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Surface Photovoltage Spectroscopy of InGaN/GaN/AlGaN Multiple Quantum Well Light Emitting Diodes

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Abstract.

InGaN/GaN/AlGaN multiple quantum well light emitting diodes (MWQ LED's) with different levels of *p*-doping in the contact layer have been characterized using surface photovoltage spectroscopy (SPS). Due to the high sensitivity of the SPS technique to the electric field, there is a strong correlation between the *p*-doping level in the contact layer and the magnitude of the SPS signal originating from the MQW region. The experimental results are confirmed by a numerical simulation.

Introduction

InGaN/GaN/AlGaN multiple quantum well (MQW) structures are now the basis for GaN based photon-emitting devices such as light emitting diodes (LEDs) [1-4] and QW lasers [5-7]. However, in spite of the progress in the industrial manufacturing of these devices control of the *p*-doping in the GaN layers is still one of the key issues. Due to deep acceptor states [8,9], the *p*-dopant activation in the contact layer remains a problem. It is highly desirable to have room temperature, non-destructive methods to monitor not only this property but also other relevant characteristics of the structure. The optical techniques of surface photovoltage spectroscopy (SPS), contactless electro-reflectance (CER) [as well as the related method of photoreflectance (PR)] and photoluminescence (PL) can be used for this purpose. These approaches are powerful tools for characterization of novel opto-electronic devices such as QW lasers [10,11] and GaN thin films [12,13] and structures [14]. SPS measures the change in the contact potential difference between the semiconductor surface and a reference probe as a function of incident photon energy [15]. The SPS signal is caused by photon absorption and charge carrier separation in the bulk, at buried interfaces as well as at the outer surface of the structure. Furthermore, it has been demonstrated that the sign of the band bending at a semiconductor surface/interface can be determined from the phase of the SPS trace [14].

In this paper we present a room temperature SPS study of three InGaN/GaN/AlGaN MQW LED's with different levels of *p*-doping in the contact layer. It has been shown that the SPS technique is very sensitive to the doping level in the GaN contact layer.

Experimental details.

Three InGaN/GaN/AlGaN MQW LED samples were grown by metal-organic chemical vapor deposition (MOCVD) on sapphire (0001) substrates with the following structure: 5 μm Si-doped (3×10^{18} cm^{-3}) *n*-GaN buffer layer followed by the active MQW region of 10 periods of 3 nm $In_xGa_{1-x}N$ wells (nominal $x \approx 0.2$) and 12 nm GaN barrier, a 50 nm $Al_yGa_{1-y}N$ layer (nominal $y \approx 0.1$), and a 350 nm thick GaN contact layer. The samples differed from each other by the *p*-doping level of the outermost 50 nm of the GaN contact layer as shown in Figure 1. The remaining 300 nm of the GaN contact layer is nominally undoped. Samples #1 and #2 had Mg concentrations of 1×10^{20} cm^{-3} and 3.3×10^{19} cm^{-3} (SIMS measurements), respectively, in this section while for sample #3 the outer GaN was nominally undoped. The doping was not intentionally activated and therefore the concentration of free carriers is expected to be substantially lower than the dopant level concentration. The concentration of free holes in the top contact GaN layer has been estimated based on the acceptor activation energy of 0.2 eV [8,9] and a heavy hole mass of 1.6 [16] (in units of the free electron mass), and has been found to be about 1% of the Mg concentration.

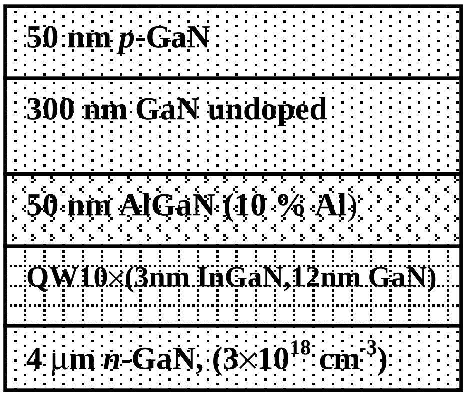

Figure 1. InGaN MQW LED structure.

Sample	Mg concentration (cm^{-3})	Free *p*-carrier concentration (cm^{-3})
#1	~1x10^{20}	~1x10^{18}
#2	~3.3x10^{19}	~3.3x10^{17}
#3	0	0

The SPS measurements were performed using a commercial Kelvin probe unit (Besocke Delta Phi, Jülich, Germany). The front surface of the sample was illuminated at normal incidence using radiation from a 0.25 m monochromator and Xenon-arc lamp. In order to reduce the influence of stray light appropriate cut-off filters were used. The SPS signal was detected by a vibrating gold grid (170 Hz) placed in close proximity to the sample surface. The reverse side of the sample was held in contact with a back metal electrode using a vacuum chuck [17].

Experimental results and discussion.

The solid, dashed, and dotted lines in Fig. 1 are the SPS spectra from samples #1, #2, and #3, respectively. All the data exhibit similar lineshapes from about 2.7 eV up to 3.42 eV (band gap of GaN). The signal at the former region is attributed to photon absorption in the MQW active region and subsequent reduction of the built-in voltage at the *p(*or *n)*-n^+ junction due to the photovoltaic effect. The negative slope of the SPS signal at this photon energy range supports this assumption. The energies of the quantum transitions in the MQW region also have been determined by CER and are found to be in this energy range [18]. There is a monotonic decrease of the amplitude of the SPS signal from the MQW region with the reduction of the dopant concentration in the contact GaN layer. The magnitude of the SPS signal corresponding to photon absorption in the MQW active region is a function of the electric field through this section. The doping levels of the n^+ buffer and *p(*or *n)* GaN contact layer determine this field.

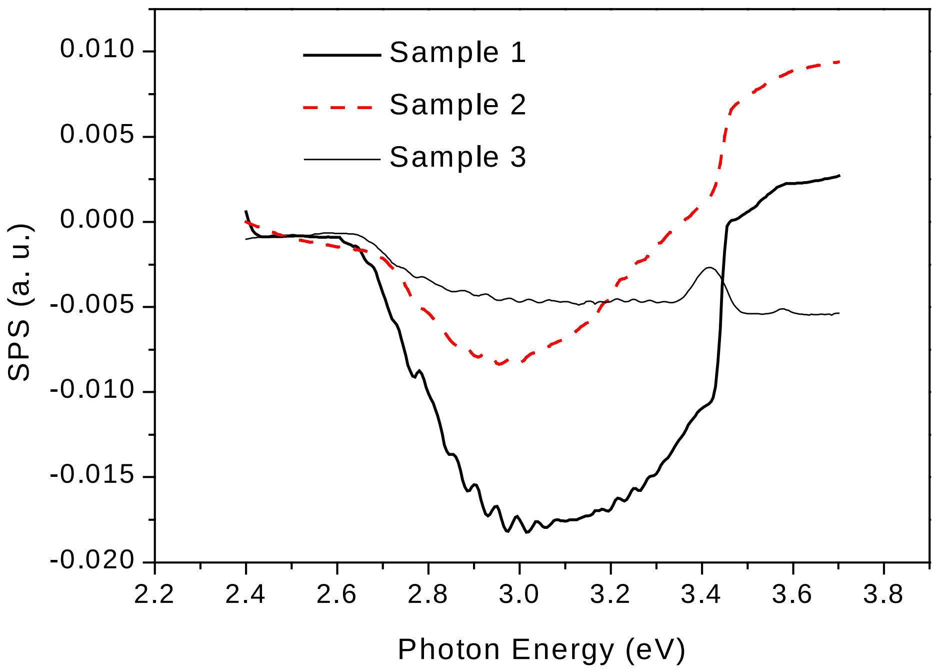

Figure 2. Experimental SPS spectra

The SPS signal at a photon energy of about 3.42 eV can only be attributed to photon induced reduction of the surface potential of the top GaN layer. The spectra from samples #1 and #2 show a positive slope near 3.4 eV that corresponds to flattening of the *p*-like band bending at the surface. On the other hand, sample #3 exhibits a peak-like feature at about the GaN band gap photon energy. This structure exhibits positive/negative slopes at photon energies below/above the GaN band gap. The latter indicates that the surface band bending is *n*-like, which is consistent with the unintentional doping type of the GaN layer [19,20]. However, the former could correspond to photon induced electron transition from the valence band to empty deep trap level [21]. The reason for the absence of this feature in the spectra of samples #1 and #2 is that that the change of the surface potential caused by absorption in the MQW active region and valence band-deep trap electron transition in the top GaN layer have the same sign. Therefore a trap related SPS feature is not detected on samples #1 and #2 spectra. The oscillatory features observed in all samples could be due to interference effects.

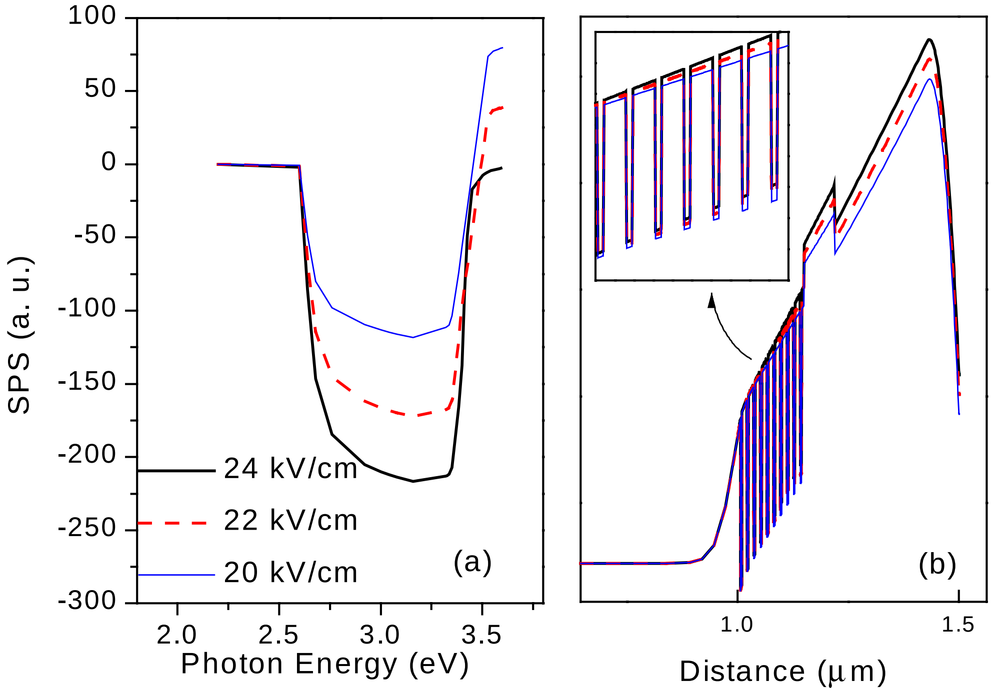

Figure 3. (a) Simulated SPS spectra with (b) corresponding band diagrams.

A numerical simulation has been performed in order to verify the influence of the doping level at the contact layer on the magnitude and shape of the SPS spectra. This simulation [22] is based on solving the continuity equation for electrons and holes and the Poisson equation. Using the intentional growth parameters of the device, simulated spectra very similar to the experimental results have been obtained and are presented in Figure 3(a). The three simulated SPS spectra correspond to different electric field values through the MQW region. As mentioned earlier this field is determined by the *p*-doping value in the contact layer. Figure 3(b) shows the band diagram of the structure as a function of the different electric fields. It can be seen that a decrease of the electric field through the MWQ region decreases the relevant SPS signal. These results show a very strong correlation between the magnitude of the SPS signal at the MQW region absorption photon energy range and doping levels in the GaN contact layer. Therefore the SPS technique can be utilized as a quality control method for monitoring the *p*-doping level in the contact GaN layer.

Conclusion.

In conclusion we have demonstrated that the relatively simple techniques of SPS could be conveniently used for InGaN/GaN/AlGaN MQW LED's characterization. It has been shown that the magnitude of the SPS spectra is very sensitive to the doping level in GaN contact layer. Therefore this method can be very useful for the production-line characterization of GaN based opto-electronic devices because the measurement is contactless, non-destructive, relatively fast, and convenient.

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