Backilluminated ultraviolet photodetector based on GaN/AlGaN multiple quantum wells

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The operation of backilluminated ultraviolet (UV) photodetector based on $GaN/Al_{0.27}Ga_{0.73}N$ multiple quantum wells (MQWs) is reported. The MQW structure was deposited on a 1-μm-thick $Al_{0.35}Ga_{0.65}N$ buffer layer which was epitaxied on a sapphire substrate. Coplanar Ohmic contacts were made on the top side of the MQW structure. By illuminating the Ohmic contact positions from the backside of the detector, a flat and narrow band spectral response is achieved in the UV wavelength range from 297 nm to 352 nm. The electron-heavy hole absorption in the MQW region produces the sharp long-wavelength cutoff at 352 nm and the band-to-band absorption of the $Al_{0.35}Ga_{0.65}N$ buffer layer introduces the sharp short-wavelength cutoff at 297 nm. The polarization-induced electric fields result in a redshift of the long-wavelength cutoff. The response time is measured to be RC limited and determined to be 5 μs at a 50 Ω load.
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The advantages of optoelectronic devices based on III-nitride compound semiconductors have attracted significant interest as the result of the rapid progress of growth techniques, such as metalorganic chemical vapor deposition and molecular beam epitaxy (MBE). High performance violet light emitting diodes (LED)[1,2] and lasers[3] have even been commercialized. Due to their direct and wide band gaps, AlGaN alloy compounds are the most suitable candidates for UV LEDs and lasers and visible-blind UV photodetectors with a cutoff wavelength tunable from 365 to 200 nm. In the past decade, various structures based on AlGaN materials have been reported, such as Schottky barrier,[4–7] $p-i-n$,[8–13] and $p-\pi-n$,[14] and metal–semiconductor–metal.[15–19] Most of the studies were performed on AlGaN bulk materials.

In this work, we demonstrate the operation of a backilluminated UV photodetector based on multiple quantum well (MQW) structure. MQW-based detectors have several advantages over bulk devices. They are expected to have higher quantum efficiency and faster response due to their high absorption coefficient and lateral carrier mobility. Moreover, the cutoff wavelength of photodetectors can be adjusted by designing different well widths and barrier heights. For the MQW-based detector reported here, GaN (4 nm)/$Al_{0.2}Ga_{0.8}N$ (7 nm) MQWs with 21 periods are used to create a long-wavelength cutoff while an additional $Al_{0.35}Ga_{0.65}N$ (1 μm) layer is used to produce a short-wavelength cutoff. A lateral geometry is applied in order to take advantage of high carrier mobility. A bandpass spectral response between 297 nm and 352 nm was experimentally observed. Both the responsivity and the response speed is limited by the vertical carrier diffusion across the MQW barriers.

The schematic structure of the GaN/AlGaN MQW photodetector is shown in Fig. 1. The sample was grown by MBE on a c-plane sapphire substrate. After depositing a thin AlN buffer layer (50 nm) following nitridation, a 1 μm $Al_{0.35}Ga_{0.65}N$ layer was grown. Then 7 nm $Al_{0.2}Ga_{0.8}N$ and 4 nm GaN films were alternatively grown to form the MQWs with 21 periods. A control sample with 0.9 μm GaN epilayer on a 40 nm AlN buffer layer was also grown on a c-plane sapphire substrate. Coplanar Ohmic contacts were fabricated by directly evaporating gold on the top surfaces of the samples. The width of the metal stripes is 1 mm and the spacing between them is 0.8 mm. The resistances between two neighboring electrodes were determined to be around 50 kΩ for the MQW sample and 10 kΩ for the control sample as measured directly by using a multimeter in dark.

The MQWs below the metal stripes are the active region to create photoresponse. Photocurrent is produced by lateral

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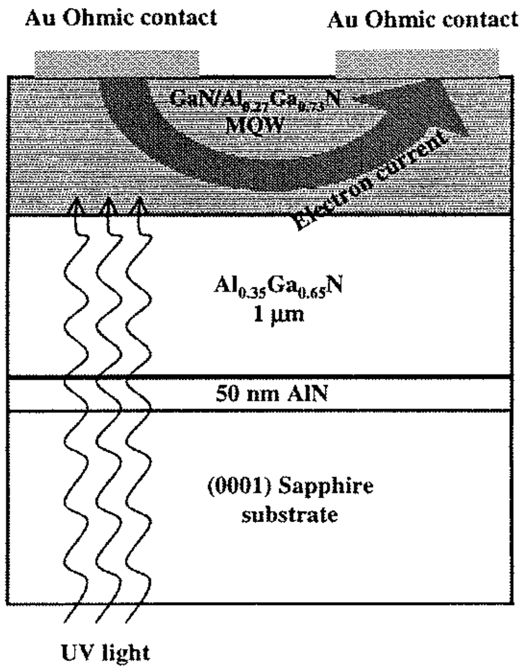

FIG. 1. Schematic structure of the backilluminated UV photodetector based on the GaN/AlGaN multiple quantum wells.

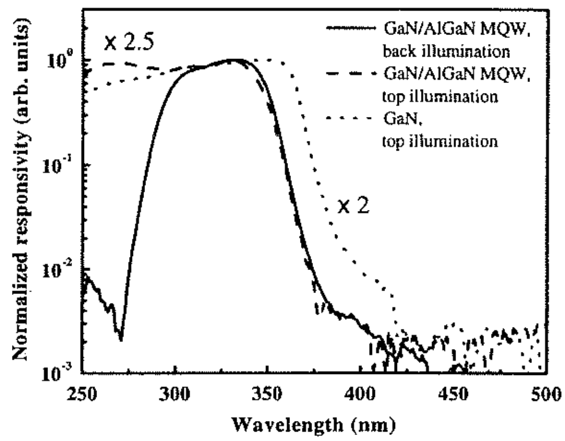

FIG. 2. Spectral response curves of the MQW-based sample for backside (solid line) and top side (dashed line) illumination, and the control GaN sample for top side illumination (dotted line). All curves are normalized to the peak responsivity of the backilluminated MQW detector.

diffusion of photogenerated carriers from one electrode to the neighboring one, as indicated by the dark arrow in the active region in Fig. 1. During the experiments, a bias of 2 mV was applied to the two electrodes. Though the Au contacts were not intentionally made semitransparent, photoresponse measurements were still carried out on these samples by illuminating the metal surfaces in order to provide a qualitative comparison with the performance of the backilluminated MQW detector.

The spectral responsivity of the detectors was measured using a UV-enhanced xenon lamp, a monochromator with a 250 nm blaze grating and a lock-in amplifier. The illuminating UV light from the monochromator was calibrated by a calibrated UV-enhanced Si photodetector and focused on the electrode positions from either the backside or the topside of the samples with a $1\times 3\ \mathrm{mm}^2$ rectangle shape. When passing a mechanic chopper, the light spot from the lamp was focused small enough to produce a frequency-independent signal. The temporal response experiments were performed by using the 355 nm third harmonic of a Nd:yttritium–aluminium–garnet laser with a pulse duration of 30 ps. The photocurrent decay across a variable load was acquired using a digital oscilloscope with a bandwidth of 500 MHz.

The spectral response for backillumination is shown by the solid line in Fig. 2, which is normalized to the peak responsivity 0.03 A/W at 330 nm. A flat and narrow band response in the wavelength range of 297–352 nm is obtained and the signal-to-noise ratio is up to 10^3. The photocurrent was found to increase linearly with the optical power as measured at 330 nm. The sharp long-wavelength cutoff at 352 nm is produced by the electron-heavy hole (e-hh) absorption in the MQW region, while the sharp short-wavelength cutoff at 297 nm is introduced by the band to band absorption of the $Al_{0.35}Ga_{0.65}N$ layer. The spectral response curve of the GaN bulk sample for topside illumination is also shown in Fig. 2 by the dotted line. Comparing to its 365 nm long-wavelength cutoff, the corresponding cutoff of the MQW-based detector shows a 13 nm blueshift. In GaN/AlGaN quantum wells, the e-hh transition energy is determined not only by quantum confinement effect but also by Stark effect due to the strong polarization-induced internal fields.[20–22] In the absence of an electric field, the e-hh transition energy is calculated to be 3.56 eV according to the structure parameters of the MQW sample, corresponding to a long-wavelength cutoff of 348 nm. However, the polarization induced internal fields existing in the MQWs result in a 4 nm redshift.

The spectral response measured by illuminating the metal surface of the MQW sample is plotted as the dashed line in Fig. 2. Without involving the contribution of the AlGaN layer, only a 352 nm long-wavelength cutoff is observed and the photoresponse curve extends to deep UV wavelengths by keeping an almost constant responsivity. It is much flatter than that for the GaN bulk detector in the active wavelength range.

The temporal response of the backilluminated MQW detector was measured across a resistive load in series. Though the responsivity is only 0.007 A/W at 355 nm, the photocurrent decay as an exponential function of time was clearly observed after a 30 ps laser excitation at 355 nm. Figure 3(a) gives the exponential decay of the photocurrent across a 560 Ω load. The decay time constant as a function of the load resistance is plotted in Fig. 3(b). The linear relationship between the response time and the load resistance indicates the response time is RC limited. The time constant goes down to 5 μs at a load resistance of 50 Ω, and is comparable to some fast AlGaN-based detectors.[5,7,9,12]

Although the absorption efficiency of GaN/AlGaN quantum wells is expected to be higher and the photogenerated carriers are expected to diffuse faster in plane compared to AlGaN bulk materials, only those carriers crossing the barriers and reaching the neighboring electrode contribute to the photocurrent. This mechanism is believed to lead to carrier loss and delayed carrier diffusion thus decreasing both the responsivity and the response speed of the MQW-based detectors. Applying vertical electric fields under the contacts will be helpful in improving the performance of this type of detectors.

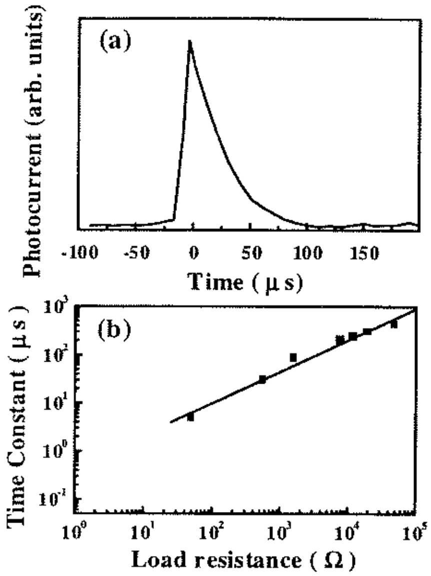

FIG. 3. Response time as a function of the load resistance for the MQW-based photodetector. The inset shows the photocurrent decay at a 560 Ω load after a 30 ps laser pulse excitation at 355 nm.

In summary, we have investigated a lateral geometry GaN/AlGaN MQW-based photodetector. A flat and narrow spectral response in the range of 297–352 nm was achieved by backside illumination. The responsivity and the response speed are limited by carrier diffusion along the growth direction.

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