國立陽明交通大學
NATIONAL YANG MING CHIAO TUNG UNIVERSITY

Tay Do University, 2025

Fabrication, characteristics, and device applications of semiconductors

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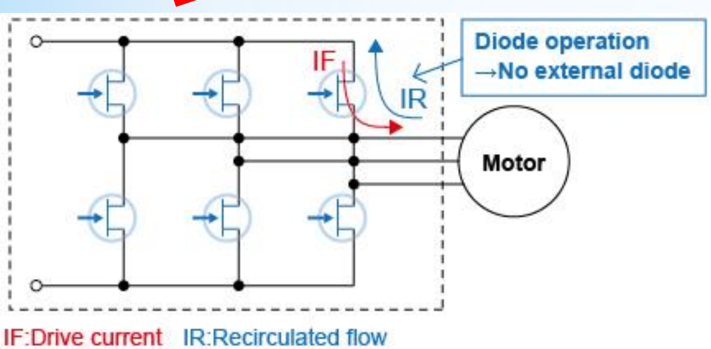
NSTC 國家科學及技術委員會
National Science and Technology Council

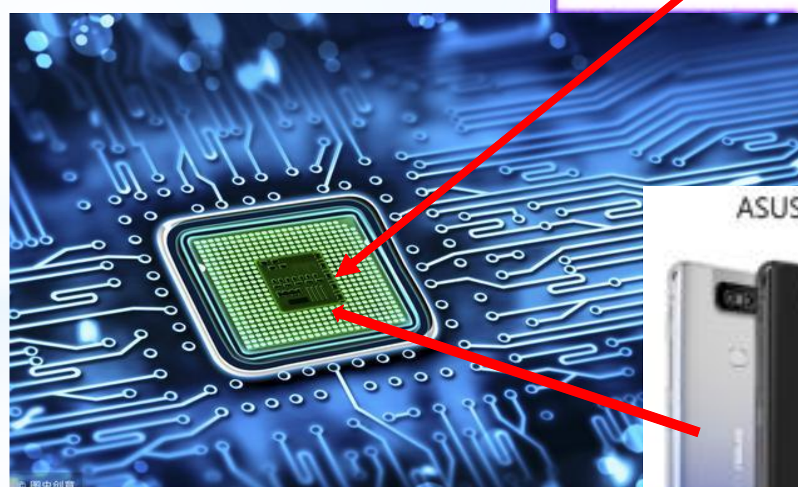
The key device of modern technology is transistor made of semiconductors

https://www.tesla.com/zh_TW/models

Tesla electric car P100D Model S



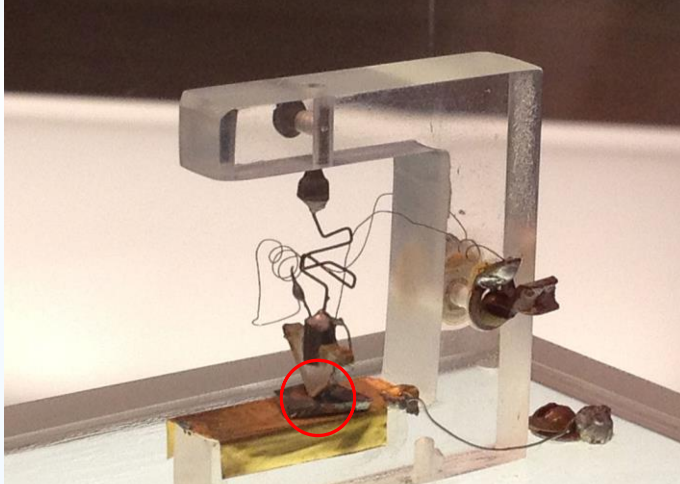
Transistors control the high power output of motor 0-100 km/hr in 2.7s



CPU（Central Processing Unit）is made up of billions of transistors.

Who invented transistor?

The first transistor was invented in 1947 by Shockley, Bardeen and Brattain



Single transistor of mm size

The Nobel Prize in Physics 1956

"For their research on semiconductors and the discovery of the transistor effect"

William Bradford Shockley

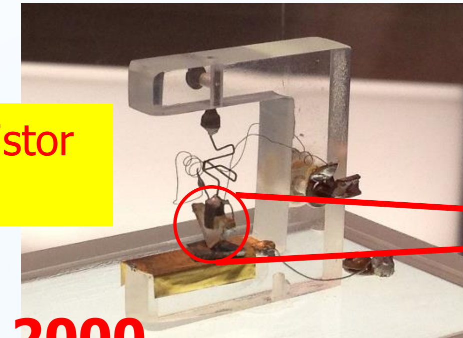
John Bardeen

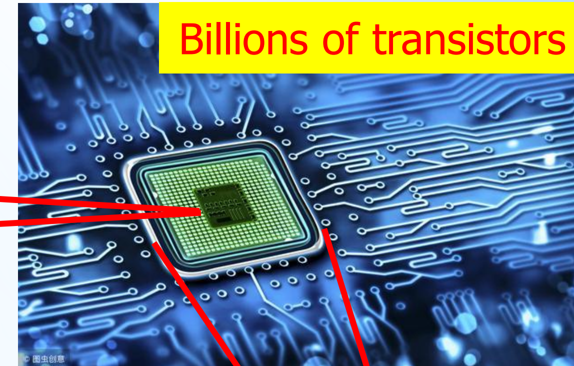
Walter Houser Brattain

How to make the transistor smaller?

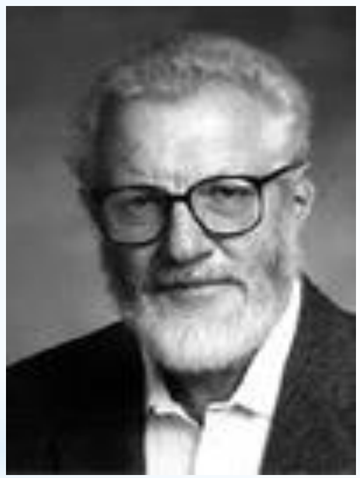
In 1958, Kilby invented the Integrated Circuit (IC).

single transistor
of mm size





The Nobel Prize in Physics 2000



Zhores I. Alferov

"for basic work on information and communication technology"

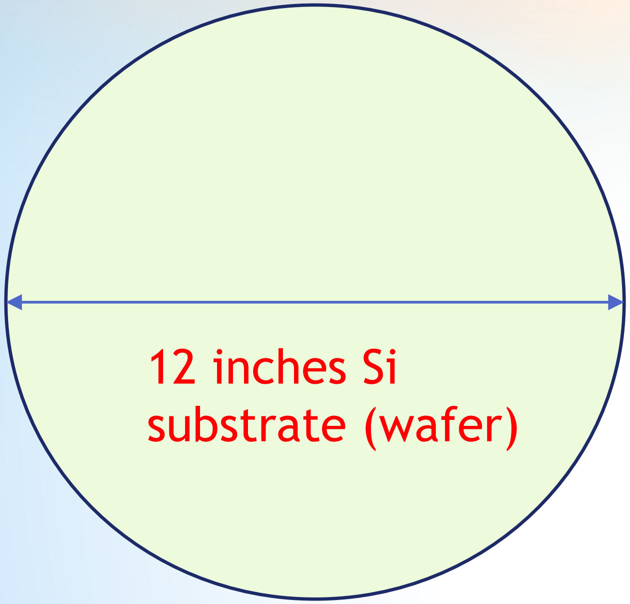
Herbert Kroemer

"for developing semiconductor heterostructures used in high-speed- and opto-electronics"

Jack S. Kilby

"for his part in the invention of the integrated circuit"

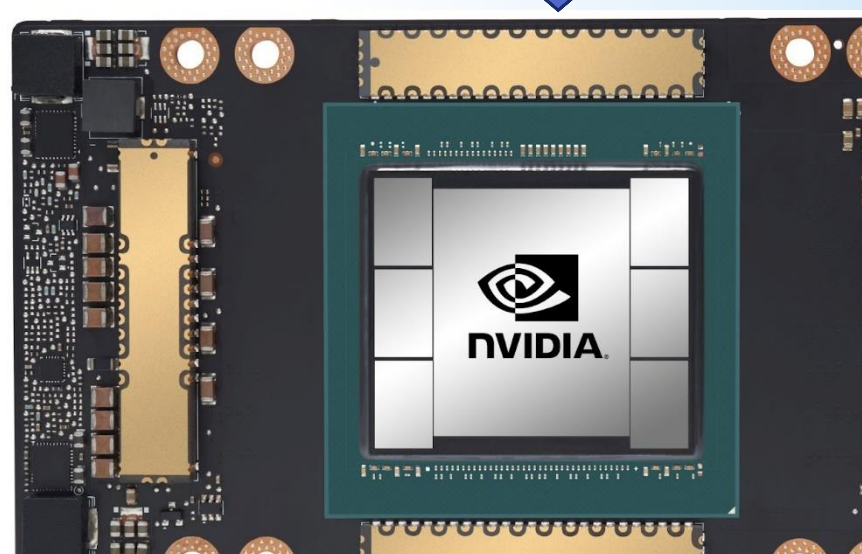
How to manufacture semiconductor integrated circuit?



A few thousands USD

Taiwan Semiconductor Manufacture Company (TSMC)

65 x NVIDIA A100



20 thousand USD
54 billion transistors

One Blackwell chip is around 30k to 35k USD

How to manufacture semiconductor integrated circuit?
How important semisonductor contribute to economics (GDP)?

TSMC
Arizona
USA

TSMC
Germany

TSMC, Hsinchu, Taiwan

TSMC
Kumamoto
Japan

Taiwan Semiconductor Manufacture Company (TSMC) / 84,000 employees
2,894,800,000,000 NT= 95 billion USD/for 2024, ≈12.9 million 12" Si wafer
Advanced Si IC, (AI chipset), Apple CPU, Nvidia GPU (graphic processing unit)
Total Taiwan semiconductor 2024 GDP = 150 billion USD
Taiwan GDP for 2024: 793 billion USD / 23.3 million citizens

TSMC, Vietnam VSMC?

Cultivation for semiconductor talent students is important.

TSMC
Arizona
USA

TSMC
Germany

TSMC
Kumamoto
Japan

TSMC, Hsinchu, Taiwan

Taiwan Semiconductor Manufacture Company (TSMC) / 84,000 employees
2,894,800,000,000 NT= 95 billion USD/for 2024, ≈12.9 million 12” Si wafer
Advanced Si IC, (AI chipset), Apple CPU, Nvidia GPU
Memory:
Micron 25.1 billion USD/2024, Samsung 66.5 Billion USD/2024

The market size, 10 billion USD, of high power transistor is much smaller. However, it is critical (key) electronic component for homeland security and military communication.

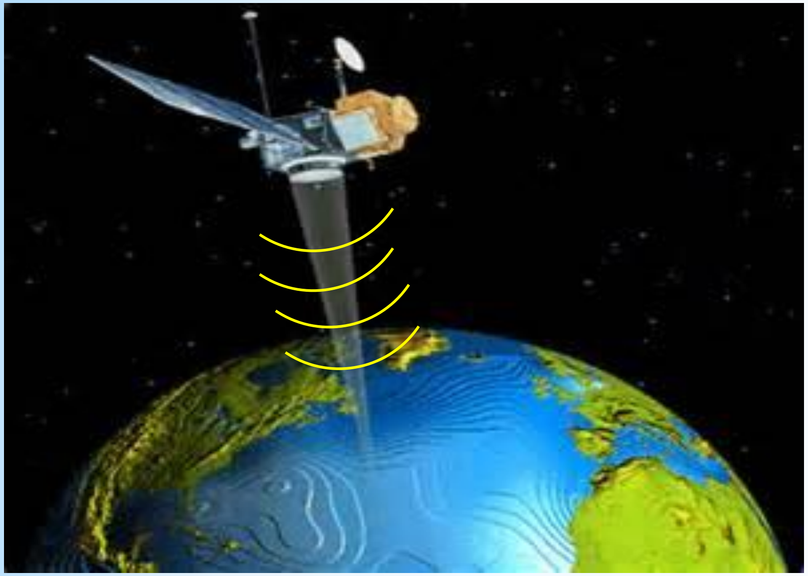
GaN high electron mobility transistor (HEMT) in the application of high power and high frequency devices.

Electrical vehicle charging station
>200 kW
10 minutes for 250 km driving
AC to DC converter

Artificial Intelligence (AI) application
GB300 Blackwell: 4.8TB/s

Quanta computer manufacture Nvidia GB300 NVL72 rack (4,000,000 USD/rack) 72 GB300
120–150 kW

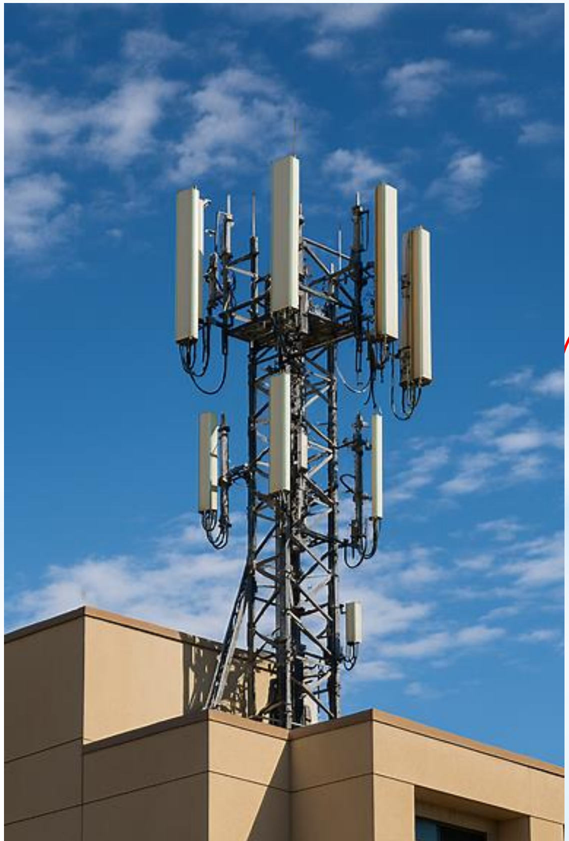
GaN high electron mobility transistor (HEMT) in the application of high power and high frequency devices.



Satellite

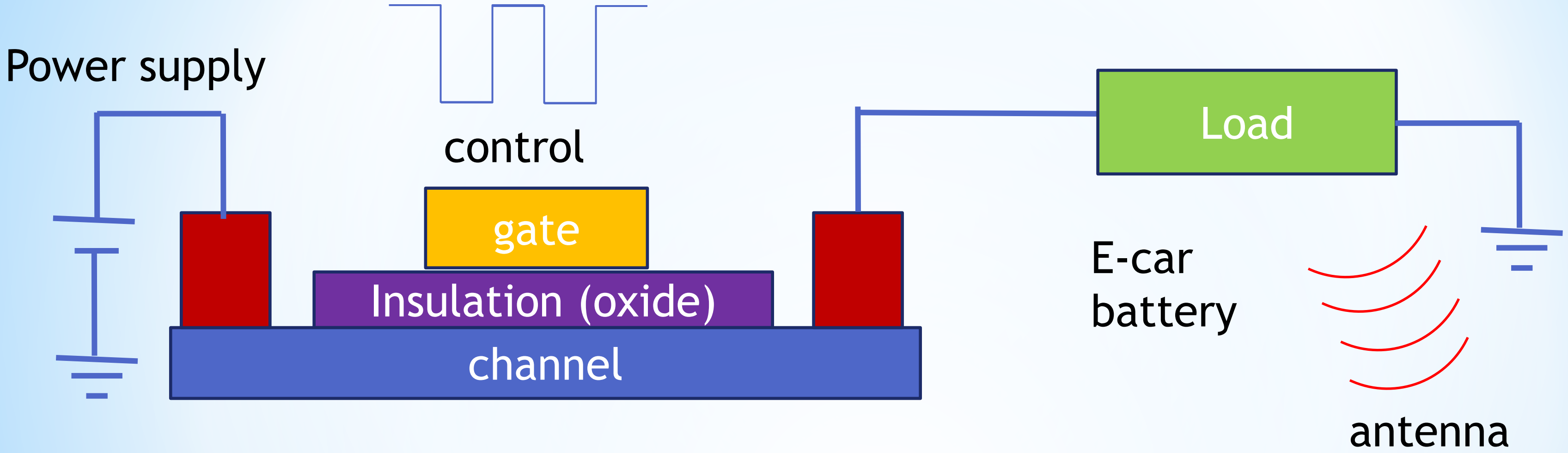
Satellite transmission power and frequency: 1000 W, up to 50 GHz

Mobile phone base station transmitter power and frequency: 100 W and up to 40 GHz



> 5GHz

GaN high electron mobility transistor (HEMT) in the application of high power and high frequency devices.



Source (S), or drain (D)

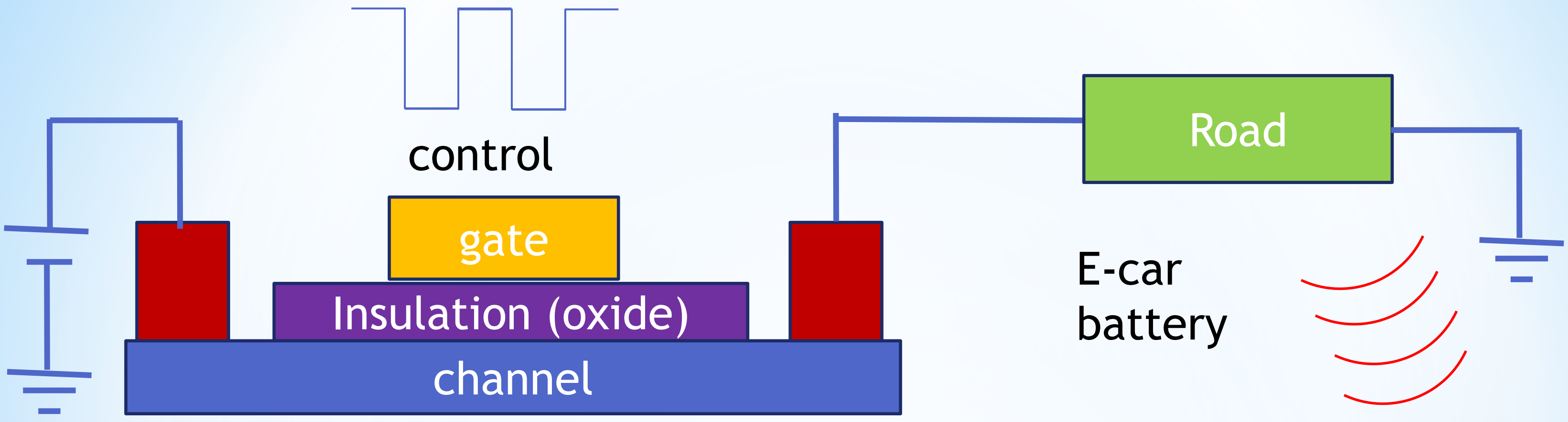
Distance between S and D = L ≅ gate length, determine the frequency f=1/T, T ≅ L/v, velocity (v) of electron or hole

Conduction carrier: electron or hole
n-HEMT: negative electron in channel
p-HEMT: positive charge (hole) in channel

$v=\mu E$, μ mobility, E electric field

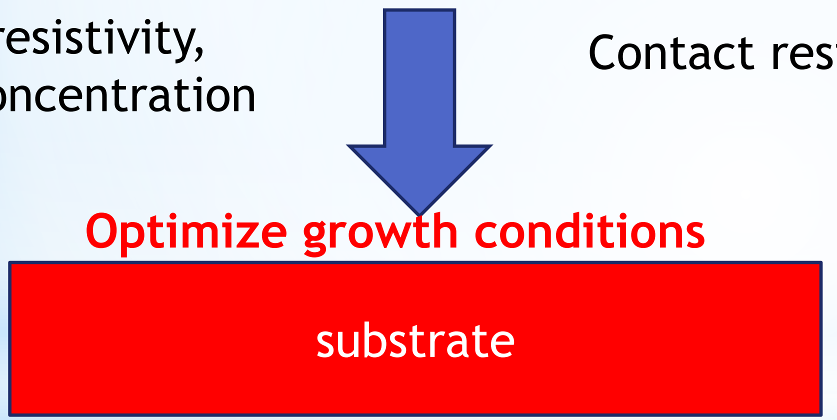
How to increase frequency? μ, L
How to increase the power? J (σ), Ω
How to increase breakdown voltage?

GaN high electron mobility transistor (HEMT) in the application of high power and high frequency devices.

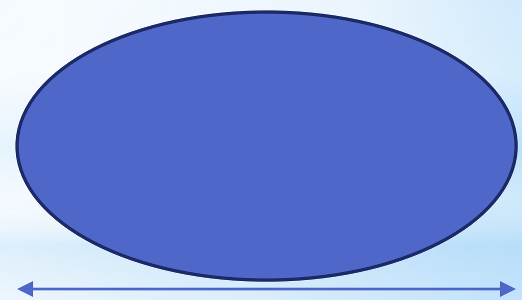


Channel resistivity,
carrier concentration

Contact resistance



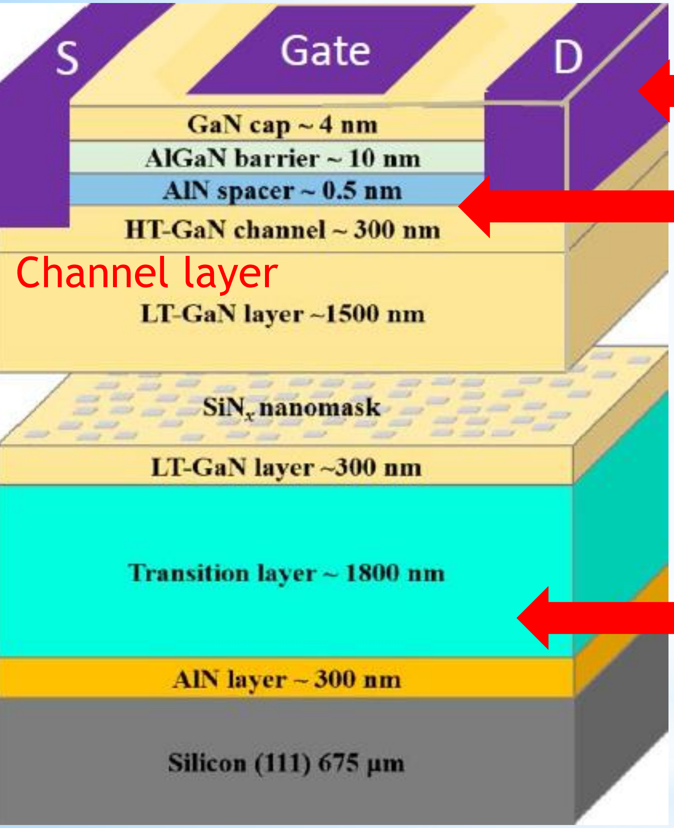
Issues of substrate:
Economic concern
Challenge of fabrication
performance



8 inches
Si substrate (200USD)
Or SiC substrate (800 USD)

Key challenges for fabricating GaN high electron mobilty transistor (HEMT) with excellent performance for the application in the high power and high frequency devices:

How to design the hetero-structure for best device performance.



1. Low contact resistance,
2. p-GaN for enhanced mode HEMT

High hole concentration of 1.3×10^{18} cm^{-3}

3. Two dimensional electron gas (2DEG): high electron mobility~ 1970 cm^2/V·s, low sheet resistance, high e density 6.42×10^{12} cm^{-2}

reduce the edge-type TDD and EPD, 2.25×10^9 and 3.24×10^8 cm^{-2}

4. High resistivity buffer (C or Fe doping)
5. Low dislocation density,

High vertical breakdown voltage >1000V

Si substrate

Hetero-structure: different materials grown together

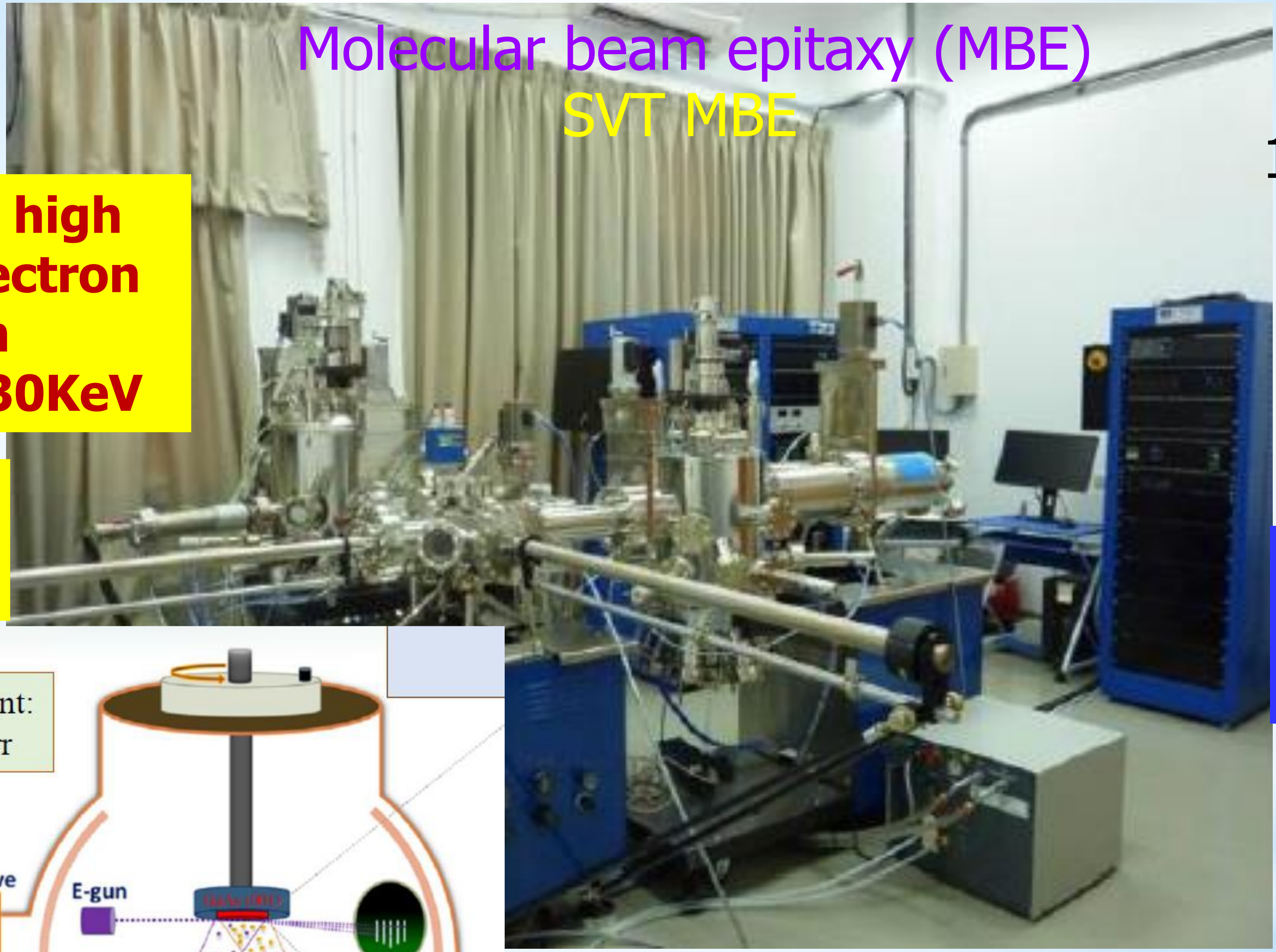
How to grow hetero-structures?

How to fabricate GaN HEMT?

Tools of hetero-epitaxy

Molecular beam epitaxy (MBE)

SVT MBE



10^{-10} torr

Reflective high energy electron diffraction (RHEED) 30KeV

Transfer rod

Vacuum system

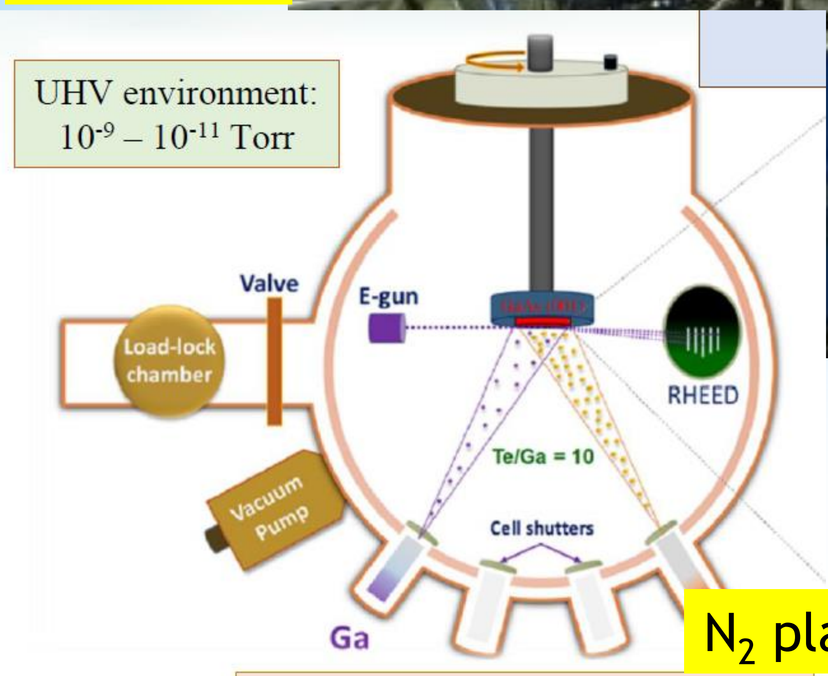
Growth Chamber

Buffer chamber (load-lock)

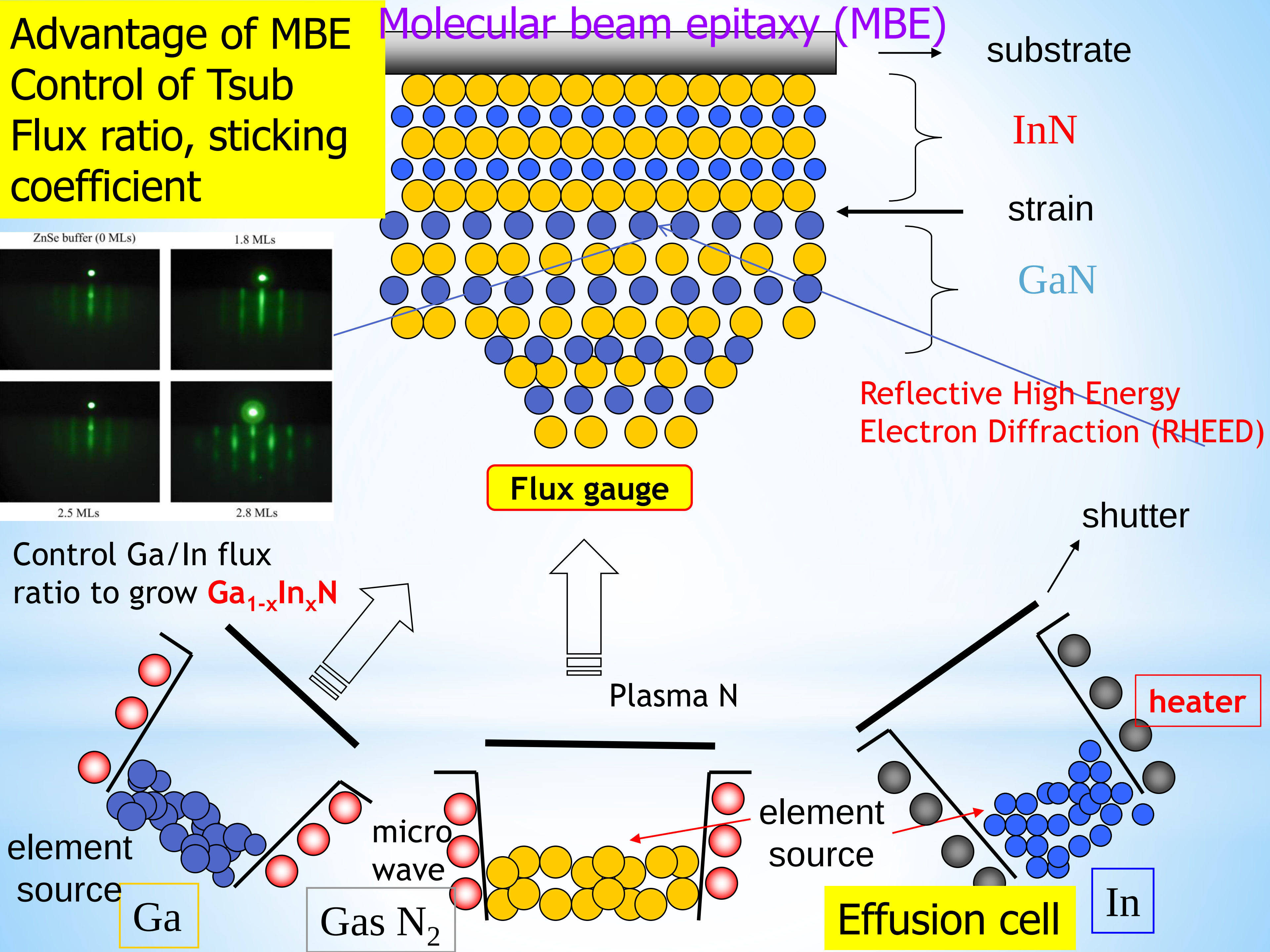
Effusion cell

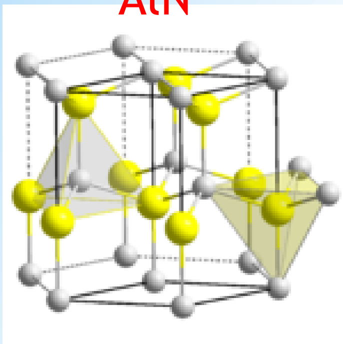
shutter

Electronic controller, power supply



N_2 plasma cell

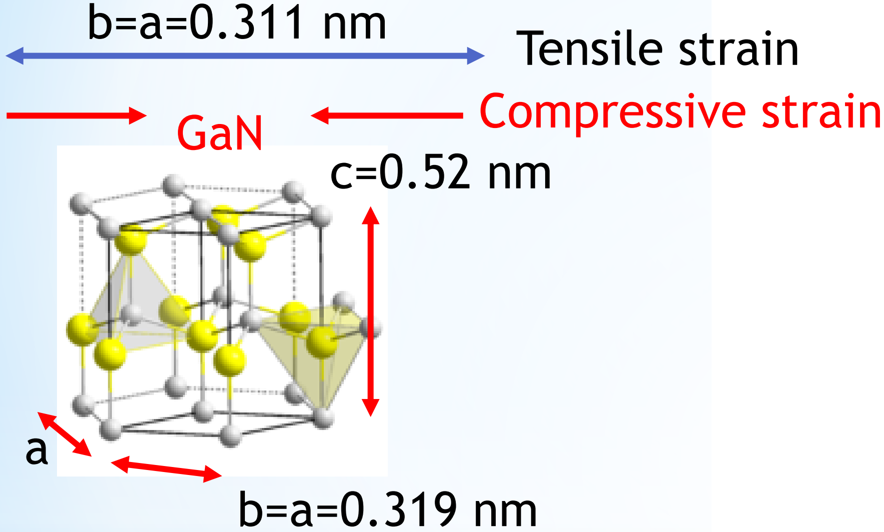

Molecular beam epitaxy (MBE)
Advantage of MBE
Control of Tsub
Flux ratio, sticking coefficient
ZnSe buffer (0 MLs)
1.8 MLs
2.5 MLs
2.8 MLs
substrate
InN
strain
GaN
Reflective High Energy Electron Diffraction (RHEED)
Flux gauge
shutter
Control Ga/In flux ratio to grow $Ga_{1-x}In_xN$
Plasma N
heater
element source
Ga
micro wave
Gas N_2
element source
Effusion cell
In

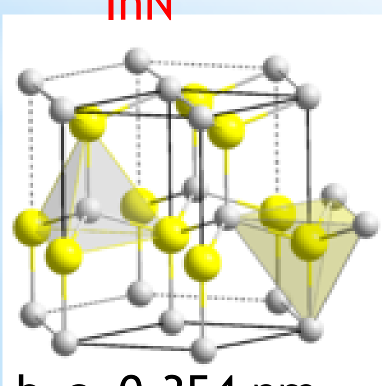


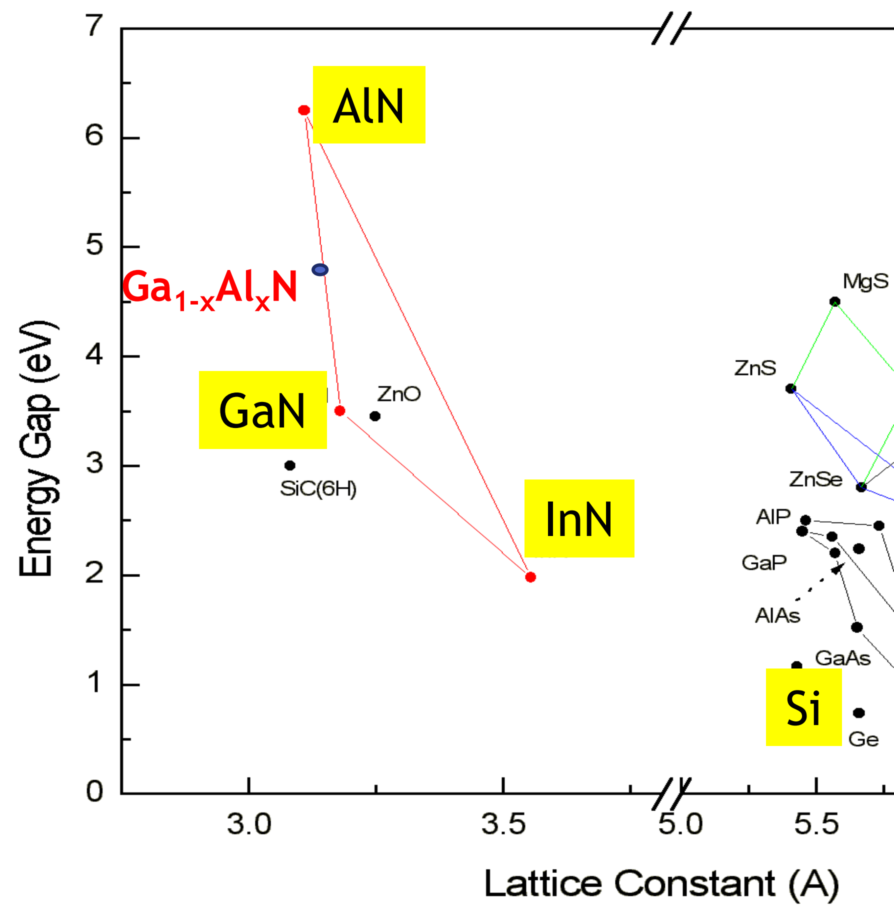
Bandgap engineering and strain engineering

Strain affects the energy gap (optical properties), electrical properties, and lattice vibration properties.

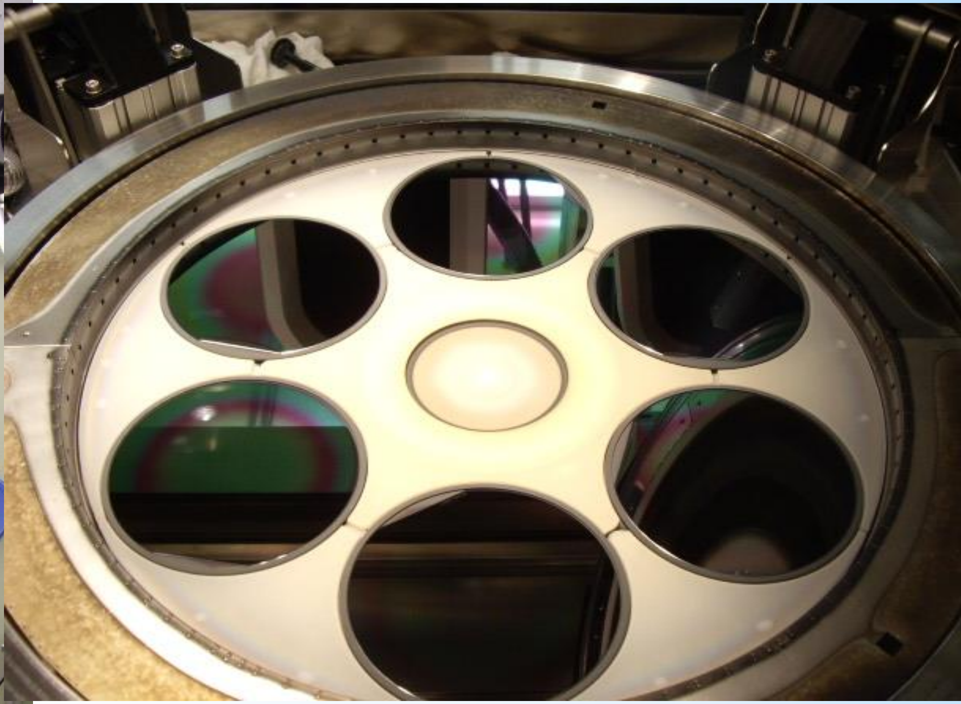
Studied by photo-luminescence, electric measurement, and Raman scattering







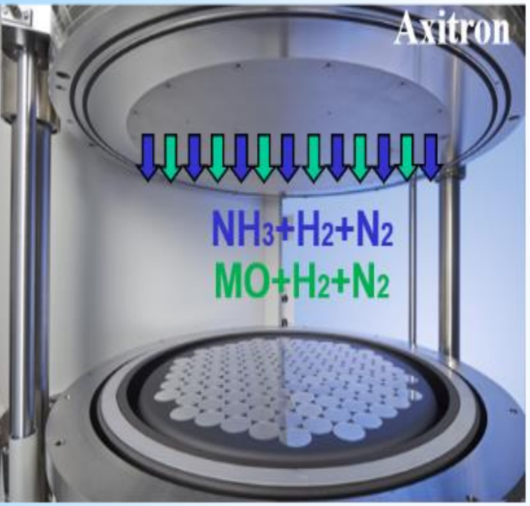
How to grow GaN HEMT? Metal organic chemical vapor deposition (MOCVD) (AIXTRON MOCVD)



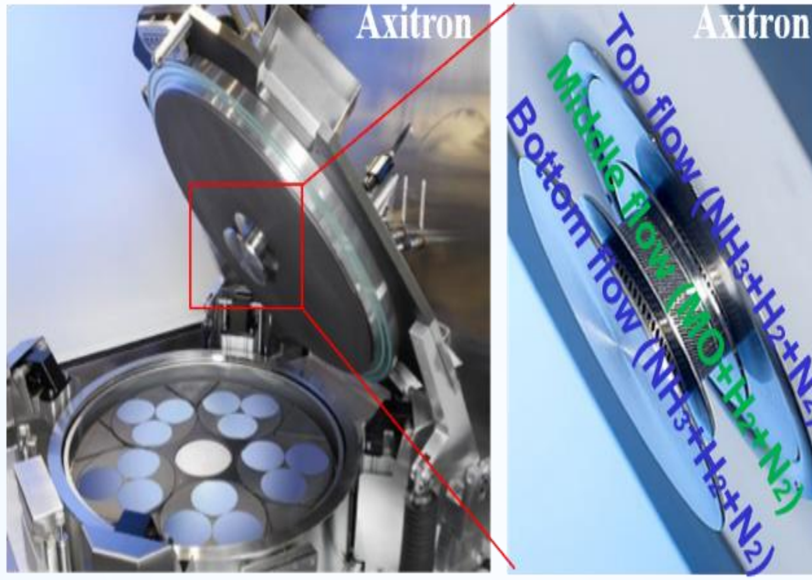
- AIXTRON, AIX 2800G4 HT Planetary Reactor

How to grow GaN HEMT?

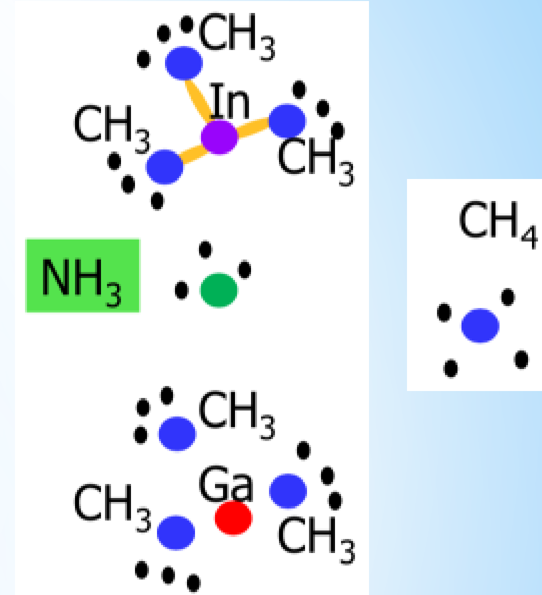
Metal organic chemical vapor deposition (MOCVD) (AIXTRON MOCVD)



Showerhead type

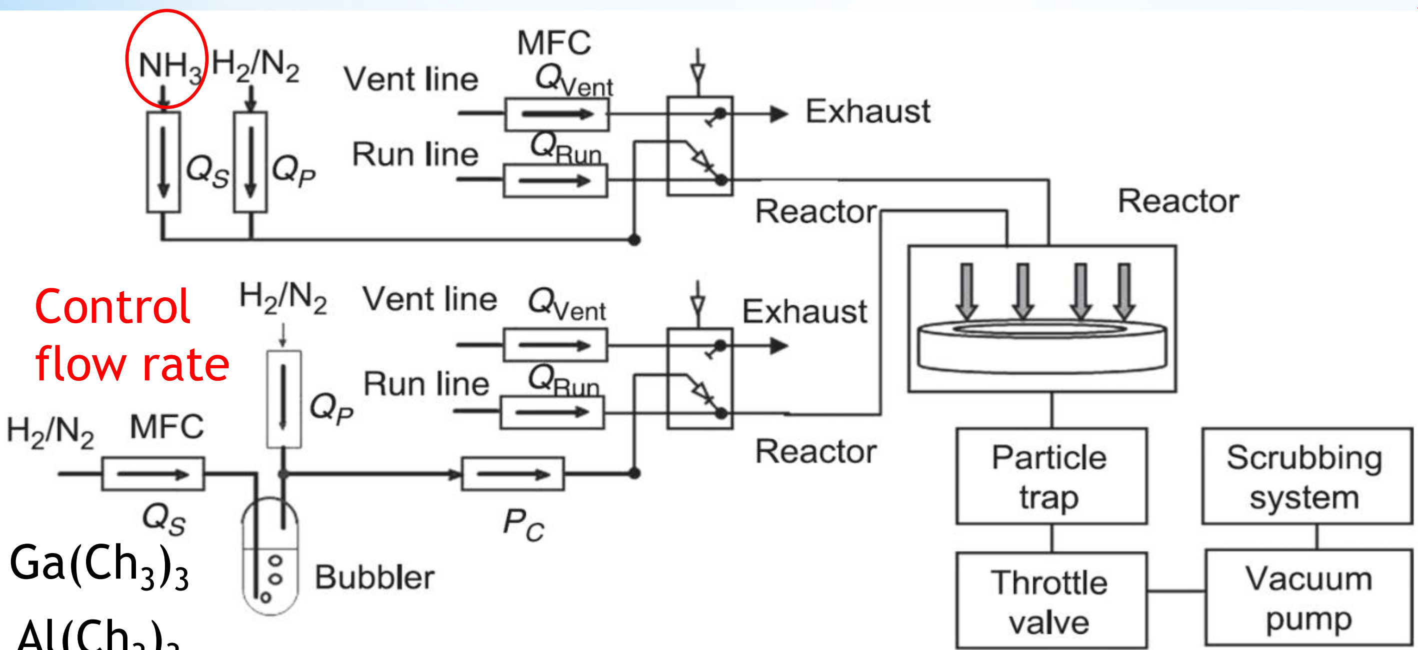


Planetary type



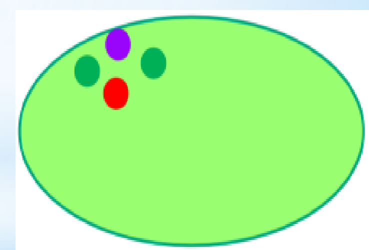
Trimethylgallium

Control flow rate



$Ga(Ch_3)_3$

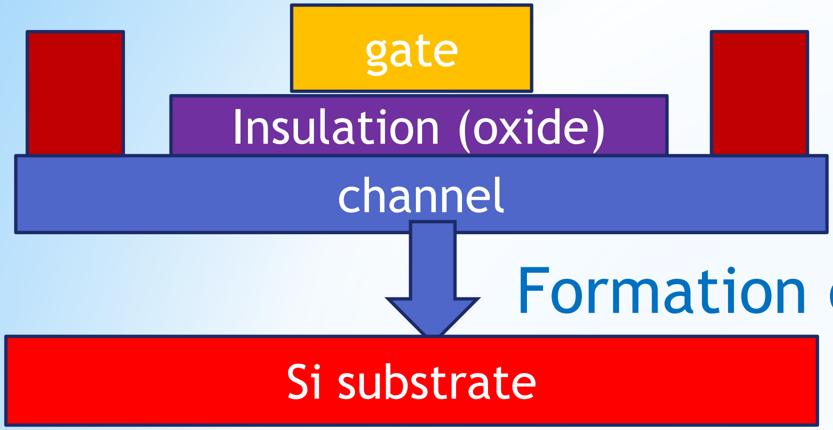
$Al(Ch_3)_3$



Wafer substrate

Control flow rate ratio to grow **$Ga_{1-x}Al_xN$ or $Ga_{1-x}In_xN$**

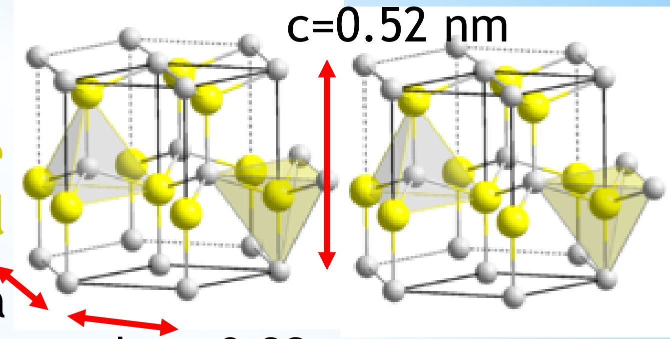
THE IMPACT OF DISLOCATION



Formation of dislocation

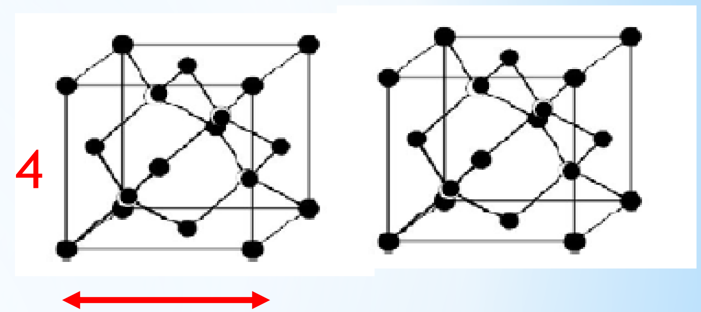
N atoms

Ga atoms have 3 outer orbital electrons

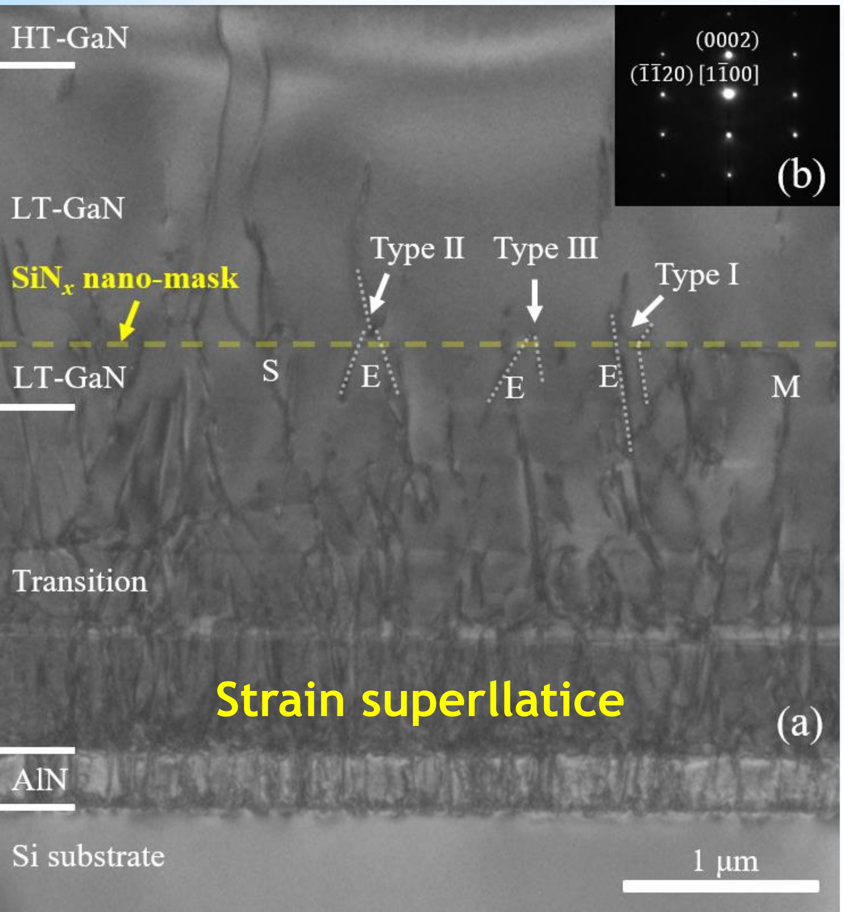


Line up of point defects

Si atoms have 4 outer orbital electrons



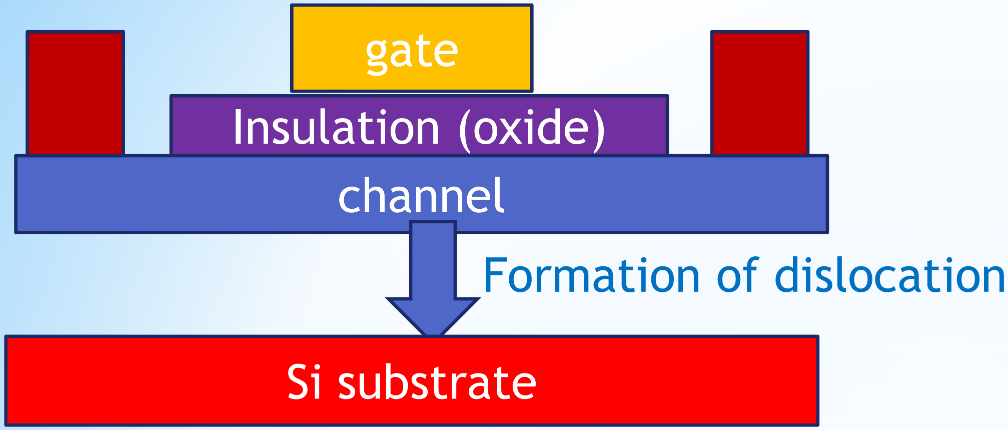
Diamond crystal structure Si

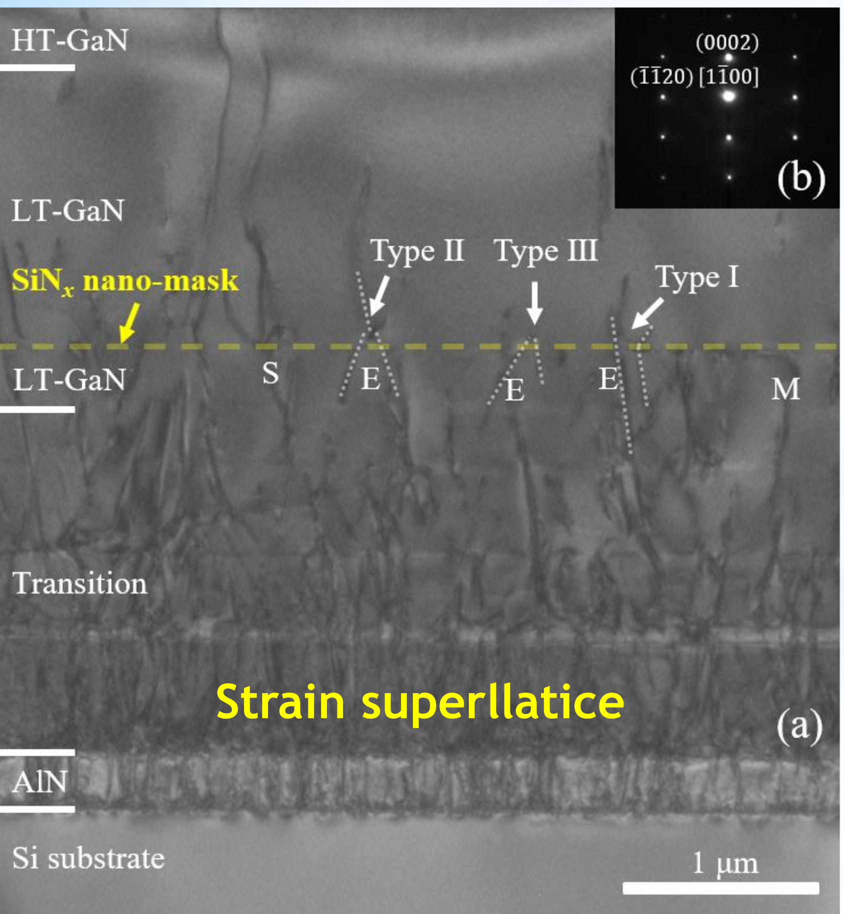


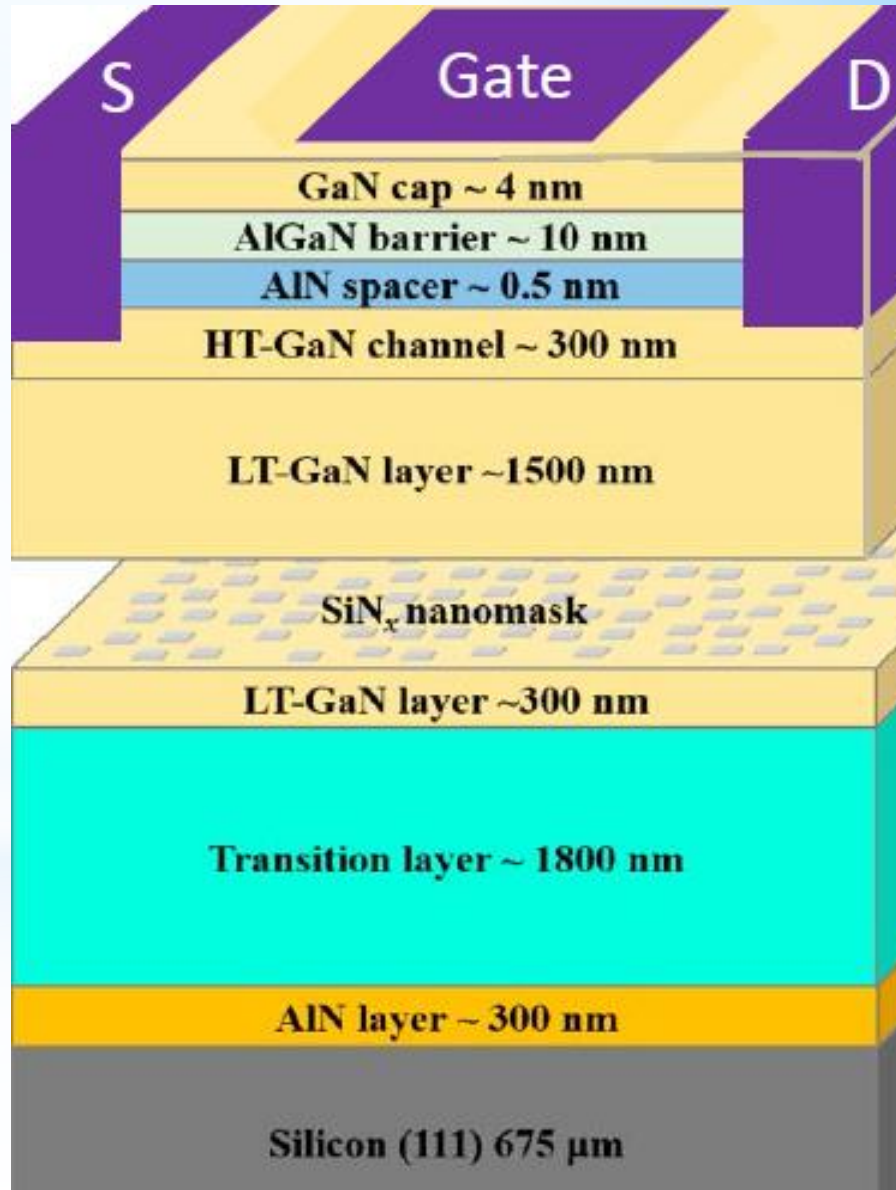
Lattice constant mismatch: 0.54 nm > 0.32 nm
Chemical bonding mismatch

Dislocations result in leakage, low breakdown voltage, low carrier density and low mobility
How to deduce dislocation density?

THE IMPACT OF DISLOCATION







THE IMPACT OF DISLOCATION

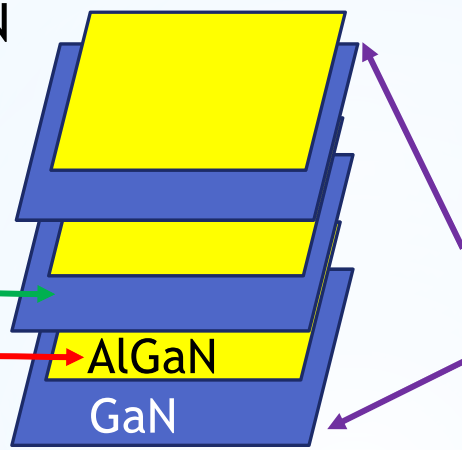
1. Strain superlattice

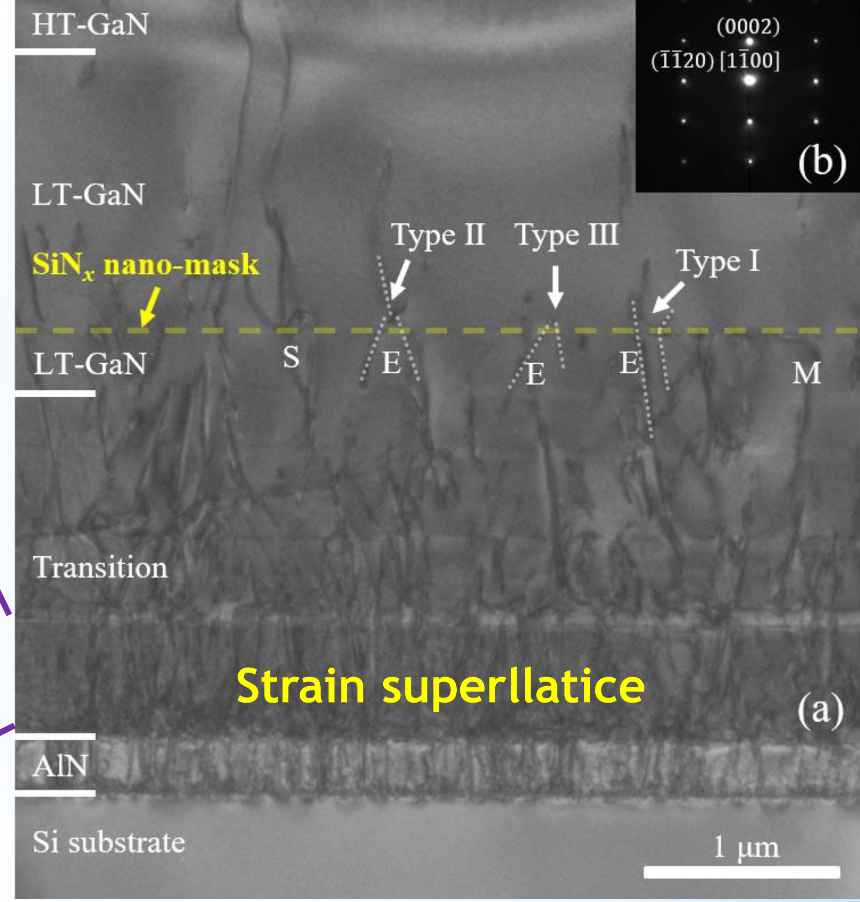
Annihilate part of dislocations

100 pairs of GaN/AlGaN

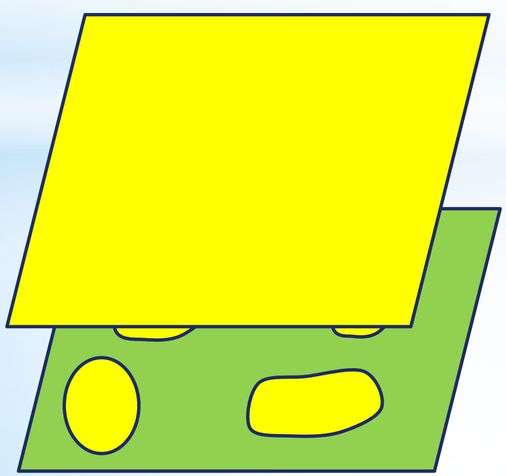
compressive

tensile



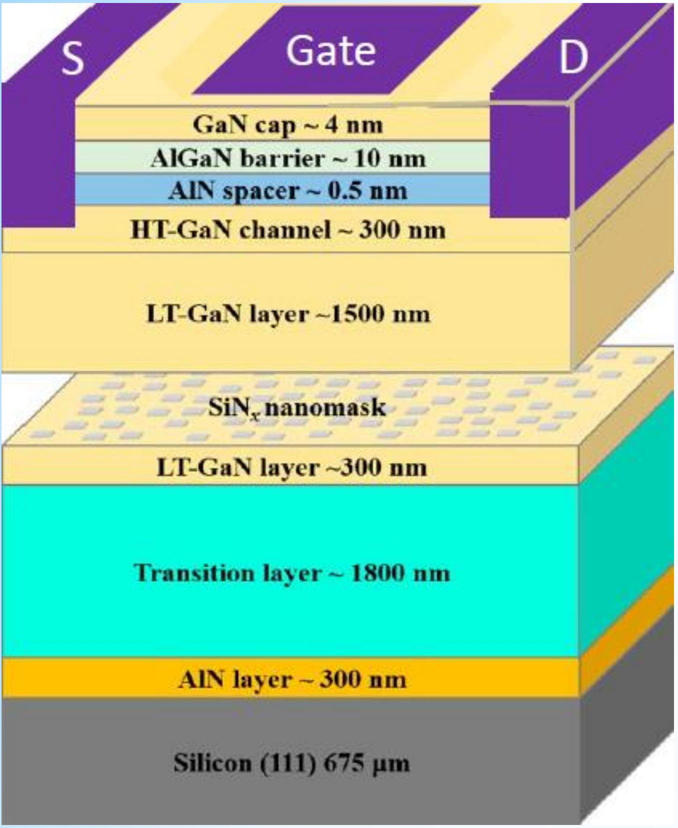


2. SiN nano-mask



Faster growth rate on the window than on SiN results in lateral growth and blocking dislocations

How to verify the effect of SiN nano-mask on reducing dislocation density?

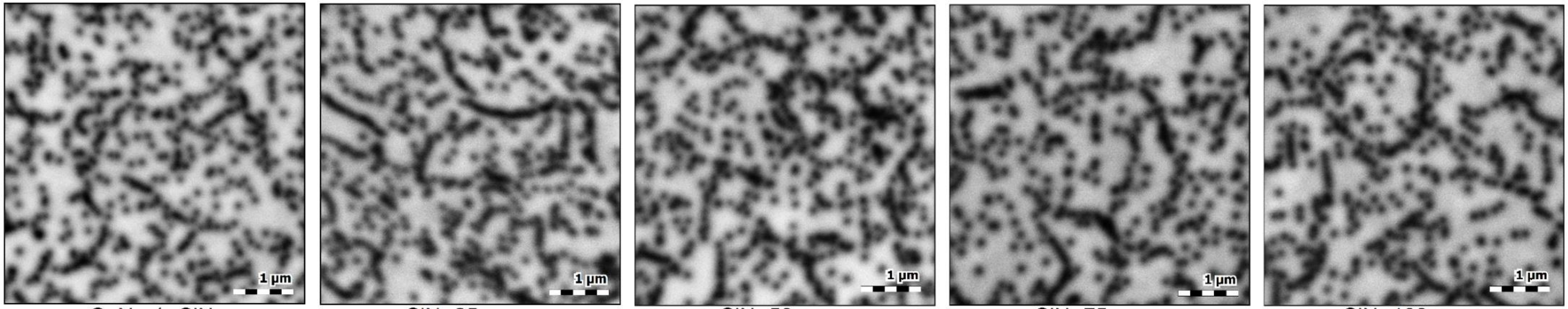


Schematic:
Side view of GaN HEMT

What is cathodo-luminescence (CL)?
Dark spots are dislocations.

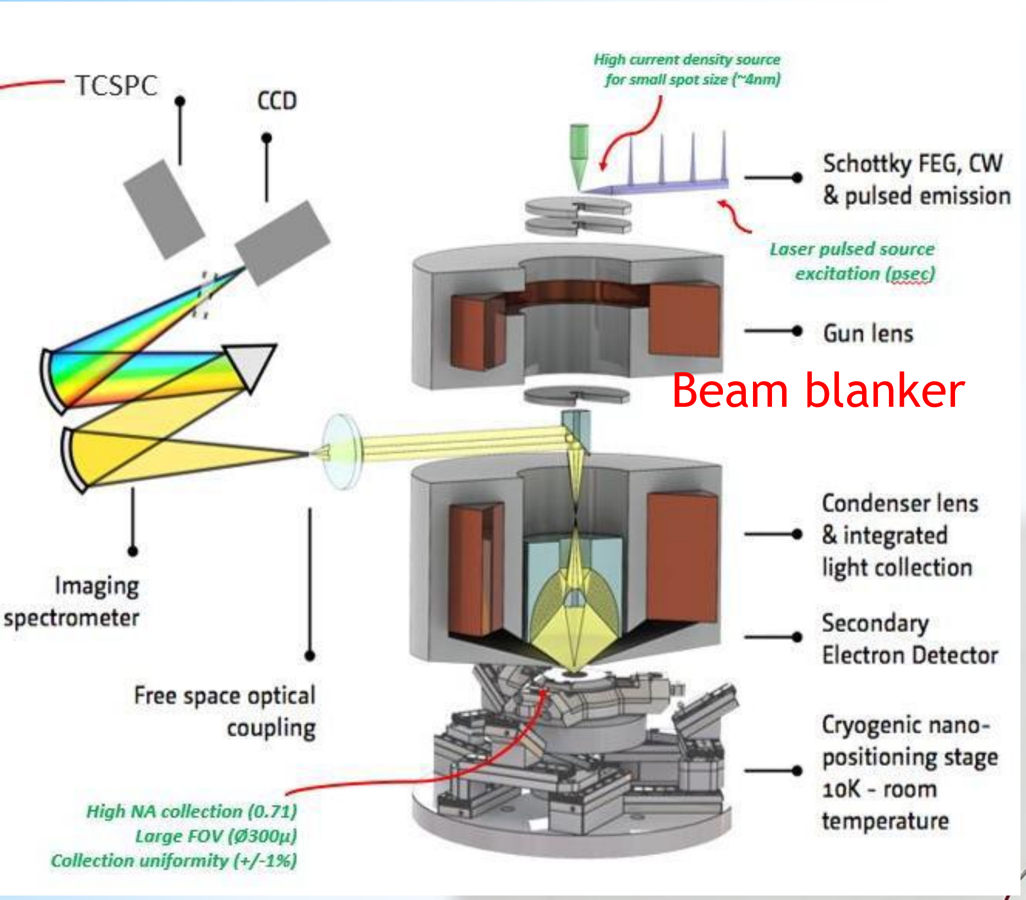
TDs density in GaN films decreases with increasing SiH_4 flow rate

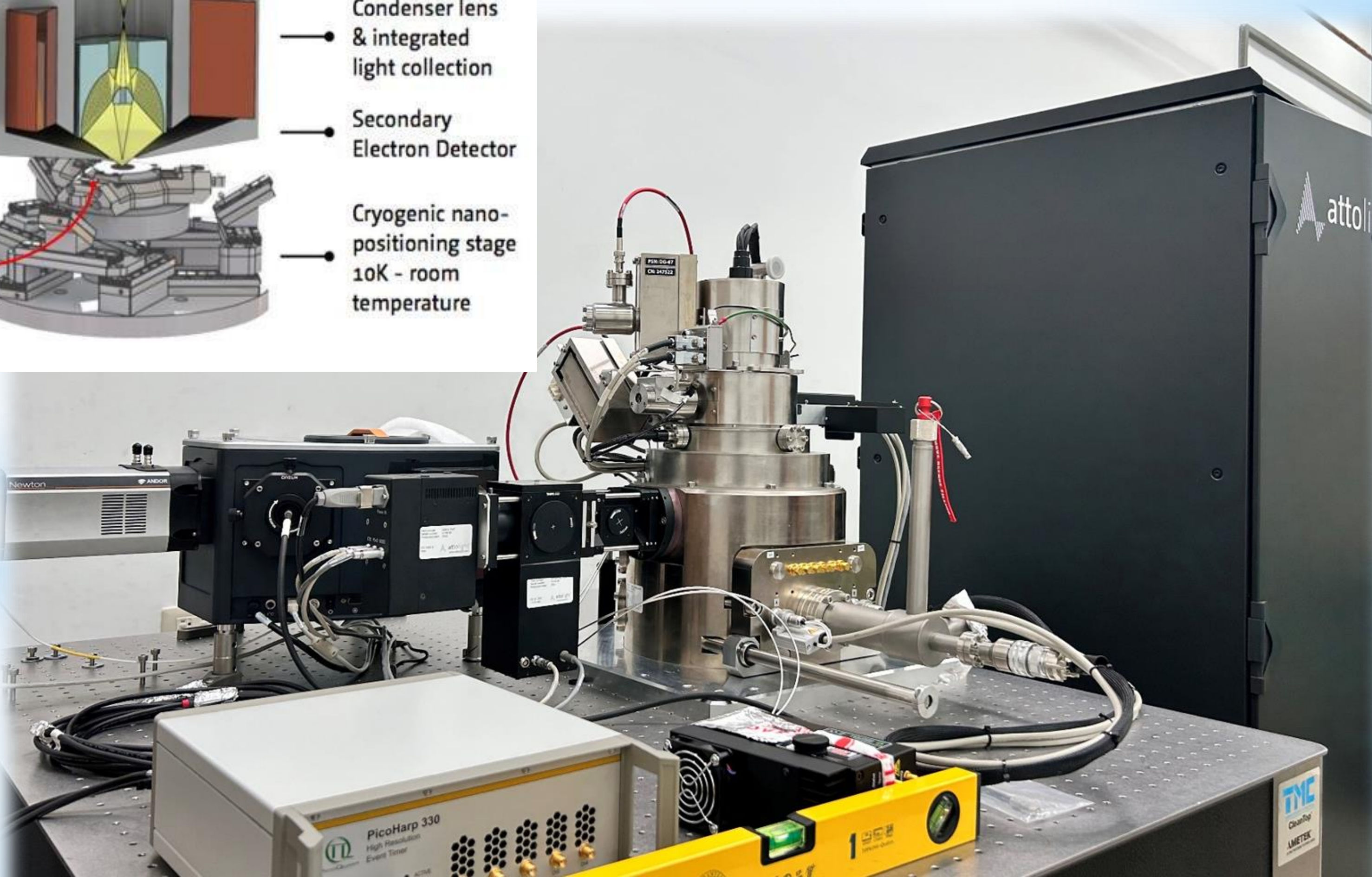
top view of GaN HEMT by cathodo-luminescence measurement

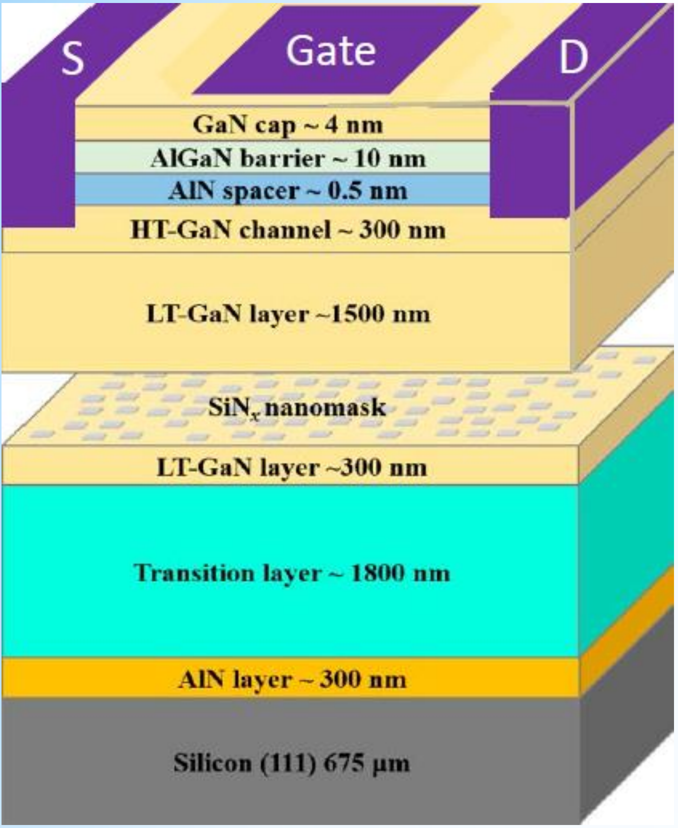


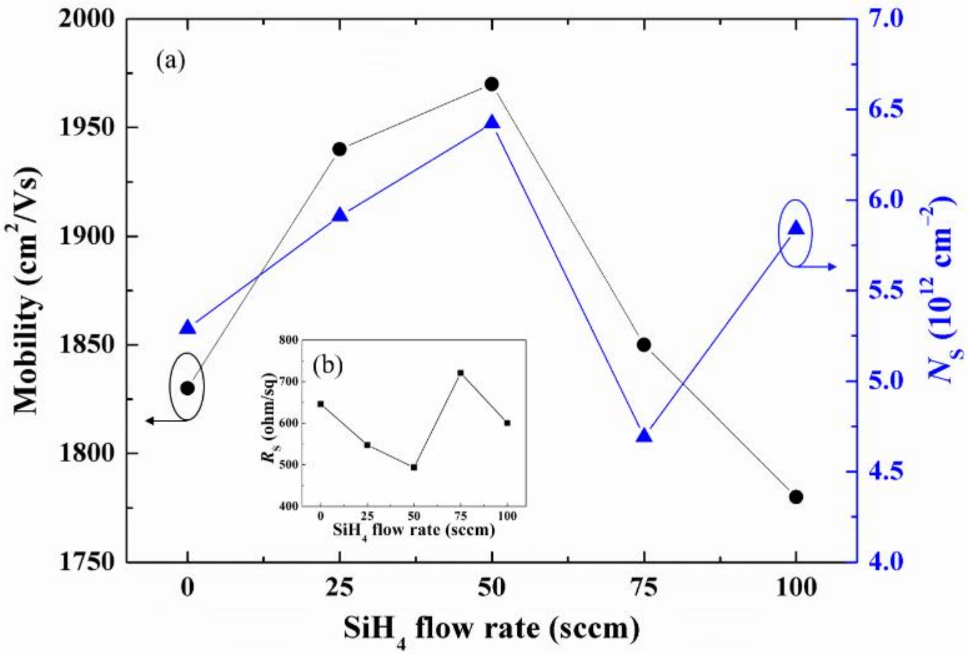
GaN w/o SiN_x | SiN_x-25 sccm | SiN_x-50 sccm | SiN_x-75 sccm | SiN_x-100 sccm

Attolight cathodo-luminescence (CL) system
Compared with photo-luminescence (PL) excited by laser



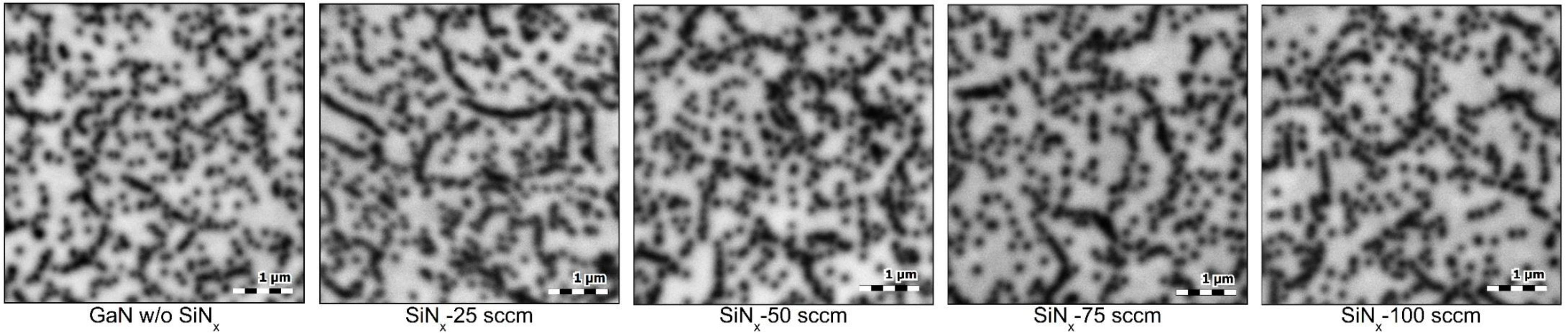




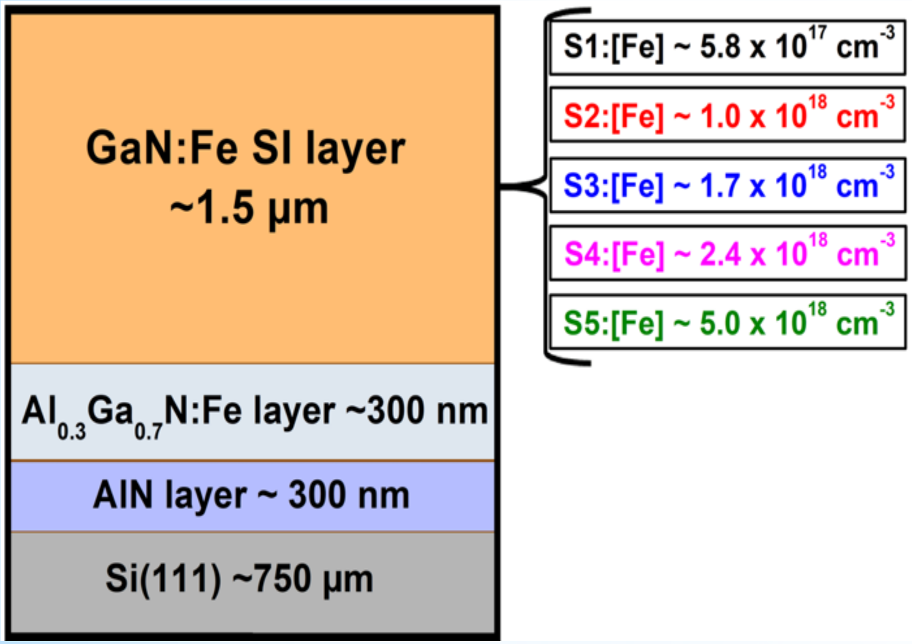


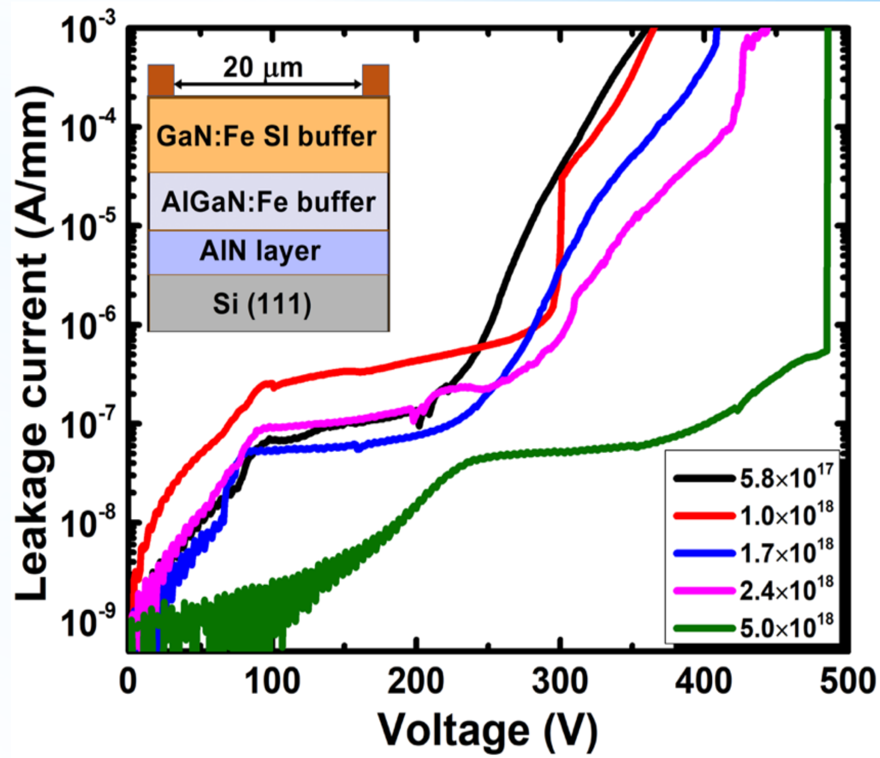
TDs density in GaN films decreases with increasing SiH_4 flow rate

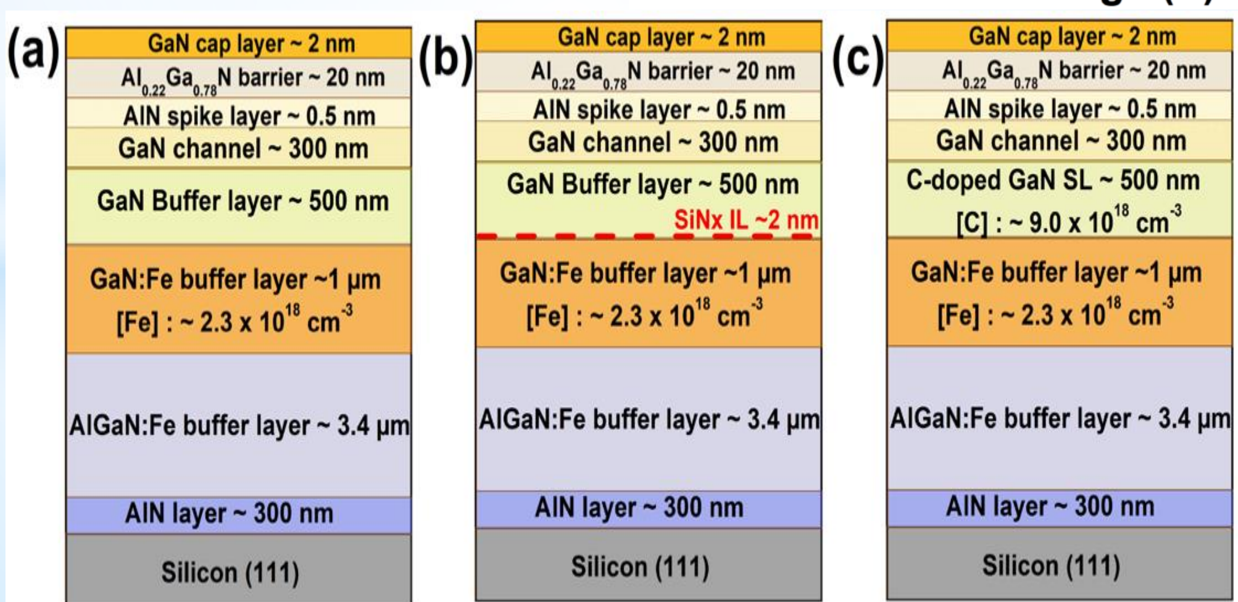
top view of GaN HEMT by cathodo-luminescence measurement



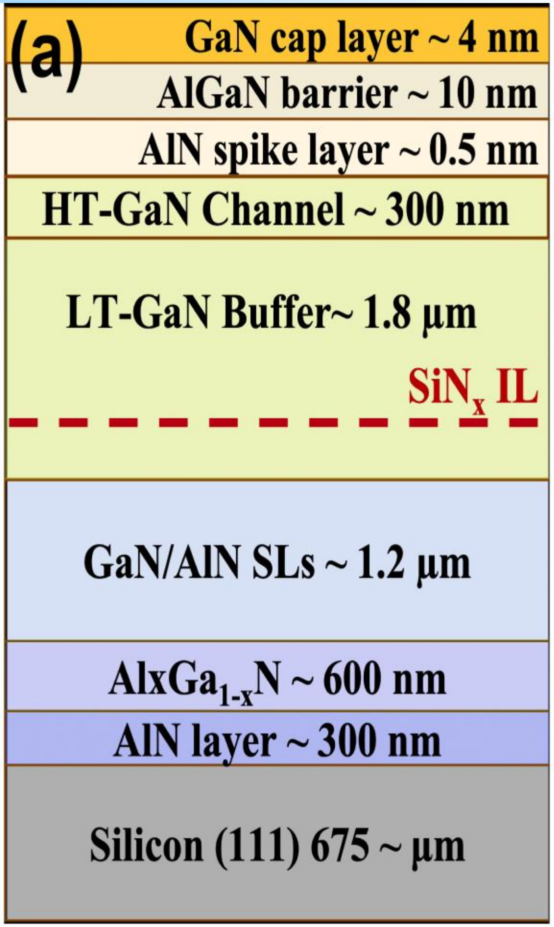
The effect of Fe and C co-doping on increasing breakdown voltage

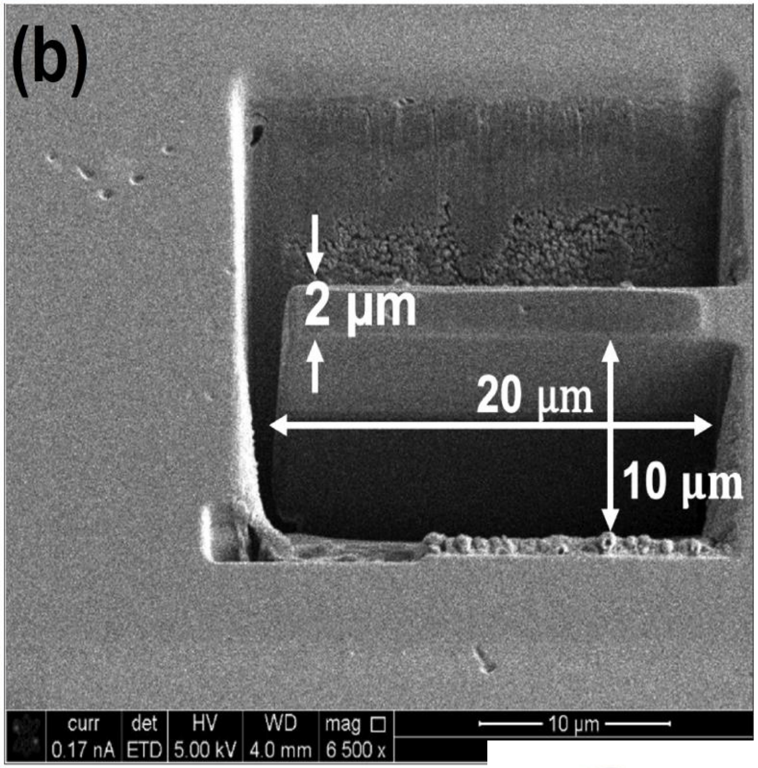






Characterization of GaN HEMT by X-ray nano-diffraction

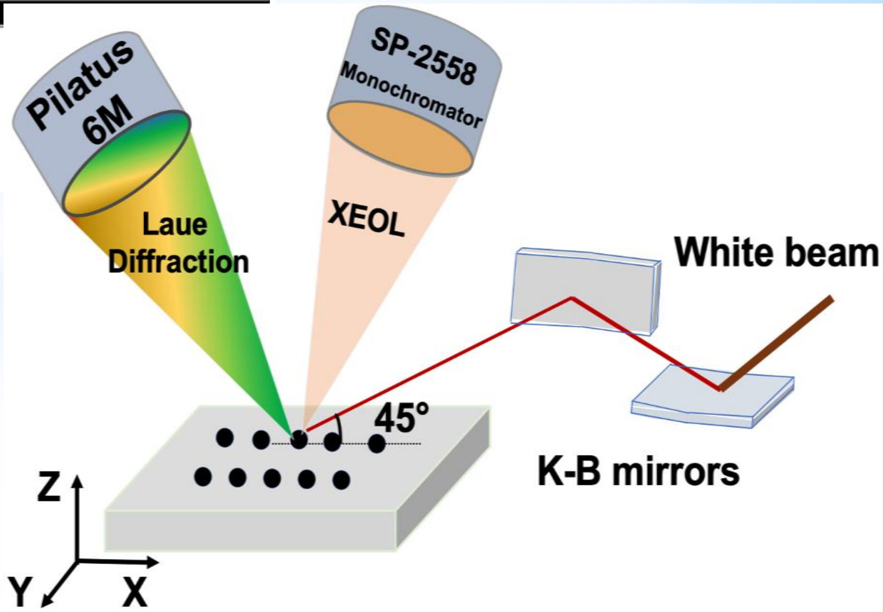


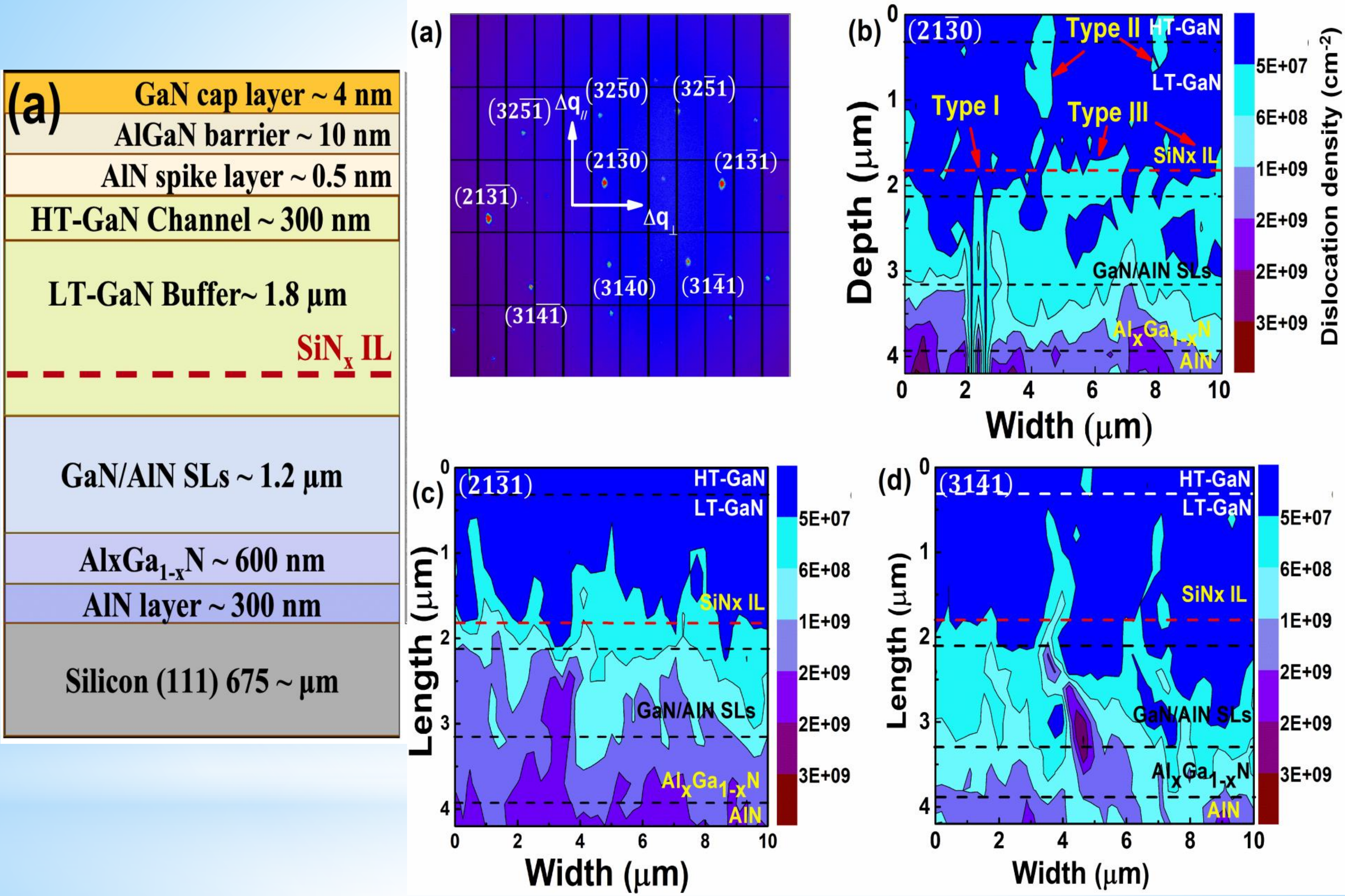


Focus ion beam
Sample preparation

ACS Applied Nano Materials 8, 15187 (2025)

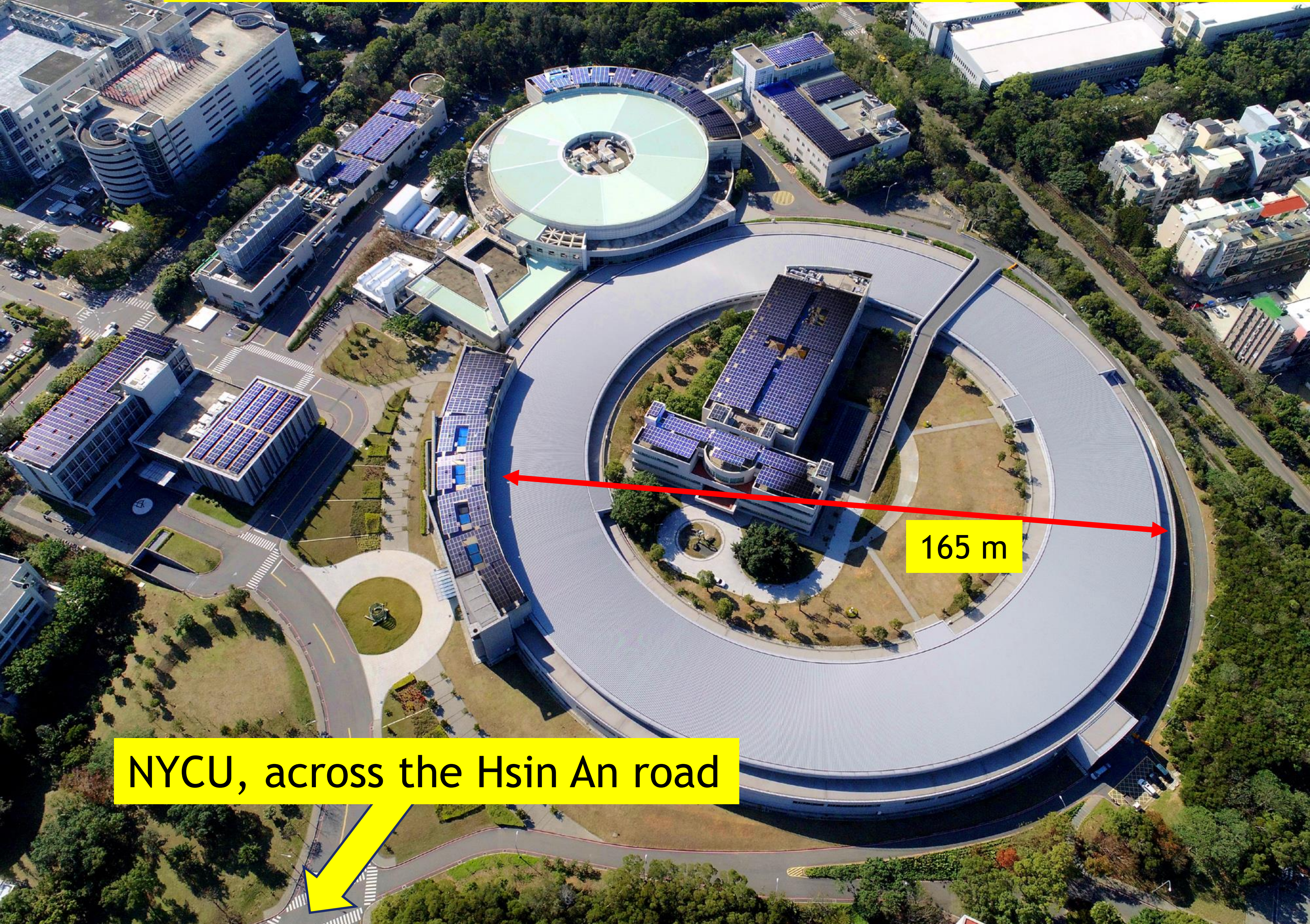
Dr. Mai Thi Thu,
Dept of Adv. Mat. Sci. and Tech.
Univ. of Sci. and Tech. Hanoi,
Vietnam





(a) The indexed Laue patterns of cross-section GaN film using XMAS software. (b) The spatial distribution of line width broadening for the calculated ETDs and MTDs densities

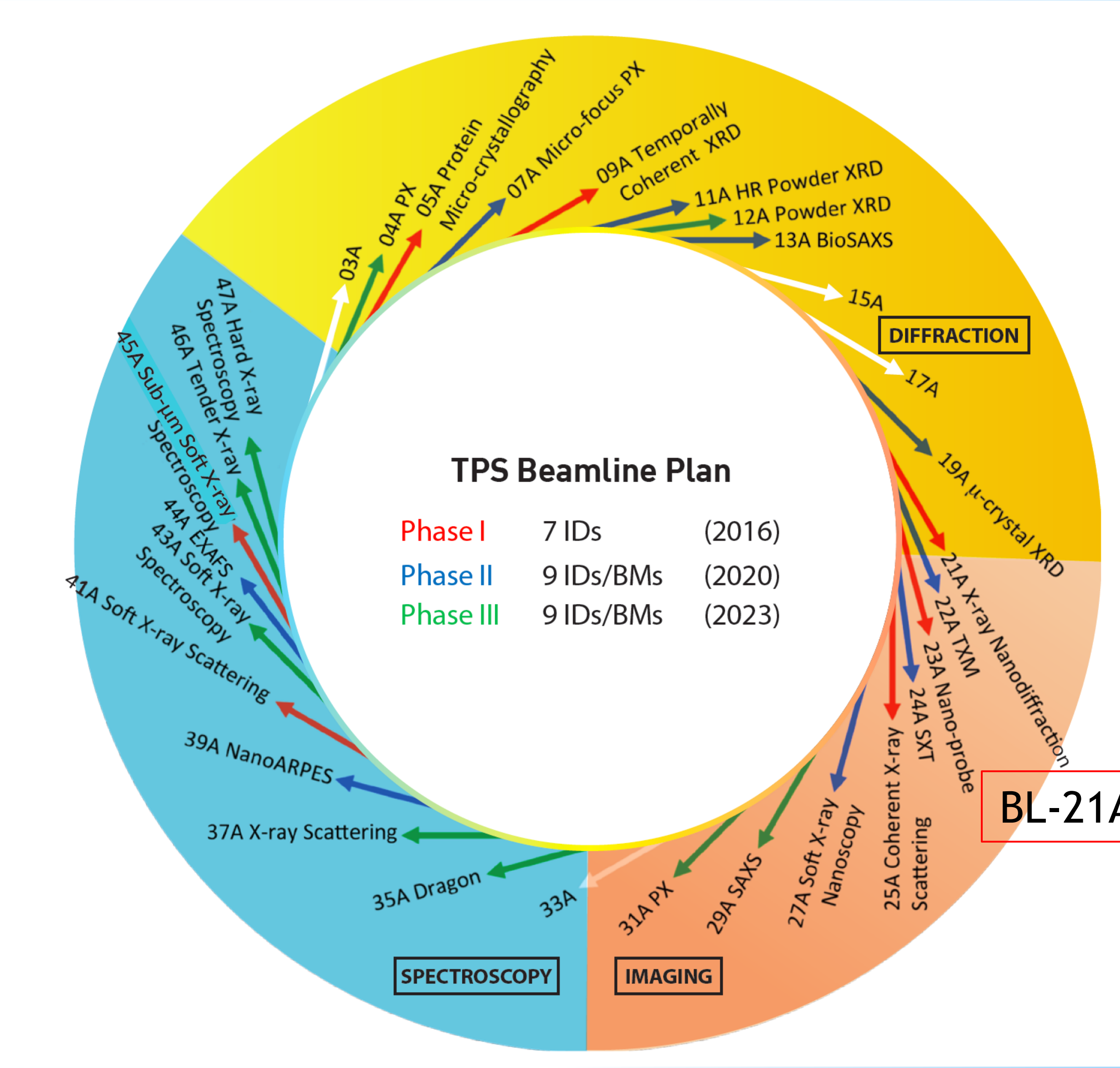
National Synchrotron Radiation Research Center (NSRRC)



National Synchrotron Research Radiation Center (NSRRC)

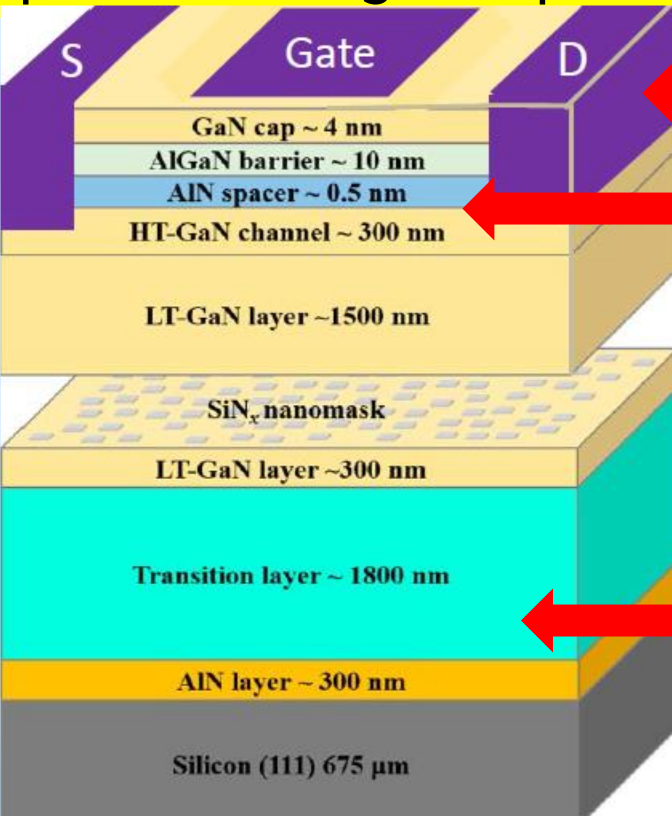
https://www.nsrrc.org.tw/english/tps.aspx

NYCU south gate



Next door 3.0 GeV synchrotron radiation source

Key challenges for fabricating GaN high electron mobilty transistor (HEMT) with excellent performance for the application in the high power and high frequency devices:



1. Low contact resistance,
2. p-GaN for enhanced mode HEMT

High hole concentration of 1.3×10^{18} cm^{-3}

3. Two dimensional electron gas (2DEG): high electron mobility~ 1970 $cm^2/V\cdot s$, low sheet resistance, high e density 6.42×10^{12} cm^{-2}

reduce the edge-type TDD and EPD, 2.25×10^9 and 3.24×10^8 cm^{-2}

4. High resistivity buffer (C or Fe doping)
5. Low dislocation density,

High vertical breakdown voltage >1000V

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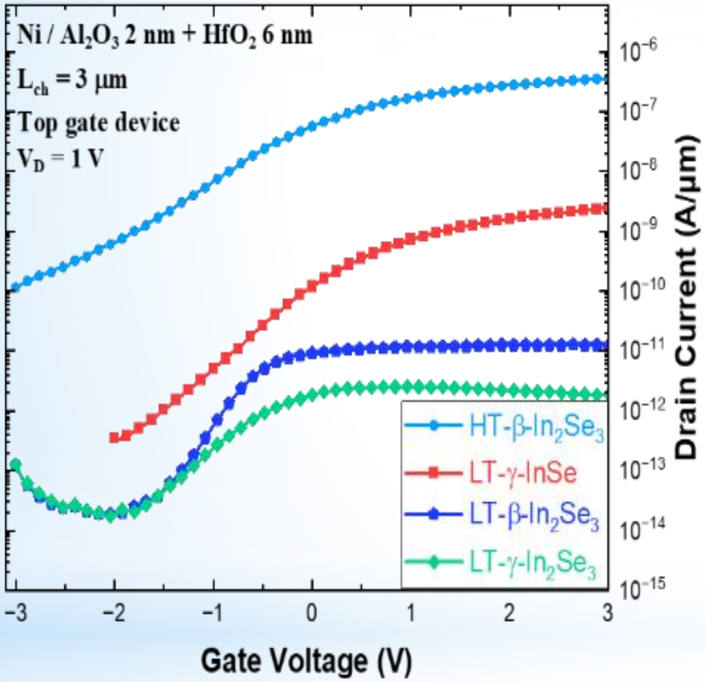
Fabrication and Characteristics of tow dimensional (2D)-In_2Se_3 field effect transistors (FET)

Ssu-Kuan Wuet al., ACS Applied Nano Materials 7, 20445 (2024).

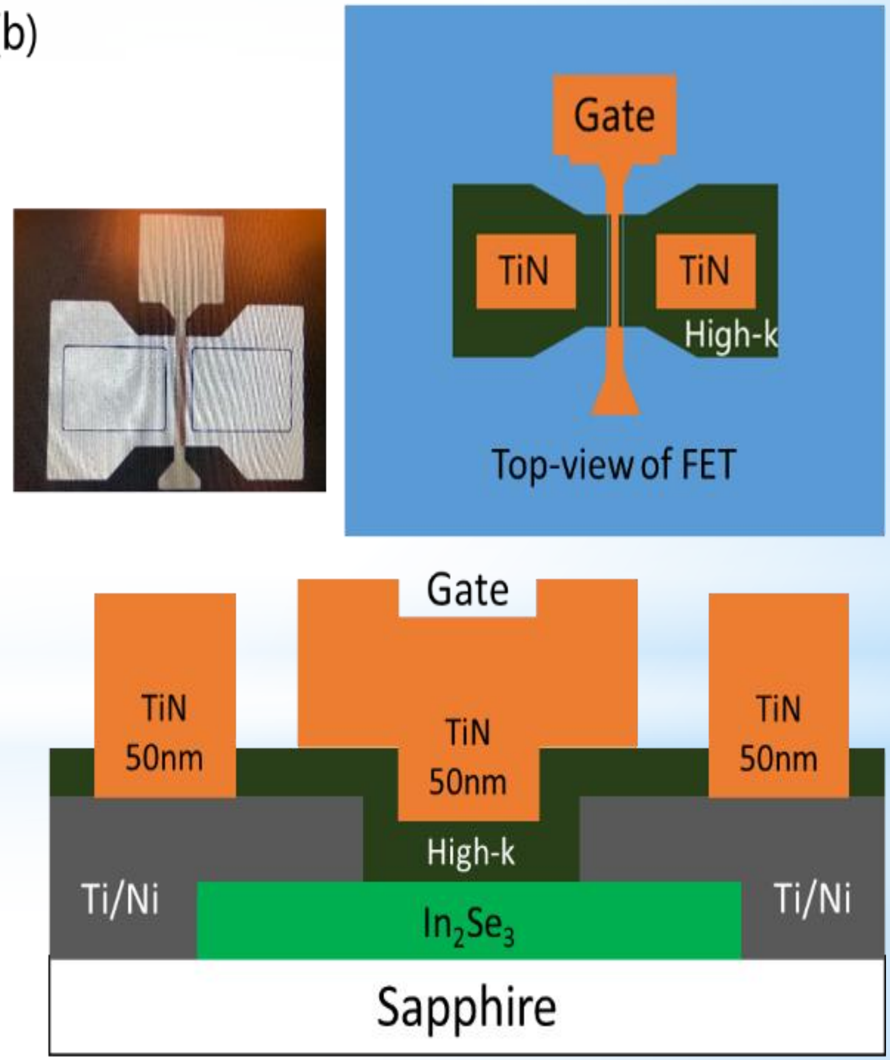
(a)



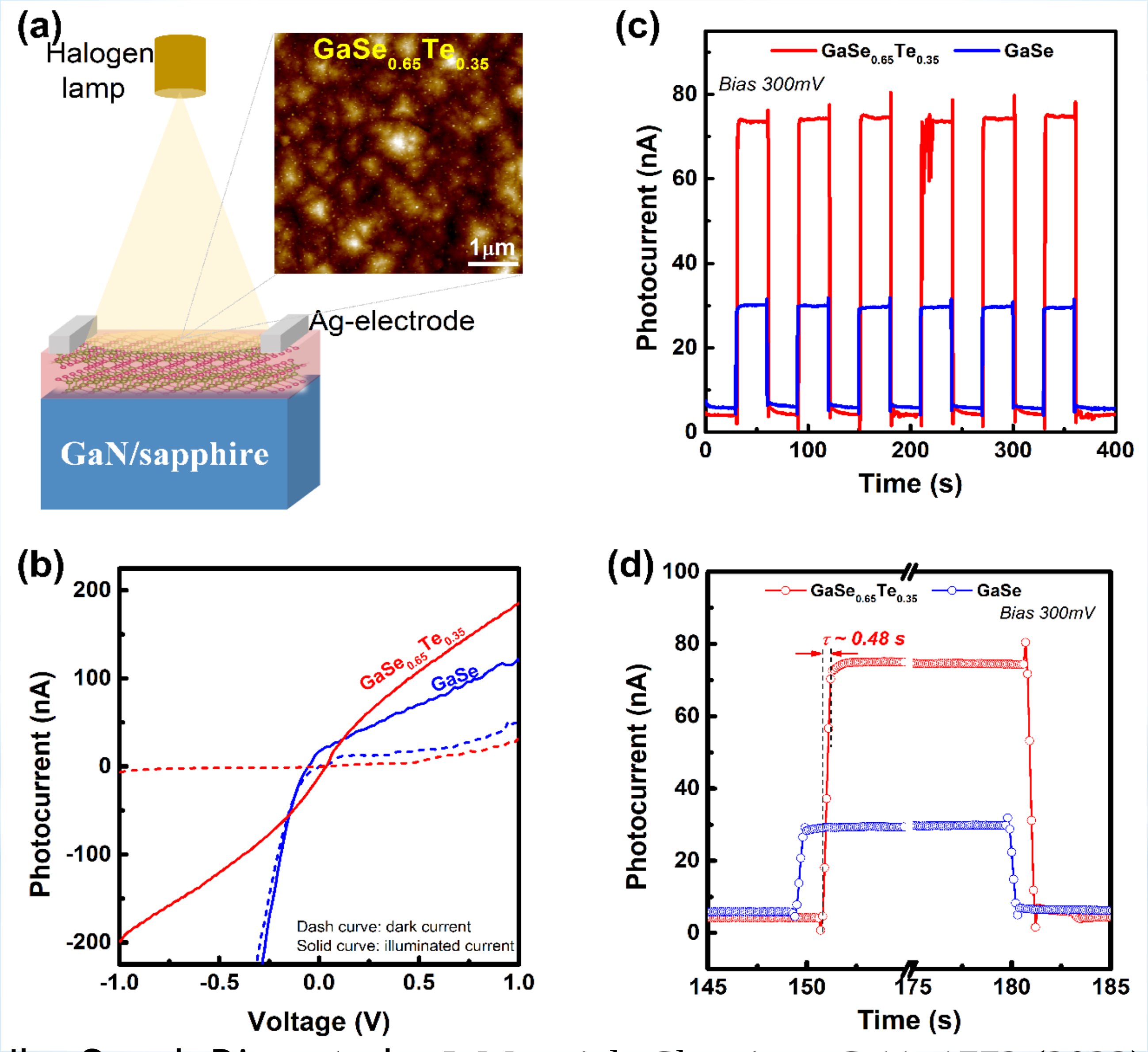
	SS (mV/decade)	V_{th} = (V)	μ ($cm^2V^{-1}s^{-1}$)
HT-β-In_2Se_3	365	-0.84	2.33
LT-γ-InSe	662	0.711	0.136

Characteristic of FET made at low temperature is poor

(b)



photodetector fabrication of 2D III-VI GaSe and GaSeTe compound semiconductors



Nhu Quynh Diep et al., J. Materials Chemistry C 11, 1772 (2023)
Nhu Quynh Diep et al., ACS Appl. Nano Mater. 7, 3042 (2024)

Conclusions

Fabrication, characteristics, and device performance of GaN high electron mobility transistors (HEMT) were demonstrated.

1. SiN nano-mask on the LT GaN significantly decreases the dislocation density
2. Layer-wise strain distribution was investigated by nano-X-ray diffraction. The layer-wise crystal quality was revealed by nano-X-ray excited luminescence.
3. Fe and C co-doping increases the breakdown voltage due to the compensate mechanism. Fe and C play the role of acceptors to compensate the native donors resulting from point defects.

Achieve fabrications of photo-detectors and FET by 2D III-VI compound semiconductors.

NSTC 國家科學及技術委員會
National Science and Technology Council

國立陽明交通大學
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Thanks for your attention !