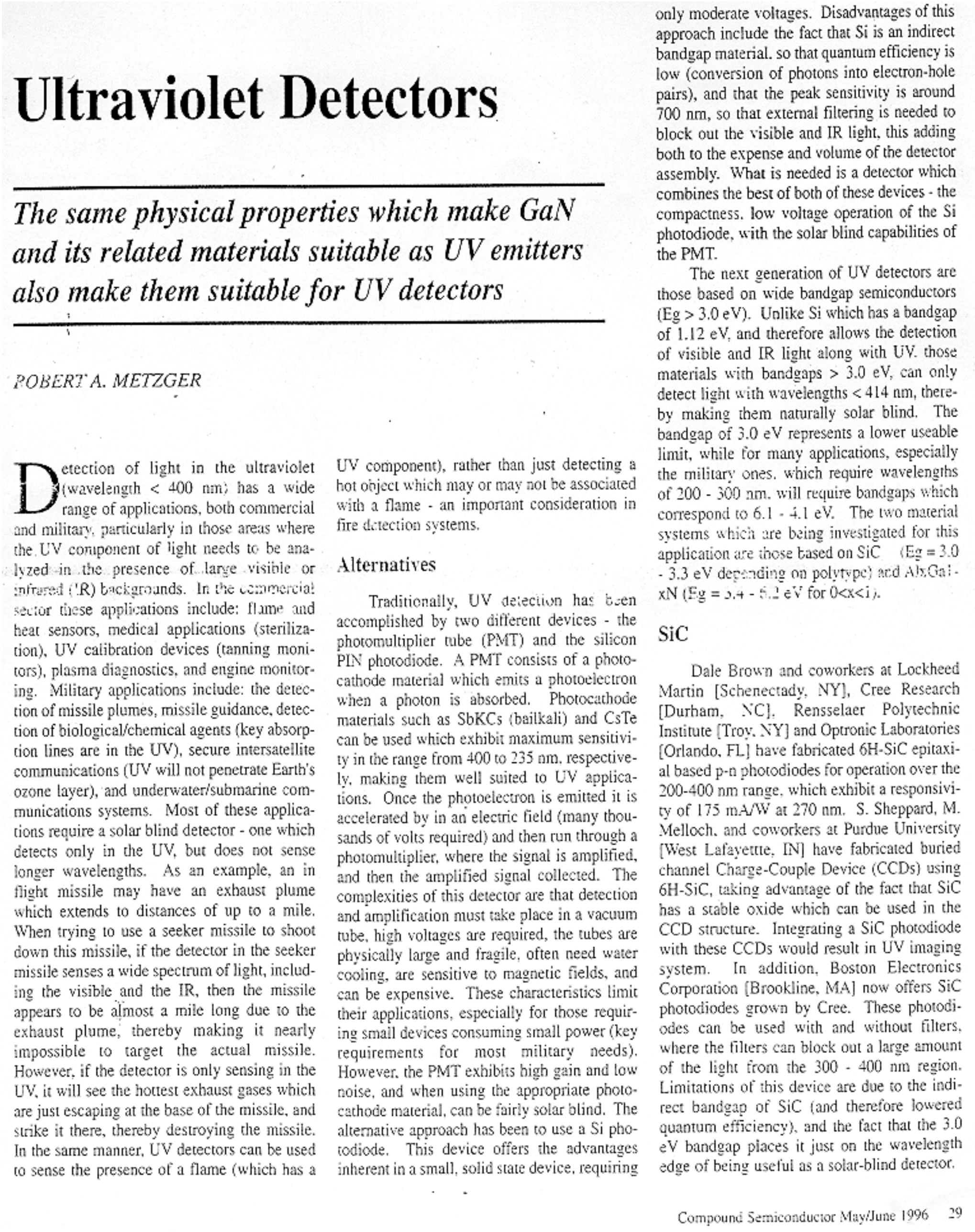
COMPOUND SEMICONDUCTOR

1996



Ultraviolet Detectors

The same physical properties which make GaN and its related materials suitable as UV emitters also make them suitable for UV detectors

ROBERT A. METZGER

Detection of light in the ultraviolet (wavelength < 400 nm) has a wide range of applications, both commercial and military, particularly in those areas where the UV component of light needs to be analyzed in the presence of large visible or infrared (IR) backgrounds. In the commercial sector these applications include: flame and heat sensors, medical applications (sterilization), UV calibration devices (tanning monitors), plasma diagnostics, and engine monitoring. Military applications include: the detection of missile plumes, missile guidance, detection of biological/chemical agents (key absorption lines are in the UV), secure intersatellite communications (UV will not penetrate Earth's ozone layer), and underwater/submarine communications systems. Most of these applications require a solar blind detector - one which detects only in the UV, but does not sense longer wavelengths. As an example, an in flight missile may have an exhaust plume which extends to distances of up to a mile. When trying to use a seeker missile to shoot down this missile, if the detector in the seeker missile senses a wide spectrum of light, including the visible and the IR, then the missile appears to be almost a mile long due to the exhaust plume, thereby making it nearly impossible to target the actual missile. However, if the detector is only sensing in the UV, it will see the hottest exhaust gases which are just escaping at the base of the missile, and strike it there, thereby destroying the missile. In the same manner, UV detectors can be used to sense the presence of a flame (which has a UV component), rather than just detecting a hot object which may or may not be associated with a flame - an important consideration in fire detection systems.

Alternatives

Traditionally, UV detection has been accomplished by two different devices - the photomultiplier tube (PMT) and the silicon PIN photodiode. A PMT consists of a photocathode material which emits a photoelectron when a photon is absorbed. Photocathode materials such as SbKCs (bailkali) and CsTe can be used which exhibit maximum sensitivity in the range from 400 to 235 nm, respectively, making them well suited to UV applications. Once the photoelectron is emitted it is accelerated by in an electric field (many thousands of volts required) and then run through a photomultiplier, where the signal is amplified, and then the amplified signal collected. The complexities of this detector are that detection and amplification must take place in a vacuum tube, high voltages are required, the tubes are physically large and fragile, often need water cooling, are sensitive to magnetic fields, and can be expensive. These characteristics limit their applications, especially for those requiring small devices consuming small power (key requirements for most military needs). However, the PMT exhibits high gain and low noise, and when using the appropriate photocathode material, can be fairly solar blind. The alternative approach has been to use a Si photodiode. This device offers the advantages inherent in a small, solid state device, requiring only moderate voltages. Disadvantages of this approach include the fact that Si is an indirect bandgap material, so that quantum efficiency is low (conversion of photons into electron-hole pairs), and that the peak sensitivity is around 700 nm, so that external filtering is needed to block out the visible and IR light, this adding both to the expense and volume of the detector assembly. What is needed is a detector which combines the best of both of these devices - the compactness, low voltage operation of the Si photodiode, with the solar blind capabilities of the PMT.

The next generation of UV detectors are those based on wide bandgap semiconductors ($E_g > 3.0$ eV). Unlike Si which has a bandgap of 1.12 eV, and therefore allows the detection of visible and IR light along with UV, those materials with bandgaps > 3.0 eV, can only detect light with wavelengths < 414 nm, thereby making them naturally solar blind. The bandgap of 3.0 eV represents a lower useable limit, while for many applications, especially the military ones, which require wavelengths of 200 - 300 nm, will require bandgaps which correspond to 6.1 - 4.1 eV. The two material systems which are being investigated for this application are those based on SiC ($E_g = 3.0 - 3.3$ eV depending on polytype) and $Al_xGa_{1-x}N$ ($E_g = 3.4 - 6.2$ eV for $0<x<1$).

SiC

Dale Brown and coworkers at Lockheed Martin [Schenectady, NY], Cree Research [Durham, NC], Rensselaer Polytechnic Institute [Troy, NY] and Optronic Laboratories [Orlando, FL] have fabricated 6H-SiC epitaxial based p-n photodiodes for operation over the 200-400 nm range, which exhibit a responsivity of 175 mA/W at 270 nm. S. Sheppard, M. Melloch, and coworkers at Purdue University [West Lafayette, IN] have fabricated buried channel Charge-Couple Device (CCDs) using 6H-SiC, taking advantage of the fact that SiC has a stable oxide which can be used in the CCD structure. Integrating a SiC photodiode with these CCDs would result in UV imaging system. In addition, Boston Electronics Corporation [Brookline, MA] now offers SiC photodiodes grown by Cree. These photodiodes can be used with and without filters, where the filters can block out a large amount of the light from the 300 - 400 nm region. Limitations of this device are due to the indirect bandgap of SiC (and therefore lowered quantum efficiency), and the fact that the 3.0 eV bandgap places it just on the wavelength edge of being useful as a solar-blind detector.

Al$_x$Ga$_{1-x}$N

Anis Husain of DARPA. program manager for several key DARPA sponsored GaN emitter programs. is also initiating GaN-based UV detector programs. Husain says. "we have not exhaustively looked at SiC, but feel that AlGaN is the superior choice for this application, since you can tailor the cutoff wavelength by varying the Al content." This is one of the key advantages that AlxGa1-xN has over SiC - the ability to vary the cutoff wavelength from 360 to 197 nm by varying x (Al content) from 0 to 100%. When this is coupled with high quantum efficiencies due to the material's direct bandgaps, capability to form heterojunctions. low surface recombination rates, and stability in harsh physical and chemical environments. DARPA finds AlGaN the most promising materials system for UV detection. Husain also says, "all the materials issues that we are addressing in our GaN-emitter programs, those of growth, defects and contact layers are the same issues that are faced in the use of GaN and its alloys for UV detectors. What we learn in emitters can be applied to detectors." In addition, he believes that the development of a compact, low power, reliable solid state UV detector will open up a whole range of new applications for UV detectors in the military - both for active guidance systems in missiles, "as well as providing another dimension in the spectrum of early identification."

APA Optics

M. Asif Khan of APA Optics [Blaine, MN] has been actively working on GaN and its related materials for UV detectors since 1980, when at Honeywell. As Khan describes it, "in the beginning, work was greatly hampered by lack of p-type doping in the nitrides. Without p-type doping p-n photovoltaic detectors could not be made, and Schottky-type detectors were also limited, due to the inability at that time to make good rectifying contacts to n-type GaN." Since then the p-type doping problem in GaN has been solved and rapid progress in detectors has been made. Khan and coworkers have recently fabricated AlxGa1-xN photoconductors where the Al content ranged from 5 to 61%. The 61% Al content device exhibited a cutoff wavelength of 240 nm, a record for the moment, but one that researchers are quickly improving upon. Photoresponsivities as high as 300 A/W were obtained for these devices. One of the critical issues that is being addressed is that of defects and the effect that they have on the bandwidth of the photoresponse. As compared to a commercially available silicon photodiode, which can operate at frequencies of 100 kHz, Khan and coworkers find that GaN-based devices can operate only up to 5 kHz, this speed limited by the charge which gets stored at defects in the AlGaN material. Khan says "that even though the GaN shows twice the responsivity of the SiC photodiode, its speed is greatly reduced by defects - this is an issue which is currently under investigation." APA Optics which has been working on the fabrication of GaN-based HFET structures, has utilized the HFET (0.2 mm gate length GaN/AlGaN structures which exhibit fmax of 70 GHz and ft of 20 GHz) as a photodetector, which has exhibited responsivities as high as 3000 A/W for wavelengths from 200 to 365 nm. These large responsivities are caused by the photoinduced shift of the HFET's threshold voltage by the trapped light-generated holes. In terms of applications and markets for GaN-based photodetectors, Khan says "at the moment, 30-40 different customers are evaluating our photovoltaic and photoconductive detectors for a wide range of activities - we believe that detector applications will be a very good market for GaN-based devices."

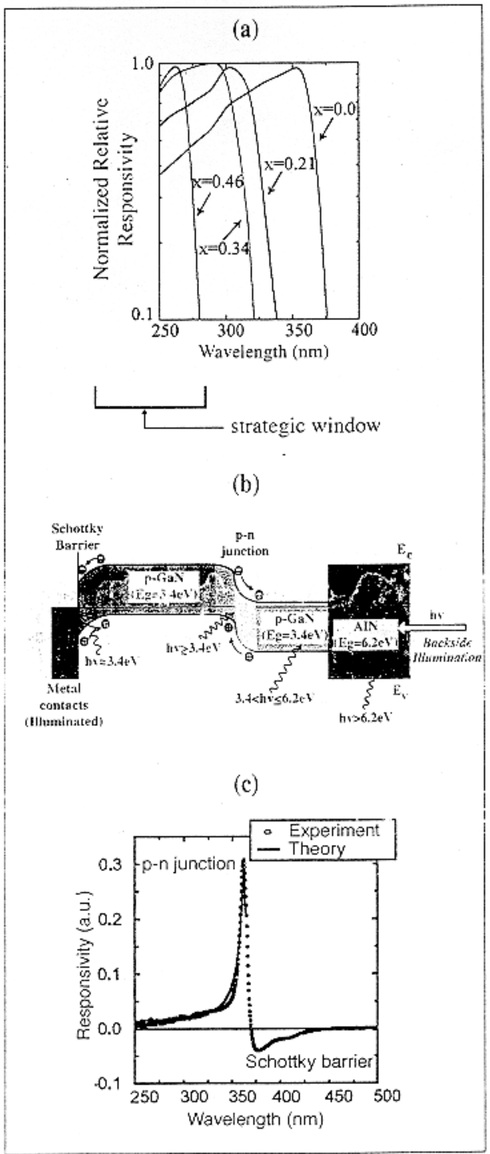


Figure 1. (a) Normalized responsivity for Al$_x$Ga$_{1-x}$N photoconductor for Al content varying from 0.0 to 0.46. (b) Band diagram of GaN-based self-filtering detector. (c) Responsivity of self-filtering detector. Courtesy of Northwestern University.

Northwestern University

Like the APA Optics effort, researchers at Northwestern University's Center for Quantum Devices, lead by Manijeh Razeghi, are actively pursing the development of AlGaN for photoconductive and photovoltaic UV detectors. Figure 1 (a) illustrates the ability of altering the cutoff frequency of AlxGa1-xAs by changing the Al content, where a cutoff frequency of 260 nm was obtained for an Al content of 46%. An interesting device which the Northwestern University group is pursuing, is that of the self filtering detector which gives a very sharp spectral responsivity. See Figure 1(b) for the energy band diagram of this detector in which the n-GaN layer is 0.5 mm thick and the p-GaN layer is 2.0 mm thick. Utilizing backside illumination through the AlN buffer layer, all light with energy above 6.2 eV is absorbed by the AlN, while permitting lower energy light to pass through. Photons with energy between 3.4 eV (GaN bandgap) and 6.2 eV (AlN bandgap) get absorbed in the n-GaN layer. Because GaN has a very high absorption coefficient (105 cm-1) the photons entering this region all get absorbed within the first 0.1 mm. The diffusion length of minority carriers in GaN is much less than the thickness of the n-GaN region, so the minority carriers recombine before reaching the p-n junction depletion region, and as a result produce no photocurrent. It is only for light which has an energy very close to that of the bandgap of GaN (3.4 eV - wavelength 360 nm) that can penetrate deeper into the device and reach the depletion region to form electron-hole pairs (light of lower energy than the GaN bandgap simply passes through the device) which in turn contribute to the photocurrent. Therefore, the responsivity of this detector is essentially tuned to the bandgap of the GaN. This effect is illustrated in Figure 1(c), showing the strong photoresponse at 360 nm. By adding Al to the GaN in this detector, it should be possible to shift this self-filtering detector response to shorter wavelengths.

In the future, all these UV photodetectors (PMT, Si, SiC, AlGaN) will be available, each exhibiting their own particular strengths and weaknesses. However, for applications requiring small volumes, low powers, and the ability to tune cutoff frequencies, AlGaN based-detectors offer clear cut advantages, which may well make AlGaN the material of choice for future UV detectors.