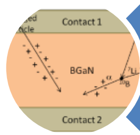
BONES
Boron Gallium Nitride High Performance Neutron Sensor

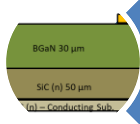
INFN Milano-Bicocca

PI: Stefano Sanguinetti
April 2023

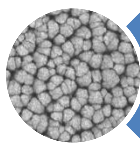
Outline



The BONES target

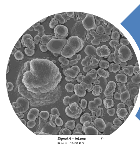


The Project



Optimized Low T GaN

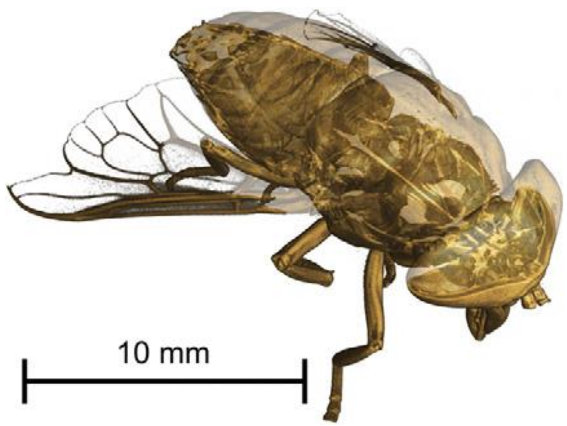
The B Source Tests



The Contingency Plan

Summary

The BONES Target 1



Efficient One-stage thermal neutron detector does not exist

One stage fast neutron detector by INFN - CSN5

Contents lists available at ScienceDirect
Nuclear Inst. and Methods in Physics Research, A
journal homepage: www.elsevier.com/locate/nima

New thick silicon carbide detectors: Response to 14 MeV neutrons and comparison with single-crystal diamonds

M. Rebai[a,b,*], D. Rigamonti[a,b], S. Cancelli[c], G. Croci[b,c], G. Gorini[b,c], E. Perelli Cippo[a], O. Putignano[c], M. Tardocchi[a,b], C. Altana[d], M. Angelone[e], G. Borghi[f], M. Boscardin[f], C. Ciampi[g,h], G.A.P. Cirrone[d], A. Fazzi[i,j], D. Giove[j], L. Labate[k], G. Lanzalone[d,l], F. La Via[m,d], S. Loreti[e], A. Muoio[d], P. Ottanelli[g,h], G. Pasquali[g,h], M. Pillon[e], S.M.R. Puglia[d], A. Santangelo[n], A. Trifiro[o,p], S. Tudisco[d]

Sicilia Project

Imaging neutron detectors

<u>Gas Detectors</u>
- 3He, BF3, Straw Tubes
- One or two stage detectors
- Quite high efficiency
- Too coarse spatial resolution
-

<u>Scintillation Detectors</u>
- LiF, CCD (used in IMAT)
- Two stage detectors
- Moderate efficiency
- High spatial resolution
- Very expensive

<u>Semiconductor Detectors</u>
- Two stage detectors
- -Low efficiency
- Moderate cost

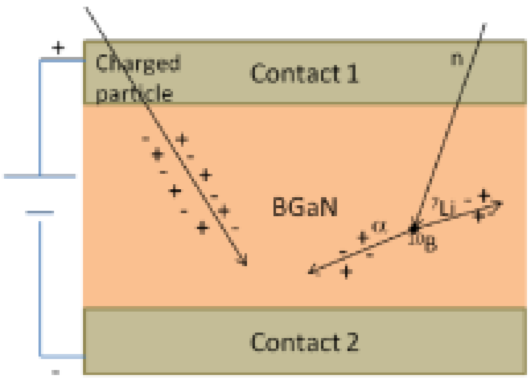
[1] A.P. Kaestner et Al. NIM A 659 (2011) 387–393, [2] ISIS website

The BONES Target 2

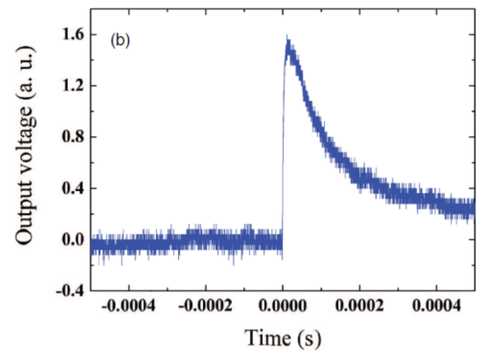
APL MATERIALS 2, 032106 (2014)

Neutron detection using boron gallium nitride semiconductor material

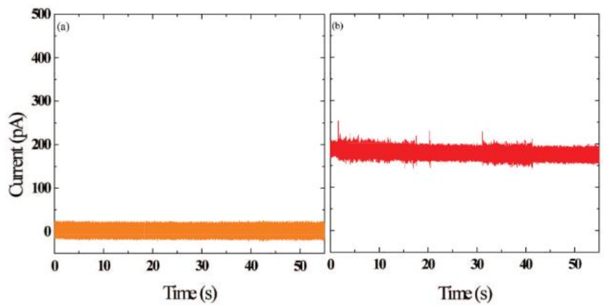
Katsuhiro Atsumi,[1] Yoku Inoue,[2] Hidenori Mimura,[3] Toru Aoki,[3] and Takayuki Nakano[2,a]



Reaction	Q
10B(n,α)7Li	2.792 MeV
10B(n,α)7Li*	2.310 MeV



α particle selectivity

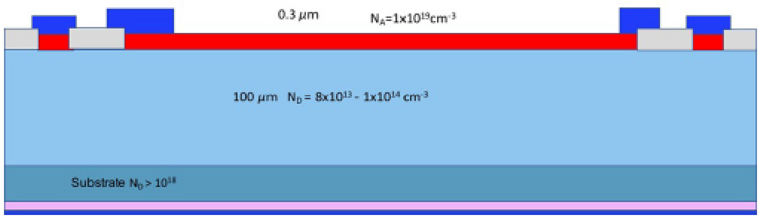


Expected efficiencies

Thickness [μm]	*$\frac{B}{B+Ga}$ fraction [%]*	*Efficiency with Nat-B (^{10}B alloyed)*
25	*20*	*1.9% (9.5%)*
50	*20*	*3.9% (18%)*

The BONES Project 1

Sicilia SiC detector



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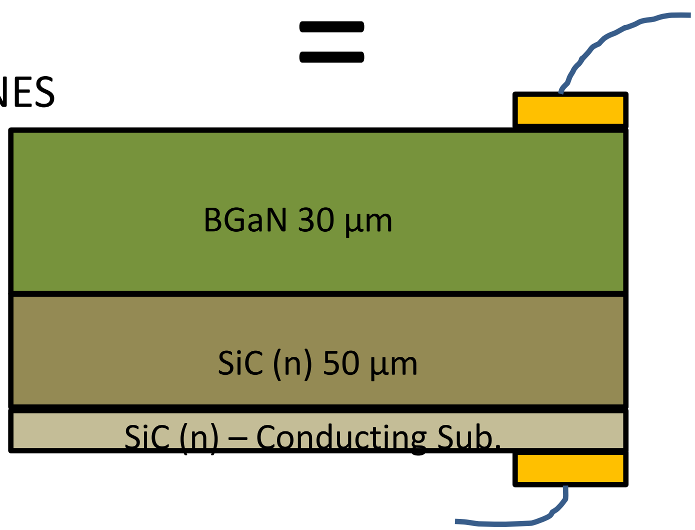
BONES



Mixed Neutron **one stage** Detector Combining "Sicilia" SiC fast neutron detector with BGaN thermal neutron detector with future imaging capabilities

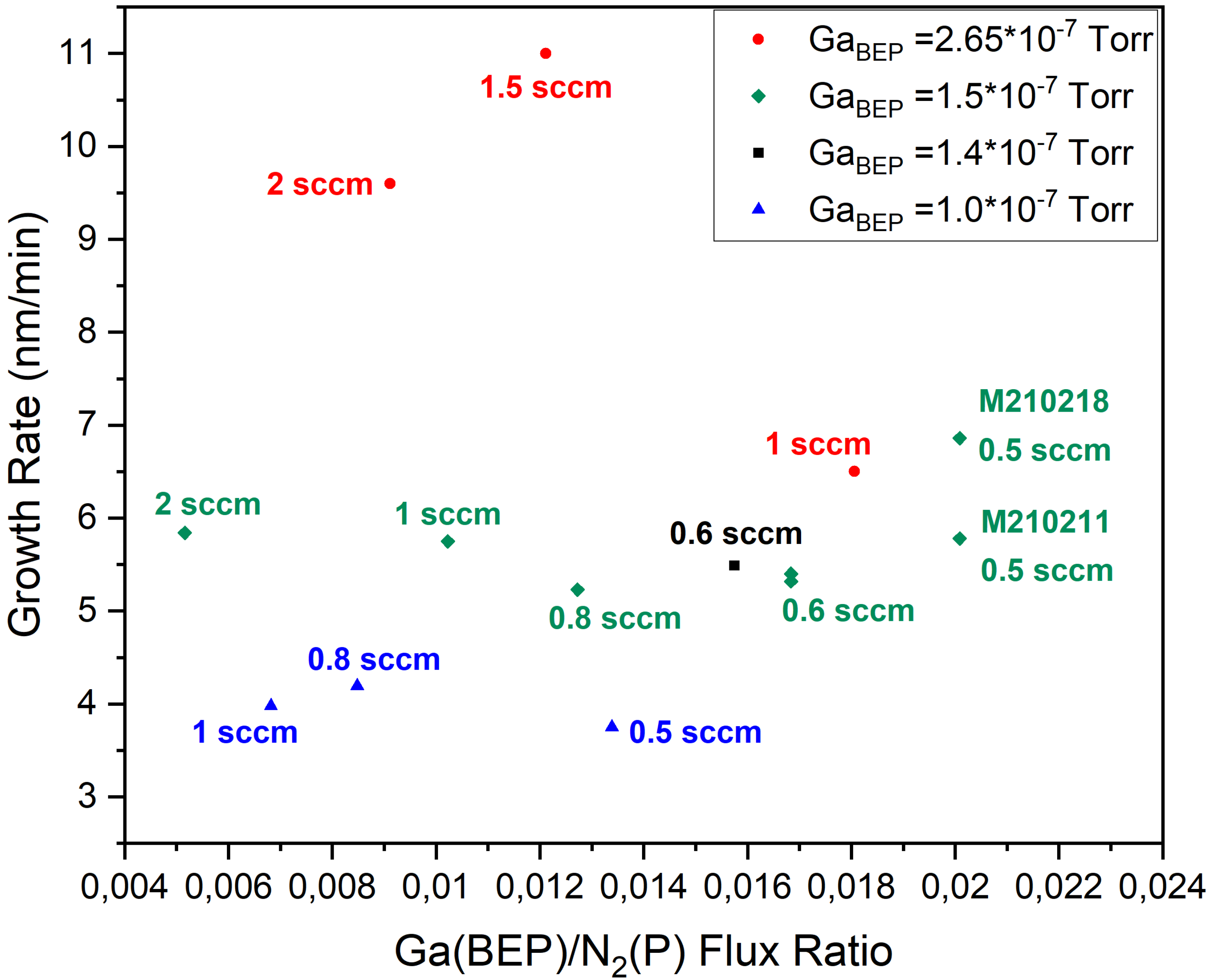
ADVANTAGES

1) Compact detector:
   - Small spaces
   - Imaging (pixels)
2) Extended energy sensitivity (meV-MeV).
3) Reduced read-out complexity

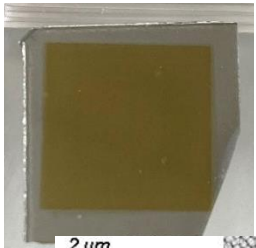
Fabrication process:

- SiC by Chemical Vapour Deposition
- BGaN by Plasma Assisted Molecular Beam Epitaxy

Optimized Low T GaN 1

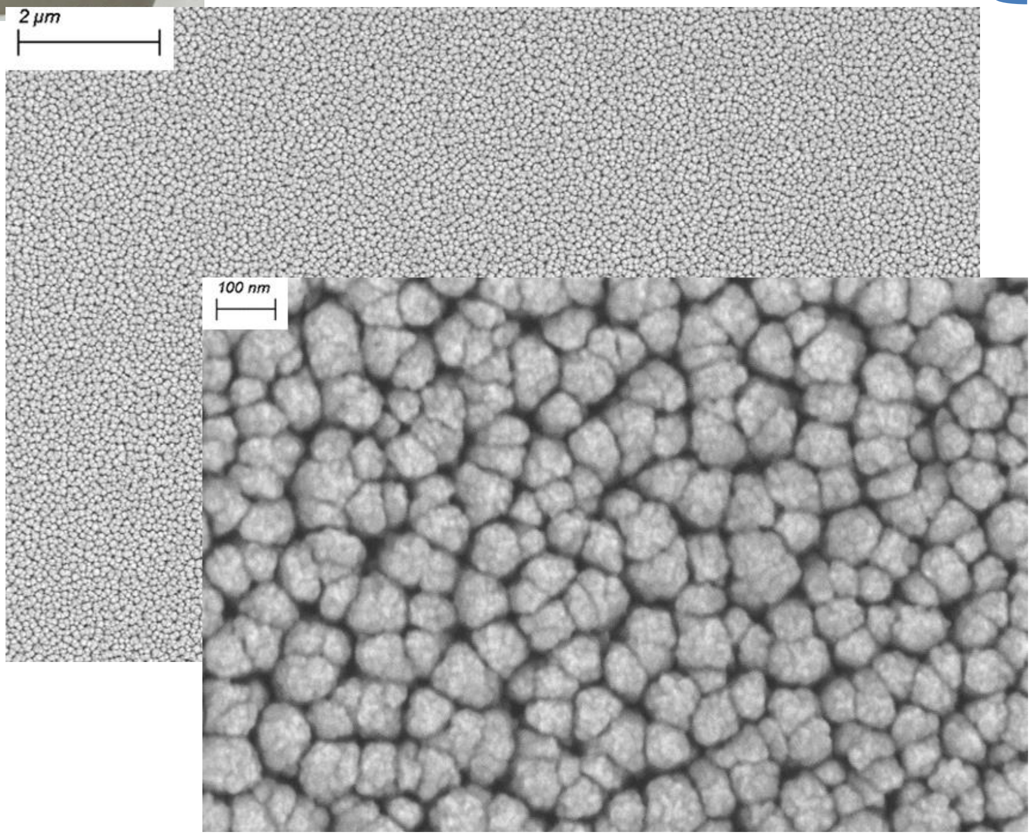


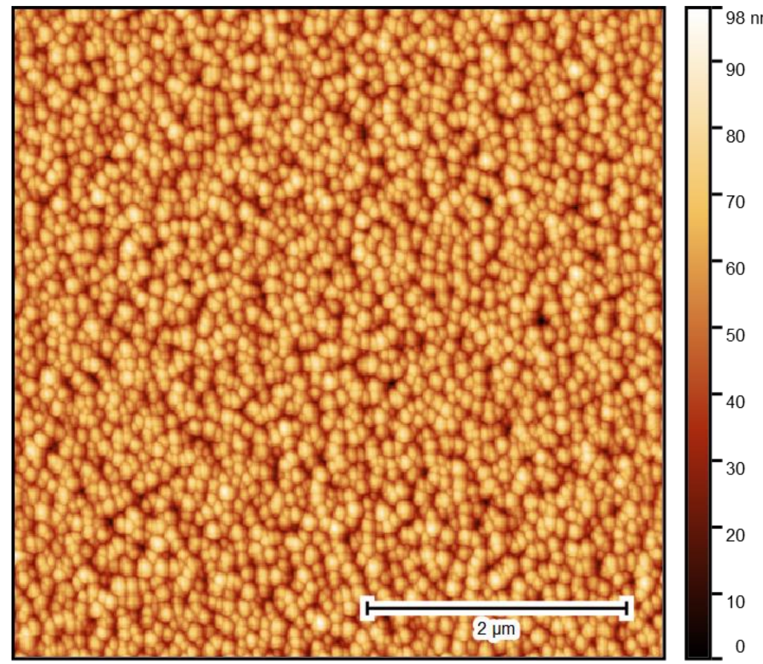
Optimized Low T GaN 2



Epilayer Characteristics

- Uniform
- 600nm/h growth speed
- Nanocolumnar





AFM

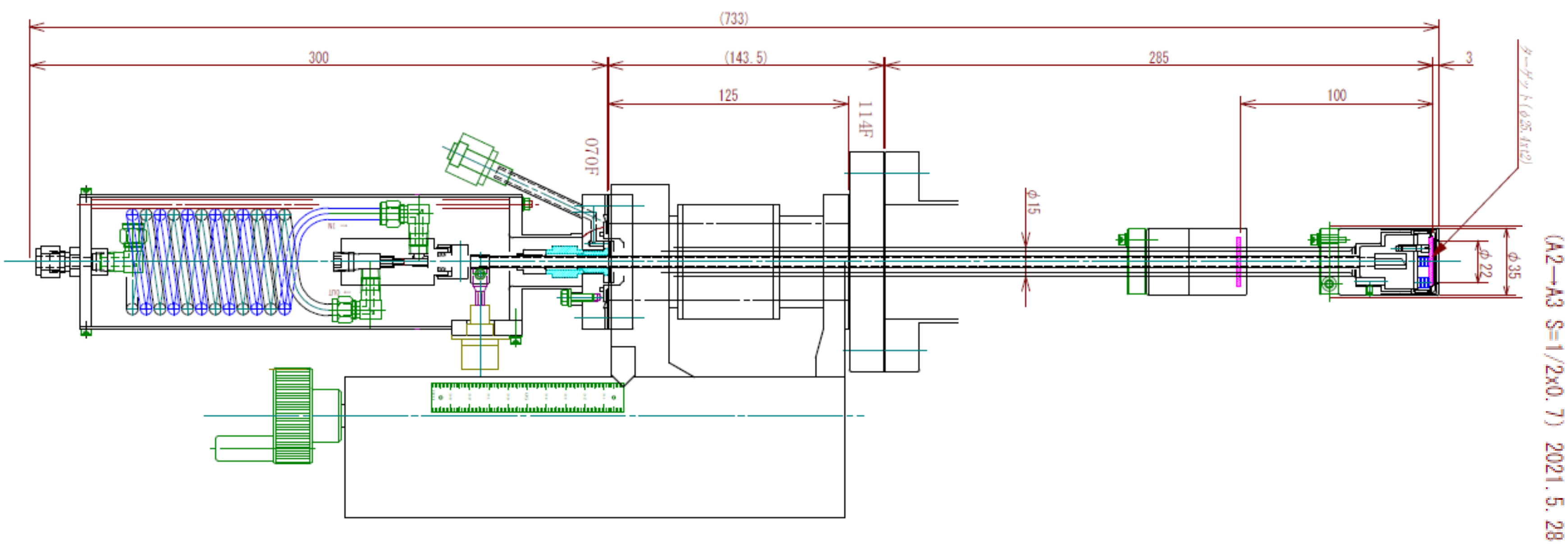
High-resolution SEM

The B Source Tests 1

Innovative B sputtering cell optimized for MBE environment

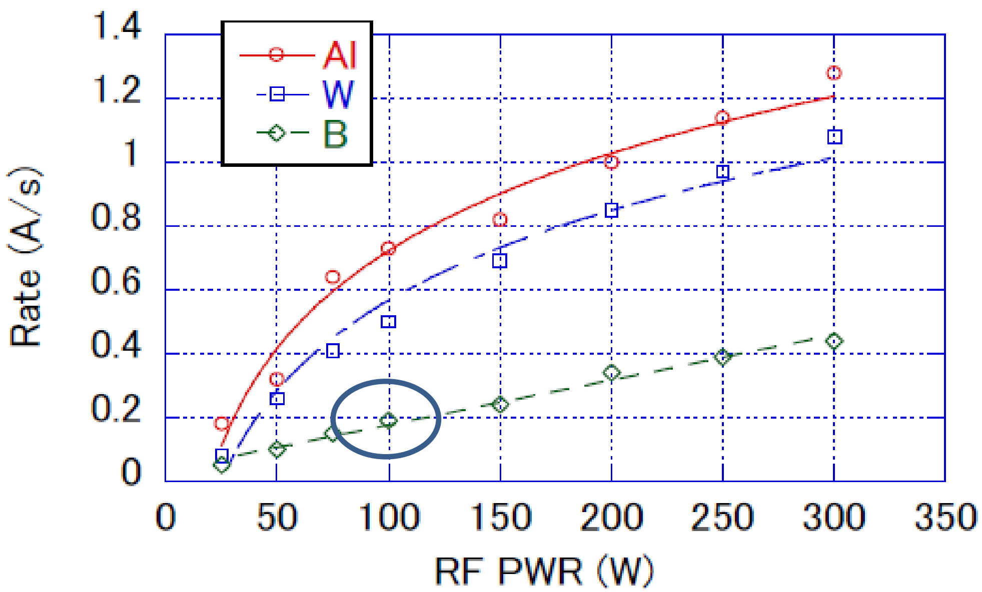
Kenix Corp. Japan

Definitive B-Cell design



The B Source Tests 2

Initial tests



target Φ2"
Ar：20sccm
TS 170
圧力 7×10-2Pa

Limitation due to MBE chamber design
Φ = 1”
RF power = 100 W

Best results @100W RF
0.5 nm/min
Obtained with new cell design
Optimized RF chamber

0.5 μm/h of $B_{0.1}Ga_{0.9}N$

TEST REPORT

2021/4/12
Test Location Kenix corp

Film Formation Rate by PGS sputtering

No.	Target Material	Sub material	Back Pressure (Pa)	Ar (sccm)	Propcess Pressure(Pa)	RF Power (W)	Time (min)	Thicknes (nm)	Film Formation Rate (nm/min)	T/S:Distance from Target to Sub
1	B powder φ1”	Si	8 ×10−4	8	2*10−2	100	60	12	0.20	TS:120mm
2	B powder φ1”	Si	8 ×10−4	12	4.8*10−2	100	240	54	0.23	TS:220mm
3	B powder φ1”	Si	×10−4	① 3 ② 5	①1.8*10−2 ②3.5*10−2	100	①90 , ②30 total:120min	15	(0.12) ※	TS:120mm with Ingenious structure

others

1.Tested by PGS sputtering･･･Ar gas is introduced from the cathode target side,the main valve is fully open.

2.The Process Pressure was visually confirmed in a stable plasma state.

3.The cause of the difference in process pressure between esch TEST is unknown,but the state of the target material may be have changed.

4.The film formation rate result by No.1 and No.2 were almost the same. ABOUT 0.2nm/min

5.The film thickness was measured by a tactile profilometer DEKTAK.

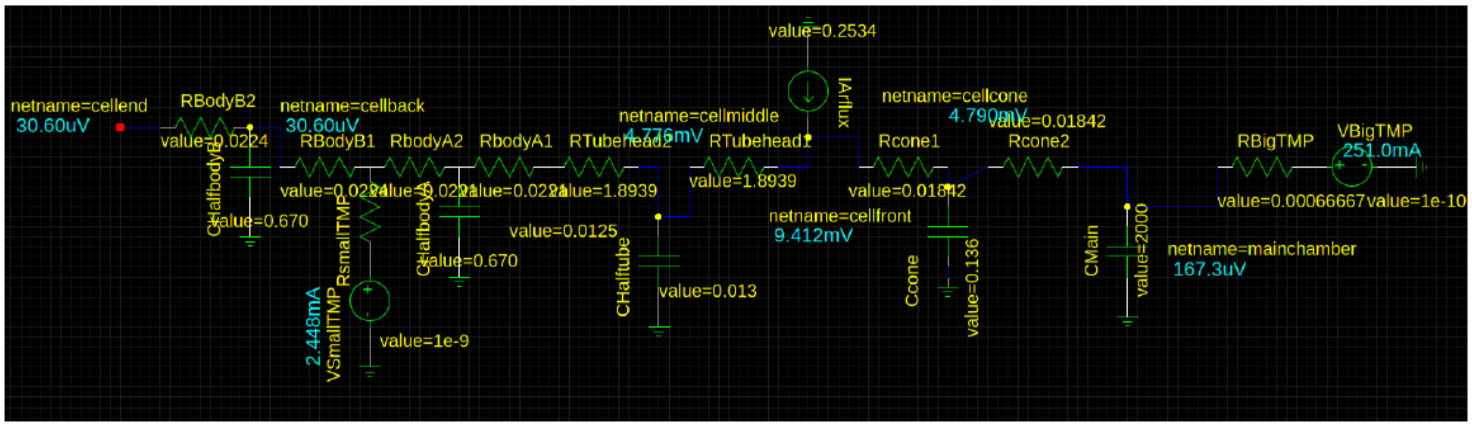
6.In the No.3 TEST,Stable plasma generation (sputtering conditions) at 3sccm Ar flow rate was comfirmed by Ingenious structure that could not be announc

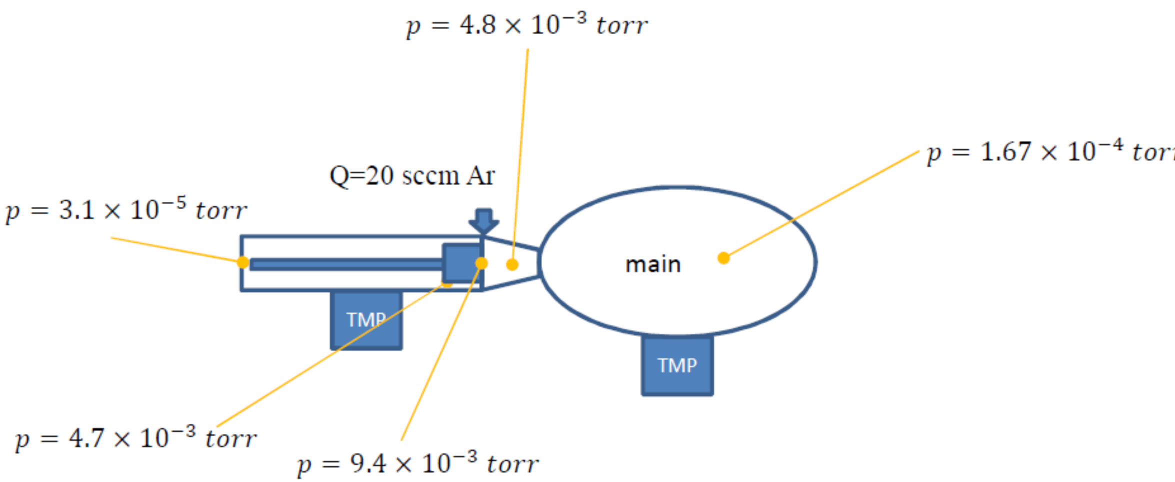
※ We confirmed the conditions under which plasma discharge can be performed at an Ar flow rate of 3 sccm. However, the plasma density is low and the film formation rate seems to be slow.

Test Date 2021/4/8 &4/12
Hiroki Oota

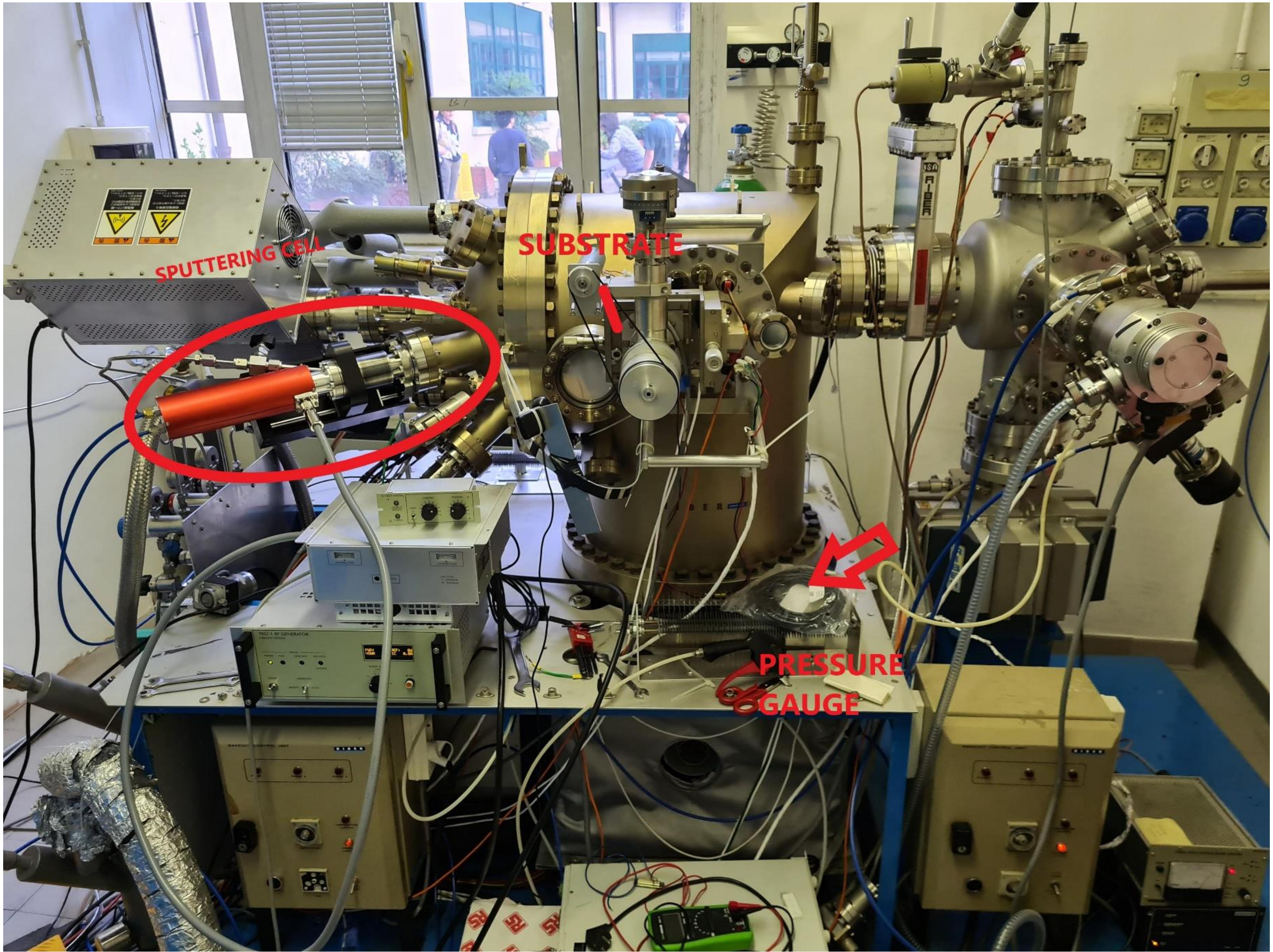
The B Source Tests 3

cell configuration in the MBE



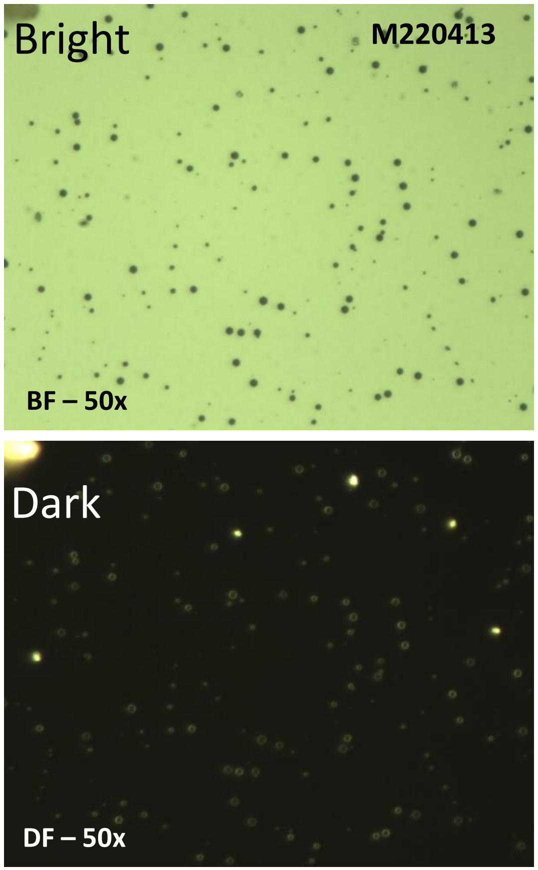


The B Source Tests 4



The B Source Tests 5

Optical microscope

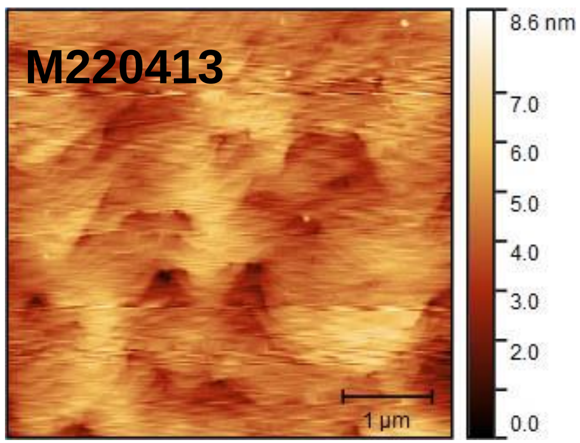


Several tests at different
- RF power
- Ar flux
- Deposition time

on GaN substrates

No B deposition observed

AFM microscope



Ar flux = 20 sccm
RF power = 100 W
B target position = 100 mm (all in)
T_{sub} = 300°C

The B Source Test 5

New tests in Japan @ Kenix Corp.

Sputtering TEST by Sintered Boron (Supplied by Bicocca)

Plasma generation Start conditions

Gas Type	Ar
Gas introduction position	Cathode
RF power	80W
Target	Sintered Boron supplied by Bicocca
Target Size]	ϕ 25 × t3
Target Shield	kenix standard
Plasma generation pressure	8 P a

(State in which Vacuum exhaust resistance is controlled by the Main Valve)

Test Method	After Plasma Generation,gradually open the Main valve and observe the Plasma state.

Ar Flow Rate 【SCCM】	Plasma unstable 【Pa】		Plasma extinction 【Pa】
10	6.0 × 10-1	→	5.6 × 10-1
12	5.5 × 10-1	→	5.0 × 10-1
14	5.2 × 10-1	→	4.5 × 10-1
16	4.6 × 10-1	→	4.2 × 10-1
18	4.2 × 10-1	→	3.9 × 10-1
20	3.7 × 10-1	→	3.3 × 10-1

Result : Plasma cannot be maintained with the Main Valve fully Open.
Plasma Generation Start is Pressure Controlled by Main Valve control.

No sputtering with sintered B targets
Only possible with B powder targets

20X maximum pressure for MBE

The Contingency Plan 1

Develop growth procedures for Nitride materials with low incorporation rate (like BGaN) where the growth of the entire composition range is challenging.

InGaN

PROS

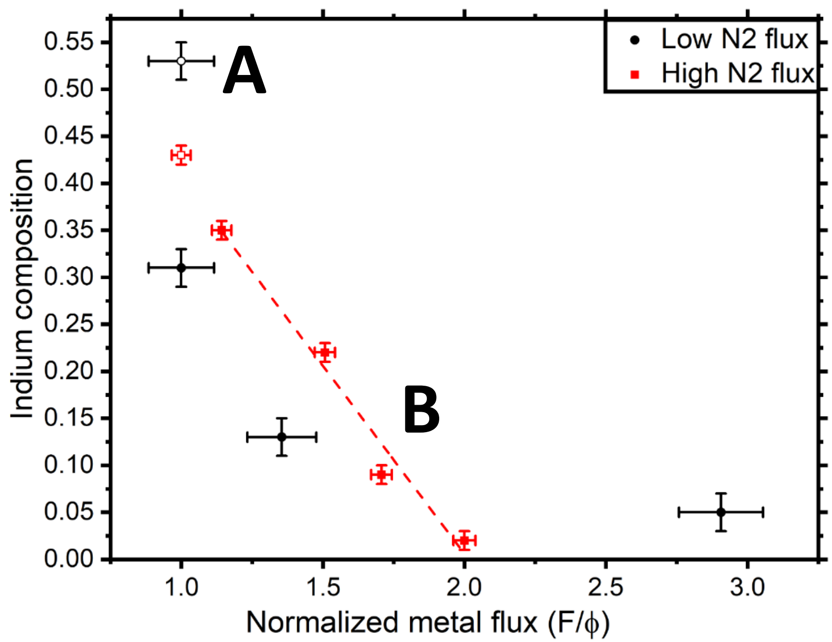
1. presence of local strain
2. surface segregation
3. presence of droplets on the grown surface
4. limited inclusion
5. fluctuations of the In content in the epilayer

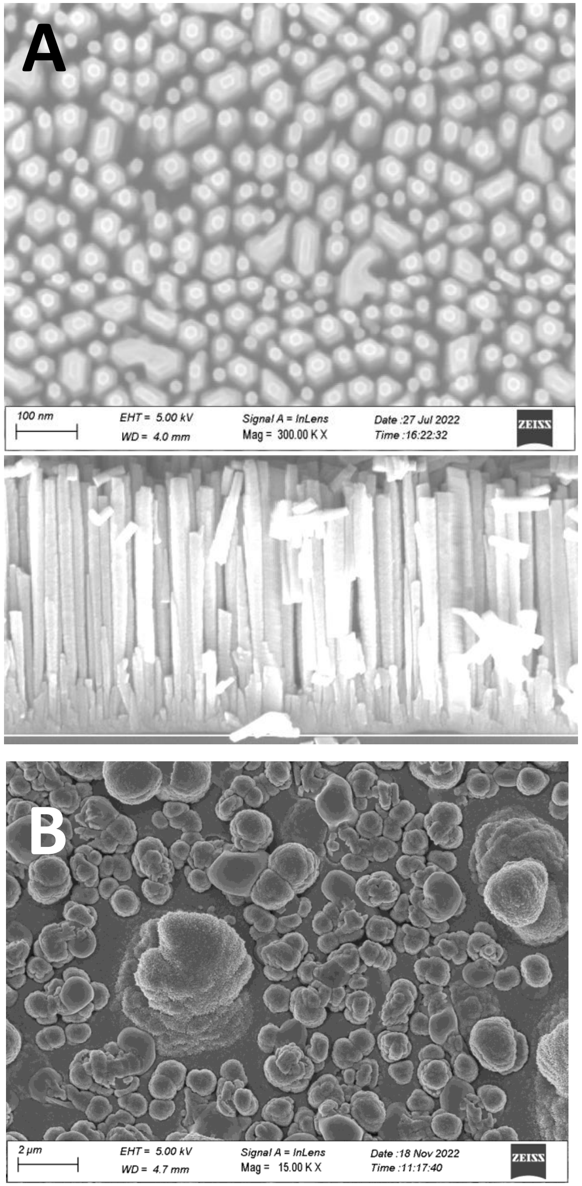
CONS

1. the local strain is tensile in the case of B and compressive in the case of In
2. the B-N bond is stronger than the Ga-N while is the reverse in the case of InN vs GaN
3. there is a strong tendency of B to make a sp_2 bond type with N

InGaN Incorporation

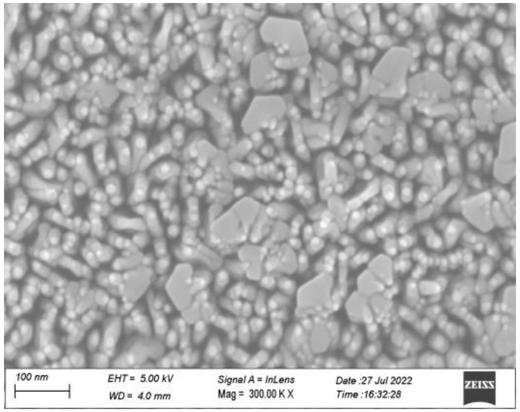
In Incorporation

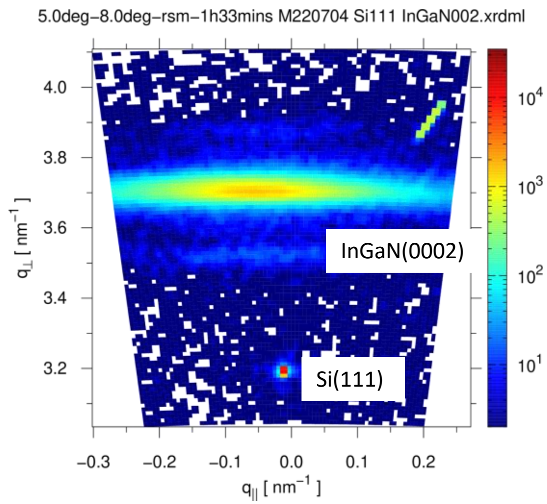


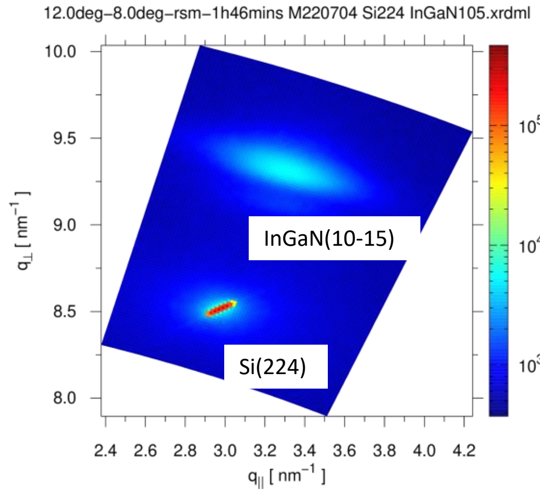


In Incorporation: Sample A

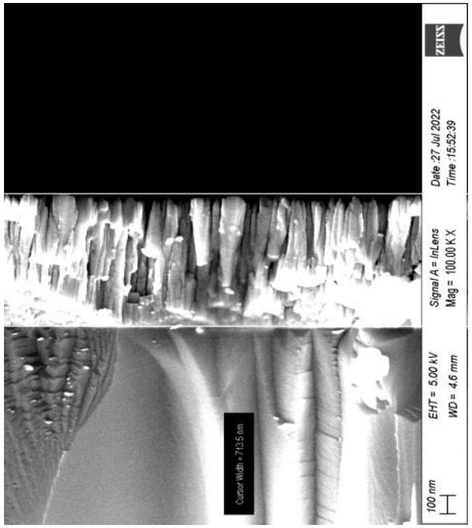
M220704 top view

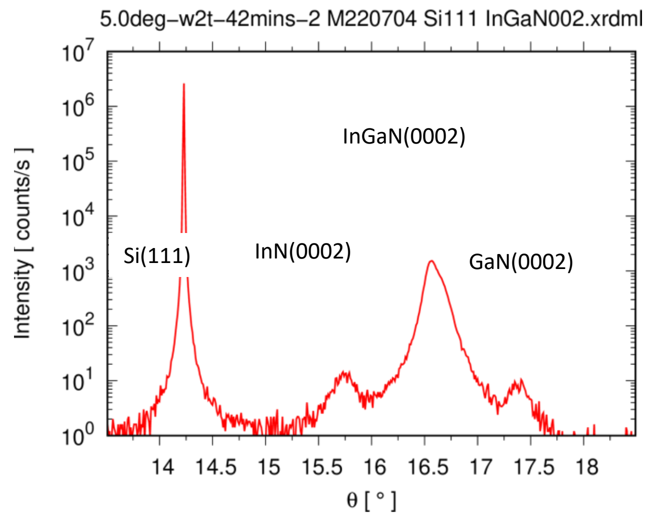




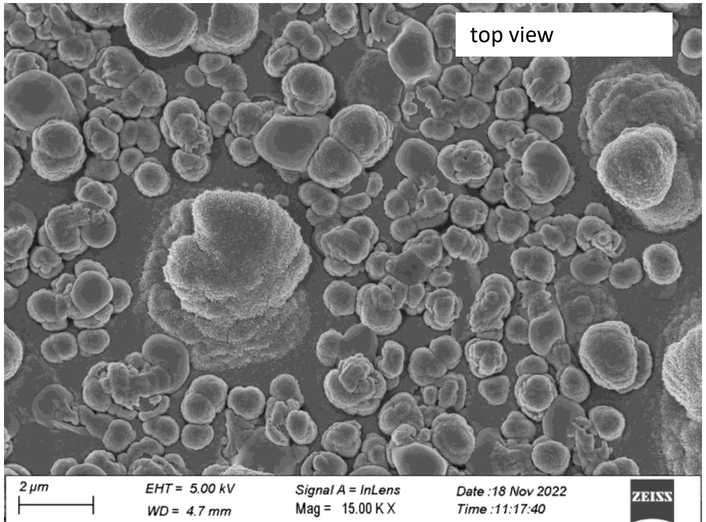


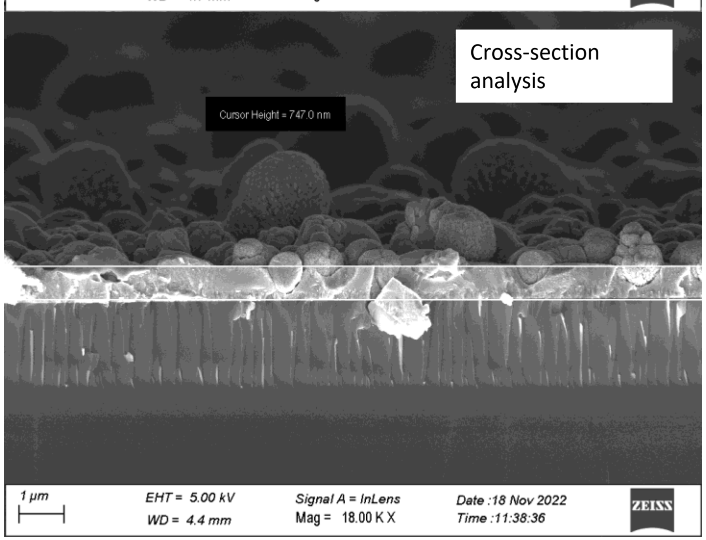
M220704 side view



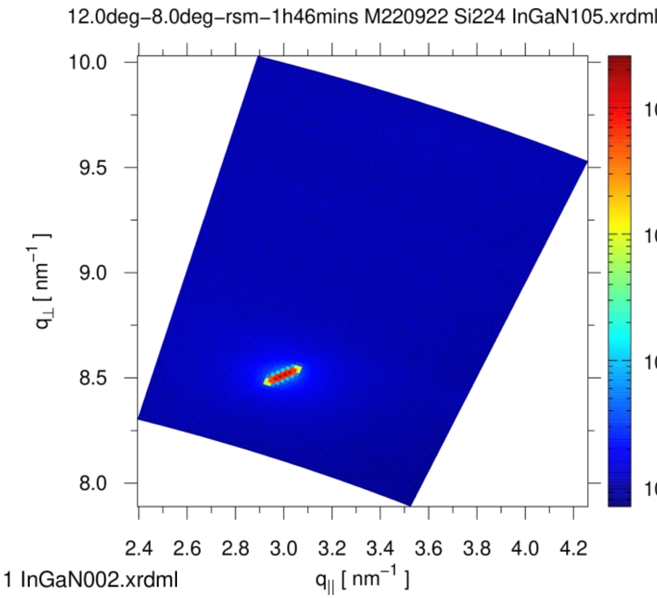


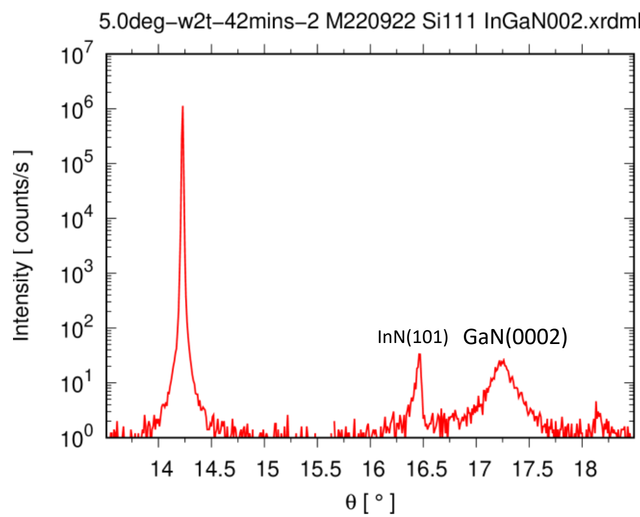
In Incorporation: sample B



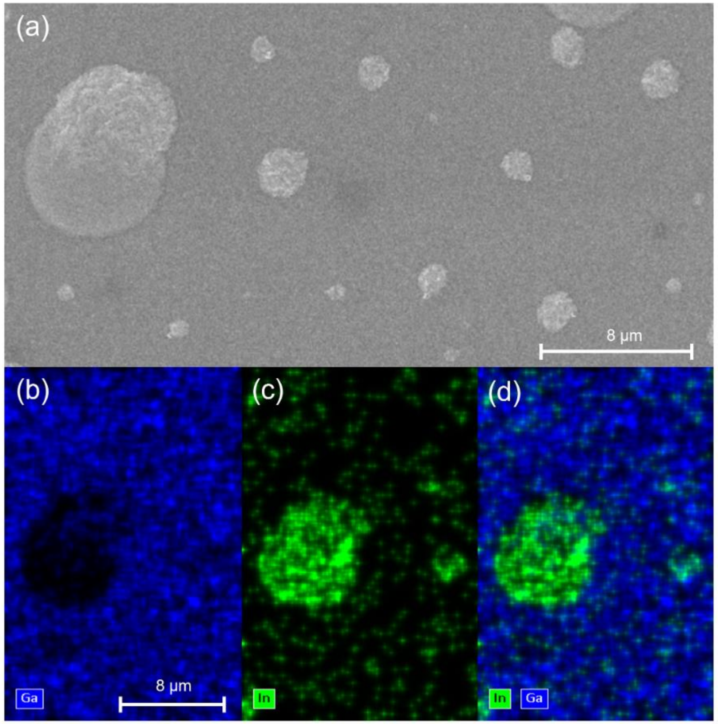


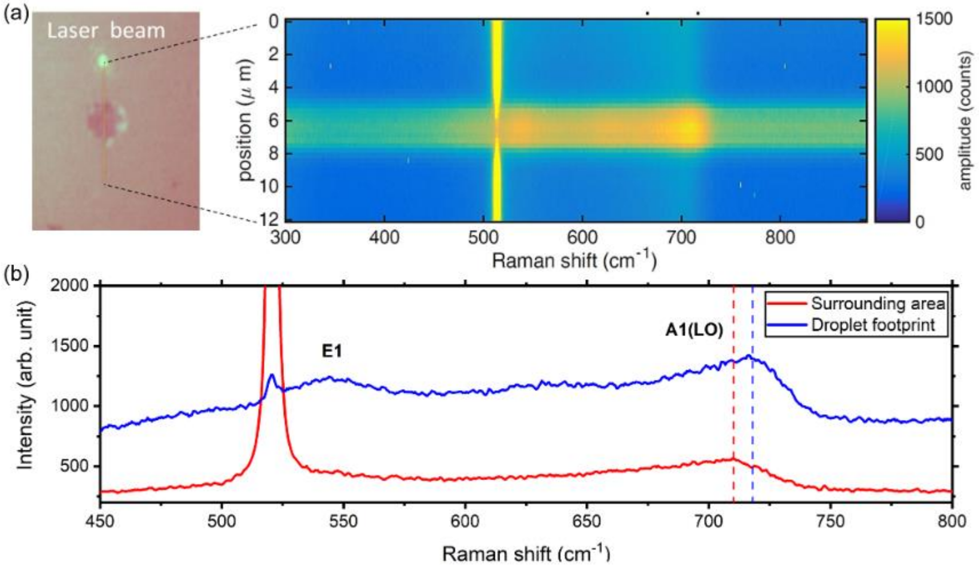
M220922

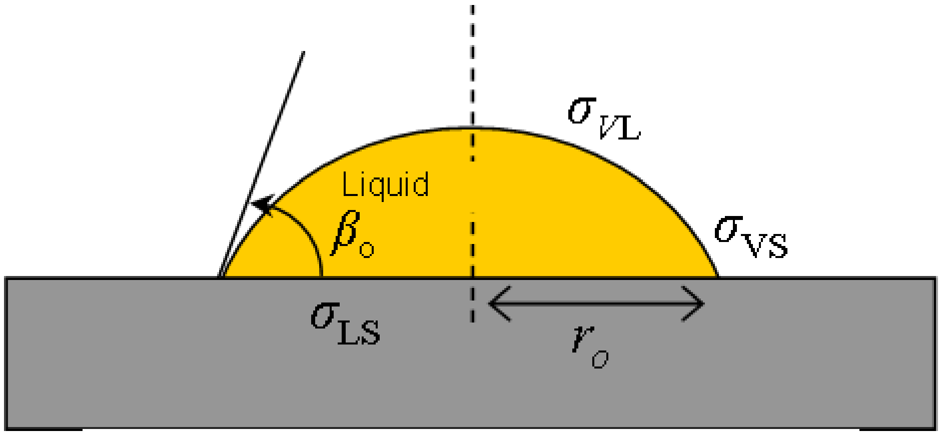




In Incorporation: VLS effect







nanomaterials
MDPI

Article

Vapour Liquid Solid Growth Effects on InGaN Epilayers Composition Uniformity in Presence of Metal Droplets

Mani Azadmand [1,†], Stefano Vichi [2,*,†], Federico Guido Cesura [1,†], Sergio Bietti [1], Daniel Chrastina [3], Emiliano Bonera [1], Giovanni Maria Vanacore [1], Shiro Tsukamoto [1] and Stefano Sanguinetti [1,2]

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2 INFN, Sezione di Milano-Bicocca, 20100 Milano, Italy
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* Correspondence: stefano.vichi@unimib.it
† These authors contributed equally to this work.

In Incorporation: dependence on N flux

$$\frac{dn_{Ga}}{dt} = F_{Ga} - n_{Ga}E_{Ga}(T) - n_{Ga}\delta_{Ga}(\phi, n_{In}) - n_{Ga}\Gamma_D \ell_{Ga}^2(\phi)$$
$$\frac{dn_{In}}{dt} = F_{In} - n_{In}E_{In}(T) - n_{In}\delta_{In}(\phi, n_{Ga}) - n_{In}\Gamma_D \ell_{In}^2(\phi)$$

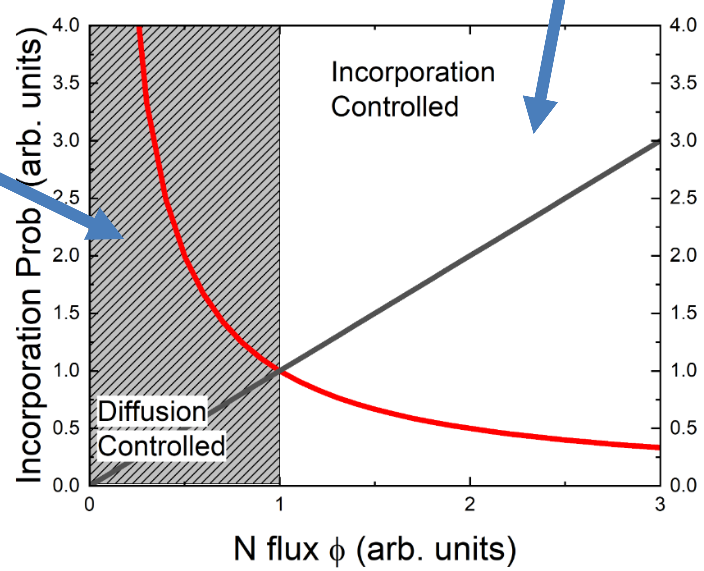
steady state

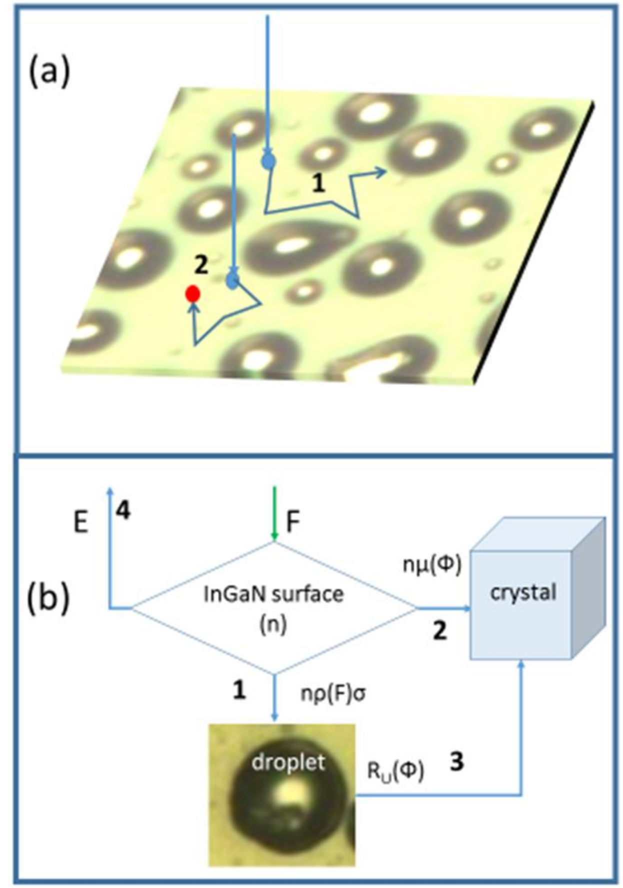
$$\frac{n_{In}}{n_{Ga}} = \frac{\Gamma_D \ell_{Ga}^2 + \delta_{Ga}(\phi, n_{In})}{\Gamma_D \ell_{In}^2 + \delta_{In}(\phi, n_{Ga})}$$

$(F_{Ga} = F_{In} = F)$

$$\zeta_{In} = 1 - \frac{F}{\phi}.$$

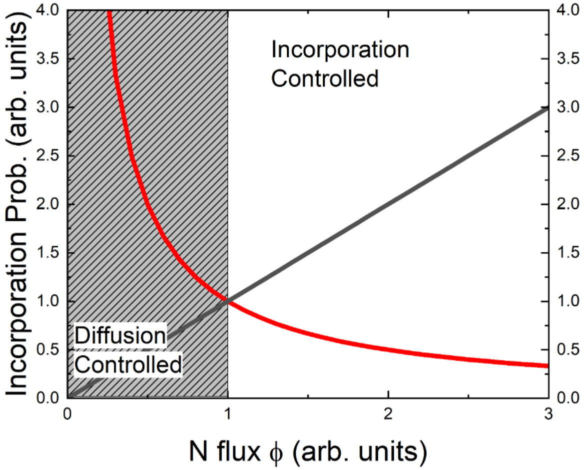
$$\zeta_{In} \approx \frac{D_{Ga}}{D_{In} + D_{Ga}}$$

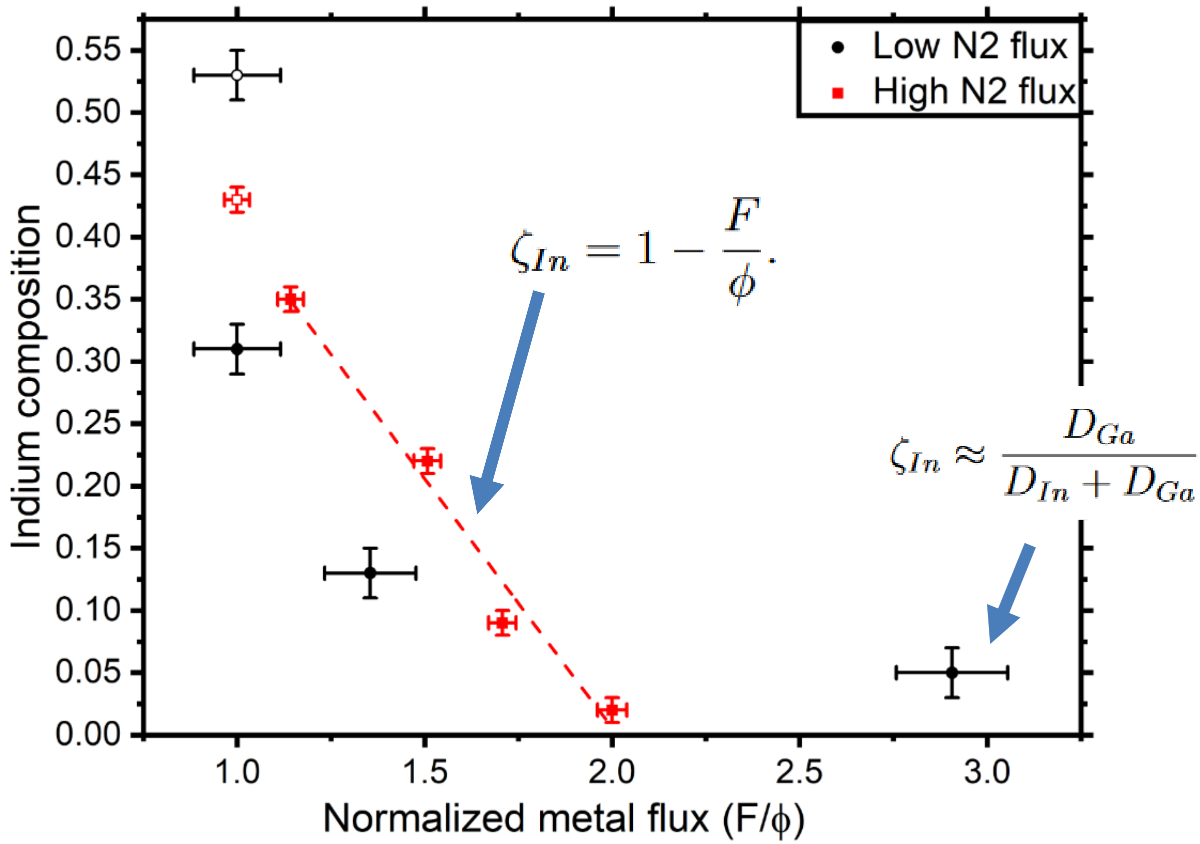




publication in preparation

In Incorporation: dependence on N flux



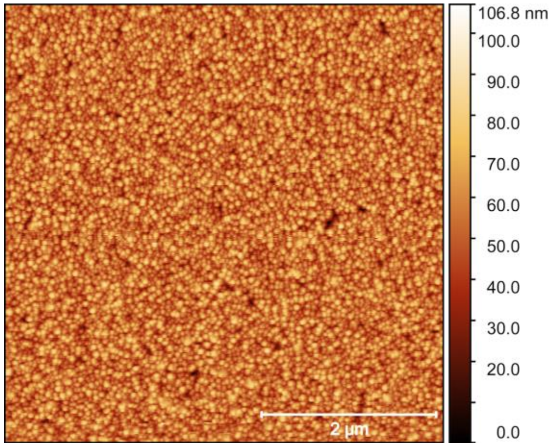
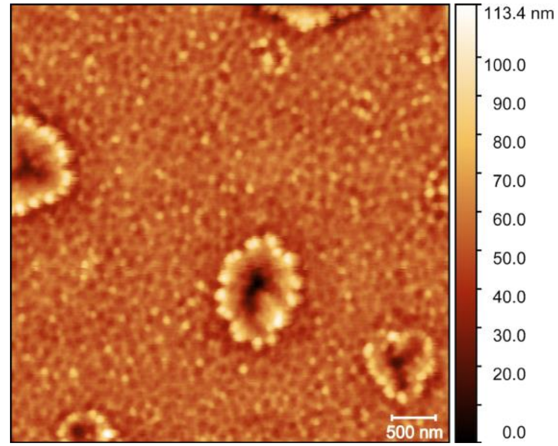
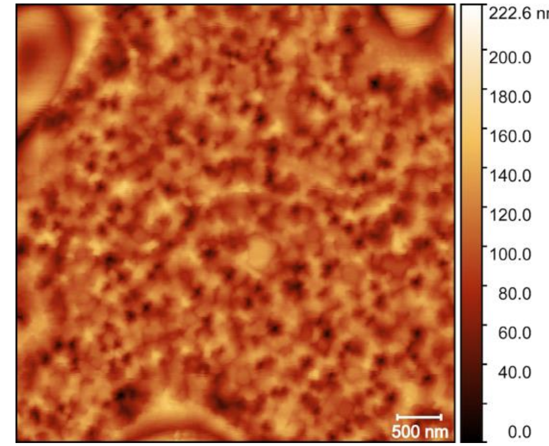
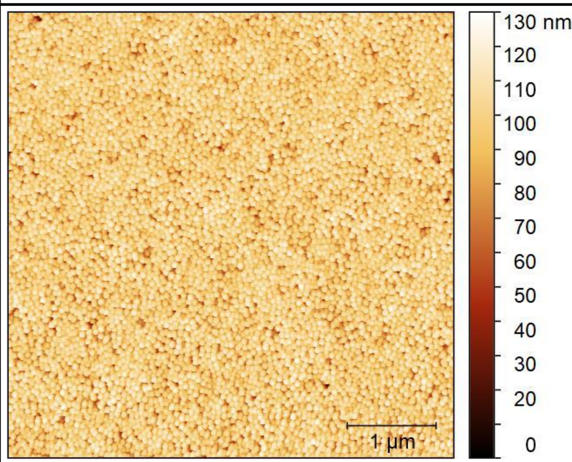
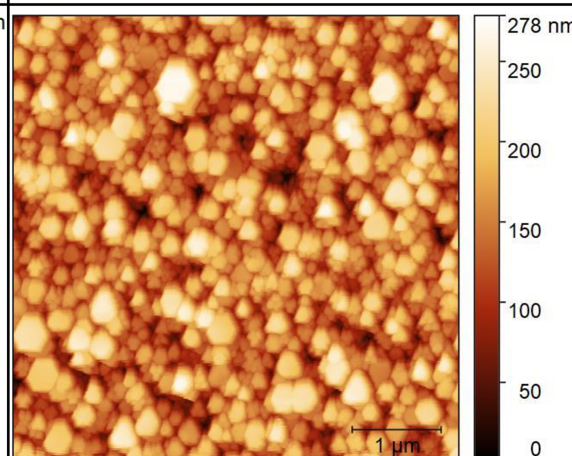
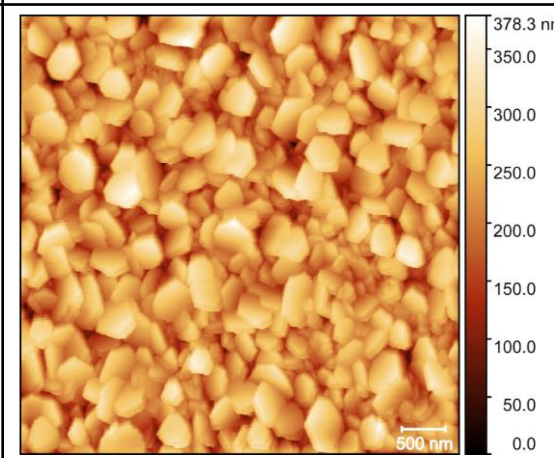


publication in preparation

Incorporation dependence on T

	450 C	500 C	550 C
1 sccm 200 W	M220704 column poly 43% In (+InN/GaN)	M220706 droplets column/walls poly 40%	M220707 droplets walls poly 23% (+In)
2 sccm 200 W	M220713 column single 48% (+weak InN)	M220720 column poly 45% (+In/InGaN)	M220712 poly 24% (not epi)

Incorporation dependence on T

	450 C	500 C	550 C
1 sccm 200 W			
2 sccm 200 W			

Summary

MBE upgrades performed:

- Pyrometer installation for precision control of T
- Sputtering cell installation for B deposition

Carried out the deposition tests B

- The cell is unable to deposit B with bulk targets
- Unable to continue the project as planned

Contingency Plan: InGaN growth process

- Understood the role of droplets in the growth of $In_{0.5}Ga_{0.5}N$
- Determined optimal growth conditions in terms of T and N flux for $In_{0.5}Ga_{0.5}N$
- One publication & one manuscript in preparation

BONES - Milestones

Milestone		deadline	Stato di completamento al 31/12/2022	Note
1	realizzazione dell'upgrade della PAMBE	M12	100%	
2	definizione delle specifiche del detector	M12	20%	In attesa selle caratteristiche elettriche dello strato di BGaN
3.1	Verifica possibilità di produrre BGaN (10%) con il nuovo sistema di sputtering	M15	0%	Si è verificata la rottura della cella sputtering del Boro. La cella MBE-sputtering non è in grado di depositare B a purezza controllata
3.2	realizzazione di un epistrato di BGaN su SiC ad alta qualità cristallina e alta percentuale di B.	M19	0%	
4	realizzazione e test di un detector a singolo pixel, 1° run	M22	0%	