Electro-optical characteristics for AlGaN solar-blind *p-i-n* photodiode: Experiment and simulation

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Abstract

The fabrication and modeling for solar-blind AlGaN-based *p-i-n* photodiode have been presented. The simulated dark current characteristics are in good agreement with the experiments. It is found that the peak responsivity of 0.005A/W can be achieved at 265nm corresponding to the cutoff wavelength of the $Al_{0.45}Ga_{0.55}N$ absorption layer. The transmission spectra drop to nearly zero due to the intense light absorption of n-type $Al_{0.65}Ga_{0.35}N$ layer.

I. INTRODUCTION

The atmospheric ozone layer filters out the ultraviolet (UV) solar radiation with wavelengths shorter than 290nm, preventing it from reaching the Earth's surface. UV photodetectors with cutoff wavelengths below 290nm, the so-called solar-blind detectors (SBDs), are thus capable of detecting feeble UV signals under solar background radiation with high signal to background ratio. Owing to this advantage, SBDs are in high demand for a number of applications such as flame detection, ozone layer monitoring, UV astronomy, water purification, submarine communication, and medical researches [1-5]. $Al_xGa_{1-x}N$-based photodetectors potentially offer significant advantages over the current photomultiplier tube and silicon-based solar-blind detector technology in terms of size, complexity, cost, robustness, stability, power demands, and bandwidth [6]. Moreover, its intrinsic solar blindness (for x>0.4) and the ability of operation under harsh conditions (high-temperature and high power levels) resulting from its wide band gap makes $Al_xGa_{1-x}N$-based photodetectors attractive for high-performance solar-blind detection applications.

A major obstacle in developing high-performance AlGaN SBDs is the poor AlGaN crystalline quality owing to the lack of lattice and thermal match substrates. The high Al-composition $Al_xGa_{1-x}N$ epilayers grown on popular substrates such as sapphire are usually with high densities of threading dislocations (TDs) or, even more serious, macroscopic cracks, caused by the large lattice and thermal mismatches between the substrate and the subsequent epilayers. It has been well pointed out that high-density TDs are the primary reason for the leakage current and reduced spectral rejection ratio in AlGaN based photodiodes [7, 8]. Accordingly, the substrate becomes a key factor concerning the epilayer quality and its influence on detector performance.

In order to reduce dislocation densities and improve AlGaN crystalline quality, we present, in this paper, the growth, processing, and modeling of $Al_{0.45}Ga_{0.55}N$ solar-blind *p-i-n* photodiodes on AlN/sapphire template. The results show that high optical responsivity and low dark current have been achieved as a result of the usage of AlN/sapphire template.

II. SIMULATION MODELS AND DEVICE STRUCTURE

The steady-state two-dimensional numerical calculations were performed using Sentaurus Device, a commercial package by Synopsys [9]. For plain drift-diffusion simulation the well known Poisson equation and continuity equations are used. The carrier generation-recombination process consists of Shockley-Read-Hall, Radiative, Auger, and optical generation-recombination terms. Additionally, the trap-assisted tunneling is included in the continuity equations. Moreover, we assume a same single acceptor type electron bulk trap level in all the epilayers. The values of the trap levels are extracted from the experimental data for the $Al_xGa_{1-x}N$. The trap density of AlGaN is $N_{AlGaN}=5\times10^{16}cm^{-3}$ with a capture cross section of $\sigma_{AlGaN}=1.0\times10^{-15}cm^{-2}$, locating approximately 2.2eV below the conduction band [10].

Samples were grown by metal-organic chemical-vapor deposition (MOCVD) on transparent AlN templates on double side polished *c*-plane sapphire substrates. First, a 0.15-μm-thick undoped $Al_{0.65}Ga_{0.35}N$ layer was grown on the top of the AlN/sapphire template to improve the material quality for the subsequent device layers by reducing the defect density. After this, there were the layers of *p-i-n* structure, which are 0.5-μm-thick Si doped *n*-type $Al_{0.65}Ga_{0.35}N$ layer, and 0.15-μm-thick unintentionally doped $Al_{0.45}Ga_{0.55}N$ absorption layer, and 0.15-μm-thick *p*-type $Al_{0.45}Ga_{0.55}N$ layer. To reduce the metal *p*-contact resistance and facilitate carrier collection, a 35-nm-thick *p*-type GaN layer were grown on top of the *p-i-n* structure. Device fabrication was completed by a series of processing, including photolithography, inductively coupled plasma (ICP) dry etching, metal evaporation, and SiO_2 passivation. The detailed structural information of AlGaN solar-blind *p-i-n* photodiode is shown in the inset of Fig. 1.

III. RESULT AND DISCUSSION

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Current-voltage (*I-V*) characteristics were measured with a keithley 4200-SCS semiconductor characterization system. The simulated and measured dark current characteristics are both shown in Fig. 1. The simulated *I-V* curve is in good agreement with the experiment, confirming the validity of $Al_{0.45}Ga_{0.55}N$ solar-blind *p-i-n* numerical model. The forward current tends to saturate when the bias exceeds 1V due to the large series resistance effect. The reverse current almost exponentially increases with bias because of the large dislocation-induced trap-assisted tunneling effect.

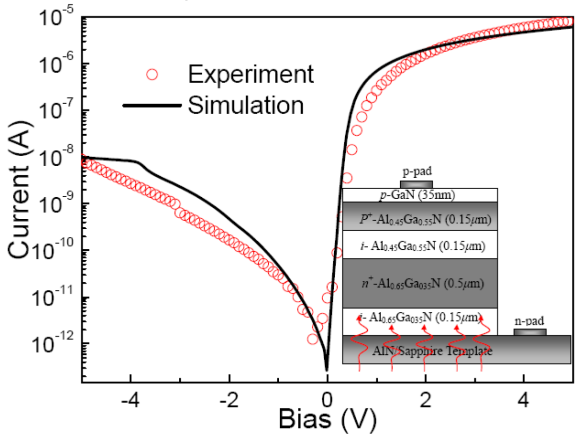

Figure 1. Dark current characteristics of AlGaN solar-blind *p-i-n* photodiode. The inset shows the device structure, the doping concentration of p^+, i, and n^+ layers are $2\times10^{18}cm^{-3}$, $3\times10^{16}cm^{-3}$, and $3\times10^{18}cm^{-3}$, respectively.

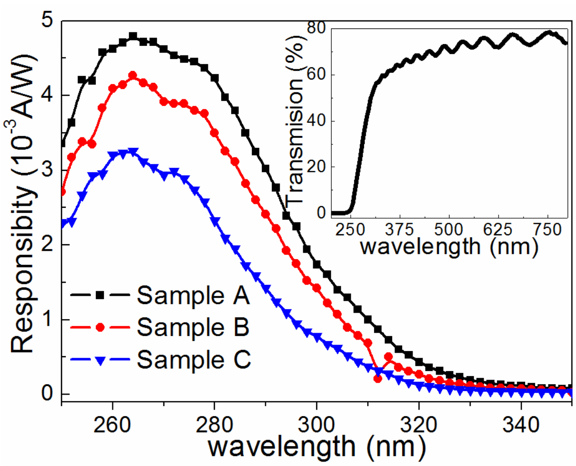

Figure 2. Spectral responsivity of three similar samples. The inset shows the spectral transmission of the wafer used in the fabrication of photodiode.

The spectral responsivity of the devices was measured using a light source consisting of a deuterium lamp and a xenon lamp, a monochromator, a chopper, and UV-grade focusing optics in a standard synchronous detection scheme. A calibrated, UV-enhanced Si detector was used to measure the illumination power density of the light source lamps over the measuring range of 200 to 500 nm. Since AlGaN solar-blind *p-i-n* photodiode often operates at small reverse bias, measuring voltage for spectral responsivity was set to -0.05V. Figure 2 presents the measured spectral responsivity of three similar samples, the fabrication processing of three samples were completely same. Therefore, notable responsivity discrepancies are attributed to different epilayer qualities of three samples. In that sense, the sample A has the best crystalline quality, and sample C worst. However, all the spectral responsivity curves exhibit peak responsivities at 265nm corresponding to the cutoff wavelength of the $Al_{0.45}Ga_{0.55}N$ absorption layer. The inset of Fig. 2 is the transmission spectra of the wafer used in the fabrication. When the wavelength is shorter than 250nm, the transmission drops to nearly zero. This is because the *n*-type $Al_{0.65}Ga_{0.35}N$ layer contributes to the light absorption. Besides, clear interface interference can be observed as the wavelength is longer than 320nm.

IV. Conclusion

The dark current characteristics for $Al_{0.45}Ga_{0.55}N$ solar-blind *p-i-n* photodiodes have been reported. The simulated *I-V* curve is in good agreement with the experiment. It is found that the peak responsivity of 0.005A/W can be achieved at 265nm corresponding to the cutoff wavelength of the $Al_{0.45}Ga_{0.55}N$ absorption layer.

Acknowledgements

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