Positron Study of Ion-Cutting process in GaN

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Outlook

- Introduction : What is GaN semiconductor (good for)?
- Ion cut process…..why?
- Experiments
- Characterization of GaN samples
- Conclusion

Introduction

GaN is an interesting semiconductor……….. Why ?

A considerable interest in GaN due to favorable properties :

- Wurtzite-structured semiconductor.
- Large direct band gap of 3.4 eV (WBG).
- High thermal conductivity.

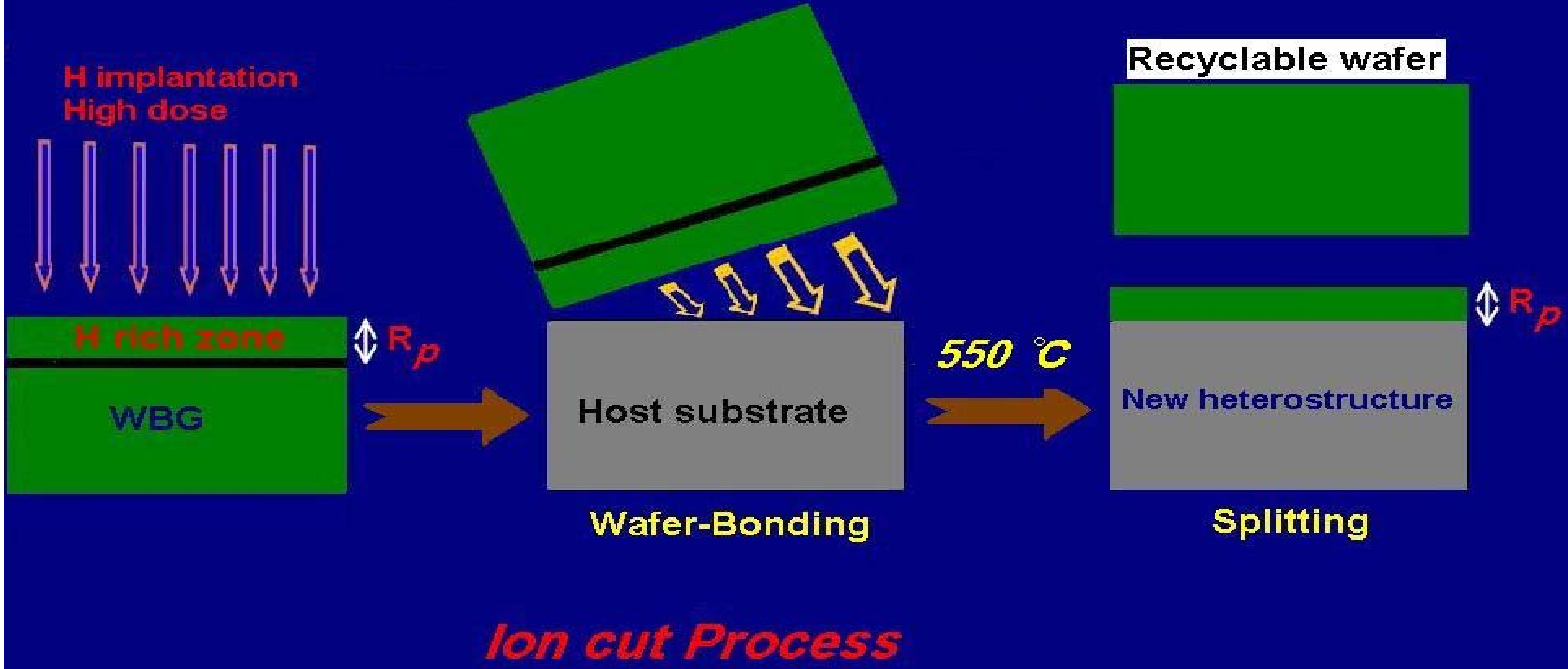
These properties make GaN a promising material for many applications:

- High-temperature electronic devices.
- Realization of blue and green light emitting diodes: widely used, for instance, in full-color displays and in traffic signals.
- Nitride laser diodes are key components in emerging high-definition DVD players.
- Other promising application areas: printing, sensors, communication, and medical equipment.
- ***Book: Nitride Semiconductor Devices, Joachim Piprek, 2006.***

- GaN is mostly grown epitaxially on lattice and thermal mismatched substrates like sapphire, SiC or even on Si due to the fact that free-standing bulk GaN substrates are very expensive and are mostly available in small sizes.
- The heteroepitaxial growth of GaN on foreign substrates leads to the formation of growth-related defects like dislocations, stacking faults, twins etc. that occur to relax the strain.
- The high density of defects in the epitaxial layers of GaN grown on hetero-substrates has deleterious effects on the performance and reliability of the devices fabricated utilizing these layers.
- **What to do….. ?**

Ion cut process……. Why ?

- One of the methods to fabricate low-cost and high structural quality substrates, comparable to free-standing GaN substrates, for the epitaxial growth of group-III nitrides is the direct wafer bonding and layer transfer of thin GaN films via a high dose hydrogen implantation and layer splitting upon annealing.



- The free-standing GaN substrate can be utilised to transfer multiple layers on other substrates.
- This process is based upon the agglomeration of hydrogen implantation-induced platelets upon annealing and the subsequent formation of over-pressurized microcracks.
- For the case of the implanted wafer bonded to a handle wafer, splitting of a thin slice of material parallel to the bonding interface occurs.
- After implantation and annealing, the comprehension of mechanisms dealing to defects formation and evolution is important.
- In this work, we tried to characterize the thermo-evolution of defects in Hydrogen implanted GaN-fs material by using Variable energy positron lifetime spectroscopy and Rutherford backscattering spectroscopy in Channeling mode.

Experiments

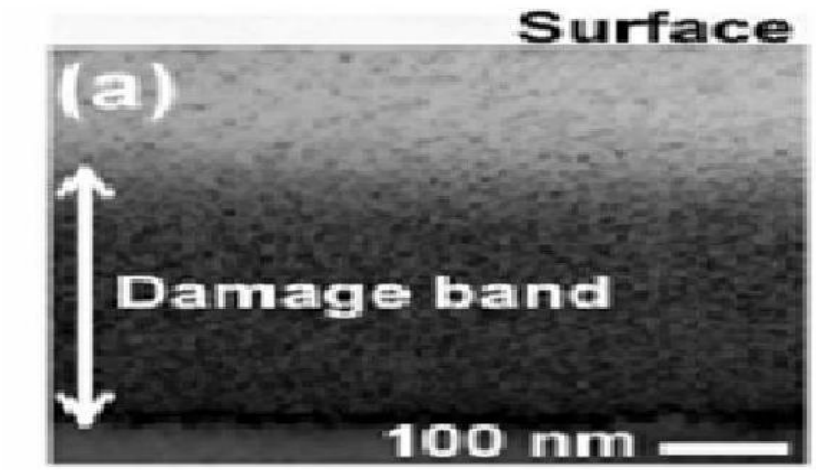
Samples preparation

- 300 µm-thick 2 in. double side polished undoped fs-GaN wafers.
- Room temperature H implantation at 50 keV with a fluence of 2.6×10^{17} atom/cm^2
- Annealing at 300 – 400 – 450 – 500 – 600 ºC for 1-2 min.

Experimental methods

- Cross section transmission electron microscopy: Study of post-implantation structural and morphological changes;
- Rutherford backscattering spectrometry in channeling mode: Characterization of displacement fields and strain build-up induced by thermal annealing of implanted substrate;
- Positron annihilation spectroscopy: To probe open volumes and vacancy clusters induced by H implantation and their thermal evolution.

Characterization of GaN samples: Transmission Electron Microscopy TEM



RT temperature implanted GaN

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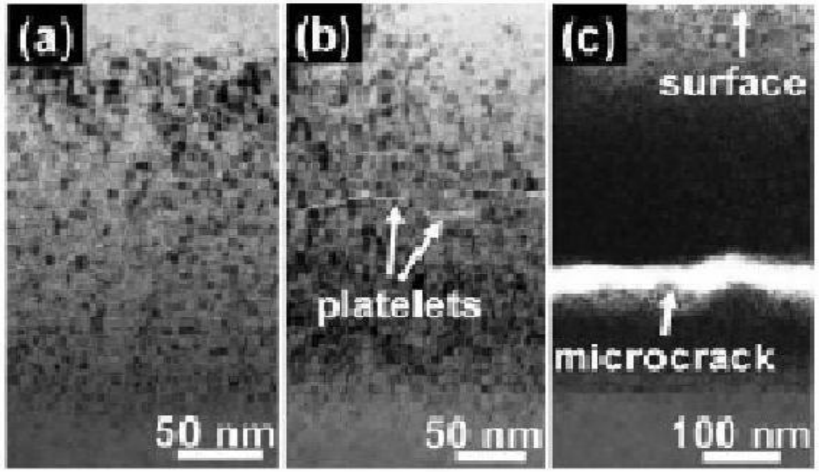

H-implanted GaN annealed at different temperatures: (a) 450 °C, (b) 500 °C, (c) 600 °C.

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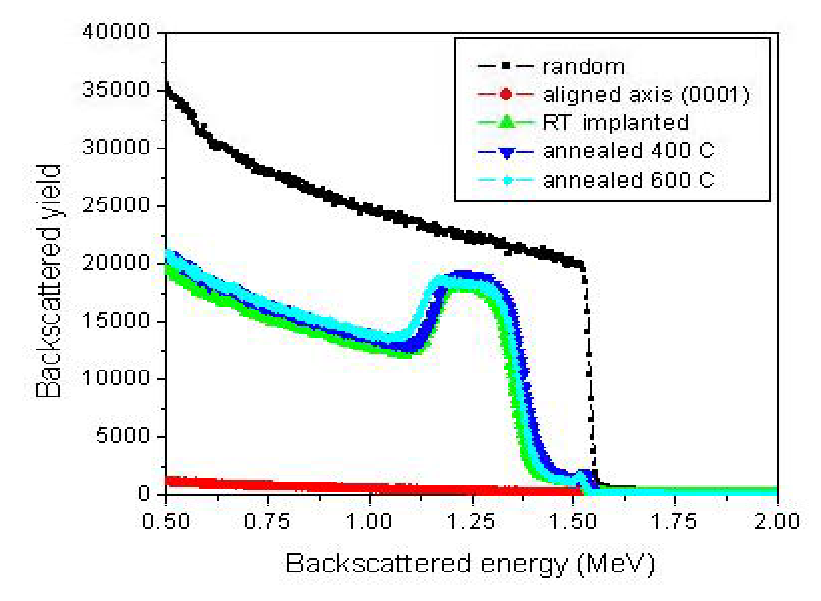
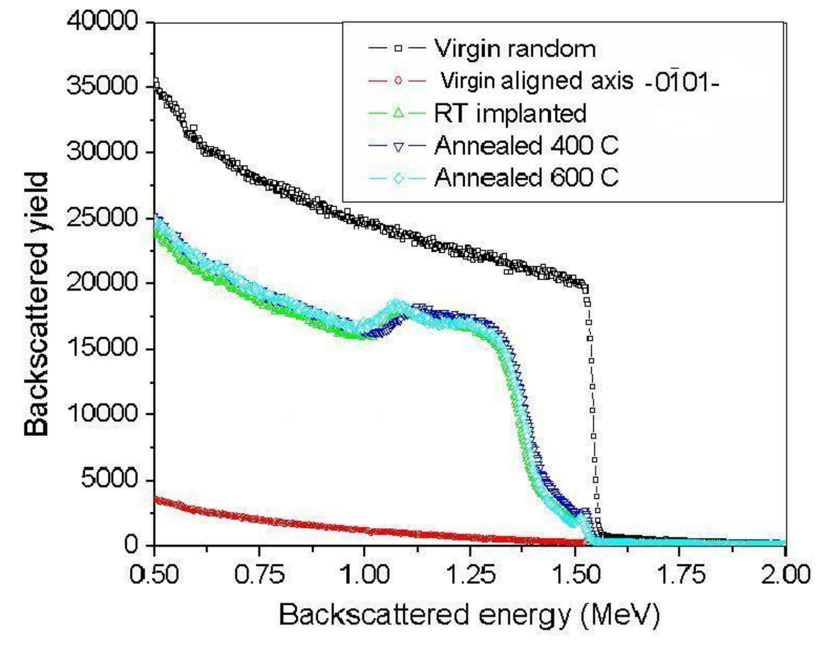
- As implanted sample: the implanted zone is decorated with nanobubbles
- Annealing at 450 °C: presence of nanobubbles.
- Annealing at 500 °C: formation of nanoscopic cracks or platelets parallel to the surface.
- For 600 °C: formation of large cracks leading to a complete exfoliation of a 340-nm-thick layer.
- The structural transitions from nanobubbles to platelets and from platelets to microcracks occur within temperature windows as narrow as 50 K.

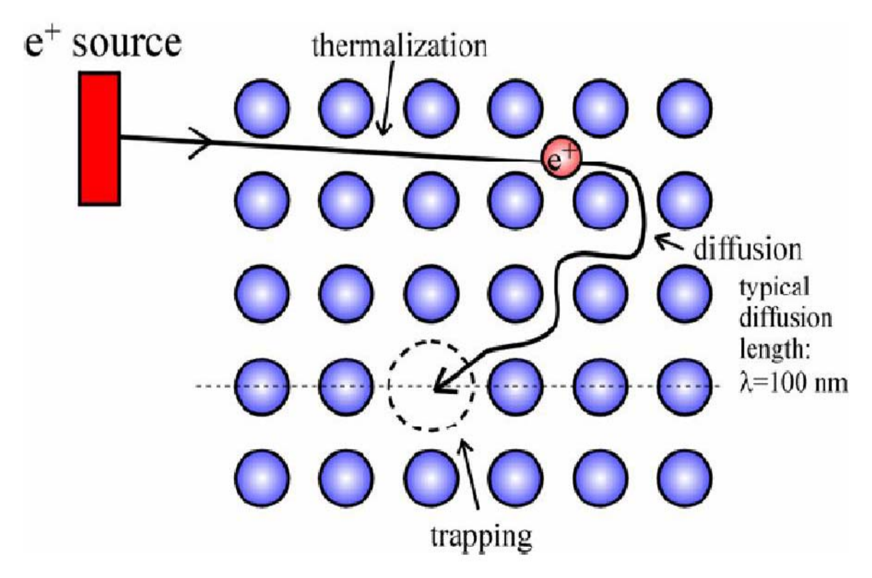
Characterization of GaN samples: RBS Channeling experiments





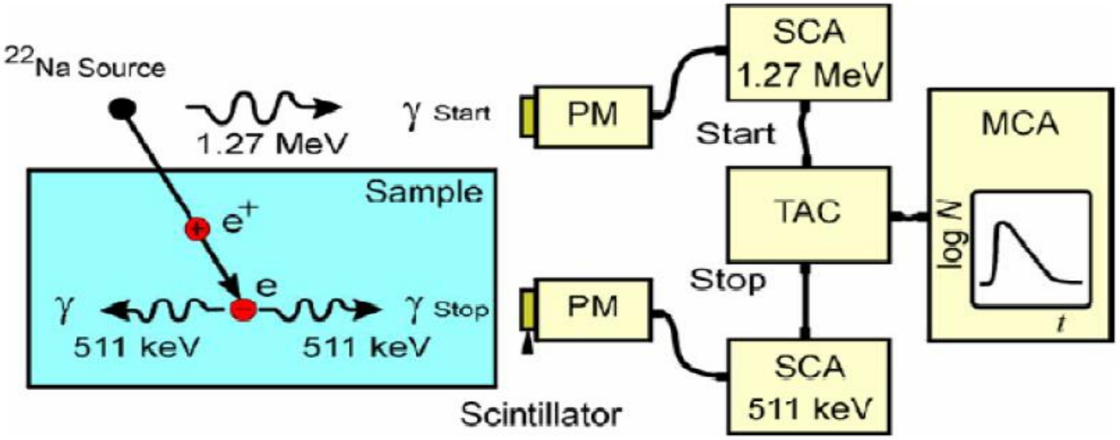
- H implantation creates a damage peak in the ion channeling yield centered at ~1.25 MeV.
- the damage peaks for <01¯01> channeling are larger than that obtained for <0001>: due to a geometric factor.
- The reverse annealing (observed for other semiconductors: example Si) does not take place for GaN.
- For 600 ºC: A shoulder appears beyond the damage-related peak for backscattered energies below 1.25 MeV.
- The existence of this shoulder coincides with the formation of nanoscopic cracks.

Positron annihilation spectroscopy PAS: Principles



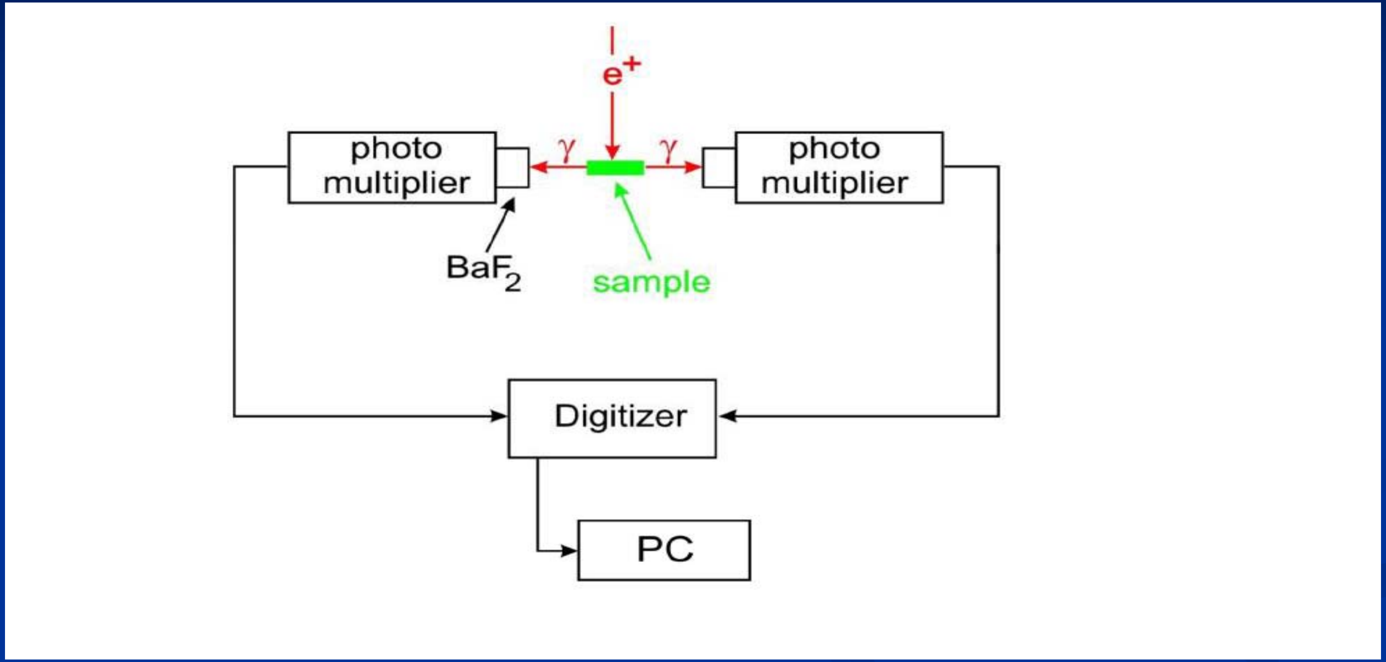
- **Positrons ejected in the solid :**
- thermalize
- diffuse
- being trapped
- **When trapped in vacancies:**
- Lifetime (*S* parameter) increases due to smaller electron density in open volume

PAS: Principles
Lifetime measurement



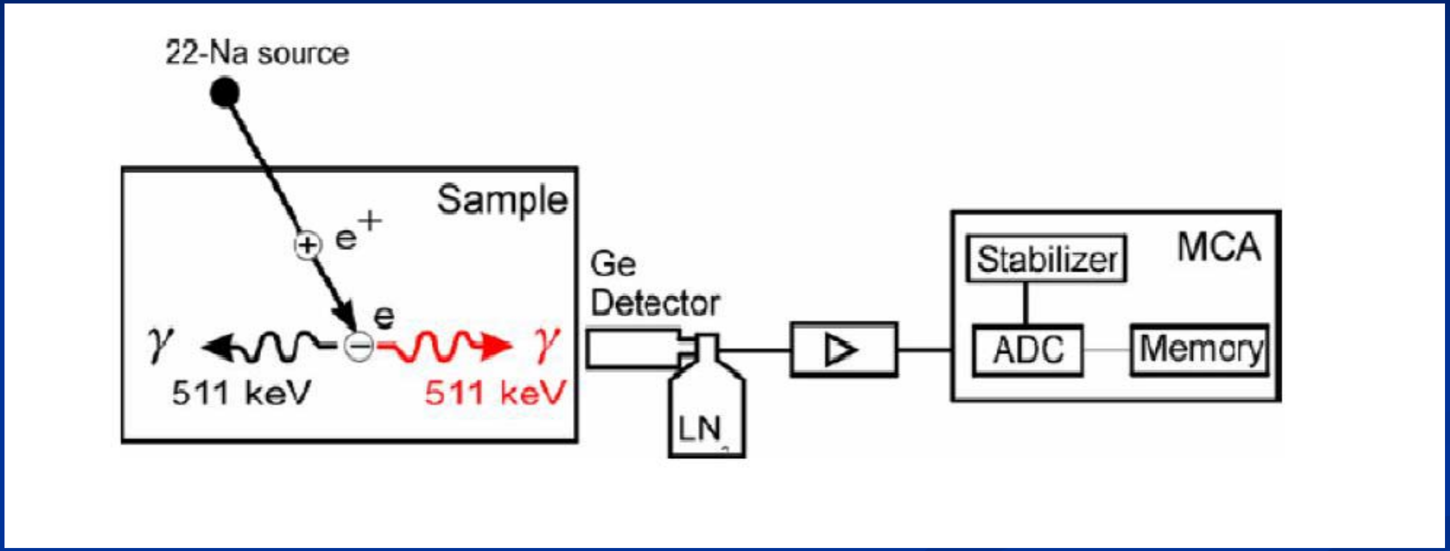
- Positron lifetime is measured as time difference between 1.27 MeV quantum and 0.511 MeV quantum.
- PM=photomultiplier, SCA=single channel analyzer (constant fraction type), TAC= Time to amplitude converter, MCA multi-channel analyzer

PAS: Principles
Digital lifetime measurement



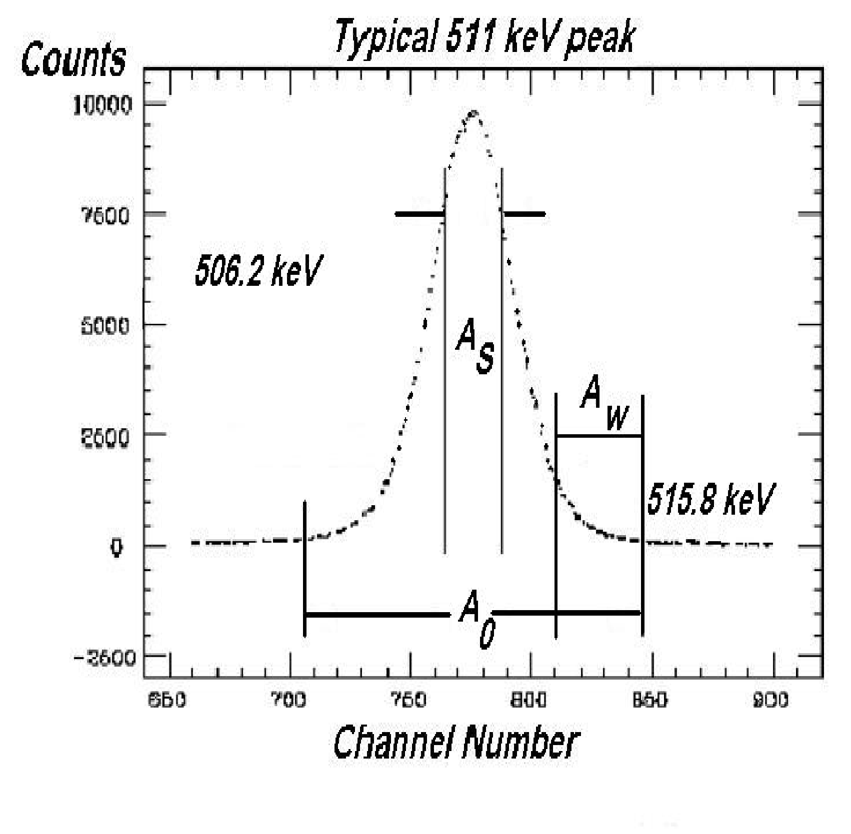
- much simpler setup
- Cheaper
- High time accuracy (10^{-6})
- each detector for start & stop (double statistics)
- Better timing resolution

PAS: principles
Measurement of Doppler Broadening



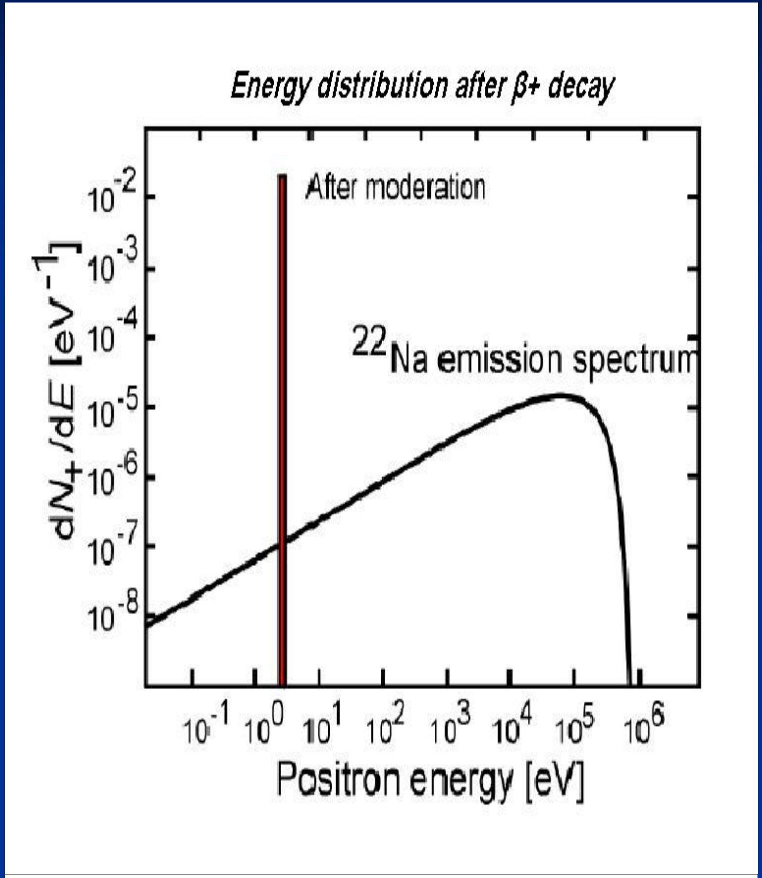
- electron momentum in propagation direction of 511 keV γ-ray leads to Doppler broadening of annihilation line.
- can be detected by conventional energy-dispersive Ge detectors and standard electronics.

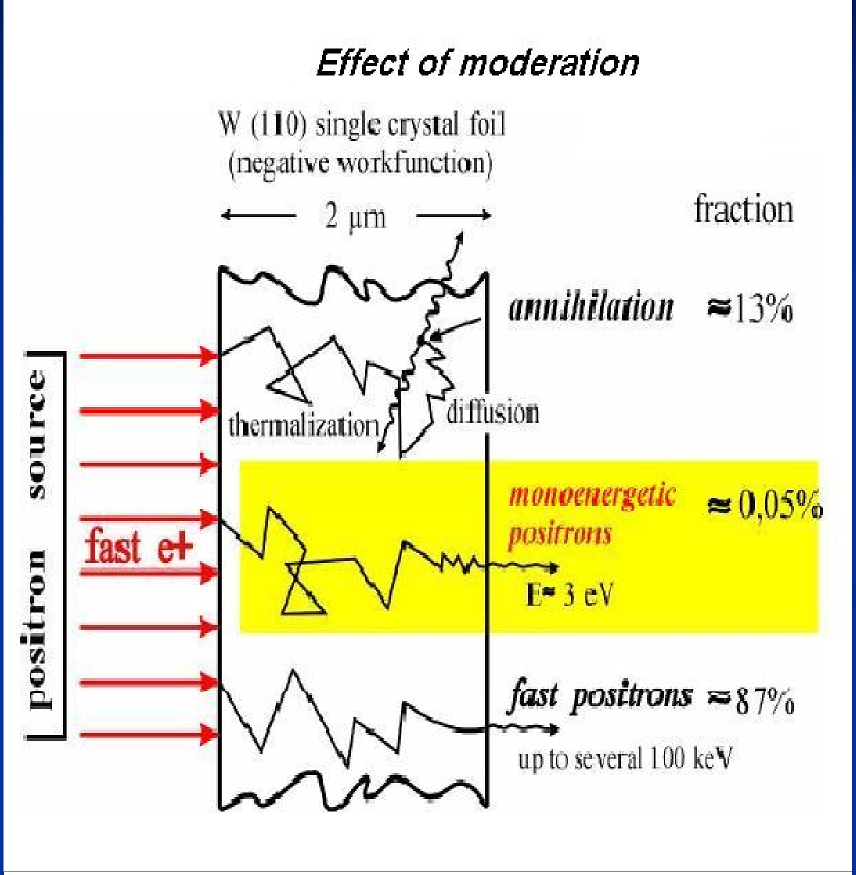
PAS: principles
Measurement of Doppler Broadening



- Shape parameter: $S = A_S/A_0$
- Wing parameter: $W = A_W/A_0$
- Both *S* and *W* are sensitive to the concentration and defect type.
- *S* parameter does not contain all information
- *W* is sensitive to chemical surrounding of the annihilation site, due to high momentum of core electrons participating in annihilation

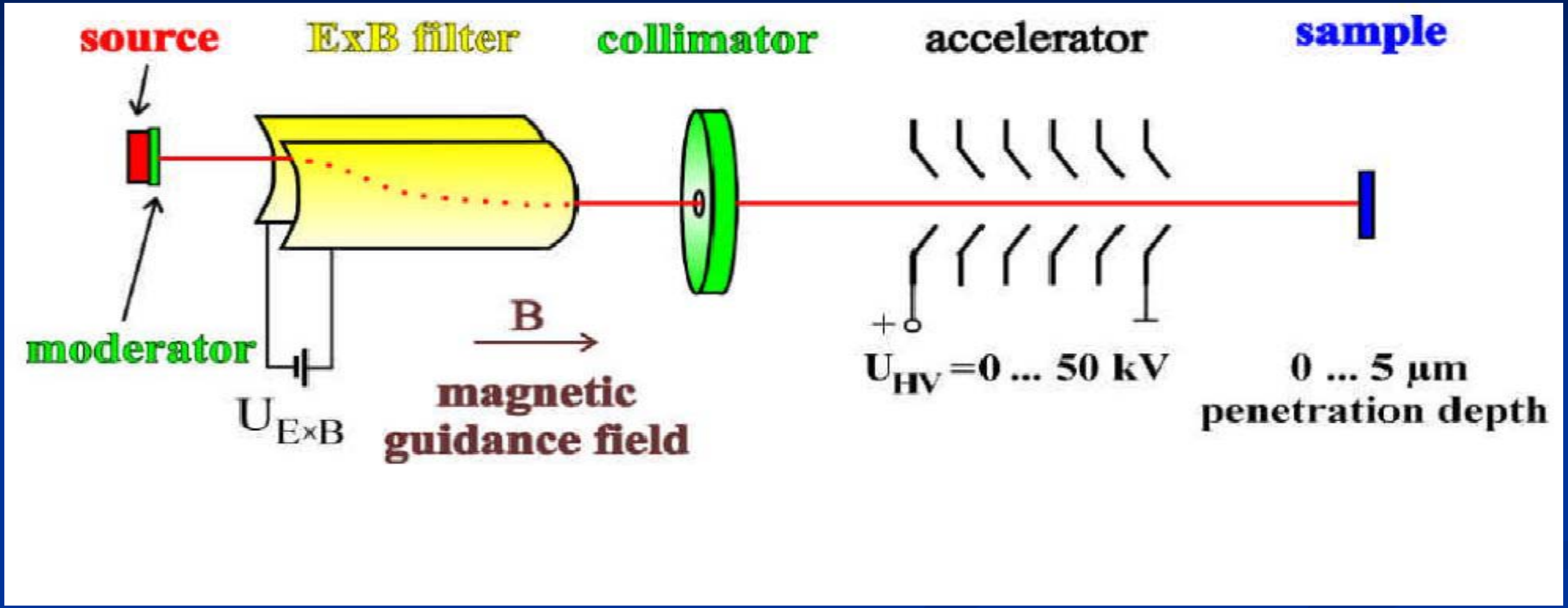
Monoenergetic positrons obtained by moderation





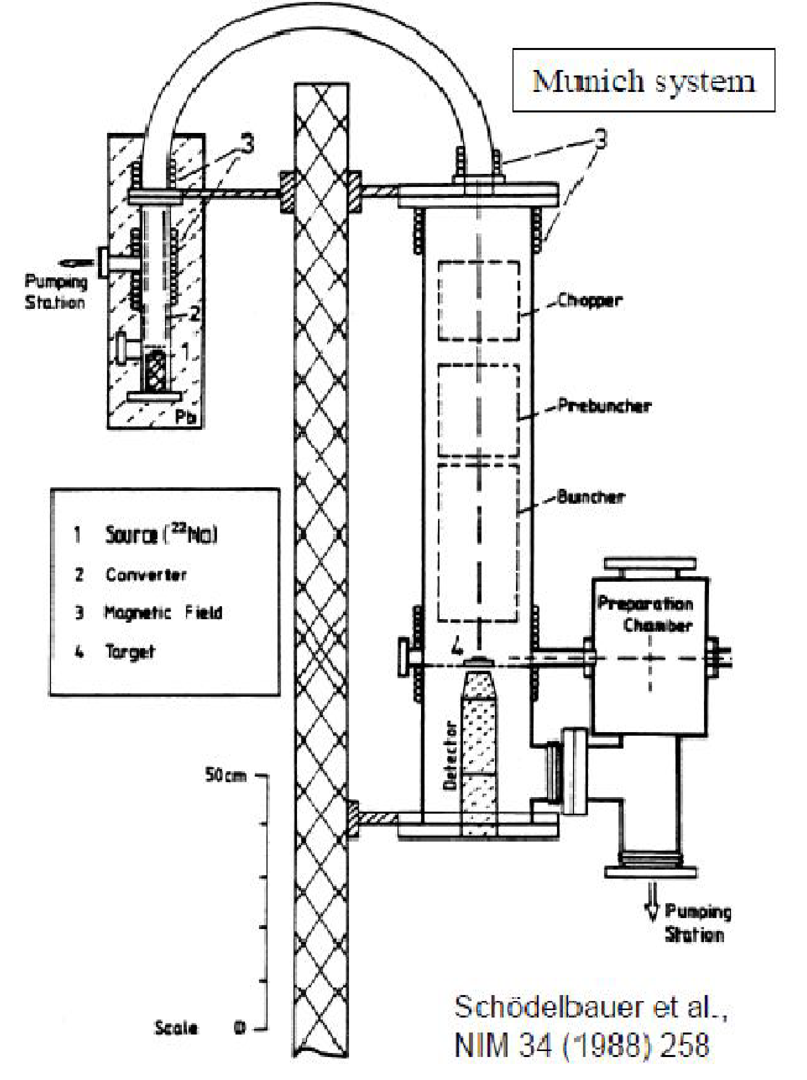
- broad positron emission spectrum
- Higher energies -deep implantation into solids-
- Bulk PAS: unsuitable for thin layers
- moderation necessary

Conventional positron beam technique: Doppler spectroscopy (VEDBS)



- positron beam can be made from monoenergetic positrons
- Magnetically guided for simplicity
- defect studies by Doppler-broadening spectroscopy
- characterization of defects only by line-shape parameters or positron diffusion length – no lifetime spectroscopy

Positron lifetime spectroscopy using monoenergetic positrons –VEPALS

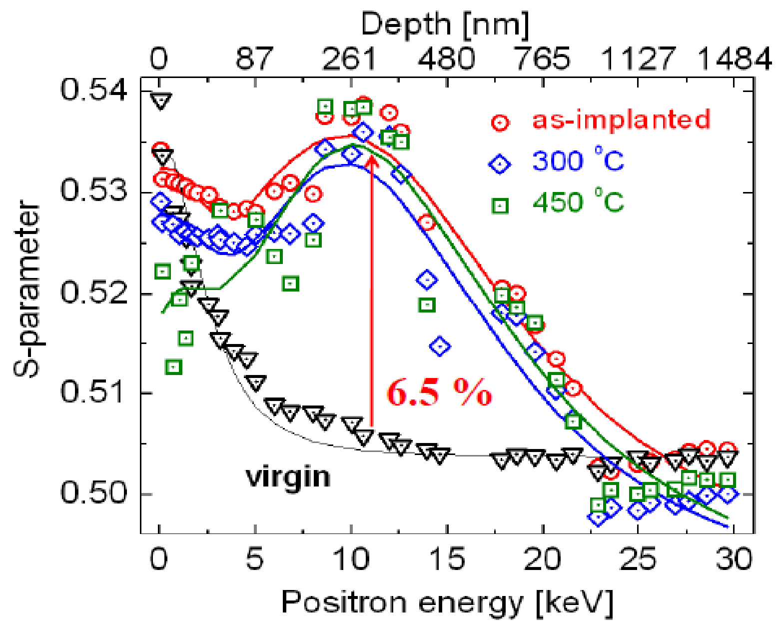


Schödelbauer et al., NIM 34 (1988) 258

- positron lifetime measurement more difficult
- PLEPS-System in Munich at FRM-II
- positron source by a nuclear reaction: 113Cd (n,γ) 114Cd.
- A system of chopper and bunchers: short pulses of monoenergetic positrons
- Time resolution of 250 ps.
- another system: Tsukuba
- EPOS: system under development

W. Egger et al. phys. stat. sol. 2007.

Characterization of GaN samples:
Positron Doppler Broadening Measurements for GaN



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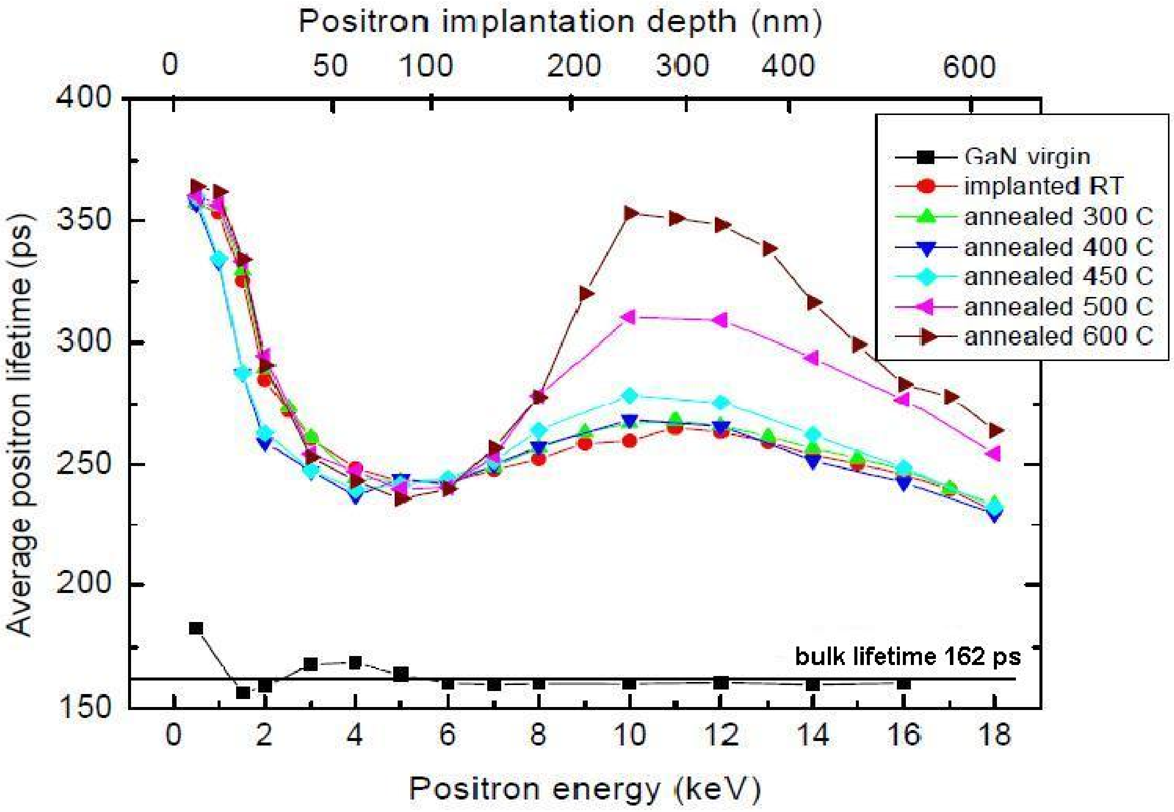
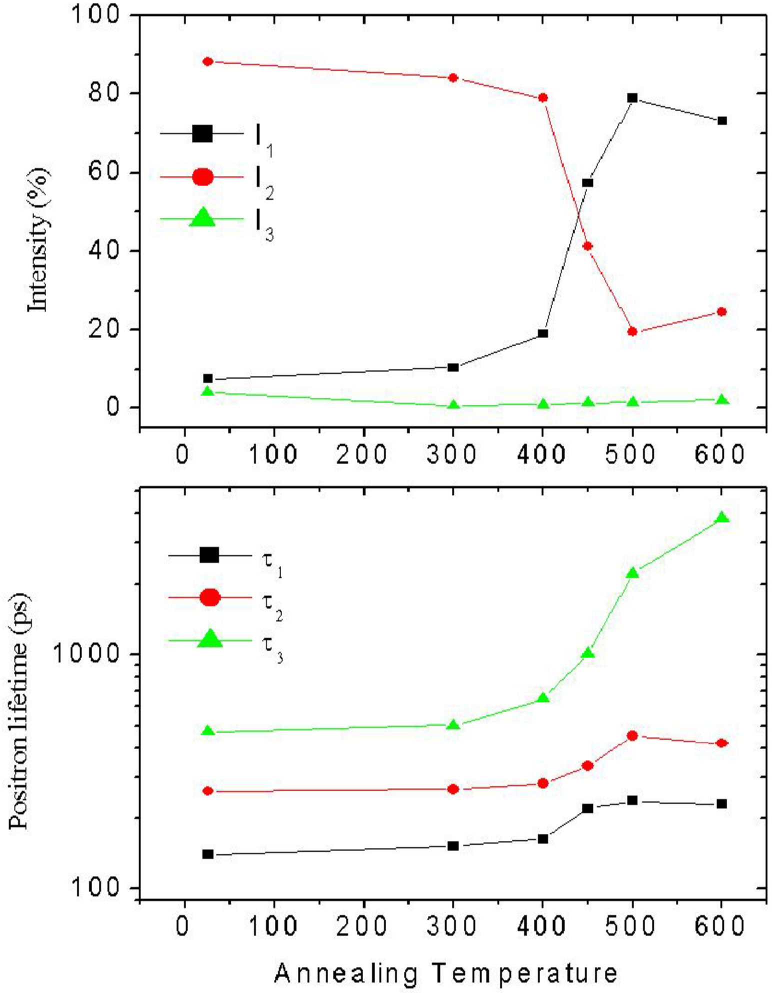
- Enhancement of *S* parameter by 6.5 % in the implanted region: presence of open volume defects (TEM observations).
- Such an increase of S parameter is far to be due to monovacancies (<2% for mono vacancies)
- Positron obviously trapped by vacancy clusters.
- The size of the clusters can only be determined by positron lifetime experiments.

Characterization of GaN samples:
Variable Energy Positron Lifetime Experiments at FRM-II Munich



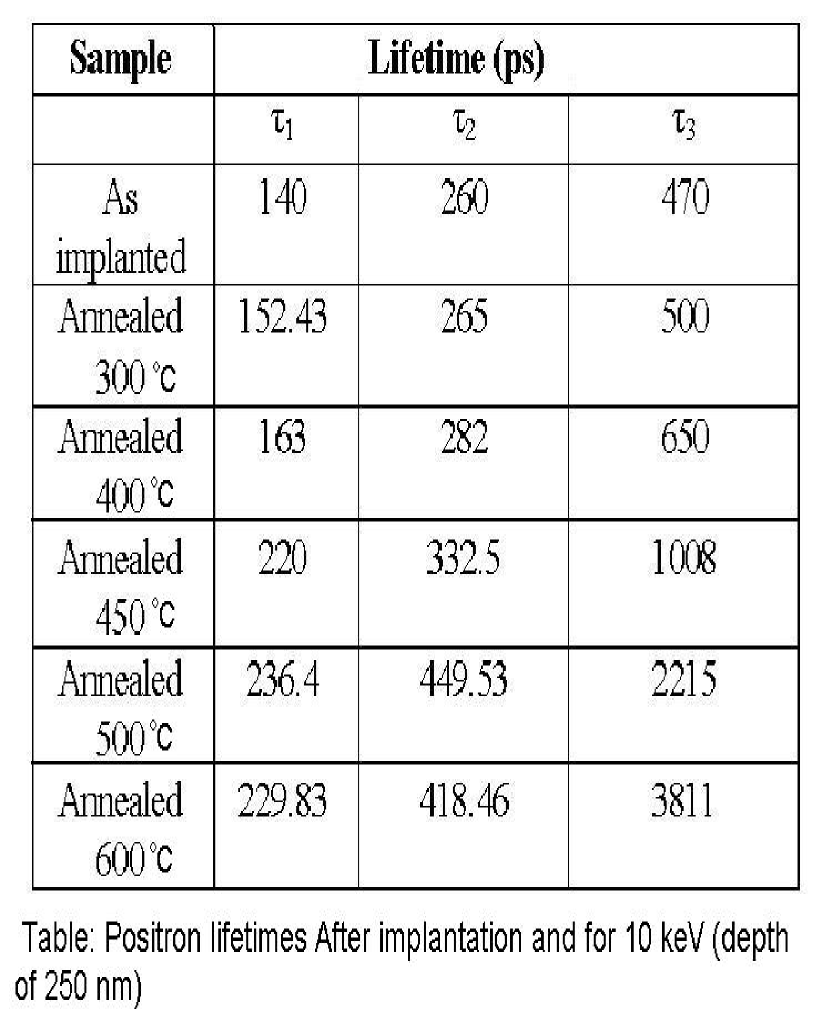
- For the virgin sample, the average positron lifetime shows the bulk lifetime equal to 162 ps
- For a depth below 100 nm, the back-diffusion to the surface dominates for the as-implanted and annealed samples
- Between 200 and 500 nm, a presence of a maximum as a result of defect generation by hydrogen implantation.

Decomposition of GaN lifetime spectra



- After implantation and for 10 keV (depth of 250 nm), the positron lifetimes are presented in the figure.
- Decomposition with three lifetime components (τ_1, τ_2, τ_3)
- Formation of monovacancies, divacancies and vacancy clusters with increasing temperature.
- Presence of a long lifetime: formation of positronium.
- Hardly seen in semiconductors before.

Decomposition of lifetime spectra: Positronium formation…..



Sample	Lifetime (ps)		
	τ_1	τ_2	τ_3
As implanted	140	260	470
Annealed 300 °C	152.43	265	500
Annealed 400 °C	163	282	650
Annealed 450 °C	220	332.5	1008
Annealed 500 °C	236.4	449.53	2215
Annealed 600 °C	229.83	418.46	3811

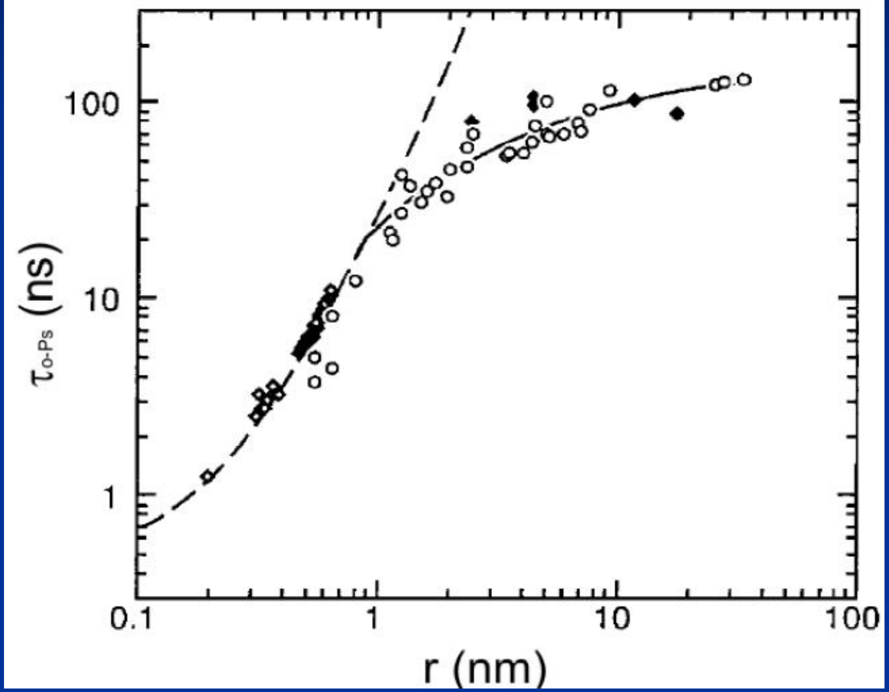
Table: Positron lifetimes After implantation and for 10 keV (depth of 250 nm)

- For 450, 500 and 600 ºC: τ_1 values indicate the presence of monovacancies (τ = 235 ps [1])
- τ_2 is typical for divacancies up to 450 ºC: increases with temperature. For 500 and 600 ºC, τ_2 values show the existence of small vacancy clusters [2].
- τ_3 values indicate the presence of vacancy clusters up to 400 ºC: τ_3 increases with increasing temperature.
- For 450, 500 and 600 ºC, τ_3 shows the formation of positronium which increases with temperature.
- Positronium: never seen before in other semiconductors.

[1] K. Saarinen et al. PRL 79(16) 1997.

[2] S. Hautakangas et al. PRL 90(13) 2003.

Positronium formation in GaN…..



- According to the Tao-Eldrup model, it is possible to estimate the wall spacing corresponding to the lifetimes.
- For 1 ns, 2.2 ns and 3.8 ns, the corresponding wall spacing values are about 0.1 nm, 0.18 nm and 0.4 nm respectively.

Conclusion

- The characterization of defects evolution in proton implanted and annealed GaN-fs was done by VEPALS and RBS-C spectroscopy.

From VEPALS experiments:

➔ Decomposition has to be done with three lifetimes

➔ Formation of three kind of defects:

- monovacancies: lifetime between 220 ps and 236.5 ps
- divacancies: lifetime from 260 ps to 332.5 ps
- Vacancy clusters: lifetime between 418 ps and 650 ps
- Positronium: lifetimes equal to 1 ns, 2.2 ns and 3.8 ns for 450, 500 and 600 ºC .
- From Tao-Eldrup model, the corresponding wall spacing values are about 0.1 nm, 0.18 nm and 0.4 nm.

From RBS-C experiments, we show:

- ➔ For 600 ºC: a shoulder appears beyond the damage peak: its existence coincides with the formation of nanoscopic cracks and positronium formation.
- ➔ The reverse annealing (observed for other semiconductors for example Si) does not take place for GaN.

Thank you

Merci