Advances in Wide-Band Gap Semiconductor Based Photocathode Devices for Low Light Level Applications

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ABSTRACT

The basic requirement for a imaging low-light level system (one capable of single photon counting) is that the device has low dark current. Photocathode based devices have the advantage over solid state devices in this regard as the dark current is inherently low. A further requirement for UV detectors is the necessity to suppress the sensitivity in the red, and wide-band gap semi-conductors fill this role well. For nitride based semi-conductors, there is still the issue of making p-type material and making alloys with Al or In to move the red cutoff to the blue (Al) or red (In). Regardless of the material (e.g. another choice is diamond) coupling the resulting photocathode to a device such as a micro-channel plate (MCP) is necessary to produce imaging. Based on advances we have made both in the production of p-type GaN photocathodes, diamond photocathodes, and read-outs of Si MCPs, we are on the verge of making high quality UV imaging systems for astronomy and other low-light level applications. However, the outstanding question is how to optimize the photo-cathode performance. In this paper we discuss this question in the context of our progress in making GaN-based photo-cathodes.

Keywords: GaN, photocathode, UV astronomy, wide band-gap semiconductor

1. INTRODUCTION

The need for UV visible or solar blind detectors has been presented in the literature many times,[1–3] and the applications range from industrial, to defense, to astronomical. In many cases, and astronomy in particular, low light level or single photon counting is necessary. Wide band gap semi-conductors are obvious choices to meet the requirement of high quantum efficiency (QE) in the UV and negligible QE in the red. This is because photo-excitation of electrons into the conduction band does not occur unless the energy of the photon exceeds the band-gap for ideal semi-conductors. Two divergent approaches have been explored: photocathodes and p-i-n diodes.

For UV visible blind imaging applications where areas of about one square cm are required, the p-i-n diodes have been quite appealing. The pin diodes are low power and run at low voltages. The problem has been and continues to be that the dark current in these devices is so high that single photon-counting remains beyond the reach of the current devices (cf. ref 4). This fact alone has been enough impetus to continue to develop photocathode based devices.

We have produced a series of papers reporting details of our previous work.[4–6] For completeness, we reproduce one of our figures (Figure 1 from previous work[4]) to show the detective quantum efficiency (DQE)

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of all 5 tubes made with GaN films produced by our Northwestern University (NU) group and converted into photocathodes by the Hamamatsu Corporation (HPK).

In the next figure (Figure 2) the best results of new work (ours and others[7]) plus, for simplicity, the DQE of two of the previous HPK tubes.[4, 6]

From Figures 1,2 it can be seen that there is a relatively large variance in performance. It is the purpose of this paper to discuss possible reasons for this variance.

2. REVIEW OF PREVIOUS RESULTS

2.1. Review Basic Considerations for Photocathodes

Effective (or true) negative electron affinity (NEA) is required to facilitate the ejection of photo-electrons from a photocathode surface. For GaN effective NEA is achieved by heavily doping the bulk material p-type and then placing a thin (about 1 nm thick) surface layer such as Cs for an n-type surface with minimal intrinsic positive electron affinity (work function). For example, in the case of a work function near 1 eV with full band gap bending of 3.4 eV, the net result is a negative electron efficiency of $1 - 3.4 = -2.4$ eV (see, for example, ref. 6). We hypothesize that if the bulk material has a carrier concentration of about 10^{18} cm^{-3} combined with a top n-type layer (e.g. Cs), then nearly full band-gap bending is achieved. The low work function surface layer of Cs then leads to an effective NEA. This hypothesis was the basic motivation behind our producing p-type material with as a high carrier concentration as possible.

2.2. Results

2.3. Discussion of Previous Work

The main points from our previous work were: (1) HPK produced tubes with various quantum efficiencies as shown in Figures 1,2; (2) The correlation of DQE appeared to be not just dependent on carrier concentration (p), however, but was, instead, better correlated with the conductivity ($1/\rho = \sigma$; carrier concentration $\times$ mobility). Point "2" was inferred from the data for "p" below 10^{17} and the data for $1/\rho$ below 0.13 as shown in Figure 4.

That conductivity might be more important than carrier concentration can be understood as follows: even if the theoretical work function is low, if the efficiency for electron ejection is low, the DQE will be low. Therefore, if the carriers are not mobile enough, the electrons that are ejected into the conduction band will not reach the surface and be ejected prior to capture at a defect site in the bulk material. Combined high mobility and carrier concentration (i.e. high conductivity) is, therefore, important for high photocathode performance. The relatively abrupt rise in DQE at a conductivity of 0.13 (Ohm-cm)$^{-1}$ in Figure 4 suggested to us that even better performing (higher DQE above the band gap and a sharper cut-off at the band gap) photocathodes could be produced with $\rho \gtrsim 0.13$ (Ohm-cm)$^{-1}$ This may not be the case, however, as the new data do not appear to be consistent with the hypothesis that high conductivity is the key. We elaborate upon this topic in section 2.4 below.

2.4. Discussion of Results

As remarked in the previous section, prior to the new results described here from processing and testing of GaN films made by NU, we had a working hypothesis that as the conductivity is increased, the QE is also increased. Further, we conjectured at about $\rho = 0.13$, the QE improvement with conductivity would be relatively rapid compared to the change below about 0.10. The point at $\rho = 0.36$ belies this conjecture. In stead, if we refer to the p versus DQE at 310 nm in Figure 4 (middle panel), carrier concentration alone may be as good a predictor as anything (as suggested by Woodgate, private communication). We have illustrated this point by the dashed line in Figure 4 which is a straight broken line (judged by eye to be a relatively good fit) described by the line from [0,0] to [0.4×18^{18},60]. However, that all our data (i.e. excluding the point from ref. 7) can be fit by a horizontal line, indicates that carrier concentration is *not* the key criterion. Conductivity data are not available from ref. 7, so we can only use our data to compare DQE with conductivity, which data we discuss in the next paragraph.

As can be seen in the bottom panel of Figure 4, above about 0.13 (Ohm-cm)$^{-1}$ the conductivity doesn't seem to matter, either. However, *if* indeed all the HPK photo-cathodes were processed exactly the same way (as reported by HPK), the data suggest that a threshold is required for good photocathode performance and this is about 0.13 (Ohm-cm)$^{-1}$. *However, we really don't know the necessary conditions for making high quality photo-tubes*, as we have very few samples.

Furthermore, for all the samples we have tested there is another characteristic that could be important, which is the bulk surface structure, e.g. smooth or columnar. For example, all the NU films discussed here are in the "smooth" category, but perhaps columnar growth which would expose more surface area at the loss of bulk conductivity might produce better photocathodes.

Also, the Stanford results[7] was based on sample that was only 0.1 μm thick (in contrast all the NU films are between 1 and 2 μm thick) build up on a AlN/AlGaN surface. The theoretical basis for this structure (which we call an "electron-mirror") is that the AlN/AlGaN sub-surface has a wider band-gap than the GaN. Then, in principle, photo-electrons that are ejected into the conduction band, but away from the surface would see the higher band-gap of the sub-surface and be reflected back toward the surface. This could increase the efficiency of opaque photo-cathode above 50%, if the electrons are not instead captured by lattice defects. Was this phenomenon operative in the Stanford sample? We don't know.

The theory of an "electron-mirror" suggests that the material should have high conductivity and few defects to improve the probability that the electron can travel far enough to be reflected and then escape the photocathode surface. This leaves open the possibility that the Stanford sample performed so well due to a combination of the structure and high conductivity (for which no value was published). Since ref 7 only reported a quantum efficiency at one wavelength, however, it is difficult to judge. Only further measurements with more samples can clarify the situation.

3. FUTURE WORK

Each potentially important physical characteristic must be isolated and films must be processed accordingly: (1) we must repeat the work done to date with more samples; (2) films that are smoother or rougher (on the sub-nm scale) but with the same carrier concentration can be processed; and more samples need to be made and tested that use the concept of the "electron-mirror" which backs the GaN with a wider band-gap AlN/AlGaN substrate. Furthermore, the thickness of the GaN top layer may also be crucial for the "electron-mirror" design.

For the sake of discussion, let us assume that conductivity above 0.13 (Ohm-cm)$^{-1}$ is the key criterion for the GaN films or at least a necessary, if not sufficient, criterion. There are (at least) two methods of improving the p-type conductivity: (1) Co-doping; and, (2) superlattices.

By co-doping with oxygen[8] (see also ref. 9) it has been possible to achieve carrier concentrations above 10^{18} and improved the conductivity as well. The theory discussed in ref. 8 suggests that Si can do even better and we have made Si samples as well. Our first Si co-doped samples, however, did not show an improvement in conductivity over non co-doped samples. This is probably because the Mg and Si don't form a stable complex which is necessary for enhanced carrier mobility. Furthermore, 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. Therefore, samples made by co-doping need to be tested before we have an answer as to how good GaN films with increased concentrations of Mg acceptors made via co-doping will be useful.

The other approach that has been used improve the carrier concentration and conductivity is to grow superlattices of AlGaN/GaN. These films have been made[10,11] (see also, refs. 12, 13) with charge carrier densities that exceeded 10^{18} cm^{-3}. However, these superlattices are built up of alternating 3 nm Mg doped layers of AlGaN and GaN. It is not clear if these superlattices behave as bulk p-type material to produce the necessary band-gap bending when combined with an n-type surface layer. The structure of the super lattice results in the high conductivity being only within the superlattice layers, not in the bulk, and therefore the probability of photo-electrons escaping the surface could be greatly diminished over that for homogeneous GaN or AlGaN. It would be interesting, however, to see how well such superlattices perform as photocathodes.

4. BEYOND GAN ON SAPPHIRE

4.1. AlGaN, InGaN, and Alternative Substrates

Diamond has a band gap (5.4 eV) close to that of AlN (6.2 eV), but the ability to tune AlGaN from 3.4 (GaN) to 6.2 eV (AlN) makes it worthwhile to consider processing AlGaN films into photocathodes as well. At the red end, InN has a band gap of 1.9 eV.[14] Therefore applications where having a slightly longer wavelength response than GaN is important, photocathodes made from InGaN would be useful. We have just begun to carry out work in this area. We are not aware of other InGaN photocathodes investigations. We have already found, however, that making high conductivity of p-type InGaN material will be challenging.

Besides working with other alloys of GaN, we are also motivated to grow high performance GaN of Si. This is because we would like to be able to coat Si micro-channel plates (MCPs) with visible blind photo-cathodes such as GaN.[5,15] Of particular importance to us is that the Si is robust, i.e. it can be heated to at least 800 C. Therefore it is appealing to consider growing GaN on a Si MCP, provided an adequate (for high quality GaN growth) buffer layer can be deposited first. This approach of coating the MCP with GaN gives us an imaging system made with the optimal efficiency configuration: an opaque photocathode. These devices, coupled with the new and better readout systems as described elsewhere15–17) will be truly impressive devices: high efficiency (near 50%), high local (< 1 nano-sec timing) and global dynamic range (> 1 MHz counting rates), large formats (better than 3000×3000) and exquisite positional accuracy ($< 3\mu$m).

5. CONCLUDING REMARKS

Above and beyond the bulk properties of the GaN-based material, the surface treatment is of utmost importance. The ideas we have so far on what are the best GaN films are based on small number statistics. We urgently need a significant data base of results from processing many different GaN films the same exact way. Only then will we be able to disentangle the complex picture we have now.

Perhaps the best process from making GaN photocathodes is yet to-be-determined. Regardless, the advances that have been made to date indicate that photocathodes based on wide band gap semi-conductors and the associated imaging systems are possible. Furthermore, we have developed a path for coupling this technology to advances in MCP technology to make high quality imaging devices for low light level UV visible blind applications. It will only be matter of time before these systems are available.

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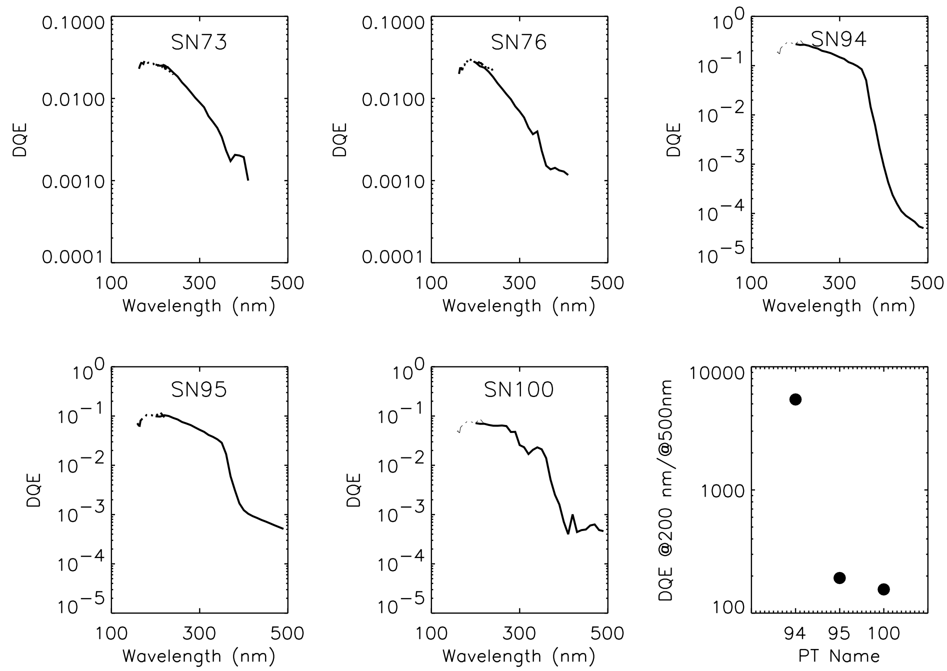

Figure 1. From previous work,[4] a summary of the response of the various photo tubes that were made. The SN label designates the photo-tube label. DQE stands for detective quantum efficiency. The solid lines are from Hamamatsu; the heavy broken lines are from Rutgers; the light broken lines are the SN95 result normalized to the SN94 and SN100 data.

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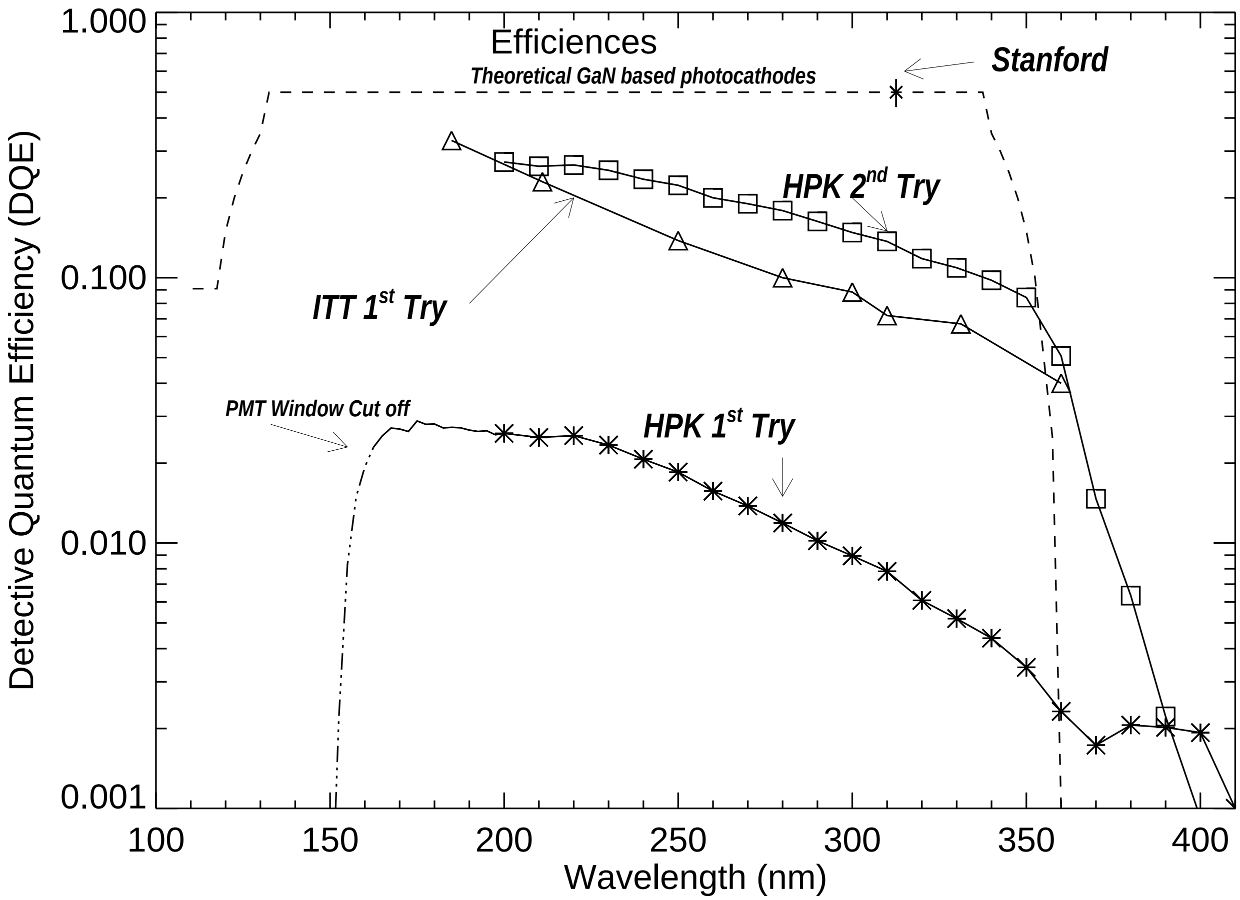

Figure 2. The detective quantum efficiency versus energy for 2 photocathodes process by HPK (SN73 and SN94 in Fig. 1) and the one processed by the ITT Night Vision (ITT) and the single data point from ref. 7 (Stanford). The dashed line labeled theoretical efficiency assumes that 50% of the photo-electrons are lost by traveling away from the surface. A hetero-structure substrate may boost 50% DQE, however, see text.

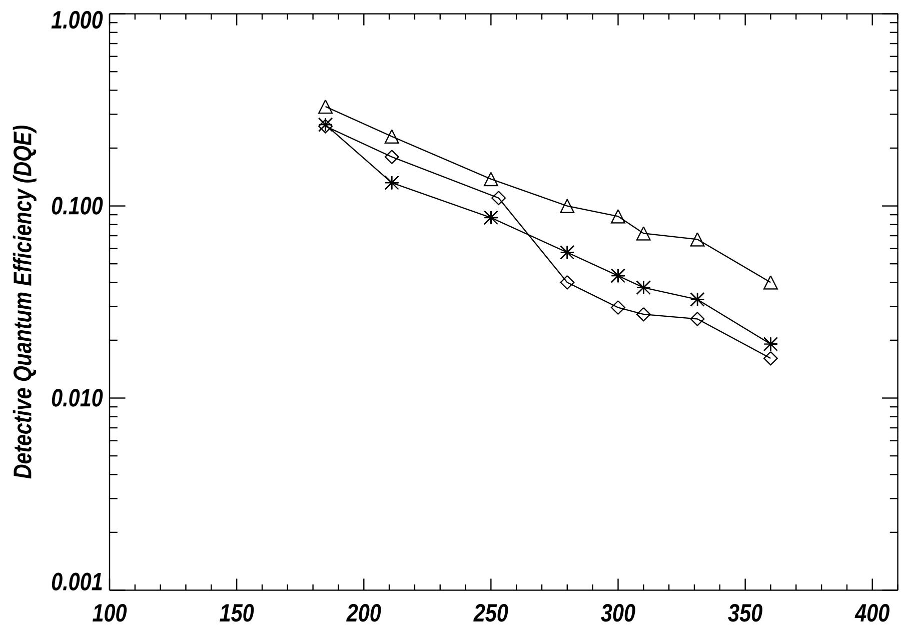

Figure 3. The QE from our most recently produced photo-photocathodes as function of wavelength, designated JG138 (triangle), JG219 (diamond), and JG238 (asterisk)

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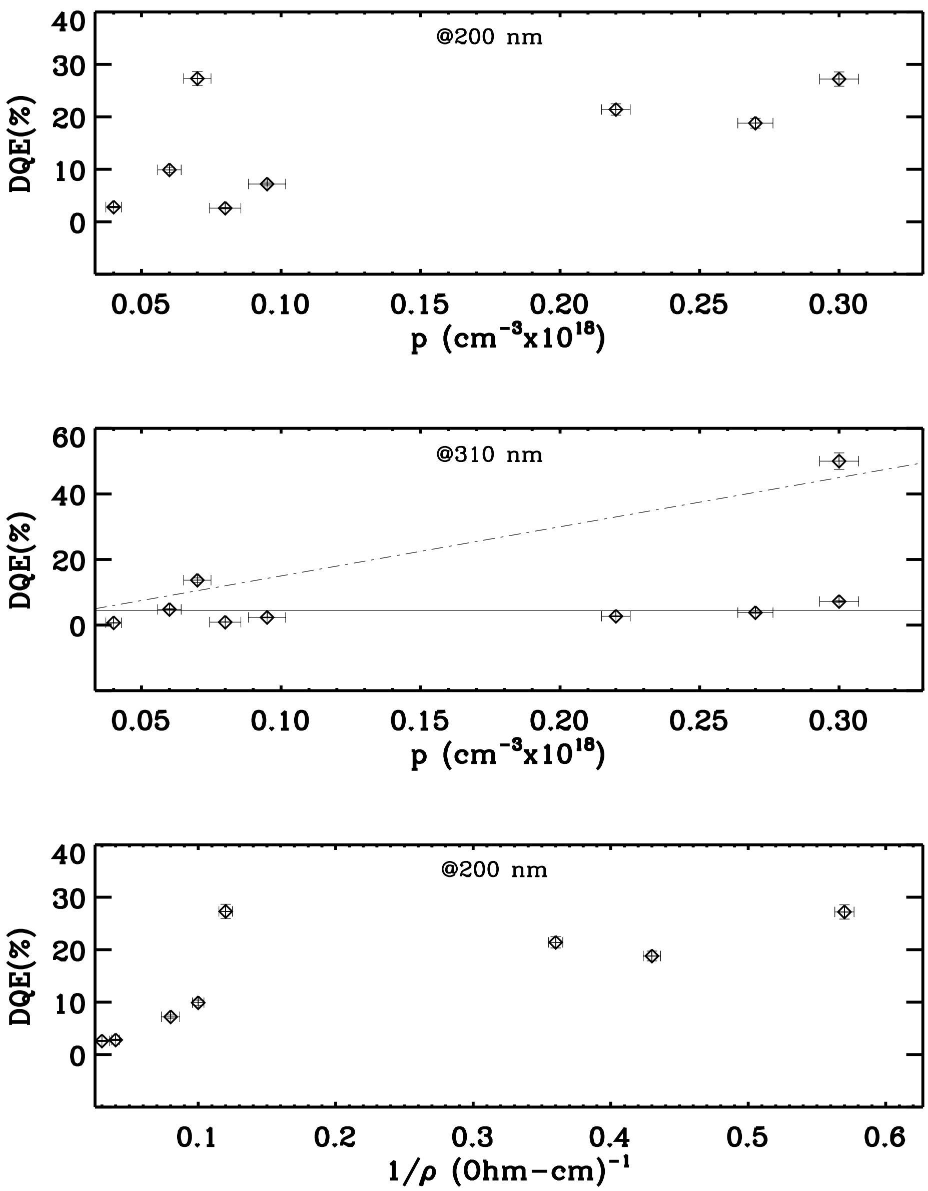

Figure 4. The top two panels are detective quantum efficiency (DQE) versus carrier concentration. The points below 0.1×10^{18} are from our previous work[6, 15] all done with HPK. The top plot is for comparison with previous work. The lower panel of these two was made to include the ref. 7 point which was only reported for 312.6 nm. The other data points are for 310 nm. The broken line was a fit drawn by eye, see text. The solid line is the average of all but the Stanford point. The lowest panel shows for the samples that were measured (ours), the DQE versus conductivity