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Progress in the Fabrication of GaN Photocathodes

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Abstract. Greatly improved ultraviolet-visible-blind imaging system are necessary for future space missions. GaN photocathode based devices are a likely choice for these missions. We demonstrate this by describing our current work on making GaN phototubes, and we suggest the path to follow to make further improvements.

1. Introduction

For astrophysics applications we have the following major requirements for ultraviolet (UV) detectors: a high (at least 0.4) quantum efficiency (QE) below the long wavelength cutoff, a low (no better than 10^{-6}) QE above the long wavelength cutoff, a tunable band-gap, and a low dark current ($\simeq 10^{-14}$ nA/μm^2) for single photon counting. Large formats (our goal is $15,000 \times 15,000$) and high dynamic range (both local and global) are important for most astronomical applications as well (see Ulmer, Razeghi, & Bigan 1995 and references therein). Microchannel plates (MCPs) currently win over CCD-like solid state p-i-n devices made from III-V semi-conductors. The dark current in the p-i-n devices is at least 10^5 times too high (e.g., Parish et al. 1999), and there is no clear path to reducing the dark current in these p-i-n devices. The development of photocathodes is the approach most likely to lead to devices for UV space missions over the next 10 years. We have, therefore, embarked on making GaN-based photocathodes.

Figure 1 shows a compilation of the QE of several devices for comparison with Figure 2. These figures demonstrate the potential for GaN based photocathodes. A single data point (QE of 50% $\pm$ 6%) at 312.6 nm from Machuca et al. (2000) is not shown. The result by an independent group plus our work demonstrates that GaN photocathodes are indeed an excellent choice for future UV space missions. Also, for comparison, in Figure 2 we have plotted the QE of diamond and CsTe photocathodes. For a narrow-band response these may prove adequate, but for a broad band with a tunable (via alloying with Al or

In) long wavelength cutoff, GaN-based (or other wide band-gap materials) films are necessary. We also remind the reader that the QE of opaque photocathodes can exceed 50%.

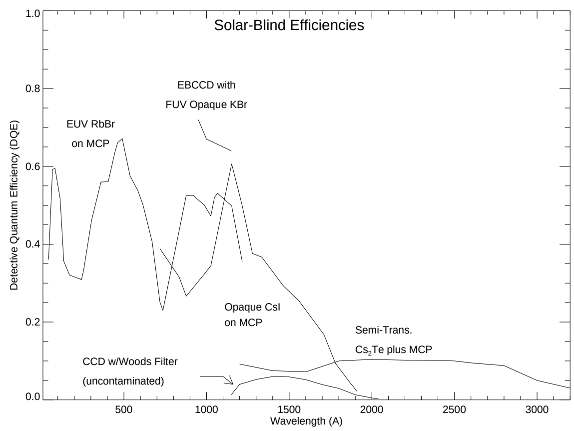

Figure 1. The detective efficiency versus energy for various devices taken from Ulmer et al. (1995).

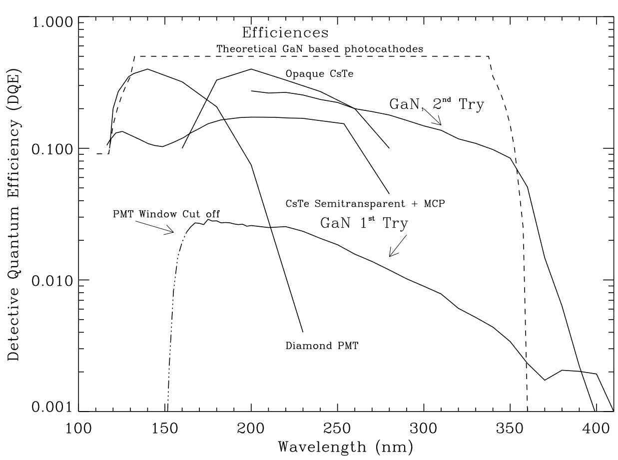

Figure 2. Previous work on GaN compared with the performance of some other photocathodes. The CsTe MCP data are from Joseph (1995) and Kimble et al. (1999). The diamond response is from a Hamamatsu phototube specification document R6800U-26, but see also Tremsin & Siegmund (2000). The opaque CsTe data are from a Hamamatsu photomultiplier tube catalog: R1220 PMT

2. Main Points About Using GaN

To use GaN as a photocathode, the GaN must be p-type with an n-type $\sim 1\,\mathrm{nm}$ activation surface layer to produce "band-gap bending". This produces the desired negative electron affinity (see Shahedipour et al. 2002, and references therein). The preferred dopant is Mg. The relatively high ionization energy of Mg (about 200 meV) results in only about a 1% contribution to the charge carrier concentration, and hence 10^{20} atoms cm^{-3} are needed to produce a carrier concentration of 10^{18} cm^{-3}. It is this number of 10^{18} cm^{-3} that we hypothesize is the level above which only marginal increases in QE will be gained. However, our own work (Shahedipour et al. 2002; Ulmer et al. 2001) suggests that high conductivity is the key factor in the bulk film property. This is demonstrated in Figure 3. We have continued our research by having photocathodes made both by O. Siegmund (presented separately, this conference) and by ITT night vision (K. Passmore & A. Smith, private communication). Their resulting photocathodes had QEs within a few % of the "second try" by Hamamatsu shown in Figure 2. However, the Figure 2 "second try" is still the best performance with our GaN. Furthermore, the film used by Siegmund had a conductivity of 0.36 (Ohm cm)$^{-1}$ and carrier concentration of 2×10^{17} cm^{-3}, and the film used by Passmore and Smith had a conductivity of 0.55 (Ohm cm)$^{-1}$ and carrier concentration of 3×10^{17} cm^{-3}. These characteristics are markedly higher than those of the films used by Hamamatsu (see Figure 3). Perhaps increasing the conductivity above ~ 0.13 (see Figure 2) will not improve the performance of GaN-based photocathodes. It is more likely that changes in the surface treatment by our new collaborators (Siegmund, Passmore, and Smith) will lead to improved QEs. Since the results achieved to date by Siegmund, Passmore, and Smith were based on their very first attempts at processing this GaN material, it is quite plausible that the limit of QE performance has not yet been reached. More work is needed with films that have conductivities exceeding ~ 0.13 (Ohm cm)$^{-1}$ to determine the importance of surface preparation versus bulk film properties.

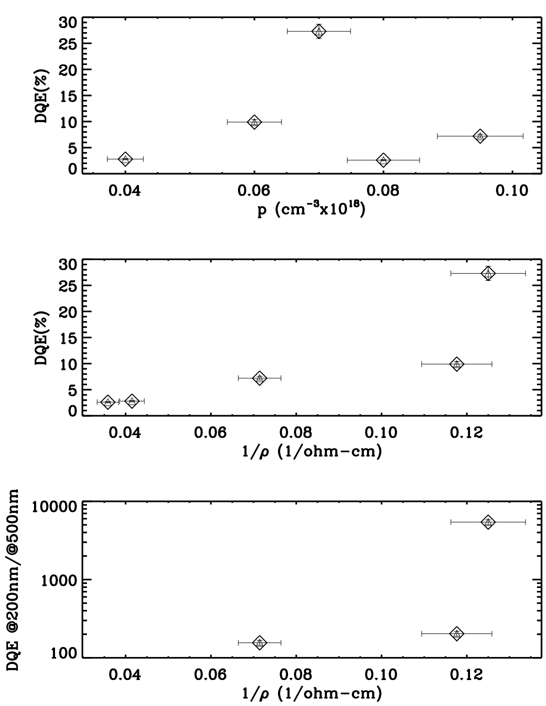

Figure 3. QE versus carrier concentration and conductivity are shown in the top two rows. In the third row we show a "figure of merit" versus conductivity. The figure of merit is defined here to be the ratio of the QE at 200 nm to the QE at 500 nm)

There are several issues yet to be addressed:

1. What is the threshold above which increased conductivity and/or carrier concentration has no measurable affect on the optimal possible photocathode performance?

2. Can the QE as function of wavelength be improved by achieving carrier concentrations of 10^{18} and/or conductivity as high as 5 (Ohm cm)$^{-1}$ via co-doping (see Korotkov, Gregie, & Wessels 2000)? However, the increased number of lattice defects caused by co-doping (Han et al. 2002) may cause a degradation in the long wavelength performance below the band-gap rather than an improvement.

3. What other avenues besides the ones discussed above are there to improve QE? One likely answer is the placement of a wider band-gap material below the active layer (e.g., AlN/AlGaN and then the active GaN surface – see, for example, Machuca et al. 2000). The wider band-gap material acts as an "electron mirror" and can effectively produce, in principle, QEs greater than 50%.

4. Can coating GaN onto Si MCPs be accomplished to produce large format detectors made with opaque GaN-based photocathodes?

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