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Impact of doping on carrier recombination and stimulated emission in highly excited GaN:Mg

R. Aleksiejūnas *, S. Krotkus, S. Nargelas, S. Miasojedovas, S. Juršėnas

Institute of Applied Research, Vilnius University, Sauletekio Ave. 9-3, LT-10222 Vilnius, Lithuania

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ABSTRACT

Light-induced transient grating and photoluminescence measurements were employed for carrier recombination studies in variously Mg doped GaN layers. Carrier lifetime and ambipolar diffusion coefficient were found to decrease with doping from 210 to 20 ps and from 2.0 to 0.9 cm^2/s,respectively, which proved the degradation of electrical quality of the layers. A threshold of stimulated emission was found to depend non-monotonously on doping and had the lowest value of 0.19 mJ/cm^2 in the most doped layer. This dependence was explained in terms of degeneracy of the hole system.

1. Introduction

Gallium nitride of high p-type conductivity is a crucial component of GaN based bipolar optoelectronic devices like LEDs or semiconductor lasers. Unfortunately, high p-type conductivity is difficult to achieve. Magnesium, currently the most popular p-type dopant for GaN, has several drawbacks, the main one being the deep nature of its acceptor level in GaN. It is generally accepted that the acceptor level of magnesium is located at about 200 meV above the valence band and, therefore, yields only a small fraction of thermally ionized atoms at room temperature. Heavy doping is thus required to achieve a background hole concentration n_{h0} as high as 10^{19} cm^{-3}, since high acceptor density leads to creation of defect band tails and a drop of activation energy to $\sim$110 meV [1] or even less than 70 meV [2]. In this way, the efficiency of doping (i.e. the percentage of ionized acceptor atoms at room temperature) can be enhanced by up to 10% [3,4]. On the other hand heavy doping is inevitably followed by high defect concentration, which in turn should cause a short carrier lifetime and low hole mobility (e.g. 0.5 cm^2/V s in [3]). A detailed knowledge as to how Mg doping affects the optical and electrical parameters of GaN is needed for proper understanding of the functionality of GaN-based devices. In particular carrier recombination and transport at high excitations, when a semiconductor approaches degeneracy, are of interest for high power photonic devices.

In this paper we present a study of carrier recombination and diffusion in highly excited GaN:Mg epitaxial layers where the density of photoexcited carriers is close to the degeneracy of the electron–hole system ($\sim 10^{19}$ cm^{-3}). We employ two optical techniques: light-induced transient gratings (LITG) to measure carrier lifetime and diffusivity and time-integrated photoluminescence (PL) to determine the threshold of stimulated emission (SE) [5]. Based on these results, we analyze how doping at various Mg concentrations affects density and transport properties of excess carriers.

2. Samples and techniques

A set of samples comprised four commercially available (TDI Inc.) p-GaN epilayers of 3–5 μm thickness grown on *c*-plane sapphire and differently doped with Mg. The background hole concentration n_{h0} (i.e. $N_a - N_d$) was measured by Hall effect measurements and was equal to 2×10^{16}, 9×10^{16}, 3×10^{18} and 7×10^{18} cm^{-3} (these layers further will be referred to as samples #1, #2, #3 and #4, respectively). Ionized donor density was approximately 10^{17} cm^{-3} in all samples.

For sample excitation we used pulses from actively mode-locked YAG:Nd^{3+} (or YLF:Nd^{3+}) lasers (Ekspla), operating at 10 Hz and emitting 25 ps (8 ps) duration pulses of λ=1064 nm (1053 nm) wavelength in fundamental harmonic. In PL experiments, samples were excited at λ=266 nm; pump energy fluence was varied from 0.06 to 3 mJ/cm^2. In backscattering geometry, samples were excited by a laser beam focused to a spot of approximately 1 mm diameter and luminescence was registered from the excited surface. The stimulated emission was excited by

* Corresponding author. Tel.: +370 5 2366036; fax: +370 5 2366037.
E-mail address: ramunas.aleksiejunas@ff.vu.lt (R. Aleksiejūnas).

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a stripe spot of 5 mm length and 0.5 mm width. Luminescence was collected in lateral geometry and dispersed by a 0.4 m grating monochromator. In LITG measurements (the LITG technique in general is described in Ref. [6], while its application for wide bandgap materials is discussed in Ref. [7]) we used two coherent pulses at $\lambda = 351$ nm to create an interference pattern $I(x) = I_0(1+\cos(2\pi x/\Lambda))$ and excite a sample; here I_0 is an excitation fluence and Λ denotes a period of interference pattern. The temporal evolution of resulting transient diffraction grating was monitored by measuring the diffraction efficiency η of a delayed probe beam at $\lambda = 1053$ nm. GaN is transparent at this wavelength allowing monitoring of the entire excited region. Grating decay time τ_G is defined for exponential decay as $\eta(t) \propto \exp(-2t/\tau_G)$, where τ_G is given by

$$1/\tau_G = 1/\tau_R + 1/\tau_D = 1/\tau_R + 4\pi^2 D_a/\Lambda^2 \quad (1)$$

τ_R, τ_D and D_a here stand for carrier lifetime, diffusive grating decay time and ambipolar diffusion coefficient, respectively. We note that τ_D in LITG experiment is controlled by choosing Λ. Eq. (1) shows that τ_R and D_a can be obtained from the $1/\tau_G = f(1/\Lambda^2)$ plot. All experiments were carried out at room temperature.

3. Results and discussion

The main results obtained by LITG are summarized in Fig. 1. Typical diffraction kinetics (i.e. diffraction efficiency η vs. probe delay) are presented in Fig. 1(a), while determined τ_R and D_a values are given in Fig. 1(b). Diffraction kinetics are monoexponential and become faster with doping; no change in decay rate has been observed while varying the pump fluence within our experimental range. Note that the density of photoexcited carriers was kept below the degeneracy threshold in all LITG experiments. The observed behavior of diffraction kinetics indicates the recombination of free carriers via defect levels. The electrical quality of the layers clearly decreases with Mg doping: τ_R drops from 210 to 20 ps and D_a—from 2.0 to 0.9 cm^2/s (D_a in sample #4 could not be obtained because of short τ_R). The dependence of carrier lifetime on the hole concentration can be fitted roughly as $\tau_R \propto n_{h0}^{-0.3}$. The sublinear dependence can be tentatively explained assuming that the dominant recombination channel is governed by deep Mg-related defect states rather than shallow ionized Mg levels and only a small part of Mg atoms contribute to carrier trapping. Similarly D_a drops due to enhanced scattering by ionized impurities and, probably, extended defects arising because of the degradation of crystalline structure at the highest Mg concentrations. Hole mobility μ_h can be calculated from D_a using the Einstein relation $\mu_h = eD_h/k_BT$ and assuming $D_h \approx D_a/2$ in bipolar carrier plasma. The latter approximation is justified provided that the densities of electrons and holes are approximately equal and $\mu_h \ll \mu_e$. These conditions are fairly well fulfilled in GaN under the band-to-band excitation [8,9]. We also note that the density of photoexcited carriers $\Delta n \sim 10^{18}$–10^{19} cm^{-3} exceeds considerably the background hole concentration $n_{h0} \sim 10^{16}$–10^{17} cm^{-3}, at least in samples #1 and #2. Extracted μ_h values vary from 40 to 18 cm^2/V s in layers #1 and #3 and are similar to those reported in Ref. [1].

Fig. 2(a) and (b) shows the PL spectra measured in backscattering and lateral geometries, respectively. Backscattered PL spectra (Fig. 2(a)) show a single broad band peaking at about 3.4 eV, typical for the room-temperature spontaneous emission in dense electron hole plasma (EHP) in highly photoexcited GaN [10,11]. EHP is the dominant electronic excited state since

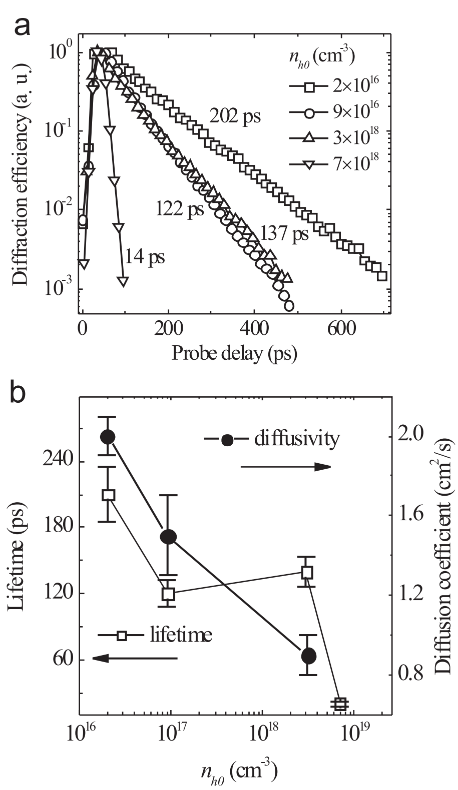

Fig. 1. (a) Diffraction efficiency kinetics and (b) carrier lifetime τ_R and ambipolar diffusion coefficient D_a measured in variously doped GaN:Mg layers; n_{h0} indicates the background hole density in the layers.

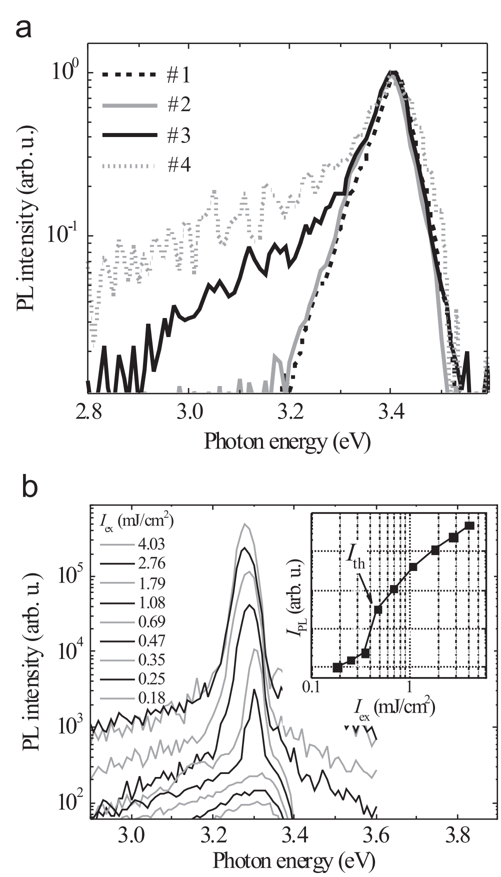

Fig. 2. (a) Normalized time-integrated PL spectra of variously doped GaN:Mg layers measured in backscattering geometry in the samples at 0.07 mJ/cm^2 pump fluence. (b) Time-integrated PL spectra measured at various pump fluencies in sample #3 with $n_{h0} = 3 \times 10^{18}$ cm^{-3}. *Inset:* PL intensity I_{PL} at 3.3 eV vs. pump fluence I_{ex}; the arrow indicates the determined threshold fluence.