ULTRAVIOLET MSM PHOTODETECTOR BASED ON GaN MICROMACHINING

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Abstract–*This paper presents the manufacturing and the characterization of GaN membrane supported MSM photodetector structures obtained by means of nanolithographic techniques. Two different runs of MSM photodetectors, with different dimensions of the MSM structures and different GaN membrane thickness, have been performed and the detectors performances are annalised. Very low dark currents and unexpected high values, in the range of 50-100A/W for the UV detectors responsivity have been obtained.*

Key Words: *GaN membranes, UV photodetector, nanolithography, dark current, responsivity.*

1. INTRODUCTION

Silicon based ultraviolet (UV) photodetectors display some dramatic limitations originating in silicon technology. The main drawbacks of Si UV photodectors are: (i) ageing due to exposure to radiation of much higher energy than the Si band-gap (ii) reduced the quantum efficiency in the deep-UV range due to passivation layers such as SiO_2 (iii) significant loss of effective area due to the needs to use filters in order to decrease the responsivity to low-energy radiation (iv) cooling if low-dark current is required.

III-nitrides (AlN, GaN, InN and their ternary compounds) offer major advantages over Si and other wide band gap semiconductors for UV detection. Nitrides have a direct band-gap (which confers to the photodetector with a highly improved spectral selectivity). Moreover, the photodector cutoff frequency can be engineered by changing the mole fraction in their ternary alloys. The saturation velocity in GaN is a few times higher then in GaAs or Si enhancing the transient response of the photodetectors.

Recently GaN and its alloys have been materials of choice in fabrication of UV detectors in the wavelength range 200-370 nm because in principle UV photodetectors fabricated up to now have a lot of applications in various areas such as engine control, solar UV monitoring, astronomy, lithography aligners, secure space to space communications, or detection of missiles as it is indicated in a recent review [1]. Photodectors based on wide-bandgap semiconductors are able to work at high temperatures in harsh environments displaying high responsivity. Most used photodetector devices are based on metal-semiconductor-metal (MSM) structures due to their simplicity. The MSM configuration consists in two interdigitated Schottky electrodes deposited on a non-intentionally doped or compensated semiconductor material. The MSM configuration shows a very low dark current due to the rectifying nature of the contacts and the high resistivity of the material. Additionally, the reduced parasitic capacitance, the low dark current, the low noise, and the large internal gain [2-5] indicate that the GaN MSM structure is very appealing for UV photodetection.

Despite of huge potential applications of GaN, the technology of this material is still immature and this represents a major difficulty to improve device performances due to the lack in the fabrication of high resistive layers. Many GaN MSM structures were manufactured up to now using GaN layers grown on sapphire substrate which is a significant drawback in the integration of the photodetector with other components manufactured on Si or GaAs substrates for integrated optoelectronics applications. Recently GaN MSM photodetectors were prepared on silicon substrate [6]. The dark current of these devices was substantially smaller in magnitude, compared with identical devices manufactured on sapphire substrate, but moderate values for the responsivity have been achieved. This year our group has reported, for the first time, the manufacturing of an UV detector based on a thin GaN membrane [7].

The aim of this paper is to present the manufacturing and the characterisation of substrateless MSM type UV photodetetector structures on a 2.2 μm as well as a 0.5 μm thin GaN membranes obtained using micromachining techniques and suspended over high resistitivity Si pillars. The MSM configuration consists in two interdigitated Schottky electrodes deposited on a non-intentionally doped or compensated semiconductor material and are obtained using botrh classical UV as well as nanolithographic techniques.

2. MANUFACTURING

The first run was manufactured on a multilayer GaN/AlN structure having a thickness of 2.2 μm, grown by metal-organic chemical vapor deposition (MOCVD) on high resistivity (ρ>10kΩcm) The wafers were 500μm thick and have been provided by AZZURRO Semiconductors AG, Magdeburg.

This layer structure has been chosen for a crack-free growth of GaN on (111)-oriented high-resistivity silicon substrate. The first AlN layer has a buffer function while the inter-layers of 10 nm thickness of low-temperature grown AlN layers help to reduce significantly the thermal stress and allow for the growth of thicker crack-free layers of GaN on Si substrates. The large difference in thermal expansion coefficients between GaN and Si (114%) leads to tensile stressed GaN layers at room temperature and cracking for layer thickness above 1 µm**.** The chosen layer thickness is the result of an optimal strain-engineering. Native doping is compensated by the Fe doping in the GaN layers [8]. The MSM interdigitated structure is symmetrical, having 20 fingers with a length of 100 µm and a width of 1 µm, and a distance between successive fingers of 1 µm. A cross section of the MSM UV photodetector structure is presented in Fig. 1. The entire active area of the device is approximately 1900 µm^2. A classical UV aligner (MA6 from Karl Suss) was used for the patterning. The Schottky metal deposition of Ni/Au (10nm /200nm) was performed by e-gun evaporation in a UHV chamber. Ni serves also as an adhesion promoter of Au on the nitride surface. Then the samples were mounted face-down on special glass plates and the Si substrate was thinned down to 150 µm by chemo-mechanical lapping. Additionally, for such deep etching, significant undercutting effects may appear which are undesirable. The final back surface was mirror polished to allow for backside alignment. After the backside lapping of the wafer to a thickness of approximately 150 µm, a 400nm thick Al layer was patterned and deposited on the backside, to be used as mask for the selective reactive ion etching of silicon. The backside mask, for the membrane formation, was patterned using double side alignment techniques and silicon was completely etched down to the 2.2 µm thin GaN layer using SF_6 plasma.

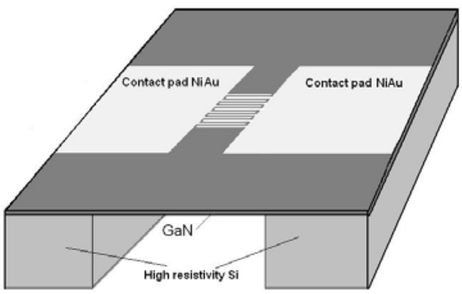

Fig. 1. Schematic cross section of the membrane MSM UV detector structure.

In Fig. 2 a top photo of the fabricated interdigitated UV detector is displayed. The thin interdigitated electrodes appear in lighter colors than the substrate and in particular in the photo half of them are connected to the big metallic electrode (Ni/Au). The Ni/Au is forming the Schottky contact to GaN membrane necessary for the MSM photodetector.

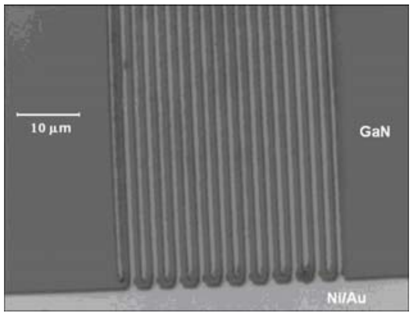

Fig. 2. SEM photo for the 1µm wide inger/interdigit detector structure manufactured on a 2.2µm thin GaN membrane.

The second run was manufactured starting from a GaN/Si wafer produced by NTT AT Japan using MOCVD techniques. The structure consists from a 0.5µm undoped GaN layer grown on a high resistivity, <111> oriented silicon wafer. A 0.28 µm thick buffer layer is grown between the silicon and the GaN layer.

The first step in UV detector structure manufacturing was the patterning of the pads of the device. For this, conventional photolithography, e-beam metallization (Ni /Au 20nm/200nm) and lift-off technique have been used.

The MSM interdigitated structure is symmetrical having a length of 100 µm and a width of 20 µm. Due to submicron dimensions of the digits/interdigits (0.5 µm) of the MSM structure, a direct writing, process using an Electron Beam Lithography (EBL) was selected. The design transfer on the wafer was performed using a Scanning Electron Microscope (Vega from Tescan), equipped with an EBL (Elphy Plus from Raith) by direct writing, using a 40nm thick PMMA resist. Semitransparent Ni/Au (5/10nm). Schottky contacts have been evaporated and lift-off techniques have been used to define the interdigited structure. Then similar procedures like for the first run have been used: the samples were mounted face-down on special glass plates and the Si substrate was thinned down to 150 µm by chemo-mechanical lapping. For the membrane formation the substrate was selectively removed using back side patterning and SF_6 plasma RIE. The total thickness of the membrane was 0.78µm (0.5µm GaN+0.28µm buffer).

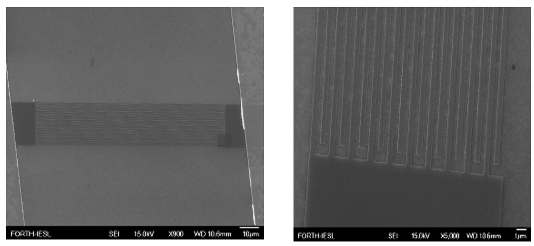

Fig. 3. SEM photo (left) and detail (right) for the 0.5 µm wide finger/ interdigit detector structure manufactured on the 0.5µm thin GaN membrane.

The total area of the MSM structure was about 2000 µm^2 but estimating a 50% transparency of the contact [9], the active area of the detector was about 1500 µm^2. The SEM photo of the structure is presented in Fig. 3.

3. ELECTRICAL AND OPTICAL CHARACTERISATION

Dark current versus voltage for the GaN membrane supported MSM photodetector structures was measured with a Keithley 6517A electrometer. The responsivity as a function of the photon wavelength was measured using an Ozone free 150W Xe-lamp UV light source from Hamamatsu. Low noise amplifiers were used to measure all the spectra.

The results of the measurements for the first run are presented in Fig. 4. The dark current is very low (approx. 20-30 pA at 2V). Measuring several photodectors the results were reproducible.

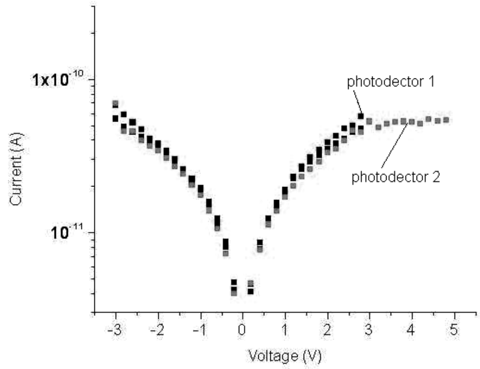

Fig. 4. Dark current vs. applied voltage for two different photodectors located on the same wafer.

The responsivity vs photon energy was measured for detector structures on bulk substrate (before membrane formation) and for detectors on the 2.2μm GaN membrane.

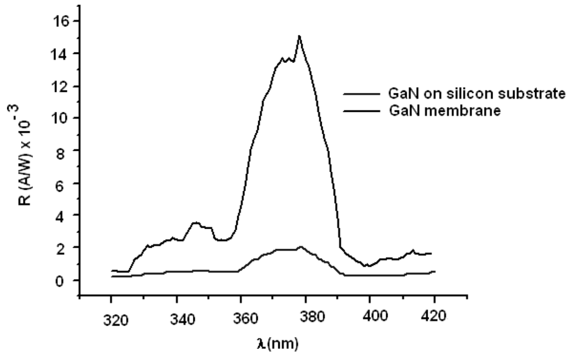

Fig. 5. Responsivity vs. photon energy for the GaN membrane UV detector and of UV GaN bulk photodectors.

Experimental results presented in Fig 5 show a maximum responsivity of about 14 mA/W at an energy peak 3.3eV (370nm) using a low bias voltage of 1.5 V. This value is a very good, (comparable to those obtained on similar structures manufactured on sapphire substrate) taking into consideration that of the applied voltage is low. We can expect a responsivity more then an order of magnitute higher, if measurements are performed at bias voltage of 10-15V. These measurements could not be done due to the low yild of the process. In any case the GaN membrane photodetector responsivity was 8 times higher than the responsivity of similar GaN/Si structures as it is evidenced in Fig. 5.

For the structures obtained in the second run, the dark current before and after membrane formation are presented in Fig 6 for v3 different structure and Fig 7.

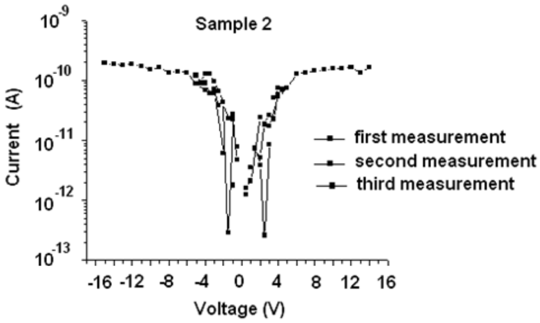

Fig. 6. Dark current for the 0.5μm finger / interdigit for the UV detector structure-before the silicon substrate removal.

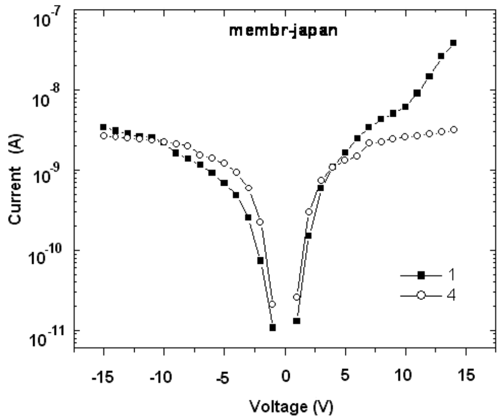

Fig. 7. Dark current for the 0.5μm finger / interdigit for detector structures on 0.5μm thin GaN membrane.

The responsivity versus wavelength at various voltages up to 15 V were measured before and after membrane formation and are presented in Fig. 8 and Fig. 9, respectively

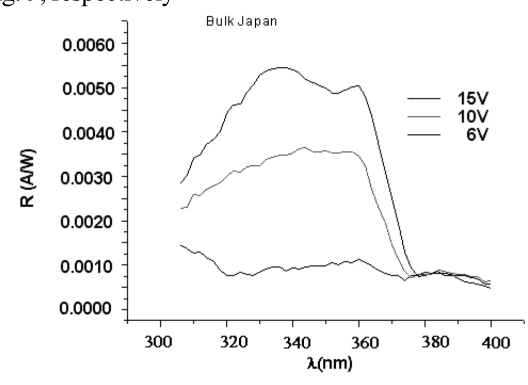

Fig. 8. Responsivity vs wavelength for the 0.5μm finger / interdigit for the UV detector structure-before the silicon substrate removal (thickness of the GAN layer 0.78μm).

In the second run, very low dark currents (1-10pA) at moderate voltages have been obtained for all structures. Unexpected high values for the responsivity (values of about 50-150 A/W for a bias in the range 6-15 V) have been obtained. The measured values for the responsivity are 3 orders of magnitude higher than those obtained for GaN on bulk silicon and almost 2 orders of magnitude higher then on GaN on sapphire photodetectors.

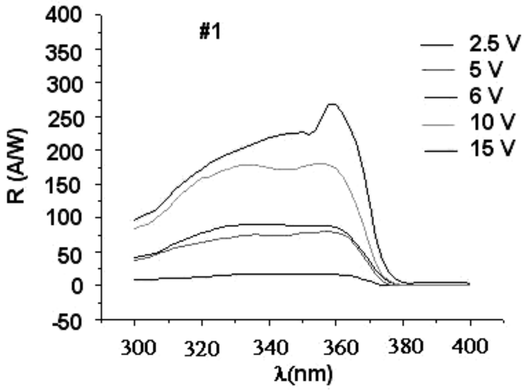

Fig. 9. Responsivity vs wavelength for the 0.5μm finger / interdigit for two UV detector structures- manufactured on 0.78μm thin GAN membrane.

The low values obtained for the responsivity before the membrane formation (GaN on silicon structures) using the same set-up (values of 1-5 mA/W for voltages in the range 6-15V) seems to confirm that responsivity measurements are correct. If we start from this assumption, it seems that we can have a major advantage using micromachining technologies to manufacture UV GaN detectors on thin membranes. As a comparison, for a 0.5 -1μm finger/interdigit detectors manufactured on GaN /sapphire a maximum responsivity of 0.3-0.5 A /W [4, 10] have been reported. The MSM structure has a gain, and the membrane can increase this gain. In contrast with the GaN /Si or GaN on sapphire structures, the case of the GaN membrane photodetector, the photo generated electrons are confined only in the membrane because of the very high barrier between the GaN membrane and the air. This inhibits the carrier flow at moderate applied voltage, and can increase the responsivity [11]. There is also the possibility that the process of substrate removal creates hole traps that could also lead to gain increase Further investigation need to be undertaken to clarify these effects. Finally, the X-Ray Diffraction (XRD) manifested high quality of the GaN material (low number of interface and volume defects) enhances the responsivity of the device.

4. CONCLUSIONS

MSM UV photodetectors structures with fingers and interdigits of 1μm wide, supported on 2.2μm GaN membranes as well as MSM detectors with fingers&interdigits of 0.5μm wide on 0.5μm thin GaN membranes, have been manufactured using nanolithographic techniques. Very high values for the responsivity (50-150 A/W for a bias in the range 6-15 V) have been obtained. A major advantage of micromachining technologies used for manufacturing UV GaN detectors has been observed. Results have to be confirmed on other structures with similar and smaller dimensions for the digit/interdigit width. Also we have to improve the yield of the process.

Acknowledgements–The Romanian authors acknowledge the Romanian Ministry of Education Research and Youth, for the support in this work under the CEEX projects Nanoscale –Conv (No 6111/2005-CALIST) and ACOMEMS (No 29/INFOSOC).

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