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PHOTONICS-INTEGRATED PHOTOCATHODES

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Abstract

Integrating the advances made in photonics with efficient electron emitters can result in the development of next generation photocathodes for various accelerator applications. In such photonics-integrated photocathodes, light can be directed using waveguides and other photonic components on the substrate underneath a thin (<100 nm) photoemissive film to generate electron emission from specific locations at sub-micron scales and at specific times at 100 femtosecond scales along with triggering novel photoemission mechanisms resulting in brighter electron beams and enabling unprecedented spatio-temporal shaping of the emitted electrons. In this work we have demonstrated photoemission confined in the transverse direction using a nanofabricated Si_3N_4 waveguide under a ~20 nm thick cesium antimonide (Cs_3Sb) photoemissive film. This work demonstrates a proof of principle feasibility of such photonics-integrated photocathodes and paves the way to integrate the advances in the field of photonics and nanofabrication with photocathodes to develop next-generation high-brightness electron sources for various accelerator applications.

INTRODUCTION

Photonics components nano-fabricated underneath a thin photoemissive film can result in advanced photocathode electron sources for several particle accelerator applications. For example, photonics waveguides under a thin film of a high quantum efficiency semiconductor cathode can cause the photons to be efficiently absorbed very close to the surface resulting in high quantum efficiency (QE), low mean transverse energy (MTE) and quick response time simultaneously, thus providing higher brightness electron beams [1]. Photonics components underneath a photoemissive surface can also be used to spatio-temporally shape the emitted electron beam by guiding light pulses to specific locations at the surface with sub-μm spatial and near 100 fs temporal resolution. This can potentially result in a new method for spatio-temporal shaping of electron beams with unprecedented resolution and enable having correlations in the spatial and temporal profiles.

Practically developing such structures has significant technological challenges related to coupling light in the waveguide structures, obtaining a thin photoemissive film on the nano-fabricated photonics substrate and practically using such cathodes in electron guns. In this paper we present a design that can be used for coupling light, demonstrate the growth of thin (~20 nm) film of Cs_3Sb photocathode on the photonics integrated substrates, and finally using a Photoemisison Electron Microscope (PEEM) [2] to show that electron emission can be confined using photonic components like waveguides. The results presented below are a proof-of-principle demonstration of photonics based cathode technology and significantly alleviate the technological barrier towards integrating such sources in electron guns.

LIGHT COUPLING TECHNIQUES

Efficient coupling of light into the waveguide fabricated on the cathode substrates is essential to make effective photonics-integrated cathodes. In most photonic applications, this is done by connecting an optical fiber to the waveguide and then coupling light into the fiber [3]. However, as these photocathodes are used under Ultra High Vacuum (UHV) conditions, this technology of coupling light into the waveguide is infeasible as the sample cannot be transferred into the UHV chamber of an electron gun with an optical fiber connected to it. Connecting the fiber to the sample while it is in the electron gun under UHV is also non-trivial. Owing to these constraints, we designed a coupling mechanism using a grating coupler which was tested in the PEEM under UHV. The grating coupling mechanism is also compatible with the geometry of many standard DC and RF electron guns.

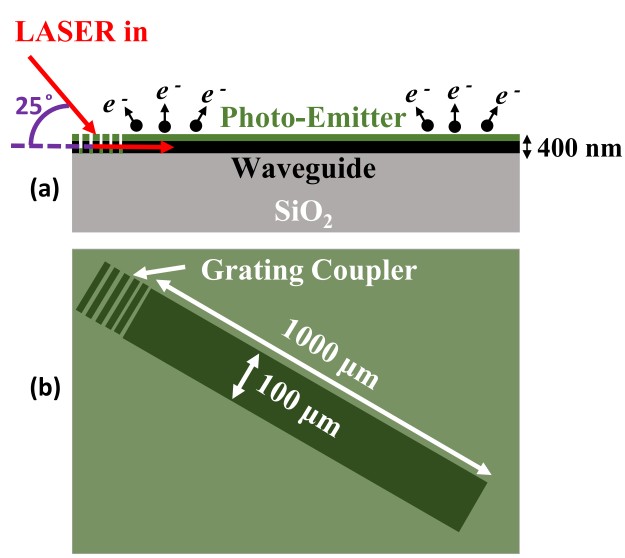

Figure 1: (a) Cross sectional view and (b) top view of light coupling into the waveguide using grating coupler.

The mechanism uses a grating coupler on the surface of the cathode with the laser incident at large angles with respect to the normal as shown in Fig. 1. The grating coupler was designed to couple light at an angle of 65° w.r.t the

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normal at 532 nm wavelength. The angle of incidence was chosen based on the angle of incidence experimentally available in the PEEM instrument. Many RF and DC electron guns used for accelerators have such large angle of incidence ports [4].

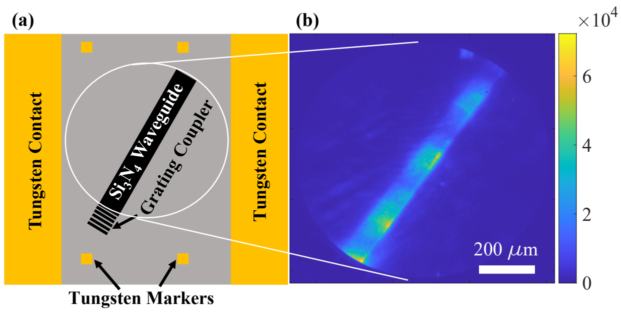

Figure 2: (a) Schematic of the fabricated sample and (b) first PEEM image showing confined emission from a ~20 nm thick film of Cs_3Sb photoemitting film for coupling wavelength λ = 532 nm.

GROWTH OF CESIUM ANTIMONIDE FILM

In photonics-integrated cathodes, the light from the waveguides nanofabricated on substrates is evanescently absorbed from the back of the photoemissive film to excite electrons. The photoexcited electrons are transported to the top surface of the film from where they are emitted. Hence, for an effective emission process in the transmission mode, it is necessary to have a thin (<100 nm) high-QE semiconductor film to be deposited on the waveguide. Simulations show that using a thin film of GaAs activated to negative electron afinity (NEA) placed on a photonic waveguide can simultaneously result in high QE, low MTE and a quick response time simultaneously resulting in high brightness electron beams [1]. Such thin NEA-GaAs cathodes are routinely used in the transmission mode in visible light. In our previous work, [5] we had transferred a 40 nm thick Zn doped (p-dopant) epitaxial GaAs film onto the Si_3N_4 waveguide fabricated on SiO_2 substrate. However, the complex transfer process of epitaxial GaAs film onto the Si_3N_4 waveguide would result in breaking of the film in certain regions after the transfer is complete. As a result, a uniform emission along the length of the waveguide wasn't observed and this process was not easily reproducible. To circumvent this issue, instead of using a GaAs emisison layer, we used a (~20 nm) film of Cs_3Sb photocathode deposited directly on the Si_3N_4 waveguide fabricated on SiO_2 substrate. Below we outline the process of growing a ~20 nm thick film of Cs_3Sb photocathode onto the Si_3N_4 waveguide.

The Si_3N_4 waveguide of length 1 mm, width 100 µm and thickness 800 nm along with a grating coupler was fabricated using electron beam lithography on a SiO_2 substrate. The sample fabricated was mounted onto an omicron type sample holder compatible with the PEEM sample stage and the UHV growth chamber used for the growth of Cs_3Sb photocathode. Prior to the growth, the Si_3N_4 waveguide on SiO_2 substrate was annealed at 450 °C for 2-3 hours in an UHV growth chamber with a base pressure in the low 10^{-10} torr range. The Cs_3Sb cathode was grown via co-deposition of Cs and Sb on the Si_3N_4 waveguide fabricated on SiO_2 substrate. By shining a 5 mW green laser in the reflection mode, the photocurrent emitted from the cathode was measured during the growth to calculate the QE, which serves as a feedback to monitor the growth and performance of the cathodes. The growth was terminated by turning down the source heaters after 1 hour of growth. This corresponds to a film thickness of ~20 nm . Further details of the growth process can be found elsewhere [6]. The final QE of the Cs_3Sb cathode was ~ 1% in green (λ = 530 nm) in the reflection mode before transfer into the PEEM.

After growth, the Cs_3Sb photocathode on Si_3N_4 waveguide fabricated on SiO_2 substrate was transported via a UHV transfer line into the PEEM. [2] The pressure in the transfer line was in 10^{-10} torr range and no QE degradation was observed during the transfer. The base pressure of the PEEM chamber was also in the low 10^{-10} torr range during the measurements.

DEMONSTRATION OF CONFINED EMISSION USING PEEM

PEEM produces images of electrons emitted from a surface with a sub 40-nm lateral resolution. A 500 kHz repetition rate femtosecond pulsed laser with a pulse length of 150 fs and wavelength 532 nm obtained from the LightConversion ORPHEUS optical parametric amplifier pumped by the LightConversion PHAROS was made incident onto the sample at 65° angle of incidence with respect to the normal of the sample surface. The spot size was focused down to 100 µm X 250 µm on the sample surface. All measurements were performed with sufficiently low power to avoid non-linear emission and space charge effects.

Figure 2 (a) shows the schematic of Si_3N_4 waveguide. A ~20 nm thick Cs_3Sb film was grown on the sample. To couple light into the waveguide, it was made incident on the grating coupler. Figure 2 (b) shows a PEEM image demonstrating that the emission is confined only to regions of the Cs_3Sb photocathode layer over the Si_3N_4 waveguide for coupling wavelength λ = 532 nm.

Figure 3 shows the PEEM image of confinement at different coupling wavelengths. As we can see, this generates transverse patters along the length of the waveguide. The period of the pattern increases as we go from λ = 520 nm to λ = 532 nm. Si_3N_4 waveguide with the cross section of the order of wavelength and high aspect ratios support fundamental as well as higher order modes at a single wavelength. We suspect that these transverse patterns are formed due to interference between these co-propagating modes and thereby generating beating patterns with significant evanescent intensities that causes the electron emission. Further theoretical

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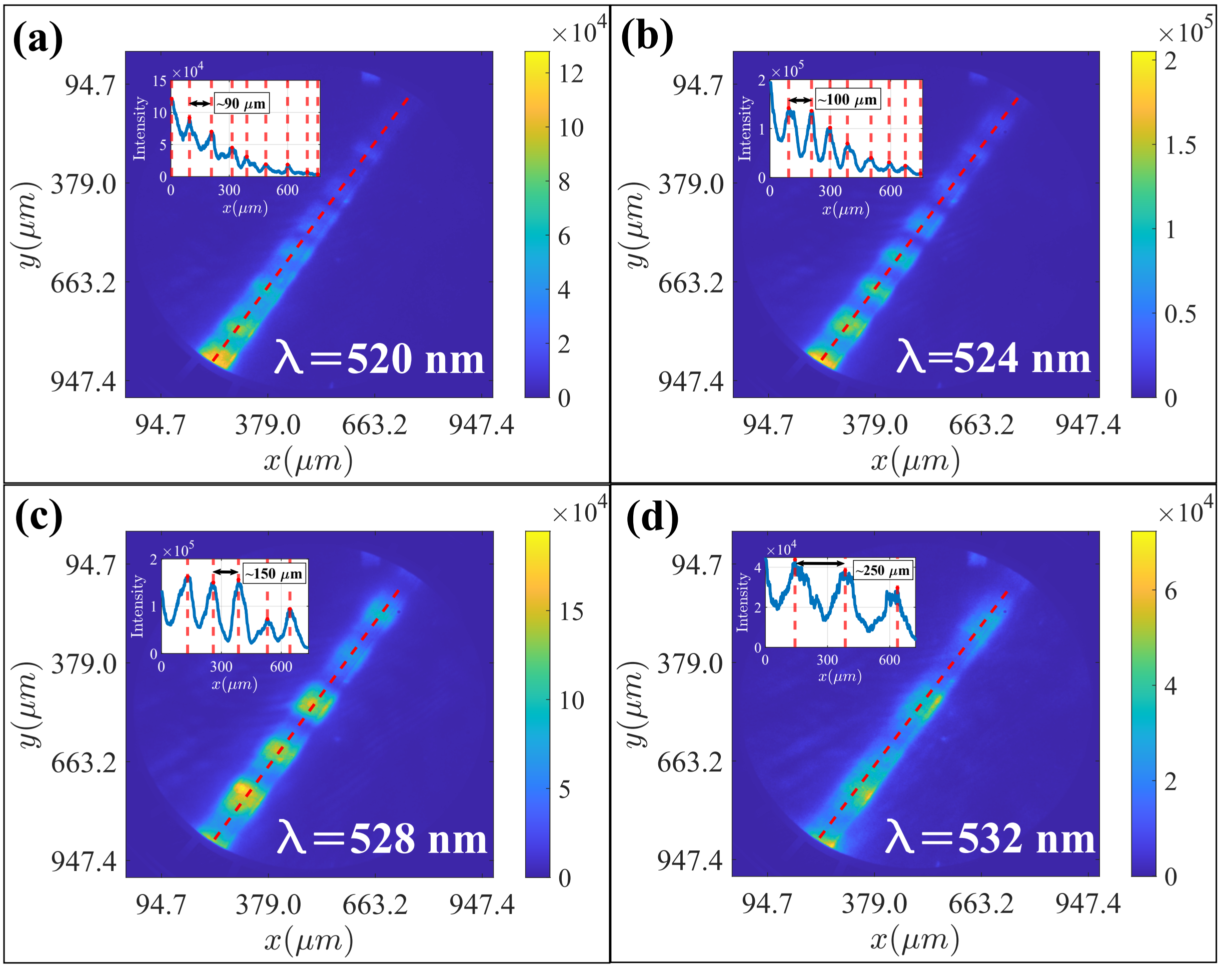

Figure 3: PEEM image showing confined emission from a ~20 nm thick Cs_3Sb film at (a) λ = 520 nm, (b) λ = 524 nm, (c) λ = 528 nm, (d) λ = 532 nm. The inset in each figure shows intensity profile along the red dotted line.

investigation is underway to understand and characterize these patterns.

CONCLUSION AND FUTURE WORK

In this work, we have developed photonics-integrated photocathodes and demonstrated photoemission confined to the transverse direction using a nanofabricated Si_3N_4 waveguide underneath a ~20 nm thick Cs_3Sb photocathode, thus demonstrating a proof of principle feasibility of tailored emission from photonics-integrated photocathodes. In addition, we also demonstrated transverse shaping of the emitted electrons along the length of the waveguide. This serves as a first step to make technologically advanced brighter photocathodes by simultaneously having a high QE, low MTE and a quick response time.

Further theoretical investigation is underway to understand the transverse patters along the length of the waveguide in a better way. As the fabrication of these waveguides is performed using electron-lithography-based techniques, the next goal of this project is to demonstrate tailored emission at sub-μm scales by changing the scale of these waveguides from 100 μm scale to sub-μm scale. In addition, after developing the basic integrated photonics-integrated photocathodes we will develop more complex integrated photonic substrate designs for advanced spatio-temporal shaping of electron bunches. This includes development of more advanced photonic circuits using multiple passive components like delay lines, combiners and splitters to route photons to desired locations, and mirrors to enable local beam shaping, all embedded into the cathode substrate to achieve advanced spatio-temporal tuning to mitigate space-charge effects and achieve high brightness electron emission.

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