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Abstract

The recent years have announced the emergence of novel photonic technologies based on IIInitrides semiconductors. Gathering the progress in materials maturity and the advance in manufacturing process, Solid-State Lighting based upon GaN-based light-emitting diodes (LEDs) has emerged as one the dominant technology for indoor/outdoor lighting as in hospital and transportation. In addition, the opportunity to apply LED for indoor/outdoor communication is a research innovation for the community. We have developed the proper design and the clean room fabrication of micro sized visible LEDs based on InGaN/GaN multiple quantum wells (MQWs) grown on sapphire substrates. A PIN configuration is selected for the design. Global experiments have been conducted by reducing the LED dimension (from 300 to 5µm) to lower the capacitance, the internal electric field of InGaN MQWs and therefore to increase the LED's emission efficiency. Optical and electrical characterizations of the fabricated samples have performed to extract the cut-off frequency. Measurements are performed under reverse bias both in the dark and under illumination by a laser source. Experimental results have demonstrated that a frequency bandwidth of respectively 300MHz and 1.5GHz could be attain for a 100µm and 25µm size structures.

Keywords: Gallium nitride, photonics, LED, light fidelity

INTRODUCTION

Gallium Nitride based SC have attracted a lot of interest for new generation of optoelectronic devices [1]. The advantage with these materials is the flexible bandgap varying from 0.7 to 6 eV hence covering a large spectrum, from deep ultraviolet up to near infrared [2], allowing the development of microelectronics and high spped photonics [3-7]. The recent years have announced the emergence of novel photonic technologies based on III-nitrides semiconductors. Gathering the progress in materials maturity and the advance in manufacturing process, SolidState Lighting based upon GaN-based light-emitting diodes (LEDs) has emerged as one the dominant technology for indoor/outdoor lighting as in hospital and transportation. In addition, the opportunity to apply LED for indoor/outdoor communication is a research innovation for the community. This well-known concept is identified light fidelity (LiFi), as a wireless technology that uses optical light to transmit informations more fast and reliable data transmission than conventional Wi-Fi. Higher Frequency results from smaller dimensions for the devices.

EXPERIMENTS

The proposed PIN structure consists of a thick not-intentionally-doped (n.i.d) GaN buffer layer (called also undoped GaN) on c-plane (0001) sapphire. In order to ensure a high crystalline quality for GaN and to move away from the GaN/sapphire interface, the thickness of this layer is chosen to be 2.5µm. This is followed by a 3.5µm thick Si-doped n-type GaN layer with a carrier concentration of 3×10^{18} cm^{-3}. The thickness of the "i" intrinsic-absorption- layer, is ~ 145 nm in order to efficiently absorb the incidentlight. The MQW structure is gown with 10 pairs of InGaN/GaN with thicknesses of 2.5nm for InGaN and 12nm for GaN within the InGaN/GaN well. 100nm Mg-doped p-type GaN layer is grown as the top layer with a carrier concentration of 5×10^{17} cm^{-3}.

Fabrication process of photodiode consists of four steps starting by p-type top contact deposition, etching process to reach n-GaN layer, n-type contact deposition and finally thermal annealing of n and p contacts. Metals have been optimized to be Pd/Au with respective thicknesses of 35nm/120nm for p-type top contact demonstrating the high work function of Pd metal associated with its high reactivity with low contact resistance. Ti/Al/Au metals with respective thicknesses of 10nm/30nm/300nm for n-type bottom contact have been used. Global experiments have been conducted by reducing the LED dimension (from 300 to 5µm) to lower the capacitance, the internal electric field of InGaN MQWs and therefore to increase the LED's emission efficiency. Proper etching and metallization optimization processes have been developed to create large or small mesa that allows a controlled parasite capacitance for the global configuration [8-9]. For RF experimens, coplanar transmission lines have been designed and fabricated on top of the samples.

CHARACTERIZATION OF PHOTONIC DEVICES

The measurement of photocurrent relies on two important factors, the wavelength of incident light and the output power. For this reason, a laser source has been used for powerful input light. Besides, fiber-coupled laser source is the optimal choice due to the ease to focus a laser beam using stripped and cleaved optical fiber. The wavelength of fiber-coupled laser source is 405nm and its output power reaches100mWatts. In order to estimate the cut-off frequency, we have first theoretically calculated it from the average value of capacitance C. For RF analysis, coplanar transmission lines have been designed and fabricated on top of LEDs samples. Previously, we have investigated the capacitance values using a C-V setup, for photodiode areas ranging from 100×100 μm^2 to 1000×1000 μm^2. The extraction of capacitance permits us to estimate the cut-off frequency and compare these results to the theoretical values. This approach gives some indications in order to optimize the design of the photodiodes and more generally to reduce the capacitive effects. Actually, any methods exist that allows the direct measurement of the photodiode cut-off frequency in UV-Vis region. For the frequency experiments, due to the lack of modulated laser source (in the wavelength range 400 to 633nm), we have performed noise figure techniques already used for III-V semiconductors technologies samples but in the IR range. This experiment is related to the noise figure measurement.

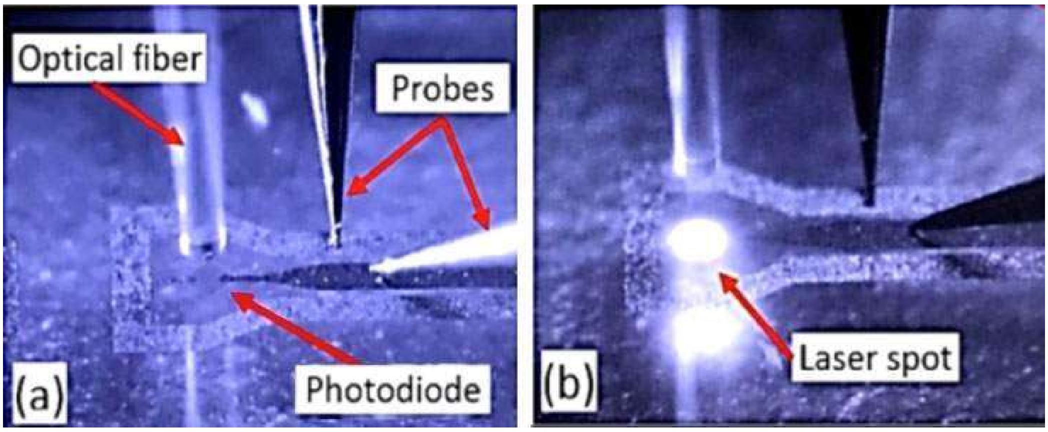

Fig1: Configuration of PIN structure using RF coplanar transmission lines (a) for dark measurement (b) under illumination

RESULTS AND DISCUSSION

Samples with different dimensions have been investigated by photocurrent measurement in order to evaluate the photodiode response. The investigation of size-dependent capacitance has been performed for large-scale photodiodes (from 100×100 to 1000×1000 μm^2) using a C-V setup. The capacitance is proportional to the photodiode size and particularly to the diameter of the mesa produced by dry etching. Dynamic measurements are performed under reverse bias both in the dark and under illumination by laser source. This method is considered as one of the most convenient technique to extract the cut-off frequency for photodiodes. It consists in the noise measurement as function of the frequency. The evolution of noise response clearly indicates a limitation in the photodiode behavior when the frequency increases, allowing the estimate of the 3dB cut-off frequency, a very convenient way to assess the dynamic response of fabricated photodiodes. Lower cut-off frequency of 9MHz is observed for 1000×1000 μm^2 demonstrating the influence of the capacitance on the dynamic response.

Fig. 2 shows the evolution of the noise intensity as function of frequency: we have selected a photodiode with diameter of 100µm and using coplanar lines for the probe connection. The photodiode has been biased under reverse voltage in dark and under illumination of laser source in order to measure the shot noise. The curve shows a drop of shot noise related to the photodiode current when frequency is increased. The difference in noise intensity between dark (N_{dark}) and under illumination ($N_{photocurrent}$) is observed very small when bias voltage of -4 V is applied for small photodiode dimensions. Difference ($N_{photocurrent}$ - N_{dark}) in average value is roughly about 0.8 dB. From fig.2, the -3dB cut-off frequency is estimated to be 300MHz for a photodiode diameter of 100µm.

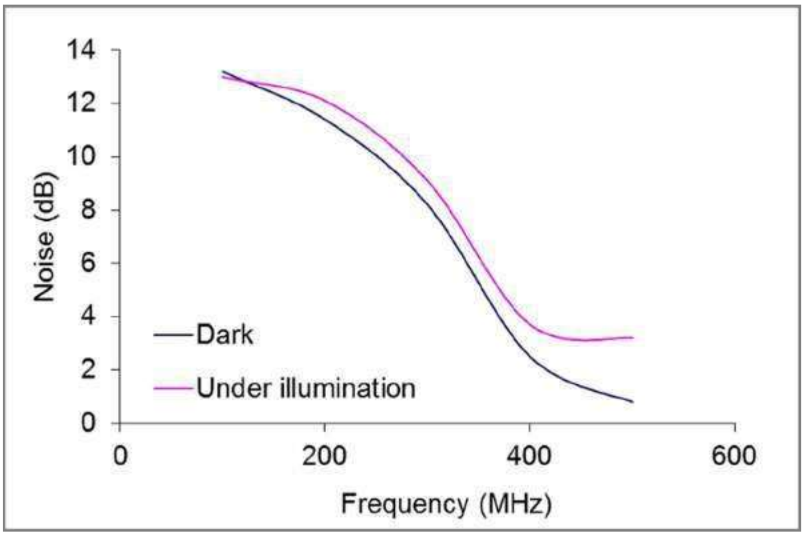

Fig 2: Noise measurement for 100×100 μm^2 photodiode

CONCLUSION

In this research activity, the design, the material characterization and the device fabrication have been performed for InGaN/GaN based photodiodes. The InGaN absorbent layer has been defined with 10% of indium content. The objective of this work has been directed towards fabrication of high speed photodiodes. The first step of this work is to optimize the photodiode design and fabrication in order to reduce the capacitive effects. Firstly, large-scale photodiodes have been employed to extract the photocurrent and the cut-off frequency. The increase of photocurrents is observed once the laser power is increased and attains 1.2 mA with EQE value of 13 %. Theoretical calculation of the photodiode frequency has been performed in order to compare it with the experimented values issued from C-V setup and Noise measurement. Results demonstrate a cut-off frequency at -3dB of 300 MHz using Noise measurement for 100×100 μm^2 photodiode. This study offers the possibility to work toward the InGaN-based μPhotodiode such as a perspective work towards LiFi configuration.

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