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LIGHT-INDUCED ENHANCEMENT OF QUANTUM EFFICIENCY IN III-NITRIDE PHOTOCATHODES

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Abstract

High quantum efficiency (QE) semiconductor photocathodes are essential for generating high average beam current and brightness. One class of semiconductor photocathodes considered for use in photoinjectors for unpolarized and polarized electron beams are III-nitride heterostructures. These materials can exhibit negative electron affinity at the surface by utilizing intrinsic polarization fields to engineer the band structure without the need for additional surface treatments. In this study, using photoemission electron microscopy (PEEM) for characterization, we investigate the effects of light exposure on the surface of III-nitride photocathodes show that the QE changes significantly when exposed to UV light. Although III-nitride photocathodes are known for their robustness, our findings indicate that laser exposure can significantly alter their QE. Our observations reveal the need for a detailed investigation of photo-induced effects on QE in III-Nitride photocathodes.

INTRODUCTION

The development of bright and high-current electron sources is critical for the advancement of accelerator-based applications such as free-electron lasers, ultrafast electron diffraction, and next-generation colliders [1–3]. Semiconductor photocathodes have emerged as key enablers due to their potential to deliver high QE, customized band structure, and tunable emission properties [4,5]. Among different semiconductors, III-nitride materials such as GaN have been the focus of considerable research due to their ability to attain negative electron affinity(NEA) using Cs overlayers [6–8]. While they are more robust than traditionally used NEA GaAs(Cs/O) cathodes, the Cs-based activation layer is still very sensitive to vacuum conditions resulting in QE degradation in poor vacuum conditions. It was recently shown that intense internal fields due to self-polarization and piezoelectric effects in the wurtzite phase of GaN can be leveraged to engineer photocathode structures that do not require cesium to achieve effective NEA [9]. Previous studies have shown high QE of over 1% and a low mean transverse energy of under 100 meV from such Cs-free NEA GaN surfaces [9,10]. Such GaN-based photocathodes have an extremely robust surface that is stable in atmospheric conditions. Because of the chemical inertness of such surfaces, it has been assumed that the QE from these surfaces will be extremely stable. In this work we show that this assumption in not entirely accurate. Despite the robust surface we show that ultraviolet laser exposure can significantly alter the surface condition and lead to significant changes in quantum efficiency. These results suggest that light exposure modifies the surface electronic structure of GaN, making it essential to perform a more systematic study of the QE when exposed to light.

EXPERIMENTAL METHODS

N-polar GaN photocathodes reported here were grown by metal organic chemical vapor deposition (MOCVD). Nominally, on-axis 2–sapphire wafers with mis-cut toward the m-plane were used as substrates. An N-polar unintentionally doped (UID) GaN template layer was grown on the sapphire substrate using growth conditions reported elsewhere [11]. The N-polar photocathode structure was then overgrown on the template layer consisting of nominally 450 nm p-GaN with 10 nm UID GaN cap layer [12]. The samples were

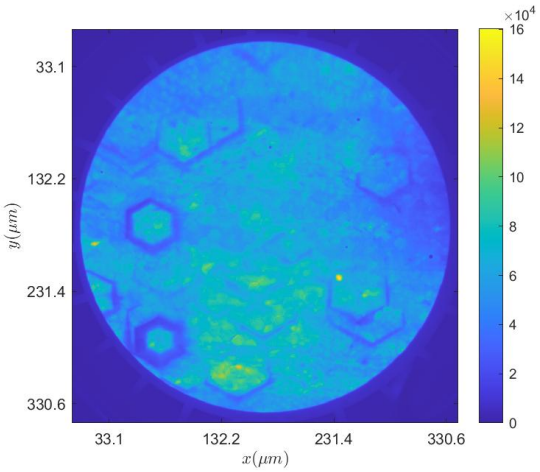

Figure 1: PEEM image of the GaN N-polar surface using the 240 nm Hg lamp source showing hexagonal structures.

grown at SUNY Albany and shipped to ASU. At ASU, they were cleaned in 30% HCl for 1 minutes and then rinsed with DI water to remove any oxide layer and surface contaminants. After the HCl cleaning, the samples were inserted in the load lock of a PhotoEmission Electron Microscope (PEEM) ultra-high-vacuum (UHV) chamber in less than 15 minutes. The samples were transferred into the chamber after a 12 hour bakeout of the load lock at 120 °C at a pressure less than 10^{-7} torr before transferring into the PEEM-UHV chamber with a pressure of 10^{-10} torr.

The PEEM was used to obtain a photoemission map of the surface and measure the QE. High resolution images of

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the photoemission map of the surface were obtained either using a 240 nm illumination from the Hg lamp or a pulsed laser. The pulsed laser had a 500 kHz repetition rate with a tunable wavelength and a pulse length of 150 fs (Light Conversion Orpheus pumped by Light Conversion Pharos).

The light from the laser was used for QE measurements and was incident on the sample at a 65° angle relative to the surface normal and focused down to a 100 µm spot size using a lens. The entire laser spot was contained within the field of view of the PEEM. The current was obtained from the intensity of the recorded images using a image-intensity to current calibration performed previously [13]. Care was taken to ensure the linearity of photoemission during the QE measurements to rule out non-linear photoemission and space charge effects.

RESULTS AND DISCUSSION

High-resolution images of the photoemission map of the surface were obtained using the 240 nm illumination from the Mercury lamp. Figure 1 shows one such image. The photoemission map shows several 100s of µm sized hexagonal features. These correspond to the characteristic hexagonal hillock structures observed on the surface of N-polar GaN [10]. Figure 1 also shows that the intensity varies by over a factor of two across the 1 mm field of view of the sample surface. This intensity variation is proportional to a QE variation on the surface as the Hg lamp illuminates the surface uniformly at the mm scale. No variation in QE or intensity of the image was observed with time when illuminated only by the Hg lamp.

Figure 2 shows the QE measurements performed at ASU compared to the measurements from a similar sample presented in previous literature [9] as a function of the photon energy. As seen in Fig. 2, the two data sets span QE values in a similar range, but are qualitatively very different.

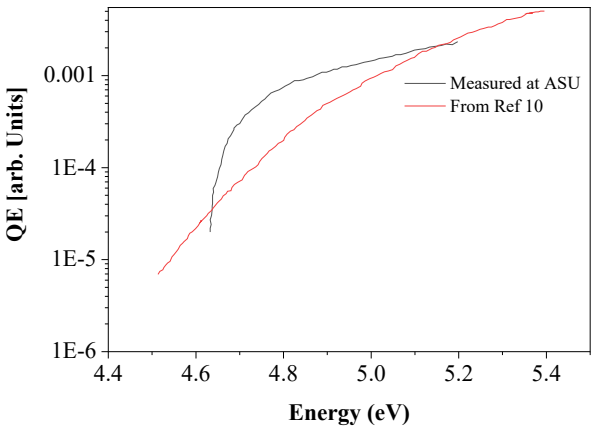

Figure 2: QE measurements performed at ASU compared to the measurements from a similar sample presented in previous literature [9].

Further analyses of the sample to find the root of this variation lead to the observation of sample change with intense light exposure. Generally, the QE showed an increasing trend with time when exposed to intense pulses of light. Figure 3 illustrates this QE increase in areas on which intense laser was incident. Figure 3a shows a PEEM image of ~ 175 µm field of view of the surface illuminated with the Hg lamp and the emission is quite uniform. Figure 3b shows the same area when illuminated by the laser at 240 nm. As seen in Fig. 3b only the area on which the laser spot is incident is illuminated. Figure 3b was taken with a significantly reduced laser power of less than 10 nW average power. After this the laser power was increased to 870 µW average power at the same location. The sample was exposed to this power for 15 minutes. No PEEM images were taken during this time. Figure 3c shows a PEEM image taken with the Hg lamp post this 15 minutes exposure. In contrast to Fig. 3a, where the Hg lamp porduced a nearly uniform image, after the intense laser exposure the Hg lamp produced a image which shows emission only from the location at which the laser was incident on indicating the laser exposure modified the surface properties at this location increasing its QE locally. Figure 3d shows a Hg lamp image after exposing the area to the high intensity laser for 45 minutes. It shows that the high QE area has increased slightly after elongated exposure. This shows the dramatic effect of exposure to intense light on the QE.

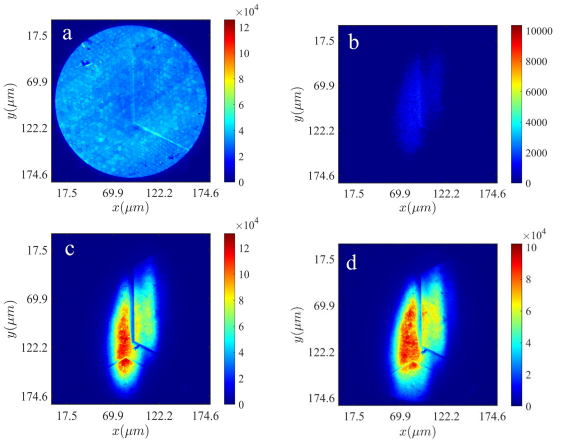

Figure 3: Images taken with the PEEM (a) Image using the Hg light source showing the overall surface structure of the GaN sample before intense laser exposure. (b) Image under attenuated laser (240 nm) illumination (averge power less than 10 nW), showing the location and shape of the laser spot size. (c) Image taken with the Hg lamp after 15 minutes of full-power laser (240 nm, 870 µW) exposure, revealing a dramatic increase in photoemission intensity and QE only in the regions that were exposed to the intense laser. (d) Image taken with the Hg lamp after 45 minutes of continuous full-power laser exposure, indicating the lateral expansion of the photoemitting region.

It is noteworthy that the effect was not uniform over the 10 mm × 10 mm sample. Most regions on the sample showed

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significant QE enhancement. Few regions that had an exceptionally low QE showed nearly 2 orders of magnitude increase in QE. Some areas also exhibited a slight reduction in QE upon laser exposure.

This change in QE can be attributed to several possible mechanisms. First, intense light exposure may induce surface cleaning or desorption of the physisorbed species. Even atomic monolayers of physisorbed species can dramatically affect the work function and the emission intensity, causing the observed changes. Intense light might also cause the passivation or reconfiguration of surface traps or defects that can change the surface band-bending to modify electron emission.

CONCLUSION

We have demonstrated that GaN based heterostructures engineered for can generate high QE without the use of Cs overlayers. The surface of such structures is extremely robust to vacuum conditions. However, despite the robustness to vacuum, there is non-trivial dependence of the QE on exposure to intense pulses of UV light. Our results show that it is necessary to understand these effects to enable the use of these cathodes as electron sources for various high brightness accelerators.

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REFERENCES

[1] B. Dunham *et al.*, "Record high-average current from a high-brightness photoinjector", *Appl. Phys. Lett.*, vol. 102, no. 3, p. 034 105, 2013. doi:10.1063/1.4789395

[2] P. Musumeci *et al.*, "Advances in bright electron sources", *Nucl. Instrum. Methods Phys. Res. A*, vol. 907, pp. 209–220, 2018. doi:10.1016/j.nima.2018.03.019

[3] A. Kachwala, M. M. Rizi, C. M. Pierce, D. Filippetto, J. Maxson, and S. Karkare, "Harnessing plasmonic interference for nanoscale ultrafast electron sources", *Phys. Rev. Lett.*, vol. 133, no. 18, p. 185 001, 2024. doi:10.1103/PhysRevLett.133.185001

[4] J. Schaber, R. Xiang, and N. Gaponik, "Review of photocathodes for electron beam sources in particle accelerators", *J. Mater. Chem. C*, vol. 11, no. 9, pp. 3162–3179, 2023. doi:10.1039/D2TC03729G

[5] S. Karkare *et al.*, "Ultrabright and ultrafast III–V semiconductor photocathodes", *Phys. Rev. Lett.*, vol. 112, no. 9, p. 097 601, 2014. doi:10.1103/PhysRevLett.112.097601

[6] Y. Du, B. Chang, X. Fu, B. Li, and J. Zhang, "Effects of NEA GaN photocathode performance parameters on quantum efficiency", *Optik*, vol. 123, no. 9, pp. 800–803, 2012. doi:10.1016/j.ijleo.2011.05.035

[7] X. Wang, B. Chang, Y. Du, and J. Qiao, "Quantum efficiency of gan photocathode under different illumination", *Applied Physics Letters*, vol. 99, no. 4, p. 042 102, 2011. doi:10.1063/1.3614555

[8] M. Boukhicha *et al.*, "UV hybrid photon detector based on GaN photocathodes and Si low gain avalanche diode", 2024, arXiv:2406.17839 [physics.ins-det]. doi:0.48550/arXiv.2406.17839

[9] J. Marini, I. Mahaboob, E. Rocco, L. Bell, and F. Shahedipour-Sandvik, "Polarization engineered N-polar Cs-free GaN photocathodes", *J. Appl. Phys.*, vol. 124, no. 11, p. 113 101, 2018. doi:10.1063/1.5029975

[10] L. Cultrera *et al.*, "Photoemission characterization of N-polar III-nitride photocathodes as candidate bright electron beam sources for accelerator applications", *J. Appl. Phys.*, vol. 131, no. 12, p. 124 902, 2022. doi:10.1063/5.0076488

[11] J. Marini, J. Leathersich, I. Mahaboob, J. Bulmer, N. Newman, and F. S. Shahedipour-Sandvik, "MOCVD growth of N-polar GaN on on-axis sapphire substrate: Impact of AlN nucleation layer on GaN surface hillock density", *J. Cryst. Growth*, vol. 442, pp. 25–30, 2016. doi:10.1016/j.jcrysgro.2016.02.029

[12] E. Rocco *et al.*, "Impurity incorporation and diffusion from regrowth interfaces in N-polar GaN photocathodes and the impact on quantum efficiency", *J. Appl. Phys.*, vol. 129, no. 19, p. 195 701, 2021. doi:10.1063/5.0049344

[13] A. Kachwala, O. Chubenko, D. Kim, E. I. Simakov, and S. Karkare, "Quantum efficiency, photoemission energy spectra, and mean transverse energy of ultrananocrystalline diamond photocathode", *J. Appl. Phys.*, vol. 132, no. 22, p. 224 901, 2022. doi:10.1063/5.0130114