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Photoconducting ultraviolet detectors based on GaN films grown by electron cyclotron resonance molecular beam epitaxy

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ABSTRACT

We report for the first time, fabrication of photoconducting UV detectors made from GaN films grown by molecular beam epitaxy. Semi-insulating GaN films were grown by the method of electron cyclotron resonance microwave plasma-assisted molecular beam epitaxy (ECR-MBE). Photoconductive devices with interdigitated electrodes were fabricated and their photoconducting properties were investigated. In this paper we report on the performance of the detectors in terms of UV responsivity, gain-quantum efficiency product, spectral response and response time. We have measured responsivity of 125A/W and gain-quantum efficiency product of 600 at 254nm and 25V. The response time was measured to be on the order of 20ns for our detectors, corresponding to a bandwidth of 25Mhz. The spectral response showed a sharp long-wavelength cutoff at 365nm, and remained constant in the 200nm to 365nm range. The response of the detectors to low-energy x-rays was measured and found to be linear for x-rays with energies ranging from 60kVp to 90kVp.

Keywords: visible-blind UV detectors, GaN, ECR-MBE, wide bandgap semiconductors

1. INTRODUCTION

Wide bandgap semiconductors, predominantly GaN, SiC and diamond, are viewed as promising candidates for production of blue-UV detectors because the large bandgap energies promise low noise and 'visible-blind' detection. Among these, the III-V nitrides, GaN and its alloys with AlN and InN, are rapidly becoming the materials of choice for the fabrication of short-wavelength emitters and detectors. The III-V nitrides are an attractive class of materials for optoelectronic devices because they form a continuous alloy system whose direct bandgaps range from 1.9eV (InN) to 3.4eV (GaN) to 6.2eV (AlN)¹. Thus, the III-V nitrides offer the potential of fabricating optical devices which are sensitive over the entire range from red to ultraviolet. In addition, they have high electron drift saturation velocities, high thermal stability and they are physically and chemically robust.

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The two techniques that have emerged most successful in growing good quality GaN thin films are metal-organic vapor phase epitaxy (MOVPE)^{2,3} and molecular beam epitaxy (MBE).^{4,5} Photoconducting UV sensors based on MOVPE grown GaN have been reported by Khan et al.⁶ In this paper, we report the fabrication of UV detectors made from GaN thin films grown by ECR-MBE, and the performance of these detectors in terms of UV responsivity, gain-quantum efficiency product, spectral response and response time. The response of the detectors to low energy x-rays was also measured and is discussed in this paper.

2. EXPERIMENTAL PROCEDURES

The GaN films used in this study were grown by the method of electron cyclotron resonance microwave plasma assisted molecular beam epitaxy (ECR-MBE). Details of the growth apparatus and procedures have been described earlier in several papers.⁷ Here, we present a short description of the process. The films were deposited on single crystal sapphire substrates whose surface, after chemical cleaning and thermal outgassing, was converted to AlN by exposing it to an ECR activated nitrogen plasma. The films were deposited by a two-step growth process in which a GaN buffer, about 400Å thick, was deposited at 550°C and the GaN single crystal film, 2µm thick, was deposited at 800°C.

Figure 1: Schematic illustration of the GaN photoconductive UV detector.

Standard photolithographic and lift-off techniques were used to pattern interdigitated electrodes on the films. The electrode width and inter-electrode spacing were 20µm. Ohmic contacts were formed by depositing a thin film of Ti (200Å thick) followed by a film of Al

(2000Å thick), by electron beam evaporation. The total area of the device was estimated to be 0.06mm^2 . However, only half of this was directly exposed to light. Figure 1 shows a schematic illustration of the device used in this investigation.

Light transmission through the films as a function of wavelength was measured using a monochromator (Bausch and Lomb Model #2D126), illuminated by a tungsten lamp and a calibrated silicon photodiode (Hamamatsu S1336-8BQ). For transmission measurements, the intensity of the optical source as a function of wavelength was recorded by measuring the photocurrent it induced in the calibrated photodiode. Then the GaN film was placed on the photodiode and the measurement was repeated. The ratio of the photocurrent with the GaN film to that measured directly gave a measure of the relative transmittance of the GaN film.

The spectral photoresponse, of the interdigitated detectors, in the 200nm to 400nm range was measured by using a UV-visible photospectrometer that used a xenon lamp as the UV light source and a tungsten lamp as the source for visible light. The photoresponse was calculated from measurements of photocurrent produced by the GaN detector as a function of wavelength and normalized to that produced by the calibrated UV-enhanced silicon photodiode of equal active area.

Photoconducting properties of the detectors were investigated by measuring the steady state and transient photoresponse of the detectors to ultraviolet radiation. Steady state measurements consisted of measuring the photocurrent induced in the detector in response to UV radiation from a lamp emitting at 254nm. The currents were measured using a sensitive current-meter (Keithley Model 614). The detector was biased in the range from 5V to 25V. The optical power of the lamp was determined by measuring the photocurrent from a calibrated UV enhanced silicon photodiode (Hamamatsu S1336-8BQ) illuminated under identical conditions as our photodetector.

Response time of our detectors was measured by illuminating them with fast laser pulses and recording the response on a digital oscilloscope. We used a pulsed N_2 laser, emitting at 337nm, as the source. The pulse duration was 10ns and the repetition rate was set at 25ms (40Hz). The output was measured using a digital storage oscilloscope (HP 54610B) capable of operating upto 500 Mhz. The response of the detectors to higher energy radiation was measured by exposing them to low energy x-rays. An x-ray tube provided x-ray photons with energies that could be set from 50kVp to 90kVp. The output of the x-ray tube was filtered by an aluminum filter. The detector was irradiated with the x-rays, and the photocurrent generated in the detector was recorded as a function of bias voltage.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Optical Transmission

The measurement of optical transmission of the film provides an accurate and simple means of estimating the bandgap of the material because absorption coefficients of most semiconductor materials exhibit a sharp increase for photon energies greater than the bandgap energy.⁸ This results in a sharp increase in transmittance at wavelengths close to or longer than that corresponding to the bandgap energy. Figure 2 shows a typical light transmission spectrum measured for our GaN films. These measurements show a sharp transition at wavelengths close to 365nm, corresponding to a bandgap energy of 3.4eV.

Figure 2: Optical transmission characteristics of a GaN film, showing a sharp transition at 365nm, corresponding to a bandgap energy of 3.4eV.

3.2 Electrical Properties

The dark current-voltage (I-V) characteristics of the devices were measured and found to be linear for bias voltages up to 50V. Beyond this value, the I-V showed some non-linearity, indicating the onset of the space-charge effects. We also tested the stability and linearity of the dark I-V characteristics at high temperatures and found them to be stable and linear up to 250°C. Figure 3 shows the dark I-V characteristics of a GaN device at 25°C (room temperature) and at 250°C.

Figure 3: Dark current as a function of bias voltage (a) at 25°C and (b) at 250°C for GaN photoconducting detectors.

From these measurements, we calculated the resistivity of the GaN film to be 1.3×10^4 ohm-cm at room temperature and 9×10^2 ohm-cm at 250°C. These measurements indicate that the Ti/Al contacts are ohmic and stable at high temperatures.

3.3 Spectral Response

The spectral response of one of our photoconducting detectors was measured and the results are shown in figure 4. The photoresponse drops by more than three orders of magnitude at the transition at 360nm, corresponding to the bandgap energy of 3.44eV. These data are consistent with the transmission measurements made on the same films. For wavelengths shorter than 365nm, it remains constant for wavelengths upto 200nm, which was the limit of our apparatus. Similar results were reported by Khan and co-workers for GaN grown by MOVPE.⁶

This result should be contrasted with the photoconducting spectral dependence of semiconductors such as GaAs, where the response falls abruptly at shorter wavelengths, due to recombination in surface states. Thus, the results of figure 4 indicate that surface states and surface recombination are not present in the case of GaN, as previously concluded by Foresi and Moustakas.⁹ The fact that the spectral response remains constant for short wavelengths is important for detector applications because it implies that detectors with high responsivity to wavelengths up to 200nm or less, may be made from this material.

Figure 4: Spectral response of the photoconducting UV detector made from GaN film grown by ECR-MBE.

3.4 Photoconductivity Measurements

Steady state photoconductivity measurements were made in order to determine the gain-quantum efficiency product and photoresponse of the detectors in the ultraviolet region of the spectrum. From the measurement of photoconductive gain (G), we estimated the mobility-lifetime ($\mu\tau$) products by using the relation $G = \mu\tau V/d^2$, where V is the applied bias voltage and d is the effective width of the device.¹⁰ We have measured the gain-quantum efficiency product of the detector to be 6×10^2 at 254nm and at a bias of 25V. We calculated the mobility-lifetime product of the carriers to be about $9.5 \times 10^{-5} \text{ cm}^2/\text{V}$ from these measurements. Responsivity relates the photocurrent flowing through the photoconductor to the incident optical power.¹⁰ We have determined the responsivity of our detector, from photoconductivity measurements, to be 125A/W at 254nm.

3.5 Response Time Measurements

Speed of response is an important performance parameter for photodetectors. The response time of a photodetector is defined as the time taken by the response of the detector to an impulse excitation to decay to half its peak value.¹⁰

Figure 5: Response of GaN photodetectors to a pulsed N₂ laser. The laser emissions were at 337nm, and of 10ns duration.

It is constrained by two main considerations: carrier transit time and the RC time constant of the photodetector and its circuitry. The transit time, given by $t_t = d^2/\mu V$, is limited by the mobilities of the electrons and holes, and can be manipulated significantly by external parameters such as device width and operating bias voltage. The response time is also influenced by the presence of traps, since carrier lifetimes are altered by the amount of time spent in the traps.

Figure 5 shows a typical plot of the response of our detectors to the laser pulses. The response shows a sharp rise time of about 2ns. The decay time is a measure of the detector carrier kinetics. The initial fast component in the decay is attributed to carrier recombination and the following slow decay to charge trapping and emission in defect states. Based on these measurements, we determined the response time, determined as the time to reach half the peak value, to be 20ns. The RC time constant of the measurement circuit was estimated to be on the order of 50ps, and therefore negligible compared to the detector response time. These measurements indicate that the bandwidth of our detectors is about 25Mhz. The response time of our detectors is significantly smaller than the response time of 1ms reported for photoconducting detectors made from GaN grown by MOVPE.⁶

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3.6 Response to X-rays

The response of GaN to low energy x-rays was measured in order to investigate the photoconducting behavior for photons with higher energy. Figure 6 shows the photoresponse measured from a detector biased at 100V and irradiated with x-rays from 50kVp to 90kVp. As seen in figure 6, the response remains linear, indicating that the GaN photoresponse remains proportional to the incident excitation even for photons with higher energies.

Figure 6: Response of GaN detector to x-ray photons as a function of x-ray photon energy at a bias voltage of 100V.

These measurements indicate the possibility of using GaN-based detectors for radiation measurements. However, one must bear in mind that only a small fraction of the x-ray beam was stopped in the GaN film, since the latter was only 2 μ m thick. Thus, issues such as energy absorption coefficient for x-rays and range of x-rays in GaN must be carefully considered before quantitative results can be obtained.

4.0 SUMMARY AND CONCLUSIONS

Photoconducting UV detectors were fabricated from GaN films grown by ECR-MBE. The UV detectors exhibited high responsivity in the UV range and were insensitive to light in the visible range. Response of the detectors to fast UV laser pulses was measured and the bandwidth of the detectors was calculated to be 25Mhz. The response of the detectors to x-rays was found to be linear in the 60kVp to 90kVp range. UV detectors are expected to find use in many diverse applications including UV surveillance, UV astronomy, UV photolithography, industrial combustion control and monitoring, and in scientific research and instrumentation.

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6.0 REFERENCES

- (1) H. Morkoc, S. Strite, G.B. Gao, M.E. Lin, B. Sverdlov and M. Burns, "Large-band-gap SiC, III-V nitride, and II-VI ZnSe-based semiconductor device technologies," J. Appl. Phys., 76(3), 1363-1398, 1994
- (2) S. Nakamura, Y. Harada and M. Seno, "Novel metalorganic chemical vapor deposition system for GaN growth," Appl. Phys. Lett., 58(18), 2021-2023, 1991
- (3) H. Amano, N. Sawaki, I. Akasaki and Y. Toyoda, "Metalorganic vapor phase epitaxial growth of a high quality GaN film using an AlN buffer layer," Appl. Phys. Lett., 48(5), 353-355, 1986
- (4) T.D. Moustakas, T. Lei and R.J. Molnar, "Growth of GaN by ECR-assisted MBE," Physica B, 185, 36-49, 1993
- (5) Cheng Wang and R.F. Davies, "Deposition of highly resistive, undoped, and p-type Mg doped GaN films by modified gas source MBE," Appl. Phys. Lett., 63(7), 990-992, 1993
- (6) M.A. Khan, J.N. Kuznia, D.T. Olson, J.M. Van Hove, M. Blasingame and L.F. Reitz, "High-responsivity photoconductive ultraviolet sensors based on insulating single-crystal GaN epilayers," Appl. Phys. Lett., 60(23), 2917-2919, 1992
- (7) C.R. Eddy, Jr. and T.D. Moustakas, "Growth of GaN thin films by ECR-microwave plasma assisted MBE," J. Appl. Phys., 73(1), 1993
- (8) J.I Pankove, Optical Processes in Semiconductors, chapter 3, 34-86, Dover Publications Inc., New York, 1975
- (9) J.S. Foresi and T.D. Moustakas, "Metal Contacts for gallium nitride," Appl. Phys. Lett., 62(22), 2859-2861, 1993
- (10) B.E.A. Saleh, M.C. Teich, Fundamentals of Photonics, chapter 17, 644-692, John Wiley and Sons, New York, 1991