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CHARACTERIZATION OF VARIOUS GaN SAMPLES FOR PHOTOINJECTORS

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Abstract

Photoemission properties (quantum efficiency, spectral response, and lifetime) of various GaN based photocathodes are summarized, including p-doped samples in its hexagonal phase, cubic GaN and a more exotic 2-D hole gas sample. The 2-D hole contains no dopant impurity but achieves high conductivity via polarization fields produced at the hetero-junction of GaN and AlN. For efficient electron production, cesium is used to achieve Negative Electron Affinity.

INTRODUCTION

Galium-Nitride (GaN) photocathodes have many interesting properties which make them exceptional candidates for the use of a variety of photoinjector applications. With reported quantum efficiencies exceeding 50% [1] and a high thermal conductivity, they may be suitable for high-current applications where thermal degradation of the QE can be a limiting factor. For high brightness applications, GaN has a prompt response time [2] and the Mean Transverse Energy of N-polar GaN has been reported to be 50 meV at 300 nm [3]. Ordinarily GaN is grown with a hexagonal crystal structure but can also be grown as a cubic structure from which it may be possible to produce spin-polarized electrons.

For efficient electron production, GaN must be brought to Negative Electron Affinity (NEA). Typically this is done by exposing the surface to Cs or Cs and oxygen. The activation layer forms a strong electric dipole on the GaN surface bringing the electron affinity level at the surface below the bulk conduction band minimum. Although this yields efficient electron production, it makes the photocathode very sensitive to vacuum conditions. Interestingly, N-polar GaN photocathodes have been engineered to achieve NEA in the absence of Cs [4], pointing to a potentially extremely robust photocathode. However, to date, the QE of N-polar GaN photocathodes has been limited to ≈ 1% for photon energies below 4.8 eV.

In this work we present measurements of the spectral response and lifetime of three novel GaN based photocathodes: (i) a sample grown in a cubic phase, (ii) a sample grown on a single-crystal Ga-polar GaN substrate resulting in a significantly lower dislocation density at the surface and (iii) a 2D Hole Gas (2DHG) which contains no doping but obtains high conductivity via polarization fields produced at a heterojunction of GaN and Aluminum Nitride [5]. All other samples are p-doped with a Mg concentration of $\approx 3 \times 10^{19}$ cm^{-3} in accordance with the results published in [1]. For comparison, a hexagonal p-GaN sample grown on a GaN template on sapphire was used. Schematics of the cathodes tested are shown in Fig. 1.

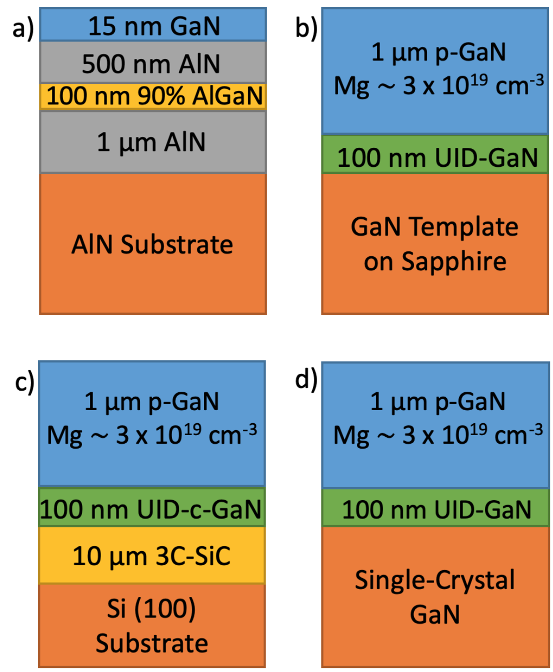

Figure 1: The four samples grown and tested in this work. *a)* The 2DHG sample, the 2DHG is found between the top GaN layer and AlN layer. *b) - d)* The hexagonal (template), cubic and single-crystal GaN samples, respectively.

Methods

The samples were grown using a Veeco Gen10 molecular beam epitaxy system equiped with standard efussion cells for elemental Gallium, Aluminum and Magnesium. Before epitaxy, the substrates were ultrasonicated in acetone, methanol and isopropanol for 10 min each, and then outgassed at 200 C for 7 hours. All the layers in each sample were grown within the step-flow growth mode and maintaining metal-rich conditions throughout the whole epitaxial process.

After growth, each of the samples were transferred into the Cornell Photoemission Laboratory main test chamber [6]. Each sample was mounted onto a sample holder compatible with the photoemission test chamber. Thermal contact was established between the samples and the holder with indium foil. During mounting and transferring of the samples between the growth and photoemission chamber, the samples were exposed to air for 5-10 minutes. The photoemission chamber has a base pressure of approximately 2×10^{-10} Torr.

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Once in the chamber, the samples were annealed at 600 degrees Celsius for 5-6 hours and then cooled down to room temperature. The samples were biased to -18V and activated to NEA by applying a layer of cesium. During activation, the QE was monitored with a 265 nm light-emitting diode (LED) with a typical power of $\approx 10\ \mu$W. The cesium source was turned off when the QE peaked. After activation, the QE was monitored for a few hours to determine the photo-cathode lifetime.

After establishing the lifetime, spectral QE measurements were taken. Measurements were done at 265, 300, 340, 365, 375 and 385 nm with UV LEDs. For visible wavelengths, a monochromator with an arc-lamp light source was used.

RESULTS

The spectral response data for the four cathodes are shown in Fig. 2 and lifetimes are shown in Fig. 3. The primary mechanism for QE degradation was determined to be vacuum poisioning, as the QE was observed to decrease independent of average power. The differing band-gaps for c-GaN (3.17 eV) and h-GaN (3.44 eV) [7] can be seen in the spectral response data. The single crystal GaN was the best-performing sample, achieving the highest QE and longest lifetime, as shown in Table 1. Among the three p-GaN samples, we see performance (QE and lifetime) decrease with hexagonal and cubic GaN.

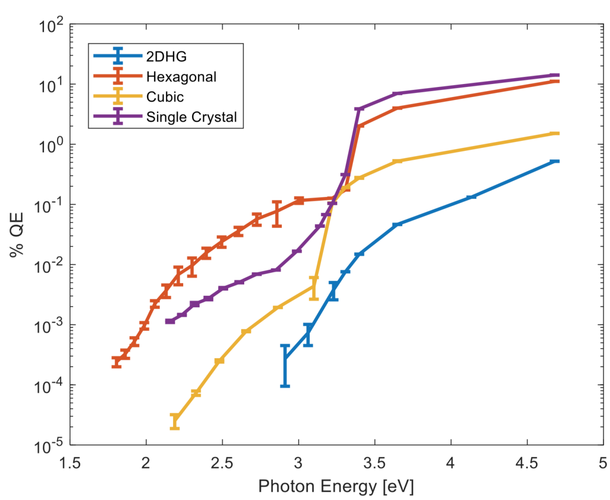

Figure 2: The spectral responses of the four cathodes tested.

Atomic Force Microscopy (AFM) images were taken from GaN samples with the same crystal structures as those of the p-GaN samples tested in this work, as shown in Fig 4. When comparing the images of the three samples, we can attribute some observations to the respective photocathode performance of the p-GaN samples. As shown, the crystal structure has a strong effect on surface roughness and defects.

In the cubic GaN we can see many anti-phase boundary (APB) defects where the crystal grain is rotated by 90 degrees, as well as a much rougher surface. GaN is notoriously difficult to grow in the cubic orientation, often resulting in a

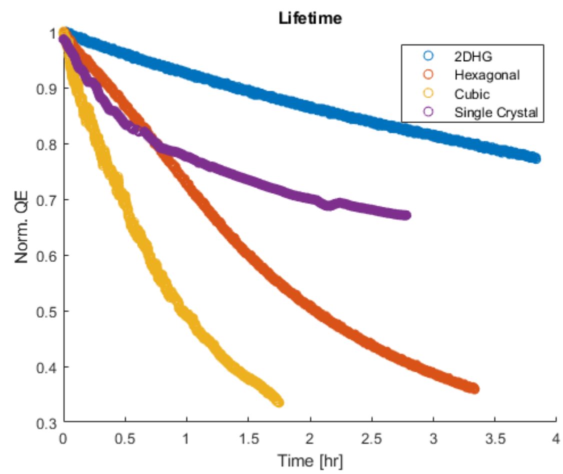

Figure 3: The lifetimes of the four cathodes tested. 1/e lifetime values shown in Table 1.

Table 1: The Peak QE and Lifetime During and After The Cs-activations. The QE was Monitored with a 265 nm LED. Note That The 2DHG Lifetime was Acquired Through Exponential Fit.

Cathode	Peak QE	1/e Lifetime
2DHG	1.4%	15.2 hr
Hexagonal GaN	11%	3.2 hr
Cubic GaN	5%	1.6 hr
Single-Crystal GaN	16.5%	69 hr

high amount of defects [8]. When growing on 3C-SiC, there are usually many APB defects, the formation of which is described in [9]. This was also observed in cubic GaN in [10]. In the hexagonal GaN, we see a much-smoother surface, however we also observe hillocks, indicative of the presence of screw dislocations [11]. Finally in single-crystal GaN, we can see a much smoother suface morphology without any hillocks or APBs. Single-crystal GaN is typically reported to have a dislocation density of $\approx 10^5$ cm^{-2}, whereas GaN templates typically measure $\approx 10^8$ cm^{-2} [12–15].

When comparing photocathode performance (QE and lifetime) and attributes found in the AFM images (surface morphology and defects), we see a relationship between the quality of the crystal structure and photocathode performance among hexagonal p-GaN samples. Previous works have shown that dislocations in GaN act as scattering and recombination centers for excited electrons [16, 17]. This would support our observation of lower QEs with higher amounts of dislocations.

The spectral response curve of the 2DHG sample exhibits a gradual decline near the bandgap, much less severe than the other cathodes. This is also seen in Fig. 2 in [1], where the undoped sample behaves the same way as compared to the heavily-doped samples.

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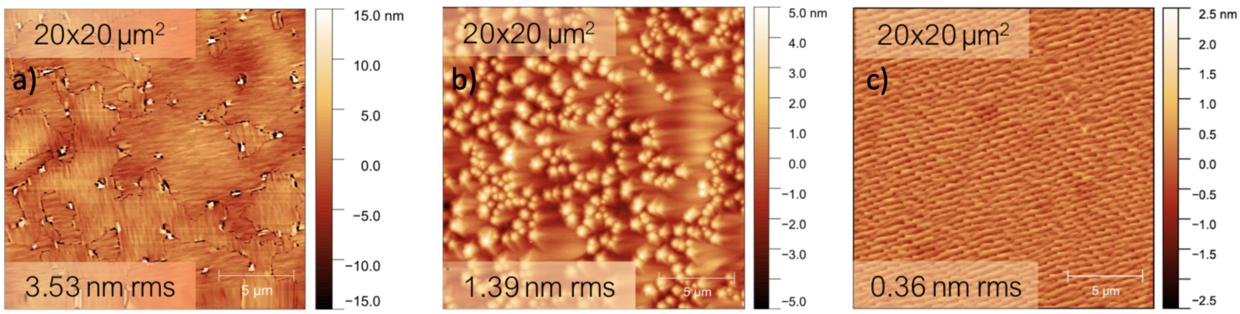

Figure 4: AFM images taken from GaN samples with the same crystal structures as those of the p-GaN samples tested. *a)* The AFM image of cubic GaN. We see domains rotated by 90 degrees and a relatively rough surface. *b)* The AFM image of p-GaN grown on a GaN template, in which we see hillocks. *c)* The AFM image of single-crystal GaN, showing a relatively smooth surface, lacking hillocks or domains.

CONCLUSION

Photoemission properties of various GaN based photocathodes have been measured. This includes three highly-doped p-GaN samples in both hexagonal and cubic GaN orientations, as well as a 2DHG sample. A relationship was identified between surface structure and photocathode performance, shown through AFM images.

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REFERENCES

[1] S. Uchiyama *et al.*, "GaN-based photocathodes with extremely high quantum efficiency", *Appl. Phys. Lett.*, vol. 86, p. 103511, 2005. doi:10.1063/1.1883707

[2] I. V. Bazarov *et al.*, "Thermal emittance and response time measurements of a GaN photocathode", *J. Appl. Phys.*, vol. 105, p. 083715, 2009. doi:10.1063/1.3110075

[3] 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, p. 124902, 2022. doi:10.1063/5.0076488

[4] J. Marini *et al.*, "Polarization engineered N-polar Cs-free GaN photocathodes", *J. Appl. Phys.*, vol. 124, p. 113101, 2018. doi:10.1063/1.5029975

[5] R. Chaudhuri, Z. Chen, D. A. Muller, H. G. Xing, and D. Jena, "High-conductivity polarization-induced 2D hole gases in undoped GaN/AlN heterojunctions enabled by impurity blocking layers", *J. Appl. Phys.*, vol. 130, p. 025703, 2021. doi:10.1063/5.0054321

[6] L. Cultrera *et al.*, "Photocathodes R&D for High Brightness and Highly Polarized Electron Beams at Cornell University", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 1601–1604. doi:10.18429/JACoW-IPAC2018-TUPML028

[7] J. Petalas, S. Logothetidis, S. Boultadakis, M. Alouani, and J. M. Wills, "Optical and electronic-structure study of cubic and hexagonal GaN thin films", *Phys. Rev. B*, vol. 52, p. 8082, 1995. doi:10.1103/physrevb.52.8082

[8] S. Adachi, *Optical Constants of Crystalline and Amorphous Semiconductors*. New York, NY, USA: Springer Science, 1999. doi:10.1007/978-1-4615-5247-5

[9] H. Nagasawa, M. Abe, K. Yagi, T. Kawahara, and N. Hatta, "Fabrication of high performance 3C-SiC vertical MOSFETs by reducing planar defects", *Phys. Status Solidi B*, vol. 245, no. 7, p. 1272, 2008. doi:10.1002/pssb.200844053

[10] Ricarda Maria Kemper *et al.*, "Anti-phase domains in cubic GaN", *J. Appl. Phys.*, vol. 110, p. 123512, 2011. doi:10.1063/1.3666050

[11] W. Qian, G. S. Rohrer, M. Skowronski, K. Doverspike, L. B. Rowland, and D. K. Gaskill, "Open-core screw dislocations in GaN epilayers observed by scanning force microscopy and high-resolution transmission electron microscopy", *Appl. Phys. Lett.*, vol. 67, no. 16, 1995. doi:10.1063/1.115127

[12] F. Kawamura *et al.*, "Growth of Transparent, Large Size GaN Single Crystal with Low Dislocations Using Ca-Na Flux System", *Jpn. J. Appl. Phys.* vol. 42, p. L729, 2003. doi:10.1143/JJAP.42.L729

[13] F. Kawamura *et al.*, "Growth of a Two-Inch GaN Single Crystal Substrate Using the Na Flux Method", *Jpn. J. Appl. Phys.*, vol. 45, p. L1136, 2006. doi:10.1143/JJAP.42.L729

[14] S. Porowski, "Growth and properties of single crystalline GaN substrates and homoepitaxial layers", *Materials Science and Engineering*, vol. 44, pp. 407-413, 1997. doi:10.1016/S0921-5107(96)01730-8

[15] C. Luo, D. R. Clarke and J. R. Dryden, "The Temperature Dependence of the Thermal Conductivity of Single Crystal GaN Films", *Journal of Electronic Materials*, vol. 30, no. 3, 2001. doi:10.1007/s11664-001-0007-1

[16] J. Yu *et al.*, "Influence of dislocation density on internal quantum efficiency of GaN-based semiconductors", *AIP Advances*, vol. 7, p. 035321, 2017. doi:10.1063/1.4979504

[17] T. Sugahara *et al.*, "Direct Evidence that Dislocations are Non-Radiative Recombination Centers in GaN", *Jpn. J. Appl. Phys.*, vol. 37, p. L398, 1998/ doi:10.1143/JJAP.37.L398