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Ionization and displacement damage effects in high voltage vertical GaN diodes

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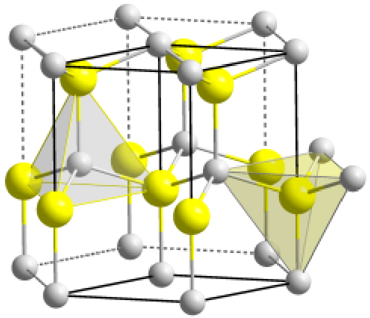
Overview

- Why GaN?
- Displacement damage (1 MeV proton microprobe, IBIC)
- Ionization effects (70 keV electron beam, capacitance vs. time)
- Summary

Power electronics, present Si, SiC → future GaN

Power electronics is the application of solid-state electronics to control and conversion of electric power.

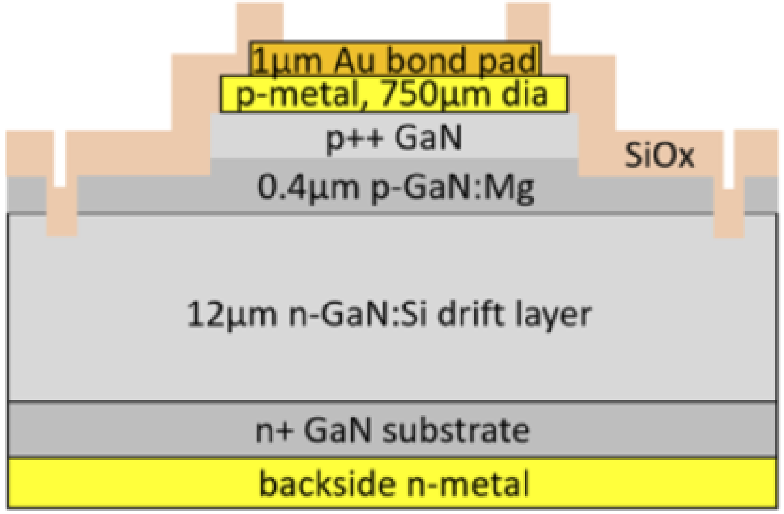
Requirements of power devices:
- High break-down voltage
- High current drive
- High efficiency
- Temperature extremes
- Radiation



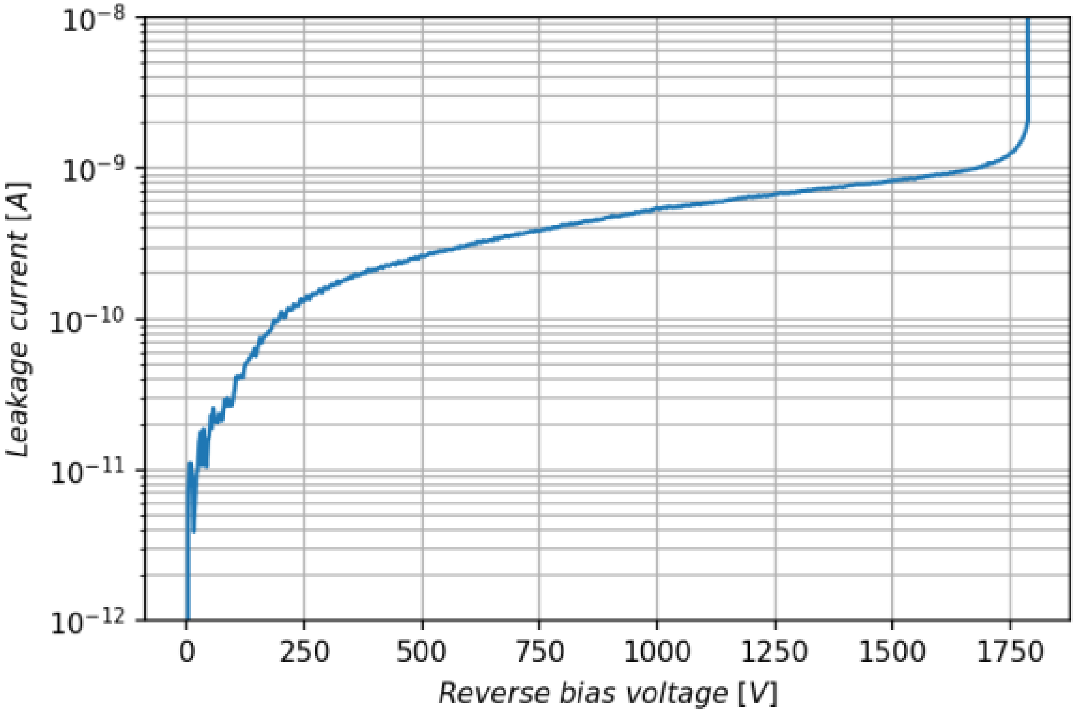
bandgap - 3.4 eV
e-h energy – 8.9 eV
Displacement threshold – 30-70 eV
melting point > 2500 C
break down field > 3 MeV/cm

- In the past there were no high quality GaN wafers, GaN devices were grown on Si, SiC, and Al_2O_3 targets with large dislocation density.
- In the past ten years high quality GaN wafers became available, dislocation density is 3-6 orders of magnitude smaller.

SNL developed high voltage GaN diodes



MOCVD grown
High breakdown voltage requires
Low net n doping ~10^{16} cm^{-3}
Compensation by unintentional C
lowers effective doping concentration



~1700 V breakdown voltage
~ hundreds of pA leakage

Measuring displacement damage by IBIC

Displacement damage creates deep level defects in the band gap

- Increased leakage current (easier to thermally emit from the defects)
- Decreased IBIC (photo) current (the created carriers are captured by the defects)

Simple diode model:

1. All carriers are created in the depletion depth
2. The life time of the carriers determined by the defect density

$$Q = -\frac{1}{d} \cdot \int_0^d dx_0 \cdot \rho(x_0) \cdot \int_{x_0}^d dx \cdot e^{-\phi \cdot c \int_{x_0}^{x} \frac{n_T(x_1)}{v(x_1)} dx_1}$$

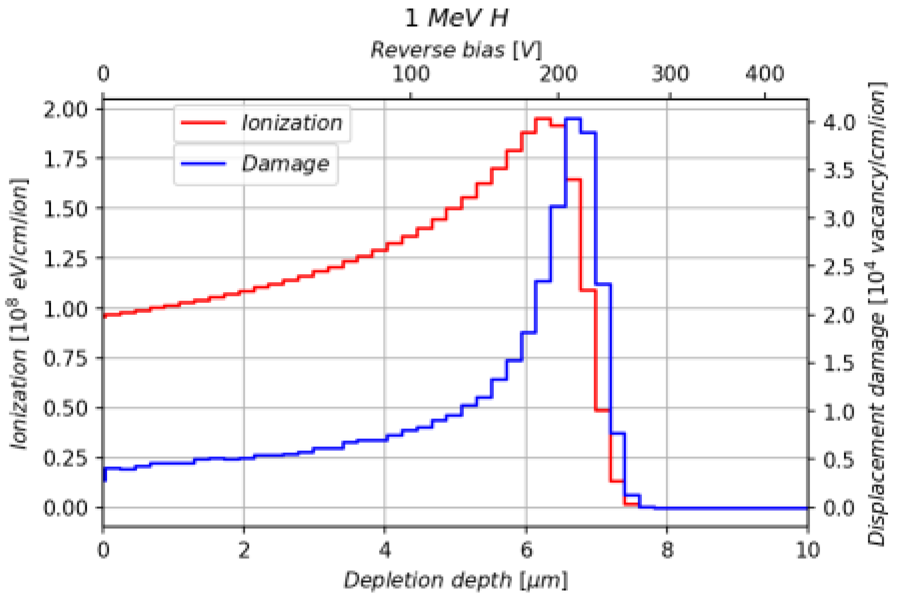
$\rho(x)$ – e-h pair density (from SRIM)
$n_T(x)$ – vacancy density (from SRIM)
$v(x)$ – drift velocity (from electrostatic calculation)
Φ – ion beam fluence (measured)
c – capture rate (to be determined)

Measuring the charge collection efficiency as the function of ion fluence allows us to determine the capture rate of electrons and holes by fitting the measured CCE to the above formula.

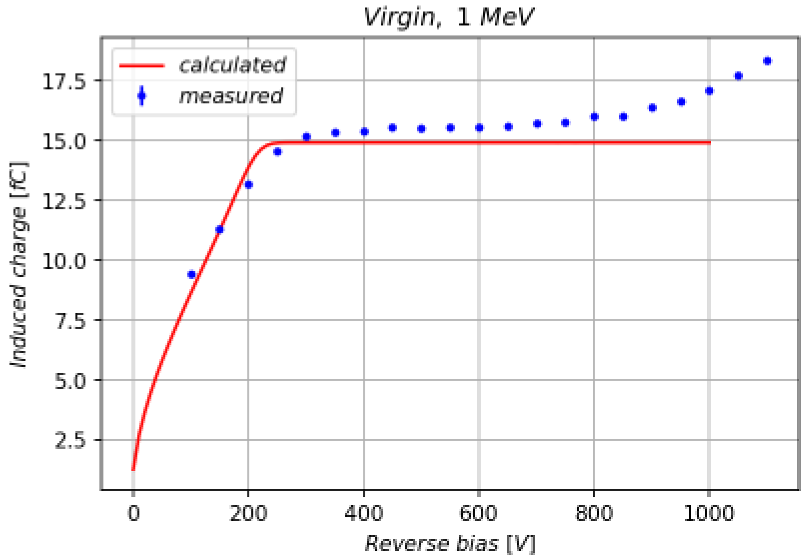
The experiment

1 MeV proton microbeam was used

- **Fluence was measured by the IBIC signal and the scanned area.**
- **Irradiation was done at a fix voltage and bias scans were done after each fluence step.**
- **The device was irradiated continuously at fixed voltage and the CCE was measured continuously.**



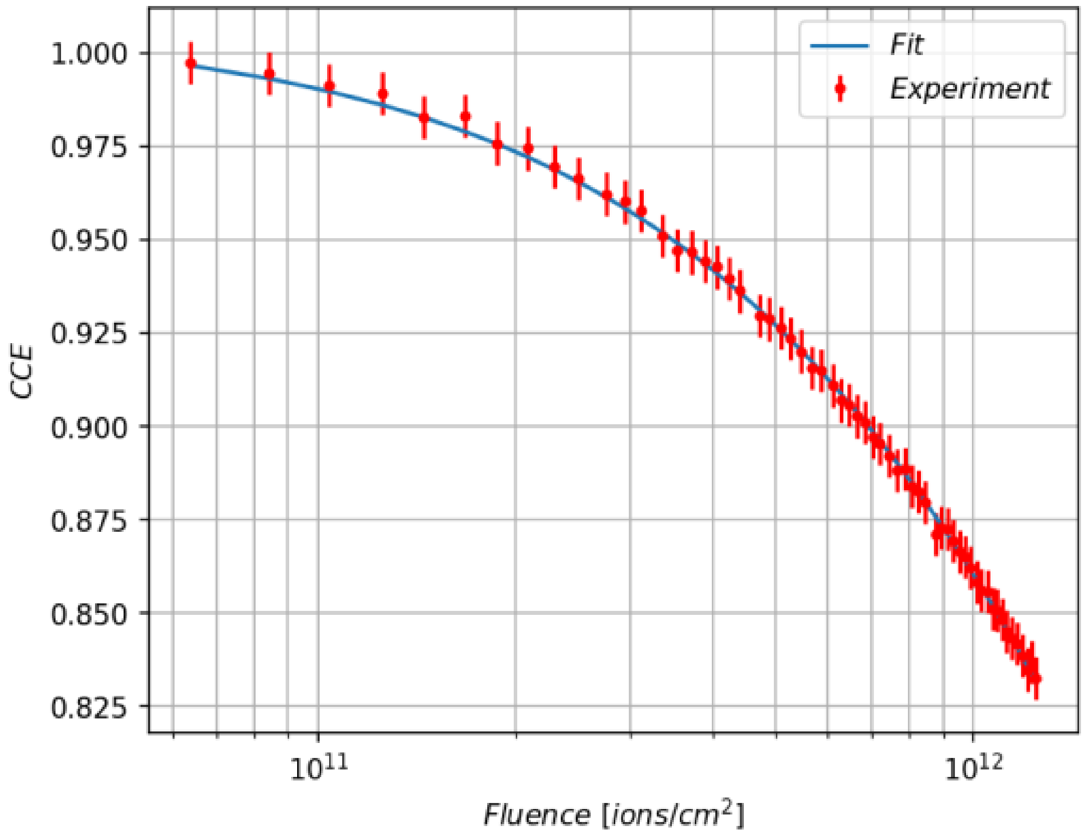
At 300 V all the carriers are generated within the depletion layer.

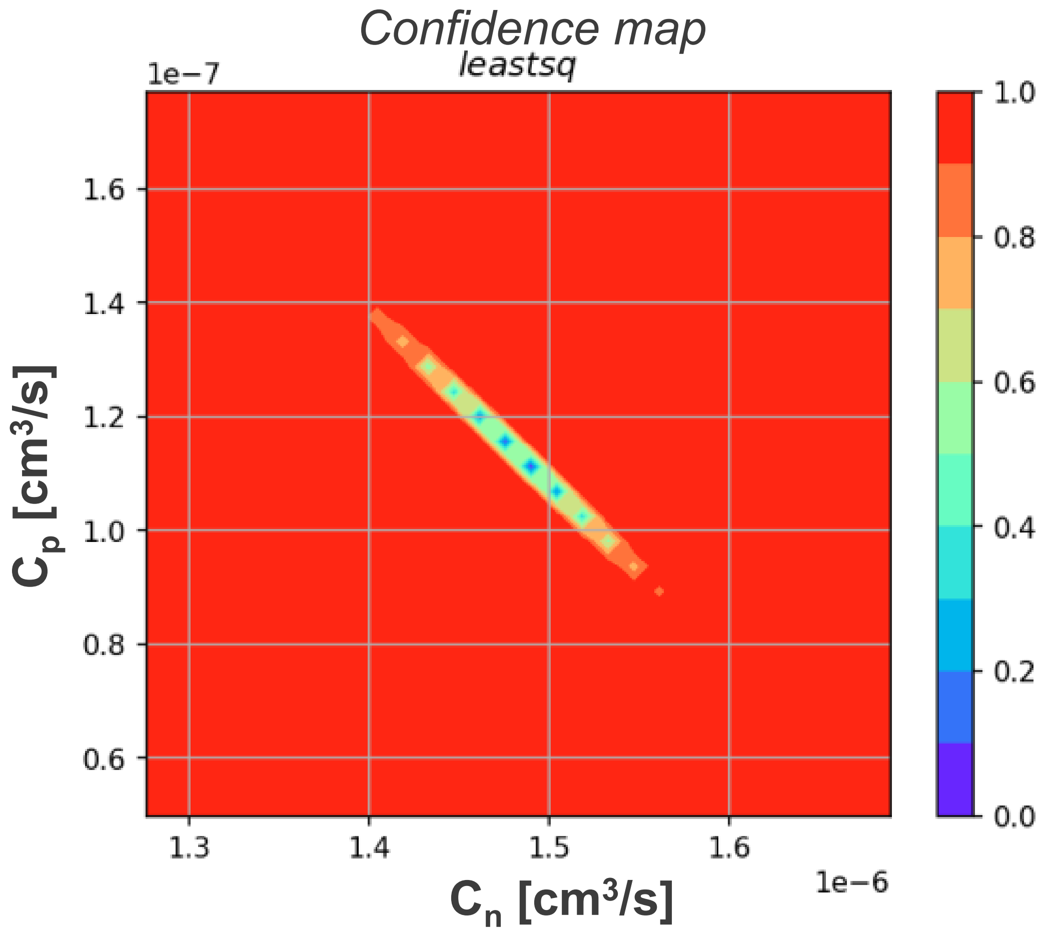


Instead of saturating the ~ 300 V the induced charge keeps increasing, CCE > 1!
For V_{bias} > 500 V charge multiplication (impact ionization) occurs, the model is invalid.

300 V seems to be an ideal bias to measure CCE vs. fluence and use the model.

The result



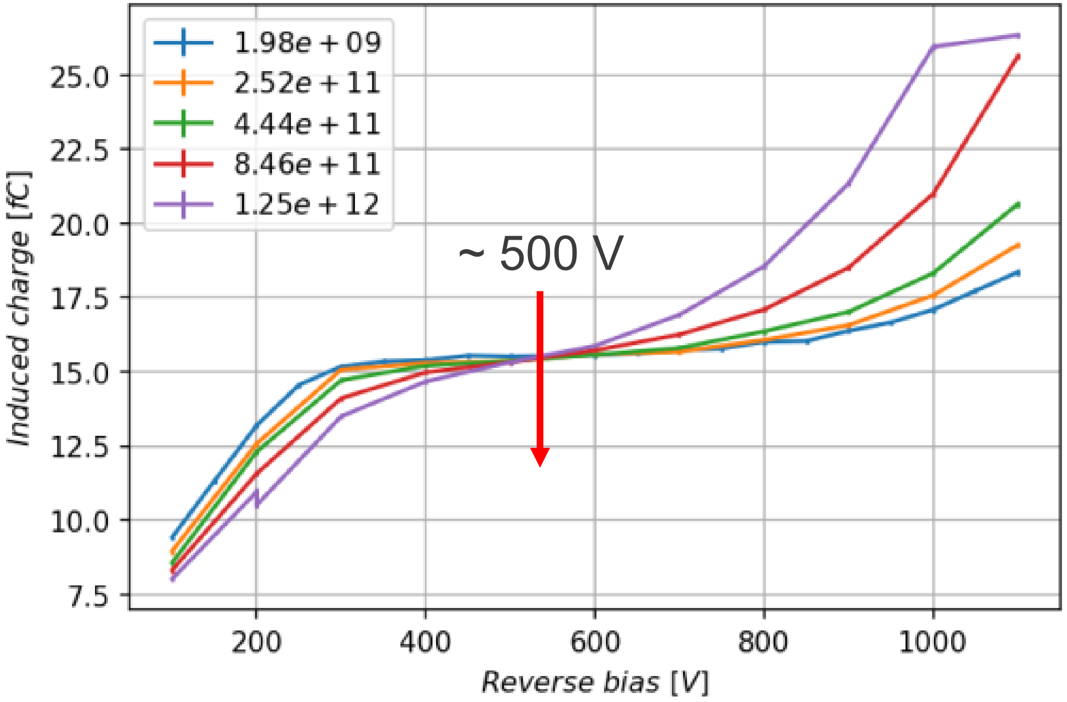


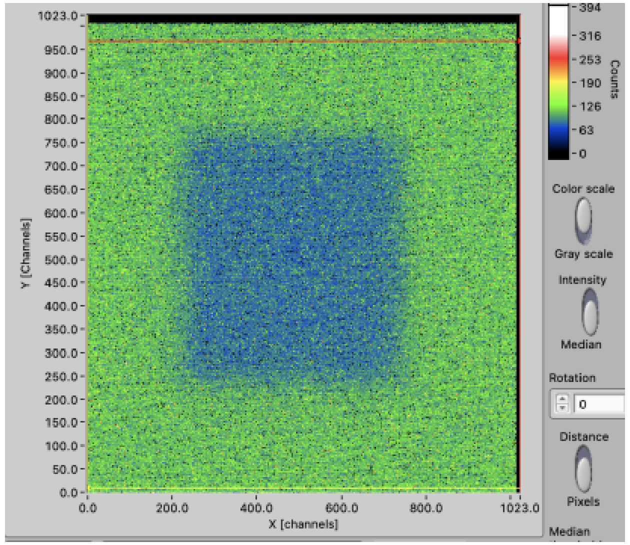
$C_e = (1.48 \pm 0.04) \cdot 10^{-6}$ cm^3/s
$C_p = (1.14 \pm 0.1) \cdot 10^{-7}$ cm^3/s

*P. Hacke et al., JAP **76** (1994)
A. Hierro et at., phys. stat. sol. **228** (2001)

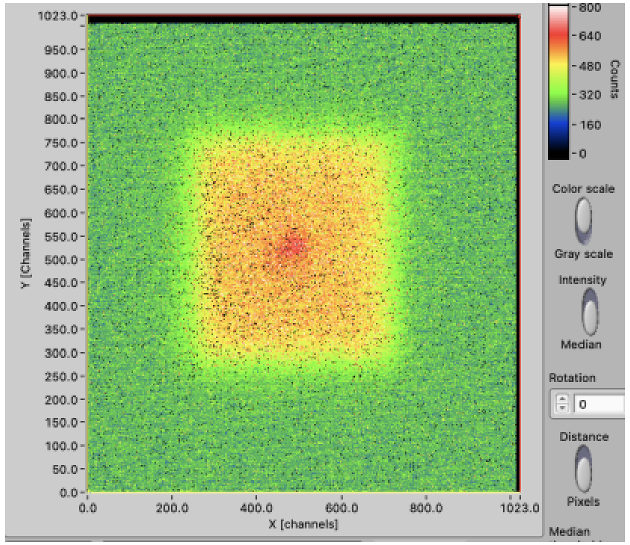
- **The fitted values are similar to literature values* withing 1-2 orders of magnitude.**
- **There is a strong correlation between the electron and hole capture rates.**

What effect do the defects have on impact ionization?





300 V

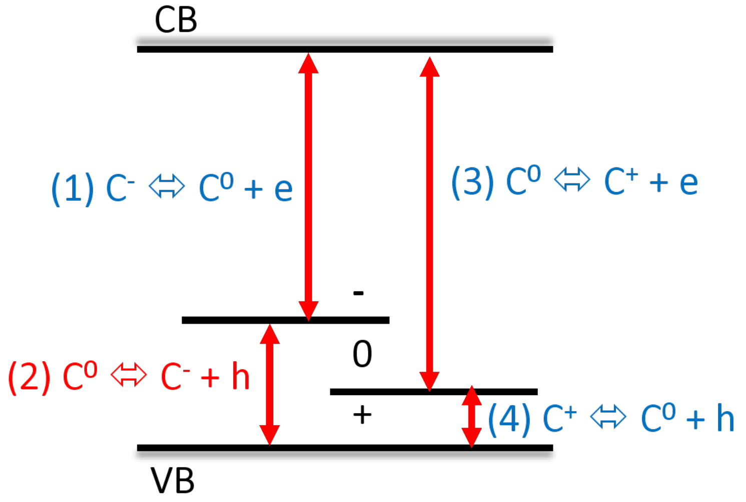


1100 V

- **The impact ionization threshold does not depend on the damage.**
- **Below the threshold the damage decreases the induced charge (defects capture carriers).**
- **Above the threshold the defect capture is not the dominant effect but the defect assisted impact ionization.**

What is the effect of pure ionization?

C_N^- lowers the effective doping. Capture of holes produced by ionization changes the carbon charge state and charge density in the depletion region. Carrier capture rates are known for carbon in GaN **.
Simulations predict how ionization affects doping compensation by carbon.



C_N has (-,0,+) charge states four carrier capture/emission reactions.

Reaction		Energy (eV)	Capture rate coefficient (cm^3/s)
1	$C^- \Leftrightarrow C^0 + e$	2.587 ± 0.003	(1.1 ± 0.1) x10^{-13}
2	$C^0 \Leftrightarrow C^- + h$	0.916 ± 0.003	(3.7 ± 1.6) x10^{-7}
3	$C^0 \Leftrightarrow C^+ + e$	3.2 ± 0.1	~ 10^{-9}
4	$C^+ \Leftrightarrow C^0 + h$	0.3 ± 0.1	~ 10^{-10}

Simulations (XPD code*) showed:

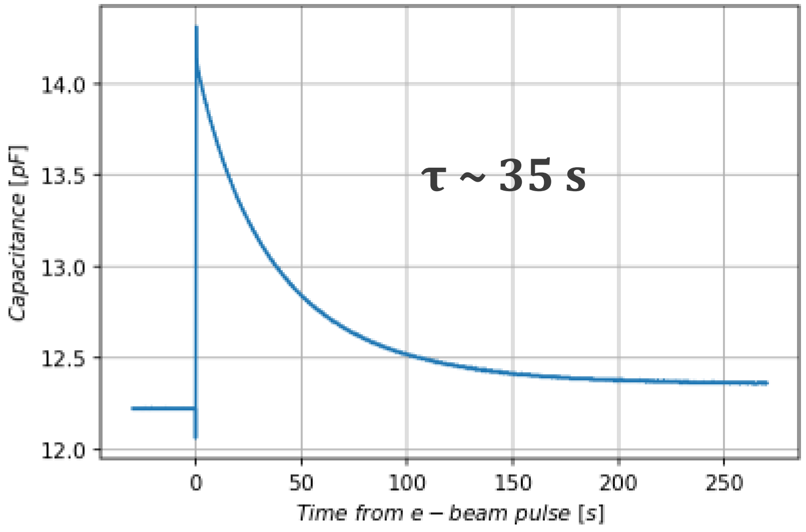
1. Carbon is negatively charged in neutral n-doped layer, offsets doping.
2. When reverse bias is applied, carbon in the depletion region remains negatively charged.
3. When ionizing radiation creates e-h pairs the C^- captures a hole → net doping level increases → depletion depth decreases → electric field increases.
4. After the radiation C^0 emits holes and returns to the negatively charged state (thermally activated ~0.9 eV slow at room temperature).

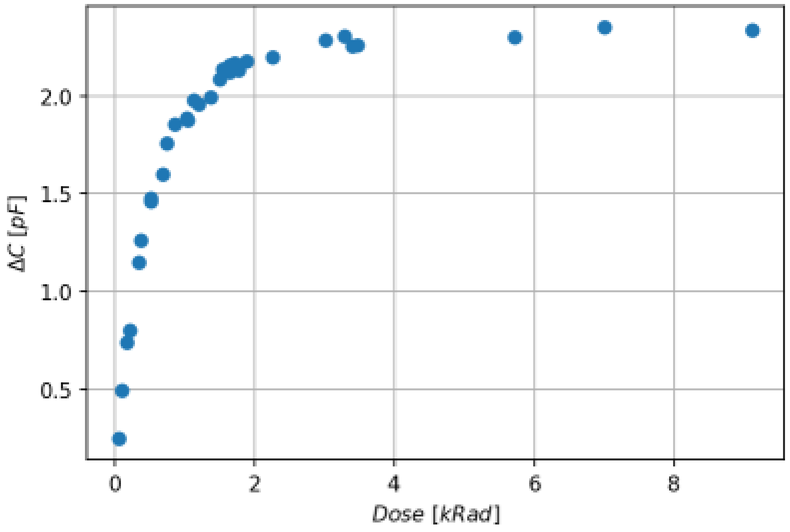
*M. Myers, W. R. Wampler, and N. A. Modine, *J. App. Phys.*, **120**, 2016.
** M.A. Reshchikov. et. al., Phys. Rev. B **98** 125027, 2018.

How can we prove/measure this effect?

- We do not want to use ions, we want pure ionization: low energy electrons.
- Capacitance is proportional to depletion depth so capacitance-time measurement will show the effect.
- The change in capacitance will give us the C density, which is hard to measure any other way.
- Performing the experiment at various temperature will allow to determine the hole capture rate and activation energy for thermal emission.

- The diode was irradiated with varying pulse length and beam current from a 70 keV e-gun.
- The capacitance was measured by a Boonton 7200 C-V meter, whose analog output was recorded with a Yokogawa 750 oscilloscope.





- There is no dose rate dependence.
- ΔC saturates ~ 4 krad (all carbon neutral).
- Results in ~ 2.5×10^{15} C/cm^3 and 8.3×10^{15} Si/cm^3, 29% of the Si is compensated by C.

Determining activation energy and capture rate

Just a few equations for the hole emission from C^0:

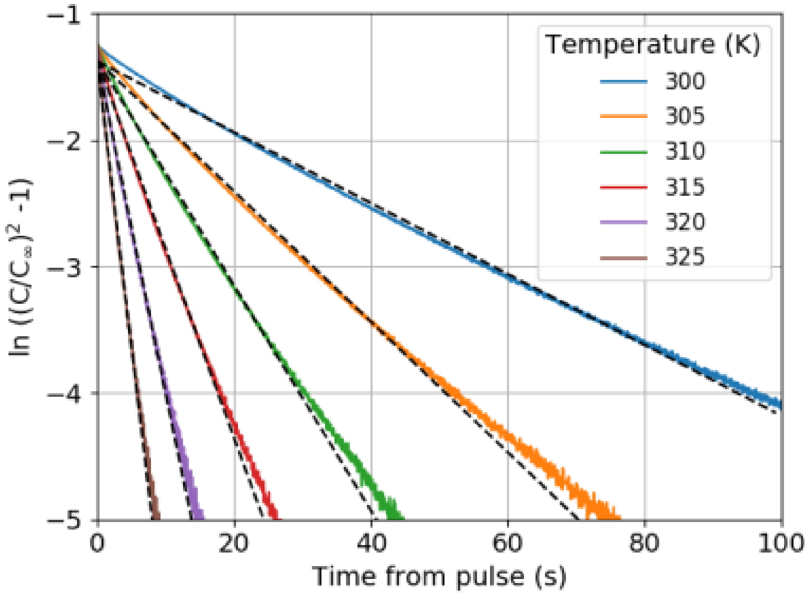
$$\left(\frac{C(t)}{C_\infty}\right)^2 - 1 = \frac{N_C}{N_d}\exp\left(-\frac{t}{\tau}\right)$$

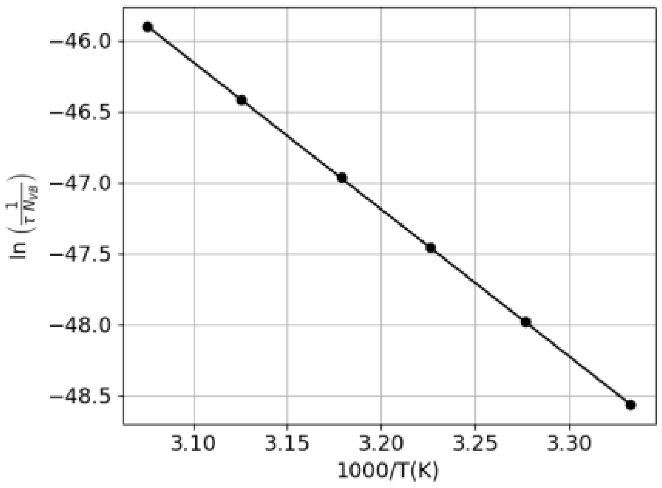
$$\frac{1}{\tau} = \kappa_2\, N_{VB}\exp\left(-\frac{E_2}{kT}\right)$$

$$ln(1/(\tau\, N_{VB})) = ln(\kappa_2) - E_2/kT$$

Fitting τ to the C-t curves at several temperatures allows us to calculate E_2 and κ_2.
κ_2 is independent of temperature for this reaction

E_2 = 0.89±0.02 eV, κ_2 = 0.66x10^{-6} cm^3/s ± factor of 3.





Summary

We investigated the effects of radiation (both displacement damage and ionization) on GaN HV diodes:

- **Using a proton microbeam we found that in GaN HV diodes the charge multiplication due to impact ionization occurs well below break down voltage.**
- **Displacement damage below the threshold caused decreased CCE due to carrier capture by defects) and increased CCE above the threshold due to defect assisted impact ionization.**
- **Using IBIC below the threshold and a simple charge induction model we determined the electron and hole capture rates for displacement damage.**
- **We found that the unintentionally doped carbon, that allows very low doping densities by compensation, can lose this compensation under ionizing irradiation leading to potentially higher electric field than the breakdown field.**
- **Using electron irradiation and C-t measurements at various temperatures we determined the activation energy and capture rate for the $C^0 \rightarrow C^-$+h process. Values agree with those from photoluminescence experiments.**