Modification of electrical properties of GaN by ion implantation and UHPA

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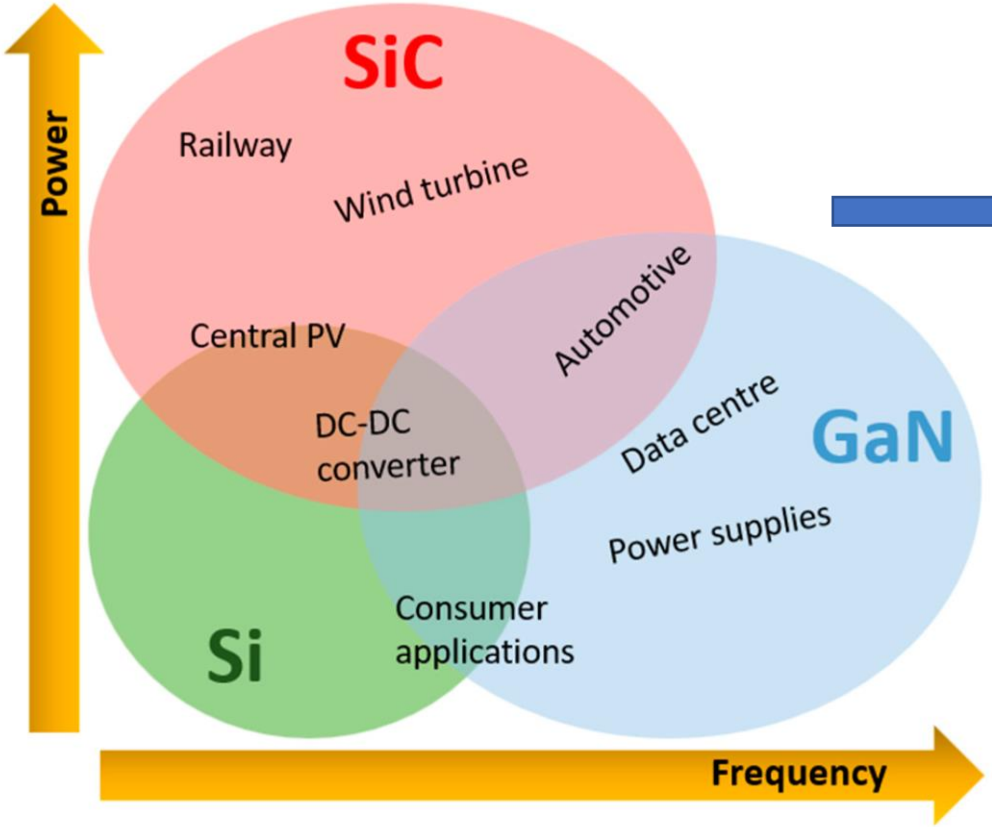
Outline

- Motivation
- Ion Implantation and UHPA
- SIMS results
- Structural analysis results: XRD and TEM
- Electrical properties
- Summary

Why GaN-based deviced?

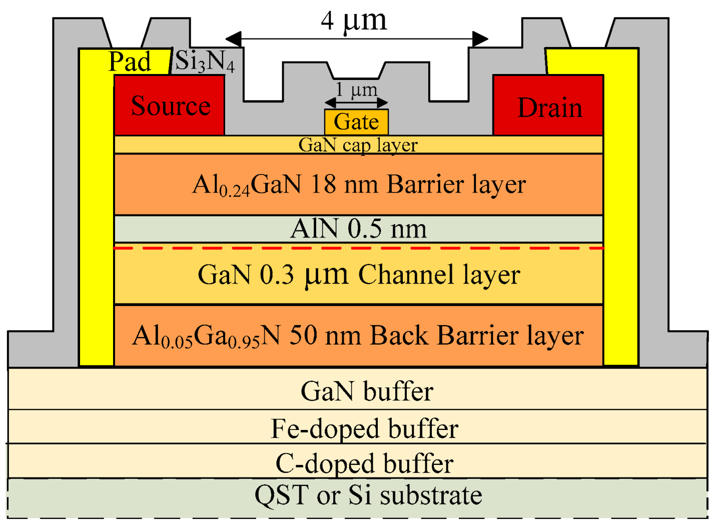


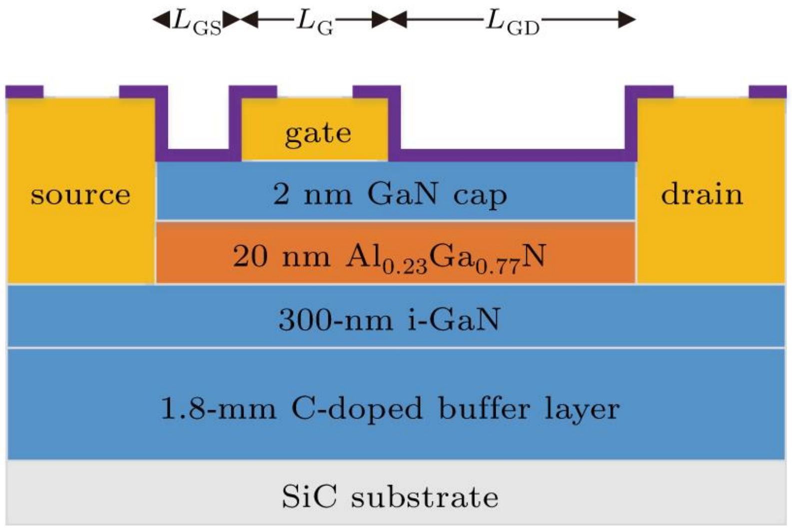
- AC-DC (power factor correction, PFC)
- PV inverters
- Data centers
- PC (DC-DC)

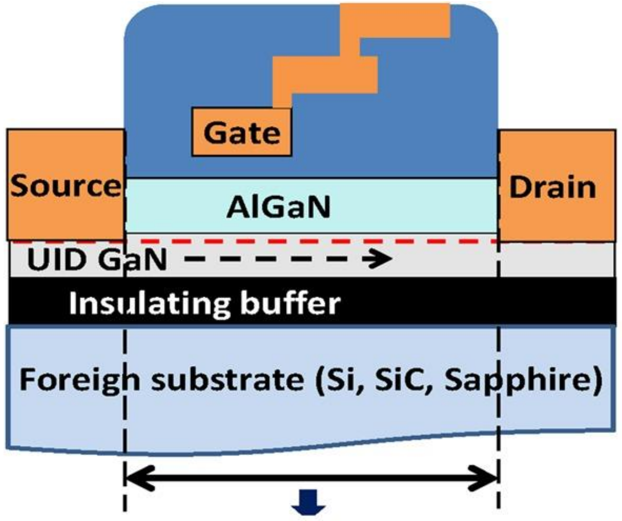
Source: Energies 2022, 15(9), 3415

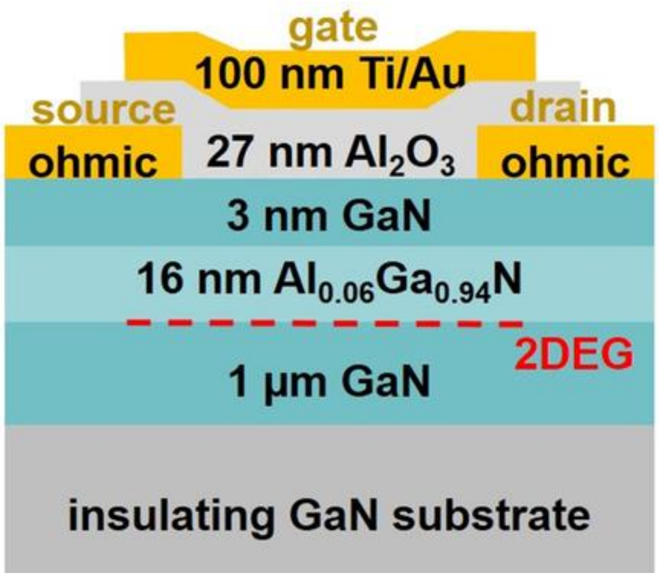
Source: www.hama.com

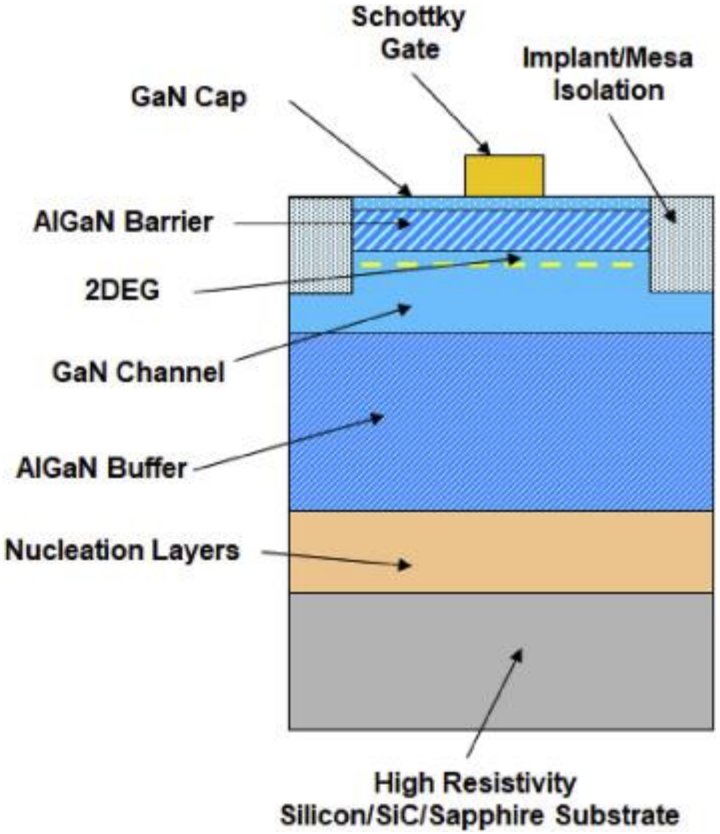
Lateral GaN-based transistors





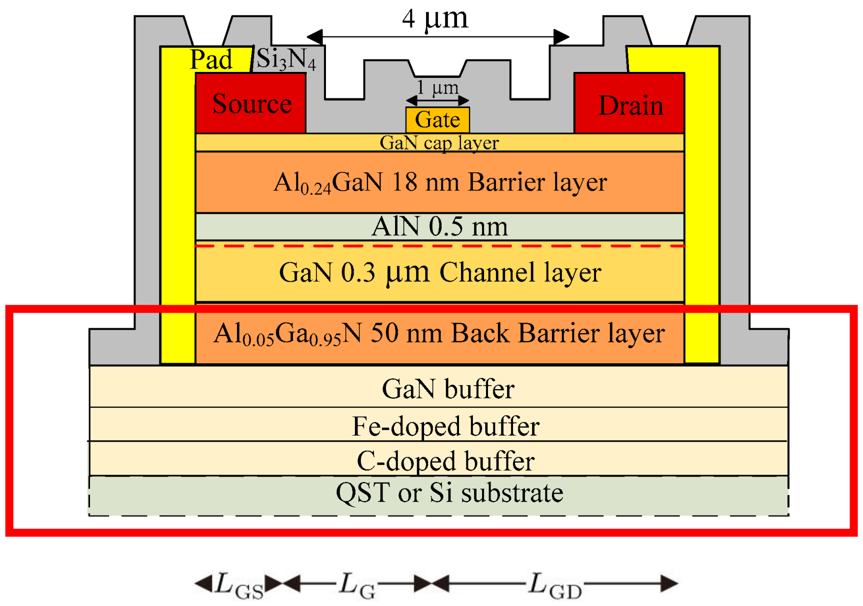


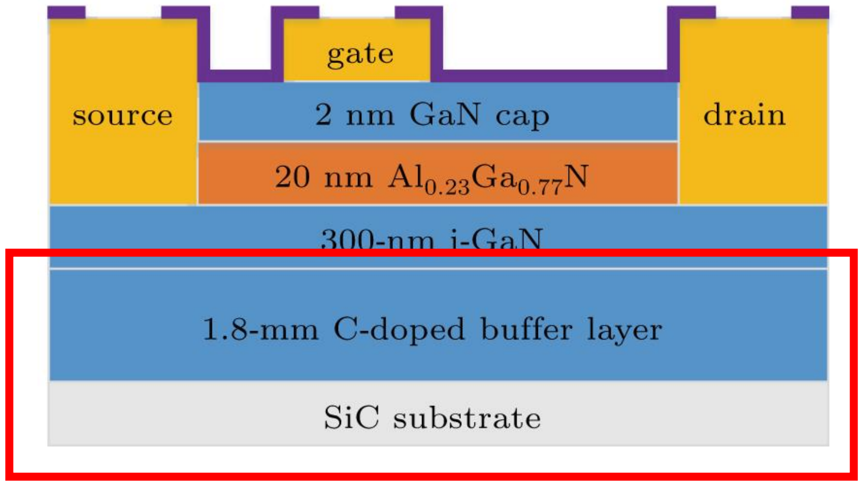


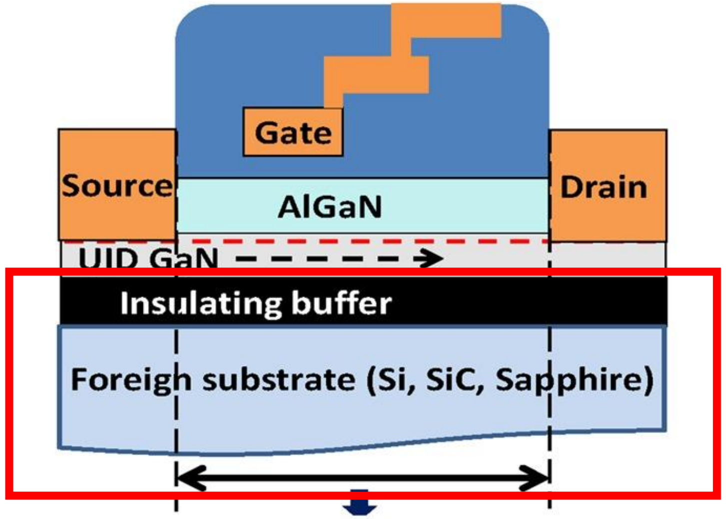


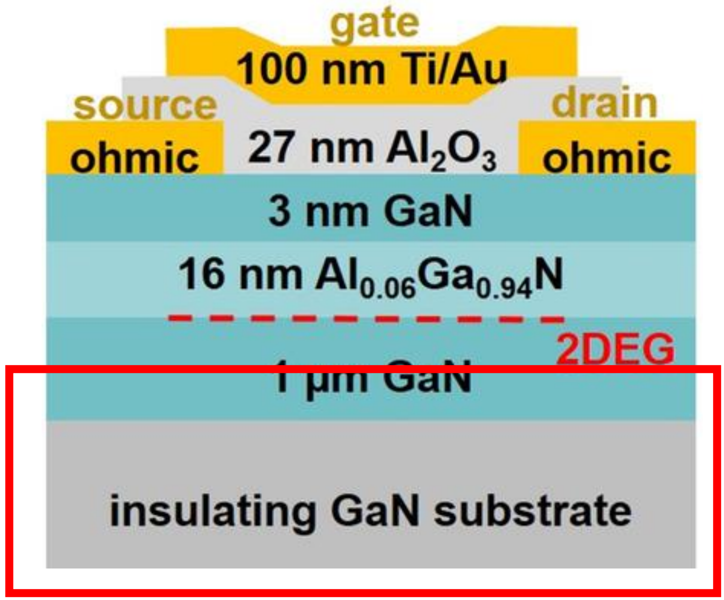
S. Chowdhury et al. Phys. Status Solidi A 212 2015
S. Schmult et al. Phys. Status Solidi A 217 2020
Mingchen Hou et al 2021 Chinese Phys. B **30** 097302
F. Iucolano et al.,Mat. Sci. Sem. Proc.Vol. 98 2019

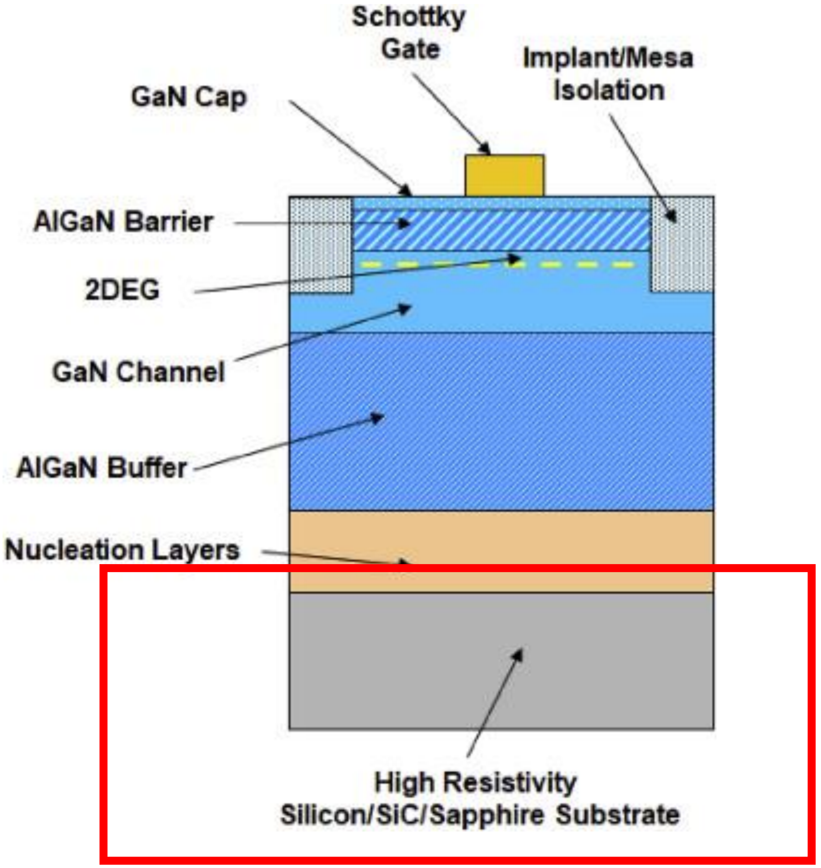
Lateral GaN-based transistors











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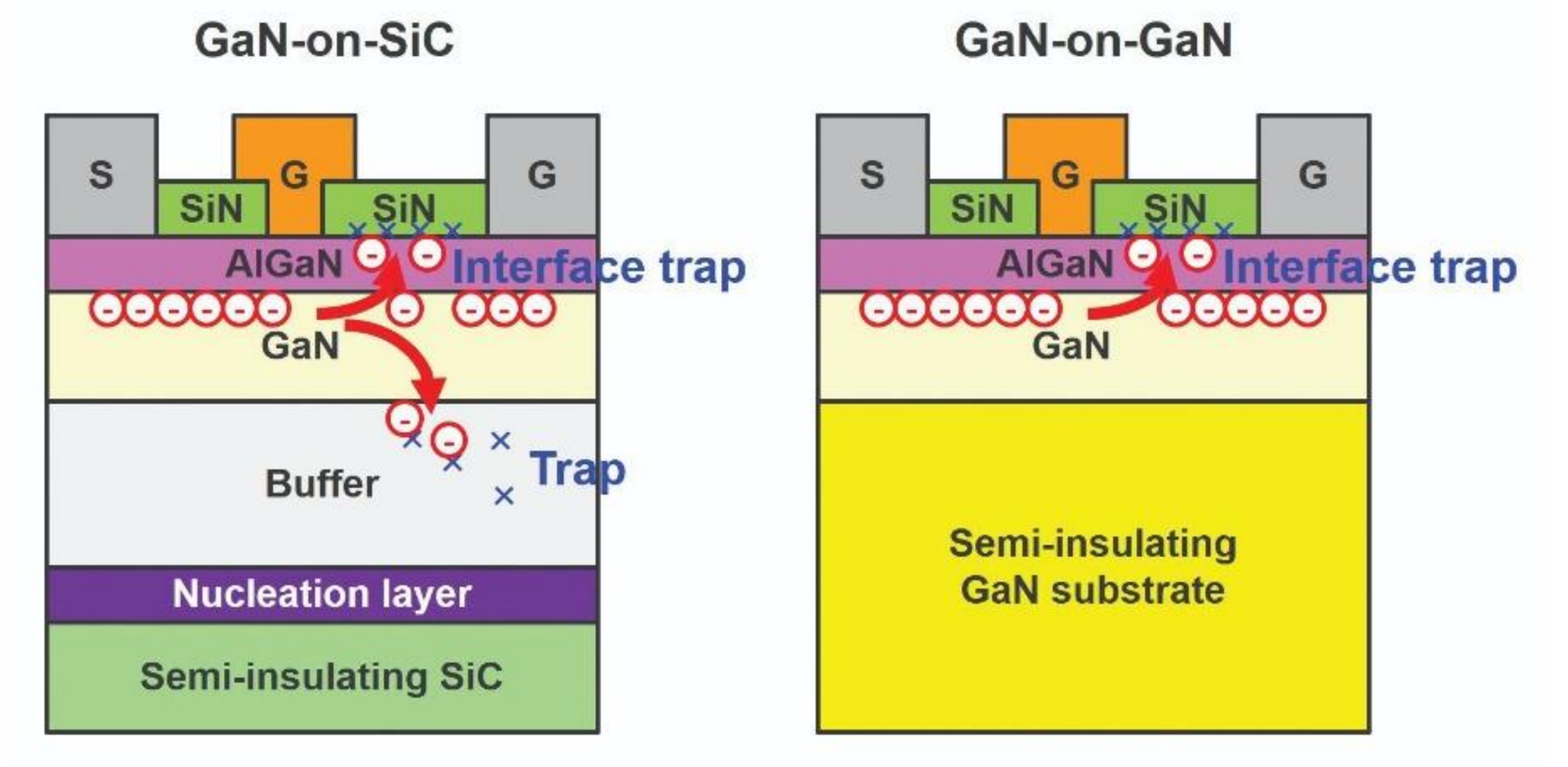
Mingchen Hou et al 2021 Chinese Phys. B **30** 097302
F. Iucolano et al.,Mat. Sci. Sem. Proc.Vol. 98 2019

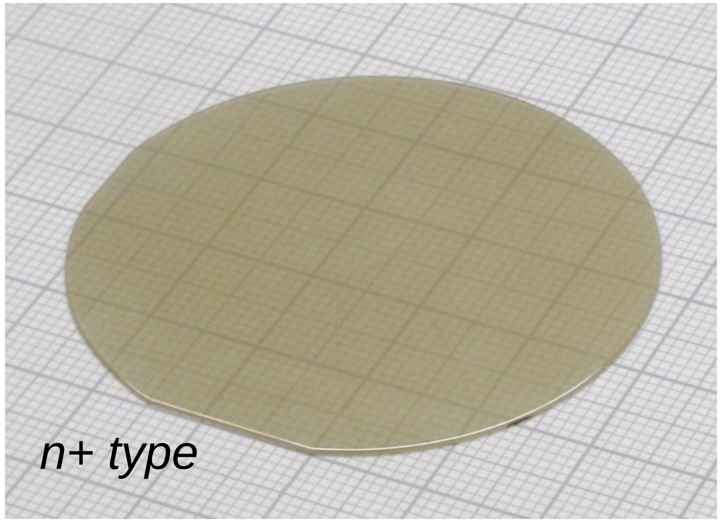
Substrate role in HEMT

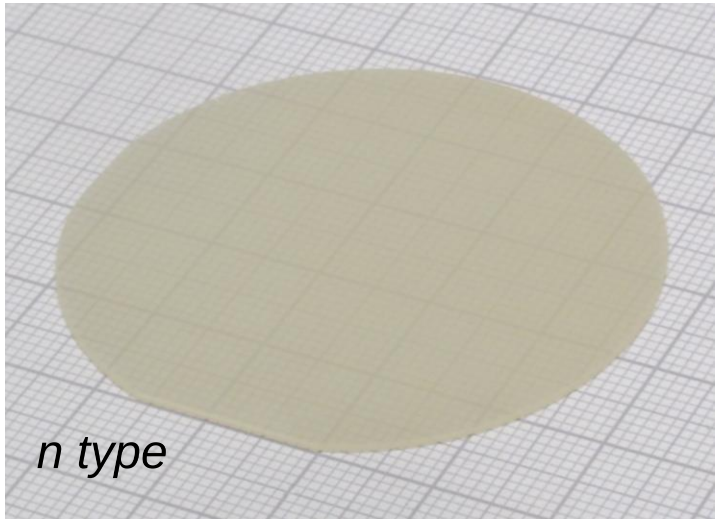


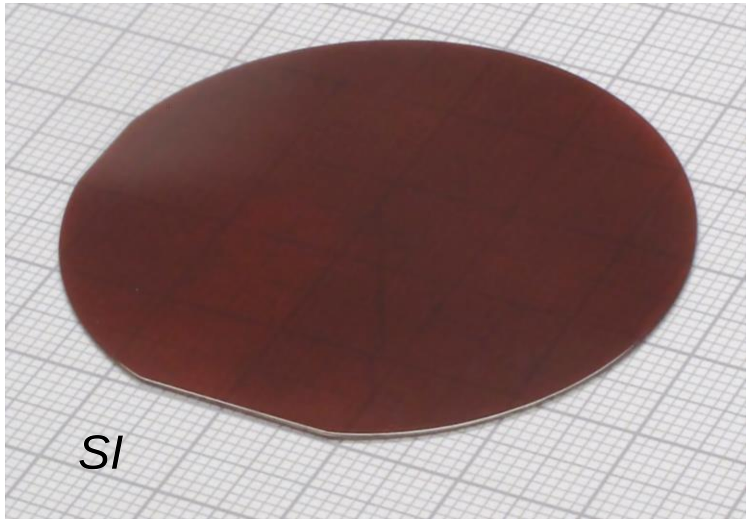
Additional trapping of electrons due to high concentration of threading disslocations

N. Okamoto et al. CS ManTech Conf., April 2019, 10.5.

2” Ammonothermal GaN wafers

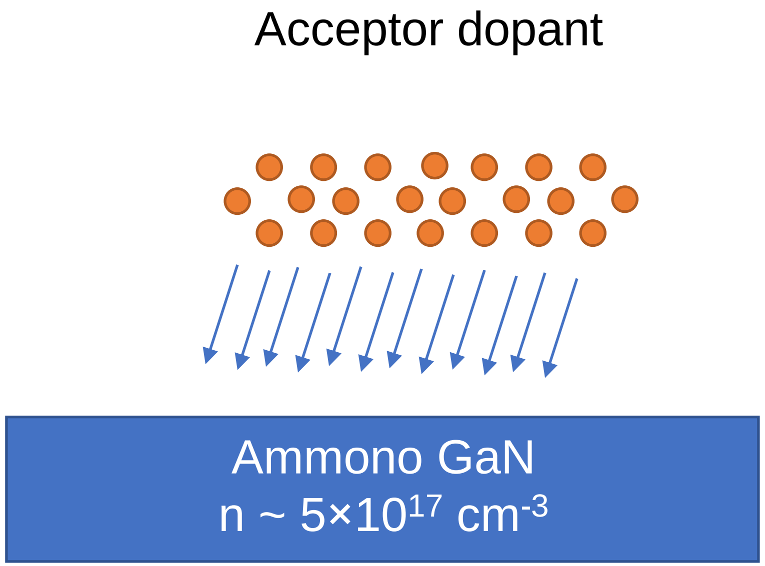

n+ type


n type


SI

Material type	*Conductivity type*	*Carrier concentration [cm^{-3}]*	*Carrier mobility [cm^2/Vs]*	*Resistivity [Ωcm]*	*Note*
High carrier concentration	***n+ type***	***~10^{19}***	*~150*	*10^{-3}*	*Low TDD*
Low carrier concentration	***n type***	***~10^{18}***	*~250*	*10^{-2}*	*Low TDD*
High resistivity (Mn-doped)	***semi-insulating (SI)***	*-*	*-*	***≥10^{8}***	*Low TDD, Difficult wafering*

Samples preparation

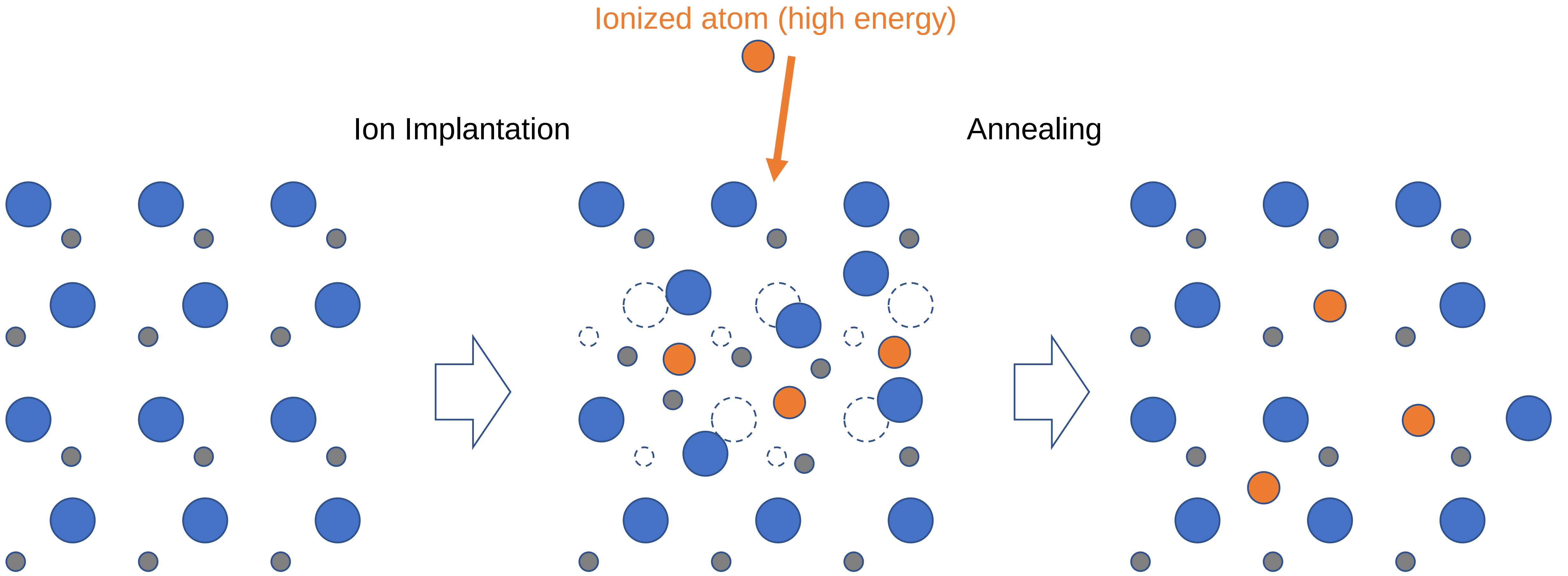


Acceptor dopant

Ammono GaN

n ~ 5×10^{17} cm^{-3}

Ion Implantation in Semiconductors

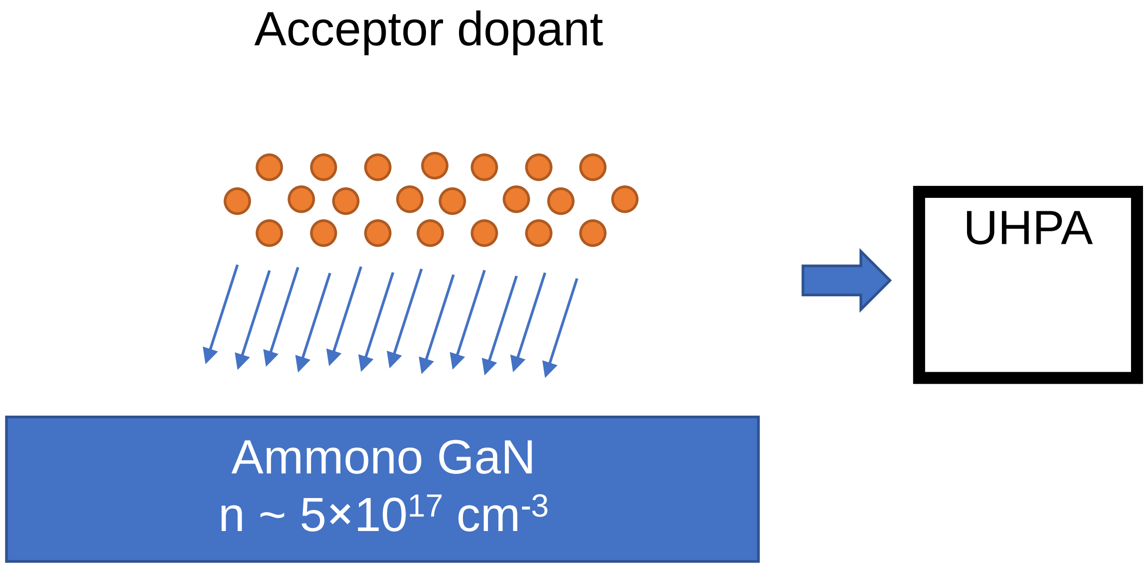


Pristine sample

As-implanted sample:
many displaced atoms

Annealed sample:
Structure healed/dopants activated

Samples preparation

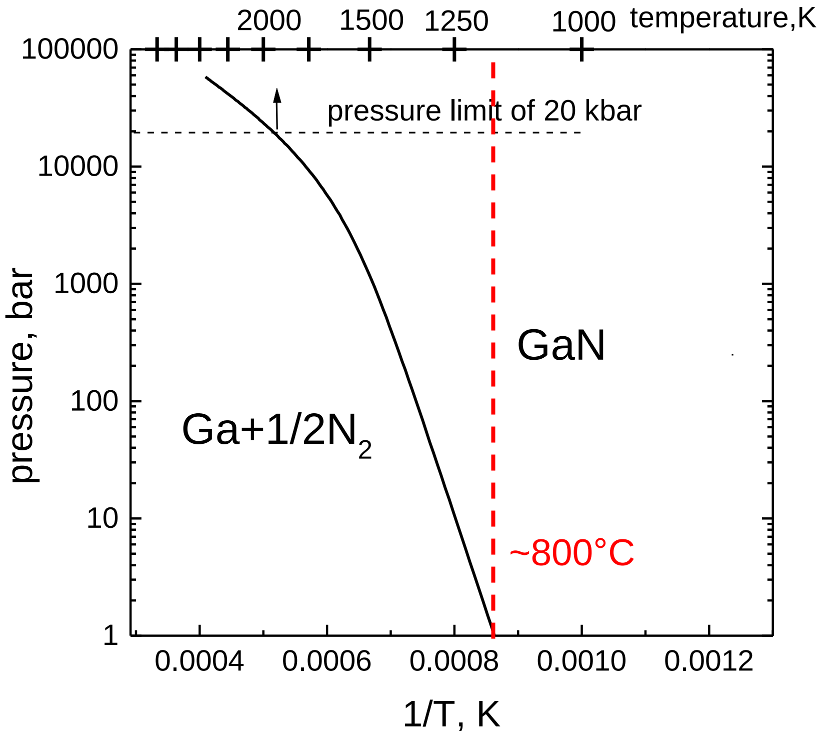


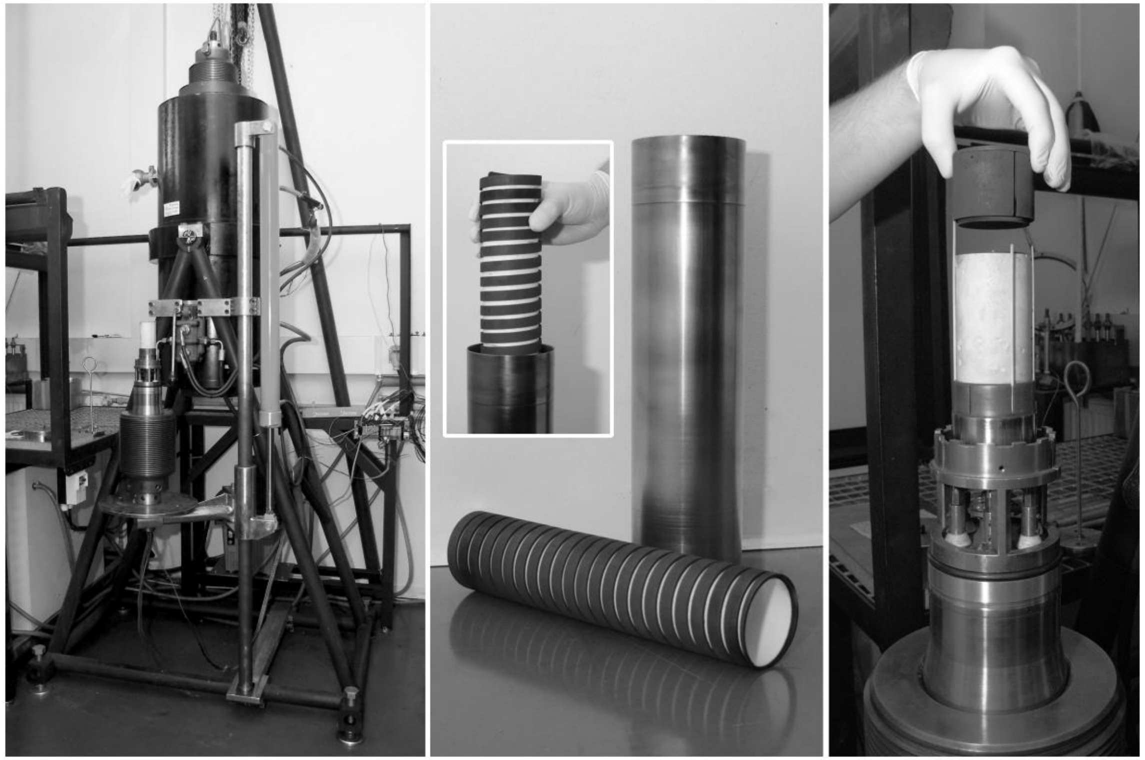
Acceptor dopant

Ammono GaN
n ~ 5×10^{17} cm^{-3}

UHPA

Annealing of implanted GaN

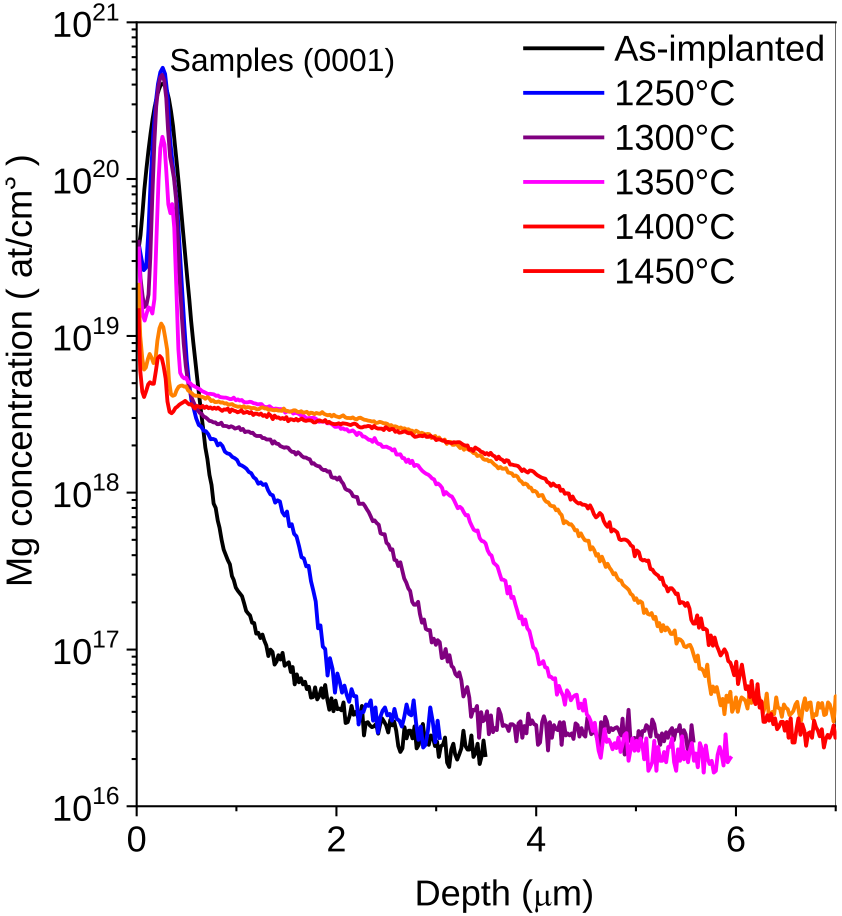




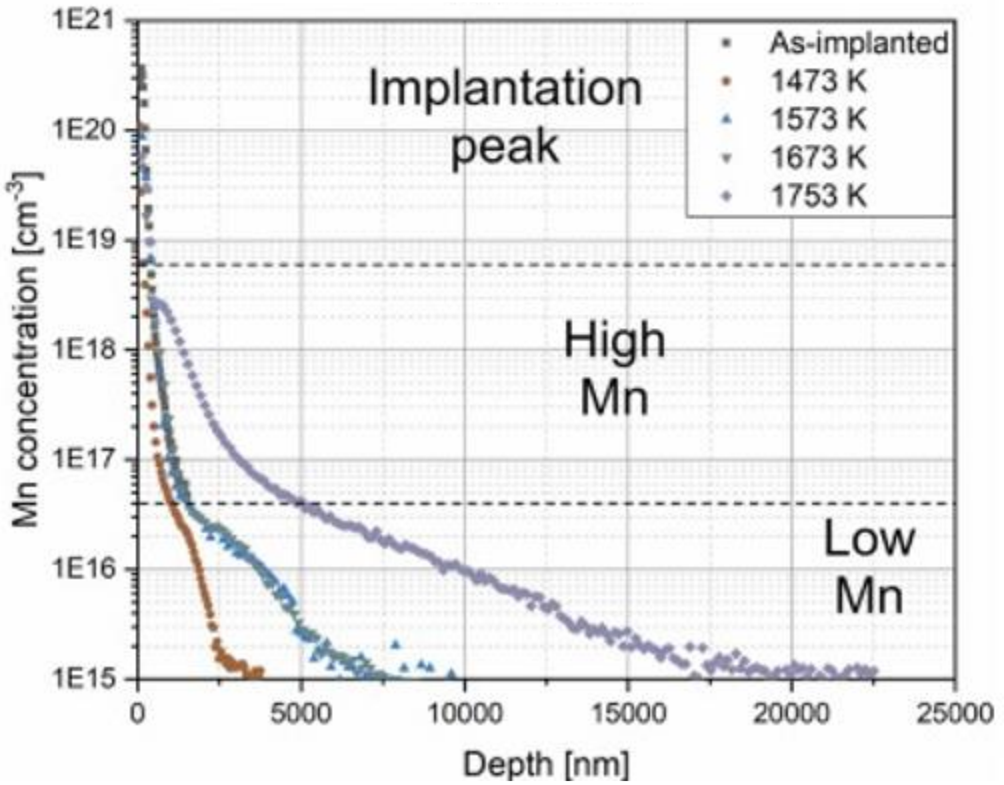
J. Karpinski et al. Journal of Crystal Growth, 66, 1984, Pages 1-10

Acceptor dopant selection

Magnesium 1.5 h UHPA



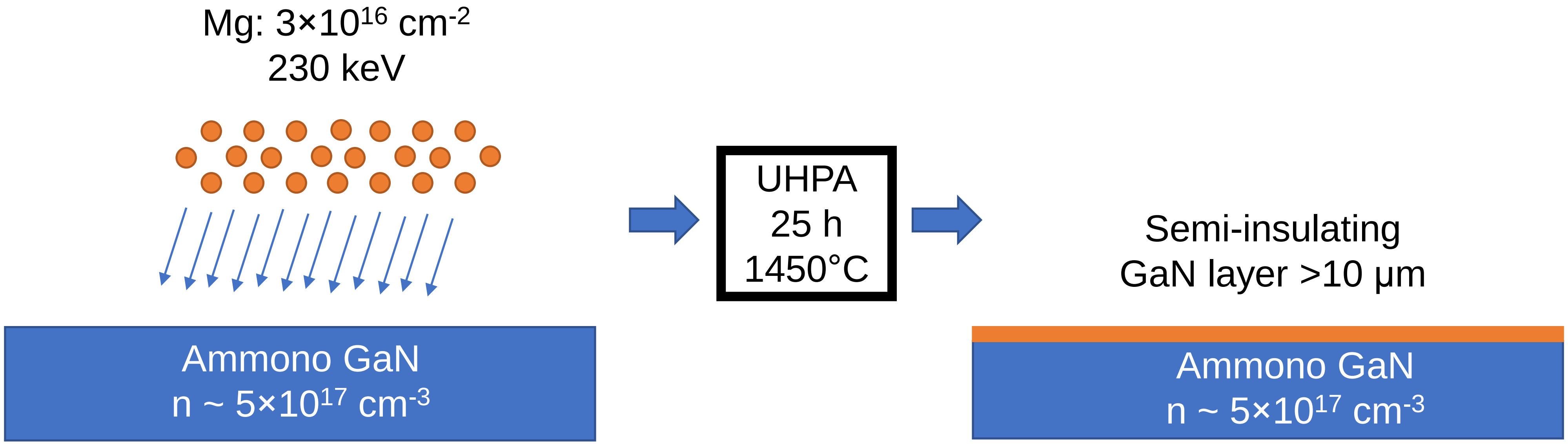
Manganese 30 h UHPA



K. Sierakowski et al., Mat. Sci. Sem. Proc.Vol. 171 2024

P. Jaroszynski et al., J. of Alloys and Compounds Vol. 966 2024

Samples preparation



Mg: 3×10^{16} cm^{-2}
230 keV

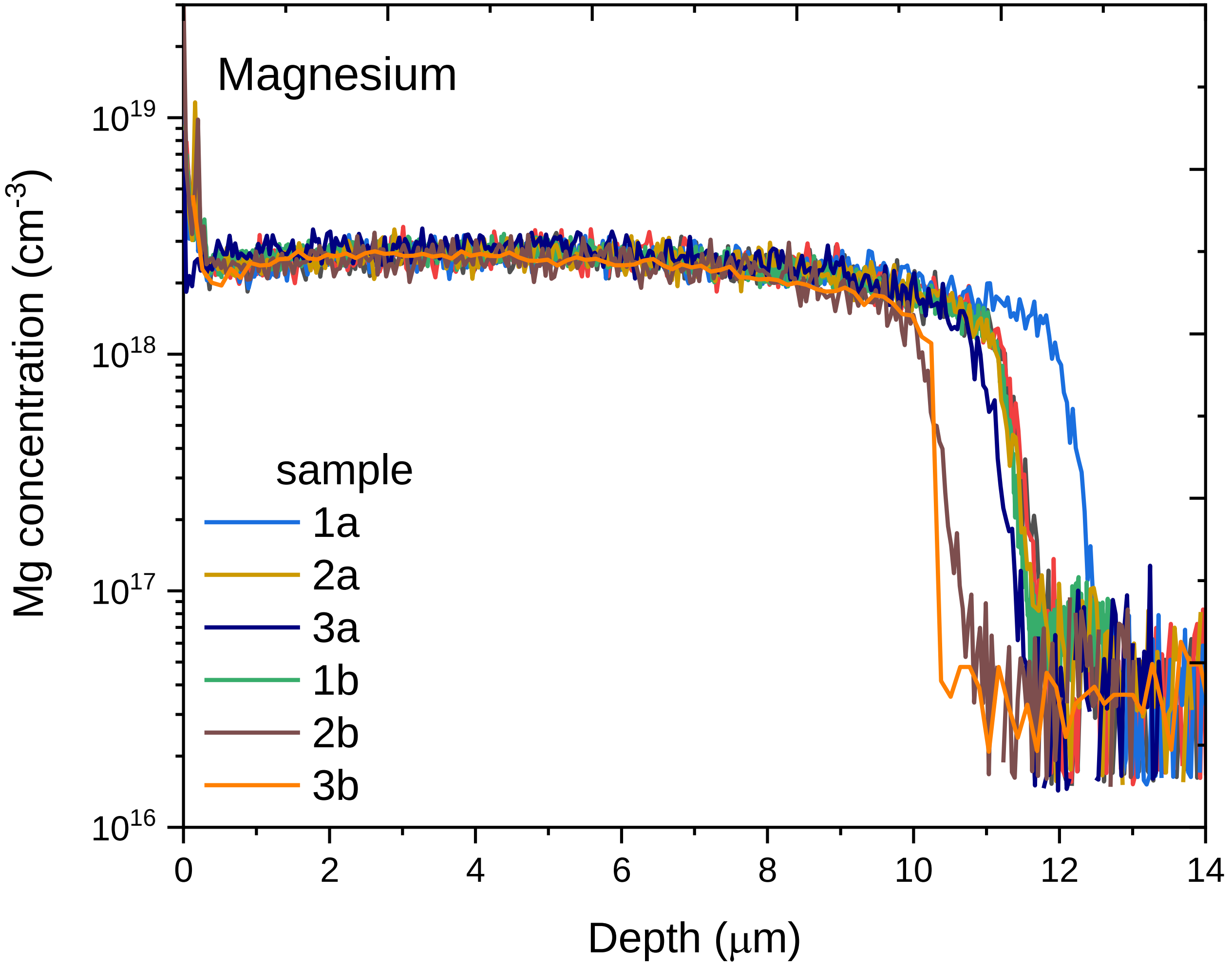
UHPA
25 h
1450°C

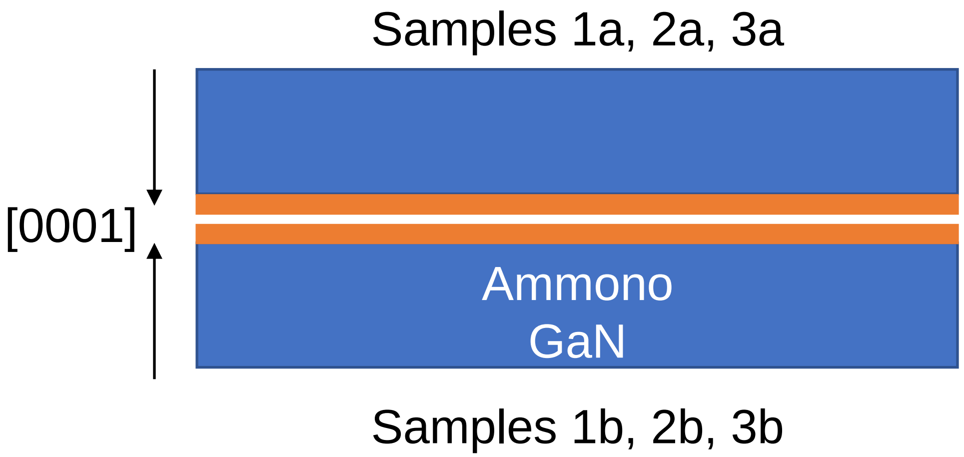
Semi-insulating
GaN layer >10 μm

Ammono GaN
n ~ 5×10^{17} cm^{-3}

Ammono GaN
n ~ 5×10^{17} cm^{-3}

Depth profiles of Mg after UHPA



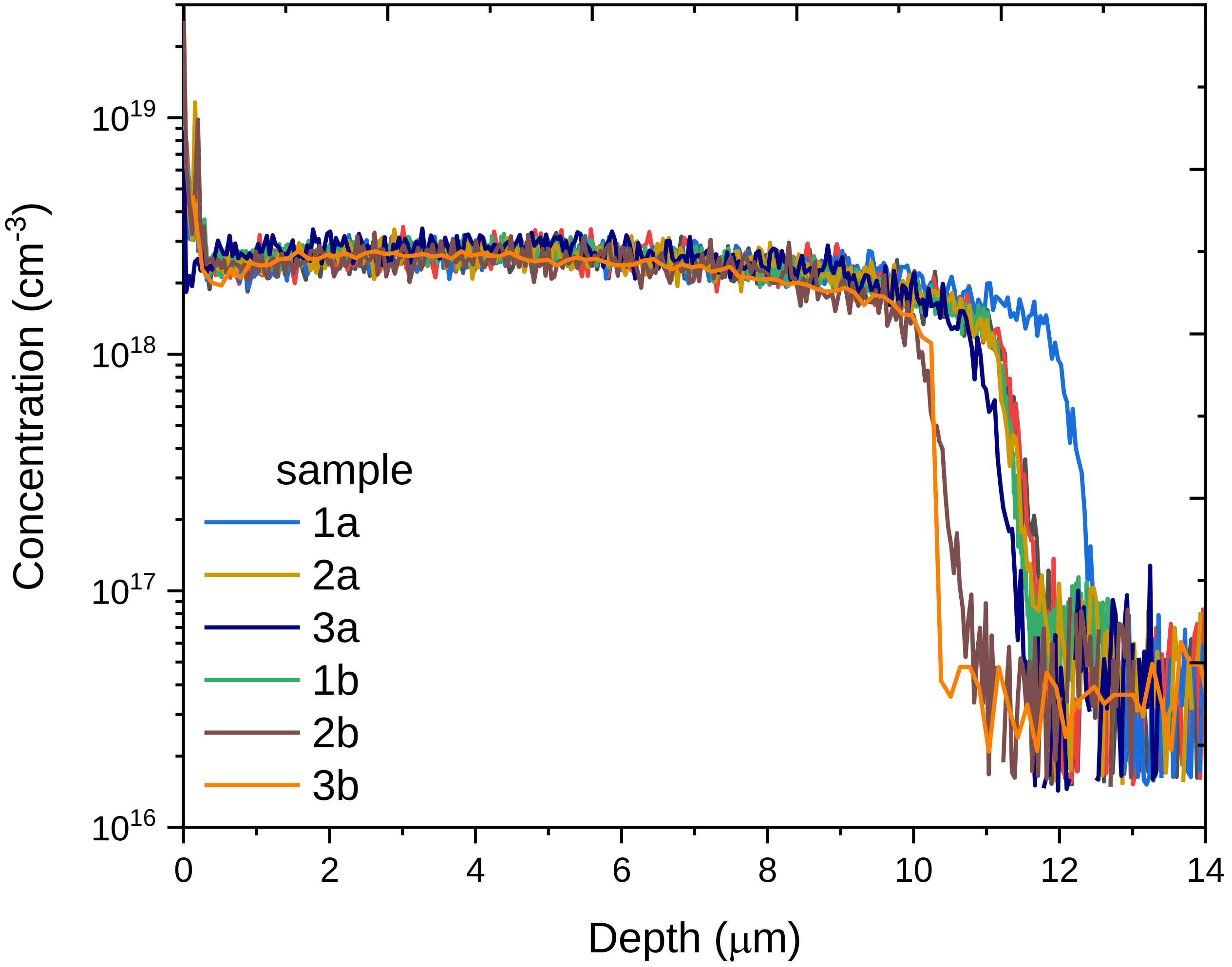

Samples 1a, 2a, 3a

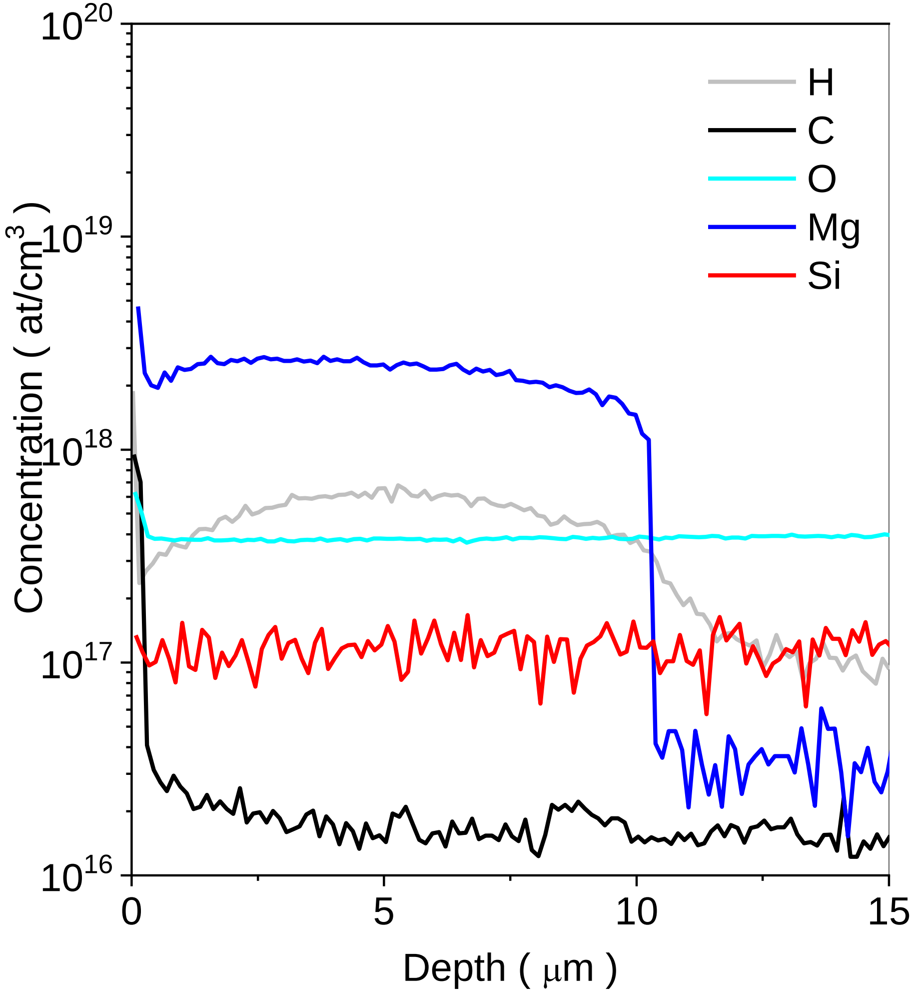
[0001]

Ammono GaN

Samples 1b, 2b, 3b

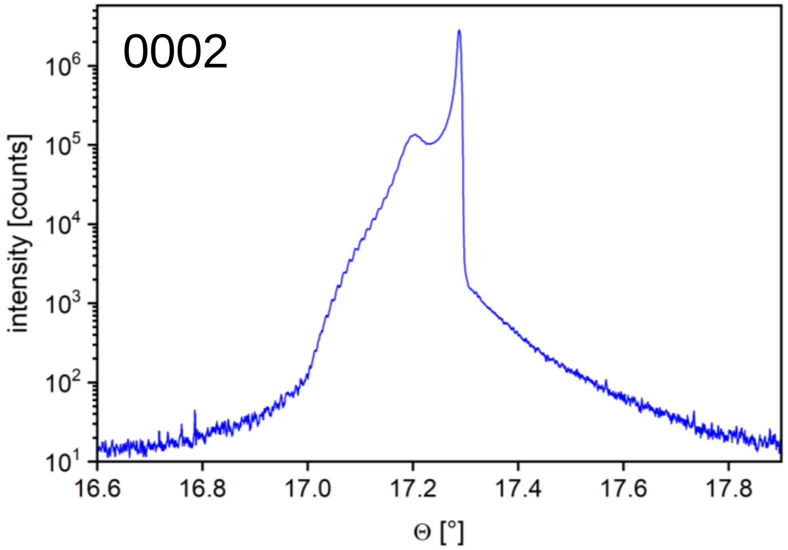
Depth profiles after UHPA

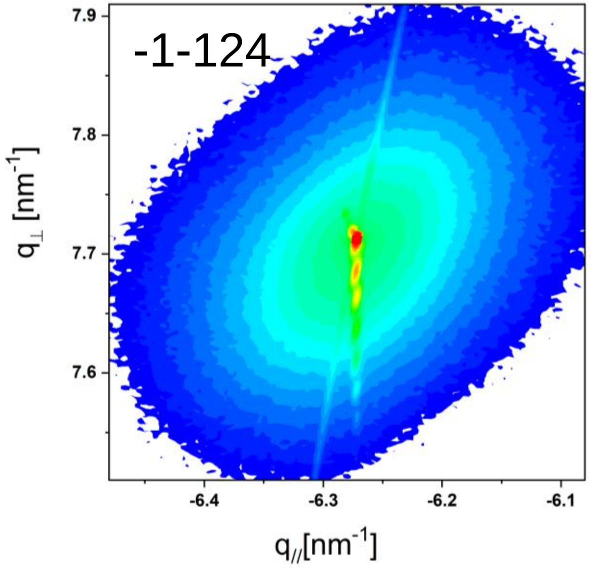




X-Ray diffraction

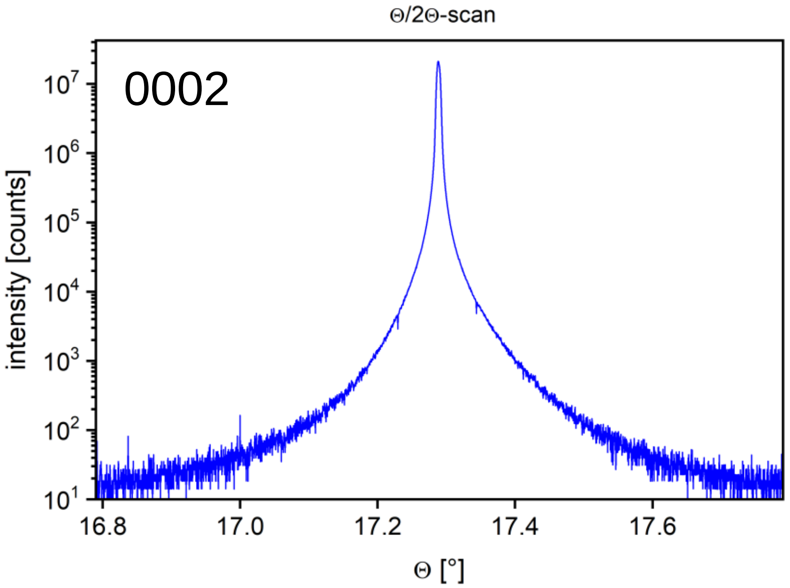
As-Implanted

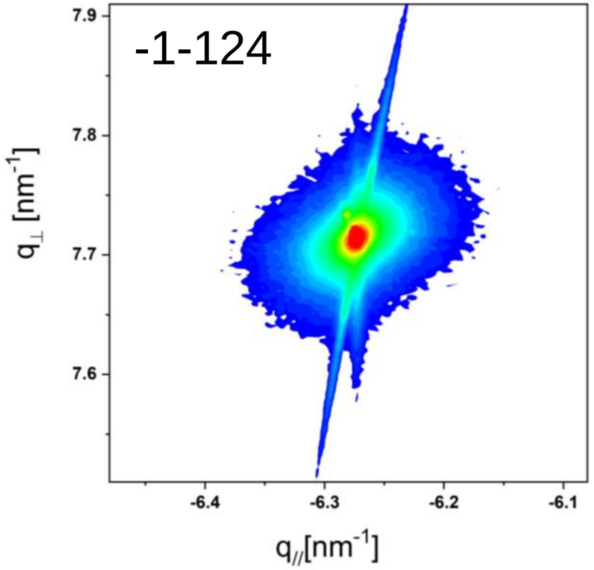




The sample shows enormous diffuse scattering after implantation.

Annealed
1450°C/25h



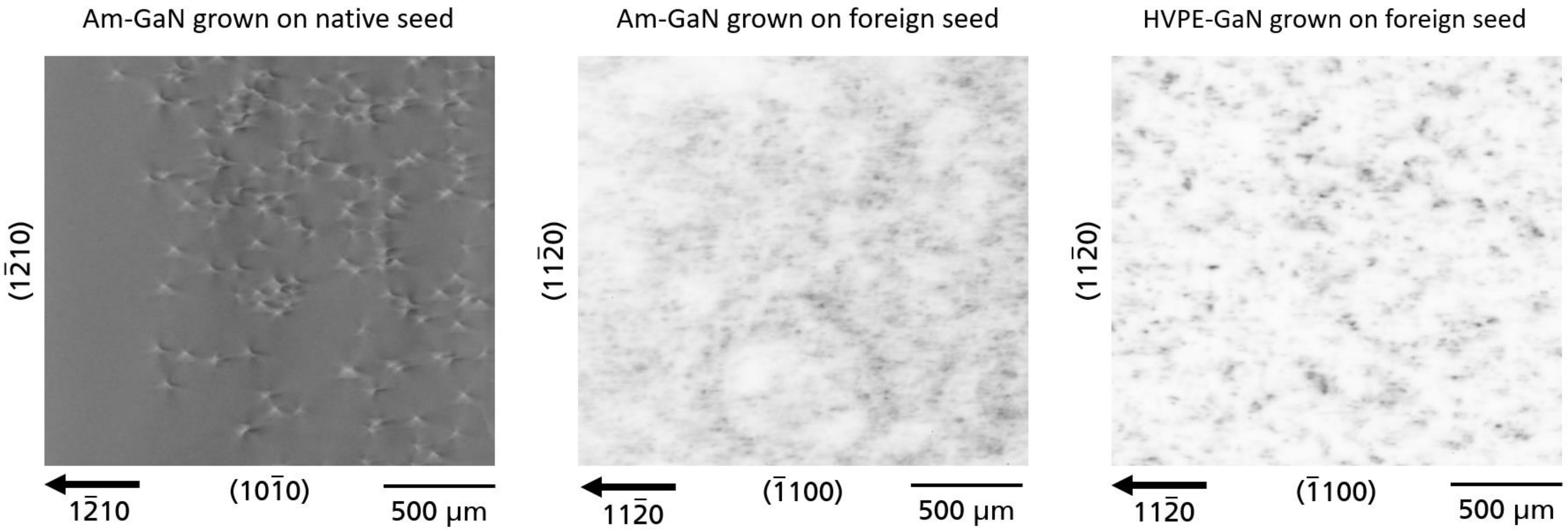


Ammonothermal GaN → high structural perfection

- ***X-Ray Topography (XRT)***

The Borrmann effect

dramatic increase in transparency for X-ray diffraction in transmission
robust method for evaluating the structural perfection of GaN
proof of the high perfection of the crystals



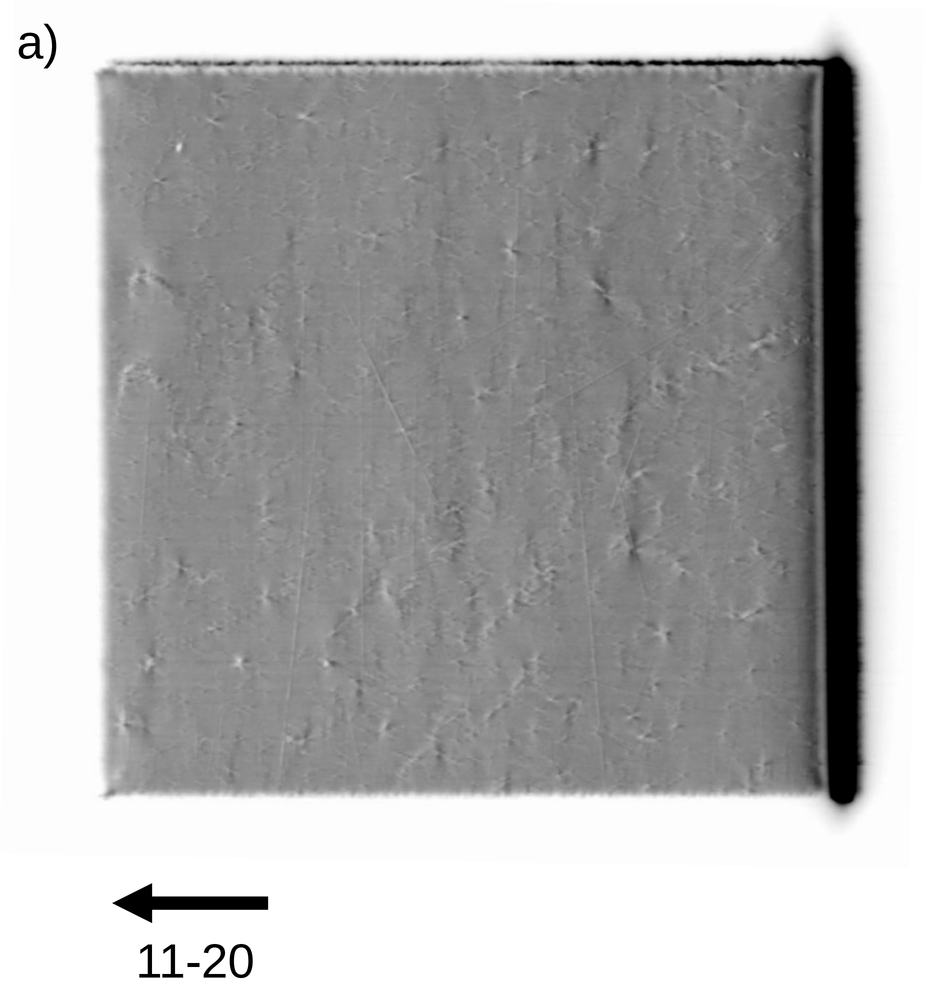
The Borrmann effect is blocked

L. Kirste et al., Materials 2021, 14, 5472.

X-Ray Topography in transmission mode

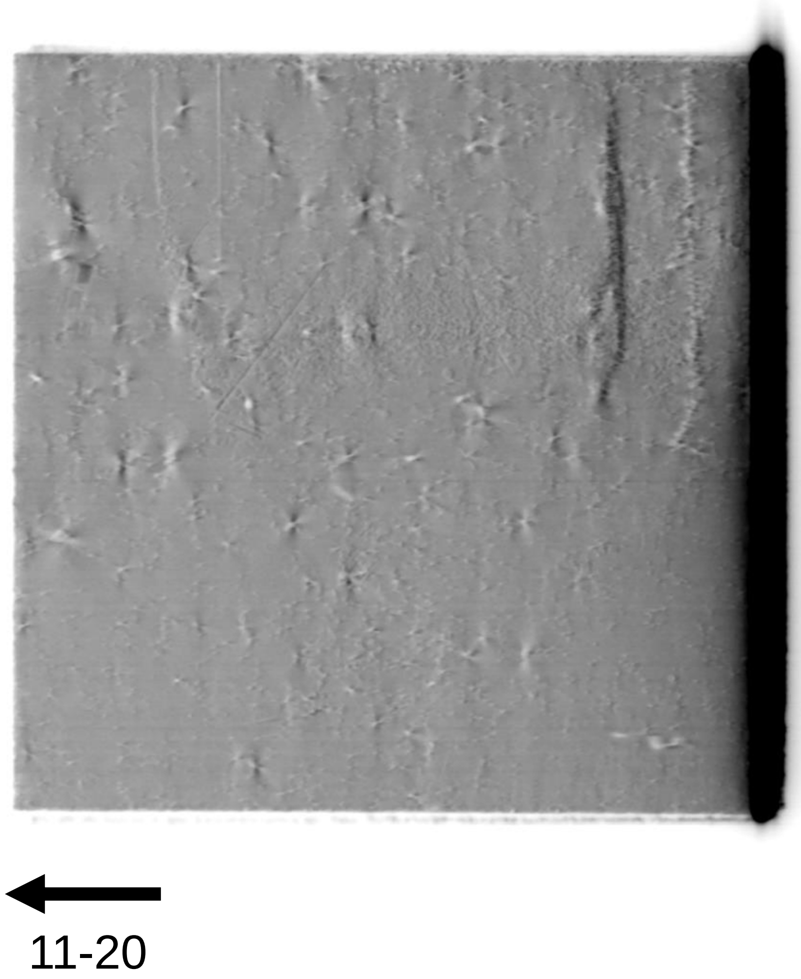
As-Implanted
transmission, Cu-radiation

a)



Annealed sample
transmission, Cu-radiation

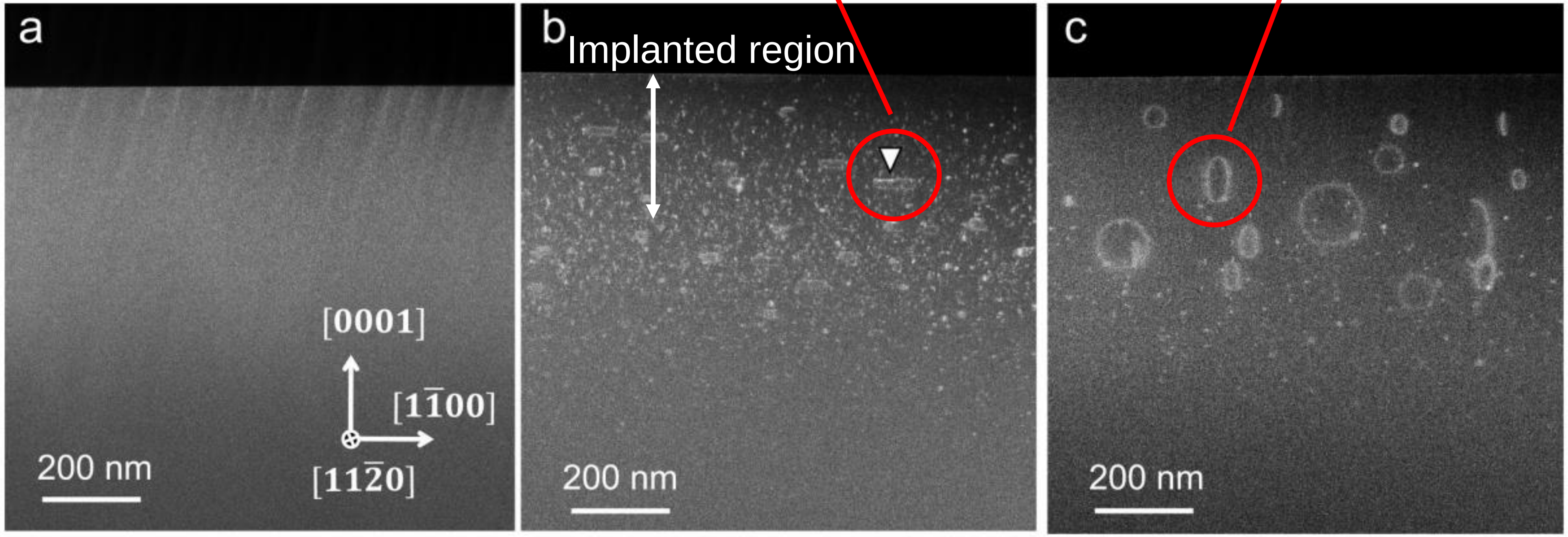
b)



TEM - literature

Inversion domain

Intrinsic defect on {11-20} plane



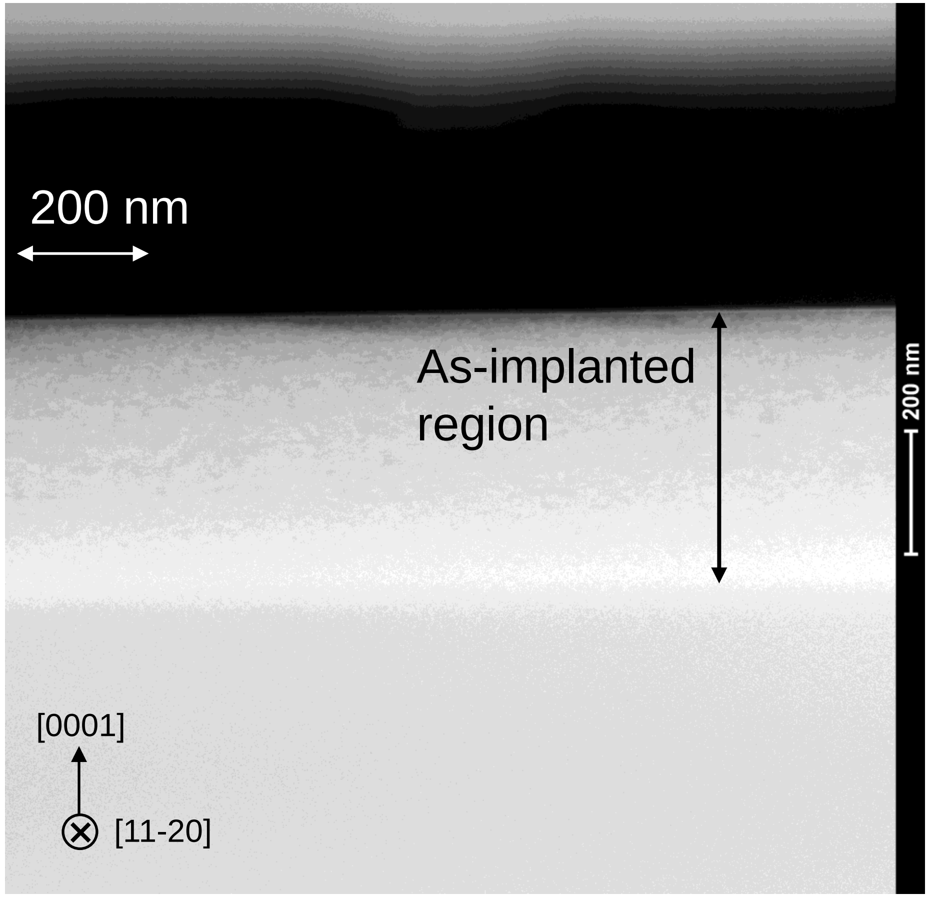
As-implanted

1300°C UHPA

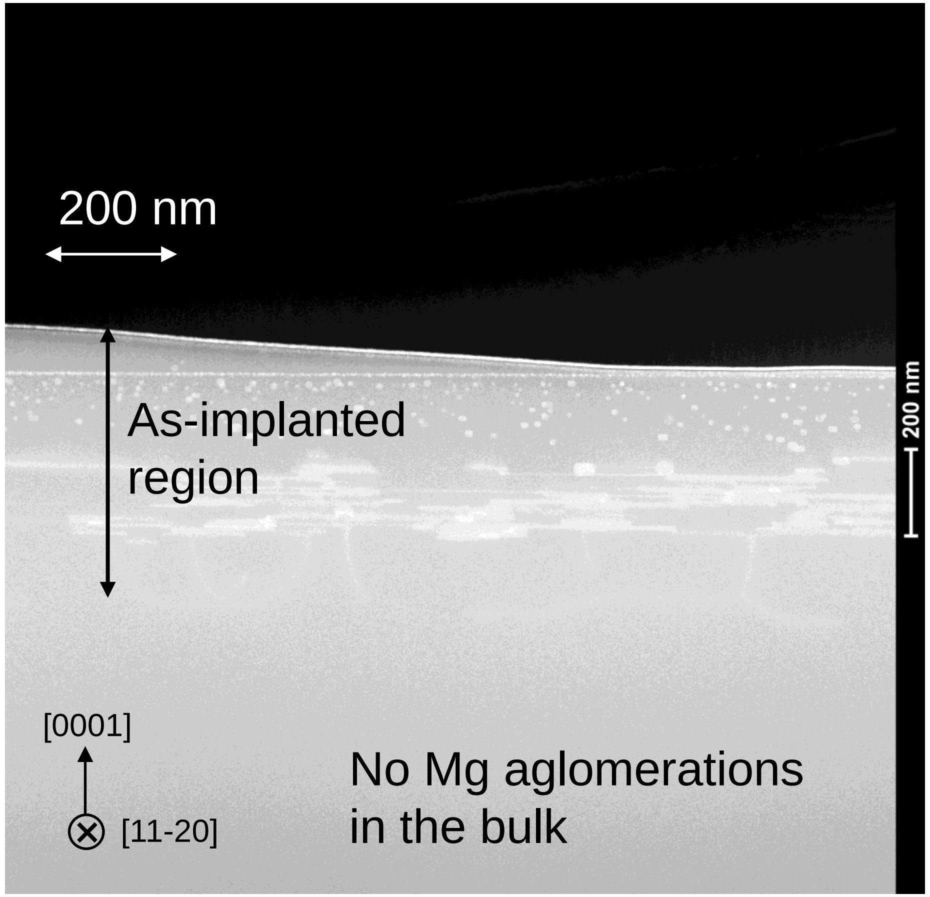
1480°C UHPA

Iwata et. Al. J. Appl. Phys. 127, 105106 (2020)

TEM



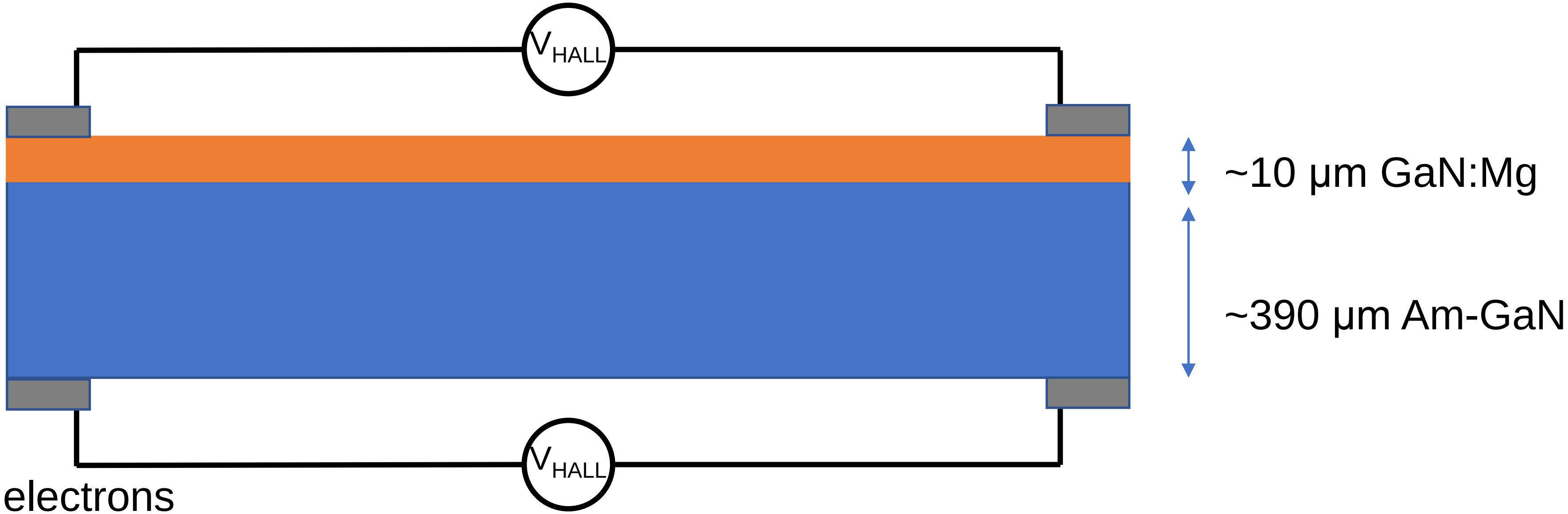
As-implanted sample



UHP-annealed sample

Electrical measurements

Majority carrier type: not possible to determine
Carrier mobility: not possible to measure
Resistivity: $\rho > 1\times10^{4}$ Ωcm (in T > 500 K)
Free carrier concentration: not possible to measure



Majority carrier type: n, electrons
Carrier mobility: $\mu = 360$ cm^{2}/Vs
Resistivity: $\rho = 1\times10^{-2} – 8\times10^{-3}$ Ωcm (in T range 180-300 K)
Free carrier concentration: $n = 4.5\times10^{17}$ cm^{-3} (well correlated with [O] from SIMS)

Magnesium ion implantation and UHPA drastically changed the electrical properties of the sample. A highly resistive layer of GaN:Mg was succesfully achieved by mentioned techniques.

Summary

- Deep diffusion of Mg was succesfully achieved while keeping the constant Mg concentration
- Semi-bulk layer (10-12 µm) of GaN:Mg was observed
- The ion-implantation induced damage was removed from the crystal
- The implanted Mg was succesfully activated resulting in semi-insulating layer

unipress

Thank you!

Acknowledgments

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NCBR
National Centre for Research
and Development