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GaN for x-ray detection

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The potential of GaN based materials for x-ray detection is investigated. The absorption coefficient in GaN is measured as a function of photon energy between 6 and 40 keV. Metal-semiconductor-metal photodetectors are fabricated and characterized. The response dependence on bias, the temporal dynamics, and the response dependence on detector geometry all together point toward a mixing of photovoltaic and photoconductive effects. Thanks to a large photoconductive gain, the detector has a decent responsivity at the expense of a large response time. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2951619]

GaN is now a commercial semiconductor that is widely used, mainly for optoelectronic devices but also for electronic devices. In the area of photodetection, it has been employed for many years in the ultraviolet, in particular for solar blind imaging.[1–3] At shorter wavelengths, in the extreme ultraviolet, there have been a few demonstrations.[4] However, at even shorter wavelengths, in the domain of x-rays, the photodetection based on GaN or its alloys has not been studied yet. In this range, detection and especially imaging remain dominated by photographic films and scintillators, and direct reading semiconductor detectors are still little developed. As a general rule, semiconductors with larger atomic masses tend to absorb more x-ray photons, which enhances the response of the detector, but tend to have a smaller band gap energy, which degrades the performance in terms of dark current. In addition, low band gap materials are in general mechanically more fragile and prone to damage by irradiation[5,6] than wide band gap materials. Hence, it is interesting to investigate GaN, which has the largest band gap energy of all commercial semiconductors, for x-ray detection.

We first measured the absorption coefficient in GaN as a function of the photon energy in the x-ray range from 6 to 40 keV. As a strong variation of absorption coefficient with energy was expected, two samples were prepared. A thick GaN layer (480 μm) grown by hydride vapor phase epitaxy has been used in order to measure low absorption coefficients. A thinner layer (110 μm) was used for measuring larger absorption coefficients. GaN layers were grown along the [0001] axis and the transmission was measured at normal incidence. Surfaces were smooth so that photon scattering is negligible. The measurement was performed on a BEDE diffractometer where the monochromators have been removed. The diffraction on a silicon wafer allowed us to filter out the beam following the Bragg law, $2d \sin\theta = n\lambda = nhc/E$, where E is the photon energy, d is the plane separation (the 004 reflection was used), and other parameters have their usual meaning.

The silicon wafer was set at the θ position and the GaN layer was positioned in front of the detector at the 2θ position. Both θ and 2θ were simultaneously varied in order to stay at the Bragg resonance for varying energies. The signal on the detector was recorded first without the GaN sample, and then with it. Both experiments were performed with a counting time of 12 s on each point. The transmission is given by the ratio of the two measurements. According to the Bragg law for the first diffracted order (reflection 004), the energy of the photons measured at 2θ varies from 6 to 40 keV when 2θ varies from 99° to 13.1°. However, higher order diffracted modes also exist associated with the 008 and 0012 reflections. More precisely, the photon flux incident on GaN at angle 2θ is given by

$$\Phi_i = \Phi(E)F_{004} + \Phi(2E)F_{008} + \Phi(3E)F_{0012}, \quad (1)$$

while the transmitted flux is given by

$$\Phi_t = T(E) \times \Phi(E) \times F_{004} + T(2E) \times \Phi(2E) \times F_{008} + T(3E) \times \Phi(3E) \times F_{0012}, \quad (2)$$

where $T(E)$ is the transmission coefficient through the GaN layer at energy E, $\Phi(E)$ is the flux incident on the Si wafer at energy E, and F_i is the diffraction intensity of the reflection i (F_i is the product of the structural factor and the Lorenz polarization factor. As the absorption of GaN strongly varies with photon energy, it is crucial to take these higher modes into account. This was done actually by doing many measurements. First, the acceleration voltage on the x-ray source was decreased to 20 kV so that the x-ray spectrum is null for energies above 20 keV. This allows us to directly measure the transmission from 10 to 20 keV. Then, the voltage is increased to 40 kV so that we could directly measure the transmission from 20 to 40 keV. The comparison between both measurements in the 10–20 keV range allowed us to determine the relative intensity of the second and third diffracted orders, which was finally used to deduce the correct transmission for energies below 10 keV by some trivial mathematical data manipulation.

The measurements were made with either the thin or the thick GaN sample in order to keep a good signal to noise ratio over the whole energy range. Hence the final result (shown in Fig. 1) is a concatenation of many measurements that are all consistent with each other.

Also, a direct measurement with the monochromators at the Cu $K\alpha_1$ energy (8.04 keV) was done and gave a value

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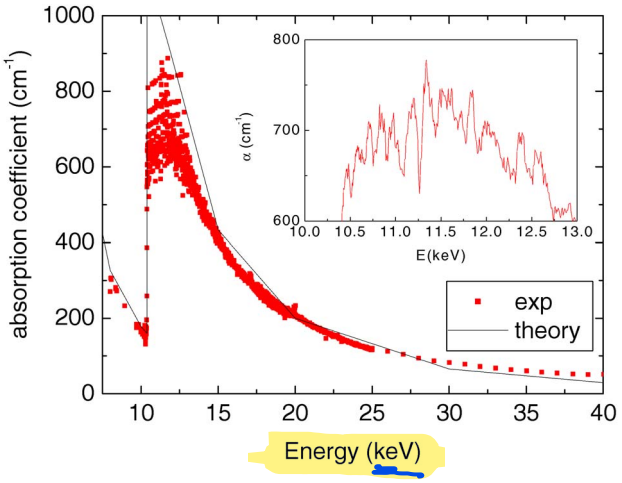

FIG. 1. (Color online) Experimental (dots) and theoretical (line) absorption coefficient of GaN as a function of photon energy. Concatenation of many measurements. Inset: details of the absorption coefficient spectrum at the vicinity of the Ga absorption edge. Single measurement.

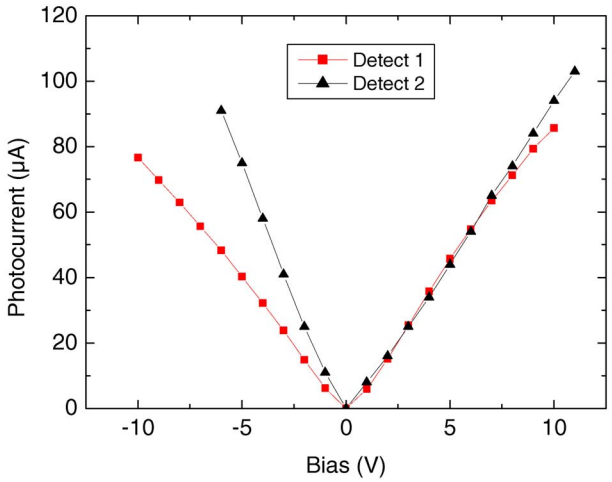

FIG. 2. (Color online) Photocurrent vs bias for two different detectors, measured with a polychromatic x-ray beam.

(271 cm^{-1}) consistent with the one in Fig. 1. This absorption spectrum is compared with the theoretical one given by

$$\alpha = \left[\left(\frac{\mu}{g} \right)_{\mathrm{Ga}} \times \frac{m_{\mathrm{Ga}}}{m_{\mathrm{Ga}} + m_{\mathrm{N}}} + \left(\frac{\mu}{g} \right)_{\mathrm{N}} \times \frac{m_{\mathrm{N}}}{m_{\mathrm{Ga}} + m_{\mathrm{N}}} \right] \times \mathrm{D}, \tag{3}$$

where D is the GaN density equal to 6.087 g/cm^3, and $(\mu/g)_i$ is the photon mass attenuation coefficient for atom i.[7] We observe a very good agreement between theory and experiment. The strong increase at 10.4 keV is due to the $K\alpha$ absorption edge of the gallium. Above this transition, oscillations (inset of Fig. 1) are visible and could be explained in terms of extended x-ray absorption fine structure oscillations. However, the signal to noise ratio is degraded and does not allow us to further comment on these oscillations which, in addition, are beyond the scope of this paper. Figure 1 shows that the absorption coefficient is large between 10 and 20 keV. At higher energies, however, it ranges between 200 and 50 cm^{-1}, corresponding to an 1/e attenuation length between 50 and 200 μm. It is important to note that the absorption coefficient in GaAs is comparable to the one in GaN, while that in Si is much smaller. For x-ray imaging in the range of 40–50 keV, very thick GaN layers will be necessary, such as GaN substrates, in order to absorb a significant part of the incoming photons.

In a photodetector, the collection efficiency depends on the intrinsic parameters of the semiconductor, and also on its quality and doping. It largely depends on the geometry. In order to study some aspects of the photoconductivity in GaN, we have fabricated GaN based x-ray detectors. A 10 μm thick GaN layer was grown by metal organic vapor phase epitaxy on sapphire. It was unintentionally doped. The donor and acceptor residual densities are not precisely known in this sample, but secondary-ion-mass spectroscopy analyses performed on samples grown in similar conditions show that these densities are below 10^{17} cm^{-3}. Due to compensation, the net electron density is much lower than this level and cannot be measured accurately by Hall effect measurements. Metal-semiconductor-metal (MSM) detectors with interdigitated metallic contacts were fabricated. Various geometries were used, with a finger width varying from 2 to 20 μm and a finger spacing varying from 2 to 10 μm. The detector area is 100×100 μm^2. For the fingers, we used a Pt/Au Schottky contact, following a process developed for ultraviolet detectors.[8] The area of the Schottky contact was limited to the fingers themselves. Contact pads were added in a subsequent technological step, and are separated from the GaN surface by an insulator in order to minimize leakage currents.[9] All measurements are done at room temperature. Dark currents were measured to be about 1 μA at a bias of 10 V. The x-ray response was measured with the same BEDE diffractometer as for the absorption. First, we performed the measurements without any monochromator by inserting the detector directly in the incident beam. Figure 2 shows the photocurrent as a function of voltage for two detectors. We observe an almost linear increase in the response with bias up to 10 V which was observed reproducibly on all detectors. The variations in the photocurrent values are observed from sample to sample and between negative and positive biases, as exemplified in Fig. 2. This is frequently observed in MSM detectors and is due to variations in the contact geometry and resistance. Above 10 V, the dependence becomes under linear. The dark current variation is less linear and varies among detectors. Hence, the photocurrent is not proportional to the dark current, so that a pure photoconductor model does not apply. In addition, the photocurrent in the present experimental conditions (polychromatic beam) is much larger than the dark current. The detector time response was measured. The beam was turned on and off with a mechanical shutter, allowing response time measurements down to about one second. Figure 3 shows a typical time response curve when the beam is turned off. A fast decrease in the signal is followed by a long exponential transient with a long typical time constant of 40 s. The initial decrease is faster than 1 s (our resolution limit). The long transient is associated with trapping and release of carriers and is typical of a wide-band gap photoconductor. A similar behavior was measured in the turn on transient. In contrast to this observation, transient measurements performed with a monochromatic beam (8.04 keV) with a much smaller photon flux showed a photocurrent smaller than the dark current and long transients only.

Then, we measured the photoresponse as a function of the detector geometry at a constant bias (5 V). For a constant finger spacing and for decreasing finger widths, the photo-

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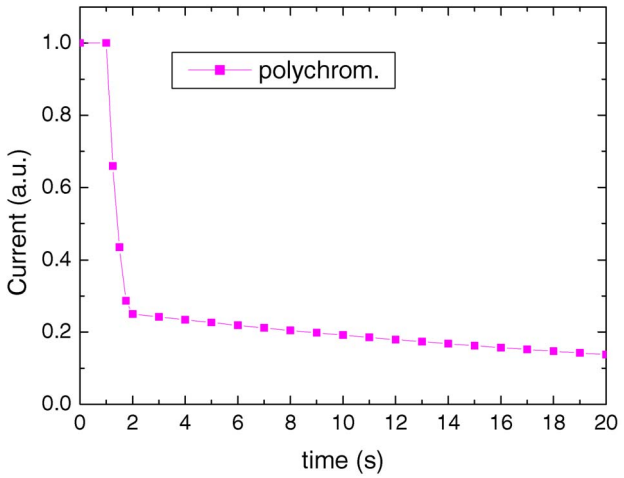

FIG. 3. (Color online) Temporal evolution of the photocurrent on turn off.

current increases linearly with the number of fingers. For a constant finger width, the photocurrent increases almost linearly with the number of fingers or the inverse of the spacing, as shown in Fig. 4. This behavior shows that carriers are collected mainly between electrodes and in a shallow region close to the surface. This can be explained in terms of the electric field configuration in the MSM.[8] The electric field below the electrodes is rapidly screened by the residual impurities (donors) and does not extend deeply into the material. Between the electrodes where the field strength is high, the detector behaves as a photovoltaic detector, with a fast response that saturates at large bias. In the region far from electrodes, the field is low, photocarriers are easily trapped and the detector behaves as a photoconductor (slow response that varies linearly with bias). The thickness of the shallow region where the field is high is of the order of $1-2$ μm.[8] When the x-ray beam is polychromatic, photons between 10 and 20 keV are significantly absorbed in the shallow region and largely contribute to the signal. For instance, when $\alpha = 800$ cm^{-1}, the absorption in the first 2 μm is equal to 15%. Some photovoltaic response is observed. For photons above 20 keV or below 10 keV, the absorption is low, and photons are absorbed deeper in a region where the field is small. Only the photoconductive behavior is then observed.

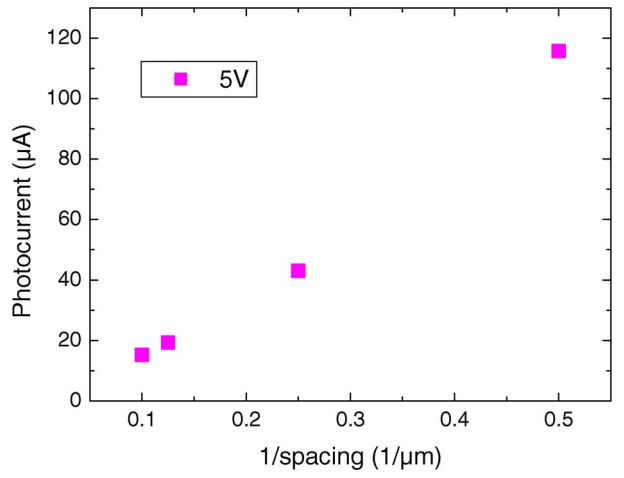

FIG. 4. (Color online) Photocurrent vs the inverse of finger spacing measured at a bias of 5 V with a polychromatic x-ray beam.

Finally, we present a very rough estimation of the sensitivity of the detector. The measurement was performed at an energy of 8 keV by two methods, leading to similar results. The first one consists in using the BEDE monochromator and aligning the GaN detector in the direct beam. The second one was based on the energy resolution provided by the diffraction on the Si, as already explained for the absorption measurements. The GaN detector was positioned at the 2θ angle, and the beam was reflected on the Si surface at the θ angle. The photon flux was estimated from the signal measured at the same angle with the diffractometer detector (scintillator and photomultiplier). We estimate the flux to be 2.4×10^3 photons/s on an area of 100×100 μm^2. The photocurrent I_p measured in the GaN detector at a bias of 14 V was 250 nA, with a very large response time (corresponding to the slow transient observed in Fig. 3). The efficiency in terms of electrons per x-ray photon is given by $\eta = I_p/(e \times \text{Flux}) = 6.5 \times 10^8$. In a 10 μm thick GaN layer at 8 keV, the absorption A can be calculated from the measured absorption coefficient to be about 5%. The number of electron hole pairs created per X photon can be estimated from a rule of thumb to be $N = E/(3 \times E_g) = 8000/10 = 800$ (E_g is the GaN band gap energy). The collection efficiency of the GaN detector is deduced to be $G = \eta/(AN) = 3.2 \times 10^6$. It is much larger than unity, showing that a large photoconductive gain exists. Such large gains have already been demonstrated in GaN photoconductors, associated with long response times and are related to efficient hole trapping and slow electron trapping.[1,10]

As a conclusion, we have shown that GaN can be used as an x-ray detector. However, the absorption spectrum of GaN, that we have measured, shows that it will be difficult to use it above 20 keV. The first studies of the photoresponse in GaN MSM structures have yielded important information on photoexcitation and gain mechanisms. Depending on the photon energy and on the photocurrent intensity, a photovoltaic or a photoconductive model can be used to explain the results, the latter dominating when the photocurrent is much smaller than the dark current and when electrodes can supply the injected current in order to sustain the gain.

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