ON-CHIP PHOTONICS INTEGRATED CATHODES

A. Kachwala[*], O. Chubenko, S. Karkare, Arizona State University, Tempe, AZ, USA
R. Ahsan, H.U. Chae, R. Kapadia, University of Southern California, Los Angeles, CA, USA

Abstract

Photonics integrated photocathodes can result in advanced electron sources for various accelerator applications. In such photocathodes, light can be directed using waveguides and other photonic components on the substrate underneath a 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 underneath a 40 nm thick cesiated GaAs photoemissive film, thus demonstrating a proof of principle feasibility of such photonics integrated photocathodes. This work paves the way to integrate the advances in the field of photonics and nanofabrication with photocathodes to develop better electron sources.

INTRODUCTION

Photonic components nano-fabricated underneath a photoemissive film can result in advanced photocathode electron sources for several particle accelerator applications. For examples 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 emittance and quick response time simultaneously, thus providing higher brightness electron beams [1]. Photonics components underneath a photoemissive surface can also be used to spatiotemporally shape the emitted electron beam by guiding light pulses to specific locations at the surface with sub-um 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 designs that can be used for coupling light, demonstrate the transfer of thin epitaxial GaAs films on to the photonics integrated substrates, demonstrate activation of these films using Cs and finally using a Photoemisison Electron Microscope (PEEM) 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 waveguides 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 [2]. However, as these photocathodes are used under Ultra High Vacuum (UHV) conditions, this mechanism 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 and developed two coupling mechanisms which were tested in PEEM under UHV. Both these mechanisms are also compatible with the geometry of many standard DC and RF electron guns.

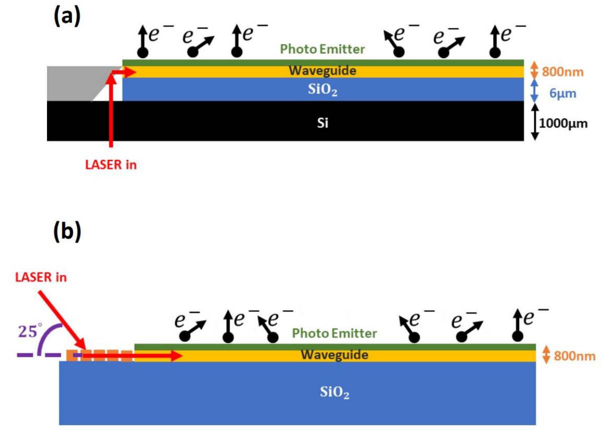

Figure 1: (a) Light Coupling into waveguide using Si etched mirror; (b) Light coupling into waveguide using grating coupler.

In the first mechanism, a gold coated Silicon (Si) mirror is etched onto the substrate. As shown in Figure 1(a) incoming laser beam is incident on this mirror at near normal incidence from the back of the cathode and after reflection gets coupled into the waveguide. The second mechanism uses grating coupler on the surface of the cathode with the laser incident at large angles with respect to the normal as shown in Figure 1(b). Although both these mechanisms resulted in photoemission confined to the waveguide region of the substrate as shown in section 4, the first mechanism was difficult to reproduce and fabricate as it requires precise alignment of

---

[*] akachwal@asu.edu

the mirror and the waveguide on the substrate. Even a slight misalignment was enough to cause the light to not couple into the waveguide and the expected photoemission wasn't observed under the PEEM. The second mechanism which required a large angle of incidence was easier to fabricate and was reproducible. The grating coupler was designed to couple light at an angle of 65° w.r.t the normal at 532 nm. The angle of incidence was chosen based on the angle of incidence experimentally obtainable in the PEEM instrument. Many RF and DC electron guns used for accelerators have such large angle of incidence ports [3].

EPITAXIAL TRANSFER OF GALLIUM ARSENIDE AND CESIUM ACTIVATION

In photonics integrated cathodes, the light from the waveguides nanofabricated on substrates is evanescently absorbed by the photoemissive film to excite electrons. These electrons, after excitation are transported to the top of the film from where they are emitted. Hence, for an effective emission process in 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 emittance 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. The optical constants of GaAs are very well understood making it easy to design the photonics components underneath. It is also possible to use a thin alkali-antimonide film [4] in stead of the NEA-GaAs cathode. However, the optical constant of alkali-antimonides are not well understood making it more difficult to design an appropriately sized waveguide. Below we outline the process of transferring a 40 nm thick epitaxial GaAs film onto the Si_3N_4 waveguide fabricated on SiO_2 substrate.

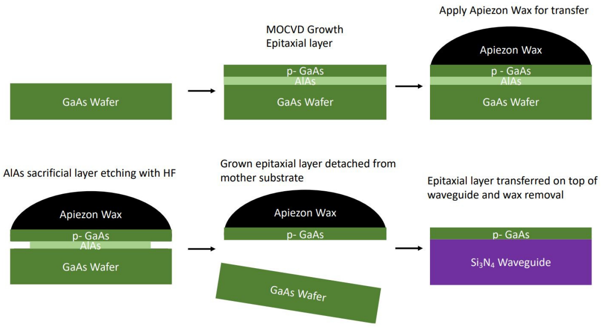

Figure 2: Schematic of GaAs transfer process.

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 lithography on a SiO_2 substrate. Figure 2 shows the epitaxial growth and transfer of GaAs. Starting with single crystal (100) GaAs wafer, a 20 nm thick Aluminum arsenide (AlAs) was grown as a sacrificial layer. On top of AlAs, a 40 nm thick Zn doped (p-dopant) GaAs epitaxial layer was grown using metal organic chemical vapour deposition (MO-CVD). For efficient coupling of light into the waveguide, we need the GaAs photoemissive layer to be deposited on the top of the waveguide only and it shouldn't cover the grating coupler. In order to achieve this, apiezon wax dissolved in trichloroethylene was sprayed onto GaAs/AlAs/GaAs stack such that it is large enough to cover the waveguide region and not the grating coupler. Wax was air-cured for 30 minutes and annealed at 100 °C for 30 minutes. After air curing, the entire assembly was treated with Hydrofluoric acid (HF). HF etching removed 20 nm thick AlAs layer without attacking the GaAs layer and the wax. This resulted in effiecient peel off of the wax/p-GaAs from the substrate. After the peel off, the p-GaAs was transferred onto the Si_3N_4 waveguide region taking care that it doesn't cover the grating coupler. Apiezon wax was removed using trichloroethylene and the p-GaAs/Si_3N_4 waveguide stack was pressed with the tungsten cube to ensure the uniform force so that the p-GaAs film sits on top of the waveguide with Van del Waals force [5].

Figure 3 (a) shows a 40 nm thick p-doped GaAs layer transferred onto the Si_3N_4 waveguides fabricated onto the Si substrate with a layer of SiO_2. This stack of p-GaAs/Si_3N_4 waveguide/SiO_2/Si was mounted onto an omicron type sample holder compatible with the PEEM sample stage. The sample was inserted in a UHV preparation chamber with a base pressure of 10^{-10} torr for heat cleaning prior to cesium activation. The sample was heat cleaned at approx. 600°C for 2 hours. After the cathode had cooled to room temperature, it was transferred into another vacuum chamber with base pressure in the 10^{-9} torr range for cesiation. A cesium source [6] was resistively heated to deliver cesium to the cathode during activation. Photocurrent under white light illumination was monitored during cesiation. Cesiation was continued until the photocurrent plateaued. This activated sample was then inserted into the PEEM with a base pressure in the low 10^{-10} torr range.

DEMONSTRATION OF CONFINED EMISSION USING PEEM

Photoemission electron microscopy (PEEM) [7] 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 focussed 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 3 (a) shows optical microscope image of a 40 nm thick p-doped GaAs layer transferred onto the Si_3N_4 waveguide fabricated onto the Si substrate with a layer of SiO_2. This film was activated using Cs to lower its work function

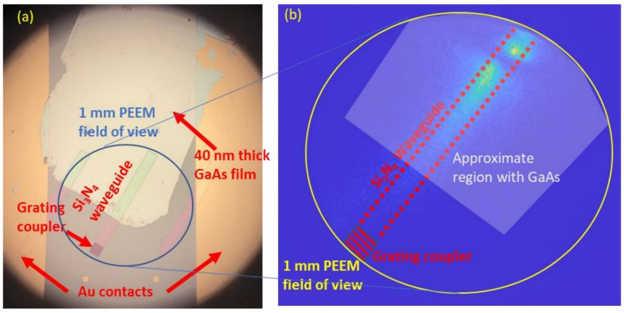

Figure 3: (a) Optical microscope image of 40nm GaAs on waveguide; (b) First PEEM image showing confined emission from cesiated p-GaAs.

and linear photoemission in the visible range (532 nm) was achieved. To couple light into the waveguide, it was made incident on the grating coupler. Figure 3 (b) shows a PEEM image demonstrating that the emission is confined only to regions of the GaAs layer over the Si_3N_4 waveguide. On moving the LASER spot within ±100 µm the emission intensity reduces and it goes to the level of background intensity on moving the LASER spot more than 100 µm. This confirms that the emission is due to coupling of light into the waveguide as the size of the grating coupler as well as the LASER spot is of the order of 100 µm.

CONCLUSION AND FUTURE WORK

In this work, we have developed photonics integrated photocathodes and demonstrated photoemission confined to the transverse direction using a nonofabricated Si_3N_4 waveguide underneath a 40 nm thick p-GaAs activated using Cs, thus demonstrating a proof of principle feasibility of tailored emission from photonics integrated photocathodes. This also serves as a first step to make technologically advanced brighter photocathodes by simultaneouly having QE, low emittance and a quick response time.

Further experimental work is underway to optimize the growth and transfer process of GaAs to have a uniform emission along the length of the waveguide and reduce the scattering outside the waveguide region as shown in Figure 3 (b). Further, 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-micron scales by changing the scale of these waveguides from 100 µm scale to sub-micron 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 beams and generating spin-polarized electron beams. 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 spin-polarized emission.

ACKNOWLEDGEMENT

This work is supported by the NSF Center for Bright Beams under award PHY-1549132, and by the Department of Energy, Office of Science under awards DE-SC0021092, and DE-SC0021213.

REFERENCES

[1] L. Blankemeier, F. Rezaeifar, A. Garg, and R. Kapadia, "Integrated photonics for low transverse emittance, ultrafast negative electron affinity GaAs photoemitters", *Journal of Applied Physics*, vol. 126, p. 033102, 2019. `doi:10.1063/1.5093938`

[2] T. Zhu, Y. Hu, P. Gatkine, S. Veilleux, J. Bland-Hawthorn, and M. Dagenais, "Ultrabroadband High Coupling Efficiency Fiber-to-Waveguide Coupler Using Si_3N_4/SiO_2 Waveguides on Silicon", *IEEE Photonics Journal*, vol. 8, pp. 1-12, 2016. `doi:10.1109/JPHOT.2016.2600037`

[3] D. Bhattacharjee, R. Tiwari, D. Jayaprakash, R.L. Mishra, A.R. Tillu, B. Nayak, R.B. Chavan, S. Chandan, V. Yadav, S.R. Ghodke, and M. Kumar, "Development of electron guns for linacs and DC accelerator", *Journal of Physics: Conference Series*, vol. 390, p. 012071, 2012. `doi:10.1088/1742-6596/ 390/1/012071`

[4] P. Saha, O. Chubenko, G.S. Gevorkyan, A. Kachwala, C.J. Knill, C. Sarabia-Cardenas, E. Montgomery, S. Poddar, J.T. Paul, R.G. Hennig, and H.A. Padmore, "Physically and chemically smooth cesium-antimonide photocathodes on single crystal strontium titanate substrates", *Applied Physics Letters*, vol. 120, p. 194102, 2022. `doi:10.1063/5.0088306`

[5] W.K. Chan, A. Yi-Yan, and T.J. Gmitter, "Grafted semiconductor optoelectronics", *IEEE journal of quantum electronics*, vol. 27, pp. 717-725, 1991. `doi:10.1109/3.81382`

[6] Alkali Metal Dispensers, `https://www.saesgetters.com/products-functions/products/dispensers/alkali-metals-dispensers/`

[7] FOCUS-IS-IEF-PEEM, `https://www.focus-gmbh.com/peem-nanoesca/peem/`