



Monolithic integration of nitride-based transistor with Light Emitting Diode for sensing applications

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ABSTRACT

A novel monolithically-integrated LED and HEMT sensor, based on III-nitrides, is designed and realized. The main aspects of the design and processing issues of such a device are presented and discussed. Satisfactory operation of both LED and HEMT parts of the device was ascertained by means of electrical characterization. The best obtained turn-on voltage for the LED part of the device was as low as ~ 4.5 V, which is quite acceptable for nitrides, while the I_{DSsat} value of ~ 26 mA/mm for the HEMT part, is rather low as compared to typical AlGaIn/GaN HEMTs. Moreover, intense light emission was readily obtained from the LED, with a large portion of light illuminating the sensor active area. The overall satisfying performance of the integrated device opens the way for actual sensing experiments to be performed.

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1. Introduction

III-nitride-based devices have been rapidly spreading over different fields of applications during the last years. Apart from their use as material for Light Emitting Diodes (LEDs) and High Electron Mobility Transistors (HEMTs), their unique surface properties have made possible the realization of electrolyte- or solution-gate HEMTs and have opened the way for their use in chemical and bio-sensing applications [1,2]. Moreover, the mature growth methods and processing technology of nitrides can give heterostructures with well controlled layer thicknesses and compositions. In this way, new sophisticated devices can be realized for unique sensing applications.

AlGaIn/GaN HEMT sensors are based on the gating effect caused by electrostatic interaction between the polar nitride surface and the species, which come in contact with the surface and finally attach to it, such as ions, radicals or even biological molecules [3,4]. For some sensor applications though, it might be beneficial to use light to catalyze a certain biological or chemical sensing action. The basic idea is the ability to electrically detect, via a HEMT, an important biological or chemical process occurring on the bare GaN surface of the HEMT, which is initiated, enforced or catalyzed by the illumination of light (LED). Therefore, the co-existence of a sensing element (HEMT) and a light source on the same chip might be a powerful tool for unique chemical and biological sensing applica-

tions. Toward this end, the most cost- and space-efficient approach is to employ lithographic techniques for the monolithic integration of the two individual devices. A schematic of a device structure, which comprises an LED and a HEMT structure, is shown in Fig. 1. A thick insulating layer must be inserted in-between of the two separate structures for electrical isolation. The illuminating wavelength can vary from UV to green, depending on the composition of the quantum wells in the LED active area, while the HEMT's characteristics and sensing ability depend on the growth and composition of the transistor's layers [5]. Therefore, one can tailor material properties and device characteristics to tune the sensor device according to the sensing needs and other requirements, like the fact that the thick insulating layer should be transparent at the LED's emission wavelength. Nevertheless, there are many technological issues that need to be considered, such as growth of the whole structure, processing and light extraction, in order to realize a working device such as the one shown in Fig. 1.

In this work we present the monolithic integration of an LED with a HEMT for potential sensing use. The main aspects of the design and realization of the device are presented and discussed. Finally, results about the operation characteristics of the device by means of electrical characterization are presented.

2. Results and discussion

The sensor structure discussed here was grown by TopGaN in a Metal-Organic Chemical Vapor Deposition chamber on a 2 in. c-axis sapphire substrate, in a single growth run. It consists of a typical AlGaIn/GaN HEMT structure on top of a typical LED one,

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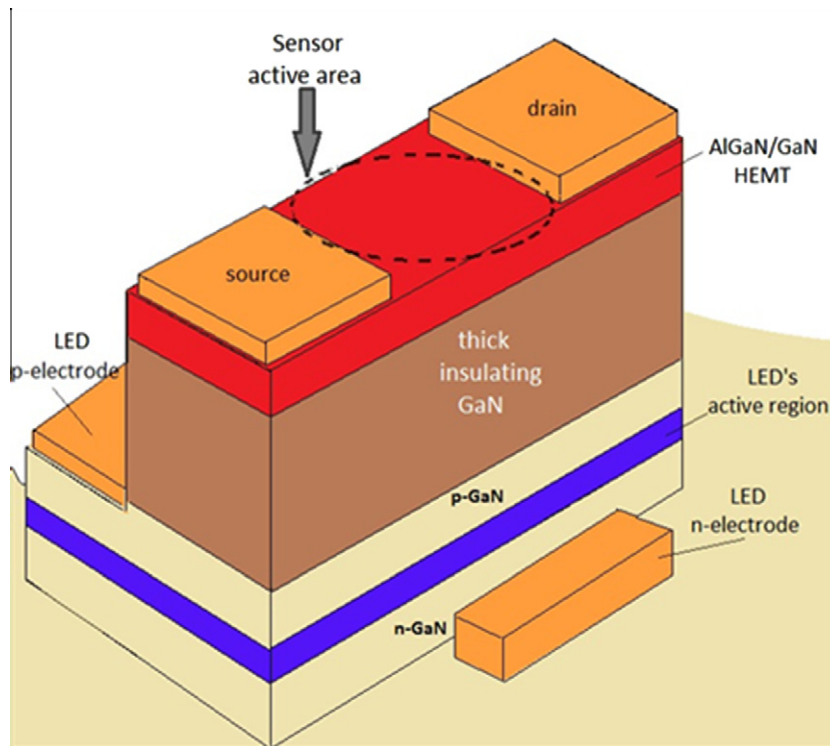


Fig. 1. Schematic of an asymmetric geometry sensor device is shown. The LED and HEMT structures are separated by a thick insulating GaN layer. In this device geometry, the LED p-electrode is on one side of the HEMT. The active area pointed in the schematic, is the area to be contacting the chemical and/or biological substances.

separated by a 1 μm thick insulating GaN layer. The LED emits at ~ 395 nm, as determined by PL characterization, which is high enough to ensure that no absorption will occur inside the thick GaN layer. Processing of the sensor device involves two dry-etching steps, ohmic contact formation, subsequent dielectric layer deposition, and final interconnect formation. For dry etching a conventional Reactive Ion Etching (RIE) system was used, with special care given to the etching parameters, in order for the sensor's active area to be intact from ion damaging [6]. Contacts were formed using an e-beam evaporator for metal deposition and a Rapid Thermal Annealing (RTA) system for thermal treatment. Annealed Ti/Al/Ni/Au was used as both the LED n-electrode and HEMT's source-drain electrodes. As LED p-electrode, the oxidized Ni/Au contact scheme was tried, as well as, as-deposited Cr/Au and Cr/Ir/Au contacts, after the use of pre-deposition surface treatment. For dielectric passivation of the device, Chemical Vapor Deposition grown SiN was used. Finally, a thick evaporated Au layer was used as contact layer for external probing of the device.

A Scanning Electron Microscope (SEM) picture of a fully processed sensor device is shown in Fig. 2, while a period with all the available device geometries is shown in the inset. The whole device is covered with SiN, except the Au interconnect pads and the sensor's active area shown with an arrow in Fig. 2. For realistic sensing experiments, there is the ability to cover the entire surface with polyamide, or any other layer that remains intact to the chemical substances to be tested, and create openings only in the active area of the transistor and the interconnect pads for probing and wire bonding, respectively.

The geometry of the device shown in Fig. 2, is one of the three available and the incorporation of this device geometry reveals one of the major considerations that had to be made when designing a sensor that uses light. This is the necessity of having a large portion of the LED photons illuminate the sensor's active area. This is the reason for incorporating such a geometry device, as the one shown

in Fig. 2, which has the LED p-electrode surrounding (not fully) the sensor active area. Another consideration is the big difference between electron and hole mobility in the n and p layers of the LED respectively. Based on the above, a logical assumption would be that the electron-hole recombination and photon emission should mainly occur in the LED active region part located underneath the p-electrode. The latter can be remedied by placing the n-electrode in a larger distance, than the p-electrode, from the active region of the LED. Due to dimension issues though, it was not practically feasible to take this effect into full account. The other two geometries have the p-electrode, either fully surrounding the sensor active area (symmetric geometry) or being just on the one side of it (asymmetric geometry as the one shown in Fig. 1). Which geometry serves the sensing purposes better, remains to be evaluated after actual sensing experiments.

I - V curves of the diode part of asymmetric and π -geometry devices are shown in Fig. 3a, while I - V s from symmetric devices were not included in this graph, due to poor electrical characteristics and the fact that these devices did not emit, most likely due to surface-related parasitic currents enhanced by the proximity of the p- and n- electrodes in this geometry, as will be explained below. From this graph, the rather good quality of the diodes is evident, in terms of turn on and breakdown voltages, with the π -geometry device achieving lower turn on voltage (~ 4.5 V), as compared to the asymmetric one (~ 5.5 V). This observation confirms the importance of p-GaN contact geometry to the diode performance. The basic difference, concerning the p-electrode, between the two geometries is the contact width and the area through which holes are injected into the active region. On the other hand, the p-electrode of the non-emitting symmetric devices fully surrounds the transistor, while is itself surrounded by the n-electrode, with the lateral spacing between them being less than 10 μm . In the inset of Fig. 3a, one can see a biased π -geometry device emit. This is an inspiring result, if one considers that the LED p-electrode is

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