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Electron beam-induced increase of electron diffusion length in *p*-type GaN and AlGaN/GaN superlattices

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The diffusion length, *L*, of electrons in Mg-doped *p*-GaN grown by metal-organic chemical vapor deposition was found to increase linearly from 0.55 to 2.0 μm during 1500 s of electron beam irradiation. Similar trends were observed for *p*-type Mg-doped GaN and AlGaN/GaN superlattices grown by molecular-beam epitaxy. While the electron diffusion length in *p*-(Al)GaN depends on irradiation time, the diffusion length of holes in *n*-GaN remains unchanged, with $L \sim 0.35$ μm. We attribute the observed diffusion length change in *p*-(Al)GaN to an increase in the minority carrier lifetime. This increase is likely due to electron beam-induced charging of the deep metastable centers associated with Mg doping. The concentration of these centers was estimated to be $\sim 10^{18}\,\mathrm{cm}^{-3}$. The minority carrier diffusion length increase in *p*-(Al)GaN, which occurs during electron injection, may lead to self-improvement of the bipolar transistor characteristics. *© 2000 American Institute of Physics.* [S0003-6951(00)03532-4]

The minority carrier diffusion length, *L*, is a critical parameter for GaN-based heterojunction bipolar transistors (HBTs) and solar blind photodetectors. The diffusion length of carriers, injected from the wide band gap emitter of an HBT, determines the base transport factor. This, in turn, defines the common-base and common-emitter current gains.[1] It is important not only to know the absolute values of *L* for the HBT base, but also to understand the factors which cause the time dependence of the diffusion length.

Several deep levels, located 1.1, 1.4, and 2.04 eV above the valence band edge, were identified in *p*-type GaN. These levels are likely associated with Mg doping and are possibly responsible for the persistent photoconductivity behavior in GaN.[2] In this publication, we report an electron beam-induced increase of the electron diffusion length in *p*-type GaN and $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}$/GaN ($x=0.1,0.2$) superlattices and attribute this increase to charging of these deep centers.

Metal-organic chemical vapor deposition (MOCVD) and molecular-beam epitaxy (MBE) were employed for growth of both *p*-type GaN layers and AlGaN/GaN superlattices. The *p*-type GaN layers were ~2.0 μm thick, whereas AlGaN/GaN superlattices had 20 periods with ~10-nm-wide barriers and wells (total thickness of ~0.4 μm). Hole concentrations of $\sim 2\times10^{18}$ and $4\times10^{18}\,\mathrm{cm}^{-3}$ were measured at room temperature for the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}$/GaN superlattices with $x=0.1$ and 0.2, respectively. The hole mobility, μ, in both superlattices was ~1.2 $\mathrm{cm}^2/\mathrm{V\,s}$. For MOCVD and MBE *p*-GaN layers, μ was ~7 and 3.5 $\mathrm{cm}^2/\mathrm{V\,s}$, respectively. The measured hole concentration was in the range of $3-4\times10^{17}\,\mathrm{cm}^{-3}$ in both cases. A 3-μm-thick MOCVD *n*-GaN layer ($n\sim2\times10^{17}\,\mathrm{cm}^{-3}$) was used as a reference sample.

The electron beam from a scanning electron microscope (SEM) JEOL 6400F was used to locally irradiate the samples. Depending on the thickness of the layers, an electron beam accelerating voltage of 10 and 20 kV was used. This corresponds to an electron range, *R*, of 0.36 and 1.20 μm, respectively.[3] *L* measurements, using electron beam induced current (EBIC), were carried out *in situ* in the SEM. A planar metal–semiconductor (Schottky) configuration was used for this purpose. *L* was derived from the EBIC line scan.[4] The scanning was carried out by moving the electron beam starting at the edge of the Schottky contact pad. After completion of a line scan (16 s), the process was repeated. Total time of the multiple line scan was up to 1500 s (for *p*-type samples), depending on the film thickness. The irradiation volume was calculated based on the beam penetration depth and the distance covered during the line scan (~4.4 μm, at ×25 000 magnification). The total charge was determined as the product of multiple line-scan time and absorbed electron beam current, measured by a Keithley 480 picoammeter (0.65 nA at 20 kV and 0.13 nA at 10 kV). A Stanford Research current preamplifier and home-written software were used to record the EBIC line scans. The samples under investigation were considered as a bulk material, since the *L* values, measured perpendicular to a sapphire substrate, were found to be at least 4 times lower than the sample thickness.[4] There were no EBIC resolution limitations as well, since the ratio $R/L \leqslant 4$ was satisfied for all of our measurements.[5]

First, we performed hole diffusion length measurements in the reference *n*-GaN sample. This resulted in *L* of ~0.35 μm, which remained constant for at least one hour of electron beam scanning across the region under investigation. The total electric charge, injected into this region, was 2.35×10^{-6} C.

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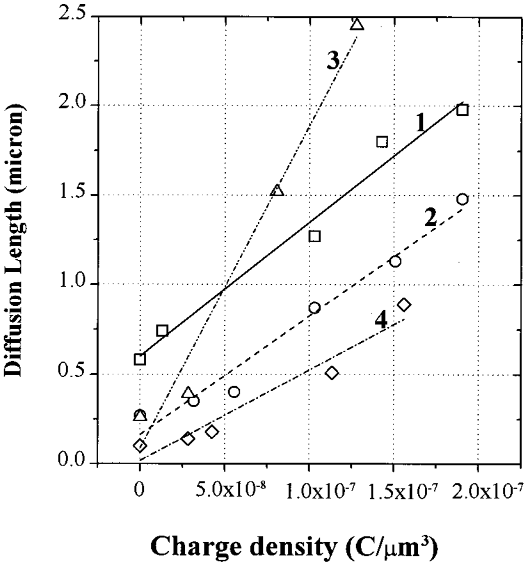

FIG. 1. Experimental minority electron diffusion length dependence on the density of electric charge injected into (Al)GaN material. Open points represent the experimental data and the lines 1, 2, 3, and 4 represent the fit for *p*-type MOCVD-GaN, MBE-GaN, $Al_{0.1}Ga_{0.9}N$/GaN, and $Al_{0.2}Ga_{0.8}N$/GaN superlattices, respectively. The charge density of 2.0×10^{-7} C/μm^3 corresponds to an electron beam irradiation time of ~1500 s for MOCVD- and MBE-grown GaN samples. The charge density of 1.5×10^{-7} C/μm^3 corresponds to an electron beam irradiation time of ~660 s for $Al_{0.2}Ga_{0.8}N$/GaN superlattice. Time scale for $Al_{0.1}Ga_{0.9}N$/GaN superlattice is the same as in the latter case.

Electron beam irradiation of *p*-type material resulted in a significant increase of the minority electron diffusion length, as shown in Fig. 1. The general trend for all the *p*-type samples is a linear four- to eight fold increase of *L* from the initial values. This takes place within ~1500 s for GaN samples and within ~540 and 660 s for $Al_{0.1}Ga_{0.9}N$/GaN and $Al_{0.2}Ga_{0.8}N$/GaN superlattices, respectively. *L* saturates when the irradiation time is larger than the above-mentioned values.

The minority electron lifetime, τ, was estimated as a function of injected electric charge, based on the measured *L* values, according to

$$\tau=\frac{L^2}{D}, \tag{1}$$

where *D* is carrier diffusivity, determined from mobility using the Einstein relation. Due to minority carrier mobility uncertainty in the superlattice structures, the estimations were done only for *p*-GaN samples.

We assumed that the room temperature mobility of minority electrons in *p*-GaN is ~1.3 times lower than that for majority ones in *n*-GaN.[6] Based on the Hall measurements of *n*-GaN samples,[4] the minority electron mobility, μ, was assumed to be ~250 cm^2/V s for a *p*-type MOCVD epilayer. This corresponds to the value of $D\sim6.5$ cm^2/s. The values of μ and *D* for electrons in MBE-grown *p*-GaN layer were 100 cm^2/V s and 2.6 cm^2/s, respectively.

Figure 2 presents a square root of lifetime dependence on injected charge (density) for the *p*-GaN samples. Based on the linear dependence of electron diffusion length on charge, we obtained the same trend for the square root of lifetime [cf. Eq. (1)].

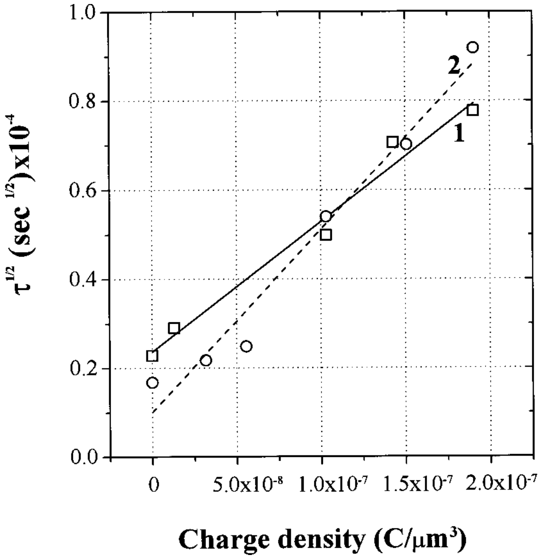

FIG. 2. Calculated minority electron lifetime dependence on the density of electric charge, injected into *p*-GaN. The calculations are based on the experimental data presented in Fig. 1 and were carried out by using Eq. (1). Open points represent the calculated values and the lines show the fit. Legend for the lines 1 and 2 is the same as in Fig. 1.

We ascribe the observed linear increase of *L* (and square root of τ) in *p*-(Al)GaN to charging of the deep metastable centers associated with Mg doping.[2] Kinetics of the observed phenomenon is similar to the one described in Ref. 7, where the injected electrons were used to activate a Mg acceptor, passivated with hydrogen. In our case, the diffusion length increases and saturates once a majority of the deep levels, which are able to capture an electron injected by SEM beam, are charged. The difference in diffusion length saturation time (charge density) between GaN (~1500 s) and $Al_xGa_{1-x}N$/GaN (~600 s) samples is likely explained by the difference in the deep center concentration.

L may increase due to an increase in lifetime or carrier mobility (diffusivity) [cf. Eq. (1)]. Reference 8 reported a three orders of magnitude decrease in *p*-GaN resistivity, induced by electron beam, due to an adequate increase in majority hole concentration with unchanged mobility. This is an argument in favor of minority carrier mobility independence of electron beam irradiation in *p*-(Al)GaN. On the other hand, capturing of the charge on the deep levels, associated with Mg doping, most likely leads to an increase in minority carrier lifetime, since the deep levels, charged by electrons of the SEM beam, are no longer available for carrier recombination.[9] Therefore, we conclude that the above-reported increase of *L* in *p*-(Al)GaN is due to an electron beam-induced increase of minority carrier lifetime. A steep increase of *L* for $Al_{0.1}Ga_{0.9}N$/GaN could be related to high internal electric fields caused by spontaneous and piezoelectric polarization.[10] The polarization effects increase the minority carrier lifetime and diffusion length in the superlattices by one order of magnitude as compared to bulk material.[11]

To estimate the concentration of deep Mg-related centers, we calculated first the capture cross section, σ_t, for these centers[9]

$$\sigma_t=1.71\times10^{-18}\varepsilon^{1/2}\left(\frac{m}{m^*}\right)E_i/T, \tag{2}$$

where E_i = center energy (eV) with respect to the valence band edge; ε = GaN static dielectric constant; m and m* = free and effective electron mass, respectively; T = temperature.

Using $\varepsilon = 8.9$ and $m/m^* = 0.2$,[7] $\sigma_t \sim 1.4 \times 10^{-21}\,\mathrm{cm}^2$ was obtained for the centers with $E_i = 2.04\,\mathrm{eV}$. This is consistent with the previously published value of $\sigma_t < 10^{-20}\,\mathrm{cm}^2$ in GaN.[12] Taking the average thermal velocity $v = 10^7$ cm/s[12] into account, the capture cross-section volume $(v\sigma_t)^1$ of $\sim 1.4 \times 10^{-14}\,\mathrm{cm}^3$ was found. If the deep center lies within this volume, the electron, injected or created by an electron beam, will be captured. Using the standard doping level of GaN with magnesium of $\sim 10^{20}$ Mg atoms/cm^3,[13] and assuming a homogeneous distribution of dopants across the sample, a volume of $10^{-20}\,\mathrm{cm}^3$, occupied by a single Mg atom in GaN, was obtained. Comparing the latter volume with the capture cross-section volume, we conclude that $\sim 10^6$ Mg atoms/centers are needed to capture one electron. Taking the total saturation charge density of $1.9 \times 10^{-7}\,\mathrm{C}/\mu\mathrm{m}^3$ for MOCVD p-GaN as an example (cf. Figs. 1 and 2), we obtained the beam electron density of $\sim 10^{24}\,\mathrm{cm}^{-3}$. Assuming that one electron is needed to charge one deep center, and accounting that only one out of 10^6 centers may capture an electron, we found the concentration of charged deep traps to be $\sim 10^{18}\,\mathrm{cm}^{-3}$.

Independence of the minority hole diffusion length with electron beam irradiation in n-GaN is an additional argument in favor of the Mg-acceptor role in electron diffusion length increase observed in p-(Al)GaN. Time-dependent EBIC measurements, carried out on MOCVD p-GaN, showed the value of $L \sim 1.7\,\mu$m, 17 h after sample charging with an electron beam. L decreased to its initial value of $\sim 0.55\,\mu$m three days after an electron beam irradiation. This is consistent with the photocurrent decay seen in Mg-doped GaN.[2]

Electron beam irradiation of p-(Al)GaN leads to a four- to eight-fold increase of minority electron diffusion length, taking place within 1500 s of electron beam excitation. This is attributed to charging of the deep levels associated with Mg doping. The density of current, injected in (Al)GaN by an electron beam, is ~60 mA/cm^2. This is 2.5 orders of magnitude lower than the current densities driven through (Al, Ga)N-based bipolar devices (~25 A/cm^2). Our experiments on MOCVD p-GaN demonstrated a twofold diffusion length increase within 900 s, under a current density of 1 A/cm^2 driven through the Schottky barrier under forward bias conditions. This indicates that self-improvement of HBT performance is possible within a reasonably short time after turning on the device.

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