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Development of GaN photocathodes for UV detectors

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Abstract

We have made substantial progress in the development of GaN photocathodes, including crystalline and polycrystalline GaN and InGaN coatings grown by chemical vapor deposition or molecular beam epitaxy on sapphire substrates. GaN and InGaN photocathodes have been developed with efficiencies up to 70% and cutoffs at ~380 nm with low out of band response, and high stability and longevity. Samples have been processed and tested at ultra high vacuum to establish cathode process parameters, and some have been integrated into sealed tubes for long-term evaluation.

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Keywords: Gallium nitride; Ultraviolet; Photocathode

1. Introduction

Photocathodes have been used for detection of ultraviolet (UV) radiation for many applications in spectroscopy and imaging. One typical configuration is a ‘semitransparent’ mode where radiation enters through a window onto which the photocathode is deposited on the interior. Photoelectrons are then emitted from the vacuum interface of the cathode (Fig. 1). Another configuration is the ‘opaque’ mode where radiation enters the cathode layer at the cathode/vacuum interface and photoelectrons are emitted from the same interface. Various loss mechanisms affect the conversion efficiency including reflection, attenuation, electron transport, and surface escape probability. Semitransparent cathodes are often used for “sealed tube” devices, and opaque cathodes are often used in “open face” short wavelength sensors (<150 nm). The nitride-III semiconductors, in particular GaN (band gap energy 3.5 eV) and its alloys $Al_xGa_{1-x}N$ and $In_xGa_{1-x}N$, are attractive as UV photo-converters for position sensitive detector systems. GaN can “fill the gap” in the 150–400 nm wavelength regime (Fig. 2) between alkali halide photocathodes (<200 nm), and the various optical photocathodes (>300 nm, multi-alkali and GaAs). Currently CsTe is the material of choice for a far UV semitransparent cathode, but it has fairly low efficiency ($<20\%$), and cuts off at <300 nm. Current results indicate that GaN photocathodes will be robust and achieve high-quantum efficiency (QE) from 100 to 380 nm with low visible response, making it an attractive replacement for CsTe (and possibly CsI).

2. GaN photocathode development

We have obtained GaN samples grown by molecular beam epitaxy (2″ diameter) on sapphire from SVT associates, and samples made by chemical vapor deposition at Northwestern University (NWU) [1]. To promote electron drift to the surface the GaN is Mg (p)-doped to increase the minority carrier diffusion length (~200 nm) [2]. The SVT samples have a thin layer of AlN (~10 nm) and a 100–250 nm GaN layer. The NWU samples have GaN layers that are from 200 to ~1000 nm thick. Dopant concentrations vary from $\sim 7\times 10^{16}$–5×10^{17}, and details of the samples are provided in Table 1. Some NWU

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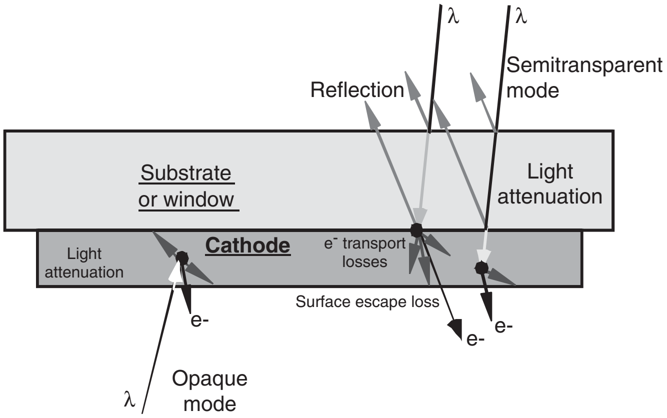

Fig. 1. Schematic of a photocathode layer on a window or substrate showing the important conversion and loss processes leading up to photoelectron emission.

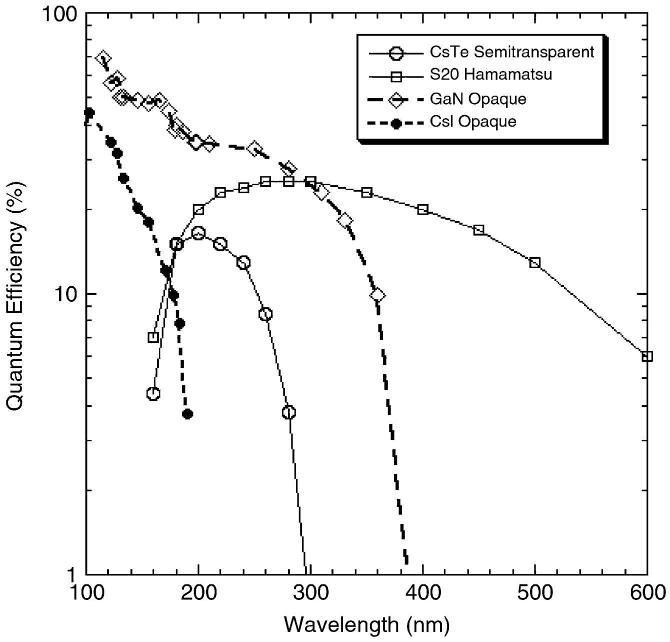

Fig. 2. Comparisons of our quantum efficiency measurements of opaque CsI on an MCP, opaque GaN, a commercial multialkali cathode, and a NIST CsTe photodiode.

samples were deposited as polycrystalline, rather than crystalline layers, but in all cases the samples were diced to ~1 cm^2.

Ideally, all photons would interact in the GaN layer and the electrons created would all drift to the exit surface and be emitted. In practice the attenuation length of photons in GaN [3] increases at longer wavelengths and increases sharply at the band edge where GaN becomes transparent. The ideal efficiency of GaN was estimated by calculating the absorption of light in 100 nm of GaN (top curve in Fig. 3) after accounting for a reflectivity of ~20% (independent of wavelength). Transport of electrons to the GaN surface, and the escape probability from the surface were not included in this estimate. One of the key features of GaN is the ability to lower the surface work function to produce negative electron affinity (NEA). Sample preparation to achieve NEA and good photocathode response include chemical cleaning, vacuum degassing, vacuum heating and surface activation with alkali metal (Cs).

We have achieved efficiencies as high as 70% for GaN at the shortest wavelengths (Fig. 3), and we have measured the out of band response showing reasonable "solar blindness" (Fig. 4). The cutoff wavelength is sharp, with a rapid decline in quantum efficiency at ~380–400 nm. Short wavelength efficiencies are high ($>60\%$) and most of the improvements made in recent work have increased the longer wavelength QEs (Fig. 3) as the electron affinity has been reduced. Determination of the relative importance of the GaN bulk electron transport, and the surface escape probability are possible through measurements of angular QE response, and of opaque and semitransparent QE for the same sample. So far our angular data on opaque cathodes shows little variation over $\pm 45^\circ$ angles, suggesting that the surface escape conditions dominate the QE. We have found that in opaque mode the variation in achieved QE at short wavelengths is quite small irrespective of the samples used. The major variations that are seen at long wavelengths are more dependent on the processing than on the sample. We also find that polycrystalline GaN performs as well as crystalline GaN, potentially allowing GaN to be grown on more varied substrates. InGaN (from NWU) was tested and seems to work (Fig. 3) with similar short wavelength response, but with monotonically decreasing QE at long wavelengths and a lack of a distinct cutoff. Ultimately with NEA process development and dopant optimization we believe that the GaN QE can be flattened out so that high efficiencies ($>60\%$) are maintained up to close to the long wavelength cutoff.

3. GaN photocathode stability

The stability of a photocathode often has a great effect on its potential applications. GaN(Cs) shows promise of stability far better than alternate photocathode materials. Our data shows that even after atmospheric pressure nitrogen exposure the efficiency does not vanish. Furthermore, we can recover $>50\%$ of the original GaN QE by a simple vacuum bakeout (200 °C). QE near the 380 nm cutoff is more significantly affected than the shorter wavelengths, as might be expected from the electron surface escape characteristics. Exposure of a cesiated GaN cathode to pressures above 10^{-7} torr [4] also showed degradation of the long wavelength QE. However, a GaN cathode in a sealed tube (JG138, Fig. 5, made in collaboration with ITT) has been stable over 3 years. In addition, samples measured over a 6-month period at 10^{-9} torr in the process tank, showed no measurable QE degradation. These observations indicate that the pressure

Table 1
Listing of a selected set of tested GaN samples with some relevant data on the GaN layer properties

Sample	Source	Thickness (μm)	Resistivity (Ωcm)	Hole cc/cm^3		Mobility (cm^2/V s)	Polish sides
2702	SVT	0.1	8.65	7.22E+16		10	2
2704	SVT	0.1	>25	—		—	1
O202	SVT	0.15	>25	—		—	1
3102	SVT	0.12	2.96	7.80E+16		26.9	2
1602	SVT	0.25	—	1.00E+17		—	2
BH071	NW	1	3.64	1–2E+17		10	1
BH091	NW	0.1	9.44	1.21E+17		5.48	1
BH092	NW	0.1	7.78	1.81E+17		4.22	1
JG219	NW	1	2.8	2.20E+17		10	1
JG220	NW	1	2.7	2.30E+17		10	1
JG238	NW	1.1	2.93	1.83E+17		11.7	1
JG243	NW	1	3.2	2.00E+17		10	1
JG138	NW	1	7.06	1.01E+17		8.75	1
JG158	NW	1	8	1.00E+17		8	1
BH011	NW	0.1	4.80	1.50E+17		8.8	1
BH100	NW	0.1	3.03	2.70E+17		7.5	1
BH183	NW	0.66	1.06	4.83E+17		13.2	2
BH184	NW	0.33	4.34	4.14E+17		4.62	2
BH190	NW	0.2	16.3	5.32E+17		0.697	2
BH195	NW	0.68	V.R.	—		—	1
BH196	NW	0.9	V.R.	—		—	2
BH197	NW	0.2	V.R.	—		—	2
BH044	NW	0.5	V.R.	—	InGaN	—	1
BH045	NW	0.5	V.R.	—	InGaN	—	1

Samples were deposited on 0.3 mm sapphire. Resistivity of V.R. (very resistive) samples was not measurable.

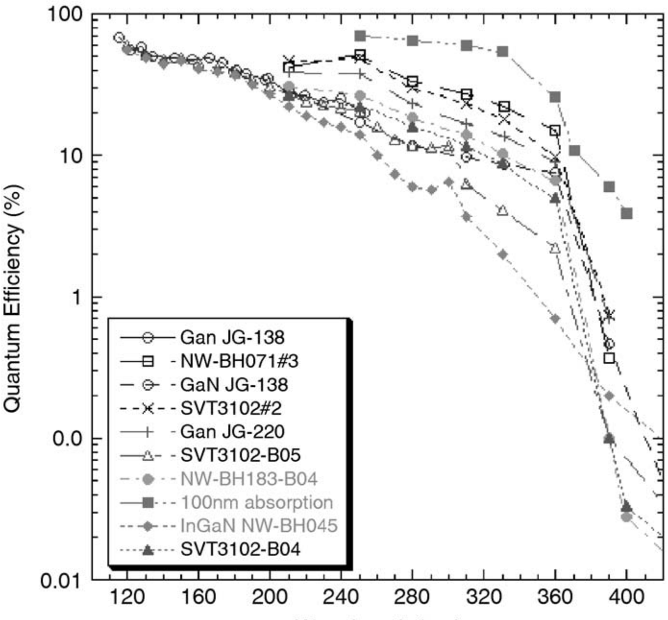

Fig. 3. Measured “opaque” mode quantum efficiency of various GaN samples activated with Cs. Some samples have been processed multiple times. For comparison the percentage of the flux absorbed in a 100 nm layer of GaN is presented (after correction for surface reflectivity) [3,5].

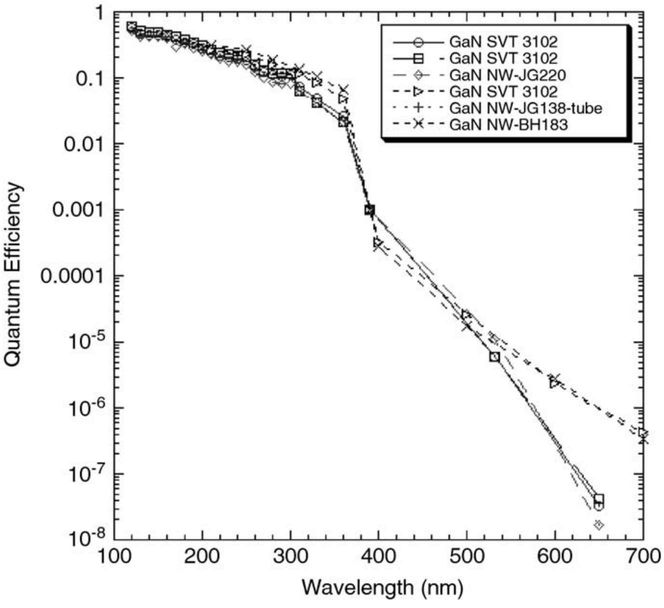

Fig. 4. Measured “opaque” mode quantum efficiency of various GaN samples activated with Cs. Longer wavelength quantum efficiency measurements are included to show the level of rejection that can be obtained for visible light.

regime for preservation of the GaN(Cs) long term QE is in the 10^{-9} torr domain. The GaN layers are nevertheless exceedingly robust and we have performed the cleaning through activation process on samples several times with no effect on the final performance. None of the common cathodes (CsI, CsTe) display this level of robustness.

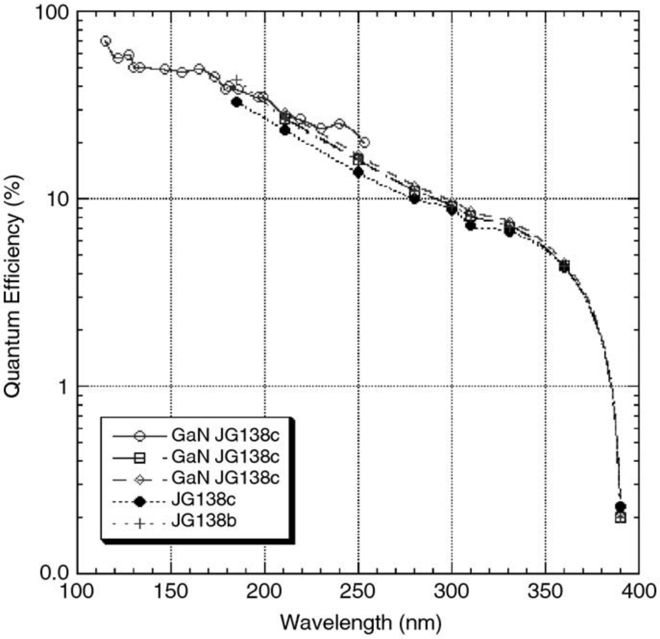

Fig. 5. Measurements of the quantum efficiency stability of a GaN(Cs) photocathode over a three year period. (a) Data taken at the beginning of the period, (b) data taken at the mid point, and (c) data taken at the end of the period.

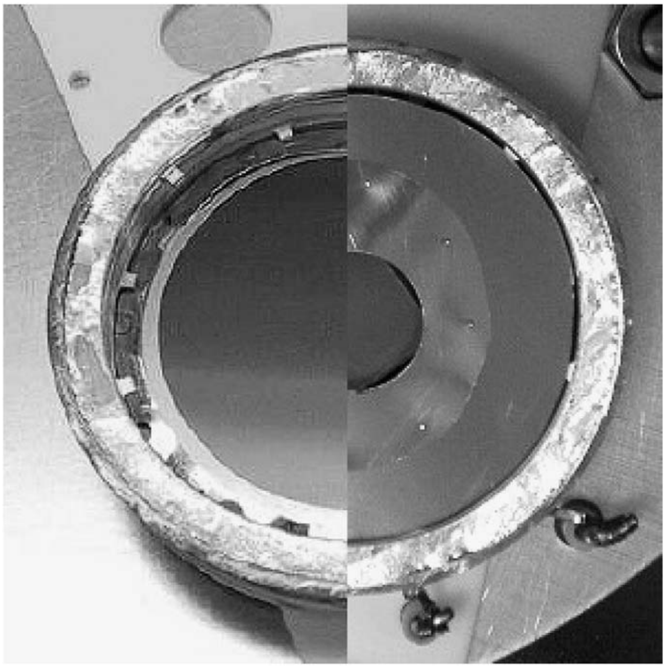

Fig. 6. Composite photo of a microchannel plate detector without (and with) a GaN sample mounted in front of the MCP to permit tests of GaN in photon-counting mode.

4. GaN photocathode implementation

GaN photocathodes can be envisaged in imaging detectors either in semitransparent or opaque modes. In both cases the uniformity, efficiency, stability, and background rate for GaN layers are important. We have already discussed some of these issues, however GaN must be used in a ‘photon-counting’ mode to assess the limiting background rate.

We have employed a sample photocathode in combination with a microchannel plate detector to perform background measurements (Fig. 6). After GaN processing and cesiation we placed the sample above the MCP to create a semitransparent mode configuration. With a bias applied to the cathode to MCP gap, UV photons detected by the GaN photocathode and resulting in photoemission were successfully detected by the MCP. The intrinsic background rate of the GaN photocathode was measured by comparing the bias ‘on’ to bias ‘off’ background rate without external illumination. We find that the GaN(Cs) background rate is no more than a few events $\mathrm{cm}^2\,\mathrm{s}^{-1}$. This is an important result because it pertains to both the semitransparent and opaque modes, and suggests that very low background devices may be achieved without cooling.

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