Ultraviolet photodiodes based on AlGaN solid solutions

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Abstract. We present the characteristics of ultraviolet photodiodes based on Schottky barriers to the Aluminum Gallium Nitride (AlGaN) solid solution. The paper is devoted to the creation of ohmic and rectifying contacts to $Al_xGa_{1-x}N$ solid solutions with a high ($x > 0.5$) proportion of AlN. The most important property of ($Al_xGa_{1-x}N$) materials is their solar blindness: the wide bandgap (Eg = 3.4 eV for GaN; 6.2 eV for AlN) makes these materials insensitive to the visual and IR light. The study of solid solutions with various mole fractions of Al has created solar-blind and see-blind ultraviolet photodetectors.

1. Ohmic contacts for ultraviolet photodiodes

In the recent years AlGaN-based devices are receiving a lot of interest. Nitrides are widely used for luminescent devices [1]. AlGaN solid solution semiconductors of the wurtzite crystal structure are increasingly used as ultraviolet photodetectors for applications such as data storage, combustion control, flame sensors, radiation dosimetry, atmospheric ozone monitoring, solar-blind detection, pollution detection, and polarization-sensitive detection [2, 3]. Optimum device performance, however, is still limited by the lack of low-resistance Ohmic contacts, both on light-emitting diode and photodiode structures. Contact formation on n-type AlGaN is understood best, and a good standard metallization scheme on n-type GaN does exist.

In this study, the properties of Ti and Ti/Al contacts, both on $Al_xGa_{1-x}N$, have been systematically studied as a function of the annealing temperature. The n-type $Al_xGa_{1-x}N$:Si ($x = 0.5 – 0.6$) and undoped $Al_xGa_{1-x}N$ ($x = 0.08 - 0.7$) epitaxial layers with a thickness of 1 μm were grown by PA MBE on c-sapphire substrates. The thermal vacuum evaporation of different metals (Ti, Au, Ni, Ag, In, Al) was used to deposit different single- and double-layer contacts onto the AlGaN layer surface cleaned preliminary with organic solvents. Thicknesses of metal layers were in the range of 15 – 75 nm. The best results were achieved for the Ti layer thicknesses of 15 nm, and the top layer Al thicknesses of 35 nm. Before the deposition of the metal contacts, the structures' surface was cleared using various chemicals, in particular, H_2O_2, CCl_4, HCl, followed by structures washing in distilled water. For better metal adhesion structures were heated to a temperature of 300 °C during the deposition. The samples were annealed after the contact deposition in the different vacuum conditions (10^{-2} - 10^{-5} Torr) of a metal deposition chamber and without the use of nitrogen or argon gas (figure 1). The n-type AlGaN layers with different contacts were characterized by specific contact resistance determined through the transmission line measurements (TLM). Study of influence of the residual gas pressure in the vacuum chamber during the annealing of ohmic contacts on their resistance is shown in figure 1. It is seen that a decrease in pressure leads to a decrease in the resistance of contact. Most likely, this effect can be explained by the influence of oxygen in the residual gas, causes oxidation of the metal layers of titanium and aluminum, followed by the formation of composition structure on the surface of metal oxide. Figure 2 shows the I-V characteristics of the Ti/Al contacts to n-type $Al_xGa_{1-x}N$:Si with aluminum mole fraction of x = 0.5.

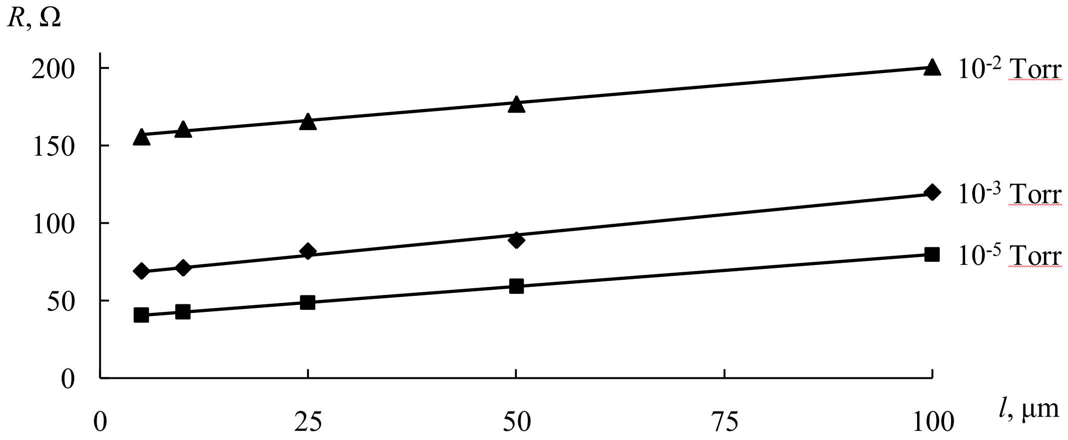

Figure 1. Resistance vs distance between the contacts deposited at the different residual pressures in the vacuum deposition setup.

As one can see, the I-V characteristics of the contacts are non-linear for untreated structures as well as for structures annealed at relatively low temperatures. Nonlinearity decreases with the temperature increase and at 750 °C the contacts become ohmic. Further increase of the annealing temperature leads to a slight increase of slope, but this increase should be recognized as insignificant.

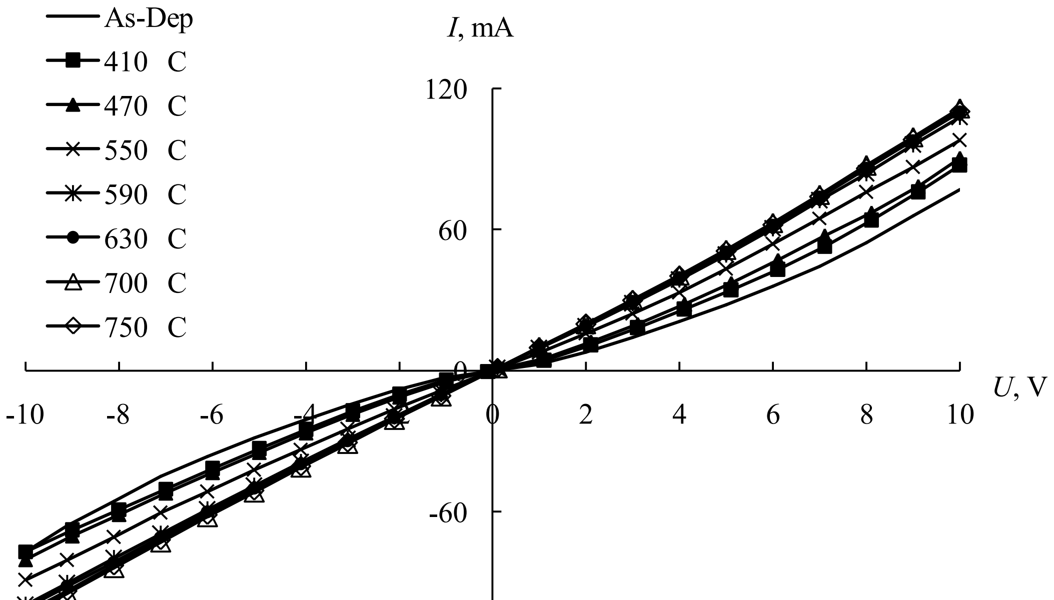

Figure 2. Current-voltage characteristics of the ohmic Ti / Al contacts to the $Al_{0.5}Ga_{0.5}N$ layer annealed at the different temperatures for 10 minutes.

To calculate the contact resistance with the TLM and to determine the optimal technological parameters of their growing, a number of structures has been created on the basis of the double-layer Ti/Al contacts with different thicknesses of the metal layers. I-V characteristics for different distances *l* between pads in these structures are shown in figure 3. The structures were annealed in vacuum at a temperature of 750 °C for 10 minutes. It is obvious that the measured resistance reduces with the decreasing of *l*. The resistivity was calculated by approximating the dependence of the resistance on the distance *l* to the intersection with the y-axis (when $l = 0$). The lowest TLM-resistance of $8 \cdot 10^{-5}$ $\Omega \cdot cm^2$ was achieved for the Ti/Al (15/35 nm) contact annealed at the temperature as high as 750 °C for sufficiently long time (above 10 min). The use of other relationships between thicknesses of metals in contact has led to a significant increase of the resistance.

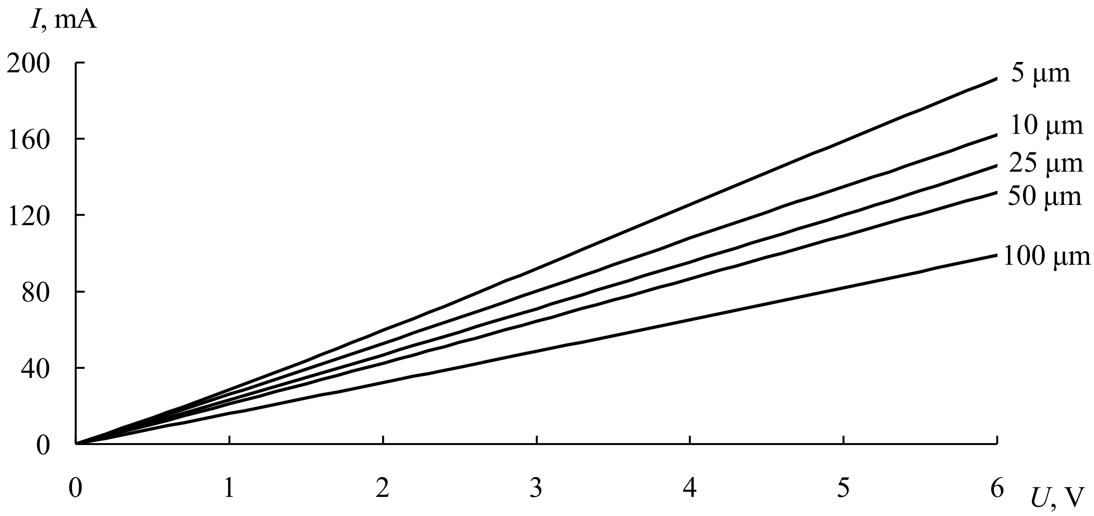

Figure 3. Current-voltage characteristics at different distances between the contacts.

2. Ultraviolet photodiodes based on Schottky barriers

$Al_xGa_{1-x}N$ is an attractive candidate for many UV detector applications, including flame and heat sensors, missile plume detection, secure-from-earth inter-satellite communications, UV calibration and monitoring devices for medical and biological applications, and other commercial applications such as plasma diagnostics and engine monitoring. These roles have primarily been filled in the past by photomultiplier tubes and Si detectors. The photomultiplier tubes are inefficient and inferior to semiconductor devices. Si has a narrow bandgap (1.1eV) and therefore requires filtering to operate as a UV detector. GaP photodetectors can be used for UV spectral range; their peak response is at about 410 nm. Moreover Ag-GaP Schottky photodiodes can be used as see-blind photodiodes [4]. However, they have an indirect band structure, which affects their performance. In contrast, the bandgap of $Al_xGa_{1-x}N$ can be tailored between 3.4 and 6.2 eV. This provides an obvious advantage over Si, as filtering can be bulky and/or expensive. The robustness of $Al_xGa_{1-x}N$ also offers the potential for stable device operation in hostile environments. SiC, although similar in robustness to GaN, has a bandgap of 2.9 eV, which is narrower than GaN, and no potential to tailor the bandgap through alloying. Therefore SiC detectors would also require filtering for many UV applications.

The Schottky contacts consist of semitransparent 15 nm thick Au disks. Au, Ni, Ag, Sn were investigated as materials of rectifying contacts. Diode diameters ranged from 1.5 mm to 3 mm. Figure 4 also plots the spectral response of $Al_xGa_{1-x}N$ Schottky diodes with different Al contents ($x = 0.08\ldots 0.9$). The spectral response measurements were carried out in the 200 - 400 nm range, using a xenon lamp, a diffraction grating monochromator and a lock-in amplifier. The cut-off wavelength shifts from 360 nm to 240 nm. The characteristics were studied without application of voltage. It is shown that an increase in surface states greatly reduces the sensitivity to short wavelengths. The height of the barrier metal-semiconductor effect on long-wavelength edge. The $Al_{0.08}Ga_{0.92}N$ solid solution can be used to produce see-blind photodiodes. This UV sensor has a sensitivity in the 240 – 360 nm wavelength range. The $Al_xGa_{1-x}N$ solid solution with a mole fraction $x > 0.38$ of Al can be used as a solar-blind photodetector in the atmospheric conditions. For example, it makes it easy to detect ozone holes and harmful UV radiation for people. Increasing the share of Al to 0.9 has resulted in the separately of a UV photodetector sensitive to the vacuum ultraviolet, which has a long-wavelength edge of the photoeffect at 200 nm. The short-wave edge is determined primarily by the state of the metal - semiconductor and the corresponding value of the surface recombination velocity. The most sensitive short-wavelength region showed a structure with gold contacts, which can be attributed to a lower surface recombination velocity in such samples.

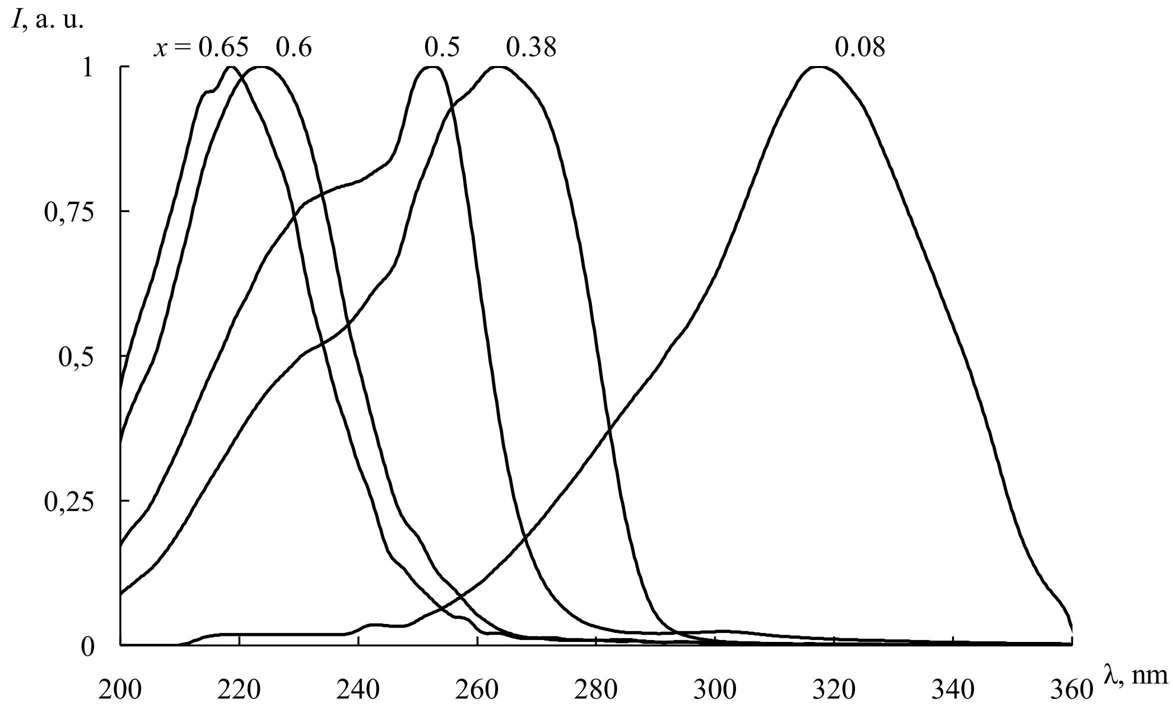

Figure 4. The spectral characteristics of photodetectors based on the sensitivity of the contact metal - $Al_xGa_{1-x}N$ with different mole fractions Al.

On the basis of contacts metal - AlGaN solid solutions, a range of photodetectors were created with the following responses in the ultraviolet spectrum:

- $Al_{0.08}Ga_{0.92}N$ → "see-blind", λ < 360 nm
- $Al_{0.42}Ga_{0.58}N$ → "solar-blind", λ < 290 nm
- $Al_{0.90}Ga_{0.30}N$ → "vacuum" UV photodetector, λ < 200 nm

The studies have lead to the conclusion of a good prospective of photosensitive structures based on metal - semiconductor nitrides contacts for usage in the ultraviolet region of the spectrum. The photodiodes with gold rectifying contacts have shown the best performance. These contacts provide not only a higher photosensitivity, but also several other advantages, such as good resistance to oxidation and high conductivity.

References

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