Impact of neutron irradiation on carrier dynamics in high-quality epitaxial GaN

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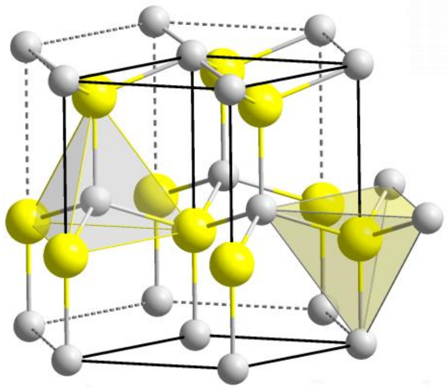
Motivation



- Gallium nitride (GaN) is a key semiconductor for optoelectronic and high-power applications such as light-emitting diodes (LEDs), laser diodes, and high electron mobility transistors (HEMTs).

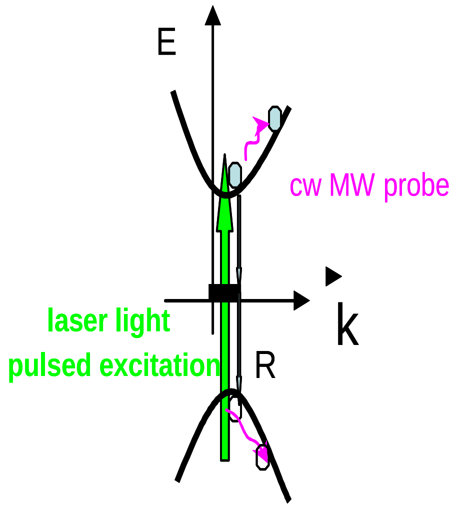
- Owing to its wide bandgap (3.4 eV), high thermal stability, and large displacement energy, GaN is also a promising candidate for ionizing radiation detection under extreme conditions.

- High crystalline quality GaN with low unintentional doping and low dislocation density is needed, which can be achieved by epitaxial growth on native GaN substrates. Additionally, the impact of irradiation on the material properties has to be verified.

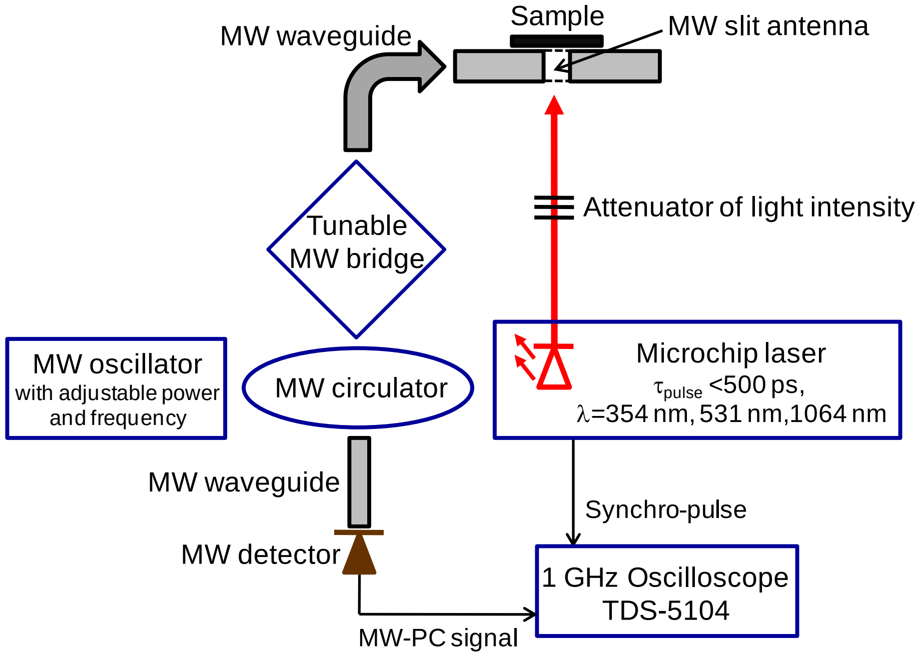
- In this work the variations of carrier dynamics in MOVPE GaN grown on Ammono substrate and irradiated by reactor neutrons were investigated to get insight into defect generation and its impact on the quality of GaN.

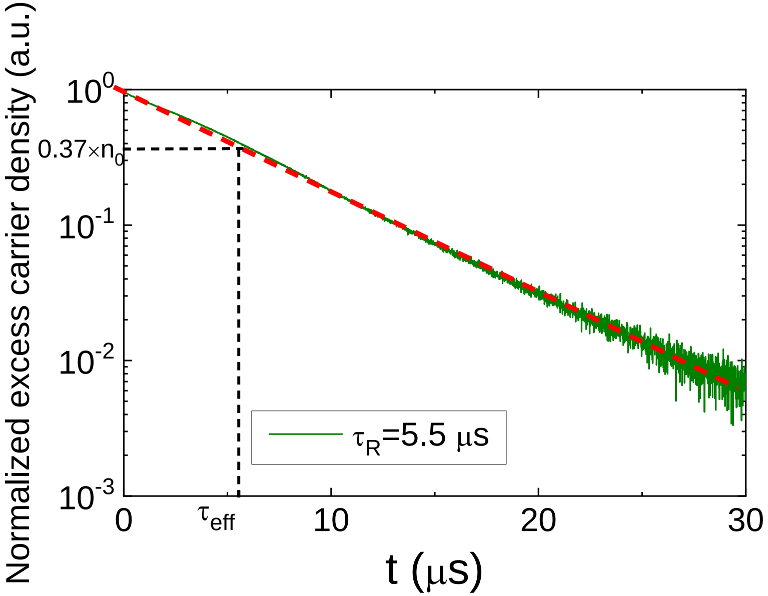
- This study is performed within the framework of DRD3 WP3 (WG6) project *“Development of radiation-hard GaN devices for MIP detection.”*

Microwave probed photoconductivity transients technique



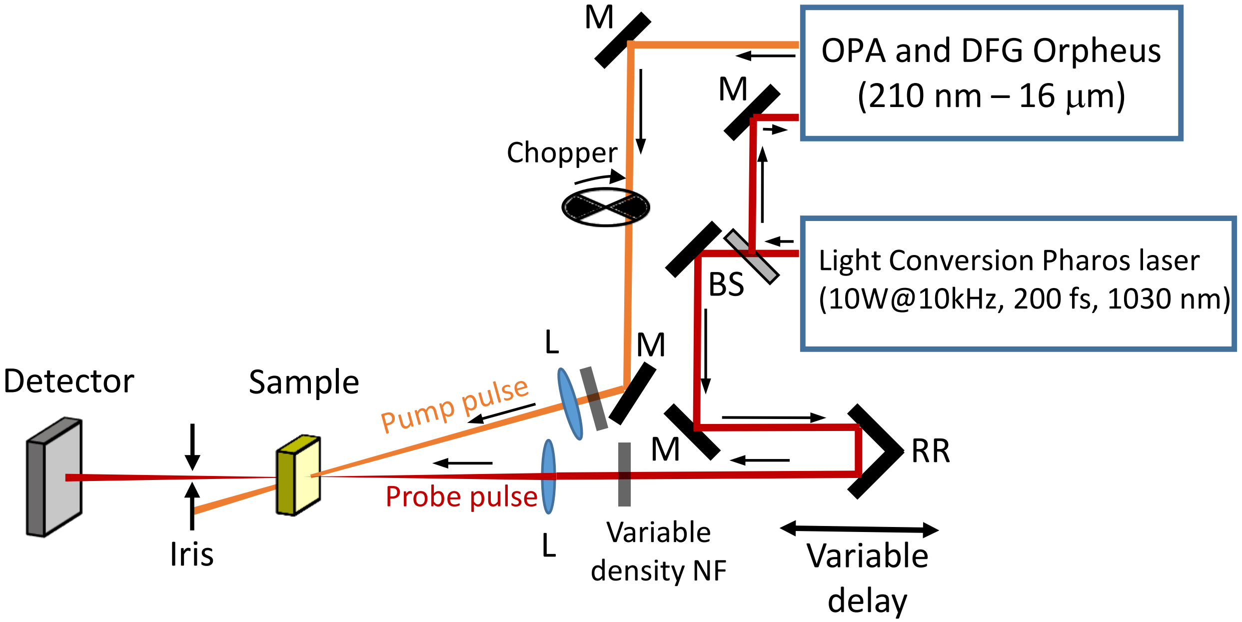
The microwave probed photoconductivity technique is based on the direct measurements of the carrier decay transients by employing MW absorption by excess free carriers.





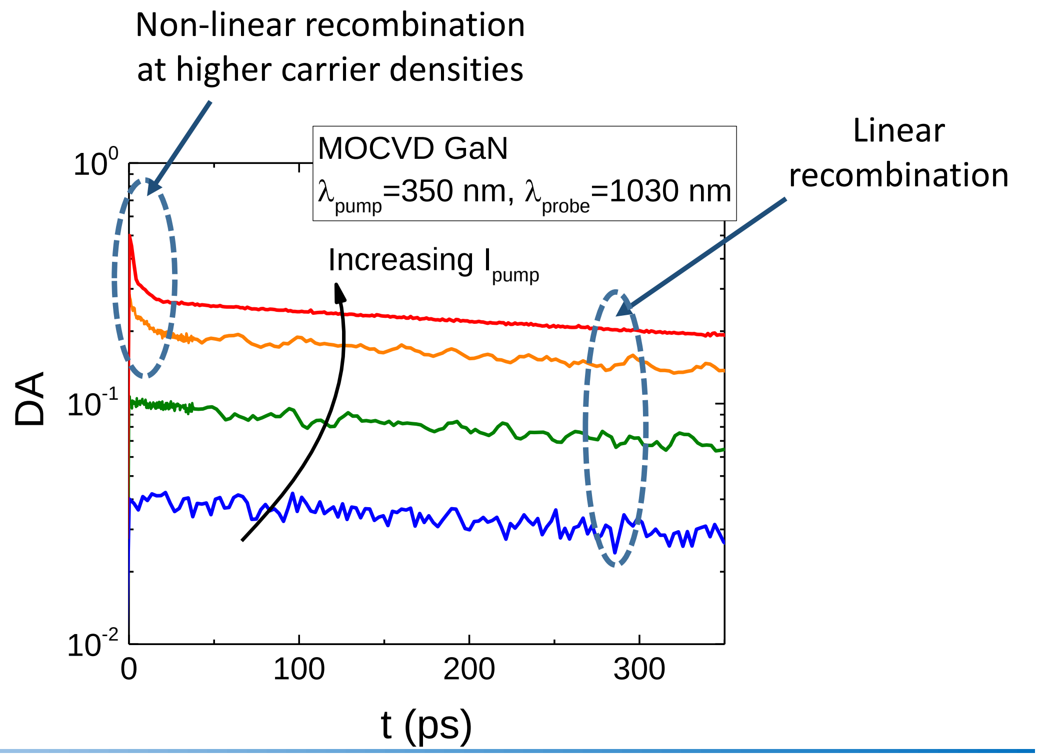
$$\tau_R = n \Big/ \left(-\frac{\partial n}{\partial t} \right) \Bigg|_{\exp(-1)}$$

Transient absorption (DA) technique in pump-probe configuration

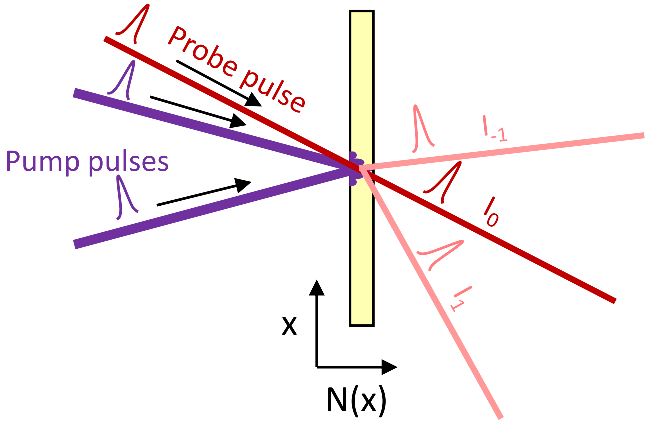


- Light Conversion Pharos laser (10W@10kHz, 200 fs, 1030 nm).
- Optical parametric amplifier (OPA) and differential frequency generator (DFG) Orpheus (210 nm – 16 μm).
- The variable delay of the probe pulse enables step by step measurements of the time evolution of the DA.
- The time resolution of the measurement depends on the pulse duration of the laser used, i.e. it is in the range of hundreds of fs.
- Variable pump and probe wavelength.

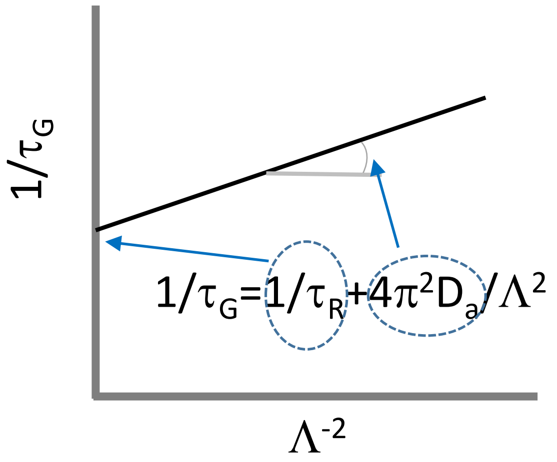
$$DA(t) = ln\frac{I_{unexc}}{I_{exc}(t)} = \Delta N \sigma_{eh} d \exp\left(-\frac{t}{\tau}\right)$$



Light-induced transient grating (LITG) technique



The light-induced transient grating (LITG) experimental setup.



Principle of extraction of D_a and τ_R parameters.

The sample is excited by a spatially modulated interference field of two coherent pump beams, which create a transient spatially modulated free carrier pattern with the grating spacing Λ

$$N(x) = N_0 + \Delta N\left(1 + cos\left[\frac{2\pi x}{\Lambda}\right]\right)$$

Diffraction efficiency $\eta_1 \sim J_1^2(\Phi) \approx (\Phi/2)^2$ $\Phi(t) = (2\pi/\lambda) n_{eh} \Delta N(t) d$

$$\frac{I_{1\,diffracted}(t)}{I_0\,(t)} = \eta_1(t) \propto \exp\left(\frac{-2t}{\tau_g}\right)$$

The grating decay time τ_g is related with recombination and diffusion times τ_R and τ_D

$$\frac{1}{\tau_g} = \frac{1}{\tau_R} + \frac{1}{\tau_D} = \frac{1}{\tau_R} + \frac{4\pi^2 D_a}{\Lambda^2} \qquad D_a = \frac{n+p}{n/D_h + p/D_e}$$

Measurements with different induced grating periods Λ allows evaluating D_a and τ_R by fitting

$$\frac{1}{\tau_g} = f\left(\frac{1}{\Lambda^2}\right)$$

Measurement regimes of probe methods applied in this work

Free carrier absorption coefficient

$$\alpha_{fc} = K_n \lambda^2 n$$

MW~ 10 GHz $\rightarrow$3 cm
IR $\rightarrow$1 μm= 10^{-4} cm

$\alpha_{MW}/\ \alpha_{IR}=(3\ cm)^2/(10^{-4}cm)^2\approx 10^9$

MW probe is ~9 orders of magnitude more sensitive in comparison with the IR probe.

MW probe $\rightarrow$ Low-moderate excitation intensities
IR probe $\rightarrow$ High excitation intensities

Samples investigated

MOVPE GaN grown on Ammono substrate at the Institute of High Pressure Physics, Polish Academy of Sciences (UNIPRESS):

- Epi-layer thickness – 10 μm;
- n = 2×10^{15} cm^{-3};
- Part of the wafer was cut into pieces of area 5×5 mm^2 and sent for irradiation with neutrons at the Ljubljana TRIGA reactor with fluences ranging from 10^{12} to 10^{18} cm^{-2}.
- Samples irradiated with fluences ranging from 10^{12} to 10^{17} cm^{-2} have already been received and investigated.

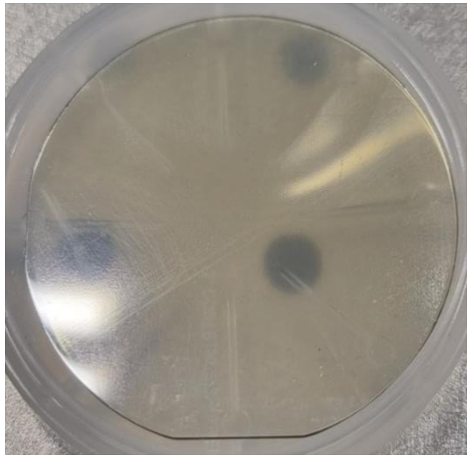
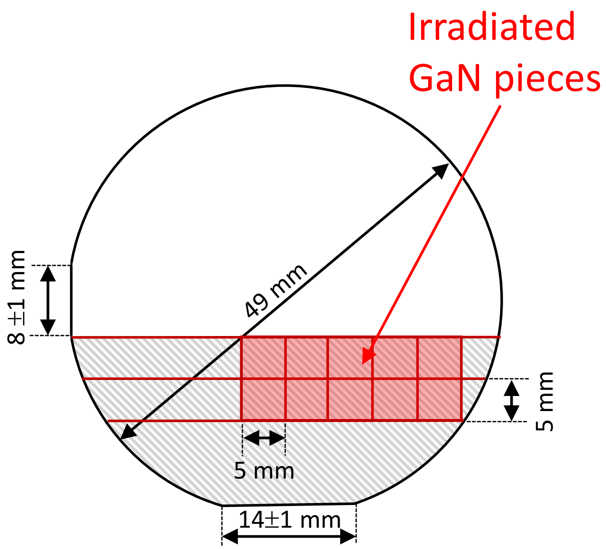
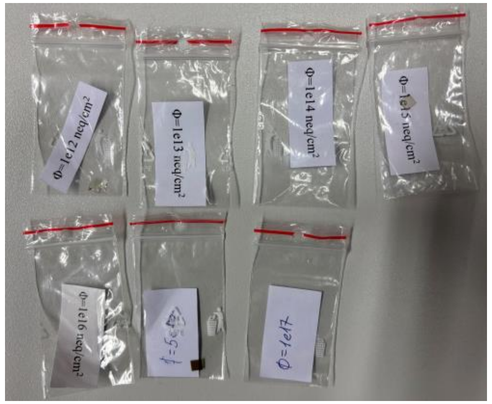


Photo of the GaN wafer.



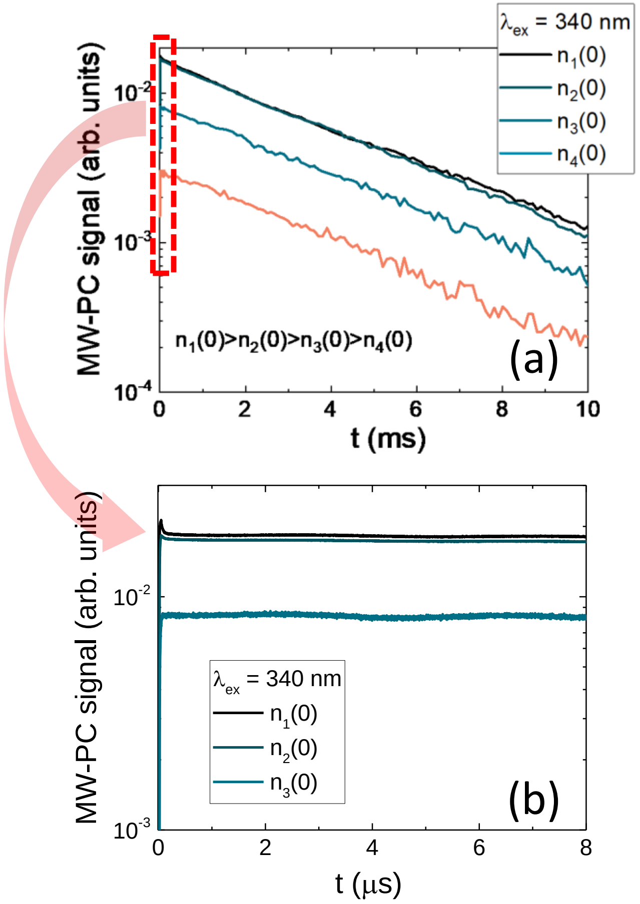
Sketch of the cutting scheme of the GaN wafer.



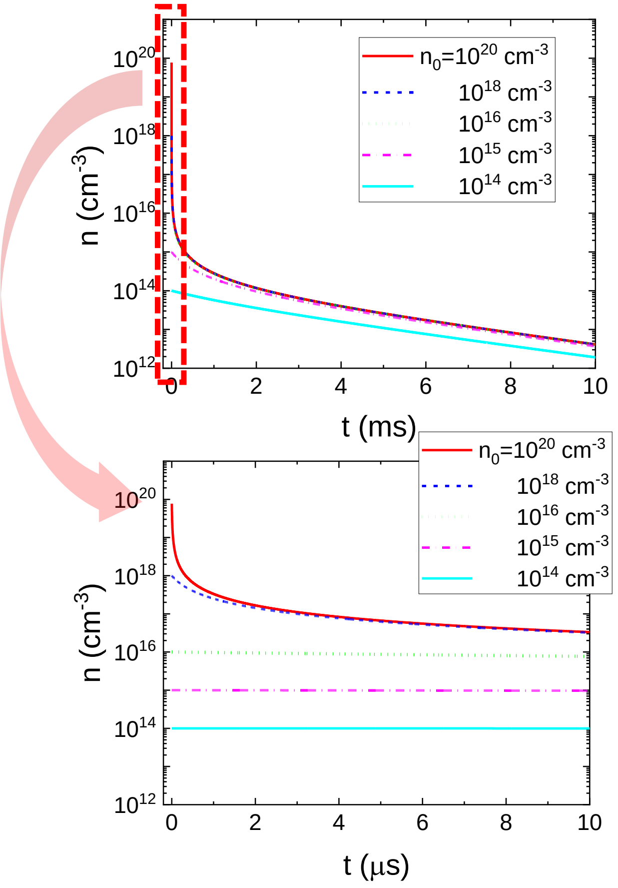
Set of irradiated GaN samples.

Carrier recombination characteristics in non-irradiated GaN obtained by MW-PC technique

Low-moderate excitation level.



MW-PC transients recorded in epi GaN displayed using different (long (a) and short (b)) time scales.



Simulated transients at the manifestation of radiative (B = 3×10^{-12} cm^3/s) and linear recombination (τ = 3 ms) regimes.

The approximation for the simultaneous radiative recombination with linear photoconductivity transients:

$$n_{r,R}(t) = \frac{n(t=0)e^{-\frac{t}{\tau}}}{1 + B_r n(t=0)\tau_R(1-e^{-\frac{t}{\tau}})}$$

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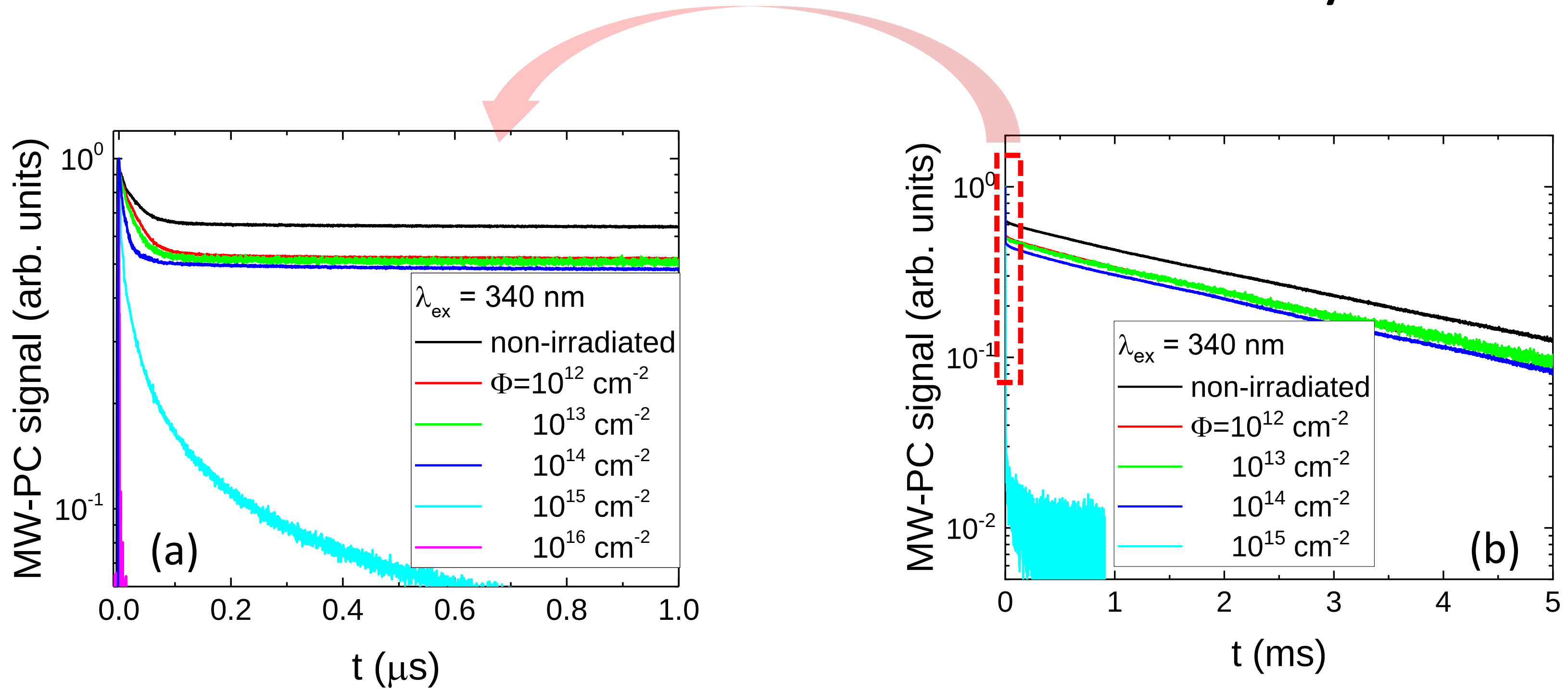
Assuming values of $\tau \approx 1$ ms for linear recombination process, carrier thermal velocity of v_T=10^7 cm/s and capture cross-section of the order of $\sigma \approx 10^{-18}$ cm^2, the trap density in the epi-layer can be estimated as:

$\boldsymbol{N_T=1/(\tau v_T \sigma)}=1/(10^{-3} \times 10^7 \times 10^{-18}) \approx 10^{14}$ cm^{-3}.

Carrier recombination characteristics in neutron irradiated GaN obtained by MW-PC technique

Low-moderate excitation level.

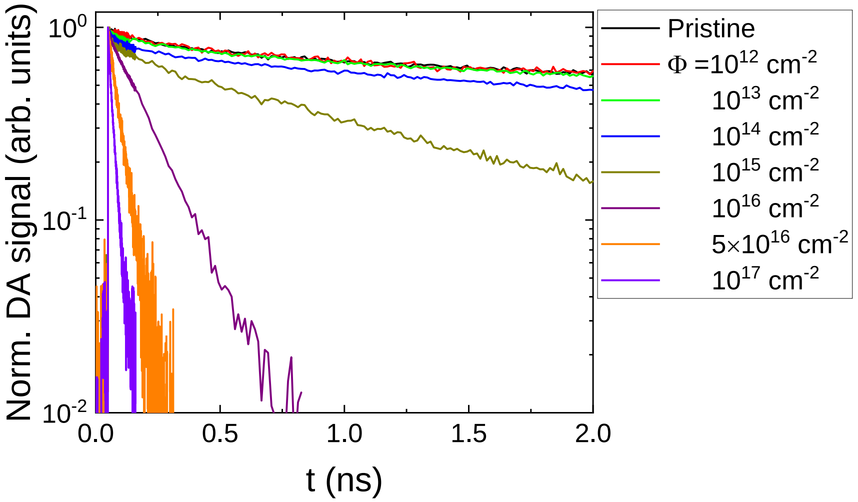


MW-PC transients recorded in epi GaN displayed using different (short (a) and long (b)) time scales.

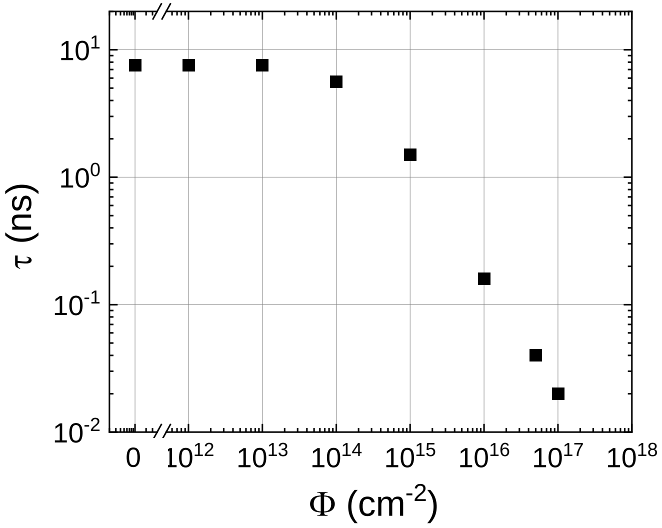
- Significant decrease of carrier lifetime is observed for samples irradiated with fluences $>10^{14}$ cm^{-2}.

Carrier recombination characteristics obtained by DA technique

High excitation level.



Normalized DA transients for samples irradiated with different fluences.



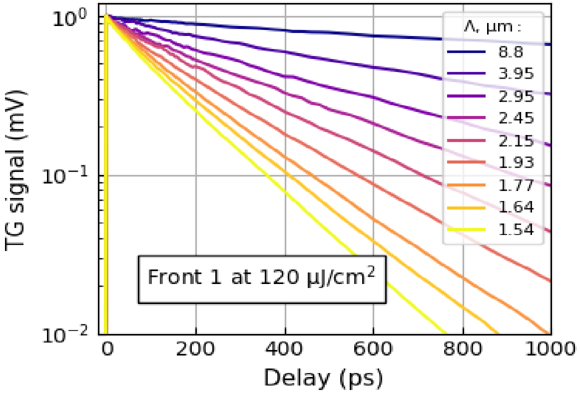
Carrier recombination lifetime variations as a function of neutron irradiation fluence.

- Recombination lifetime is not affected by irradiation for $\Phi \leq 10^{13}$ cm^{-2}.

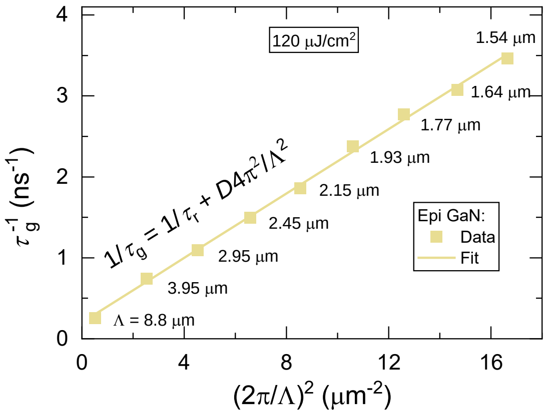
- Recombination lifetime decreases for fluences ≥10^{14} cm^{-2} and is inversely proportional to irradiation fluence in the Φ range 10^{15}-10^{17} cm^{-2}.

LITG transients in non-irradiated GaN

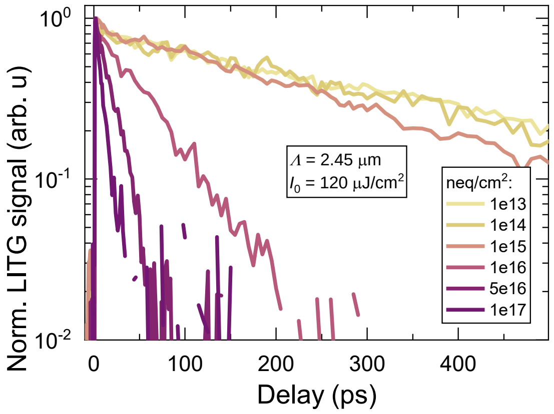
High excitation level.



Normalized LITG transients as a function of the grating period measured at fixed excitation intensity.



The inverse decay time constants plotted over the inverse grating period squared, for the simultaneous evaluation of the non-equilibrium carrier diffusion coefficient *D* and lifetime τ_R.



Normalized LITG transients as a function of neutron irradiation fluence at fixed grating period Λ and excitation intensity.

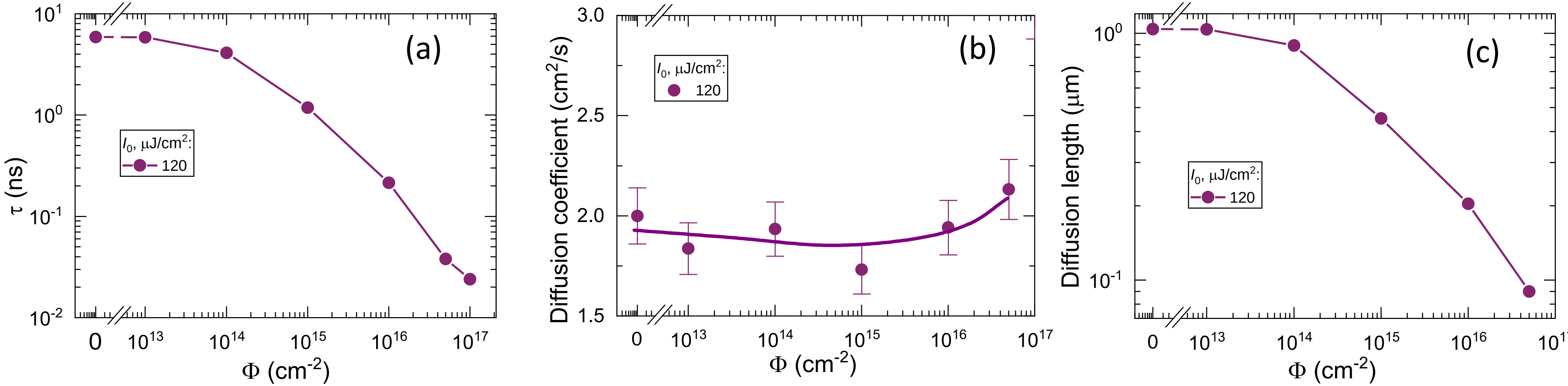
- LITG transients are single exponential.
- Relaxation rate increases with the enhancement of irradiation fluence.

Non-irradiated epi GaN layer:

- τ_R = 5 ns, D=2.0 cm^2/s, L_D=1 μm

Carrier lifetime and diffusion coefficient evaluations using LITG technique

High excitation level.

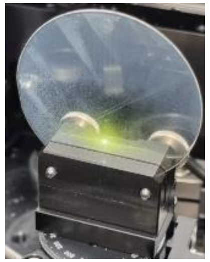


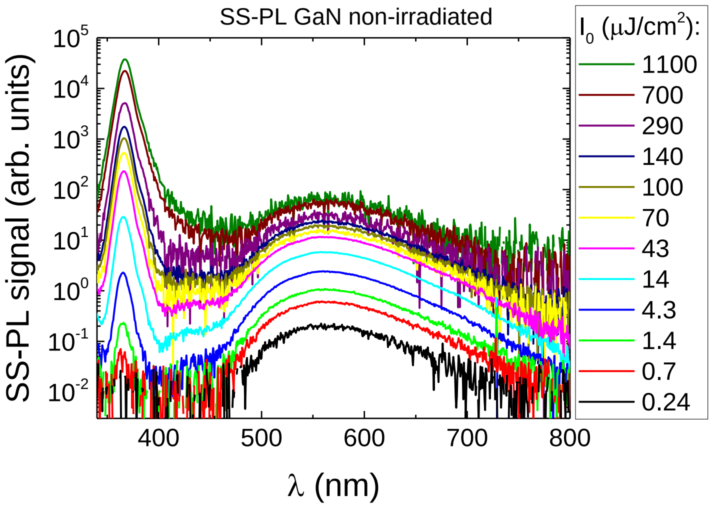
Carrier recombination lifetime (a), ambipolar diffusion coefficient (b) and diffusion length (c) variations as a function of neutron irradiation fluence.

- The carrier recombination lifetime decreases from ~5 ns for the non-irradiated sample to ~20 ps for sample irradiated with neutron $\Phi = 10^{17}$ cm^{-2}.
- The ambipolar diffusion coefficient varies insignificantly among the investigated samples and was estimated to be ~2 cm^2/s.
- The diffusion length decreases from ~ 1 μm for the non-irradiated sample to less than 100 nm for sample irradiated with neutron $\Phi = 5\times10^{16}$ cm^{-2}.

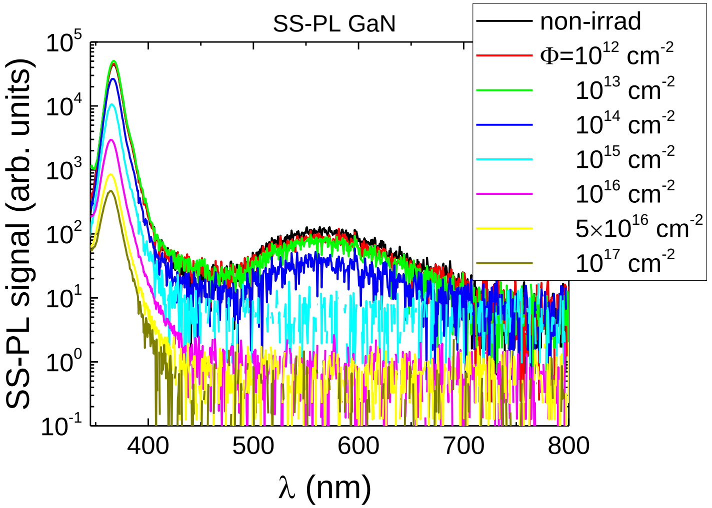
Variations of photoluminescence spectra

High excitation level.

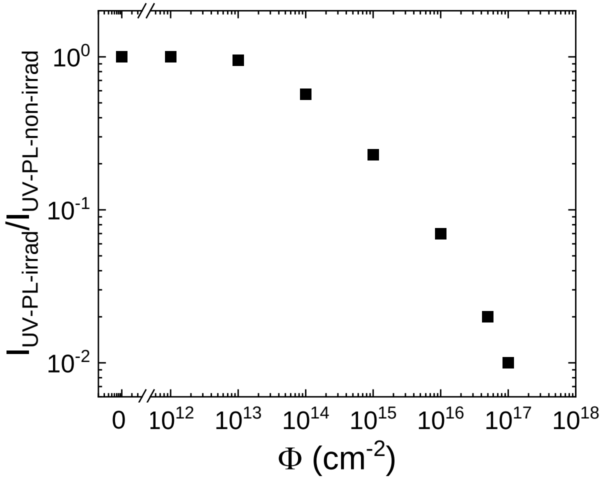




SS-PL spectra as a function of excitation intensity for non-irradiated GaN epi-layer.



SS-PL spectra as a function of irradiation fluence at fixed excitation intensity.

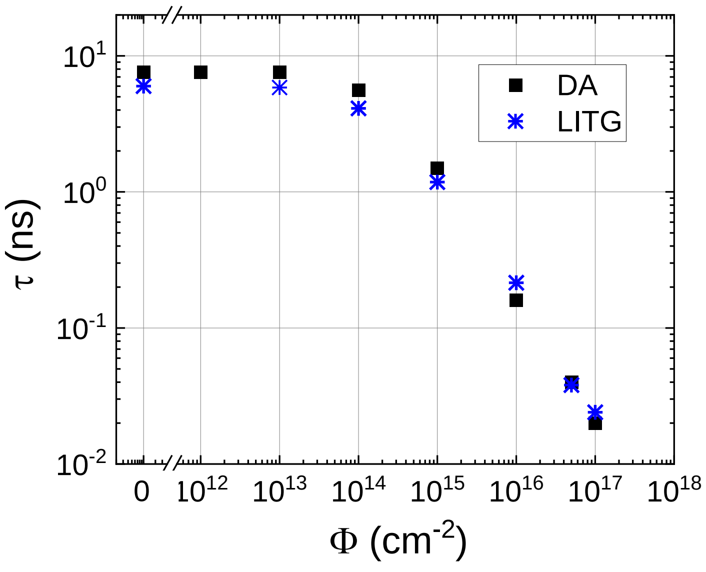


UV band PL intensities normalized to the UV-PL intensity for the non-irradiated sample as a function of irradiation fluence.

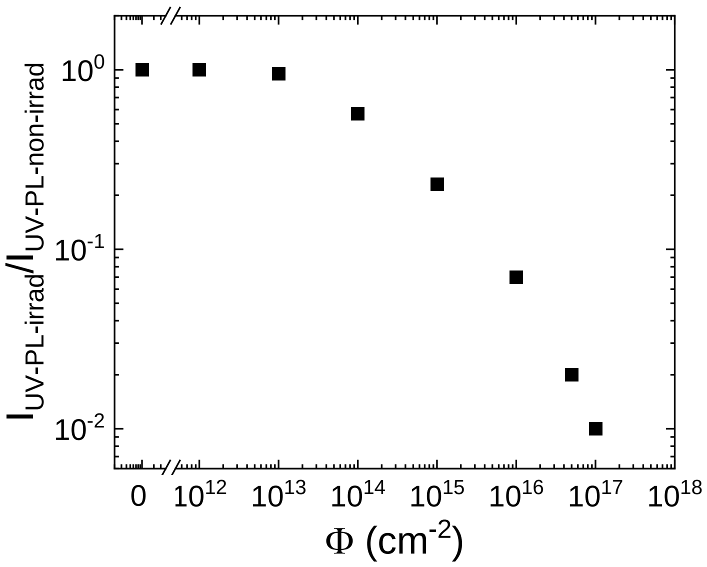
- The intensity of the UV band PL increases quadratically vs excitation intensity for the non-irradiated sample.
- The intensity of the UV band PL decreases at irradiation fluences $\geq 10^{14}$ cm^{-2} due to radiation-induced defects acting as non-radiative recombination centres.

Correlation of radiative and non-radiative characteristics

High excitation level.



Carrier recombination lifetime variations as a function of reactor neutrons irradiation fluence, evaluated using different characterization techniques.



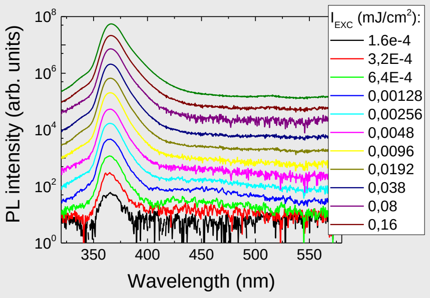
UV-PL intensities normalized to the UV-PL intensity for the non-irradiated sample as a function of irradiation fluence.

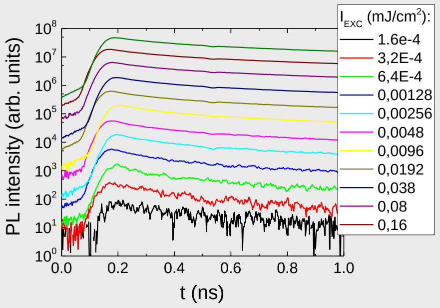
- The estimated recombination lifetime by DA and LITG techniques are close.
- The normalized UV-PL band intensity estimated in GaN epi-layers is almost invariable for irradiation fluences $\leq 10^{13}$ cm^{-2} while it decreases at irradiation fluences $\geq 10^{14}$ cm^{-2} due to increased density of radiation-induced defects acting as non-radiative recombination centres.

Variations of spectral and temporal decay characteristics to reveal prevailing defects using streak camera technique

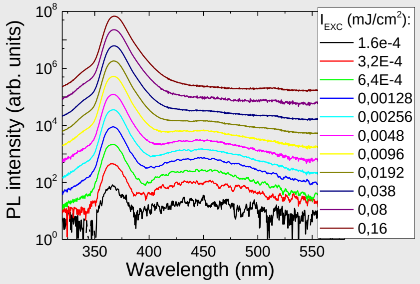
Time scale window 1 ns | **Time scale window 20 ns** | **Time scale window 100 μs**

Non-irradiated

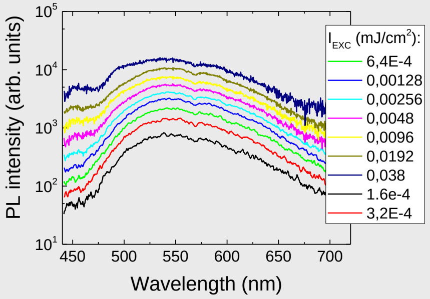




Inherent decay time ~100 ps for prevailing UV (345 nm - 380 nm) luminescence.

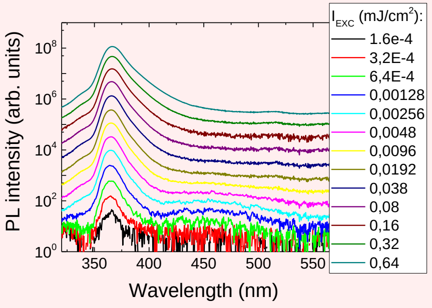


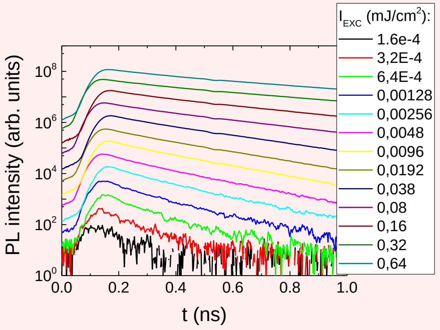
Inherent decay time ~5 ns for blue (410 nm – 480 nm) luminescence.



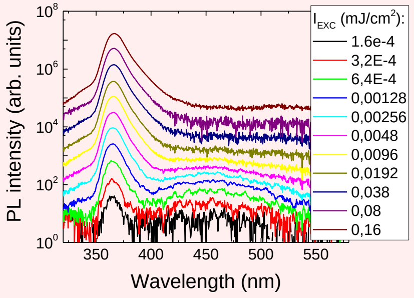
Inherent decay time >100 μs for prevailing yellow-green (550 nm) luminescence.

Φ=10^15 cm^-2

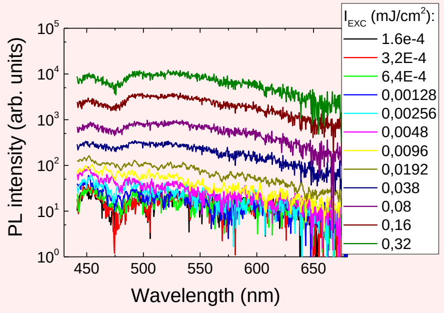




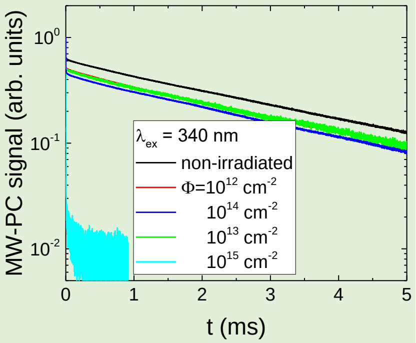
Inherent decay time ~100 ps for UV (345 nm - 380 nm) luminescence.



Inherent decay time ~2 ns for blue (410 nm – 480 nm) luminescence.



Inherent decay time >100 μs for yellow-green (550 nm).



Temporal evolution of PL spectra correlate with MW-PC transients recorded in epi GaN.

Summary

- Combining the MW-PC, DA and LITG techniques allows the estimation of carrier lifetime values ranging from picoseconds to milliseconds at different excitation levels.

- Recombination lifetime is not affected by irradiation for $\Phi \leq 10^{13}$ cm^{-2}, while it decreases from ~7 ns to ~20 ps for fluences ≥10^{14} cm^{-2}, as obtained using DA and LITG techniques.

- The ambipolar diffusion coefficient varied insignificantly among the investigated samples and was estimated to be 2 cm^2/s in all the investigated samples irradiated with different fluences. Whereas the diffusion length decreased from ~ 1 μm for the non-irradiated sample to less than 100 nm for sample irradiated with neutron $\Phi = 5\times10^{16}$ cm^{-2}.

- The UV band PL intensity in irradiated samples normalized to that of the non-irradiated GaN epi-layer is almost invariable for irradiation fluences ≤10^{13} cm^{-2} while it decreases at irradiation fluences ≥10^{14} cm^{-2} due to increased density of radiation-induced defects acting as non-radiative recombination centres.

- The evolution of photoluminescence spectra obtained by streak camera confirm the presence of technological defects in initial epi GaN material and the prevalence of radiation-induced defects at irradiation fluences ≥10^{14} cm^{-2}.

Thank you for your attention

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