Influence of electron injection on performance of GaN photodetectors

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It is demonstrated that short-time (up to 1200 s) electron injection into the p-region of GaN $p-n$ junction, as a result of forward bias application, leads to a long-term multifold enhancement of the device peak responsivity as well as to a spectral broadening of the photoresponse. The effect is found to persist for several days and is related to an increased minority carrier diffusion length in the p region, due to an injected electron trapping on deep levels associated with Mg acceptors. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1448382]

The high-energy cutoff of GaN-based photovoltaic $p-n$ junction detectors is generally limited by the large absorption coefficient at high energies and the small minority carrier diffusion length. As a result, high-energy photons are absorbed in the cladding layer rather than in the space-charge region. Several design changes have been recently reported to overcome these limitations including the use of $p-i-n$ instead of $p-n$ junctions,[1–4] employment of $Al_xGa_{1-x}N$ instead of GaN windows,[1–3] use of semitransparent recessed windows,[2] and back-illuminated detector configurations.[3]

Despite the considerable broadening of spectral range and the increase in peak responsivity attained due to the designs,[1–4] a direct control of fundamental GaN transport properties, such as minority carrier diffusion length and lifetime, has never been achieved. The control of these parameters is highly desirable to improve the performance of optoelectronic devices.

Minority carrier diffusion length and lifetime are the crucial material properties, which determine a photodetector's quantum efficiency. In $p-i-n$ and $p-n$ photodetectors, it is either the p-type or the n-type side which predominantly contributes to the photosignal. Assuming that most light absorption takes place in the p side, the expression for the quantum efficiency η can be presented as

$$\eta=(1-R)\left(1-\frac{e^{-\alpha W}}{1+\alpha L}\right). \tag{1}$$

Here R and α are the reflection and absorption coefficients, respectively; W is the intrinsic (depletion) layer width; and L is the minority electron diffusion length in the p side. It is evident from Eq. (1), that increasing the minority electron diffusion length leads to a more efficient device.

It was recently discovered that in p-GaN ($Al_xGa_{1-x}N$), electron injection (for up to 1500 s) increases the minority carrier diffusion length and lifetime.[5–7] The controllable changes in the material's properties were attributed to charging of metastable Mg-related deep centers. This indicated that a performance improvement for GaN-based solar blind detectors could be achieved by electron injection over a reasonably short time (at most 1500 s). This is because the increased diffusion length improves the minority carrier collection and eliminates the so-called "optical dead space" where carriers recombine without being collected.[3] As a result, the quantum efficiency of the detector increases as inferred from Eq. (1).

This letter demonstrates a practical significance of electron injection for an enhancement of spectral responsivity in GaN $p-n$ junctions. The study was carried out on a Molecular Beam Epitaxy (MBE)-grown GaN wafer with several $p-n$ junctions fabricated according to the following sequence of epitaxial layers (from top to bottom): 0.6 μm p^+-GaN, Mg doped, $p\sim5\times10^{17}$ cm^{-3}, 0.5 μm n-GaN, Si doped, $n\sim1\times10^{17}$ cm^{-3}; 1.3 μm n^+-GaN, Si doped, $n\sim1\times10^{19}$ cm^{-3}; sapphire substrate. The $p-n$ junctions were isolated from each other by etching a trench down to n-GaN epilayer, using chemically assisted ion beam etching (rate ~75 nm/min), thus creating mesa structures of ~500 and 200 μm in diameter. The n-type contact metallization was Ti/Al/Ni/Au, annealed at 800 °C for 30 s. The p-type contact metallization was Ni/Au, annealed at 500 °C for 300 s. Resistivities of $<10^{-5}$ Ω cm and $<10^{-3}$ Ω cm were obtained for n-type and p-type GaN contacts, respectively.

Electron injection into the p region of $p-n$ junction was carried out by forward biasing a $p-n$ junction and passing a current ranging from 25 to 80 mA under an applied voltage from 6 to 8 V. A $p-n$ junction forward current–voltage $I-V$ curve is presented in the inset of Fig. 1. Spectral photoresponse measurements were performed at zero bias by illuminating the p side of the $p-n$ junction. A characterization setup comprising a mercury light source and a monochromator was used. The excitation beam was modulated with a mechanical chopper, and the light-induced change in photoresponse was detected using a lock-in technique.

To exclude the effects of sample heating on minority carrier transport, the photoresponse measurements were delayed by at least 20 min after electron injection. Previously

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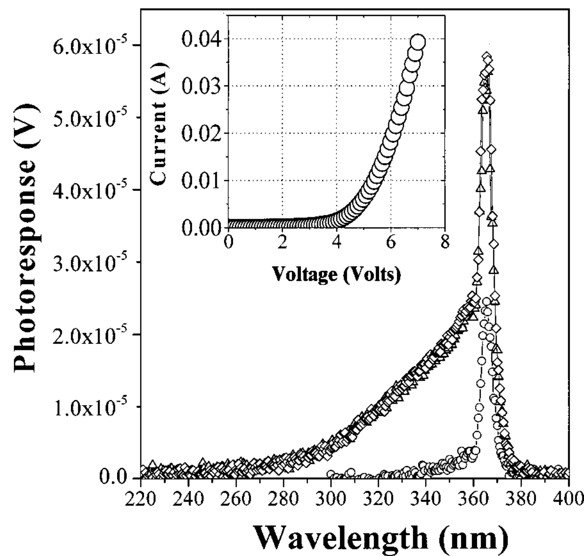

FIG. 1. Photoresponse vs wavelength for a p-side illuminated 500-μm-diam $p-n$ junction detector at zero bias. Open circles represent the initial photoresponse before electron current injection. Open diamonds and triangles correspond to the situation 40 min and 60 h, respectively, after 80 mA (8 V; 20 min) electron current injection. (Inset) $p-n$ junction forward current $I-V$ curve.

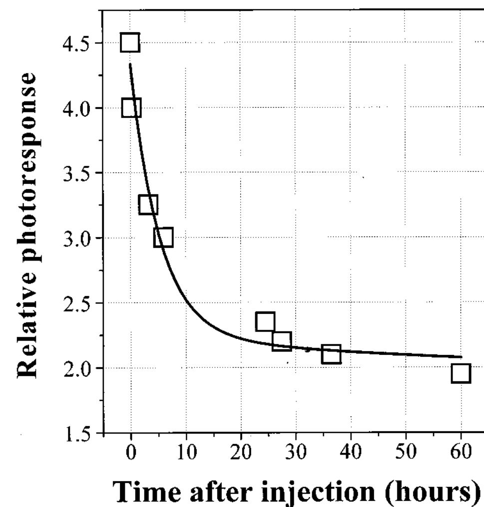

FIG. 2. Decay of a total zero-bias photoresponse after 5 min of electron current injection (40 mA; 7 V) into a 200-μm-diam $p-n$ junction. The signal is normalized relative to its value immediately after an external bias was switched off.

we have demonstrated an increase of L by a factor of 2.5 in the temperature range from 20 to 250 °C.[8] Our experiments and estimations indicate that the maximum electric power of ~640 mW, dissipated around a forward biased $p-n$ junction, leads to a local temperature increase not higher than ~80 °C (60 °C overheating). This is due to the large thermal conductivity of GaN (up to 2 W/cm K).[9]

Figure 1 shows a spectral response from the $p-n$ junction before and after electron injection. In the particular case presented here the forward current of 80 mA (8 V applied voltage) was flown through a 500-μm-diam $p-n$ junction for 20 min. While no changes in $p-n$ junction's $I-V$ curves were found after bias, a 250% increase of detector's photoresponse at the GaN band edge and a broader photoresponse spectral range were observed. The effect of electron injection-induced enhancement of the photoresponse persisted for at least 60 h at the level indicated in Fig. 1.

In a separate experiment the forward current of 40 mA (7 V applied voltage) was flown through a 200-μm-diam $p-n$ junction for 5 min. The goal of this experiment was to explore the kinetics of photoresponse relaxation to its initial value before electron injection. In contrast to the spectrally resolved measurements, a total photoresponse was measured in this experiment. The results are presented in Fig. 2. The signals are normalized relative to the initial photoresponse before forward current injection. One can see that it takes ~60 h for a signal to exponentially decay by more than a factor of 2 relative to its value immediately after electron injection.

A photoresponse decay after an electron injection in Fig. 2 is consistent with a decay for the room temperature band-to-band photoluminescence transition intensity in p-GaN after 1500 s of electron injection into it.[6] The difference in dynamics of photoresponse relaxation in Figs. 1 and 2 is explained by the different current densities for 500 and 200-μm-diam $p-n$ junctions.

We relate the observed effect of $p-n$ junction's photoresponse enhancement to an injection-induced increase of minority electron diffusion length L in the p region of $p-n$ junction.[5–7] This was confirmed by the electron beam induced current measurements.[7] As was already pointed out in Ref. 5, L ($[D\tau]^{1/2}$) may increase due to an increase in lifetime τ or carrier mobility μ related to diffusivity D via the Einstein equation. Based on the experimental results of Ref. 10 on an electron beam-induced change in p-GaN electrical conductivity, we suggested that an electron beam-induced increase of L, observed in our experiments reported in Ref. 5, is determined by an increase of τ, with unchanged mobility. It is, therefore, very likely that the same mechanism is responsible for an increase of L in the case of forward current electron injection.[6,7] The recombination process after bias is predominantly nonradiative (as is evident from a dramatic decrease of the room temperature photoluminescence transition intensity at the GaN band edge),[6] due to a trap activation. Capturing the injected charge on the deep levels traps, associated with Mg doping, excludes these levels from carrier recombination and, therefore, the minority electron lifetime and diffusion length in p-GaN increase.[5] Our estimations gave the value of 10^{18} cm^{-3} for the Mg traps able to capture an injected electron.[5]

From the previous experiments we found that L increases up to a factor of 10 due to an electron injection into p-GaN under the above described conditions.[5–7] From Eq. (1), using the values of $\alpha=10^5$ cm^{-1},[1] $L_{\text{initial}}=10^{-5}$ cm,[5–7] $L_{\text{final}}=10^{-4}$ cm,[5–7] and $W=10^{-5}$ cm,[7] we obtain that the quantum efficiency η increases by a factor of 2. This is in good agreement with the results presented in Fig. 1. It must be noted that the detector's spectral range broadens with electron injection. This is very likely related to an improved carrier collection at higher energies (higher absorption). The impact of electron injection on the detector's responsivity is similar to the one achieved due to a decrease of p-layer thickness in the $p-i-n$ photodetector.[1] This is because both

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approaches result in suppression of minority carrier recombination in the p region, by either decreasing the geometrical length or increasing the electron diffusion length.

We note that $\sim$60 °C $p-n$ junction overheating as a result of forward bias application cannot by itself account for the observed effect of photoresponse enhancement due to dissociation of Mg complexes[11] or temperature-induced increase of L.[8] This was verified by heating the $p-n$ junction up to 80 °C for $\sim$1500 s (with no electron injection) and measuring a zero-bias total photoresponse before and after the temperature was raised. No change in the photoresponse amplitude was observed.

In conclusion, we demonstrated a long-term significant increase of $p-n$ junction photodetector peak responsivity and broadening of its spectral range as a result of short time (up to 1200 s) electron injection from the p to the n region under a forward bias. The effect is likely related to electron capturing on the deep levels associated with Mg dopants. Further studies of the electron injection-induced effects are underway. This will eventually allow implementation of a simple method for improving a photovoltaic detector performance,[12] which will likely be used in combination with design and technology improvements.

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