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Leonid Chernyak
University of Central Florida

William Burdett
University of Central Florida

Andrei Osinsky

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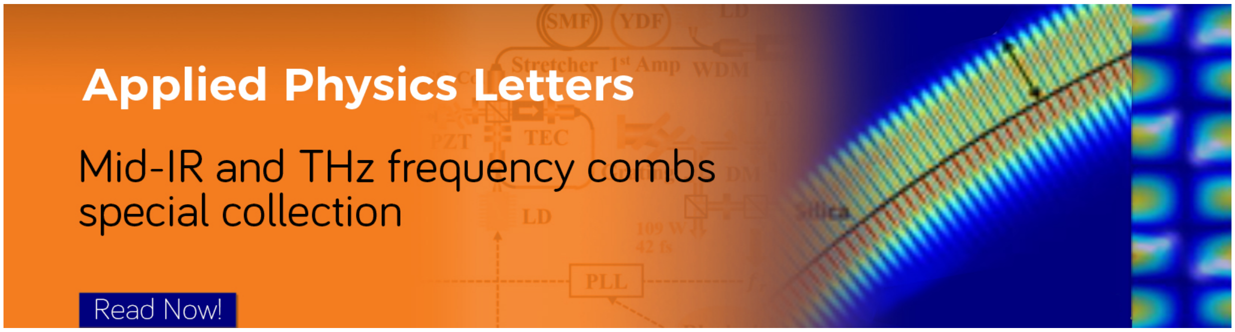
Leonid Chernyak, William Burdett, and Andrei Osinsky



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Study of temperature dependence for the electron injection-induced effects in GaN

Leonid Chernyak[a)] and William Burdett
Physics Department, University of Central Florida, Orlando, Florida 32816-2385

Andrei Osinsky
Science and Technology, Corning Incorporated, Corning, New York 14831

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Electron-beam injection-induced increase of minority carrier diffusion length in *p*-type GaN was studied as a function of sample temperature ranging from 25 °C to 130 °C. It was found that the rate for diffusion length increase exponentially decays with increasing temperature. This decay was attributed to a temperature-activated release of electron-beam injected electrons trapped on Mg levels. The activation energy of these levels was found to be ~178 meV. This is in good agreement with the previously reported position for Mg levels in the GaN band gap. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1503407]

The transport properties of minority carriers are an important indicator for the quality of semiconductors. One of the main difficulties that must be overcome in III-nitride technology, is a reduced minority carrier diffusion length in GaN.[1]

It has been recently found[2–5] that electron injection into *p*-GaN—either from the electron beam of a scanning electron microscope (SEM) or from the application of an external voltage in a solid-state device ($p-n$ junction or Schottky barrier)—increases the critical minority carrier diffusion length and lifetime. Consistent changes were observed in the optical[3] and optoelectronic[5] properties of the material and were attributed to charging of deep Mg-related centers.[2]

In this letter, we report an electron-beam injection-induced increase of minority carrier diffusion length, *L*, in *p*-GaN, measured at variable temperatures. These measurements allowed us to estimate the activation energy for the electron injection-induced effect, and, therefore, to obtain evidence for the role of Mg in this phenomenon.

Metalorganic chemical vapor deposition (MOCVD) was employed for growth of bulk *p*-type GaN layers of ~2–3 μm thick. Hole concentrations of $\sim(3-4)\times 10^{17}$ cm^{-3} were measured at room temperature. The hole mobility, μ, was ~7 cm^2/V s.

The electron beam of an SEM Philips XL 30 was used to locally irradiate the samples. An electron-beam accelerating voltage of 20 kV was used. This corresponds to an electron range of 1.20 μm in the sample.[6] *L* measurements, using electron-beam induced current (EBIC), were carried out *in situ* in the SEM at variable temperatures ranging from 25 °C to 130 °C. A planar metal—semiconductor (Schottky) configuration was used for this purpose. *L* was derived from the EBIC line scan.[6] The scanning was carried out by moving the electron beam starting at the edge of the Schottky contact pad (500 μm diameter). After completion of a single line scan (16 s), the process was repeated. The total time of the multiple line scans was up to 2500 s. The distance covered during a single line scan was ~4.4 μm, at ×25 000 magnification. We note that for every measurement temperature, a new location in the vicinity of the Schottky contact pad was selected.

Figure 1 presents a typical dependence of *L* on time of electron injection obtained at different temperatures on one of the *p*-type MOCVD samples. The general trend is a linear several-fold increase of minority electron diffusion length for the time of electron-beam injection up to 2100 s (at 130 °C sample temperature), corresponding to the total injected charge of 1.365 μC. At larger times of injection, *L* saturates (this is not shown in Fig. 1). Notice that it takes less time for diffusion length to saturate when the sample temperature is lower (compare 1500 s for 25 °C and 75 °C versus 2100 s for 130 °C). Once an increase of *L* is induced by electron injection, it persists for several days. The kinetics for *L* relaxation is discussed in Refs. 2 and 5.

Previously, we have demonstrated an increase of *L* by a factor of 2.5 for the temperature ranging from 20 °C to 250 °C.[6] The results in Fig. 1 suggest, however, that in the present case, the electron injection impact on *L* is dominant, and the increasing incremental temperature leads to a slower diffusion length growth with injection time. We explain this in more detail next.

The rate, *R*, for minority-carrier diffusion length increase

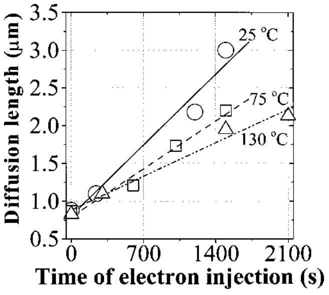

FIG. 1. Variable temperature dependence of minority electron diffusion length in *p*-GaN on electron injection time. Open circles, squares, and triangles are experimentally obtained values for 25 °C, 75 °C, and 130 °C, respectively. Solid and dashed lines represent the fit.

[a)] Electronic mail: chernyak@physics.ucf.edu

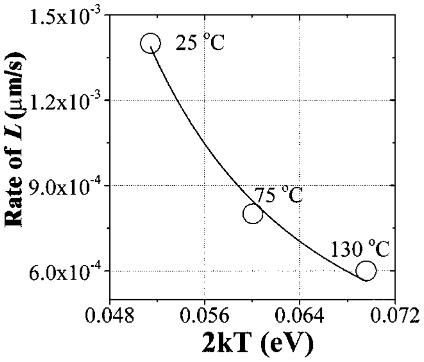

FIG. 2. Temperature dependence for the rate, *R*, of minority carrier diffusion length increase. The best fit for this dependence is obtained at 178 meV activation energy.

was calculated for every measurement temperature based on the linear dependencies in Fig. 1. Figure 2 shows the dependence of *R* on thermal energy (2 kT). This dependence was fitted as:[6]

$$R=R_0\exp\left(\frac{\Delta E_A}{2\mathrm{kT}}\right). \tag{1}$$

Here, R_0 is scaling constant, and ΔE_A is process activation energy. For Eq. (1), the best fit was obtained for the activation energy of 178 meV. Note that this activation energy is in excellent agreement with that of Mg acceptors.[7]

Now, as the activation energy for the electron injection-induced effect is determined, we are ready to present the model for the observed phenomenon (cf. Fig. 3). The key point in this model is that less than 1% of the total number of Mg impurities ($\sim10^{20}\,\mathrm{cm}^{-3}$) is ionized at room temperature[8] (see also above for Hall majority-carrier concentrations of the samples under investigation). The nonionized impurities, part of which are positioned at ~170 meV above the top of the valence band, act as traps for electrons injected from the SEM beam. If the Mg level traps such electrons, it stops playing a role in the recombination process (cf. Fig. 3). As the number of levels occupied by trapped injected electrons increases (with increasing time of electron injection), the electrons of the conduction band (minority carriers in *p* GaN) are forced to stay there longer, until a free Mg level (with no trapped electron) is available for recombination. As a result, the minority electron lifetime in the conduction band increases, leading to a decrease in the radiative recombination rate. This is expressed in a lower near-band-edge microphotoluminescence intensity (proportional to the rate of radiative recombination), measured in *p*-GaN after electron injection and compared to that before injection.[3] Since $L=(D\tau)^{1/2}$, the increase in minority-carrier lifetime, τ, leads to a longer minority-carrier diffusion length. As to a possible increase of diffusivity, *D*, we refer to the experiments by Nakamura *et al.*,[9] indicating that carrier diffusivity (mobility) remains unchanged before and after electron injection.

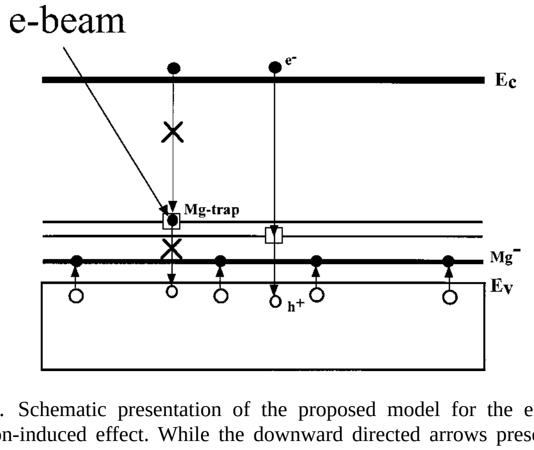

FIG. 3. Schematic presentation of the proposed model for the electron injection-induced effect. While the downward directed arrows present the recombination process, the upward directed arrows show the process for acceptor activation. This ionized acceptor is denoted as Mg$^-$.

As the temperature of GaN sample irradiated by SEM beam increases, the probability for a trapped electron to escape from the charged Mg level also increases (cf. Fig. 3). Therefore, this level again becomes available for the recombination process. This, in turn, will reduce the minority electron lifetime in the conduction band and, thus, the diffusion length as well as its rate, which slows down with sample heating (see Figs. 1 and 2). We note that there is a competing process of additional Mg acceptor activation with increasing temperature, due to the transitions of valence band electrons to Mg levels (see upward directed arrows in Fig. 3). This process, however, is secondary in the temperature range of 25 °C–130 °C.

The measurements, carried out in this work, allowed us to unambiguously identify the level of Mg, which is involved in the observed phenomenon. Our previous hypothesis was that much deeper levels, positioned at 1.1, 1.4, and 2.04 eV above the valence band edge, are involved in the electron injection-induced effects in III-nitrides.[2] The latter levels are believed to be responsible for the persistent photoconductivity in GaN semiconductor.[10] In Ref. 2, based on the assumption that the 2.04 eV Mg level is involved in the phenomenon of electron injection, we calculated the capture cross section, σ_t, for the trap.

We can now recalculate σ_t, taking into account the newly obtained value for the activation energy and assuming that it coincides with the level energy:

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

Here, E_i is level energy (eV) with respect to the valence band edge, ε is GaN static dielectric constant ($\varepsilon=8.9$), m and m^* are free and effective electron mass, respectively ($m/m^*=0.2$), and T is temperature.

From Eq. (2), we obtained $\sigma_t=0.6\times10^{-21}\ \mathrm{cm}^{-2}$ versus the previously calculated value of $1.4\times10^{-21}\ \mathrm{cm}^{-2}$. Using the approach described in Ref. 2, we recalculated the concentration of Mg, associated with levels responsible for the observed phenomenon, to be $\sim2\times10^{18}\,\mathrm{cm}^{-3}$ versus $\sim10^{18}\ \mathrm{cm}^{-3}$ that was previously reported.

It should be stressed that similar to electron-beam injection, solid-state electron injection, due to a forward bias application to a $p-n$ junction or Schottky barrier, leads to a pronounced increase of minority electron diffusion length in *p*-GaN.[3,4] The results in Fig. 1 show that regardless of the slower *L* increase at elevated temperatures, it is still fairly pronounced at 130 °C (more than two fold within 2100 s). This indicates that the effect of electron injection may be used at elevated temperatures in the wide-band-gap bipolar devices. We have already demonstrated a significant improvement of photoresponse for a GaN $p-n$ junction photovoltaic detector due to an electron injection in its p-type region under forward bias.[5] The experiments are under way to demonstrate the applicability of the electron injection for amplification enhancement in the AlGaN–GaN $n-p-n$ heterojunction bipolar transistors.

An electron-beam-induced increase of minority-carrier diffusion length was studied at variable temperatures. This allowed the estimation for the process activation energy, which was found to coincide with the known position of Mg levels in GaN. It was, therefore, concluded that the mechanism for the observed effect was related to trapping of injected electrons on these levels.

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