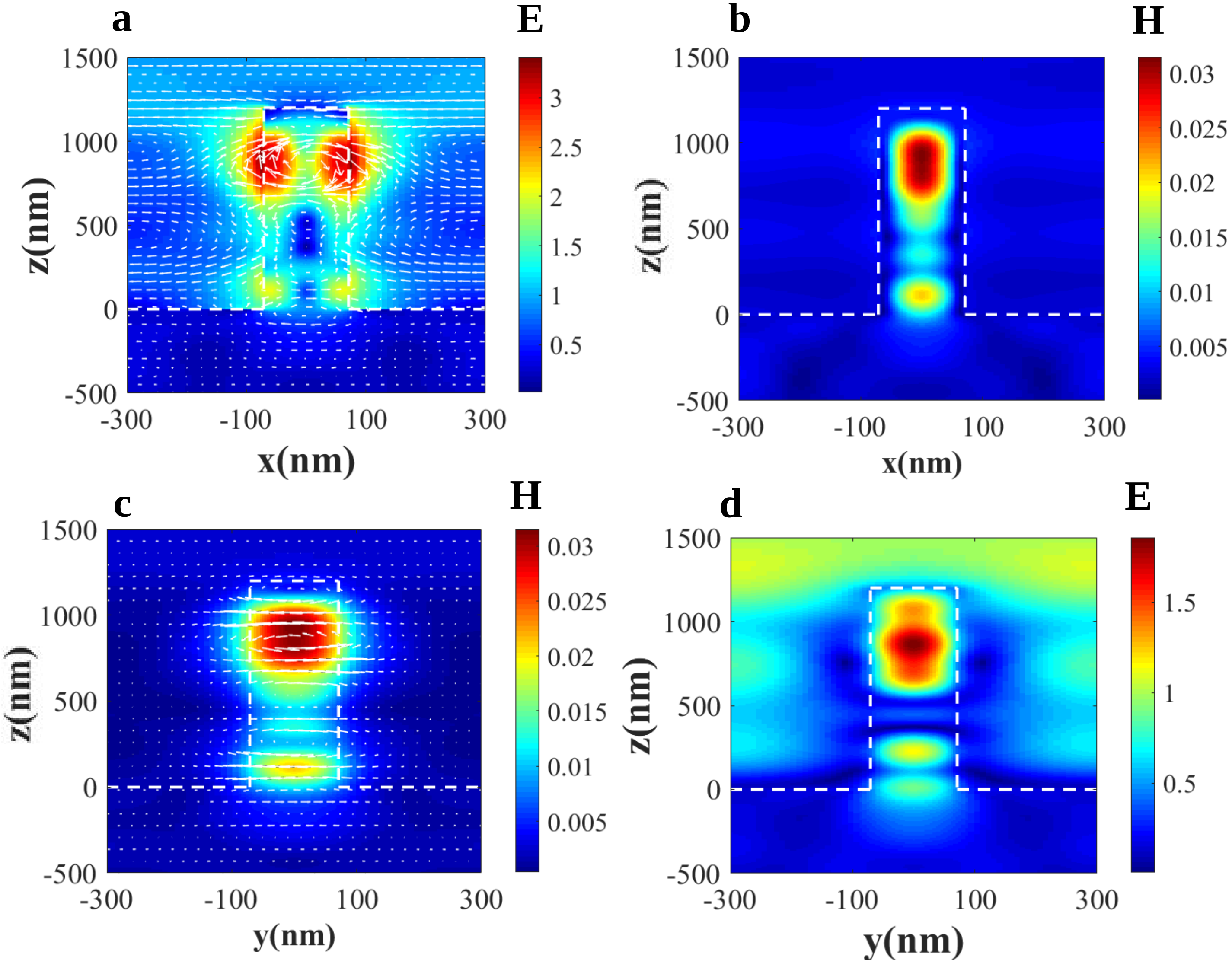
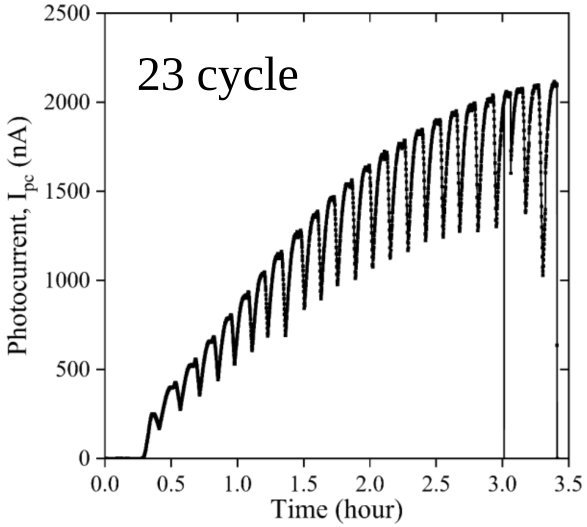


Figure : a) E-field distribution and field lines (white arrow), b) resonance enhanced H-field c) H-field distribution and field lines (white arrow) and d) resonance enhanced E-field distribution in Mie type nanosquare column.

[a] Optically resonant dielectric nanostructures, Science 354(6314), (2016). DOI: 10.1126/science.aag2472

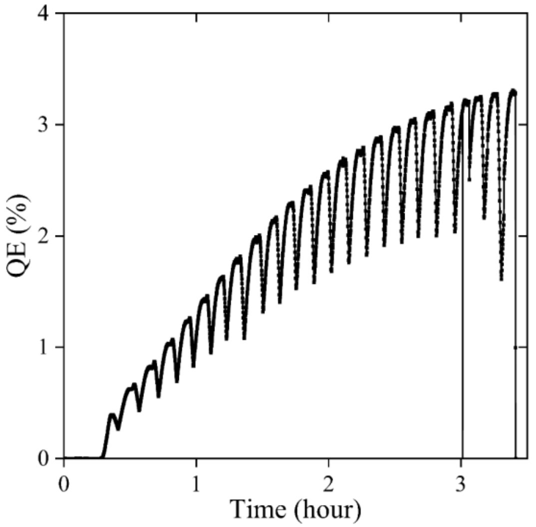
Experimental Results

Activation (Photocurrent Vs. Time)



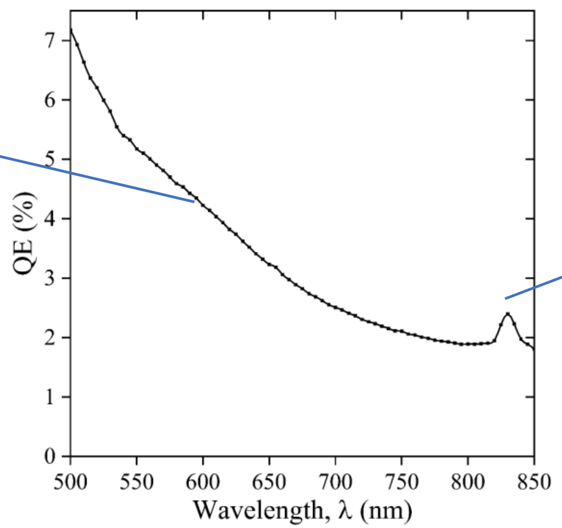
$$QE = \frac{Ihc}{\lambda eP} \times 100\% \approx 124 \times \frac{I(\mu A)}{\lambda\,(nm) \times P\,(mW)} \times 100\%$$

Activation (QE Vs. Time)



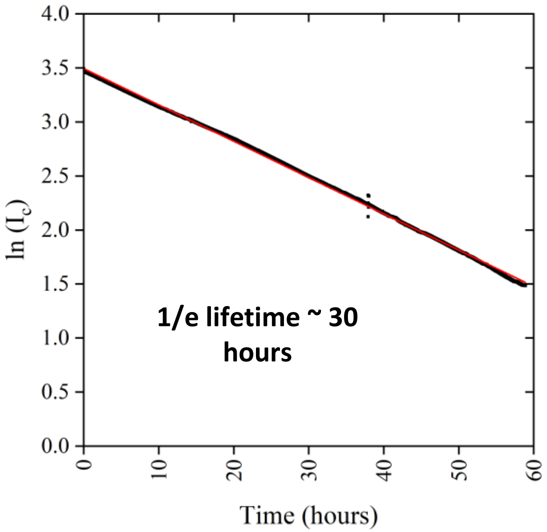
Spectral Scan

QE = ~ 4.3% at 600 nm (quadrupole mode excitation)

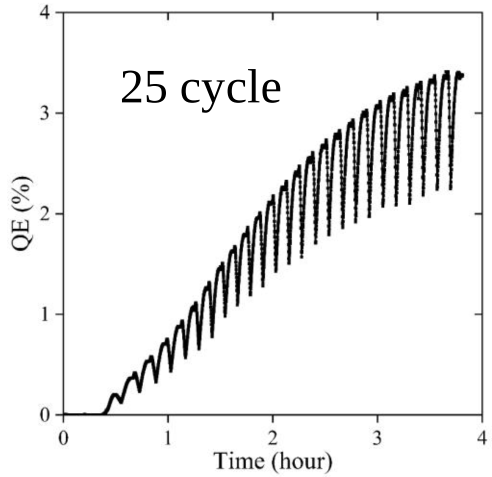


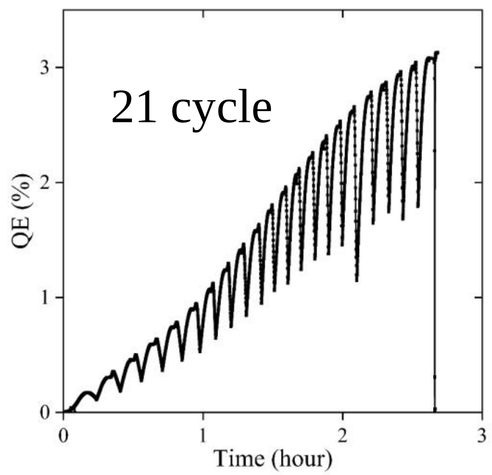
QE = ~ 2.4% at 830 nm (dipole mode excitation)

Lifetime at 830 nm

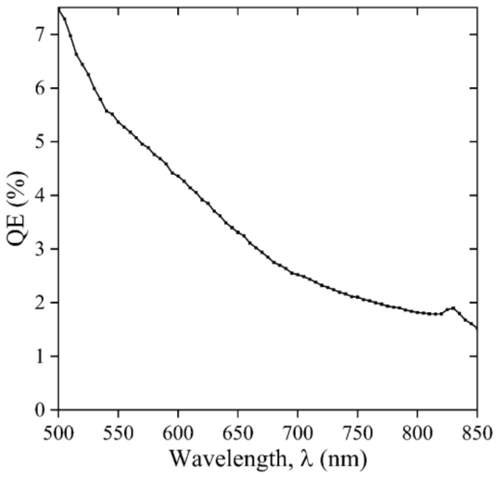


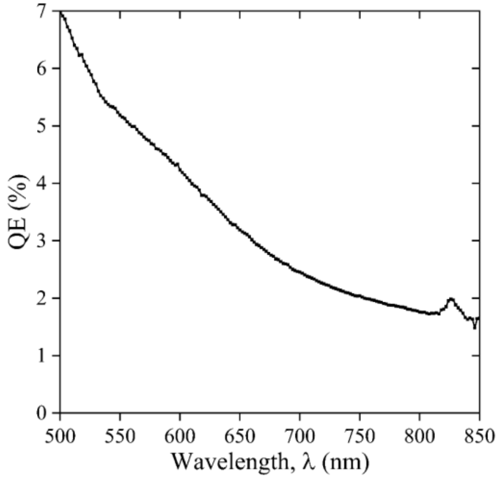
Activation (QE Vs. Time)



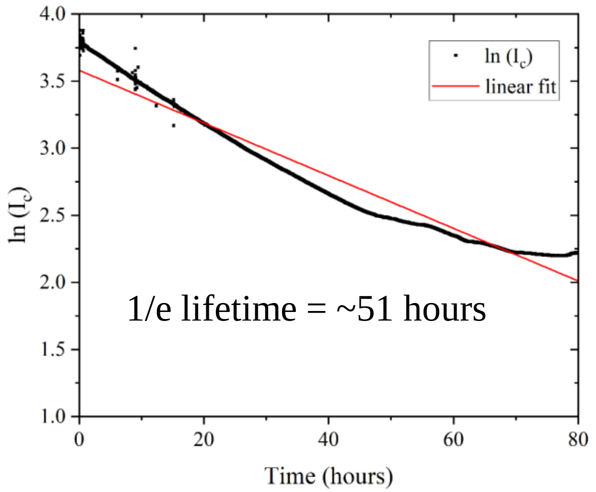


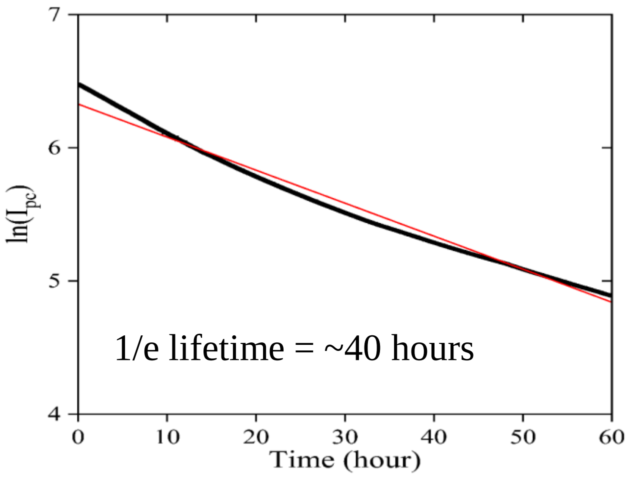
Spectral Scan



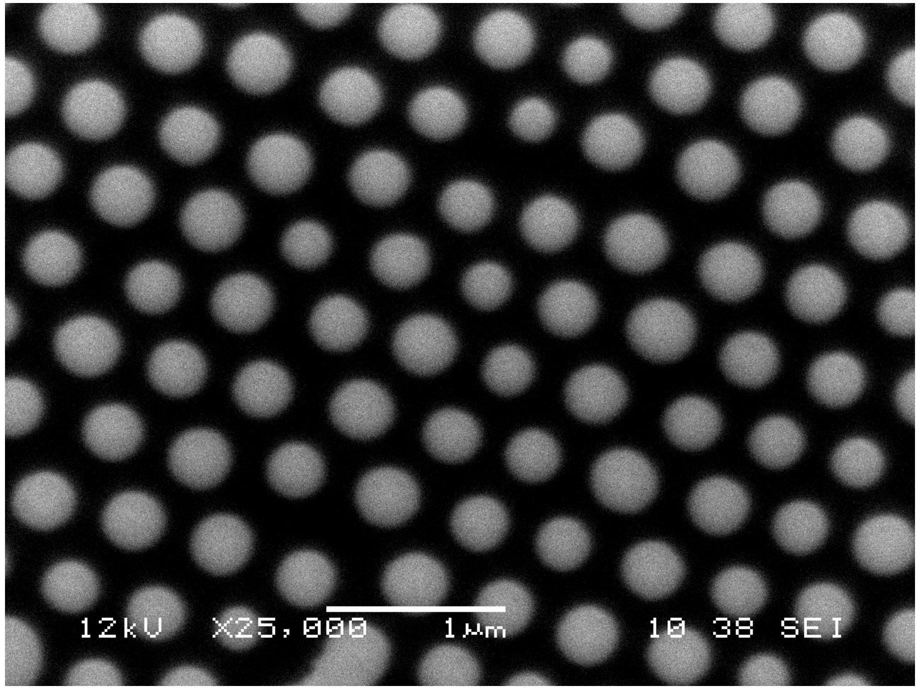


Lifetime at 830 nm

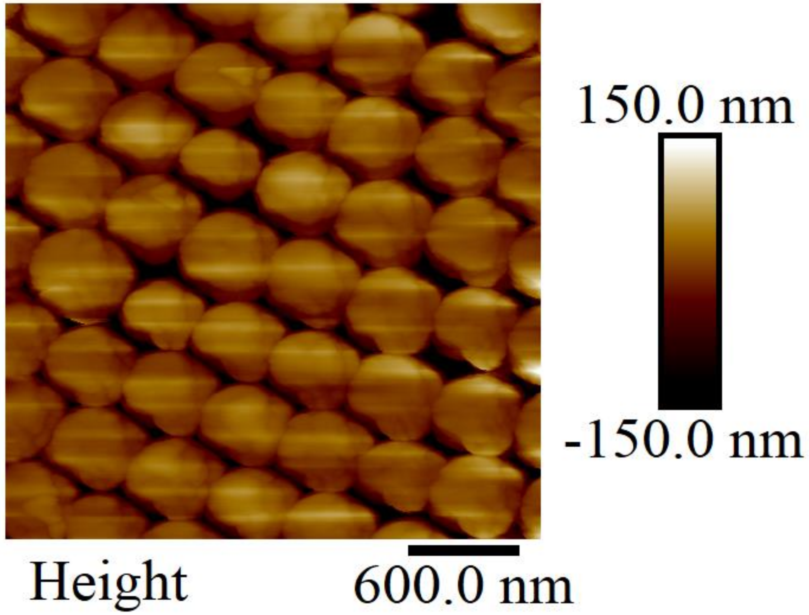




Sample:
22225a



SEM image for GaAs nanopillar array



Height = ~230 nm

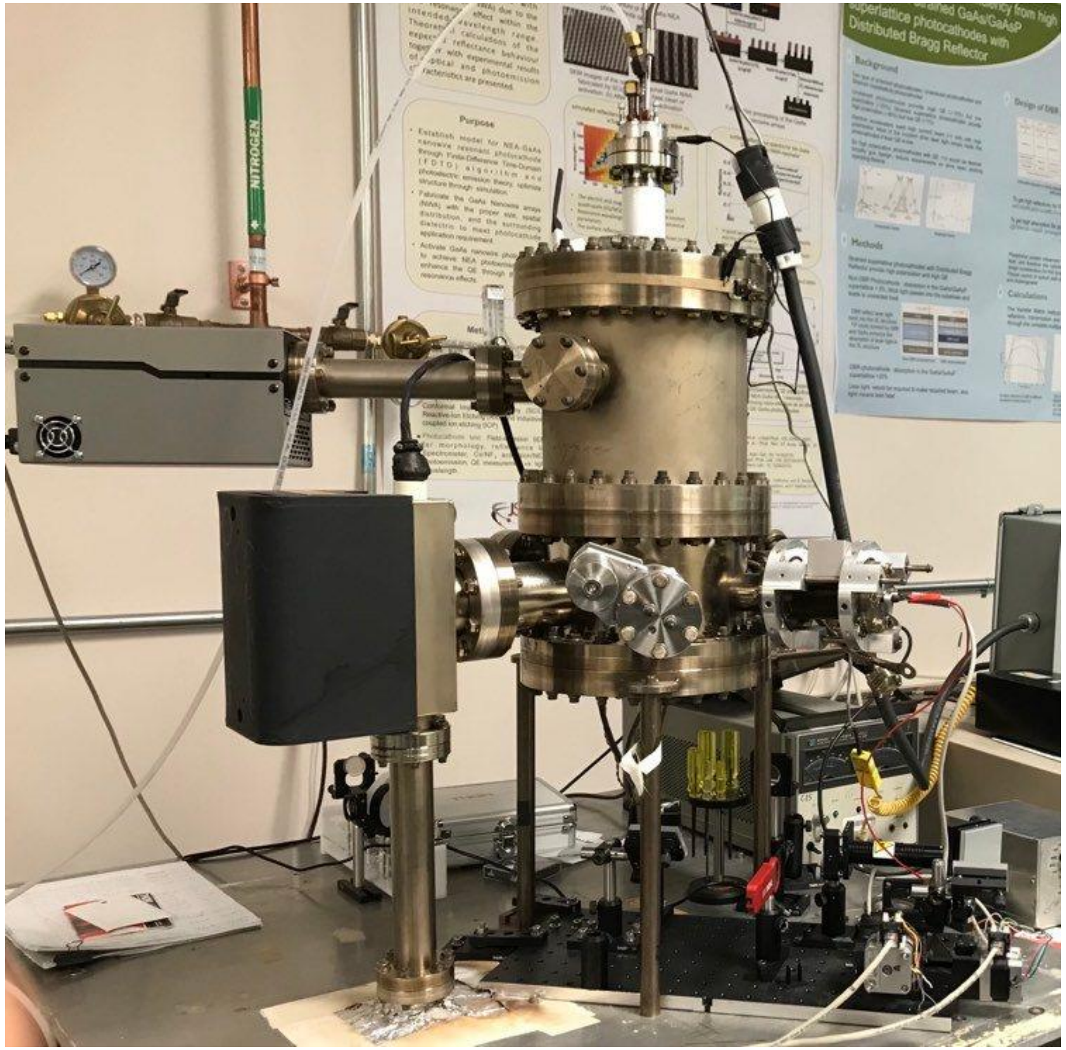
AFM image for GaAs nanopillar array

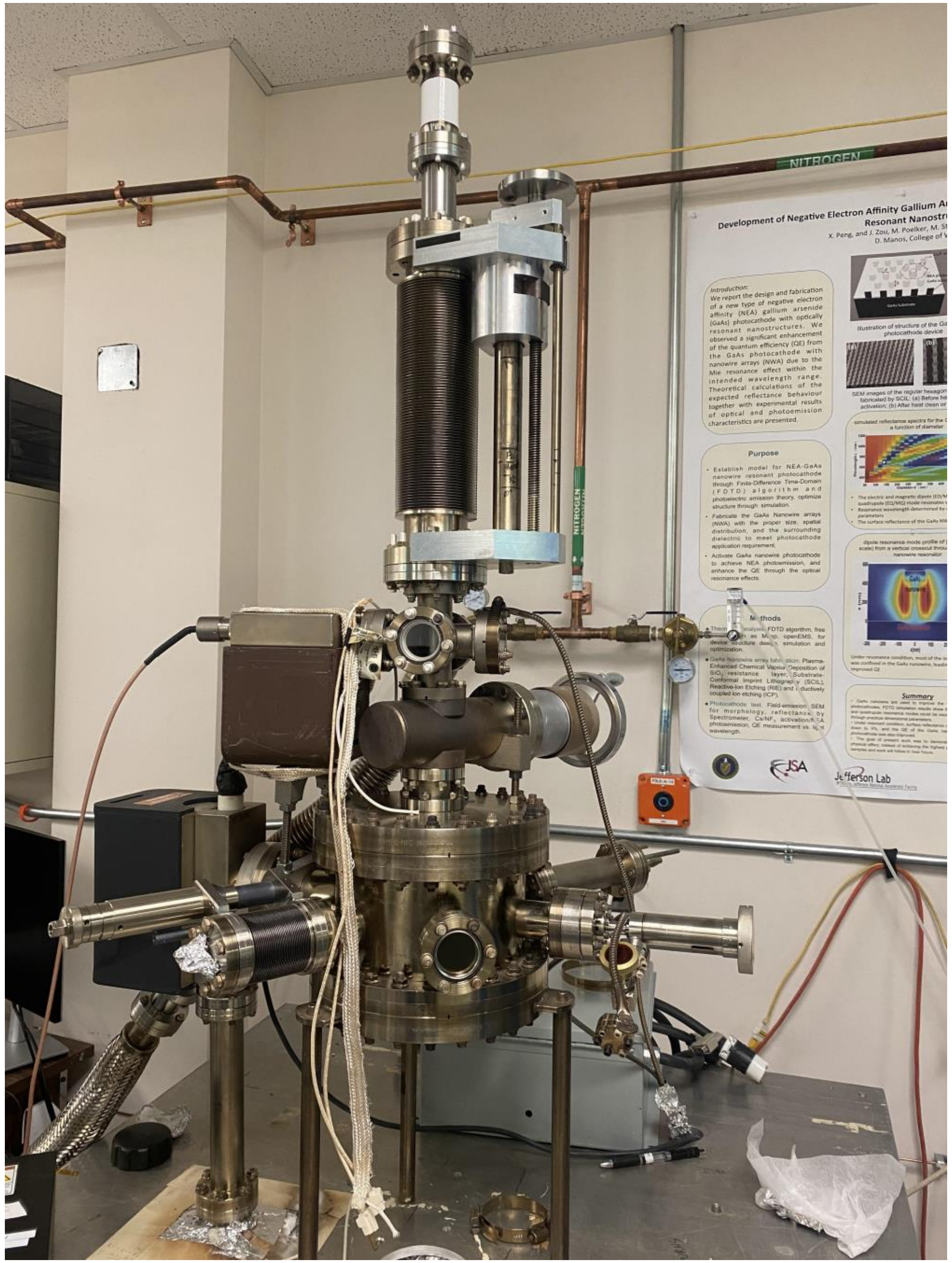
Diameter varies between 200-331 nm
Period: 480-560 nm

Mie resonance theory:
$\frac{nD}{\lambda}$=1 (Dipole), $\frac{nD}{\lambda}$=2 (Quadrupole) [a]

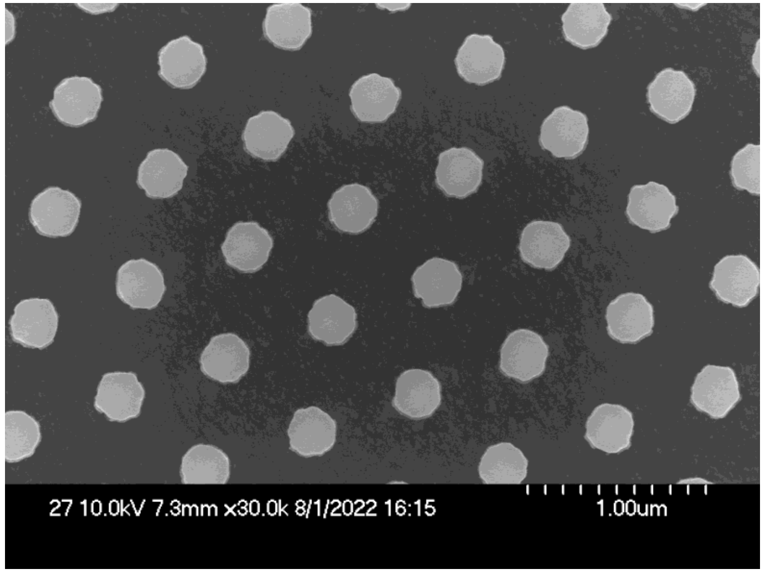
Pillar diameter, D (nm)	$\frac{nD}{\lambda}$	
	λ=830 nm	λ=600 nm
279.16	1.2	1.8
303.27	1.3	1.9
251.54	1.1	1.6
201.92	0.88	1.28
330.60	1.44	2.099

[a] Optically resonant dielectric nanostructures, Science 354(6314), (2016).
DOI: 10.1126/science.aag2472


NITROGEN
Purpose
Distributed Bragg Reflector
Methods

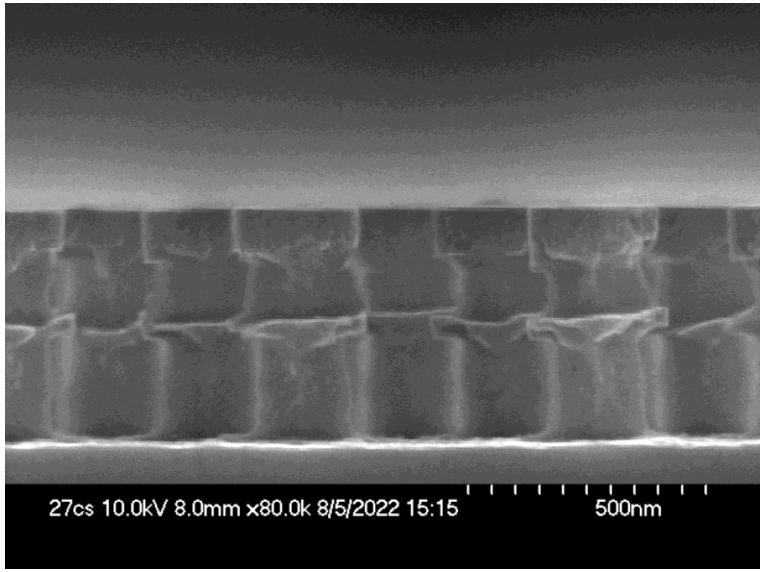

NITROGEN
Purpose
Summary

a



Diameter:
245-260 nm

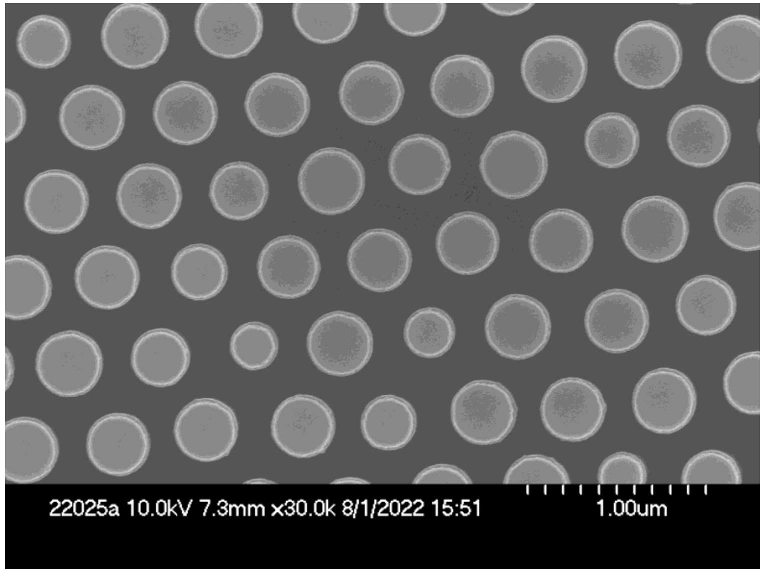
Period:
~630 nm



Height = 482-487 nm

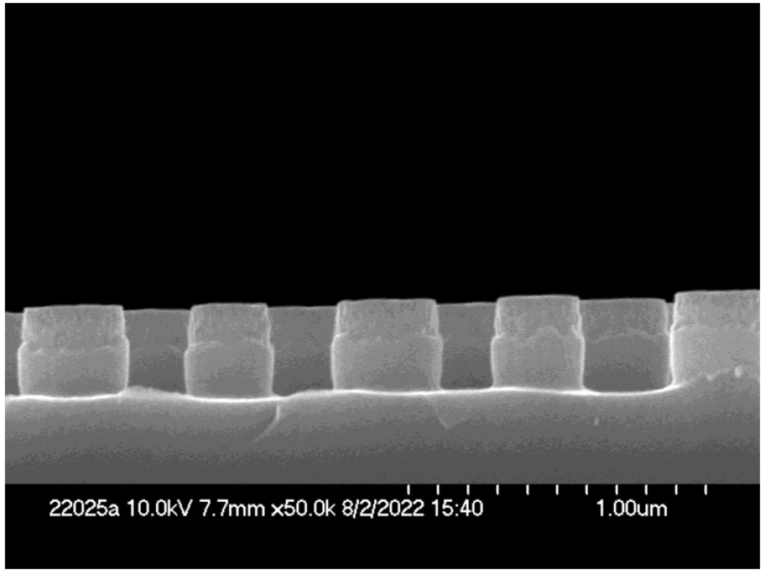
$\lambda_{dip.} = 760 - 840$ nm

b



Diameter:
270-330 nm

Period:
500-515 nm

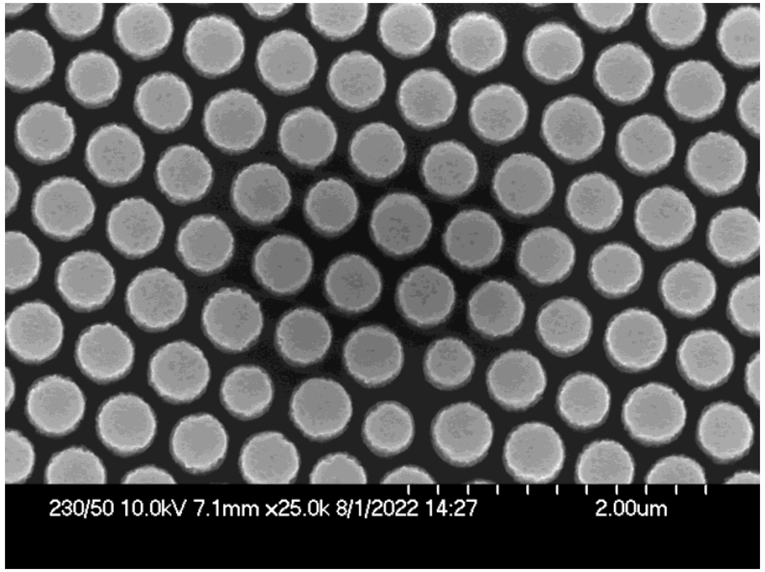


Height = 310-320 nm

$\lambda_{dip.} = \sim 830\ nm$

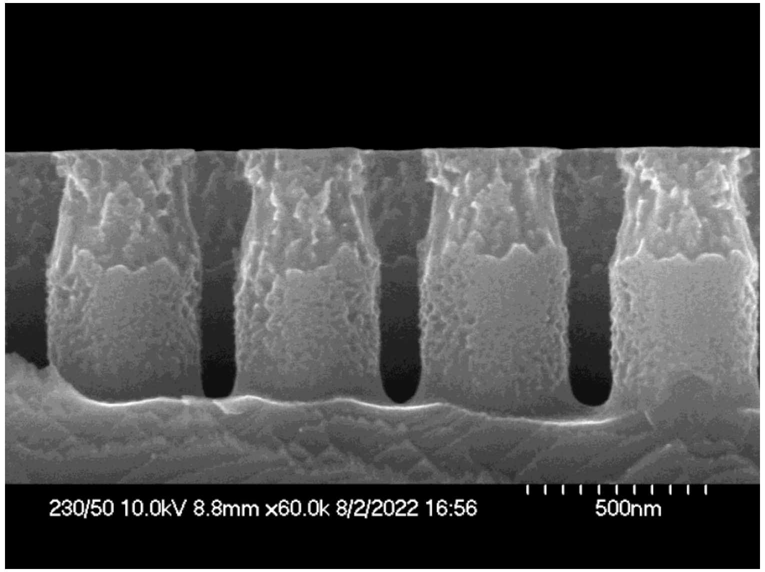
$\lambda_{quad.} = 600 - 700\ nm$

c



Diameter:
330-360 nm

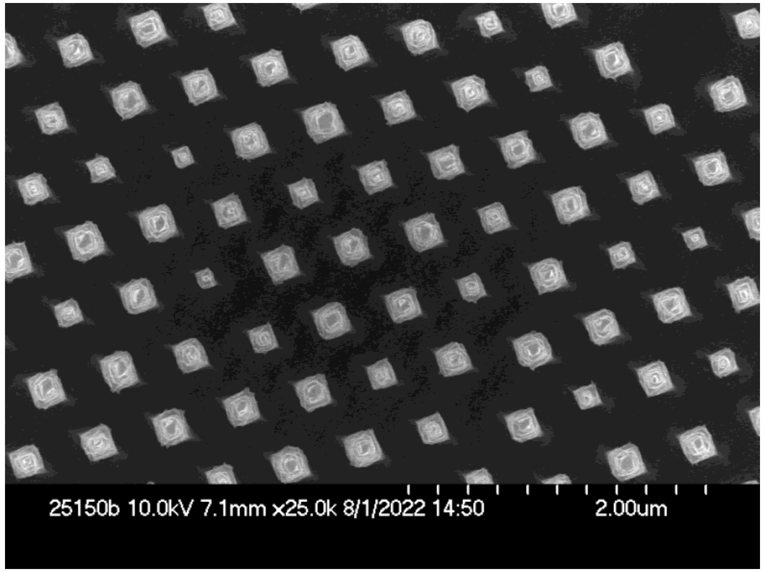
Period:
480-510 nm



Height = 730-760 nm

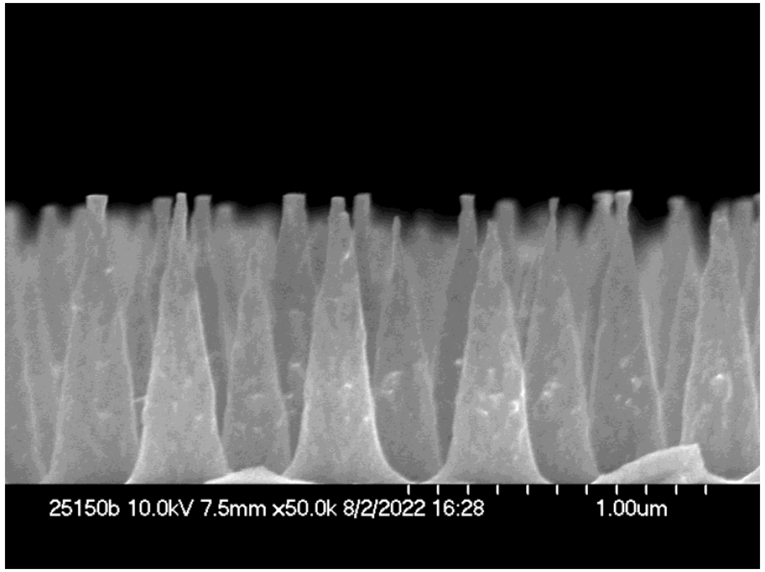
$\lambda_{quad.} = 650 - 800\ nm$

d



Side:
170-180 nm

Period:
~470 nm



Height =
950-1000 nm

Simulation of Different Mie-type Nanostructures: Simulation Setup:

Simulation is based on Spicer's three step model:

1. Photoexcitation of electron — Lumerical FDTD →

Photoelectron generation probability,

$$P_g = \frac{\int g(\lambda, x, y, z)dxdydz}{\Phi}$$

where $g(x, y, z, \lambda) = \frac{\pi \epsilon_{im}(\lambda) E(x,y,z,\lambda)^2}{h}$ is photoelectron generation rate, and Φ is incident photon per unit time.

2. Photoelectron transport to the emission surface. — Lumerical CHARGE →

Photoelectron transport probability,

$$P_t = \frac{I_t}{e\int g(\lambda,x,y,z)dxdydz}$$

I_t is the electron current at short-circuit condition.

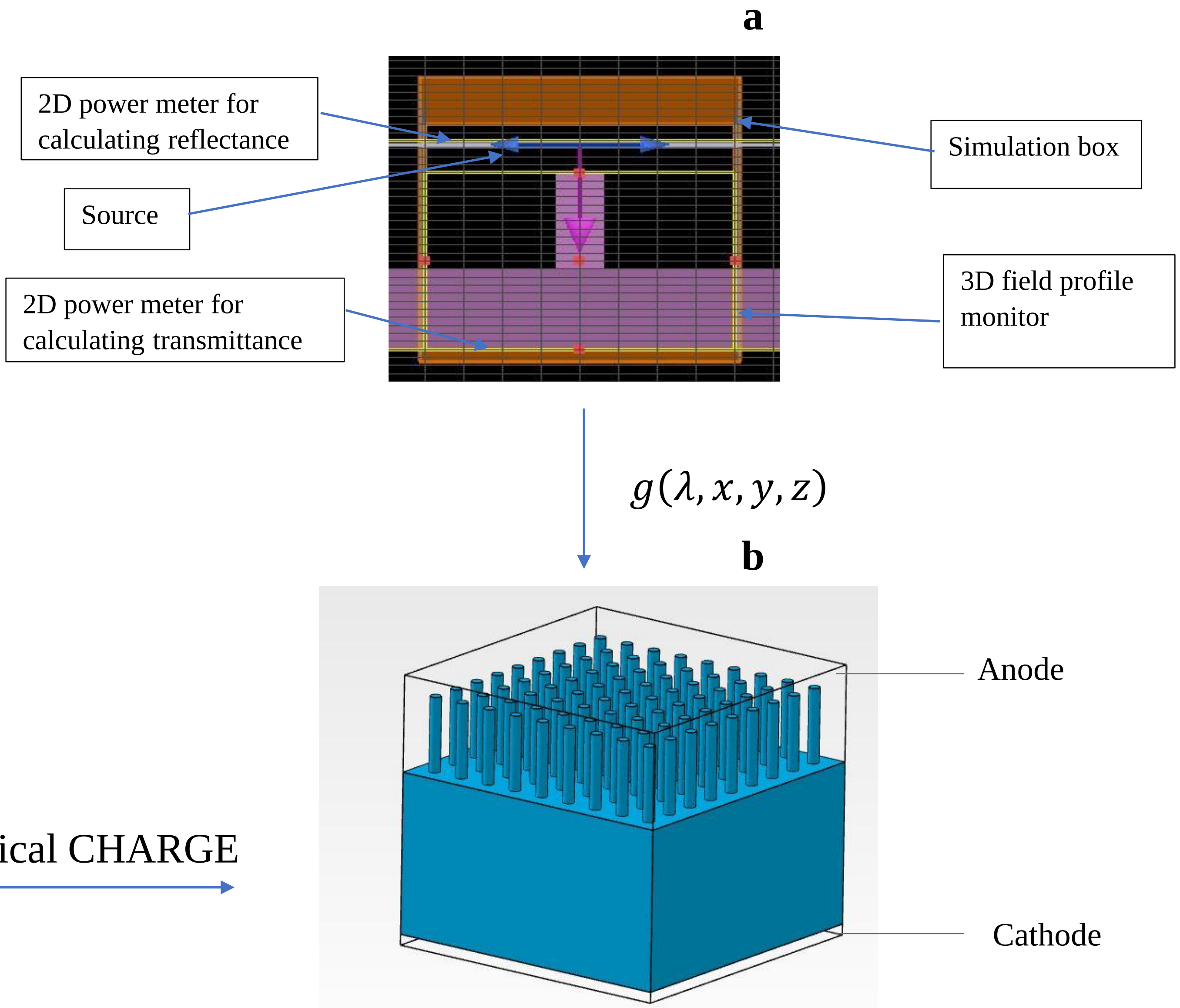


Figure: a) FDTD simulation setup b) CHARGE simulation setup for GaAs NPA.

Simulation Setup:

3. Photoelectron emission into vacuum through emission surface.

- P_g (λ) and P_t(λ) is calculated for bulk GaAs wafer using Lumerical FDTD and CHARGE tool.
- The emission probability P_e is obtained by fitting the P_g and P_t spectra to the published QE spectra of NEA GaAs flat wafer.

$$P_e(\lambda) = \frac{QE(\lambda)}{P_g(\lambda) \times P_t(\lambda)}$$

Finally, the QE is measured for studied nanostructure by,

$$QE(\lambda) = P_g(\lambda) \times P_t(\lambda) \times P_e(\lambda)$$

N1 : *Diameter* =100 nm, *Height* =700 nm, *Period* =300 nm
N2 : *Diameter* =160 nm, *Height* =1200 nm, *Period* =500 nm

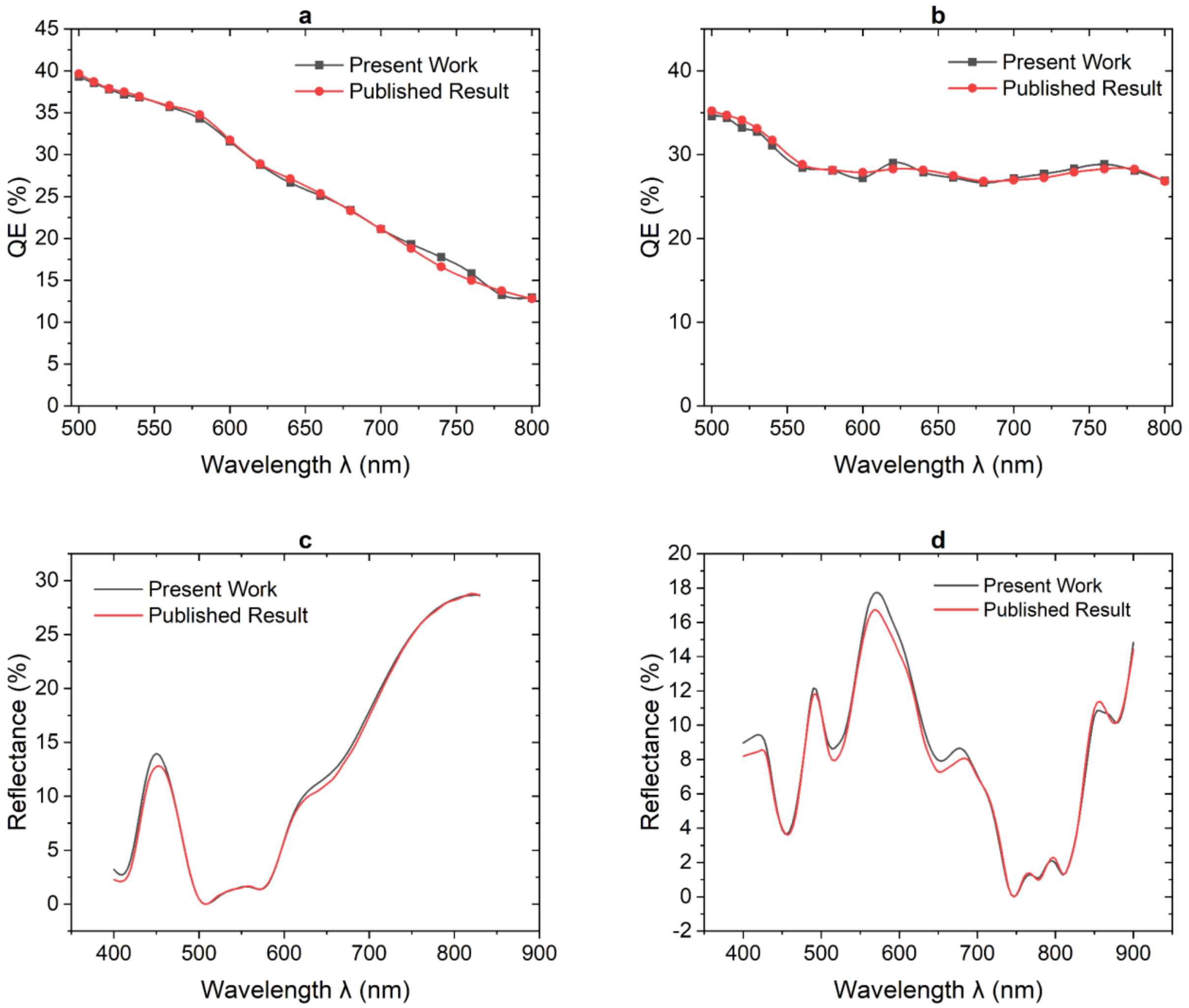
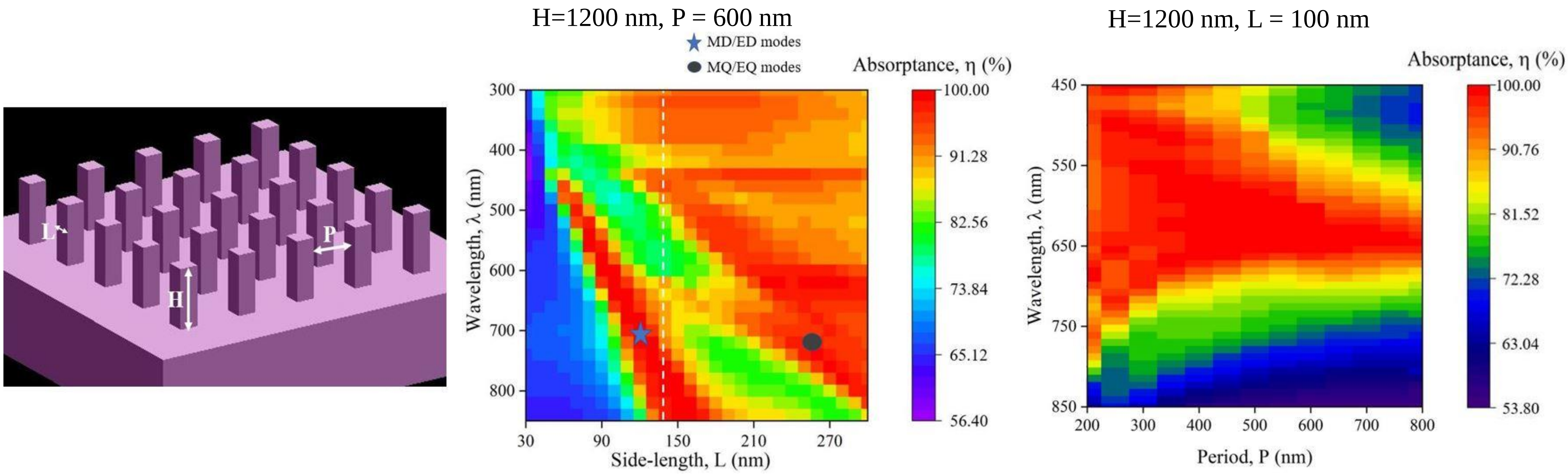


Figure: Comparison of QE for a) N1, b) N2 and comparison of reflectance for c) N1, d) N2 between previous published result [a] and present research work.

[a] Mie-type GaAs Nanopillar Array resonators for negative electron affinity photocathodes, Optics Express 28 (2), (2020). DOI: https://doi.org/10.1364/OE.378194

Simulation of Different Mie-type Nanostructures:
Simulation Result:

Nano-square column Array (NSCA):



a. **b.** **c.**

Figure: a) GaAs NSCA structure, 2D plot showing the variation of absorptance η with wavelength and (b) side-length L, and c) period P of nano-square column.

Nanosquare column Array (NSCA):

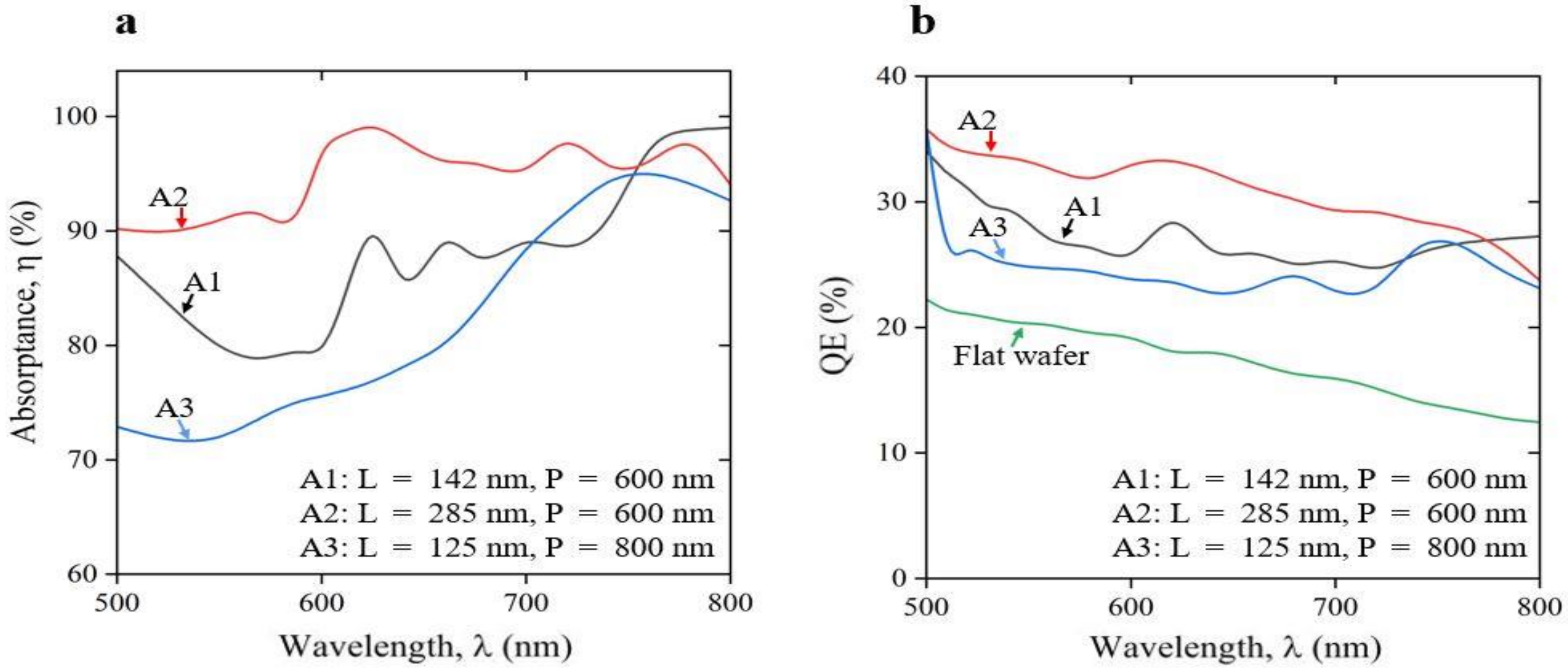


Figure: (a) Comparison of absorptance and (b) QE between different NEA GaAs NSCA and flat wafer photocathode [1], (c-d) excitation of magnetic dipole (MD) mode at 780 nm in A1 and (e-f) excitation of magnetic quadrupole (MQ) mode at 625 nm in A2.

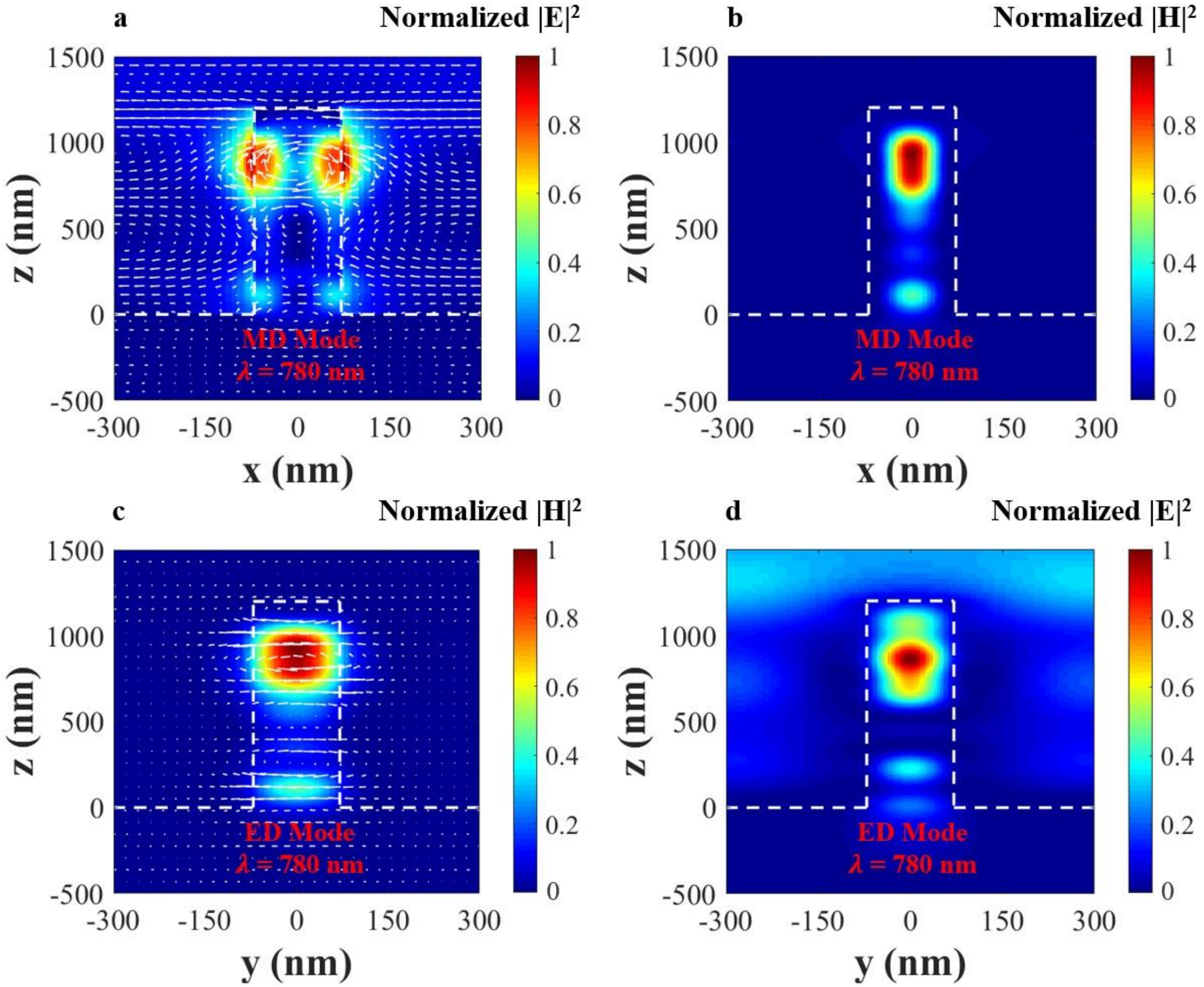
Table: Comparison of QE between three NSCA structures:

GaAs NSCA	Side-length L (nm)	Period P (nm)	Height H (nm)	Resonance Wavelength (nm)	QE at resonance	QE at 780 nm wavelength
A1	142	600	1200	~625 ~780	~28% (MD/ED) ~27% (MD/ED)	27.00% (MD/ED)
A2	285	600	1200	~625	~33% (MQ/EQ)	26.33% (MQ/EQ)
A3	125	800	1200	~750 ~680	~27% (MD/ED) ~24% (MD/ED)	24.67% (MD/ED)
Flat GaAs	-	-	-	-	-	~12.83% [1]

[1] The effects of ion bombardment on bulk GaAs photocathodes with different surface- cleavage planes, Phys. Rev. Accel. Beams **19**, 103402 (2016).

Nano-square column Array (NSCA):

Electric/Magnetic field profile distribution for A1 at 780 nm incident wavelength :

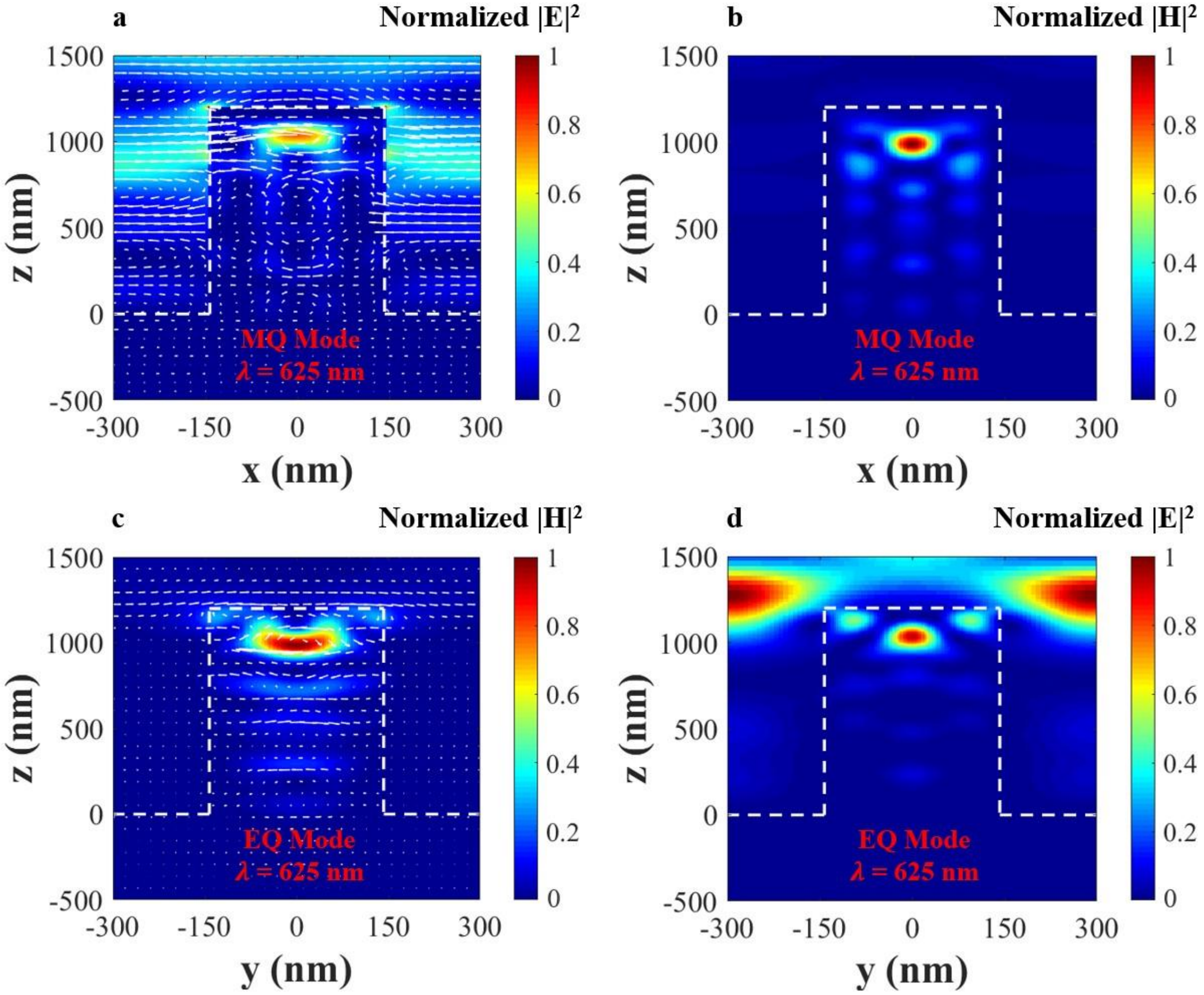


- $D_{eq} = \frac{2L}{\sqrt{\pi}} = 160.23$ nm.
- Mie resonance theory:
  $$\frac{nD_{eq}}{\lambda} = 0.75 \approx 1 \text{ (MD/ED)}$$
- The intense field is observed within 50-100 nm of the emission surface.

Figure : a) $|E|^2$ distribution and field lines (white arrow), b) resonance enhanced $|H|^2$ c) $|H|^2$ distribution and field lines (white arrow) and d) resonance enhanced $|E|^2$ (squared) distribution for A1 at 780 nm.

Nano-square column Array (NSCA):

Electric/Magnetic field profile distribution for A2 at 625nm incident wavelength :



- The equivalent cylindrical diameter $D_{eq} = \frac{2L}{\sqrt{\pi}} = 321.59$ nm.
- Mie resonance theory:
$$\frac{nD_{eq}}{\lambda} = 1.99 \approx 2 \text{ (MQ/EQ)}$$
- The intense field is observed ~100-150 nm from the emission surface.

Figure : a) $|E|^2$ distribution and field lines (white arrow), b) resonance enhanced $|H|^2$ c) $|H|^2$ distribution and field lines (white arrow) and d) resonance enhanced $|E|^2$ distribution for A2.

Nanocone Array (NCA):

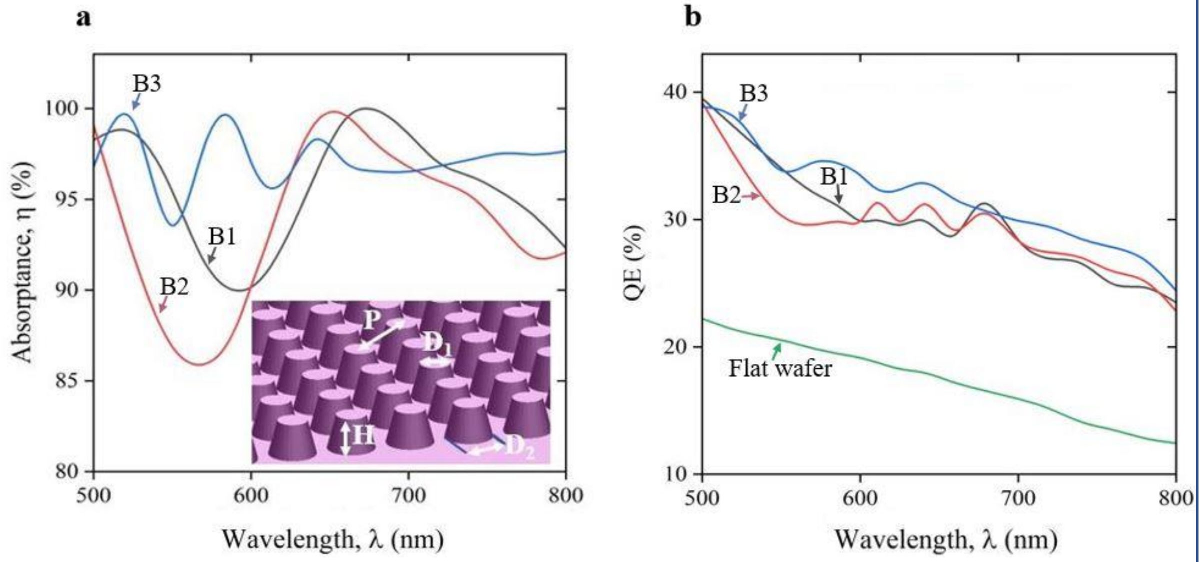


Figure: a) Absorptance spectra (with nanocone array photocathode in inset image), b) QE spectra of three different NCA structures and flat wafer GaAs [1].

Table: Comparison of QE between three NCA structures:

GaAs NCA	Top Diameter D_1 (nm)	Base Diameter D_2 (nm)	Period P (nm)	Height H (nm)	Resonance Wavelength (nm)	QE at resonance	QE at 780 nm wavelength
B1	150	240	300	550	~675	~31.13% (MD/ED)	24.65% (MD/ED)
B2	150	200	300	550	~720	~29.15% (MD/ED)	25.16% (MD/ED)
B3	137	182	300	1400	~585	~34.22% (MD/ED)	26.83% (MD/ED)
Flat GaAs	-	-	-	-	-	-	~12.83% [1]

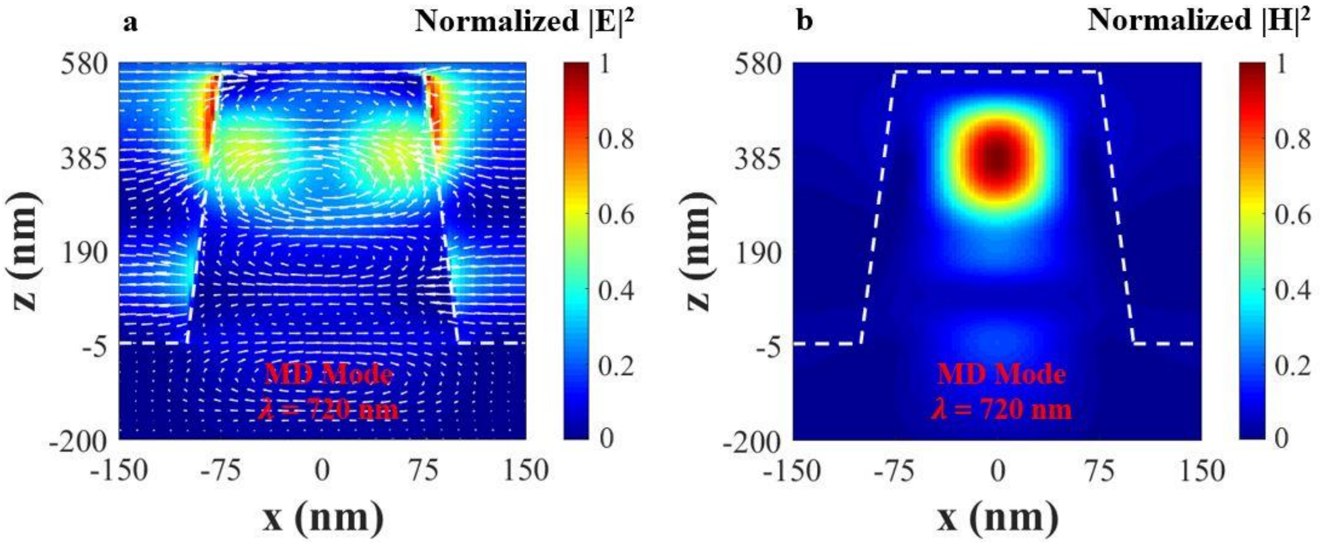


Figure : a) $|E|^2$ distribution and field lines (white arrow), b) resonance enhanced $|H|^2$ for B2 at 720 nm

[1] The effects of ion bombardment on bulk GaAs photocathodes with different surface- cleavage planes, Phys. Rev. Accel. Beams **19**, 103402 (2016).

Nanopyramid Array (NPyA):

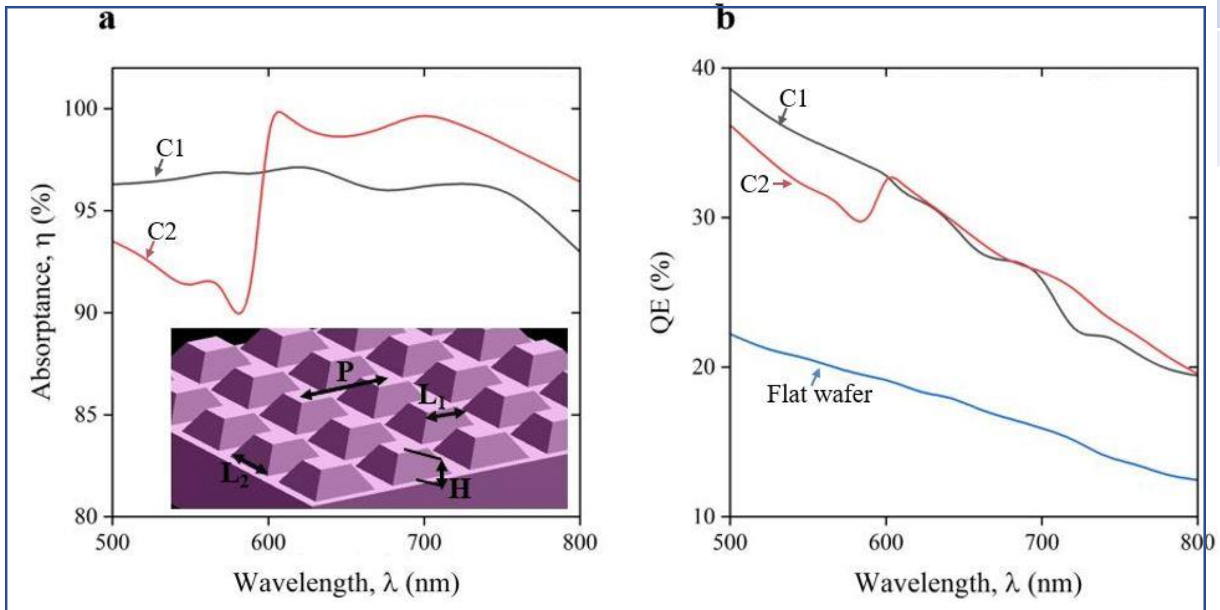


Figure: a) Absorptance spectra (with nanopyramid array photocathode in inset image), b) QE spectra of three different NPyA structures and flat wafer GaAs [a].

Table: Comparison of QE between two GaAs NPyA structures:

NCA	Top Side-Length L_1 (nm)	Base Side-Length L_2 (nm)	Height H (nm)	Period P (nm)	QE at resonance (%)
C1	150 nm	300 nm	550 nm	300 nm	31% at 625 nm 21% at 760 nm ~20% at 780 nm
C2	232 nm	464 nm	550 nm	600 nm	32% at 605 nm 26% at 710 nm ~21% at 780 nm

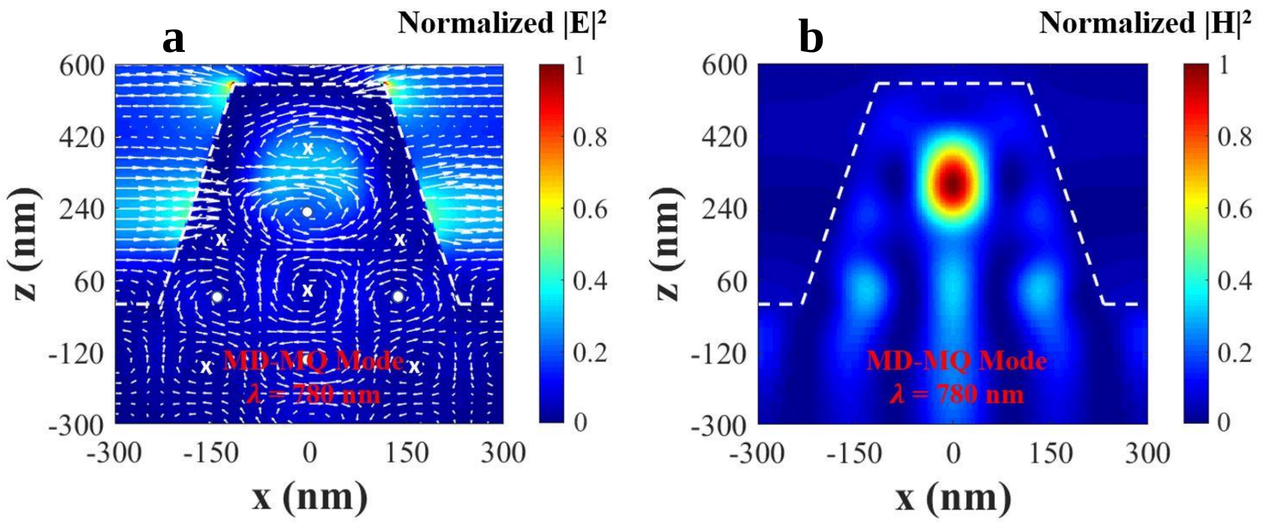


Figure : a) $|E|^2$ distribution and field lines (white arrow), b) resonance enhanced $|H|^2$ for C2 at 780 nm.

[a] The effects of ion bombardment on bulk GaAs photocathodes with different surface- cleavage planes, Phys. Rev. Accel. Beams **19**, 103402 (2016).

Goal:

- **QE measurement of remaining Nanopillar Array photocathodes**
- **Fabrication and testing of designed photocathodes**
- **Extending our work to spin polarized electron sources**

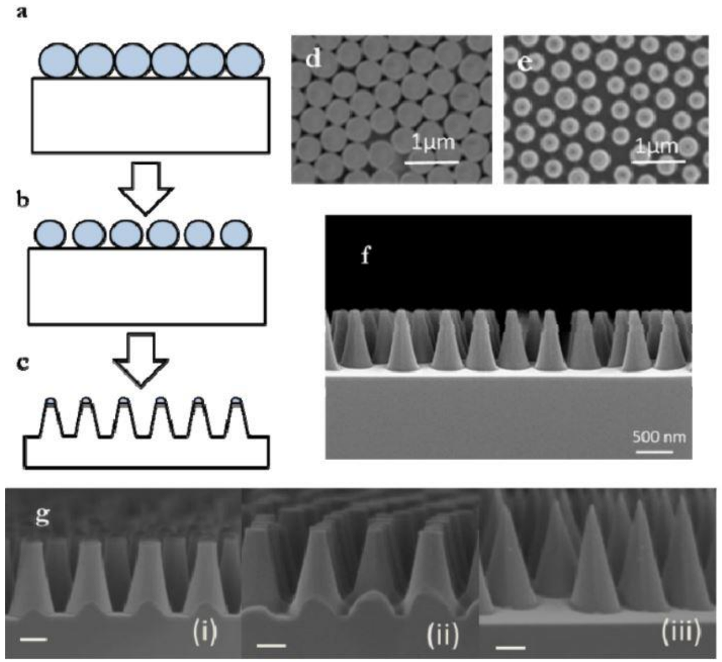


Figure: Fabrication of GaAs nanocone and truncated nanocone [a]

Thank you!

[a] GaAs nanopillar arrays with suppressed broadband reflectance and high optical quality for photovoltaic applications, Optical Materials Express, Vol. 2, Issue 11, pp. 1671-1679 (2012)
DOI: https://doi.org/10.1364/OME.2.001671C