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Surface photocurrent nonuniformities in MSM detectors fabricated in gallium nitride heteroepitaxial layers

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A correlation of surface potential maps and photocurrent distribution images in metal–semiconductor–metal (MSM) structures allows to notice spatial nonuniformities in detector principle of operation. This effect exists only for low frequency modulation of optical excitation. This phenomenon was explained by the inhomogeneity of potential barriers and surface states density in heteroepitaxial gallium nitride layers caused by their columnar structure.

Keywords: metal–semiconductor–metal (MSM), UV detector, gallium nitride, optical beam induced current (OBIC), scanning surface potential microscopy (SSPM).

1. Introduction

Heteroepitaxial layers of nitrides deposited on sapphire substrates do not have monocrystalline structure but consist of columnar grains with different lateral sizes. Columnar structure is an effect of a three-dimensional growth mode of gallium nitride layers deposited on foreign substrate. The average size of crystallites is in the range of several hundreds of nanometers and could vary from tens of nanometers to micrometer [1]. The mismatch of a thermal expansion coefficient and lattice constants between the epitaxial layers of nitride and the substrate results in a large number of threading dislocations, typically in the range of 10^7–10^8 cm^{-2}, which are created during the growth of the layer. Most of them are concentrated in the boundaries region between grains. Atoms of impurities can be trapped in the stress field of those dislocations. They create deep acceptor levels in the forbidden band gap of the gallium nitride. Trapping of electrons on these energy levels results in the formation of depletion regions around dislocations and the creation of potential barriers at the lines of grains boundaries [2]. These regions, where internal electric fields occur, affect carrier transport mechanism and generation-recombination processes in the layers and cause local changes in the spatial distribution of electrical and optical properties of nitride layers [2–4].

2. Experiment

The planar interdigitated structures of metal–semiconductor–metal (MSM) detectors (Fig. 1) were fabricated in *n*-type Si-doped GaN layer ($n = 1\times10^{17}$ cm^{-3}) grown on sapphire substrates by metalorganic vapor phase epitaxy (MOVPE). Surface potential maps were measured by Multimode V AFM microscope. Optical beam induced current (OBIC) system which was used for measurements of local response of the structure to UV (266 nm) laser beam excitation was described in our previous publication [5]. The OBIC system allowed measurements in two modes – low frequency and nanosecond pulse excitation mode. The diameter of laser beam was about 1.5 μm.

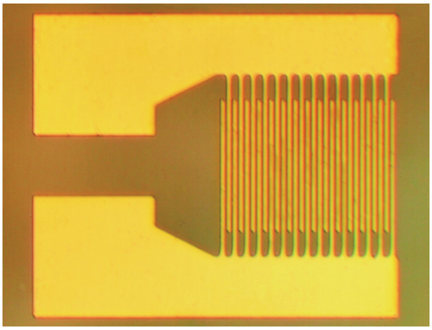

Fig. 1. Optical image of interdigitated MSM structure.

3. Results

Figure 2 presents a photocurrent response and surface potential maps of the same area of MSM detector fabricated in GaN layer. The local changes in photocurrent value observed in OBIC image could be connected with the areas of larger expanding of low surface potential near cathodes. Also a micro-region of a large photocurrent signal – 100 times higher than average value – was observed in the center of the OBIC image. In this case, the occurrence of such region could not be correlated with any changes in potential distribution – no significant change, compared to the rest of the structure surface, was observed. These regions of large signal had random distribution on the surfaces of detectors and were observed in all MSM structures, fabricated in different heteroepitaxial layers of nitrides.

In Figure 3, a local time response of MSM detector to excitation by one-nanosecond long laser pulse is presented. Three time constants could be distinguished in that time response: τ_1 – direct generation in the depletion region, τ_2 – carriers lifetime in

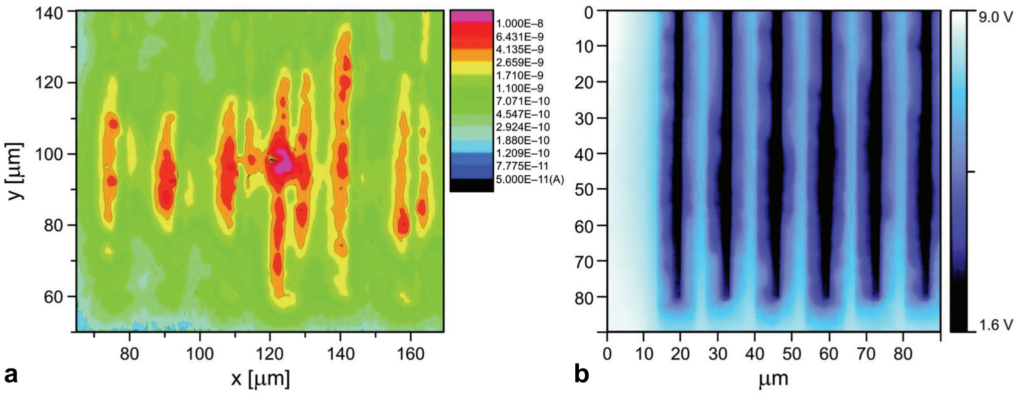

Fig. 2. Map of photocurrent response (**a**) and surface potential (**b**) of Si-doped GaN MSM detector structure polarized with 8 V.

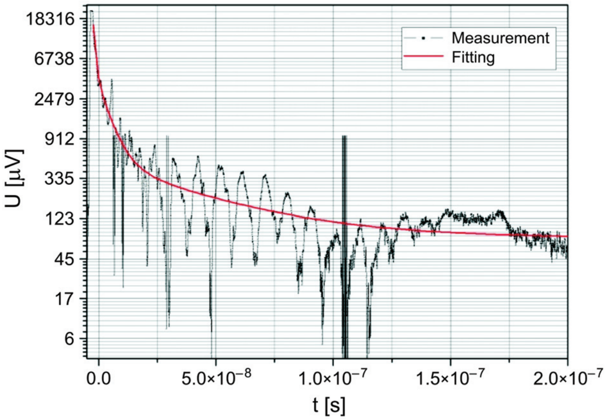

Fig. 3. Local time response of MSM detector fabricated in Si-doped GaN layer to excitation by UV illumination pulse.

the semiconductor, τ_3 – carriers lifetime in deep energetic levels in dislocations and grain boundaries. The measured curve in Fig. 3 could be fitted using the following values of time constants: $\tau_1 = 0.8$ ns, $\tau_2 = 4.9$ ns, $\tau_3 = 40.6$ ns. It was observed that in the micro-regions of large signal measured in a low frequency mode, only the third time constant was changed and was approximately ten times larger. The first and second time constant, but also the peak of the amplitude of excited photocurrent, did not change in these regions during high frequency measurements.

For Si-doped GaN layer in which detector structures were fabricated, additional OBIC measurements applying an electrolytic cell were performed. In this case, the rectifying junction was created by the contact of layer surface with electrolyte – Tiron. The sample was excited by the light from the top through a quartz plate.

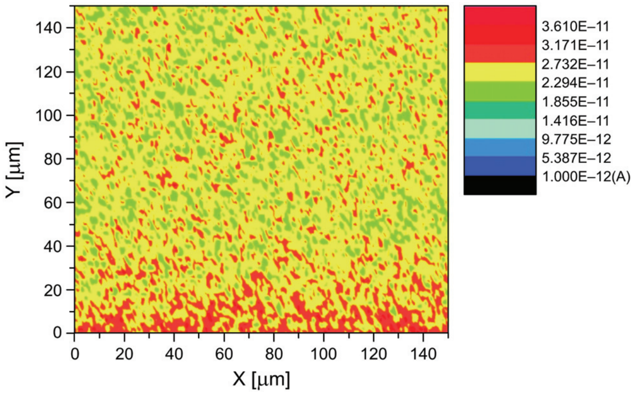

Fig. 4. OBIC image of Si-doped GaN layer measured in electrolytic cell.

A photocurrent map measured in that configuration is presented in Fig. 4. No significant changes in values of generated current were noticed. The measured nonuniformities in the signal were at the level of the system noise.

Two types of non-uniformities of photocurrent were observed in MSM detector structures fabricated in gallium nitride layers: local fluctuation of generated current near the cathodes and the existence of regions where measured signal was much higher (even 100 times) than the average value in the rest area of the detector. In this region, calculated external local quantum efficiency exceeded 100%. The first phenomenon could be connected with the existence of a potential barrier at grain boundaries in heteroepitaxial nitrides layers. Potential barriers could limit the expansion of a depletion zone and the expansion of electric field near the cathode which was responsible for the drift of photogenerated carriers. The effect of the limitation of depletion zone expansion differed spatially in the structure because of the variation in grain boundaries density caused by the existence in the epitaxial layers of nitrides grains of different lateral sizes [1].

The micro-regions of the large signal were only observed for the low frequency modulation of optical beam which excited the sample. The effect of DC photocurrent gain in GaN MSM was reported previously in the literature. It was explained by several theories: change in distribution of electric field in the structure caused by large concentration of optically generated carriers [6], electron tunneling enhanced by holes accumulation in the cathode area [7], persistent photoconductivity effect for small heights of Schottky barrier [8], Schottky barrier height lowering due to hole trapping on threading dislocation under metallization and causing an increase in the leakage current [9]. Results of micro-scale characterization of an optical response and surface potential distribution in MSM detector confirmed the last hypothesis, but with an additional observation that for this effect only the areas of several square micrometers were responsible. The calculated (based on [9]) values of local Schottky barrier lowering and surface states density under the cathode responsible for an increase in leakage current in those places were respectively: $\Delta\phi = 0.19$ eV and

$N_{ss} = 1.5\times10^{10}$ cm^{-2}. These areas existed randomly in the layer and were also caused by the columnar structure of the heteroepitaxial GaN layers, which could result in the local increase in threading dislocations density in the regions where larger density of grain boundaries exists. It could occur in small regions where lateral dimensions of crystallites are in the range of several nanometers, while in the layer there mainly exist crystallites of sizes of hundreds nanometers. A lack of changes in photocurrent observed in measurements using an electrolytic cell could be explained by no influence of surface states on potential barrier height of the junction or/and by different direction of depletion zone expansion and, due to it, different photocarriers motions direction. In this case, the drift and diffusion of carriers were vertical to the surface (contrary to MSM structure where motion was in a horizontal plane) and there were no effects of potential barriers at the grain boundaries on the transport of optically generated carriers.

4. Conclusions

Scanning characterization methods of the optical response and surface potential distribution allowed us to reveal the existence of spatial nonuniformities in generated photocurrent in MSM detectors fabricated in heteroepitaxial layers of nitrides. These nonuniformites, which existed only in small areas of detector structure, affected the performance of the whole device. The existence of micro-regions of large signal for low frequency was explained by local lowering of Schottky barrier height. Local variations in values of photocurrent were connected with different widths of the region of low potential near the cathode.

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