AlGaN/GaN SOLAR-BLIND PHOTODETECTORS

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INTRODUCTION

The sun is a strong source of ultraviolet radiation. Thanks to the ozone layer we are not exposed to the harmful portion of the solar UV energy. The ozone layer acts as a natural low-pass filter by absorbing the high energy photons with wavelengths shorter than 290 nm. The photodetector which responds only to radiation with $\lambda<290$ nm is often defined as solar-blind detector [1]. In the recent years solar-blind detectors have received much attention. Both civil and military applications require solar-blind detectors for engine control, solar UV monitoring, source calibration, UV astronomy, flame sensors, detection of missile plumes and secure space-to-space communication. Gallium nitride and related ternary compounds are most suitable candidates for the fabrication of semiconductor UV detectors. The bandgap energy of AlGaN can be adjusted to match up the wavelengths shorter than 290 nm. Various types of AlGaN based detectors have been proposed such as p-n junctions, PIN diodes, Schottky barrier detectors and photoconductors. Among these devices the metal-semiconductor-metal (MSM) photodetector has simple device technology, fast response, small capacitance and dark current, as well as large active device area. We report on the growth, fabrication, characterization and modeling of high-speed AlGaN/GaN solar-blind MSM photodetectors.

SAMPLE GROWTH

At first we have produced GaN based heterostructures of different thickness and alteration of active layers, Fig.1. The heterostructures were grown on two-inch sapphire (0001) substrates by low pressure MOCVD (40-60 mBar). Thin buffer layer of 55nm AlN (sample A) or 25 nm GaN (sample B) were first grown at 1050 ^{0}C and 550 ^{0}C accordingly. The role of these layers is to improve the crystalline quality of the latter AlGaN layer. Then unintentionally doped AlGaN active layers with a thickness of 400 nm (sample A) and 330 nm (sample B) were grown at the temperature 1000 ^{0}C. The growth rate was 0.5-0.8 Å/s and has been controlled in situ by multiwavelength reflectometry. The AlN-mole fraction was estimated by X-ray diffraction and according to measurements AlN-mole fraction is equal to 0.40 (sample A) and 0.55 (sample B). Room temperature PL-measurement of the sample A (Fig.2) shows emissions whose position coincides with the cutoff wavelengths of AlGaN and GaN. The transmission data (Fig. 3) correlate well with PL and X-ray data. Finally, thin AlN cap layer (12 Å for the sample A and 48 Å for the sample B) was grown on the AlGaN surface. The surface roughness has been evaluated by atomic force microscopy, Fig.4. Any cracks could not be seen over the surface of the sample.

RESULTS AND DISCUSSION

The MSM-photodetector is a planar device consisting of two fork-shaped interdigitated contacts oppositely laying on the semiconductor surface [2]. For our samples the diode fingers were defined by optical lithography and formed by evaporation and subsequent etching processes of Ni or Mo as barrier metals. The finger gaps were 1.5, 3 and 7 μm and square active areas were equal to 100x100 μm^2. Fig. 5 shows the surface view of the MSM-detector with 1.5 μm gap between the fingers.

The measurements of spectral responsivity were performed by using a xenon arc lamp. The monochromator light was calibrated with optical power meter and focused onto the photodetector using an optical lens system. The photocurrent was measured in ac-conditions with a chopper and PAR-124A lock-in amplifier. Fig.6 shows the spectral response of our MSM-detectors with different AlN-mole fractions. Both MSM-structures demonstrate an UV/visible contrast. The optical response shifts towards the shortwave region as the Al content increases due to the broadening of semiconductor energy bandgap. The response plateau between 270 and 360 nm of the sample B is due to the GaN buffer layer which is grown under the active AlGaN whereas the AlN buffer layer of the sample A prevents any contribution to the response in the longwave region. As a result the UV/visible rejection for detector A equals to about 450, while detector B has a contrast of only 40. The cutoff wavelength reached ~290 nm for sample A and ~260 nm for sample B, demonstrating the capability of these detectors for solar-blind applications. The maximum current responsivity at 280 nm is about 0.27 A/W (detector A) and ~0.1 A/W at 250 nm (detector B). Even at zero bias we could observe a low detector response possibly caused by slight asymmetry of the Schottky interdigitated contacts.

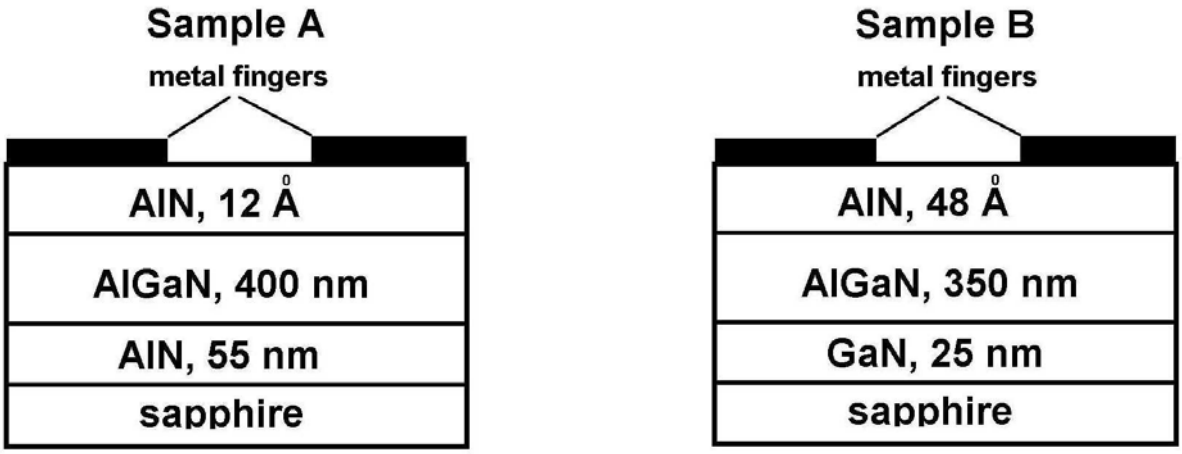

Fig.1. Cross section through the heterostructure layer sequence.

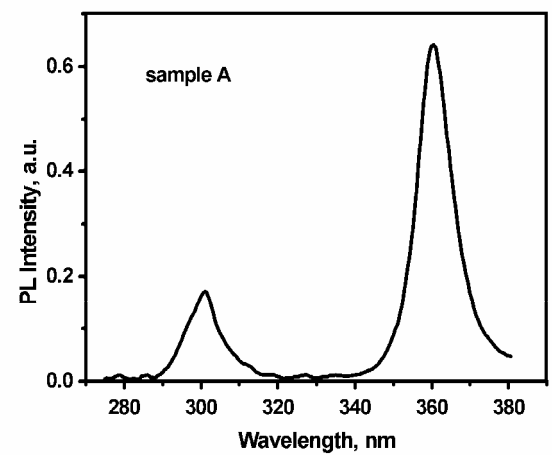

Fig.2. Room temperature photoluminescence of the $GaN/Al_{0.4}Ga_{0.6}N$ heterostructure.

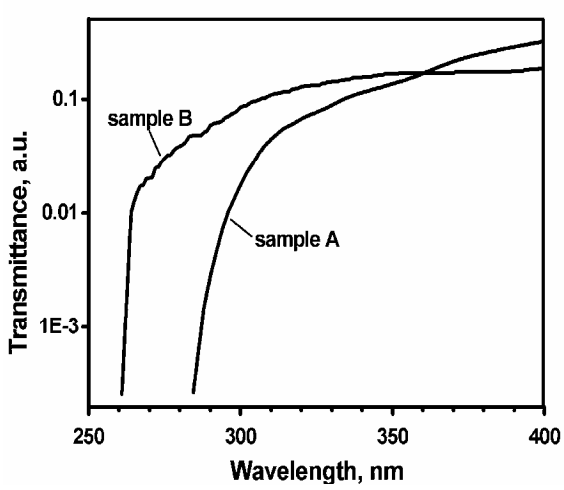

Fig.3.Optical transmission through the samples.

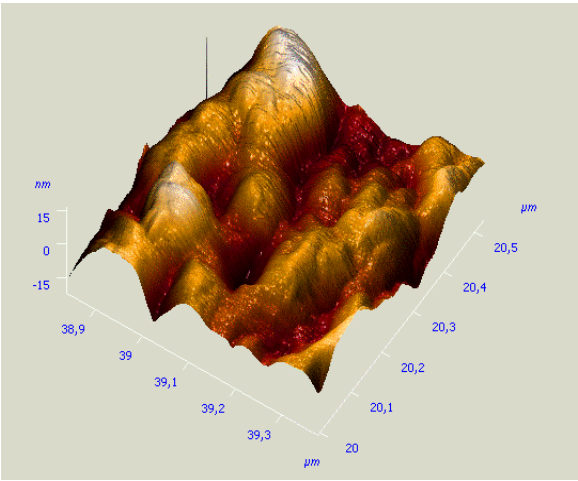

Fig.4. Surface roughness of the heterostructure (sample A).

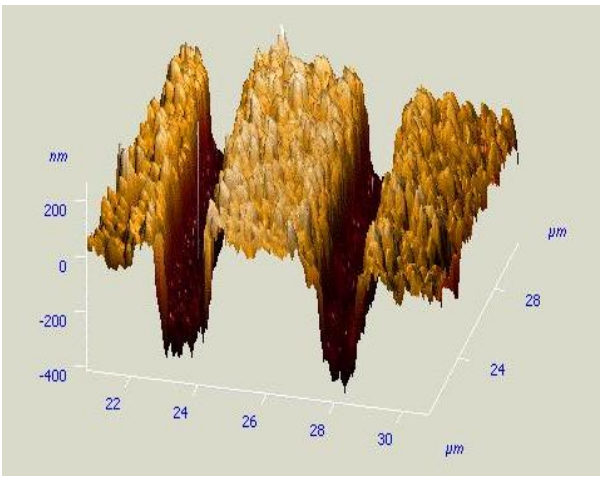

Fig.5. Atomic force microscope view of AlGaN MSM-PD.

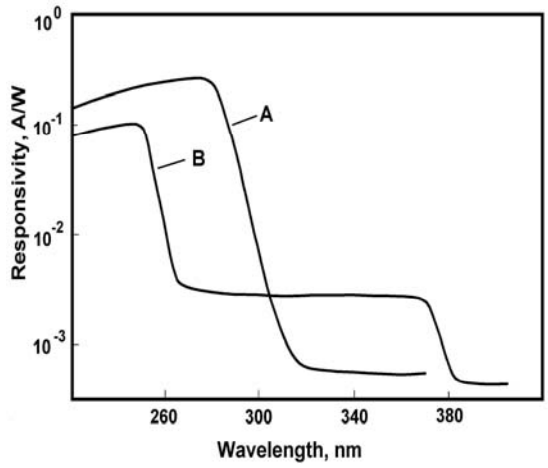

Fig 6. Spectral response of AlGaN MSM-PD's. Bias 10V, A: x=0.4, B: x=0.55.

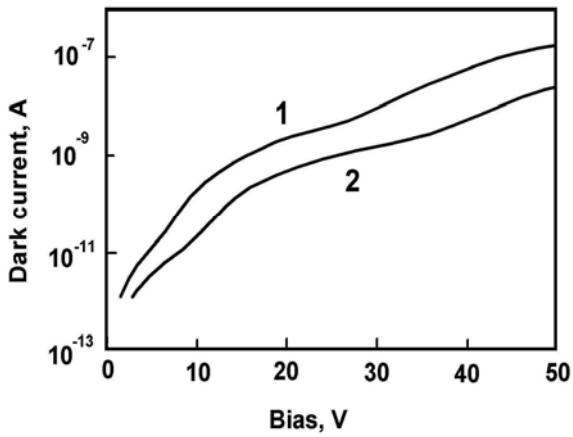

Fig.7. Dark current of AlGaN MSM-PD's. The gap between the fingers 3 μm. Sample A:1-Ni, 2 - Mo Schottky contacts.

The I-V measurements showed very low dark currents of 0.4 nA when Mo was used as the metal of the barrier and 10 nA for Ni contacts at 30 V bias, Fig.7. These values are lower than the reported 0.3 μA at 40 V for $Al_{0.15}Ga_{0.75}N$ epi layers [3]. The dark current is qualified by simple thermionic emission below ~30 V after that the current is strongly dominated by significant tunneling component due to the Schottky barrier lowering at high fields [2]. Using simple technique to extract the Schottky barrier height and junction ideality coefficient from the modified I-V plot of the MSM-diodes [2] we have deduced a barrier height of 1,1 eV for Ni-AlGaN contacts and 1,4 eV for the sample with Mo-AlGaN contacts. The dark current for Ni-AlGaN MSM-devices due to the lower barrier height was larger. The junction ideality coefficient is in the range of 1.1-1.24 demonstrating a good quality of the Schottky barriers in the AlGaN MSM-interdigitated contact system. The breakdown voltage for these detectors with 3 μm separation was 90-100 V. We have also fabricated MSM-devices with larger (7 μm) separation between the interdigitated fingers. In this case a dark current is due to thermionic emission up to 150V, after that a breakdown occurs. For smaller devices with 1.5 μm finger separation the breakdown voltage was at about 50-70 V.

One of the strong tendencies in the development of photodetectors is to obtain a short pulse response. In general the response speed of the MSM-PD is greatly limited by the capacitance of the interdigitated contact system of the diode itself. The smaller the spacing between the contact fingers the shorter the drift time of the carriers and intrinsic response but if the spacing is getting smaller the capacitance becomes larger and the external response is usually poorer. Thus, the optimal design of the MSM-PD geometry is a compromise between transit time of the carriers and RC-time constant of the interdigital diode structure. This is a simple first order approximation to the overall response time of the MSM-PD [4].The model assumes that the field is uniform between the interdigitated contacts and the carriers are moving at saturated velocities and is valid only for low levels of optical excitation. The increase of the optical illumination energy will give rise to a variety of effects; in particular, it will increase the density of photogenerated carriers in the active region of the MSM-PD. One then can expect modification of the internal electric field that governs the carrier drift processes in these structures. Therefore a two-dimensional time-dependent simulation technique [5] has been applied to investigate electron-hole transport processes in the active region of GaN-based MSM-PD and to analyze detector high-speed response at different energy levels of optical illumination and to compare dynamic range potentialities of GaN based MSM detectors with that of on GaAs. Modeling shows that in these detectors when the energy of the incoming optical pulse exceeds a certain level, the space charge of photogenerated carriers (slow holes) can screen significantly the dark electric field of the MSM-PD thus making the detector response dependent on the optical energy.

We have deduced a simple relation between the optical radiation energy level before starting the harmful screening effects and geometry and semiconductor parameters of the MSM-detector [5]:

$$E < \frac{\varepsilon_0(\varepsilon_s + 1)L^2 V(t + D)hc}{4\lambda q t^2 (1 - r)[1 - \exp(-\alpha d)]}, \qquad (1)$$

where E is optical pulse energy at wavelength λ, h is the Planck constant, c, the velocity of the light in vacuum, r, the reflection coefficient, d, the thickness of the active layer of the MSM-PD, α, light absorption coefficient, V, external applied voltage, t, finger spacing and D, finger width.

This expression recently has been experimentally approved by several research groups [6, 7] and thus it seems it can be used as simple design guidance for elaboration of high-speed MSM-PD's working at high energy levels of optical illumination. One may see that the most effective way to minimize the space-charge effects and to increase the dynamic range of the MSM-PD *is an increase of the bias voltage*. As the level of optical excitation is increased, a higher bias should be applied to create an internal field large enough to compensate the space charge induced field. Thus, the bias voltage has to be determined not only from the condition of total depletion of the intercontact area, but the level of optical illumination should also be considered. The calculations show that for GaAs MSM-diode with t=D=3 μm and total area of 100x100μm ^{2} the pulse energy which does not affect the detector response should not exceed 6 pJ at 10 V bias. We need at least ten times increasing of the bias to reach peak velocity conditions of electrons for the GaN based MSM-detector. This situation is very favorable for high-speed detection at high levels of optical illumination. Now the internal electric field is much stronger and modeling shows that a charge of delayed holes does not modify detector internal field at high energy level of optical radiation. It should to be noted that he breakdown field in GaN: >5 10^6 V/cm [8] is much higher than that of in GaAs: 4 10^6 V/cm and the experimental results show that we may apply up to 100 V bias to AlGaN MSM diode with 3 μm separation between the fingers without driving it into breakdown.

The other benefit lies in much shorter wavelength of operation of GaN based detector. Detection of radiation at shorter wavelength would increase the dynamic range of the MSM-PD since then, for a fixed energy of the incoming optical pulse, fewer e-h pairs are photogenerated. Therefore, the transition from 850 nm to 280 nm wavelength would lead to about 3 times increasing the upper limit of linear operation of the GaN-based MSM-PD. Thus, in total, we may expect at least 30 times increase of upper limit of linear operation of GaN-based MSM detector as compared with GaAs device, other parameters being the same.

CONCLUSION

We have reported the fabrication and characterization of the AlGaN-based MSM-photodetectors with AlN mole fraction up to 0.55. Interdigitated Schottky contacts were fabricated using Ni and Mo as the barrier metals. Directly on the MSM-diode we have measured a Schottky barrier height and junction ideality factor. The spectral responsivity demonstrates the ability of these detectors for solar-blind applications. We show effect of different buffer layers on the detector performances. Photodetectors fabricated on a sample with AlN buffer layer demonstrate smaller dark current and larger UV/visible rejection. Under low illumination intensity impulse response of the MSM-diode is found to be dominated mainly by carrier transit time and RC-time constant. Charge accumulation and screening of the dark electric field at high optical excitation levels greatly modify the drift conditions of the photogenerated electrons and holes in the active region of the MSM-PD and result in considerable distortion of the impulse response and reduced bandwidth and efficiency. Higher operating bias of GaN based detector increases the threshold optical energy which starts harmful space charge effects. We propose some guidelines for the design and optimization of UV MSM-detectors.

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