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QUANTUM EFFICIENCY AND LIFETIME STUDY FOR NEGATIVE ELECTRON AFFINITY GaAs NANOPILLAR ARRAY PHOTOCATHODE *

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Abstract

Recent studies showed significant improvement in quantum efficiency (QE) by negative electron affinity (NEA) GaAs nanopillar array (NPA) photocathodes over their flat surface peers, particularly at 500 – 800 nm waveband. However, the underlying physics is yet to be well understood for further improvement in its performance. In this report, NEA GaAs NPA photocathodes with different dimensions were studied. The diameter of the nanopillars varied from 200 – 360 nm, the height varied from 230 – 1000 nm and the periodicity varied from 470 – 630 nm. The QE and photocathode lifetime were measured. Mie-resonance enhancement was observed at tunable resonance wavelengths. Simulations was also performed to understand the mechanism of photo-absorption and possible ways to further improve the photocathode performance to meet the stringent requirement of the electron sources in large scale electron accelerators.

INTRODUCTION

GaAs-based photocathodes are widely used in large scale electron accelerators for electron beam generation. The high quantum efficiency (QE), ability to generate spin polarized electron beam and relatively long lifetime are the vital aspects that made GaAs a preferred candidate in this field. QE of ∼22% was reported at 500 nm wavelength for negative electron affinity (NEA) GaAs flat wafer photocathode, though only ∼13% at 780 nm [1]. The spin polarized GaAs/GaAsP superlattice photocathode with distributed Bragg reflector shows ∼84% electron spin polarization, but the QE is ∼6.4% at 780 nm wavelength [2].

Recent studies on nanostructured photocathodes have shown 2 – 3 times improvement in QE [3–6] compared to flat wafer photocathodes. The key idea of implementing nanostructures is to enhance light absorption. For nanostructures made of dielectric with high refractive index, e.g. GaAs, the enhancement in light absorption occurs due to the excitation of Mie resonance modes [3, 5–7].

In this report, the QE of five different NEA GaAs nanopillar array (NPA) photocathodes were studied over the 500 – 850 nm waveband. The photocathodes varied in diameter, height and periodicity of the nanopillars. Besides QE, the charge lifetimes of these nanostructured photocathodes were studied and compared with that of GaAs flat surface photocathode. Also, the best performing NPA photocathode was simulated to understand the underlying physics of photoemission.

EXPERIMENTAL SETUP

Five different GaAs NPA photocathodes (e.g., Fig. 1(a)) and a fresh flat surface GaAs (100) photocathodes were activated inside an ultra-high vacuum (UHV) chamber shown in Fig. 1(c), following the "yo-yo" activation method to obtain NEA. The photocathode fabrication procedure is discussed in a previously published article [5]. After loading the photocathode sample into the load-lock chamber, the chamber was pumped down to $\sim 10^{-6} - 10^{-7}$ Torr using a turbomolecular pump and then vacuum baked at 160 $^{\circ}C$ for 12 hours. The ion pump was turned on near the end of the soaking period.

After cooling down to room temperature, the vacuum reached $\sim 10^{-11}$ Torr. Prior to activation, the photocathode wafer was heat-cleaned at 550 – 612 $^{\circ}C$ for 1 – 2 hours (depending on the initial surface cleanliness). During activation the photocathode was illuminated by a 650 nm 10 μW laser source (NKT Photonics Product). The Cs was provided using Cs evaporative source (from SAES Getters) and the NF_3 was bled from a reservoir via a leak valve. The photocathode was activated by depositing Cs and NF_3 alternatively following the "yo-yo" procedure for NEA activation. The basic principle of NEA activation is described in Fig. 1(b).

RESULTS

The photocathodes reported in this work vary in their geometric parameters (Table 1), which results in a shift of resonance wavelengths according to the Mie resonance theory [3]. Fig. 2 shows the QE over 500 – 850 nm wavebands. The NPA 1 has a maximum QE of ∼8% at 500 nm which is close to half of that for flat wafer GaAs photocathode (∼18%). The Cs evaporator is located below the photocathode facing upward towards the photocathode surface. The evaporated Cs can be uniformly distributed over flat surface. For NPA, the Cs flux impinges on the top surface of the cylindrical nanopillars, but might not uniformly cover the side walls of the nanopillars and the flat areas at the bottom of the nanopillars between them. The NPA 1 has a QE enhancement at ∼740 nm (2.65%) due to the dipole mode excitation. Also, the QE enhancement at 530 nm (7.99%) and 565 nm (7.65%) are due to quadrupole mode excitation which are verified using Mie resonance theory [3]. For NPA 3 and NPA 5, the QE enhancement due to dipole mode excitation occurs at 700 nm (1.75%) and 825 nm (1.78%), respectively.

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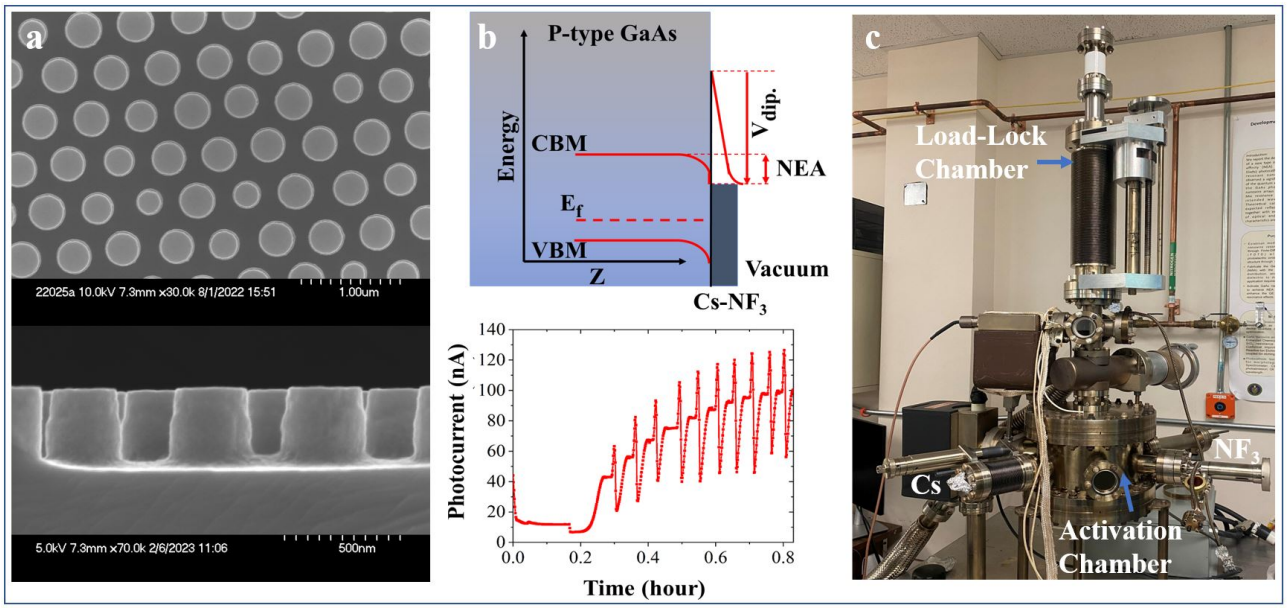

Figure 1: a) SEM image of GaAs NPA photocathode (p-type material with dopant concentration of 10^{19} cm^{-3}), b) basic principle (top) and a "yo-yo" method (bottom) for NEA activation, and c) the UHV chamber with base pressure of 10^{-11} Torr used in this experiment.

The NPA 1 is more uniform in geometric parameters and has cleaner emission surface which enabled NPA 1 to outperform other studied NPA photocathodes.

Table 1: Diameter (D), Period (P), and Height (H) of NEA GaAs NPA are listed below:

Sample	D (nm)	P (nm)	H (nm)
NPA 1	245 – 260	630	482 – 487
NPA 2	330 – 360	480 – 510	730 – 760
NPA 3	170 – 180	470	1000
NPA 4	270 – 330	500 – 515	310 – 320
NPA 5	200 – 331	480 – 560	230

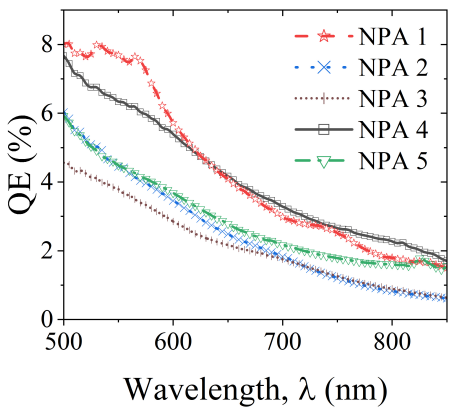

Figure 2: QE of five different NEA GaAs NPA photocathodes. QE enhancement due to dipole and quadrupole mode excitation is observed.

Two different methods of lifetime measurement are usually considered for photocathodes: operational lifetime and charge lifetime. The operational lifetime usually refers to the time when the QE has dropped to the threshold value (usually 1/e of initial QE) required for any specific purpose, while the charge lifetime is defined as the extracted amount of charge from the photocathode throughout its 1/e lifetime [8]. The latter one is preferred for practical purpose of sourcing electron beam. For the charge lifetime measurement, the photocathodes were placed under continuous illumination of 15 μW laser at 650 nm. Fig. 3 shows that the maximum charge lifetime obtained is 264.5 mC for NPA 1. The 1/e operational lifetime observed for NPA 1 is 396.8 hours. NPA 2, NPA 3, and NPA 4 showed charge and 1/e lifetimes of 155.27 mC (392 hours), 107.02 mC (314 hours), and 34.13 mC (56 hours), respectively. For flat wafer GaAs photocathode, the charge lifetime is 57.67 mC with corresponding 1/e lifetime of 43.1 hours which is very low compared to NPA 1, NPA 2 and NPA 3. The extracted amount of charge from the flat wafer photocathode up to 396.8 hours (1/e lifetime of NPA 1) is 102.1 mC which is less than half of the charge lifetime of NPA 1. Bae *et al.* have reported a charge lifetime of about 1.9 mC for flat wafer NEA GaAs photocathode activated by Cs and O_2 [8]. The lifetime measurements were done while the UHV chamber pressure was $\sim 10^{-11}$ Torr. The key factor that degrades the photocathode lifetime is ion back-bombardment. For flat wafer photocathode, the ion back-bombardment is higher because of its high photocurrent. For NPA 4, the photocathode was heat-cleaned at 612°C to get optimum QE, which impacted the lifetime. Starting from comparable photocurrents (varying the laser intensity) is expected to result in a more consistent measurement of the photocathode lifetime.

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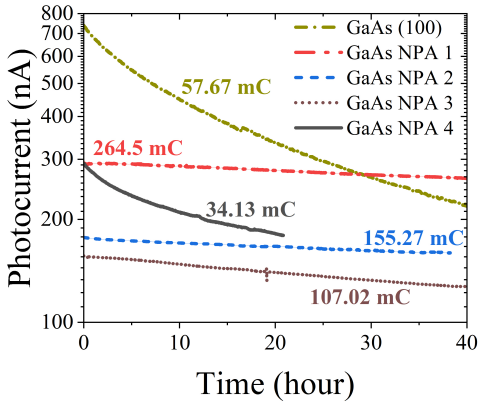

Figure 3: Charge lifetime of five different NEA GaAs NPA and flat wafer photocathodes. The photocurrent is represented in log scale along the vertical axes.

SIMULATION

The ANSYS Lumerical Finite Difference Time Domain (FDTD) [9] tool was used to study the Mie resonance effect in GaAs NPA 1 photocathode. When light passes through the sub-wavelength sized nanostructures of dielectric material with high refractive index (e.g. GaAs), the field components of light tend to bend resulting in curling field lines which can excite magnetic and electric dipoles and higher order modes. At Mie resonance condition [3], coupling of these modes with the field components of light result in resonance, giving rise to photon absorption. Fig. 4 shows the excitation of magnetic quadrupole mode at 530 nm. This accounts for the QE enhancement at this wavelength (Fig. 2). In Reference [6], it was reported that, with the increase of separation between the pillars, the absorption peak region tends to be narrower while centered at the resonance wavelengths. The nanopillar separations (period) in NPA 1 photocathode is the largest (630 nm) and more uniform compared to other studied photocathodes, which causes the resonance peaks to be distinctively visible in QE spectra (Fig. 2) for this photocathode. Fig. 5 also shows the resonance enhancement due to electric and magnetic dipole (ED-MD) mode excitation at 740 nm and electric and magnetic quadrupole (EQ-MQ) mode excitation at 565 nm.

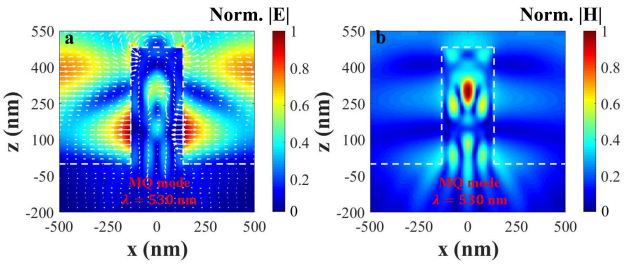

Figure 4: (a) Normalized electric field (**E**) distribution with field lines (in white arrow), and (b) resonance enhanced magnetic field (**H**) distribution due to the excitation of magnetic quadrupole (MQ) mode at 530 nm wavelength.

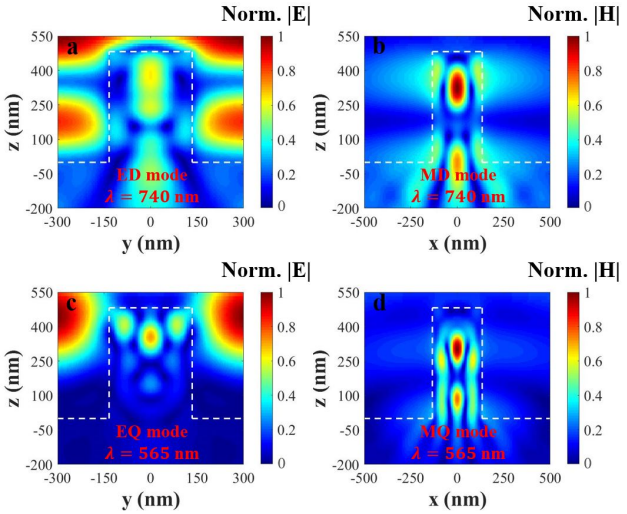

Figure 5: Resonance enhanced (a) electric field (**E**) and (b) magnetic field (**H**) distribution due to the excitation of electric dipole (ED) and magnetic dipole (MD) modes respectively at 740 nm wavelength. Resonance enhanced (c) electric field (**E**) and (d) magnetic field (**H**) distribution due to the excitation of electric quadrupole (EQ) and magnetic quadrupole (MQ) modes respectively at 565 nm wavelength.

From Fig. 4 and 5, it is observed that the high intense field regions (the regions with high photoelectron generation rate [3]) are within 200 nm from the top surface of the nanopillars. Therefore, a large flux of photoelectrons can reach to the top surface of the nanopillars without losing energy significantly. At resonance wavelengths, the reflectance from the surface of the photocathode can be as low as ∼2%. A low reflectance reduces the light reflected back into the vacuum chamber. Light reflected from the photocathodes can create unwanted electron emission from the chamber walls, beam loss, and vacuum load near the photocathode. The reduction in the photocathode reflectance can result in extended photocathode lifetime for NPA compared to flat wafer photocathode.

CONCLUSION

Experiment with a NEA GaAs NPA 1 photocathode showed an improved charge lifetime by a factor of ∼4.6 over the flat wafer photocathode and a maximum QE of 8%. Our simulation indicates the curling **E**-field lines within the nanopillars [Fig. 4(a)] are suspected to trap part of the photoexcited electrons, resulting in low QE. A full QE simulation model is under development which includes the effect of **E**-field loops, due to Mie resonance, on electron transport within the nanopillars. Also, it should be pointed out the photocathodes activated in the present experiment were fabricated few years ago and have been exposed to air. A fresh NPA photocathode is expected to improve the QE and charge lifetime.

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