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Effects of Bias on the Responsivity of GaN Metal–Semiconductor–Metal Photodiodes

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We report on the fabrication and characterization of AlGaN MSM photodetectors, which show a low dark current density and a sharp cutoff, with a visible rejection of four to five orders of magnitude, at 5 V bias. The devices behave linearly with optical power, for illumination over and below the bandgap. The study of the responsivity of AlGaN MSM photodiodes reveals a gain mechanism which is only active at bias over 2 V, and for excitation over the bandgap. This mechanism is responsible for the superlinear increase of the responsivity with bias, and also for the enhancement of the UV/visible contrast observed in these devices. A NEP* lower than 2 pW/Hz$^{1/2}$ has been obtained in GaN MSM photodetectors, at 28 V bias.

1. Introduction

The recent demonstration of $Al_xGa_{1-x}N$ photoconductors [1,2], p–i–n photodiodes [3], Schottky barrier photodetectors [4,5], and metal–semiconductor–metal (MSM) photodiodes [6,7] has confirmed that $Al_xGa_{1-x}N$ alloy is the most promising semiconductor for visible-blind ultraviolet (UV) detection, in the range from 365 to 200 nm. MSM photodiodes present some advantages over other photovoltaic detectors, like their fabrication simplicity, low dark current, high bandwidth capability, and suitability for integration with field effect transistors. In this work, the performance of AlGaN MSM photodiodes has been analyzed.

2. Experimental

The devices were fabricated on 1.5 μm thick, non-intentionally doped (n.i.d.) $Al_xGa_{1-x}N$ ($0 \leq x \leq 0.25$) epilayers, grown by low-pressure metalorganic vapor phase epitaxy on c-sapphire [8]. The MSM structure consists of two Ni/Au (300 Å/1000 Å) interdigitated electrodes, with finger widths and gap spacings of 2, 4, and 7 μm, in an active area of 250×250 μm^2. Larger devices, with a finger width of 7 μm and a pitch of 12 μm, in an active area of 1×3 mm^2, have also been fabricated. The detectors are biased with a voltage source and connected in series with a transimpedance amplifier. Spectral responsivity studies were performed with a Xe arc lamp and a monochromator. The photodetector responsivity and its dependence on the optical power were determined by exciting with non-focused gas lasers (He–Cd, $\lambda = 325$ nm; Ar, $\lambda = 458$ nm,

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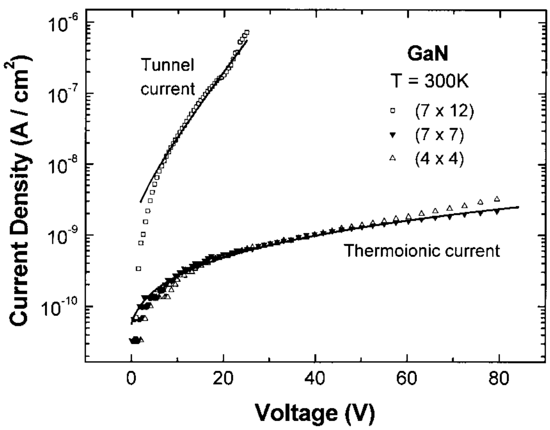

Fig. 1. Dark current density of MSM photodiodes with different sizes. Solid lines correspond to fits assuming thermoionic emission transport and tunnel transport

488 nm). The response time of the detectors was measured using a Nd-YAG laser ($\lambda = 266$ nm), with 10 ns Gaussian pulses. Noise characterization was performed using a SR530 lock-in amplifier.

3. Results

The detectors show a very low dark current density, as shown in Fig. 1. The current density of small devices fits quite well the thermoionic emission model for MSM structures, including the Schottky barrier lowering due to image force effects [9]. Considering the ideal GaN Richardson constant ($A^* = 26$ A cm^{-2} K^{-2}), a barrier height $q\Phi_0 = 1.04$ eV and a doping concentration $N_D = 6 \times 10^{16}$ cm^{-3} are obtained. Large area devices, in contrast, present an important tunnel transport contribution [10], as also shown in Fig. 1.

Fig. 2 shows the spectral response of GaN MSM photodiodes at 1 V and 5 V bias. The responsivity is quite flat over the bandgap, with a sharp cutoff wavelength that shifts to shorter wavelengths with increasing Al content [7]. A visible rejection of four to five orders of magnitude is obtained at 5 V, and the same behavior is observed for higher bias. However, the UV/visible contrast decreases by one decade when the bias is

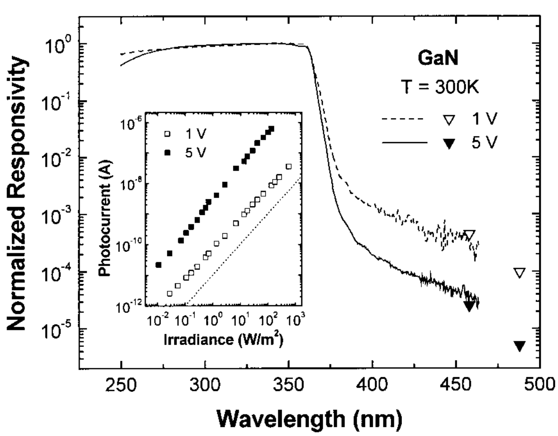

Fig. 2. Spectral response of GaN MSM photodiodes, biased at 1 and 5 V. Triangles were obtained with the 458 and 488 nm lines of an Ar$^+$ laser. Inset: variation of the photocurrent with the irradiance, measured at 1 and 5 V bias, with an He–Cd laser (325 nm)

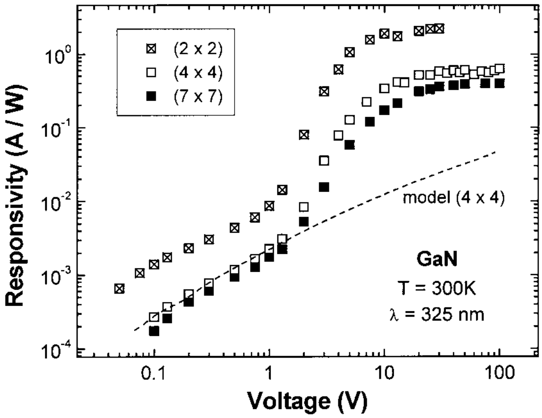

Fig. 3. Responsivity dependence on bias for GaN MSM photodiodes, measured for excitation over the bandgap (325 nm). Dashed line corresponds to a theoretical estimation of the responsivity in the device with finger width and gap spacings of 4 μm

reduced from 5 V to 1 V, and remains at $\sim 10^3$ for lower bias. The photocurrent scales linearly with the optical power for wavelengths both over and below the bandgap. This behavior is independent of bias, as seen in the inset of Fig. 2.

The variation of the responsivity with bias has been analyzed (see Fig. 3). For $V_B < 2$ V, the responsivity scales sublinearly with bias ($R \propto V_B^{0.7}$), which fits the theoretical behavior expected for an MSM photodiode in absence of gain (dashed line in Fig. 3). An abrupt increase of the responsivity is observed between 2 and 5 V, indicative of a bias-activated gain mechanism, which is responsible for the superlinear increase of the responsivity with bias observed in AlGaN MSM photodiodes [7,11]. The gain mechanism is also wavelength dependent, as shown in Fig. 4. For wavelengths longer than the bandgap, the device follows the trend expected for a MSM photodiode in absence of gain. The deviation from this behavior appears only for wavelengths shorter than 370 nm, so that the enhancement of the visible rejection with bias and the gain are due to the same mechanism.

Regarding time behavior, photocurrent decays are exponential, with time constants corresponding to the RC product of the measuring system, independently of bias. The variation of photocurrent response time with load resistance presents no trace of saturation for low load resistances, the minimum response time being far below 10 ns.

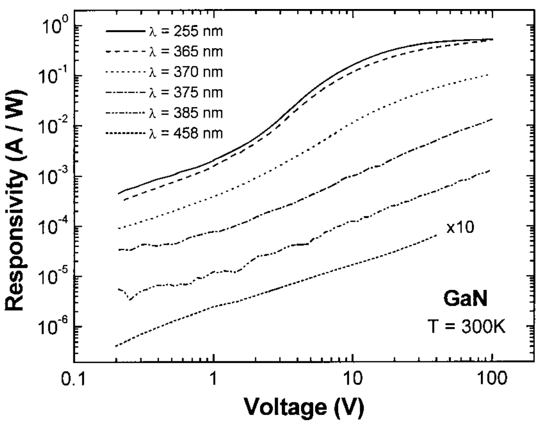

Fig. 4. Responsivity dependence on bias voltage, measured for different excitation wavelengths

The spectral noise power of the GaN detectors remains always below the background noise level of the system ($\sim10^{-26}$ A^2/Hz) up to 28 V bias, which implies a normalized noise equivalent power (NEP^*) lower than 2 $pW/Hz^{1/2}$ in devices with finger width and gap spacings of 2 μm. At 28 V bias, a $NEP^* \approx 24$ $pW/Hz^{1/2}$ was measured in $Al_{0.25}Ga_{0.75}N$ photodiodes [10].

4. Discussion

Given material data (doping concentration, barrier height) and the device geometry, the reach-through voltage of these MSM structures should be >200 V, even for the devices with a pitch of 2 μm. The absence of any "knee" in the current–voltage characteristic measured up to 100 V supports this statement. Thus, most of the applied voltage drops in the reverse biased contact (cathode), and the photocurrent is produced by absorption in the cathode space charge region, with a small negative contribution by the anode. The higher responsivity observed in devices with a shorter gap spacing is not due to a more intense electric field, but to a higher number of fingers in the illuminated region.

Gain in interdigitated MSM photodiodes has been reported [12 to 14], and is generally attributed to electron tunneling enhanced by hole accumulation at the cathode. This accumulation may be due to traps located either in the semiconductor surface, in the bulk material, or in a thin insulating layer between the metal and the semiconductor. Trapping at surface states or dislocations produces persistent photoconductivity effects and a sublinear behavior with optical power, and degrades the spectral response of the devices. Both the linearity and the fast response of MSM photodiodes prove the absence of this gain mechanism. On the other hand, the presence of deep hole traps is responsible for the photoresponse at excitation wavelengths longer than the bandgap, but the fact that gain is not observed for $\lambda > 370$ nm rules out trapping at these levels as the origin of this gain.

The increase in hole density close to the cathode can also be explained by the difference in transit speeds between electrons and holes [12]. However, this phenomenon cannot justify either gain which is only active for wavelengths over the bandgap. Finally, we can speculate about an avalanche process in the valence band as responsible for the gain. At high bias, holes generated in the valence band near the cathode move towards the contact driven by the intense electric field, and might have enough energy to provoke new transitions by impact-ionization.

5. Conclusion

AlGaN MSM photodetectors have been fabricated and characterized, showing low dark current densities, low noise, linearly with optical power, and a visible rejection of four to five orders of magnitude at 5 V bias. The RC product of the measurement system limits the time response, the device transit time being far below 10 ns. From the study of the responsivity of GaN MSM photodiodes we detect a gain mechanism, which results in a superlinear increase of the responsivity with bias, and an enhancement of the UV/visible contrast. Further research is necessary to clarify the physical origin of these phenomena.

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