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FIRST DEMONSTRATION OF SPIN-POLARIZED ELECTRONS FROM GALLIUM NITRIDE PHOTOCATHODES

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Abstract

For the first time, photoemission of a spin-polarized electron beam from a gallium nitride (GaN) photocathode is observed and characterized. The spin polarization of the emitted electrons from epitaxially grown cubic GaN photocathode activated to Negative Electron Affinity (NEA) via Cesium deposition are measured in a retarding-field Mott polarimeter.

INTRODUCTION

For both high energy and nuclear physics experiments, it is highly desirable to have a photocathode that can robustly deliver a high average current (>10 mA) spin polarized electron beam [1–4]. Spin polarized beams can also be used to enhance electron microscopy techniques [5–7]. Currently, the only viable method of achieving such a beam in a photoinjector is with a GaAs based photocathode [8]. For spin-polarized production from GaAs, electrons must be excited from the top of the material valance band. By using circularly polarized light, conservation of angular momentum and quantum mechanical selection rules allow preferential excitation from the degenerate $P_{3/2}$ state resulting in a net spin-polarized beam. For efficient operation at the material bandgap, GaAs is brought to Negative Electron Affinity (NEA) by depositing an activation coating of Cs and an oxidant (typically oxygen or NF_3) resulting in percent level Quantum Efficiencies (QE) [9]. Because the $P_{3/2}$ degeneracy is 4-fold, bulk GaAs can theoretically produce a maximum beam polarization of 50 %; experimentally the value tends to be lower due to depolarizing effects [10]. The use of strained GaAs/GaAsP photocathodes, which break the degeneracy, has achieved >90% spin-polarizations [11].

Although GaAs photocathodes have been reliably producing spin-polarized beams for decades, they are characterized by low operational lifetimes. The NEA activation layer tends to be highly reactive to residual gas in the electron gun resulting in a degradation of the cathodes QE over time [12, 13]. In addition to this vacuum poisoning effect, during high current operation ion-back bombardment [14] and laser induced thermal desorption [15] reduce the cathode lifetime. A major area of research is to develop more robust GaAs photocathodes via alternative NEA activation schemes [16–20].

The III-V direct bandgap material, GaN has been less studied as a photocathode because the ability to produce high quality epitaxially grown samples came considerably later than GaAs [21]. Nonetheless, GaN has many interesting properties that may lead to a more robust, spin-polarized source. Like, GaAs, GaN is a NEA photocathode; QEs as high as 50 % have been reported [31], making it an attractive option for high current production and, unlike GaAs, the NEA activation procedure is simpler as only Cs and no oxidant is required [32]. The thermal conductivity of GaN is significantly better than GaAs, which has resulted in it being adopted for high power electronics [33, 34]. The higher thermal conducitivity may be beneficial during high current operation to reduce QE degradation through thermal desportion. Finally, GaN's larger bandgap results in a stronger bonding of Cs to the surface, potentially resulting in a more robust NEA activation layer [22].

GaN may be grown in the Wurtzite (hexagonal) or zinc-blende (cubic) crystal lattices, with bandgaps of 3.4 and 3.2 eV, respectively. GaN exhibits spin-orbit splitting in both crystal structures, but the the value of the zinc-blende (20 meV) is larger than Wurzite (8 meV). Additionally, the smaller bandgap of the zinc-blende conveniently corresponds to the photon energy of a frequency doubled Ti:Sapphire laser operated at 780 nm. For these reasons, in this proceeding we focus on GaN zinc-blende photocathodes.

METHODS

Cathode Preparation

At the Xing/Jena group laboratory, the zinc-blende GaN sample was grown using a Veeco Gen10 molecular beam epitaxy system equipped with standard effusion cells for elemental Gallium, Aluminum and Magnesium. The substrate was diced from a 4 inch silicon carbide on silicon (3C-SiC) wafer purchased from NOVASiC into a 10x10 mm square. Before epitaxy, the substrate was ultrasonicated in acetone, methanol and isopropanol for 10 min each before placing under vacuum. Once under vacuum, the sample was heated to 200 C for 7 hours to allow outgasing. The growth thickness was 1 μm and the magnesium (p) doping concentration was set to 3×10^{19} cm $^{-3}$ which was based on results reported in [31] of maximum achievable QE as a function of doping concentration. The sample was grown within the step-flow growth mode with metal-rich conditions throughout the whole epitaxial process.

After growth, the sample was removed from the Veeco Gen10 chamber and transported under high, static vacuum to the Photocathode Laboratory at Cornell [23]. The sample was exposed to air for approximately 10 minutes during mounting into a puck compatible with the activation chamber and Mott polarimeter (see below). To ensure good electrical contact, the sample was indium soldered to the puck cap.

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After moving into the activation chamber, the sample was heat annealed at 600 C for 6 hours.

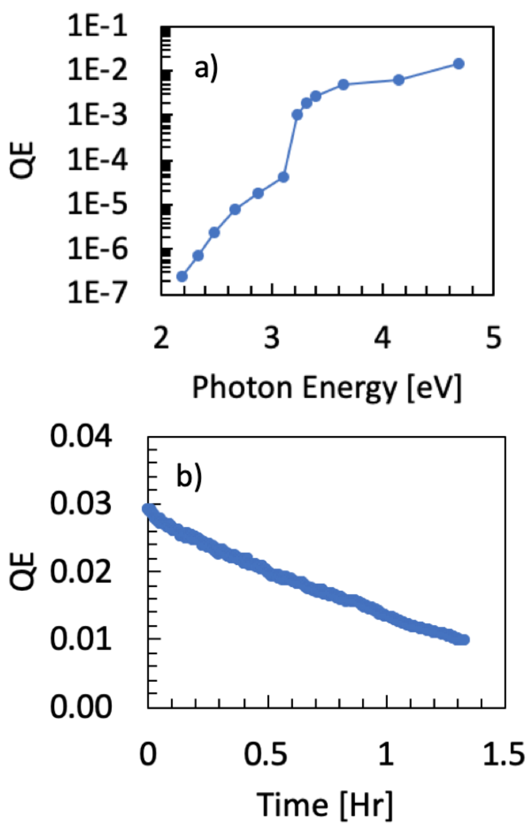

Figure 1: *a*) The measured QE of the cubic GaN photocathode. *b*) The lifetime of the photocathode, as monitored with a 265 nm LED.

Cathode Characterization and Spin Polarization Measurement

The photocathode was activated to NEA with Cs using a 265 nm diode with approximately 10 μW power. A peak QE of 5% was achieved. Immediately after activation a spectral response was performed as shown in Figure 1a. After the spectral response was performed, the cathode's QE was monitored and it can be seen to degrade on the order of an hour, as shown in Figure 1b. As shown in an earlier GaN photocathode characterization [24], the surface of epitaxially grown cubic GaN is known to have many anti-phase boundary (APB) defects in which there is a 90 degree rotation in the crystal grain. It had been previously reported that anti-phase domains exhibited on cubic GaN grown on 3C-SiC/Si are substrate induced [25] and a consequence of lattice mismatching [26]. The resulting rougher surface of cubic GaN may affect how Cs bonds to the surface and consequently increases the photocathode's susceptibility to chemical poisoning.

Once characterized, the cathode was brought into a 20 keV Retarding-Field Mott polarimeter with a Tungsten target. For cathode illumination, the output of a Xenon lamp was sent through a monochromator to produce a tunable UV light source. Throughout the spectral range the monochromator slits were adjusted to produce a typical minimum bandwidth of 2.8 nm bandwidth as verified with a compact CCD spectrometer. As explained in [28,29], Mott polarimetry exploits the scattering asymmetry between spin up and down electrons off of the target, causing unequal count rates in two detectors placed symmetrically about the target. To account systematic errors in the detector rates, the (circularly) polarized light direction is switched, flipping the net beam polarization from up (down) to down (up) and thus reversing the count rate asymmetry.

Figure 2 shows the measured spin polarization as a function of illumination wavelength. A peak polarization of 25.3 $\pm$1.49% occurs at 386.5 nm (3.21 eV). At each wavelength the measurement was repeated 10 times. The measurement uncertainty is derived from the standard deviation of the repeated measurements divided by the number of repeats.

DISCUSSION

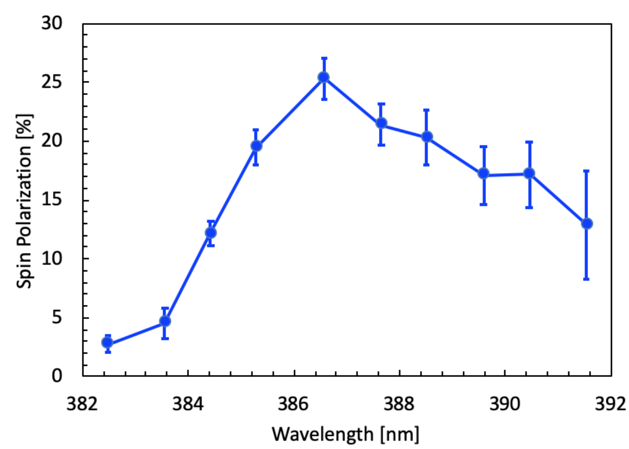

Figure 2: The measured spin polarization of cubic GaN. The peak is 25.3% at 386.5 nm.

We have presented the first ever measurements of a spin-polarized beam produced from a zinc-blende NEA GaN photocathode. The obtained degree of spin polarization is lower than what is typically obtained with bulk GaAs. The most likely explanation for this is the spin-orbit splitting of zinc-blende GaN has a relatively small value of 20 meV. At the bandgap wavelength, this energy splitting width corresponds to a wavelength spread of 2.4 nm which is smaller than the obtainable minimum bandwdith of 2.8 nm of our monochromator. Consequently, electrons from both the heavy and light hole bands participate in the photoemission process, and thus dilute the net spin polarization.

To improve upon the obtainable degree of spin-polarization, we our currently developing an adjustable bandwidth, tunable UV light source based on intra-cavity frequency doubling of a continuous wave Ti:Sapphire laser, similar to what is reported in [30]. For high-voltage, high-

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current applications where space-charge is more suppressed, the use of a mode locked Ti:Sapphire oscillator would allow for efficient frequency doubling of the fundamental external of the cavity, providing a convenient way to obtain high current spin-polarized beam production from GaN.

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