Ion Implantation in GaN

Nutzertreffen FhG-IISB 25.11.2021

Neuauflage 18.05.2022

K.-H. Stegemann (Fellow), xfab Dresden

xfab

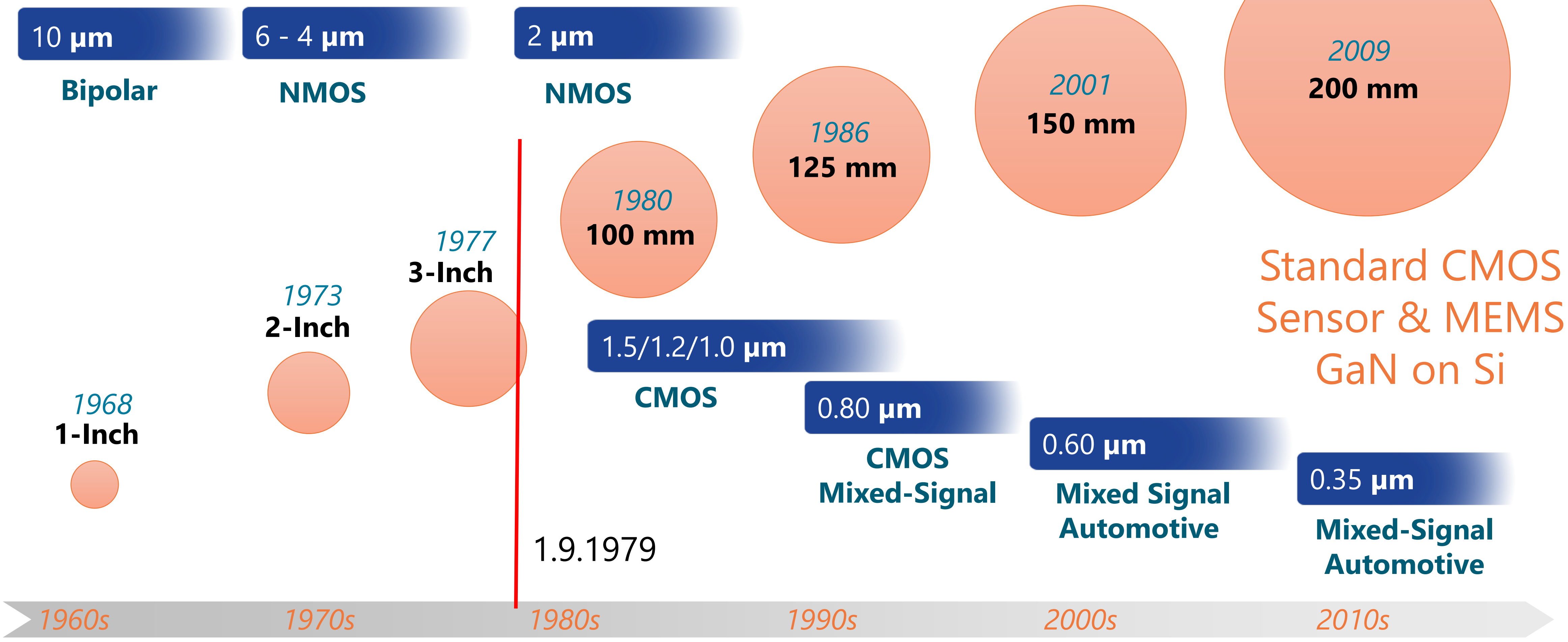
Introduction “40 years Microelectronic, Nanoelectronic and Solar”

Nutzertreffen FhG-IISB Erlangen

K.-H. Stegemann (Fellow), xfab Dresden

History Dresden Technology Roadmap

Roadmap: Critical Dimension & Wafer size



10 µm
Bipolar

6 - 4 µm
NMOS

2 µm
NMOS

1.5/1.2/1.0 µm
CMOS

0.80 µm
CMOS Mixed-Signal

0.60 µm
Mixed Signal Automotive

0.35 µm
Mixed-Signal Automotive

1968 **1-Inch**

1973 **2-Inch**

1977 **3-Inch**

1.9.1979

1980 **100 mm**

1986 **125 mm**

2001 **150 mm**

2009 **200 mm**

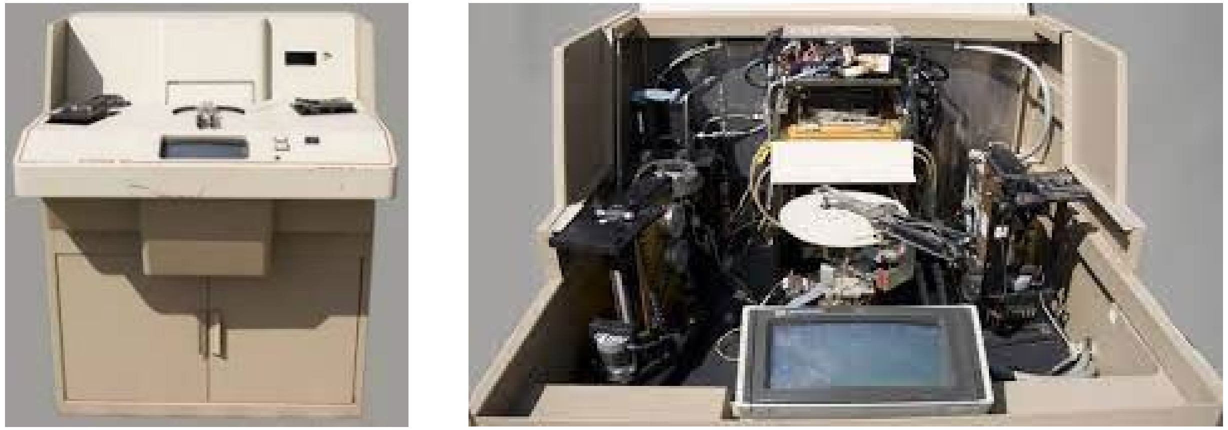
Standard CMOS
Sensor & MEMS
GaN on Si

1960s *1970s* *1980s* *1990s* *2000s* *2010s*

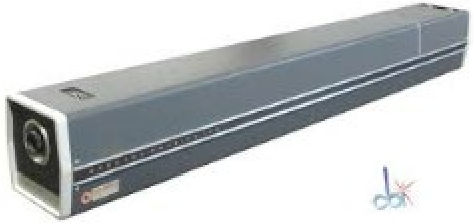
High Lights in 40 years

- Start 09/1979 im IMD, Prozessingenieur für Diffusion und Reinigung
- Ab 01/1981-04/1986, Entwicklungsingenieur für Ionen Implantation, RTP und Laserausheilung
- Ab 05/1986 Prozessintegration DRAM, nach der Wende Manager

BALZERS-Implanter SCANIBAL SCI 218 und MPB 200



AG Associates Heatpulse 2101-01 RTP System



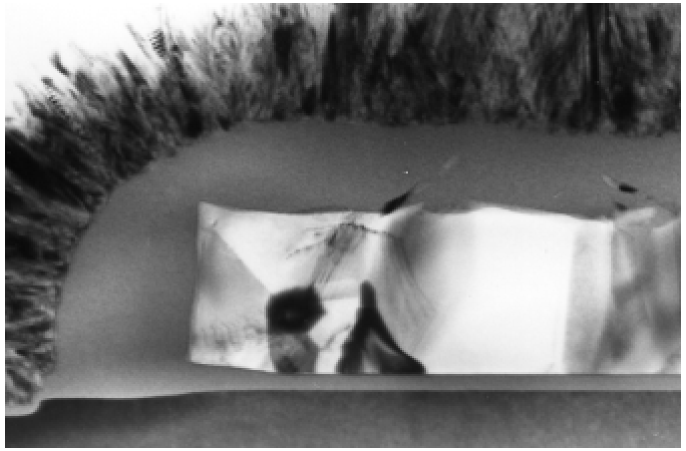
Spectra-Physics 20W Ar Ionen Laser (Scanner und Heizer Eigenbau)

Die große Liebe Ionen Implantation

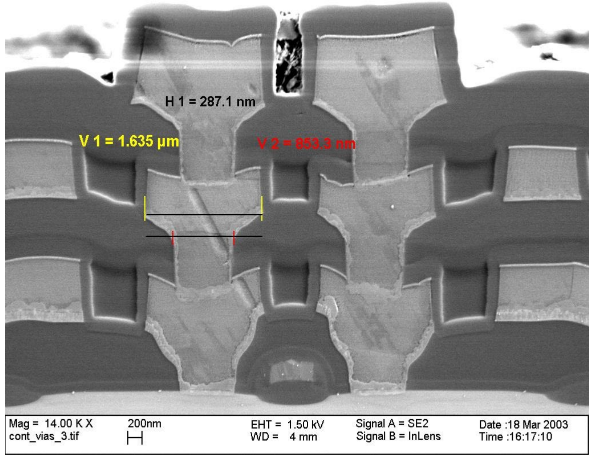
- Ost “TZ-Ionen Implantation” und West „Nutzergruppe Ionen Implantation“
- 12/1993 Zusammenschluss im ZMD Dresden (Beitritt war schon 1991)
- Es wächst zusammen was zusammen gehört
- IIT 2000 in Alpach (Mitglied im Org. und Programm Komitee), Vortrag Nanocluster
- 11/2013 Jubiläum 50. Nutzertreffen Ionen Implantation in Frankfurt/Oder
  Vortrag: „Die Historie der Ionen Implantation - Prozess und Technologie
  Entwicklung im IMD/ZMD Zeitraum 1975-1990“
- 9/2018 IIT2018 in Würzburg (lokales Org. Komitee)

High Lights in 40 years

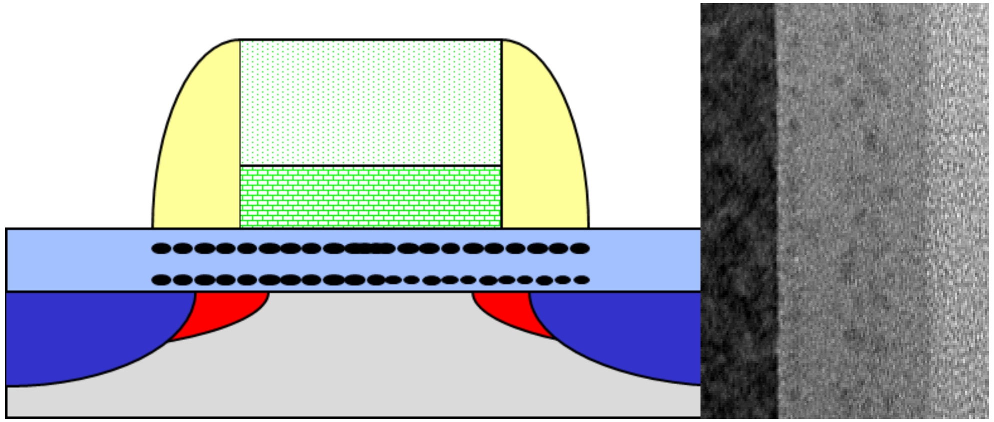
- 1986 256k DRAM



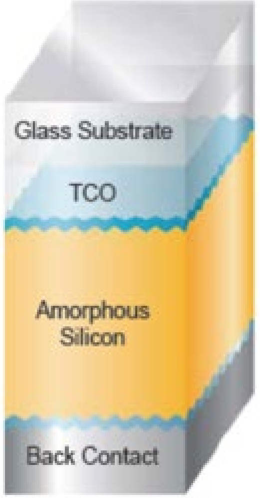
1999 C7 Technology



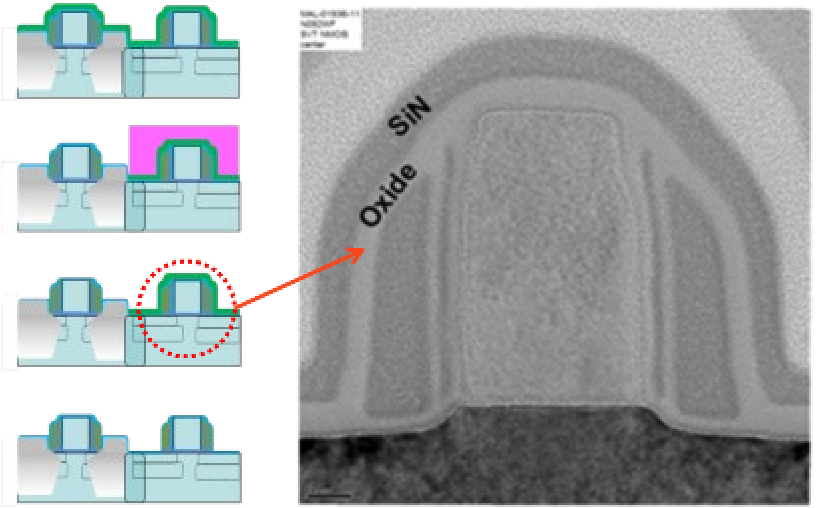
2003 Nano Cluster Memory



- 2008 aSi Thin Film Solar

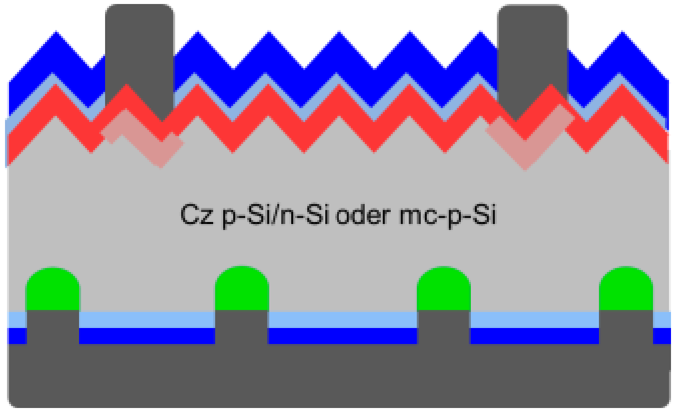


2011 28 nm Poly-SiN



High Lights in 40 years

- 2013 PERC Solar Cell



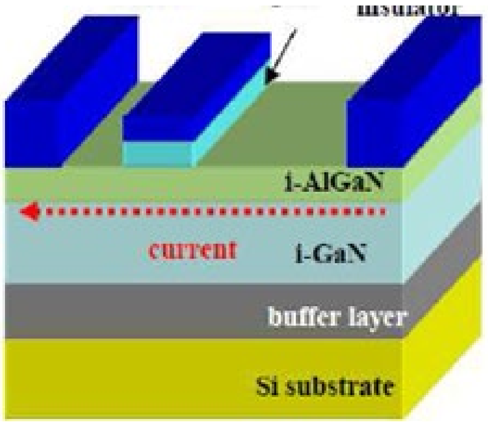
passivated emitter rear *solar cell* technology

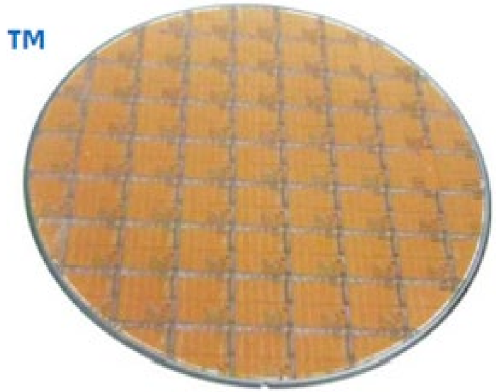
Solar modules

- Never stop learning
- Never stop thinking
- Believe not that we have technical

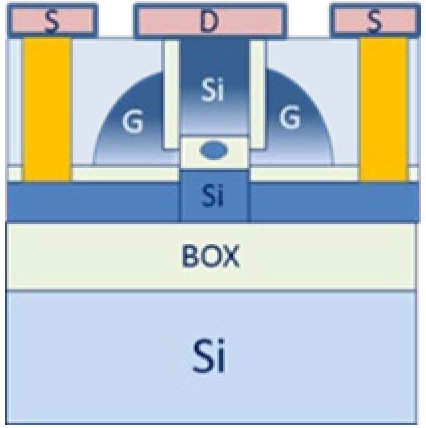
  or physical limitation, verify it

2014 GaN on Si for Power

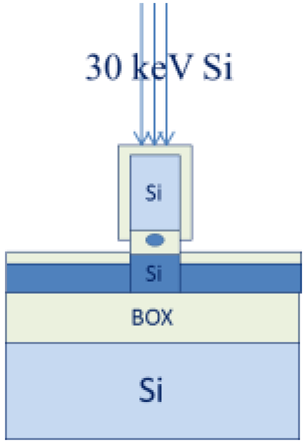




2015 Single Electron Transistor



EU project ION4SET



Si,-II &Cluster RTA

Admont

2015-2019 Key Applications and Demonstrators

xfab

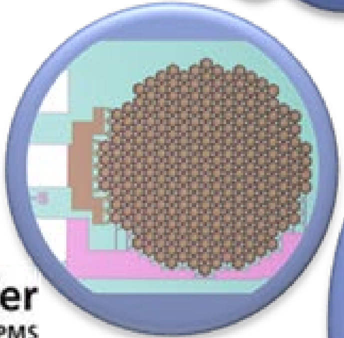
IMMS

ONCOMPASS Medicine

Cancer Cell Detection

Fraunhofer IPMS

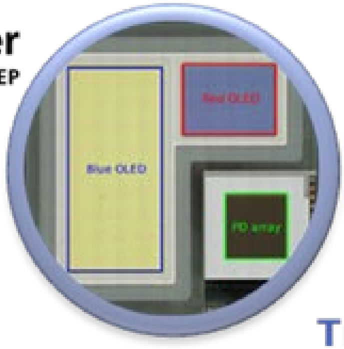
CMUT Actuator



CMOS-Line
XH035
XU035
XA035

Fraunhofer FEP

OLED on CMOS



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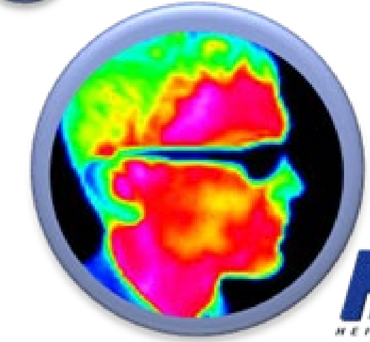
True Color Sensor

PEPPERL+FUCHS
SENSING YOUR NEEDS

Energy efficient ultrasonic Sensing



Thermopile Array in CMOS

HEIMANN Sensor
HEIMANN SENSOR GMBH

SenseAir
Sensors for Life

Mobile Gas Detection

Rare Cell Sorting

MENARINI silicon biosystems

Ein Freund ist für immer gegangen

Für uns alle unfassbar müssen wir Abschied nehmen von unserem
Institutsleiter, Lehrstuhlinhaber, Kollegen und Freund

Prof. Dr. rer. nat. Lothar Frey

der plötzlich und unerwartet verstorben ist.

Unsere Gedanken sind bei seiner Familie.

In tiefer Trauer
die Mitarbeiterinnen und Mitarbeiter

Fraunhofer-Institut für Integrierte Systeme und Bauelementetechnologie IISB, Erlangen
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Lehrstuhl für Elektrische Energietechnik der Friedrich-Alexander-Universität Erlangen-Nürnberg

Lothar Frey, 1958 - 2018

ION IMPLANTATION IN GAN FOR N^+- & P^+- DOPING

Presenter: KHS

Rev. 01 – 11/2021

Outlook

- Ion Implantation in GaN Overview
  - Doping WBG semiconductor
  - GaN application and GaN material
  - Doping from GaN
  - Advantage and disadvantage of ion implantation
- Si^+ Implantation & Annealing
  - Si^+ ion range in GaN
  - Defect generation in GaN, amorphisation
  - Si annealing and activation
  - X-FAB results
  - Summary

Outlook

- Mg^+ Implantation & Annealing
  - Mg^+ ion range in GaN
  - Defect generation in GaN
  - Mg annealing and activation
  - Summary
- Application for Ion Implantation in GaN
  - Contact and S/D Engineering for RF
  - Power Devices
  - Summary

Ion Implantation in GaN Overview

Doping WBG Semiconductor

Material	GaN	4H-SiC	ZnO	Diamond	GaAs	Si
Bandgap (eV) @300K	3.37	3.26	3.37	5.47	1.42	1.12
n-type dopant & Ed	Si on Ga site (~ 25meV)	N on C site (~ 85meV)	B on Zn (~30-60meV)	N (~ 1.7 eV)	Si (6mV)	P (45mV)
p-type dopant & Ea	Mg on Ga site (~160 meV) Zn~340 meV	Al on Si site (~200 meV)	N on O site (~ 170-200 meV)	B (~ 370 meV)	C(BE) ~28 meV	B 40 meV
N-conductivity	~0.002 Ωcm	~0.01 Ωcm	~0.02 Ωcm	>1000 Ωcm	~0.001 Ωcm	~0.001 Ωcm
P-conductivity	~0.2-2 Ωcm	~0.5-2 Ωcm	0.5-40 Ωcm	10-100 Ωcm	~0.001 Ωcm	~0.001 Ωcm

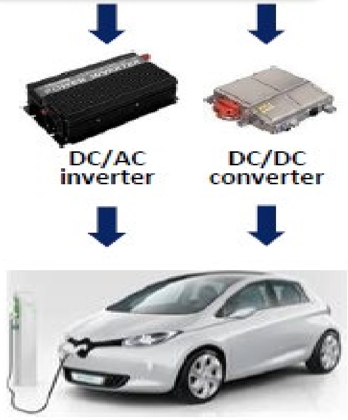
Application for GaN

- LED
- Laser
- Power
- RF
- Sensors

Power

IT & Consumer

Automotive



Industrial

30V 200V 650V (1200V)

Si MOSFET SiC

RF

Space & Defence

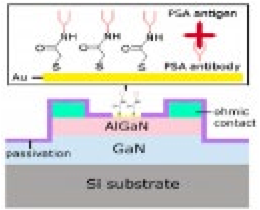
Telecom

CATV

Sensors

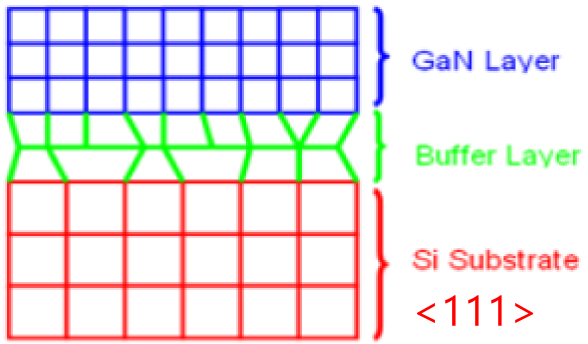
MEMS devices

Bio sensorics

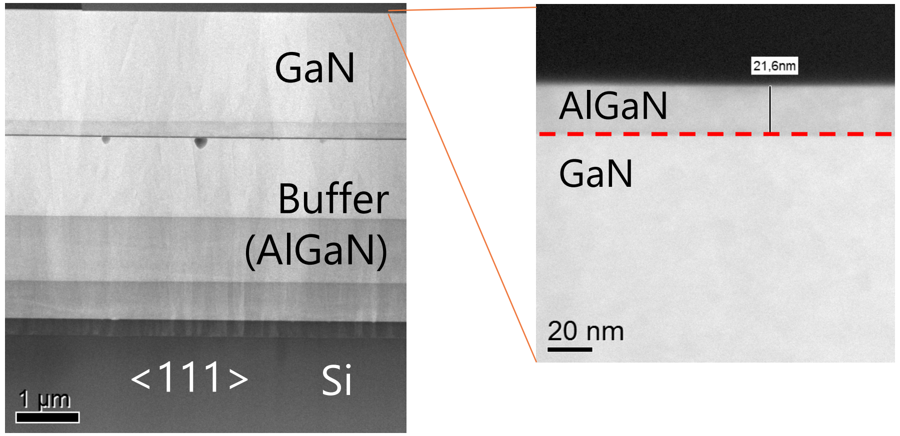


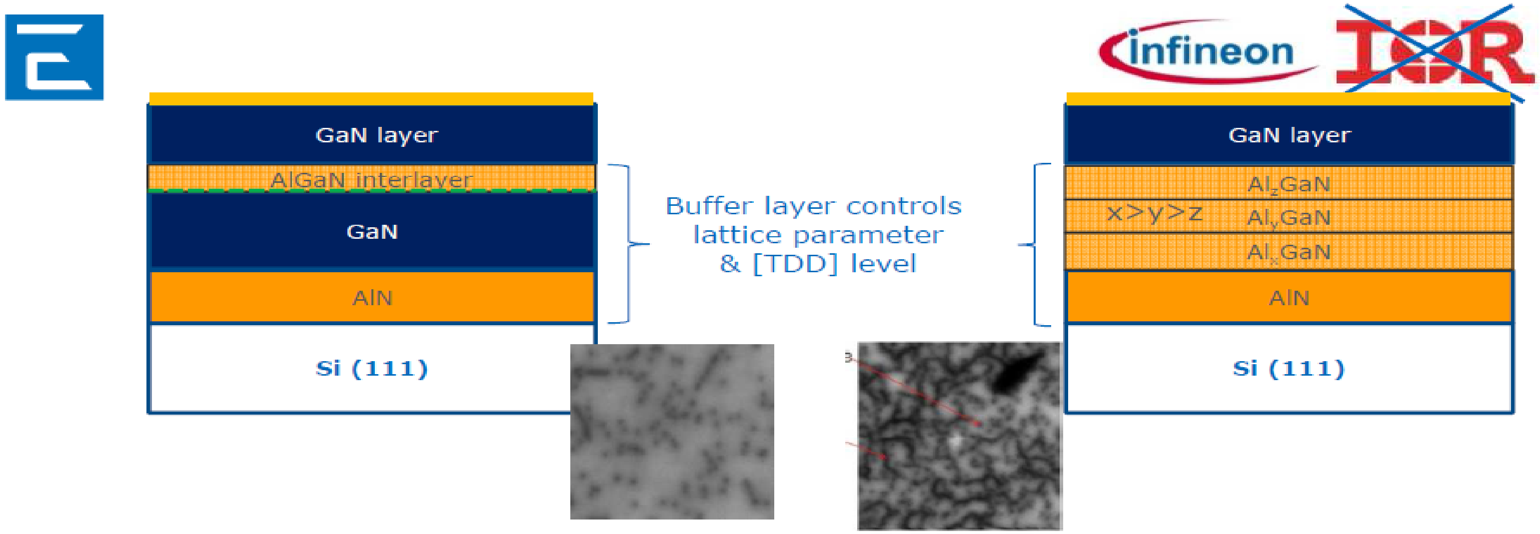
Partely sourced from EpiGaN

GaN-on-Si: Properties & Challenges



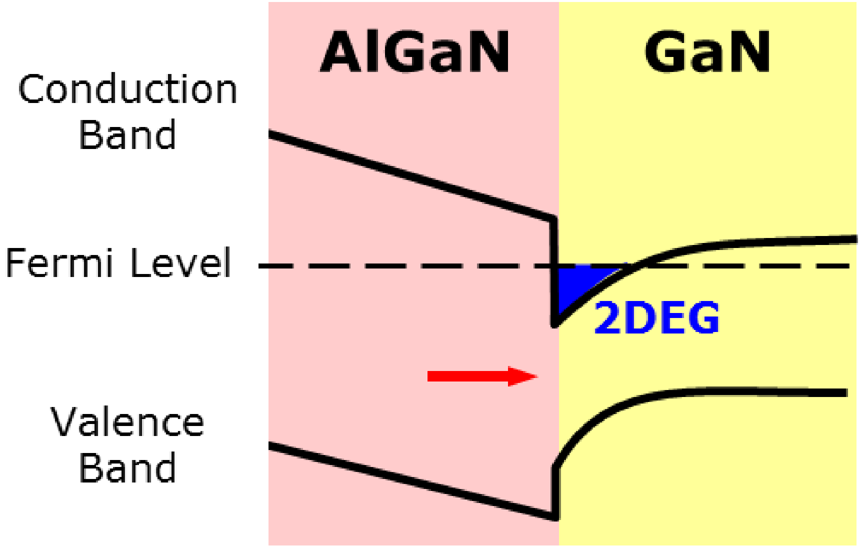
- Lattice mismatch GaN vs Si:17 %
  - Large number of cristalline defects like dislocations
- Thermal expansion mismatch GaN vs Si : 116 %
  - Wafer cracking at room temperature
- **Challenge increased with larger wafer size**





Lattice parameter and quality can be managed independently

Lattice parameter evolution and quality are interdependent



N and P Type Doping in GaN

- N-type doping for GaN
  - Is simple and similar to other common semiconductors
  - Si has Ea~25 meV (mobility ~80 – 1000 $cm^2V/1s^{-1}$, doping depended)
  - Ge not so good for doping due to low incorporation and activation
  - AlGaN doping with Si is more difficult (higher bandgap)
  - PN-junction formation in p-GaN is possible

- P-type doping for GaN
  - Is complicated and quite different from other semiconductors
  - Mg has activation energy of Ed~0.160 eV (mobility few tens of $cm^2V/1s^{-1}$)
  - Mg forms complexes with hydrogen, which have been broken first for Mg to act as acceptors (deactivation and compensation by defects or donors)
  - Mg-H complexes can be broken down by:
  - Annealing in nitrogen atmosphere
  - Low energy electron beam irradiation (LEEBI)

Advantages & Disadvantages of Ion Implantation

- Advantages of ion implantation
  - Excellent uniformity, reproducibility and high throughput
  - Precise dopant and energy control (<1%)
  - Concentration above their equilibrium solid solubility limit
  - High dopant purity by mass separation
  - Wide range of process temperature during ion implantation (-77K ….800°C)
  - Selective area doping by masking
  - Ion implantation through cap layer (SiN, AlN, SiO_2,….)
  - Dopant profile forming by multi energy ion implantation
- Disadvantages of ion implantation
  - Radiation damage causing undesirable electrical and optical properties
  - Very high temperature annealing (>1100°C) for dopant activation and damage reduction necessary
  - Implantation layer depth limited on <~1µm
  - Secondary effects like channeling, diffusion, scattering, amorphization, ……

Si^{+28} Ion Implantation in GaN

Si^+ Implantation & Annealing (1)

- Si^+ ion range in GaN
  - Electron & nuclear stopping power (LSS Theory)
  - Simulation with TRIM or other codes

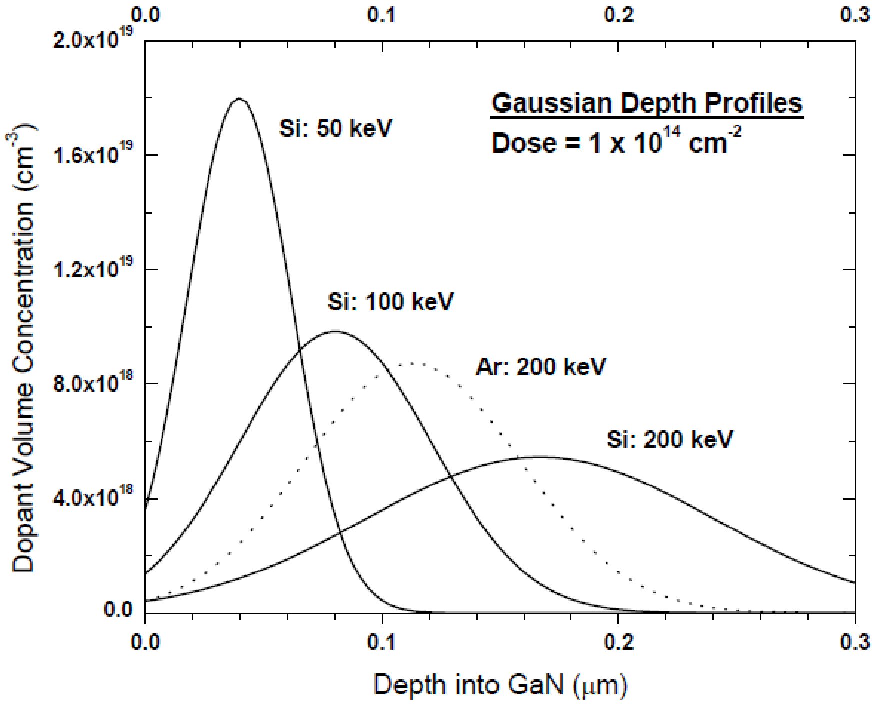


Figure 7. Gaussian implantation depth profiles showing the effects of ion energy and mass for various Si and Ar implants each at a dose of $1x10^{14}$ cm^{-2}.

James A. Fellows,_II-Si-Annealing-GaN, PHD

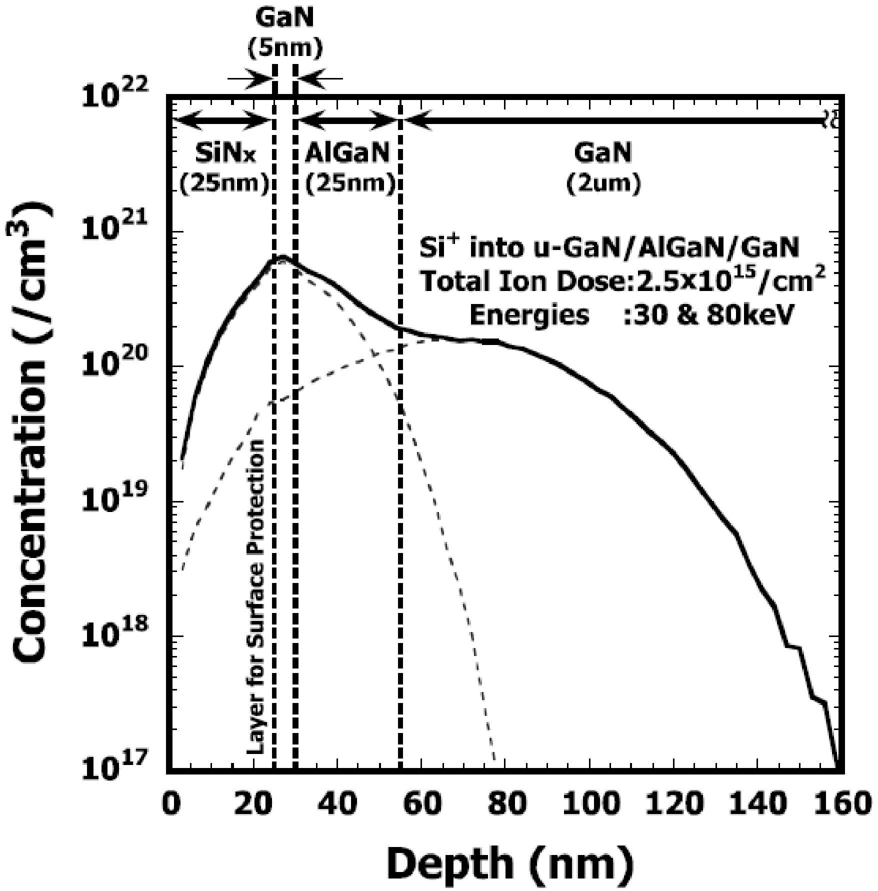


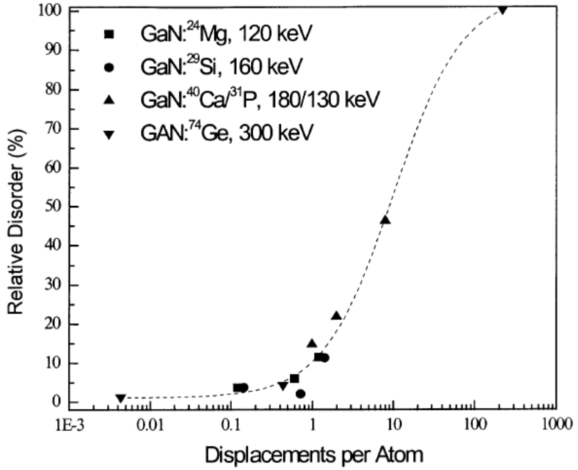
Fig. 2. Simulated impurity profiles of Si ion-implated source/drain resions.

K. Nomoto, Multiple Ion-Implanted GaNAlGaNGaN HEMTs with Remarkably Low Parasitic Source Resistance

Si^+ Implantation & Annealing (2)

Defect generation in GaN, amorphization

- Damage of crystal structure, point defects (interstitials, vacancies, anti-sites, or extended defects)



- Typical defects are:
- Ga or Nitrogen vacancy (V_{Ga}, V_N)
- Ga or N interstitials (Ga_i, N_i)
- Ga or N anti-site (Ga_N, N_{Ga})
- Frenkel pair (vacancy with displaced atom with a neighboring interstitial)
- Combined defects like di-vacancies, tri-vacancies, di-acceptor, interstitial clusters, ….
- All defects can act as donor or acceptor type (N_i is a triple acceptor, Ga_i triple donor, Ga_N is double acceptor, N_{Ga} double donor, V_{Ga}^{-}-Si_{Ga}^{+} double acceptor complex)
- Si_{Ga} is single donor, Si_N is single acceptor, after annealing mainly donor
- Amorphization doses @77K ~2.4E16Si^+/cm^2, at RT ~4E16Si^+/cm^2
- GaN lattice reconstruction after amorphisation is not possible

James A. Fellows,_II-Si-Annealing-GaN, PHD
C. Ronning et al. / Physics Reports 351 (2001) 349-385

Si⁺ Implantation & Annealing (3)

Si Annealing and activation

- Si annealing in GaN shows abnormality, low doses has low activation, doses >5E14 – 1E15 Si/cm² are needed for activation >50%, for Si ion implantation @RT
- Temperature >1100°C up to 1400°C are necessary for high activation
- High density capping layer like AlN or SiN are necessary (prevent surface damage)

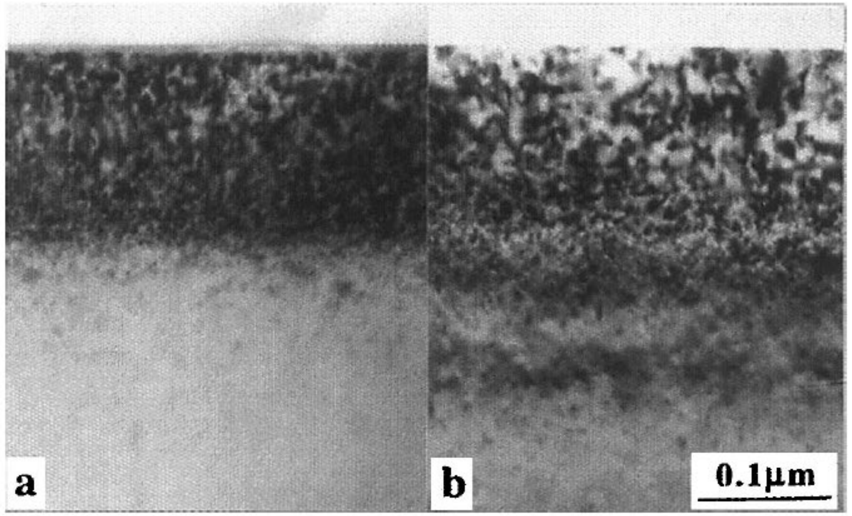
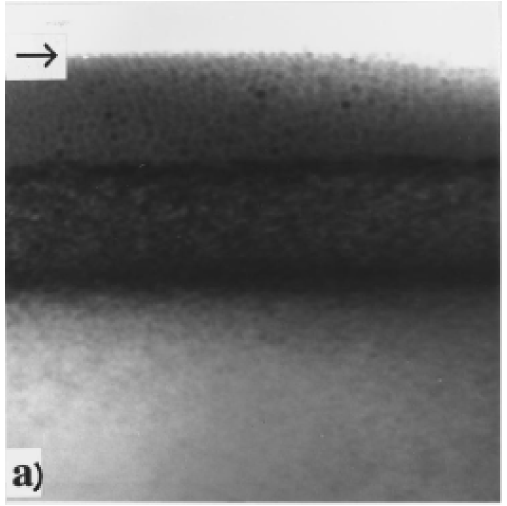


Fig. 22. Bright-field XTEM images of a GaN sample bombarded with 90 keV Si ions at LN_2 to a dose of 6×10^{15} cm^{-2}. Shown are images before (a) and after (b) post-implantation annealing at 1100°C for 30 s. /4/

James A. Fellows,_II-Si-Annealing-GaN, PHD

S.O. Kucheyev et al. / Materials Science and Engineering 33 (2001) 51–107



Amorphous GaN Layer
Si 90 keV, 4E16Si/cm²

Appl. Phys. Lett., Vol. 69, No. 16, 14 October 1996

Si⁺ Implantation & Annealing (4)

- Si Annealing and activation, Si implantation @RT

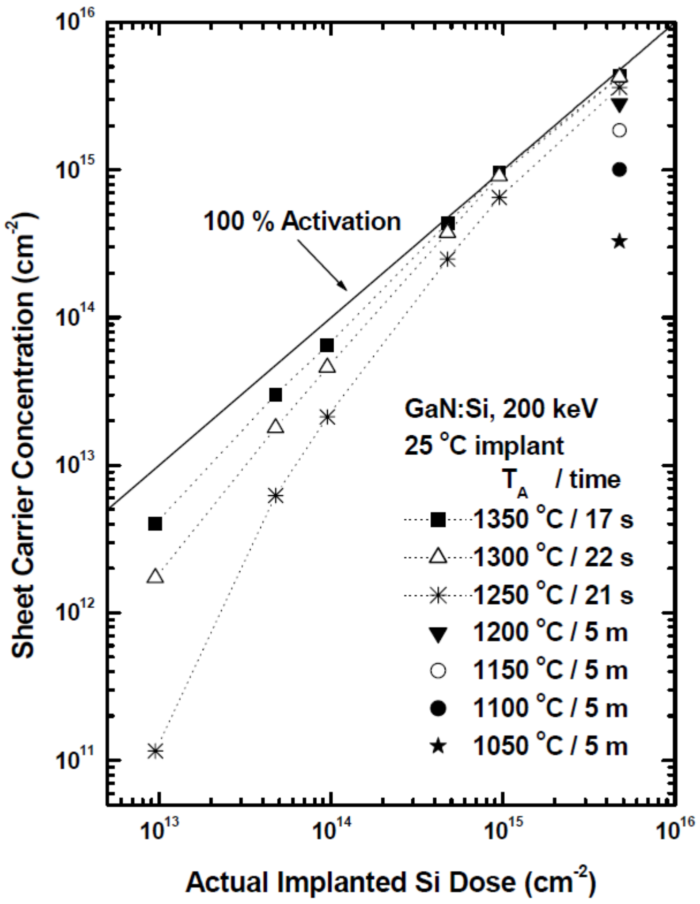


Figure 29. Sheet carrier concentration versus actual implanted dose for GaN implanted at 25 °C with 200 keV Si ions at doses ranging from 1x10^{13} to 5x10^{15} cm^{-2} and annealed at 1050 to 1350 °C from 5 min to 17 sec in a flowing nitrogen environment.

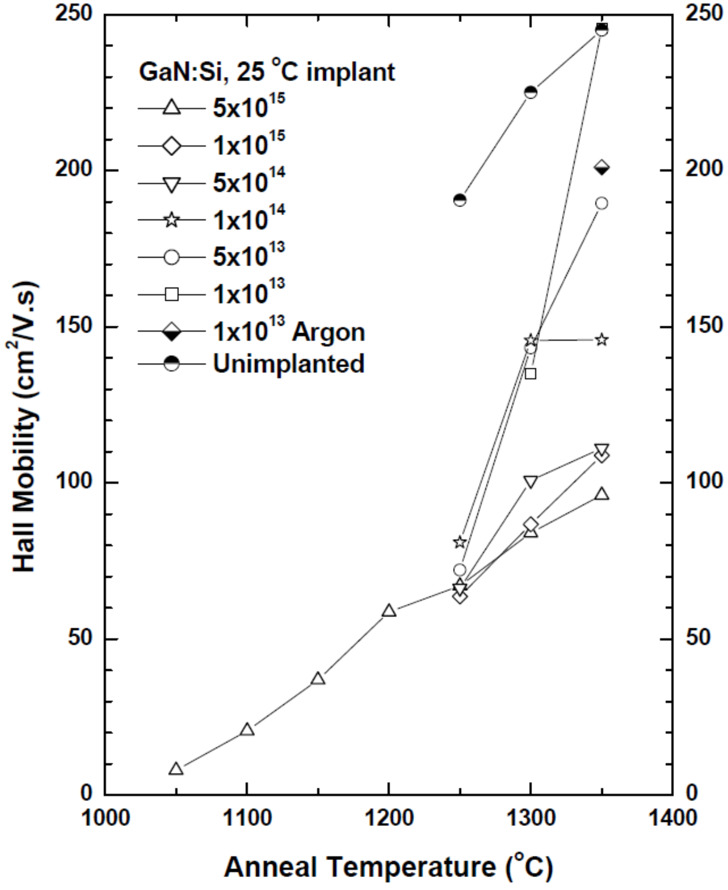


Figure 30. Room-temperature Hall mobility for GaN implanted at room temperature with 200 keV Si ions at doses ranging from 1x10^{13} to 5x10^{15} cm^{-2} and annealed at 1050 to 1350 °C from 5 min to 17 sec in a flowing nitrogen environment.

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Si^+ Implantation & Annealing (5)

- Si Annealing and activation, Si implantation @800°C

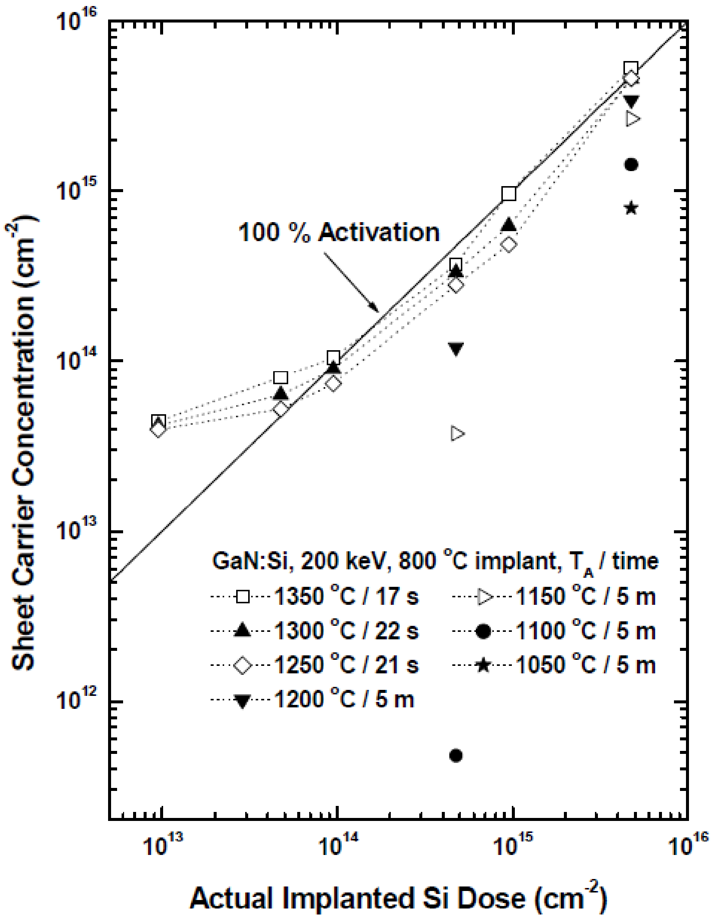

Figure 46. Sheet carrier concentration versus actual implanted dose for GaN implanted at 800 °C with 200 keV Si ions at doses ranging from $1x10^{13}$ to $5x10^{15}$ cm^{-2} and annealed at 1050 to 1350 °C from 5 min to 17 sec in a flowing nitrogen environment.

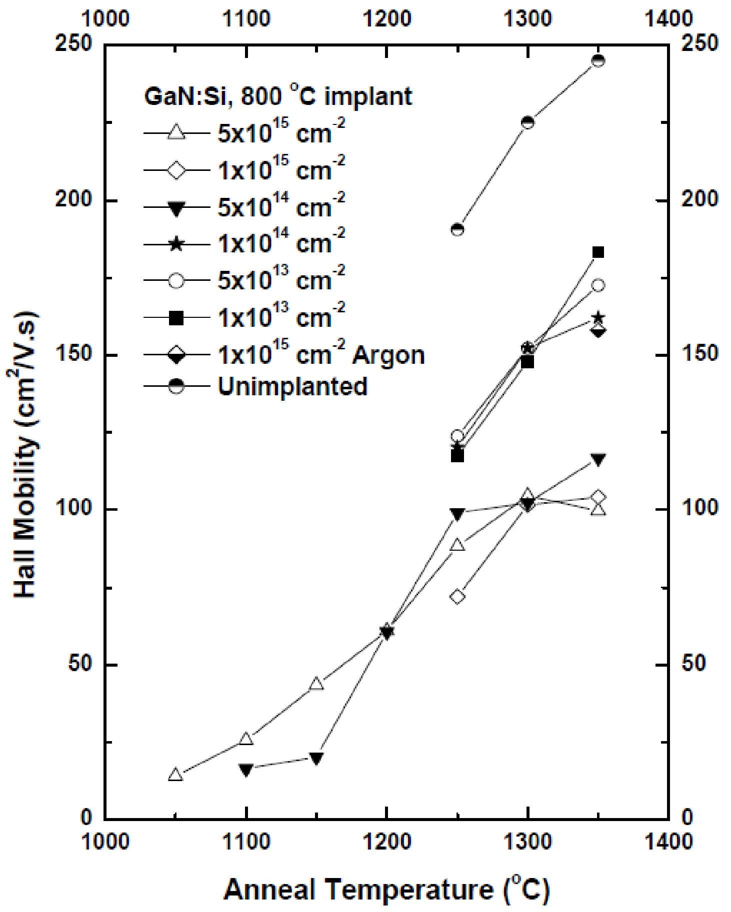

Figure 47. Room-temperature Hall mobility for GaN implanted at 800 °C with 200 keV Si ions at doses ranging from $1x10^{13}$ to $5x10^{15}$ cm^{-2} and annealed at 1050 to 1350 °C from 5 min to 17 sec in a flowing nitrogen environment.

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Si⁺ Implantation & Annealing (6)

- Si Annealing and activation, Si implantation @RT & @800°C comparison

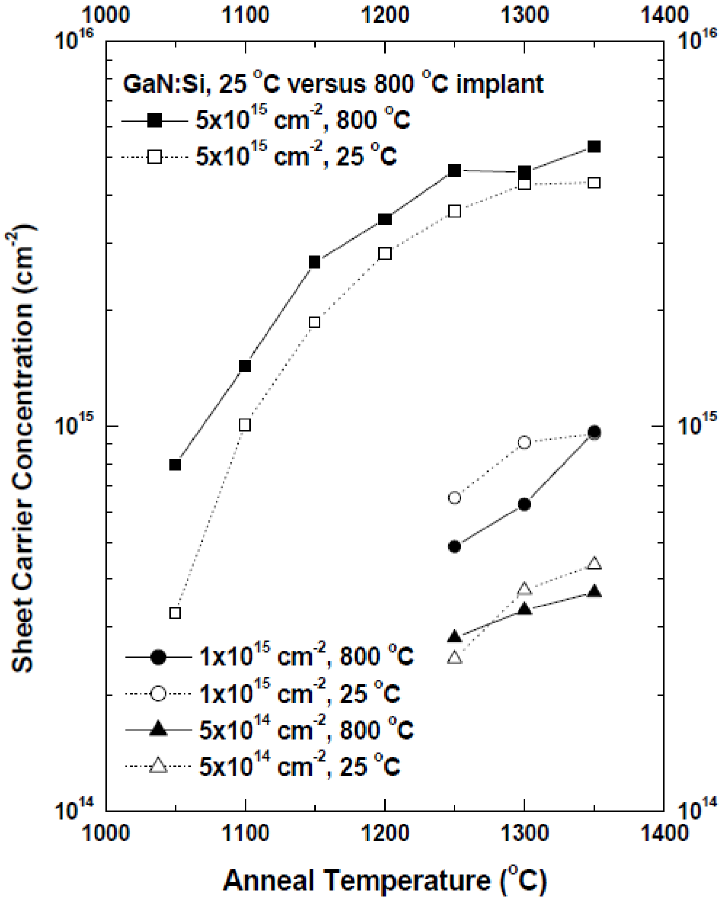

Figure 55. Room-temperature sheet electron concentrations for GaN implanted at 25 and 800 °C with 200 keV Si ions at doses ranging from 5×10^{14} to 5×10^{15} cm^{-2} and annealed at 1050 to 1350 °C from 5 min to 17 sec in a flowing nitrogen environment.

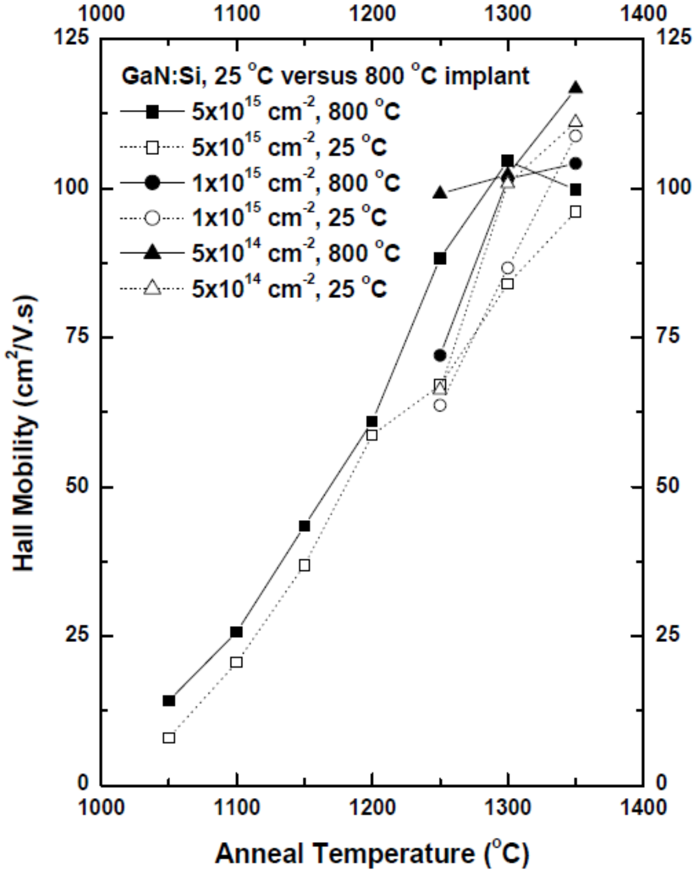

Figure 56. Room-temperature Hall mobility for GaN implanted at 25 and 800 °C with 200 keV Si ions at doses ranging from 5×10^{14} to 5×10^{15} cm^{-2} and annealed at 1050 to 1350 °C from 5 min to 17 sec in a flowing nitrogen environment.

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Si^+ Implantation & Annealing (7)

- Si Annealing and activation in GaN: Summary
  - Si is a donor in GaN with E_d~0.25meV
  - GaN wafer capped with 50nm AlN were implanted @RT and 800°C with 200keV Si^+ in ion doses range from 1E13Si+/cm^2 to 5E15Si/$^+cm^2$
  - A 100% activation was obtained for 1E15Si^+/cm^2 and annealing with RTA 1350°C, N2 17sec
  - With 5E15Si+/cm^2 are >20% activation possible at 1100°C ,N2 for 5 min or 90% for 1300°C, N2 for 23 sec or 1350°C for 17 sec
  - Doses ranges from 1E13Si^+/cm^2 to 5E14Si^+/cm^2 has lower activation or need T>1350°C
  - Si ion implantation at 800°C has no decisive advantage compared to RT
  - Outstanding Hall mobility values for Si-implanted GaN were obtained

James A. Fellows,_II-Si-Annealing-GaN, PHD

X-Fab Results

KHS, Martin Sterger(1), Libor Janovsky(2), Andreas Rödel, Ronny Müller-Biedermann, Victor Sizov

(1) Bosch Dresden, (2) Global Foundries Dresden)

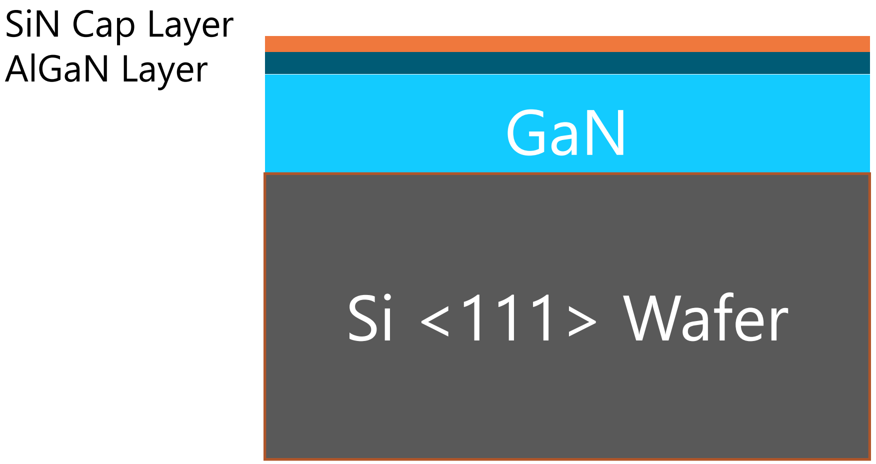
Si Ion Implantation in GaN Experiments

- GaN Wafer
- Ion Implantation & Preparation
- RTA Annealing
- SIMS Results
- Contact Measurements
- Summary

GaN Wafer

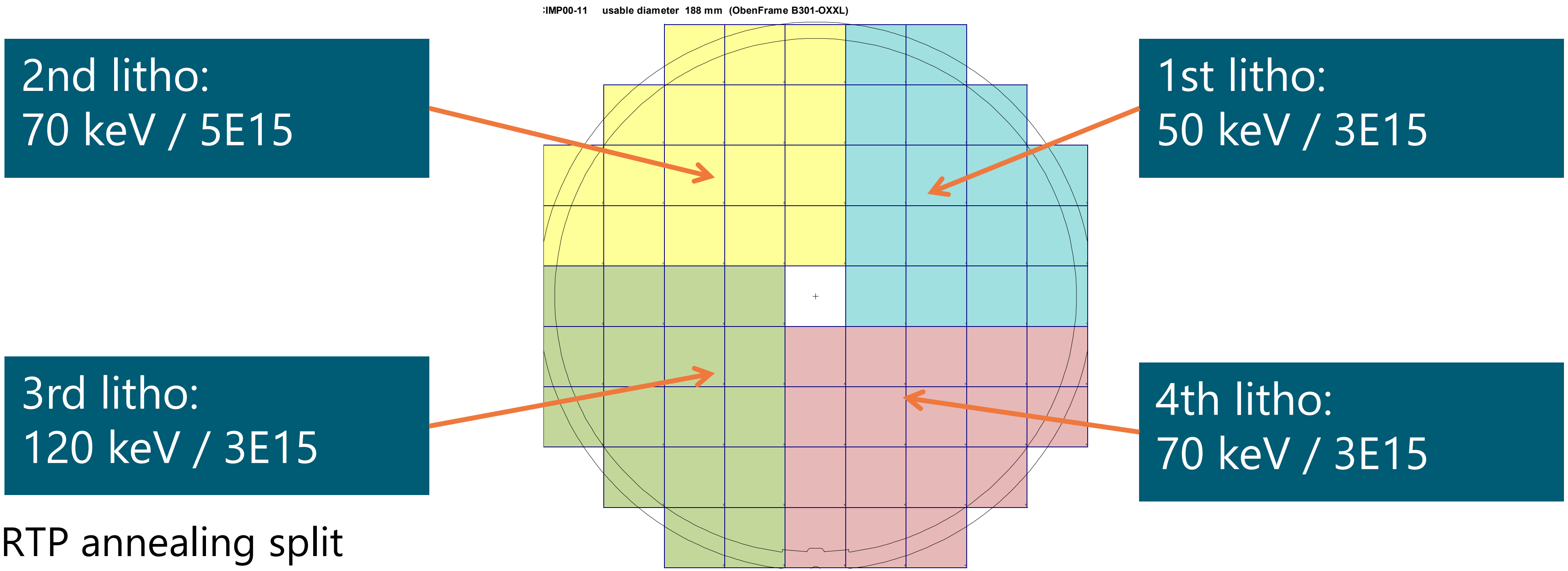
- EpiGan RF Wafer

Wafer thickness	725µm
GaN/AlGaN Total layer thickness	(1.5-2)µm
AlGaN layer thickness	20nm +/- 2 nm
AlGaN layer composition	25% +/- 1%
SiN cap	3nm



Ion Implantation and Preparation

- Use of wafers 03/05/07/09 of D17708
- 21nm LP nitride before 1st litho
- 4 litho layers, order of quadrants are same for Cartesian coordinate system
- Ion implantation in every quadrant



2nd litho:
70 keV / 5E15

1st litho:
50 keV / 3E15

3rd litho:
120 keV / 3E15

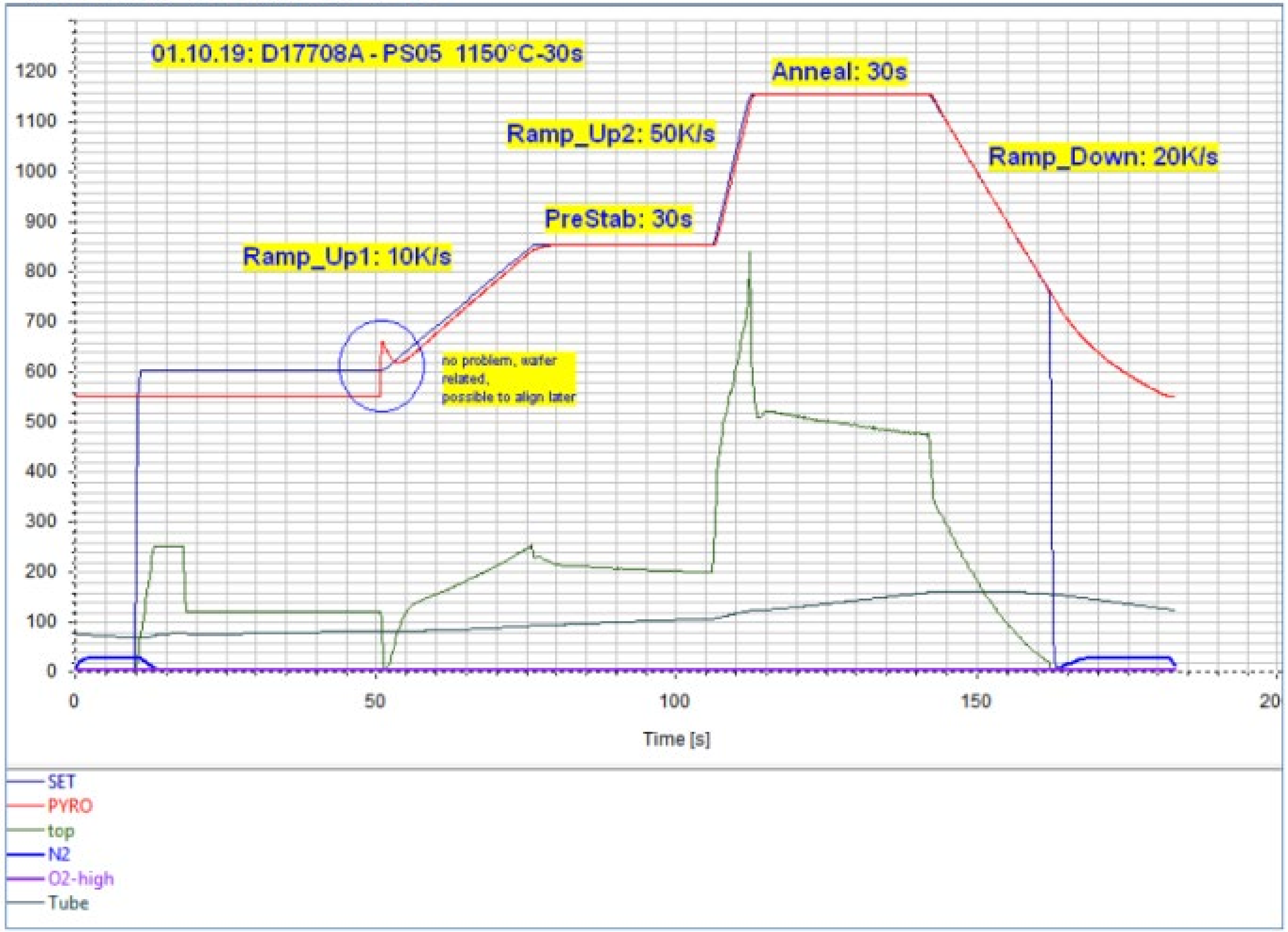
4th litho:
70 keV / 3E15

- RTP annealing split
- Nitride strip step at end of product for Rs-measurement

RTA Annealing

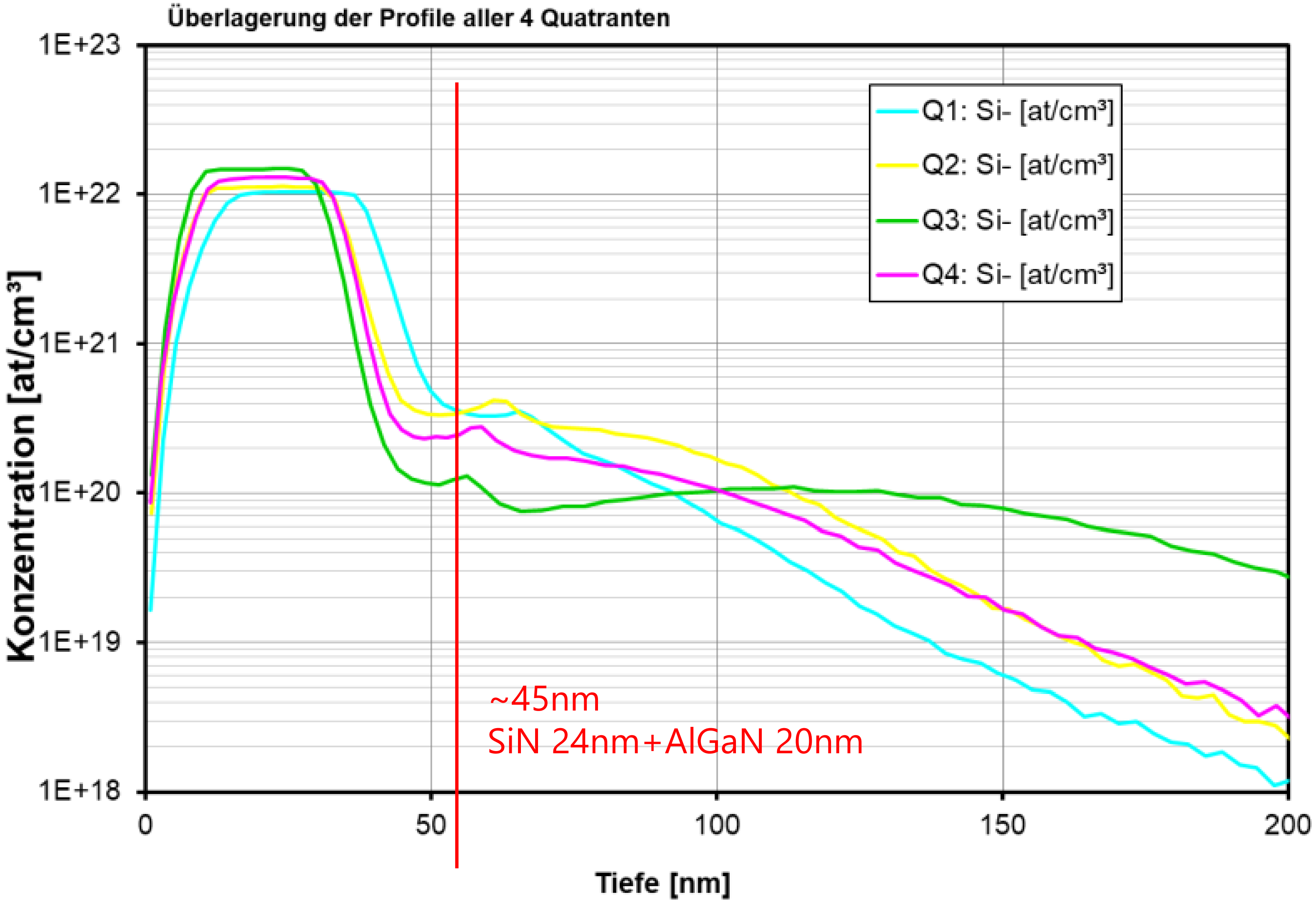
- RTA annealing split
- 1150°C, 30s, N2/O2 W5
- 1200°C, 30s, N2/O2 W7
- 1250°C, 10s, N2/O2 W9
- Longer time @1250°C needs upgrade cooling system
- Only N2 not possible (Si ring degradation)
- Wafer 3 SIMS as implanted

Process Run 1: **D17708A –PS05**

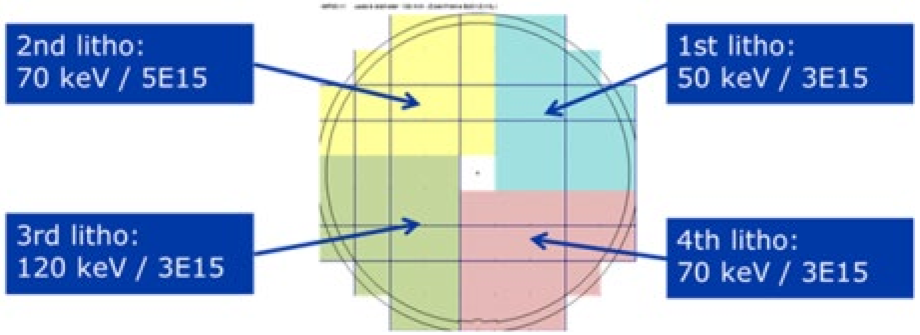


no problem, wafer related, possible to align later

SIMS Results W3



~45nm
SiN 24nm+AlGaN 20nm



2nd litho:
70 keV / 5E15

1st litho:
50 keV / 3E15

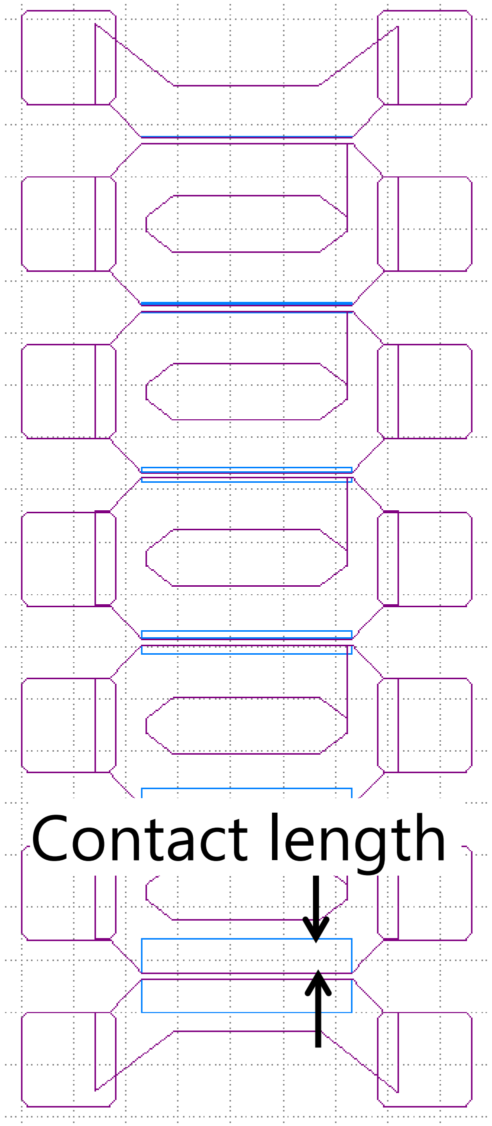
3rd litho:
120 keV / 3E15

4th litho:
70 keV / 3E15

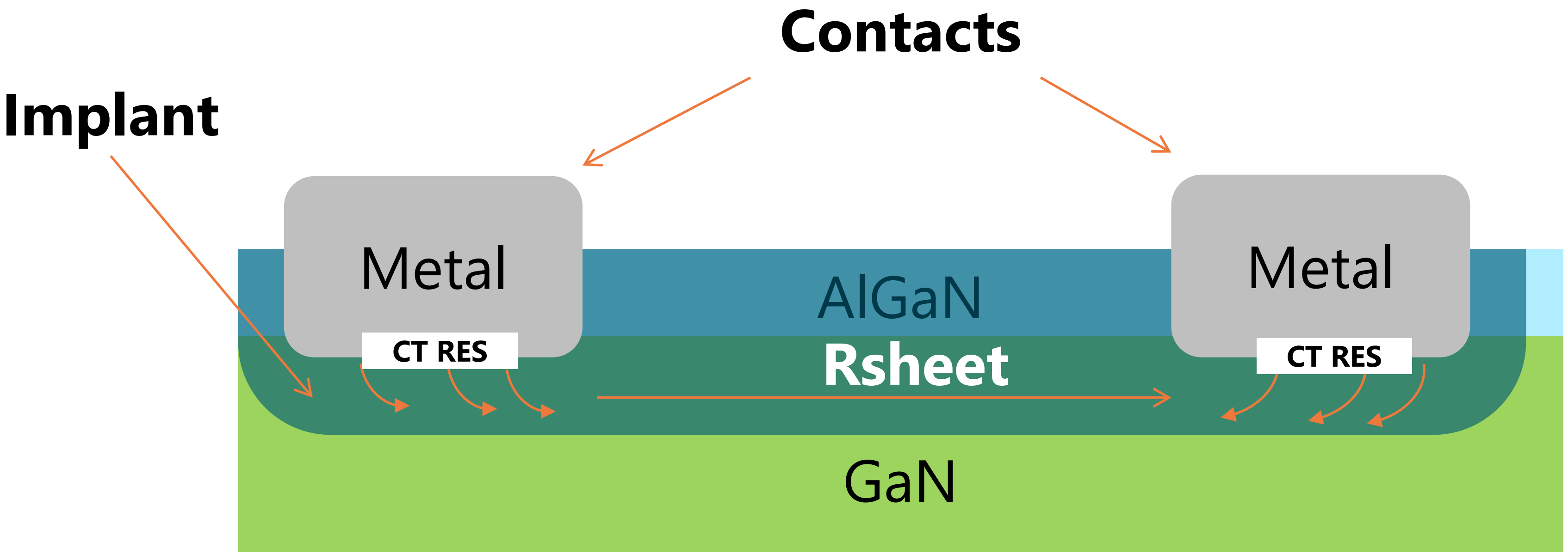
Different implant conditions clearly visible

70keV/5E15 preferred option since highest Si concentration near AlGaN/GaN interface

Structure description

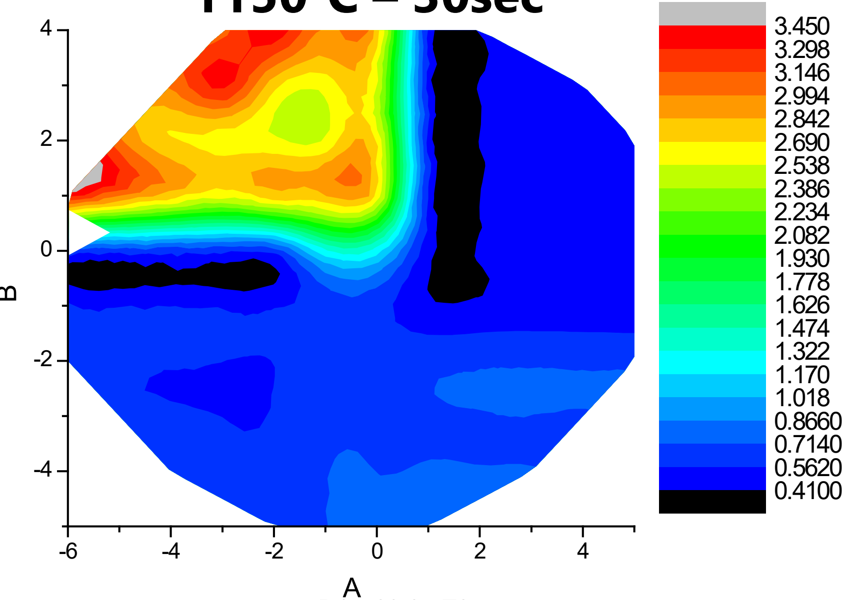


- TLN (transfer length structure) is a set of ohmic contacts with different length (1-32um)
- The space between contact is 6um and width is 200um
- Due to such aspect ration absebse of active isolation could be neglected in first approximation.

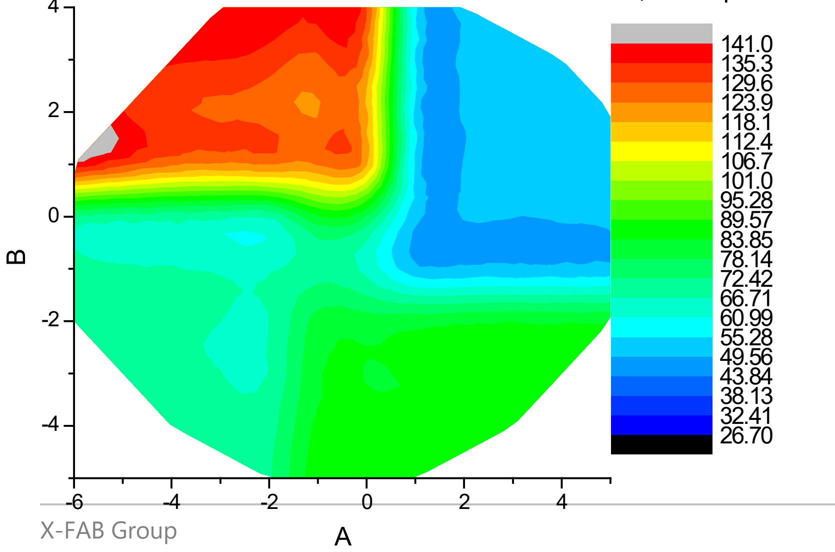


TLN 1um contact and Rsheet map

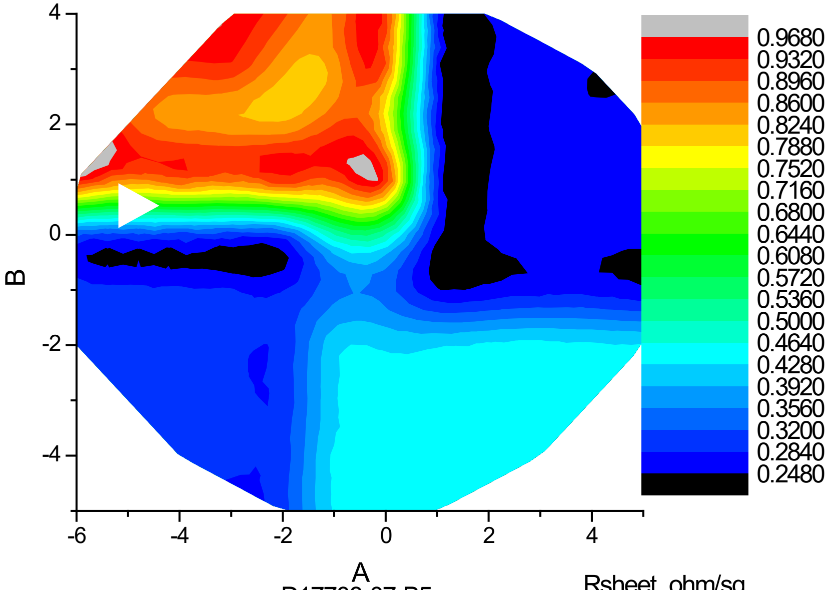
1150°C – 30sec



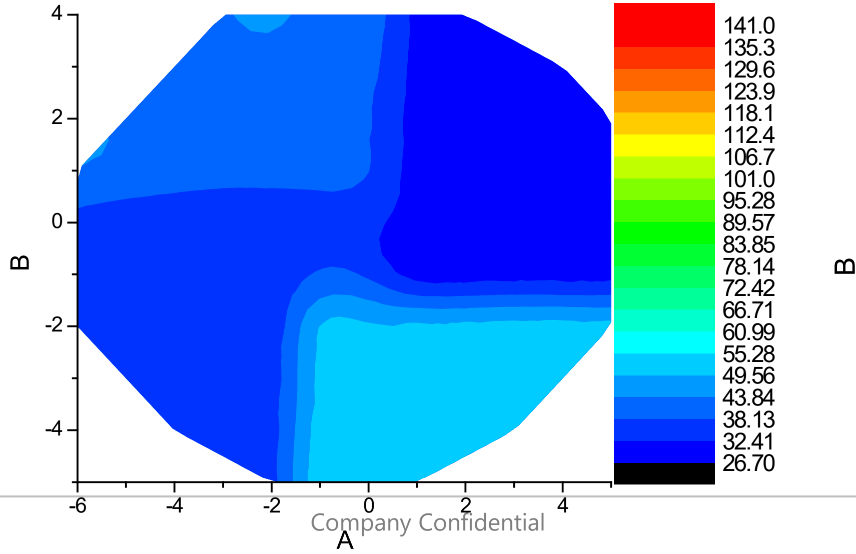
D17708-05-E2



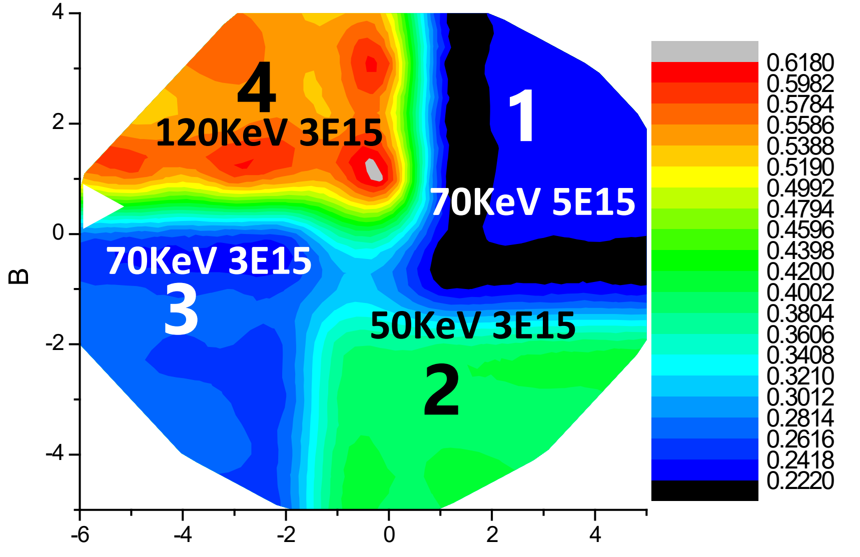
1200°C – 30sec



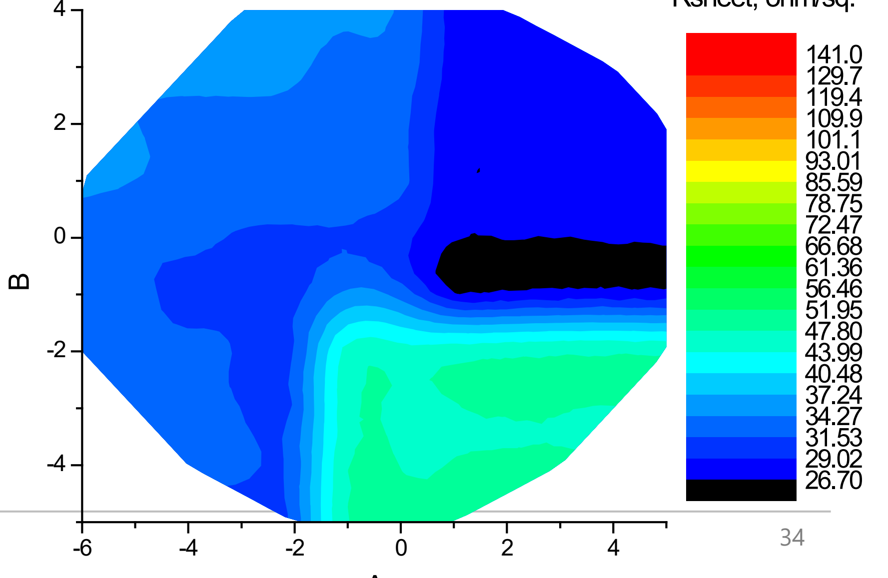
D17708-07-B5



1250°C – 10sec



D17708-09-G3

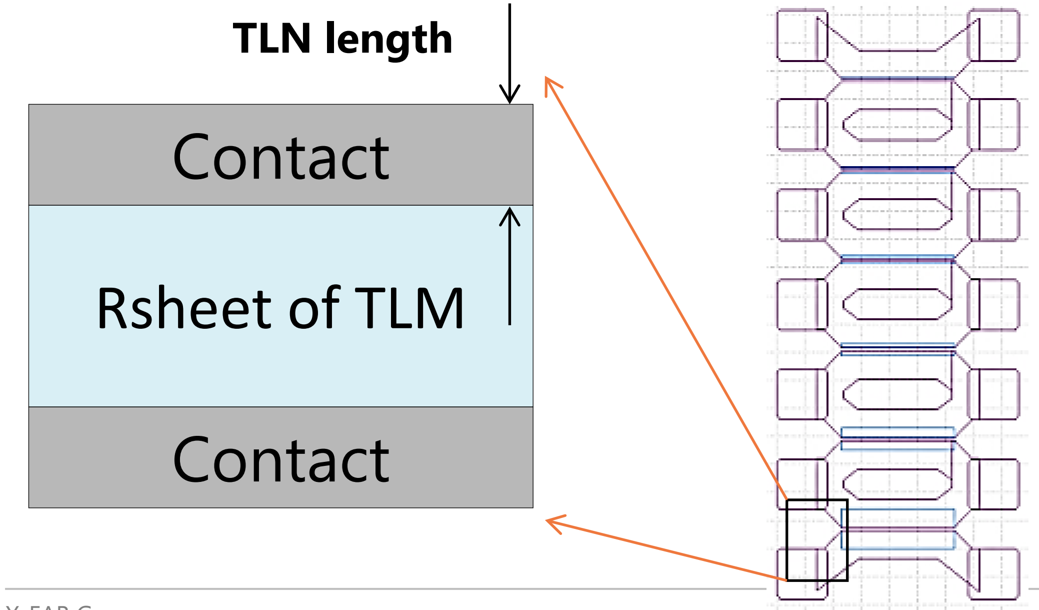


Summary (1)

	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4
	D17708-05				**D17708-07**				**D17708-09**			
	1150C 30sec				**1200C 30sec**				**1250C 10sec**			
	70KeV 5E15	50KeV 3E15	70KeV 3E15	120KeV 3E15	70KeV 5E15	50KeV 3E15	70KeV 3E15	120KeV 3E15	70KeV 5E15	50KeV 3E15	70KeV 3E15	120KeV 3E15
Rsheet, ohm/sq.*	51	86	68	131	30	53	36	42	27	48	32	34
TLN 1um, ohm*mm	0.44	0.70	0.58	2.87	0.26	0.44	0.30	0.88	0.23	0.39	0.26	0.55
TLN 32um, ohm*mm	0.45	0.70	0.57	1.83	0.26	0.44	0.29	0.55	0.22	0.38	0.26	0.41
Rsheet of TLM, ohm*	0.31	0.51	0.41	0.78	0.18	0.32	0.21	0.25	0.16	0.29	0.19	0.20
CT res 1um, ohm/mm	0.28	0.45	0.37	2.48	0.17	0.28	0.19	0.75	**0.15**	0.25	**0.17**	0.45
CT res 32um, ohm/mm	0.30	0.45	0.36	1.44	0.17	0.28	0.19	0.43	**0.14**	0.24	**0.16**	0.31

* Due to no isolation implant were used here the number can be up to factor of two wrong.

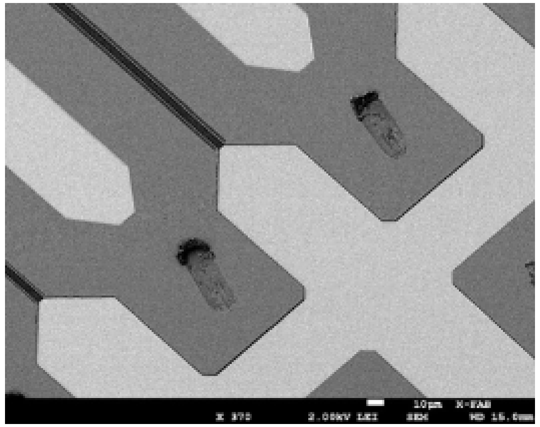
Tot RES=2*CTres+Rsheet

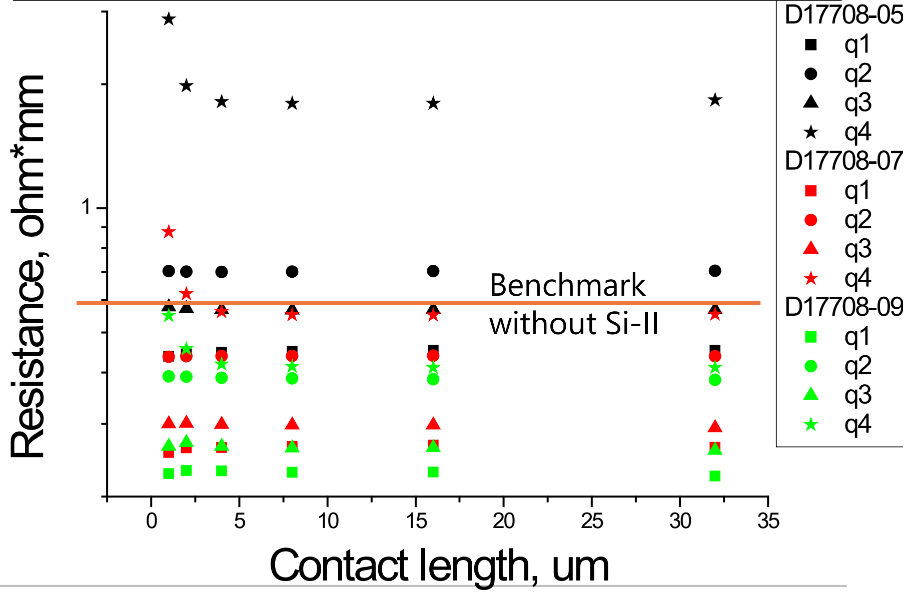

TLN length

Contact

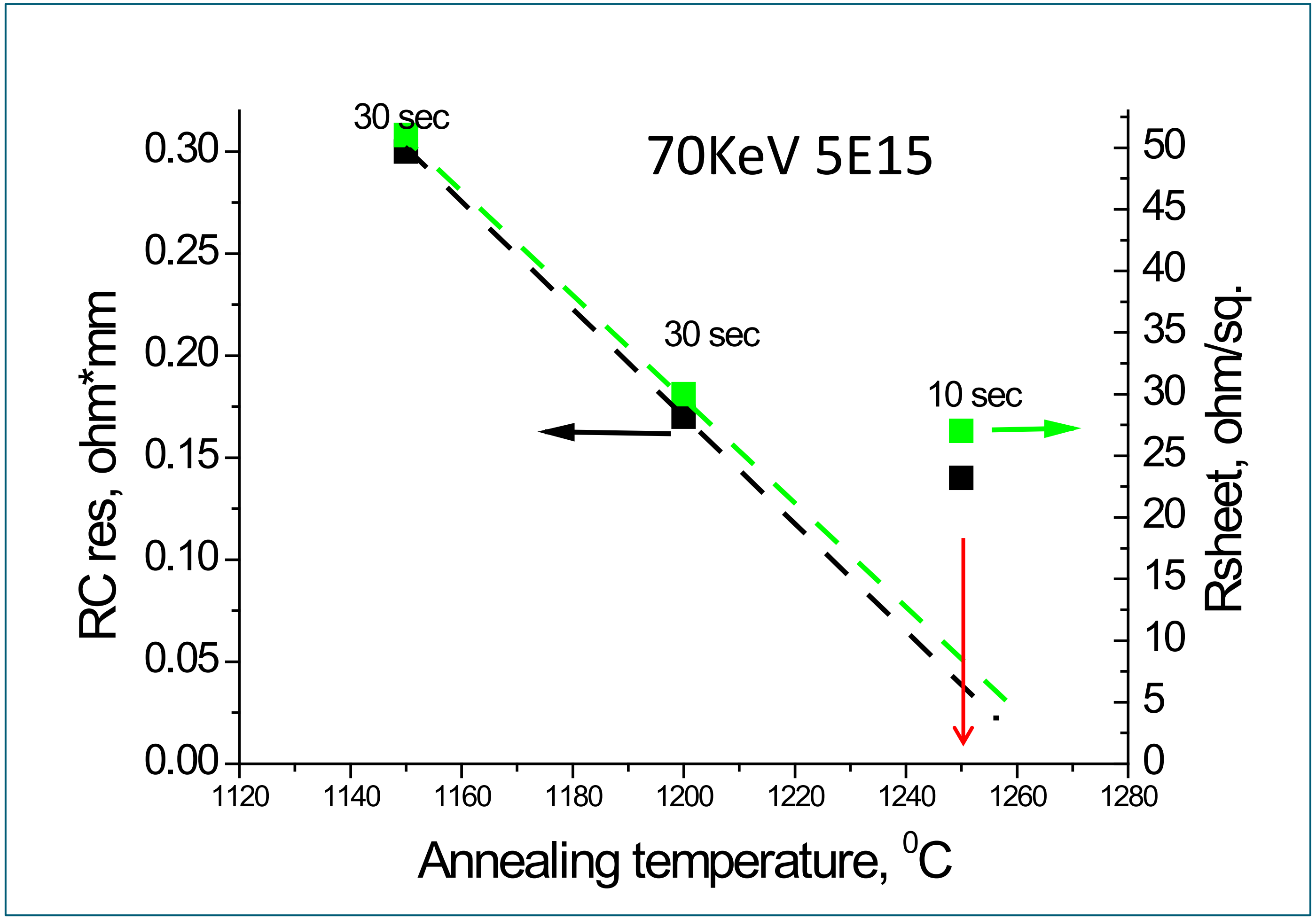
Rsheet of TLM

Contact



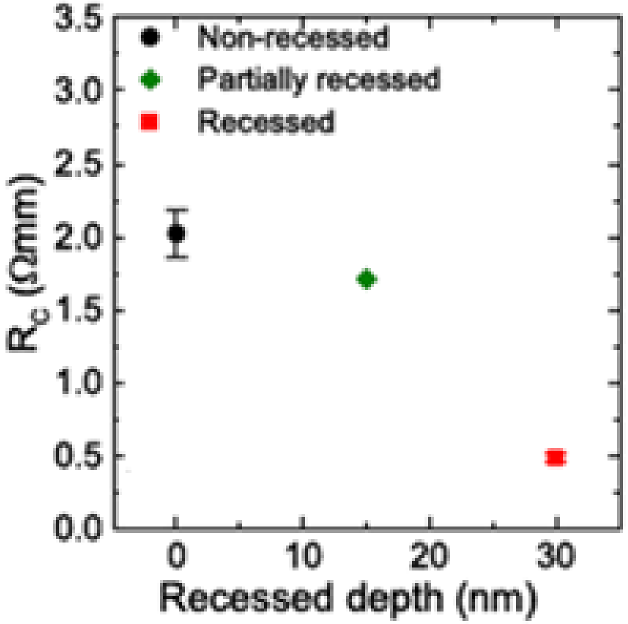


Summary (2)



How much annealing time for 1250°C can be extended?
With new cooling system are 30sec possible

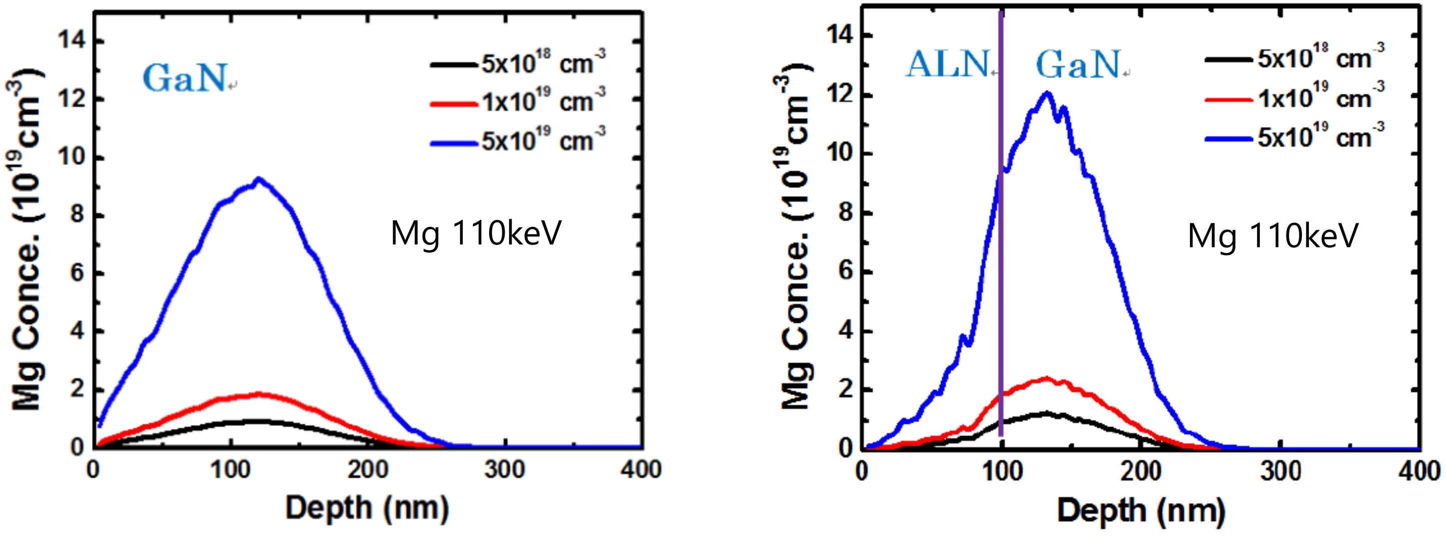
Benchmark for Ti/Al-contact
0.5 Ohm*mm with N vacancies
for n-doping



Mg^{+24} Ion Implantation in GaN

Mg$^+$ Implantation & Annealing (1)

- Mg$^+$ ion range in GaN
  - Electron & nuclear stopping power (LSS Theory)
  - Simulation with TRIM or other codes

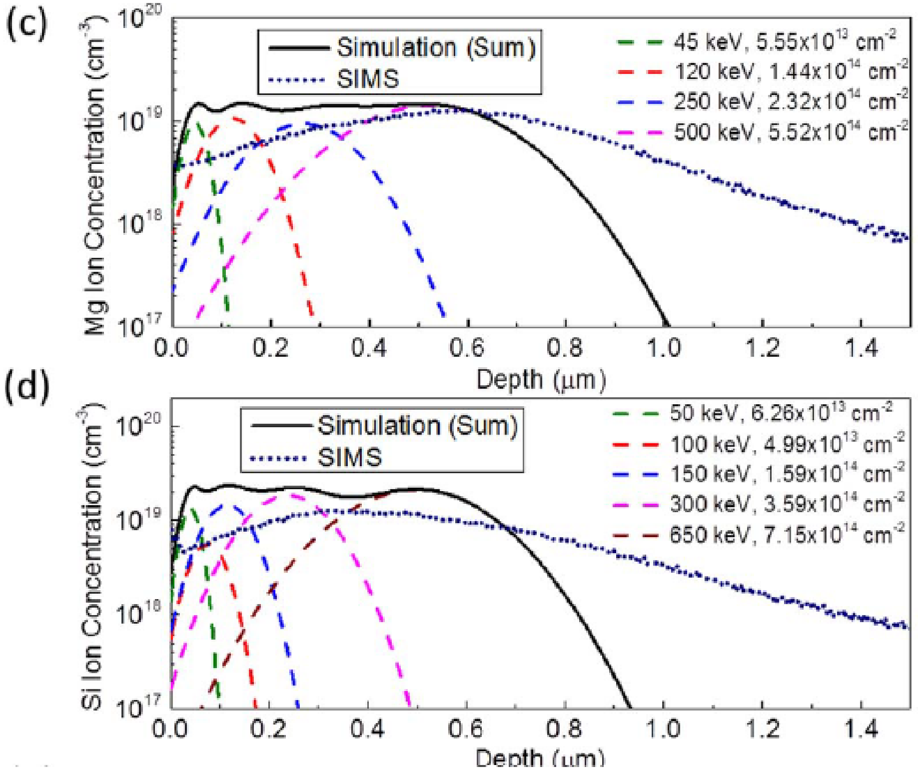


(a)

(b)

Fig. 2.4 Mg-ion distributions simulated by TRIM.

Zheng Sun PHD „Reduction in Mg Ion Implantation Damage ….“



The simulated (c) Mg and (d) Si ion profiles as a function of depth, and the ion profiles after high-temperature activation measured by SIMS
Zhihong Liu: IEEE ELECTRON DEVICE LETTERS, VOL. 38, NO. 8, AUGUST 2017

Mg^+ Implantation & Annealing (2)

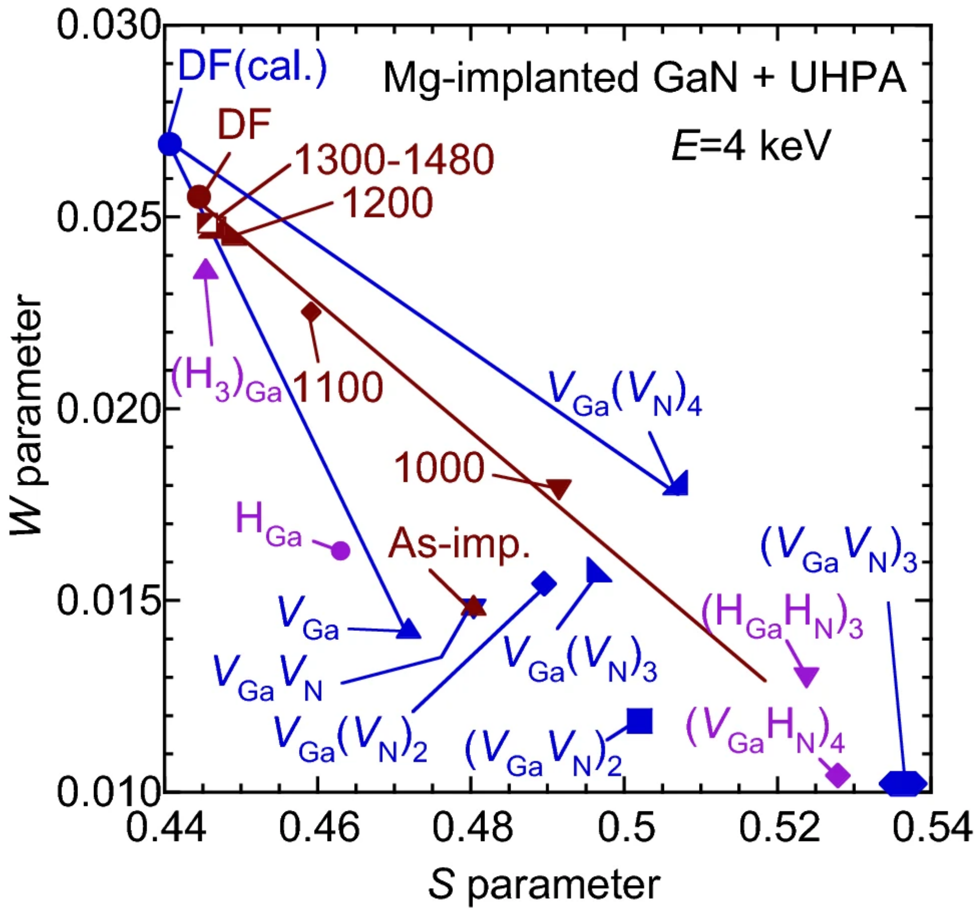
Defect generation in GaN, amorphization

- Damage of crystal structure, point defects (interstitials, vacancies, anti-sites, or extended defects)
- Typical defects are:
- Ga or Nitrogen vacancy (V_{Ga}, V_N)
- Ga or N interstitials (Ga_i, N_i)
- Ga or N anti-site (Ga_N, N_{Ga})
- Frenkel pair (vacancy with displaced atom with a neighboring interstitial)
- Combined defects like di-vacancies, tri-vacancies, di-acceptor, interstitial clusters, ….
- All defects can act as donor or acceptor type (N_i is a triple acceptor, Ga_i triple donor, Ga_N is double acceptor, N_{Ga} double donor)
- Mg_{Ga} is single acceptor, deep donor/acceptor defect complex $Mg_{Ga}–V_{N,}$ $Mg_I–V_N$
- Amorphization doses @RT >~2-4E16Mg^+/cm^2
- GaN lattice reconstruction after amorphization is not possible

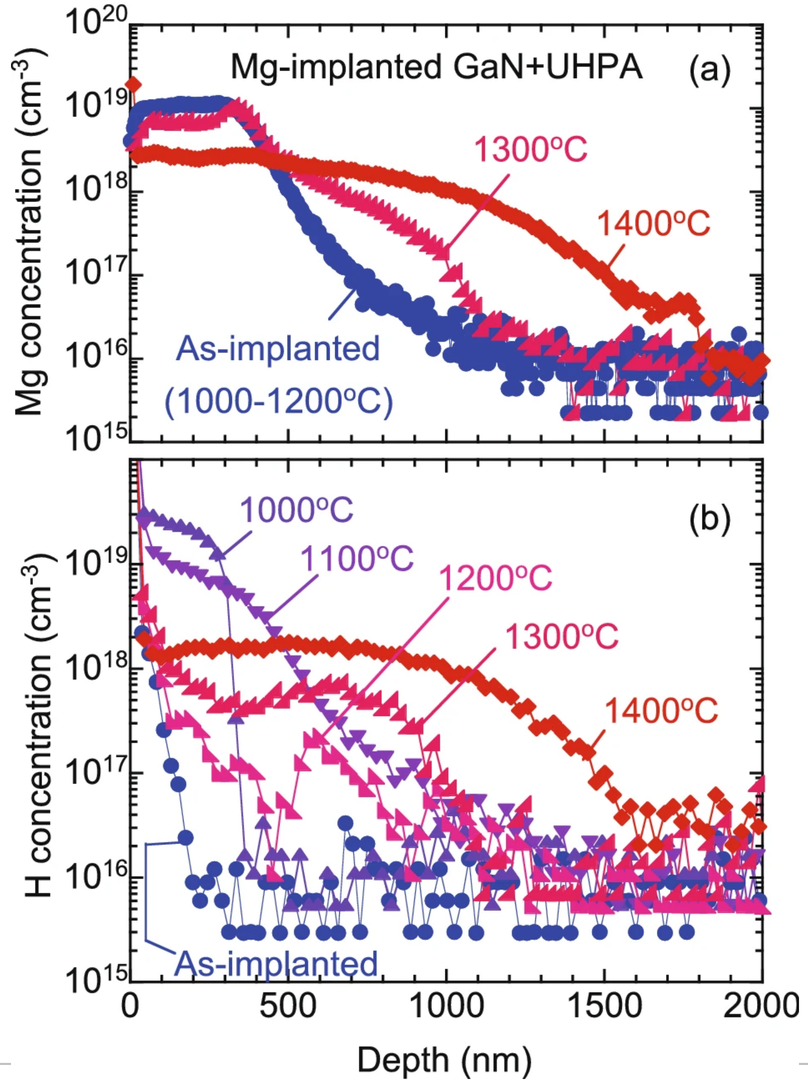
James A. Fellows,_II-Si-Annealing-GaN, PHD, *C. Ronning et al. / Physics Reports 351 (2001) 349-385*

Mg^+ Implantation & Annealing (3)

- Mg Annealing and activation, defect Mg & H concentration and distribution



Brown line connects (*S*, *W*) values for un-implanted sample and samples annealed above 1000 °C.



The energies of Mg ions were 30, 70, 150, and 300 keV, and the correspond ding dosages were 2.0 × 1013, 5.0 × 1013, 1.1 × 1014, and 3.0 × 1014 cm−2,

Depth distributions of Mg and H for Mg-implanted GaN measured by SIMS

Temperatures between 1000 and 1480 °C (5 min) under a N2 pressure of 1 GPa

Effects of ultra-high-pressure annealing on characteristics of vacancies in Mg-implanted GaN studied using a mono-energetic positron beam
Akira Uedono, Hideki Sakurai, Tetsuo Narita, Kacper Sierakowski, Michal Bockowski, Jun Suda, Shoji Ishibashi, Shigefusa F. Chichibu & Tetsu Kachi
Scientific Reports volume 10, Article number: 17349 (2020)

Mg$^+$ Implantation & Annealing (4)

Mg Annealing and activation with RTA or MRTA

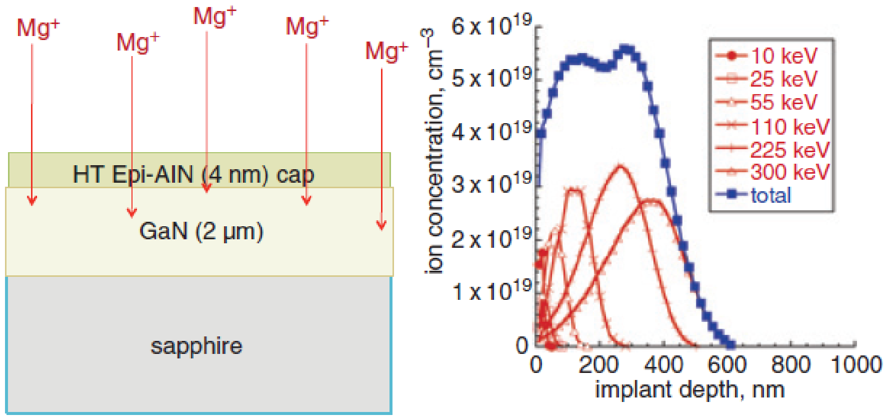


Fig. 1 *Cross-section schematic of layer structure (left) and implant profile (right)*

Sample: 2µm GaN epi-layer, 4nm AlN
Mg ion implantation for a total dose of 7.1 × 1014 cm2. The wafer was diced, and the samples were then annealed in a 200 PSI N2 overpressure atmosphere, first at 1000°C for 1 h to remove a part of the implant damage, followed by the multicycle rapid thermal anneal technique described elsewhere in the literature to activate the implanted impurities. The peak temperature was ~1350°C, the cycle time was varied from 10 to 25 s, and the number of cycles varied from 10 to 60, for a total time above 1100°C ranging from 4 to 8 min, shown in Table 1.

Table 1: Summary of annealing conditions

Sample	Peak T (°C)	Cycle time (s)	Number of cycles	Total time >1340°C (s)
A	1410.9	6.62	19	125.8
B	1417	3.14	40	125.6
C	1421.8	3.87	15	58.1
D	1341.5	0.24	30	7.2

Table 2: Summary of film parameters for different annealing conditions

Sample	R_{SH} (kΩ/□)	μ(cm^2/V-s)	N_A (cm^{-3})	Activation
A	42.6	5	8.4×10^{17}	1.4
B	4850	1	3.7×10^{15}	<0.1
C	5.38	20	1.7×10^{18}	8.2
D	2.69	40	1.7×10^{18}	8.2

ELECTRONICS LETTERS 30th January 2014 Vol. 50 No. 3 pp. 197–198

The results were verified, and under the best annealing conditions the RSH was <3000 Ω/□. Since the sheet resistivity is directly related to the mobility and the carrier density by (1), the µ*Np product can be calculated to be ~2.3 × 1015, assuming Np > > Nn:

Mg^{+} Implantation & Annealing (5)

Mg Annealing and activation with RTA or MRTA

Experimental
Samples of 2 µm thick GaN:Si (2.8 × 10^{16} cm^{-3} at 300 K, measured by Hall) , (1100°C) MOCVD AlN, followed by additional 25 nm low-temperature (660–680°C) MOCVD AlN.[17–19,25] A 1 µm thick SiO_2 implantation hard mask was deposited by plasma-enhanced CVD. The oxide mask was then patterned to define selectively-implanted areas, and each wafer received a triple-implanted with Mg ions at room temperature at a 7° angle to reduce ion channeling. The implantation energy and dose for each implant step were: 1) 50 keV / 5 × 10^{13} cm^{-2}, 2) 140 keV / 1.1 × 10^{14} cm^{-2}, 3) 300 keV / 3 × 10^{14} cm^{-2}. SRIM simulations of the implantation. Annealing MRTA or 900°C 70min 28,6atm)

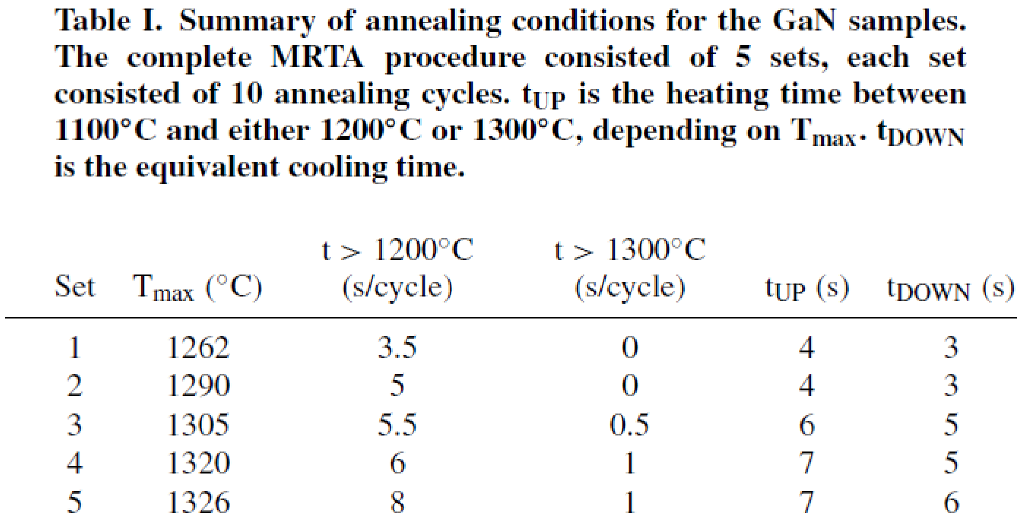


Table I. Summary of annealing conditions for the GaN samples. The complete MRTA procedure consisted of 5 sets, each set consisted of 10 annealing cycles. t_{UP} is the heating time between 1100°C and either 1200°C or 1300°C, depending on T_{max}. t_{DOWN} is the equivalent cooling time.

Set	T_{max} (°C)	t > 1200°C (s/cycle)	t > 1300°C (s/cycle)	t_{UP} (s)	t_{DOWN} (s)
1	1262	3.5	0	4	3
2	1290	5	0	4	3
3	1305	5.5	0.5	6	5
4	1320	6	1	7	5
5	1326	8	1	7	6

ECS Journal of Solid State Science and Technology, 5 (2) P124-P127 (2016)
The Electrochemical Society "Selective p-type Doping of GaN:Si by Mg Ion Implantation and Multicycle Rapid Thermal Annealing" Marko J. Tadjer, et al.

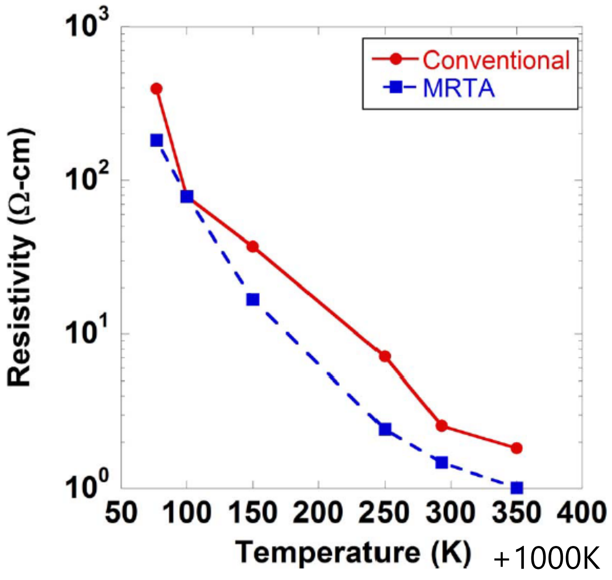


Figure 3. Temperature-dependent resistivity of Mg-implanted Si-doped GaN after conventional and MRTA annealing.

Mg^+ Implantation & Annealing (6)

- Mg Annealing and activation in GaN: Summary
  - Mg is an acceptor in GaN with E_a~0.160meV
  - GaN wafer capped with AlN or thin Si_3N_4 or SiO_2 (<10nm) or blanket before Mg ion implantation (Si back scattering, n-doping) are typical
  - Capping after blanket ion implantation with AlN or thin Si_3N_4 or SiO_2 before annealing (RTA, MRTA)
  - Less 10% activation is possible annealing with RTA or MRTA >1200°C, 30-60sec
  - MgH-complexes and donor like defects or Si (back scattering) are reducing activation from Mg or compensate Mg-doping
  - High temperature Mg ion implantation has no advantage compared to RT (higher defect density after Mg high temperature ion implantation)
  - With conventional high T and long time annealing no really p-doping is possible

James A. Fellows,_II-Si-Annealing-GaN, PHD

Application for Ion Implantation in GaN

Contact and S/D Engineering for RF (1)

Low Parasitic Source Resistance for RF

- GaN/AlGaN/GaN, 5 nm GaN cap layer
- SiNx 25nm cap layer (PE-CVD)
- Si^+ ion implantation tolal 2.5E15Si^+/$cm^{2,}$ 30-160keV,
- Annealing 1200°C, 120s, N_2, no surface damage
- Metal stack: Ti/Al (30/200 nm)

- measured contact resistance 1.4 × 10-7 Ω·cm^2, 30kev and 7.0 × 10-7 Ω·cm^2, 80keV
- effective dose 1E15Si^+/cm^2
- high surface concentration is necessary

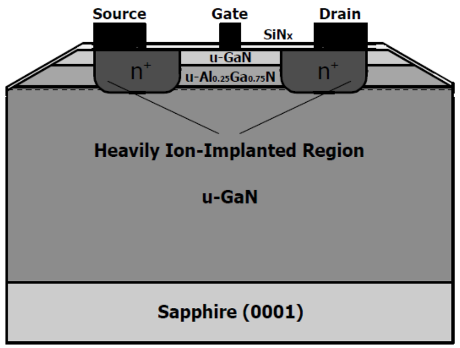


Fig. 1. Schematic cross-section of Ion-Implanted GaN/AlGaN/GaN HEMT structure.

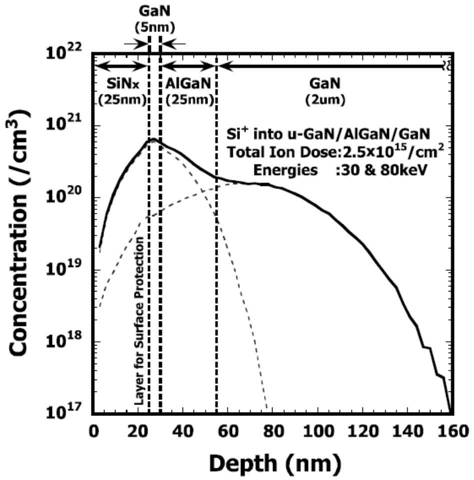


Fig. 2. Simulated impurity profiles of Si ion-implated source/drain resions.

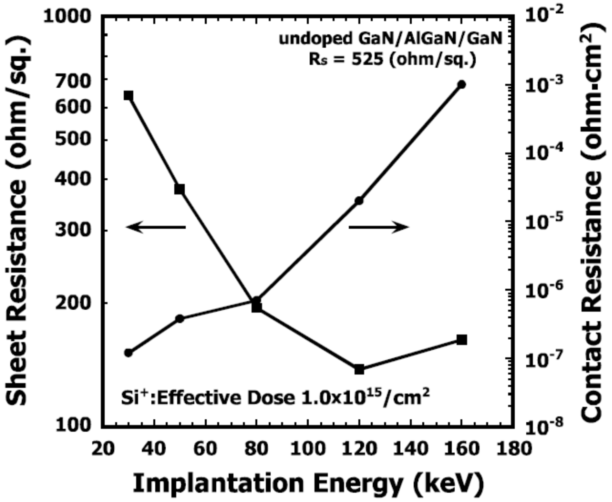


Fig. 3. Sheet resistance and contact resistance of ion implanted GaN/AlGaN/GaN structure
as a function of Si ion energy

K. Nomoto, Multiple Ion-Implanted GaNAlGaNGaN HEMTs with Remarkably Low Parasitic Source Resistance

Contact and S/D Engineering for RF (2)

Low Parasitic Source Resistance for RF

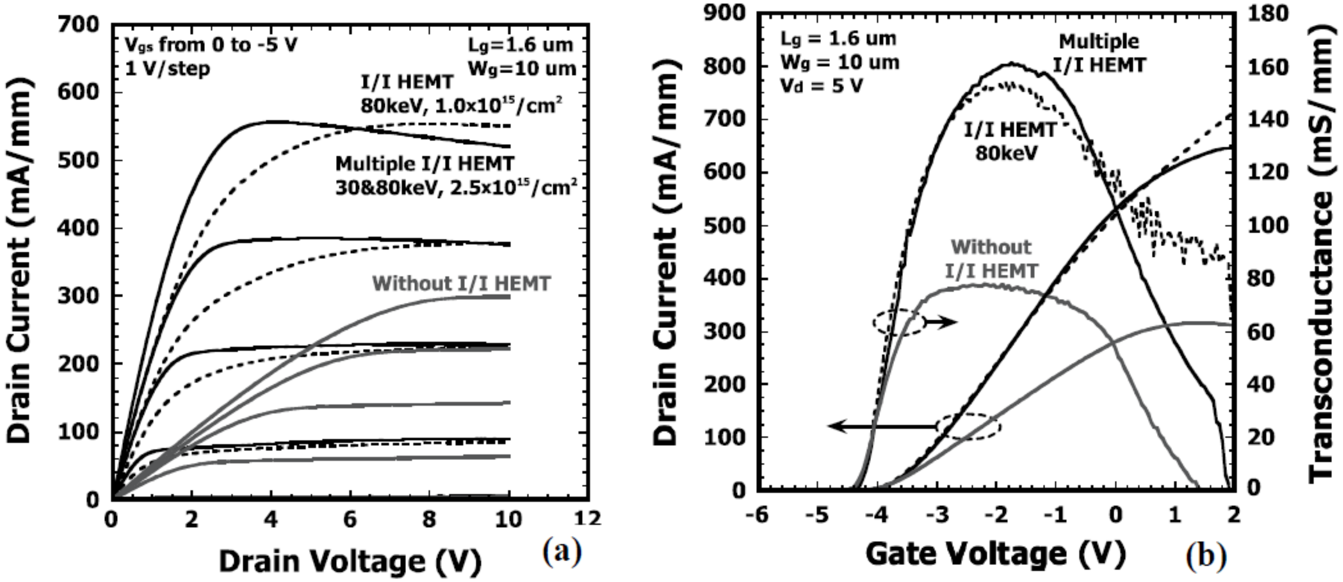


Fig. 4. (a) I_d-V_{ds} characteristics and (b) transconductance of GaN/AlGaN/GaN HEMTs with and without ion implantation.

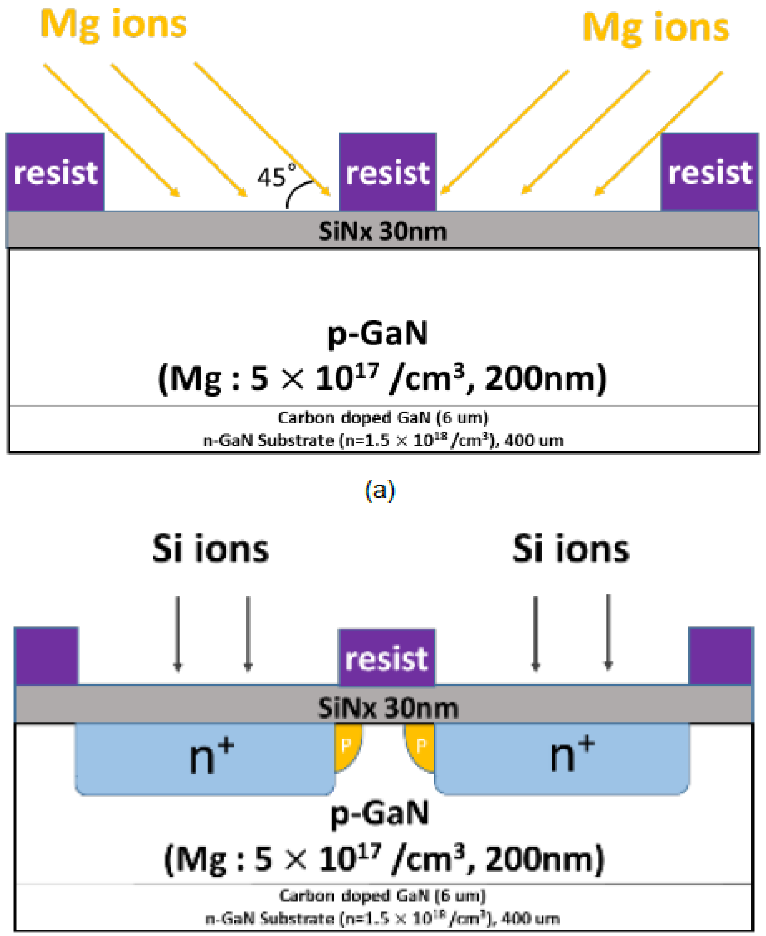
- 30keV & 80keV S/D ion implantation with Si
- On-resistance reduced from 9.9 to 3.5 Ω·mm.
- Saturation drain current increased from 300 to 560 mA/mm
- maximum transconductance increased from 75 to 160 mS/mm

K. Nomoto, Multiple Ion-Implanted GaNAlGaNGaN HEMTs with Remarkably Low Parasitic Source Resistance

Mg Tilted-Angel Ion Implantation (1)

Short Channel Engineering with Mg Ion Implantation

The epitaxial layers consist of Mg-doped-GaN (Mg: 5 × 1017/cm3, 200nm)/carbon-doped-GaN (C: 1.1 × 1019/cm3, 6 µm) layer on a GaN substrate (n=1.5 × 1018/cm3, 400 µm). A 30 nm-thick SiNx film was deposited on the layers. Mg ions were implanted to the SiNx film surface with a tilted angle of 45 degrees at doses of 1 × 1013/cm2, 4 × 1013/cm2 and 8 × 1013/cm2 at an energy of 60 keV as shown in Figure 1(a). The SiNx films were then removed and 40 nm thick SiNx films were deposited again, followed by activation annealing at 1230˚C for 1 min in ambient N2. N ions were implanted into field regions at a dose of 1 × 1015/cm2 at an energy of 80 keV to perform device isolation of GaN MISFETs as shown in Figure 1(c) [9]. The simulated impurity profiles of Mg, Si, and N ions are shown in Figure 2. Source/drain electrodes were formed by depositing Ti/Al (50/300 nm) layers, followed by metallization annealing at 550˚C for 1 min. Finally, gate electrodes were formed by depositing
Ni/Al (50/200 nm) layers as shown in Figure 1(d).



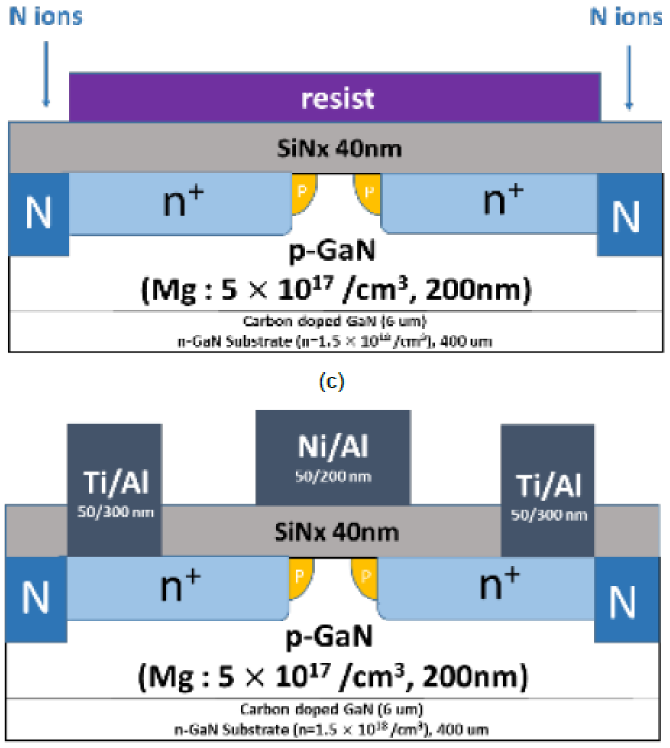
(a)

(b)

Journal of Materials Science and Chemical Engineering, 2017, 5, 48-53

Mg Tilted-Angel Ion Implantation (2)

- Short Channel Engineering with Mg Ion Implantation



(c)

(d)

Figure 1. Fabrication processes of GaN MISFETs. Tilted Mg ion implantation for controlling threshold voltage (a), vertical Si ion implantation for forming source/drain regions (b), N ion implantation for forming isolation regions in SiNx film (c) and the fabricated GaN MIFETs (d).

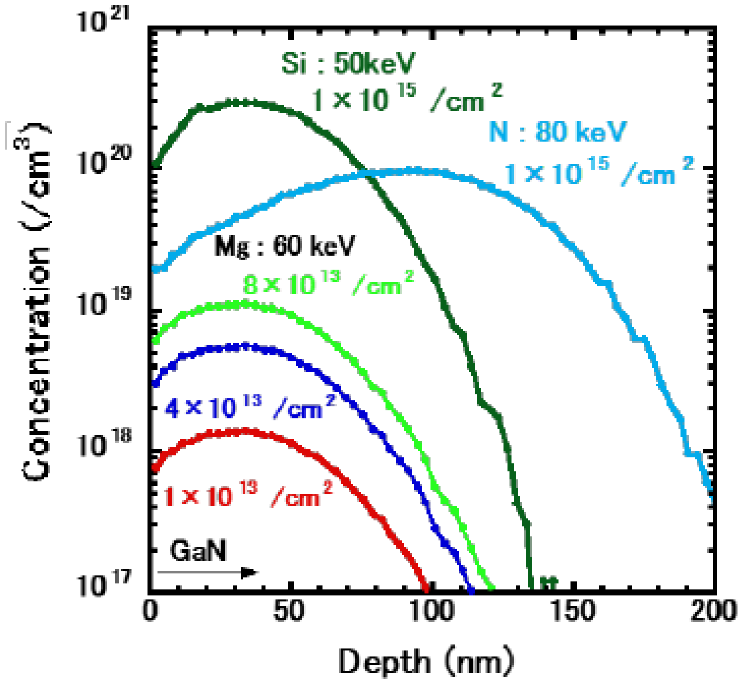


Figure 2. Simulated implanted impurity depth profiles of Si ions for the formation of source/drain regions, Mg ions adjacent to the source/drain regions, and N ions for field isolation regions.

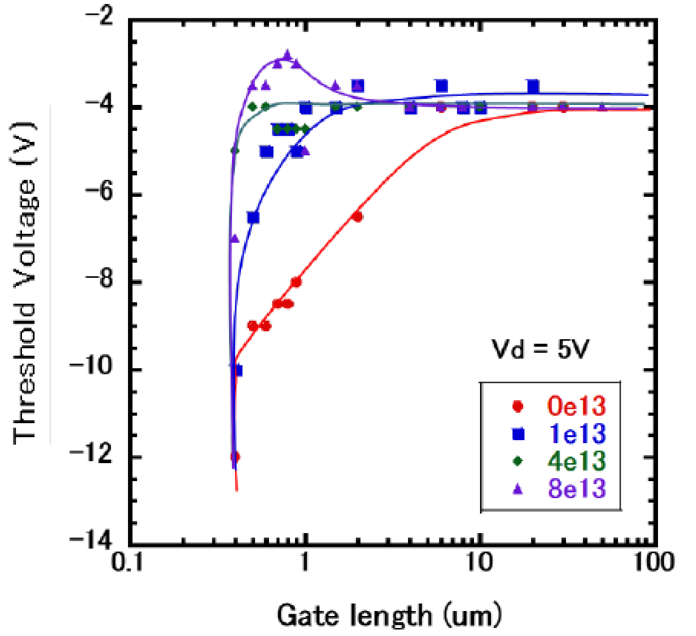


Figure 5. Relationship between the threshold voltage and gate length for the devices.

Table 1. Comparison of characteristics of GaN MISFETs.

Tilt angle Mg implanted GaN MISFET	Threshold Voltage V_{th} (V)	Maximum Transconductance g_{mmax} (mS/mm)	Drain Current I_d (mA/mm) ($V_g - V_{th} = 5$ V, $V_d = 5$ V)
Mg dose: $1 \times 10^{13}/cm^2$	−6.5	73	225
Mg dose: $4 \times 10^{13}/cm^2$	−4	55	188
Mg dose: $8 \times 10^{13}/cm^2$	−3.5	40	106

Journal of Materials Science and Chemical Engineering, 2017, 5, 48-53

Power DMOS GaN on GaN (1)

- Fully implanted normally-off DMOSFET with ALD-Al_2O_3 Gate Dielectric (1)

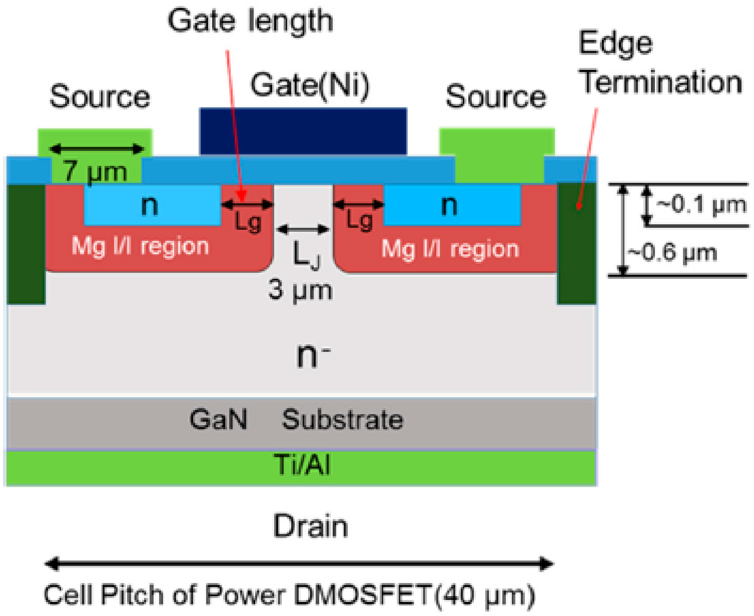


Figure 4. Schematic cross section of the fully ion implanted vertical GaN DMOSFET

GaN layer 5µm Si doped 5E16Si/cm^3 on GaN substrate,
Top layer30nm SiNx, Mg implant 0° 50keV 1E15Mg/cm^2
Mg implant 30°, 200, 100, and 50 keV with doses of 1.0E14, 3.2E13, and 1.5E13 cm2 (single side total dose:1.47E14 cm2) SiN etch,
50nm LP-CVD SiN
RTA 1230°C 60sec, N2

Materials 2019, 12, 689; doi:10.3390/ma12050689

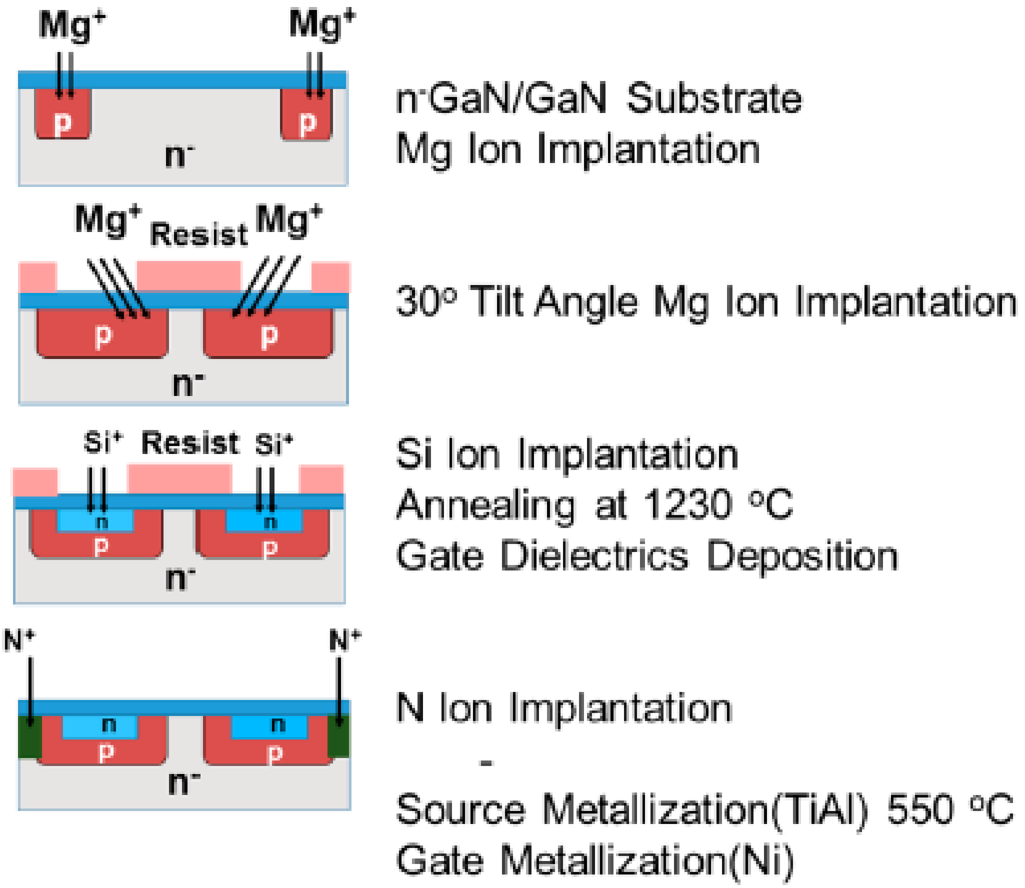


Figure 5. Fabrication process of the GaN DMOSFET by triple ion implantation.

Power DMOS GaN on GaN (2)

- Fully implanted normally-off DMOSFET with ALD-Al_2O_3 Gate Dielectric (2)

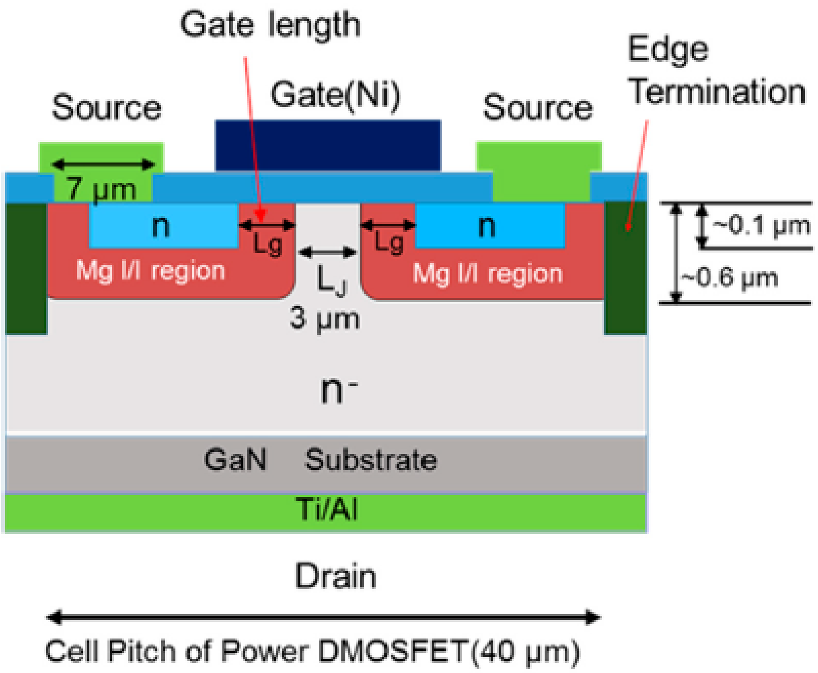


Figure 4. Schematic cross section of the fully ion implanted vertical GaN DMOSFET

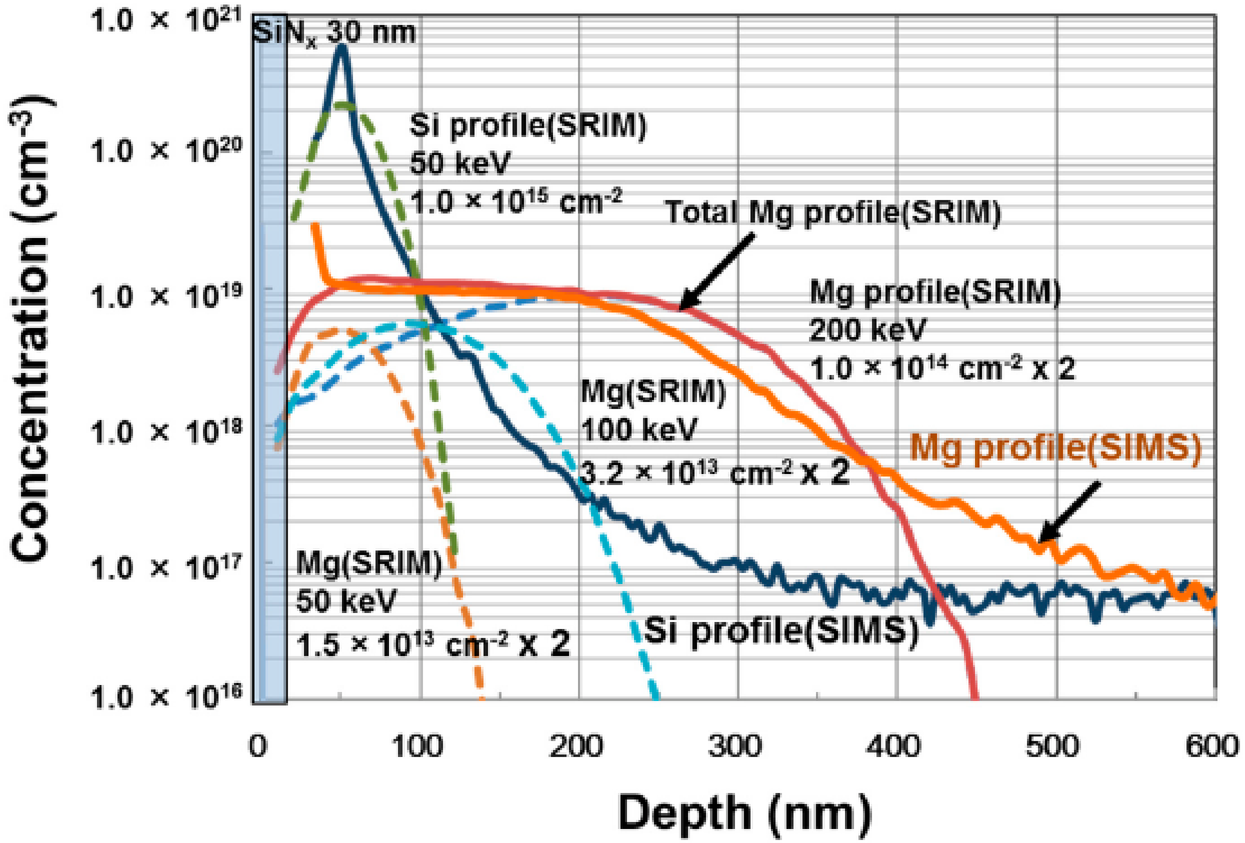


Figure 6. Ion-implanted Mg and Si profiles in a free-standing GaN substrate. Si background concentration in the substrate was about 5E10^{16}cm^3.

Materials 2019, 12, 689; doi:10.3390/ma12050689

Vertical Power MOS GaN on GaN

Vertical Power Devices Overview

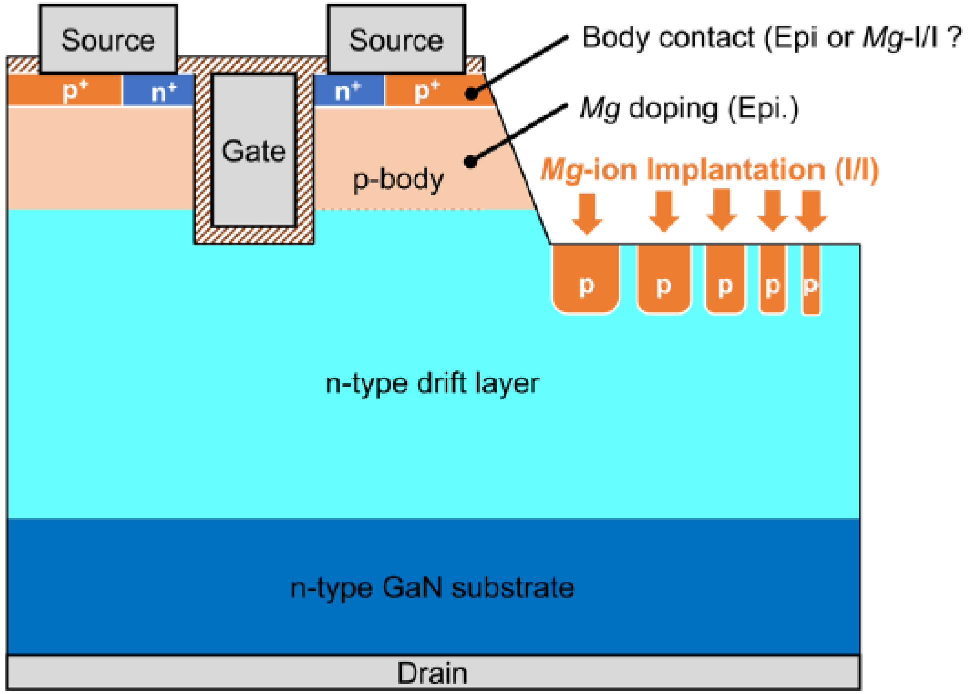


FIG. 1. Cross-sectional schematic of a T-MOSFET. A p-type body layer uniformly doped with Mg below 10^{18} cm^{-3} can be formed by the MOVPE method. Selective-area doping for the edge termination will be achieved by Mg ion implantation. The p$^+$ body contact can be formed by either MOVPE growth or Mg ion implantation.

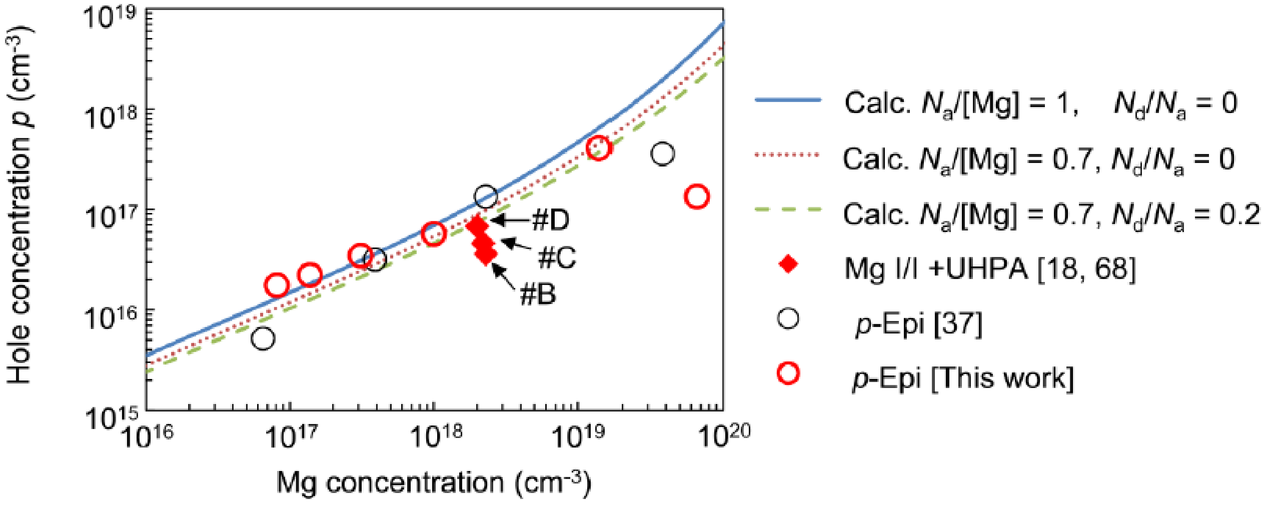


FIG. 13. Hole concentration p at 300 K (symbols) as a function of Mg concentration estimated by Hall-effect measurements. Closed symbols are from Mg-ion-implanted samples #B, #C, and #D after UHPA, while open circles
show data from MOVPE-grown Mg-doped GaN samples. Solid, dotted, and dashed lines are calculated by Eq. (2), assuming different activation ratios and compensation ratios.

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Summary

- Si ion implantation and activation is „easy going“
- High temperature RTA $\geq$1200°C, N2, 20-30sec are necessary
- 100% activation are possible (depending doses and Temperature)
- Mg ion implantation is a challenge
- High temperature RTA or MRT $\geq$1250°C, N2; 20-30sec are necessary
- Only <10% activation are possible (defects, Mg:H, donor compensation)
- Full implanted power devices and diodes with Si and Mg ion implantation are demonstrated on GaN on GaN or GaN on Si
- Advantage from GaN on GaN is lower defect density for epi layer (1E6D/cm^2 compared to 1E8D(cm^2)
- Disadvantage for GaN on GaN is wafer diameter (only 2″ or 3″)
- Advantage of GaN on Si is wafer diameter (6″ or 8″)

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Thank you.

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