Influence of minority carrier lifetime on photoresponse characteristics of visible-blind $Al_{0.25}Ga_{0.75}N$ MSM photodetectors

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***Abstract*—We report on numerical simulations of photoresponse characteristics of visible-blind $Al_{0.25}Ga_{0.75}N$ metal-semiconductor-metal (MSM) photodetectors. Good agreement with experimental data is obtained with an assumed minority carrier lifetime of 30 ps. The carrier transit times between the electrodes of the devices are in the same range, consequently this parameter strongly influences the recombination processes of photogenerated carriers and the resulting photocurrent under UV illumination. In order to investigate this in detail, we have analyzed I-V characteristics for different minority carrier lifetimes. The simulation results predict up to one order of magnitude higher photocurrents for increased lifetimes in the absorber layer.**

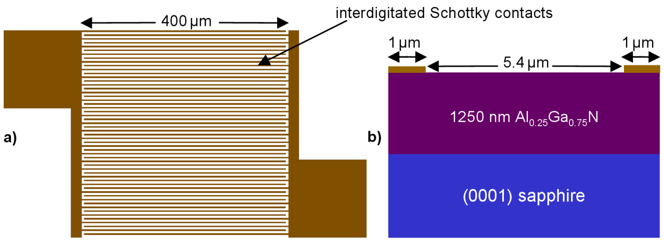

Fig. 1. (a) Interdigitated finger contact structure of the $Al_{0.25}Ga_{0.75}N$ MSM photodetectors: The detector area is 400 x 400 μm^2, the finger width is 2 μm and the spacing is 5.4 μm. (b) 2D cross section of the device structure for the simulation model.

I. INTRODUCTION

AlGaN-based metal-semiconductor-metal (MSM) ultraviolet (UV) photodetectors are very attractive candidates for applications like secure space-to-space communication or missile warning because of their potential high quantum efficiency, high speed and linearity with optical power [1][2]. Due to the simple device structure (see Fig. 1) they are also practical for a scientific approach that combines experimental work and simulation of device properties. Only a few theoretical studies of the influence of specific material properties or contact geometries on the device performance have been reported.

In this paper, the photoresponse characteristics of $Al_{0.25}Ga_{0.75}N$ MSM photodetectors with a cut-off-wavelength of 315 nm are investigated by numerical simulation using the 2D modeling software APSYS. The model as well as the physical input parameters have been verified by comparing the results with experimental data. The I-V characteristics are calculated in a drift-diffusion model for carrier transport. Recombination processes are included using Shockley-Read-Hall (SRH), radiative and Auger recombination rates. Due to the n-type background carrier density in the AlGaN absorber layer of the photodetectors, the SRH recombination rate is limited by the hole capture rate at deep level traps. Consequently the hole lifetime is considered to be the dominant parameter for recombination processes. The influence of this parameter on the device performance has been investigated by minority carrier lifetime dependent simulation of the photocurrent characteristics.

II. DEVICE STRUCTURE AND SIMULATION MODEL

MSM photodetectors with a 1.25 μm thick $Al_{0.25}Ga_{0.75}N$ layer grown on (0001) sapphire substrate by metalorganic vapor phase epitaxy (MOVPE) were fabricated using a low-temperature AlGaN nucleation. Subsequently, Ti/Al/Mo/Au Schottky contacts were deposited. The interdigitated contact structure is illustrated in Fig. 1a. The detector area is 160.000 μm^2. The 27 contact fingers of each electrode are 2 μm wide with a spacing of 5.4 μm between neighboring fingers.

The photodetectors have been characterized by I-V measurements and photocurrent spectroscopy using a 150 W Xenon arc lamp and a monochromator on the incoming light path. The incident optical power has been measured with a calibrated UV enhanced silicon photodiode.

In the simulation model we use a cross section of the device structure from the center of one finger to the center of the neighboring finger as shown in Fig. 1b. The contact metals are assumed to be non-transparent, thus the incident monochromatic light is defined only in the area between the contact electrodes with homogeneous power density and perpendicular angle of incidence.

III. RESULTS AND DISCUSSION

In order to obtain best agreement between measured and simulated dark I-V characteristics of the photodetectors, we assumed a Schottky barrier height of 0.843 eV at the contacts and a n-type carrier density of $4 \cdot 10^{15}\,cm^{-3}$ in the $Al_{0.25}Ga_{0.75}N$ layer. The resulting dark I-V characteristics are shown in the

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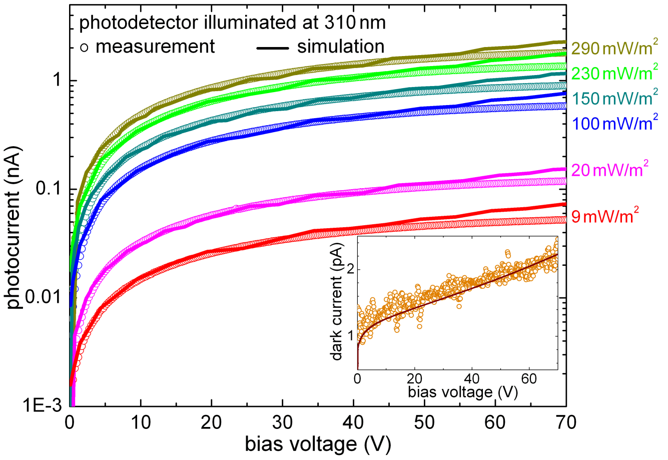

Fig. 2. Simulated and measured I-V characteristics of an $Al_{0.25}Ga_{0.75}N$ MSM photodetector with illumination at 310 nm and varied incident optical power densities. Inset: Dark current characteristics. The input parameters for the simulations were 0.843 eV Schottky-barrier height, $4 \cdot 10^{15}\,cm^{-3}$ background electron density in the $Al_{0.25}Ga_{0.75}N$ layer and 30 ps minority carrier lifetime.

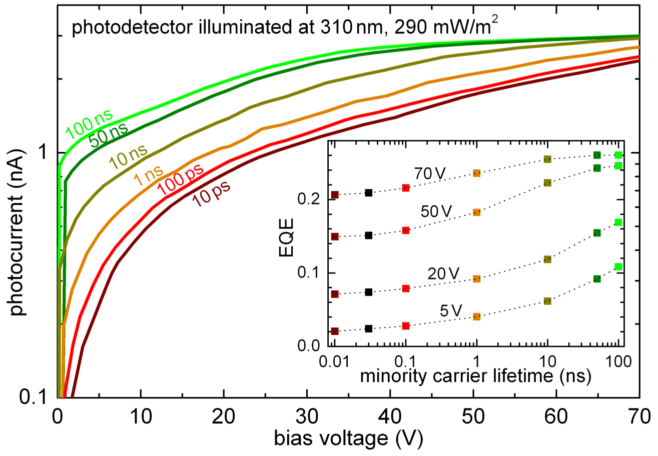

Fig. 3. Simulated I-V characteristics for varied minority carrier lifetimes in the $Al_{0.25}Ga_{0.75}N$ absorber layer. Inset: Calculated external quantum efficiency (EQE) as a function of the lifetime for fixed bias voltages of 5 V, 20 V, 50 V, and 70 V.

inset of Fig. 2. The dark current is below 2.5 pA in a bias voltage range up to 70 V.

The photocurrent characteristics under UV illumination have been investigated at 310 nm, which is close to the maximum of the spectral responsivity of these detectors. Fig. 2 shows the measured and simulated I-V characteristics for incident optical power densities between $9\,mW/m^2$ and $290\,mW/m^2$. The photocurrent is linear with optical power. In the simulation model we have assumed a minority carrier lifetime of 30 ps to obtain best agreement with the experimental results. Onuma et al. [3] reported values in the same range measured on strain-free AlGaN layers with similar Al-contents. At 5 V bias voltage the carrier transit time between the electrodes of our photodetectors can be estimated to be about 1 ns for holes and one order of magnitude lower for electrons, which is in a similar range as the hole lifetime. Consequently, the lifetime strongly influences the device performance. If the hole transit time is much longer than the lifetime, the photocurrent is significantly reduced due to SRH recombination. With decreasing ratio of transit time and lifetime an increasing amount of photogenerated carriers reaches the electrodes without recombination, and eventually the photocurrent saturates.

In order to investigate this influence of recombination processes on the detector characteristics in detail, simulations with different minority carrier lifetimes between 10 ps and 100 ns have been performed. The results show the potential to enhance the external quantum efficiency (EQE = collected carriers at the electrodes per number of incident photons on the detector area) of the photodetectors (see Fig. 3). The photocurrent increases with increasing lifetime and saturates for long lifetimes and high voltages at 3 nA under illumination at 310 nm with $290\,W/m^2$ optical power density. At 5 V bias voltage, increasing the minority carrier lifetime from 10 ps to 100 ns leads to about one order of magnitude higher photocurrents, corresponding to an increase of the EQE from approximately 2 % to 11 % (see inset of Fig. 3). The effect is less pronounced at high bias voltages due to the short carrier transit times in high electric fields. At 70 V the EQE of our photodetectors saturates at 26 % for minority carrier lifetimes above 10 ns in the $Al_{0.25}Ga_{0.75}N$ absorber layer.

IV. CONCLUSION

We have simulated the photoresponse characteristics of $Al_{0.25}Ga_{0.75}N$ MSM photodetectors and investigated the minority carrier lifetime dependence of the device performance. Increasing the minority carrier lifetime from 30 ps to 10 ns yields up to one order of magnitude higher photocurrents and EQEs, showing a potential to enhance the device performance without changing the design. The influence is most pronounced at low bias voltages due to longer carrier transit times between the electrodes in weak electric fields and thus reduced photocurrents resulting from the higher propability for recombination processes.

ACKNOWLEDGMENT

This work has been funded by the EU (IBB ProFIT 10141408) and the German Federal Ministry of Education and Research (WideBaSe 03WKBT02C,D).

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