Universidade de São Paulo
Instituto de Física

"Produção e Caracterização

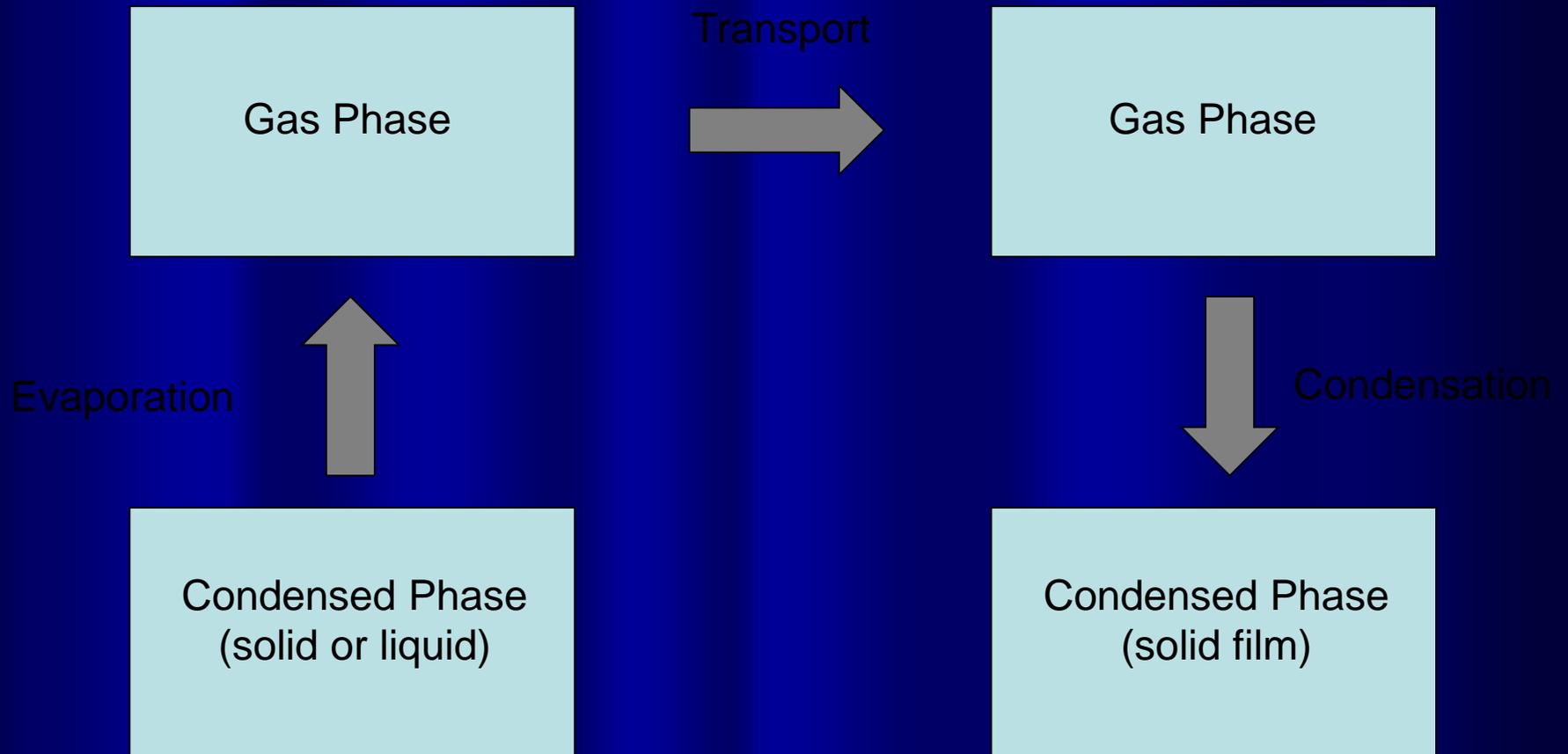# de Filmes Finos"

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Summário

☞ Filmes Finos - processos;
● Processos de formação de filmes finos;
● Óxidos e Nitretos;
● Perspectivas.

Physical Vapor Deposition (PVD).

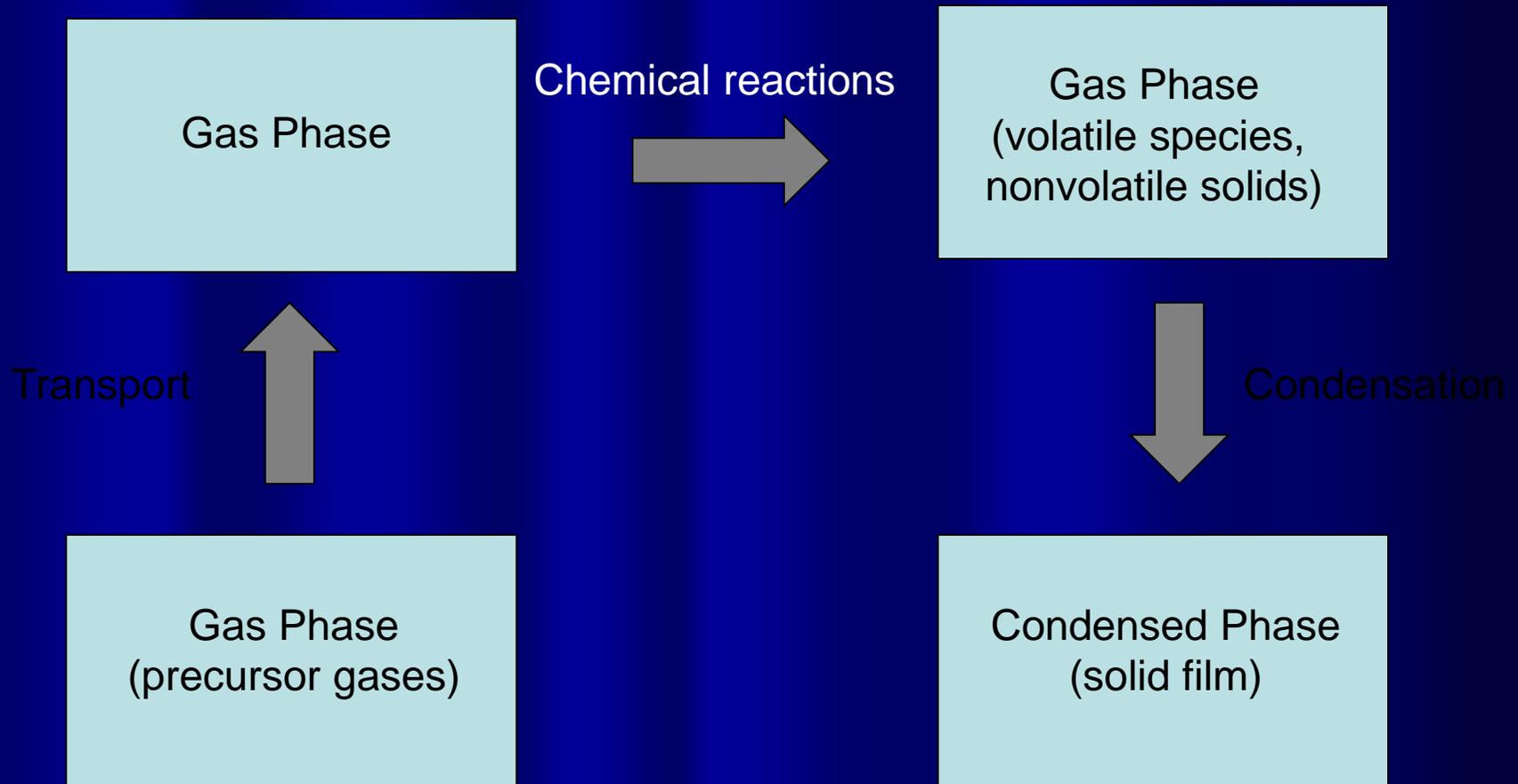Pyrolysis: SiH_4 (g) $\rightarrow$ Si (s) + $2H_2$ (g), 650°C
Reduction: $SiCl_2$ (g) + $2H_2$ (g) $\rightarrow$ Si (s) + 4HCl (g), 1200°C
Oxidation: SiH_4 (g) + O_2 (g) $\rightarrow$ SiO_2 (s) + $2H_2$ (g), 450°C

Carbide: $SiCl_4$ (g) + CH_4 (g) $\rightarrow$ SiC (s) + 4HCl (g), 1400°C
Nitride: BF_3 (g) + NH_3 (g) $\rightarrow$ BN (s) + 3HF (g), 1100°C

Gas Phase

Chemical reactions

Gas Phase
(volatile species,
nonvolatile solids)

Transport

Condensation

Gas Phase
(precursor gases)

Condensed Phase
(solid film)

Chemical Vapor Deposition (CVD).

PVD
- Evaporation
- Sputtering
  - DC
  - Radiofrequency (RF)
  - Magnetron
  - Ion beam
- Hybrid or modified Processes
  - Reactive evaporation
  - Ion Plating
  - Ionized Cluster Beam
  - Ion Beam Assisted Deposition (IBAD)

CVD
- Thermal excitation
- Optical excitation (Laser): LECVD
- Electromagnetic excitation (ECR, ICP): PECVD

Thin-Film Formation Processes.

Ultra-High Vacuum	High Vacuum	Rough (Low) Vacuum
Surface Analysis	e-beam evaporation	DC, RF, magnetron sputtering
Molecular Beam Epitaxy (MBE)	Ion beam sputtering	Ion plating
	Ion Implantation	Reactive evaporation
		Low-Pressure Chemical Vapor Deposition (LPCVD)

Deposition processes at three vacuum ranges.

Chemical Vapour Deposition (CVD)

- Gaseous compounds react to form a dense layer on a heated substrate. The most widely deposited wear-resistant coatings are TiC, TiN, chromium carbide and alumina. Deposition temperatures are generally in the range 800-1000°C which restricts the range of materials which can be coated and can lead to component distortion. Thicknesses are limited to about $10\mu m$ due to the thermal expansion mismatch stresses which develop on cooling which also restrict the coating of sharp edged components.

- **Advantages**
- High coating hardness
- Good adhesion (if the coating is not too thick)
- Good throwing power (i.e. uniformity of coating)

- **Disadvantages**
- High temperature process (distortion)
- Sharp edge coating is difficult (thermal expansion mismatch stresses)
- Limited range of materials can be coated
- Environmental concerns about process gases

Physical Vapour Deposition (PVD)

- **Advantages**
- Excellent process control
- Low deposition temperature
- Dense, adherent coatings
- Elemental, alloy and compound coatings possible

- **Disadvantages**
- Vacuum processes with high capital cost
- Limited component size treatable
- Relatively low coating rates
- Poor throwing power without manipulation of components

- **low pressure coating processes in which the coating flux is produced by a physical process. There are two main types:-**

- Evaporation

- Sputtering

- In both cases the source material is a solid (metal or ceramic). A reactive gas may be used in the deposition chamber to deposit compound coatings from an elemental source or maintain the stoichiometry of coatings from compound sources. Typical coating thicknesses range from 1-$10\mu m$ for wear-resistant coatings, though thinner layers are used in microelectronics and thicker layers are used for high temperature corrosion protection of gas turbine components.

Evaporation Processes

The vapour pressure of most materials increases with temperature and if it exceeds the ambient pressure the material will rapidly evaporate into the environment. In a coating chamber the pressure is reduced and the source material heated until a desired vapour flux is maintained which is controlled by the source material, the source temperature and the system pressure.

Heating can be performed in several ways:-

- Resistive heating (e.g. aluminium evaporation from TiB_2 boat)
- Electron beam evaporation (e.g. metals such as tungsten)
- Cathodic arc evaporation (e.g. titanium evaporation for TiN coatings)

The vapour pressures of different metals vary over several orders of magnitude so it is difficult to evaporate alloys and control composition.
As-deposited evaporated coatings are porous due to the limited mobility of coating atoms on component surfaces. This can be controlled by heating or ion plating (see later)
Spatter from localised boiling can lead to droplet formation which affects coating performance

Sputtering Processes

- **Main sputtering processes:-**
- DC diode sputtering (for conducting targets)
- RF sputtering (for insulating targets)

- When energetic ions strike a surface, material is ejected by the transfer of momentum from the ion to the target atoms (akin to billiard ball collisions at the atomic scale). This can be conveniently achieved in a low pressure glow discharge of an inert gas such as argon.

- In such a process the target material is made the cathode and is raised to a potential of several hundred volts. Electrons leaving the cathode stream out into the gas phase where they can impact with argon atoms, ionising them. The positively charged argon is then accelerated to the cathode where it impacts and sputters away material.

- The sputtering yields of different elements for given impact conditions do not vary very much so target alloy compositions can be maintained in the coating except in cases where there are large differences in the atomic weights of alloy constituents.

The coating rate scales with the electrical power used to sustain the discharge. The coating rate also depends on the plasma density, so techniques to increase this (e.g. by confining the electrons close to the target using magnets) will increase the coating rate. However, as much as 95% of the power is dissipated as heat in the target so good cooling is essential.

Ion Implantation

- **Advantages**
- Low temperature process
- Very versatile - every stable element in the periodic table can be implanted into any vacuum compatible target
- Highly controlled
- No distortion - can be applied to finished components
- Not a coating process
- **Disadvantages**
- Line of sight process
- Expensive vacuum equipment needed
- Very thin treated layer

- A vacuum process in which a beam of ions is directed at the surface and injected into it. The ions lose energy in collisions with the target atoms and come to rest in the surface layer of the material with an approximately Gaussian distribution. The ion penetration depth depends on the ion species, ion energy and target material, bur is generally less than $1\mu m$. For steels the main ion used is nitrogen, which hardens the surface by forming nitride precipitates and solid solutions. The damage introduced by the implantation process also introduced a compressive residual stress which improves fatigue performance.

Ion implantation is routinely used for semiconductor doping and treatment of expensive plastics injection moulding tools where any wear is detrimental.

Welding Processes

- **Advantages**
- Cheap
- Applicable to large components
- Localised coating possible
- Excellent adhesion
- **Disadvantages**
- Limited range of coating materials
- Minimum thickness limits

- The same methods which can be used for joining materials can be used to deposit wear resistant coatings (hardfacings). Coating materials range from low alloy steels to tungsten carbide composites.

- High deposition rates are possible and very thick coatings can be produced. It is impractical to produce layers less than 2-3mm thick.

- There can be problems with cracks in weld deposits

Thermal Evaporation in Vacuum: From Source to Substrate

we will first discuss the thermal evaporation parameters, such as vapor pressure, evaporation rates and directionality. This will be followed by a technical description of various types of evaporation sources, both resistively heated and electron beam heated.

We will then discuss how to monitor and control the evaporation processes, with emphasis especially on in-process techniques.

Filaments Boats
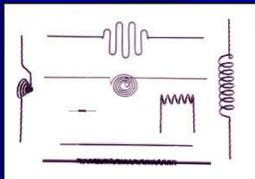
Crucible Heaters

Filaments Boats

$$\vec{F} = -e\vec{v} \times \vec{B}$$

$\vec{B}$

$\vec{F}$

$\vec{v}$ e⁻
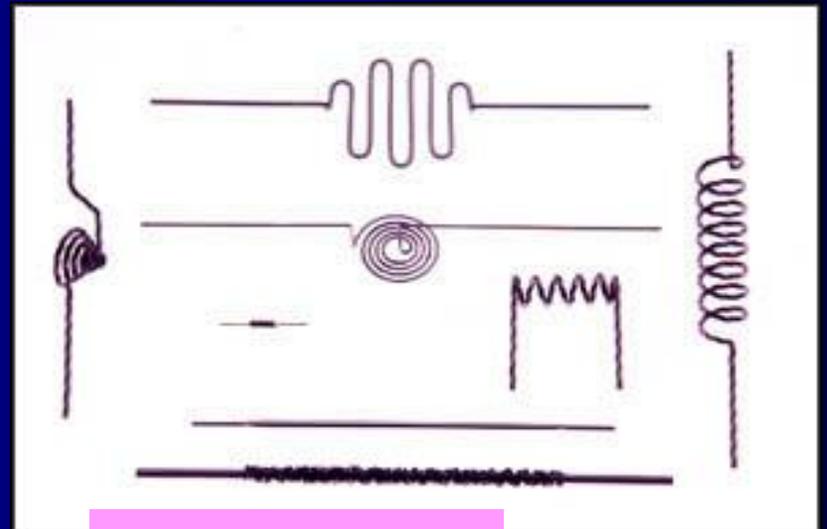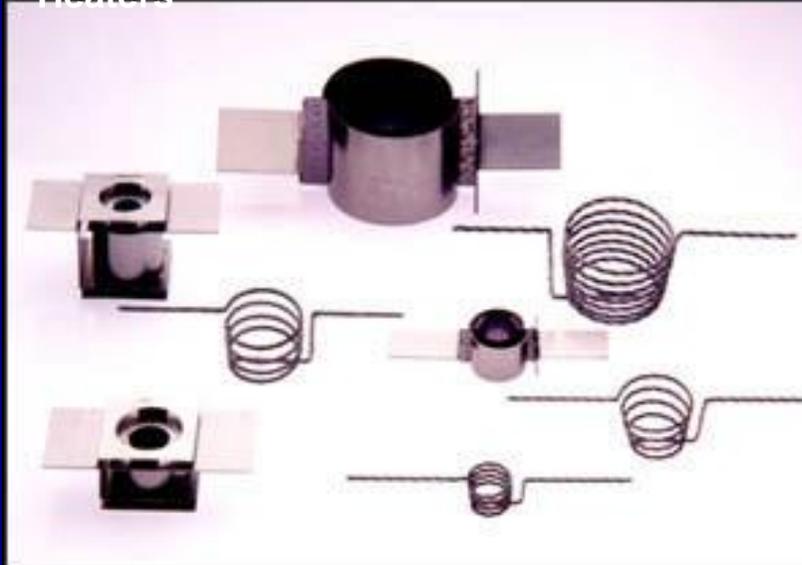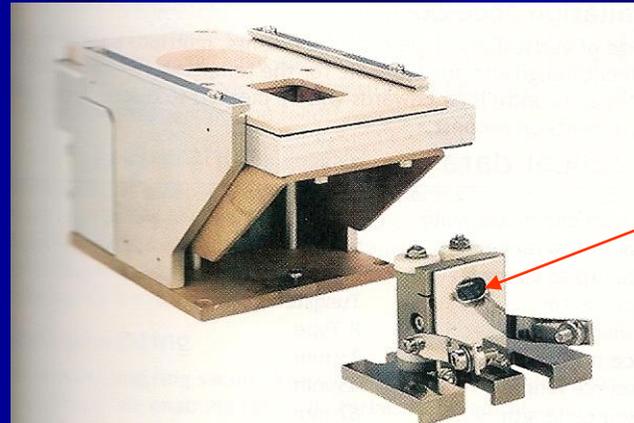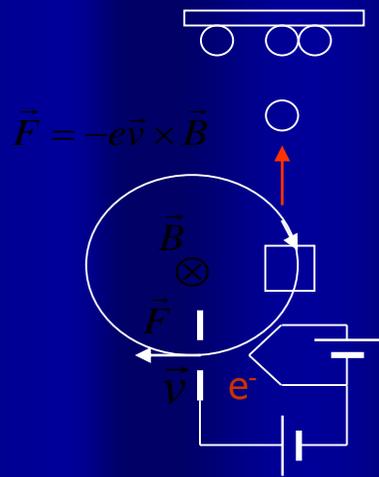
Filament (cathode)
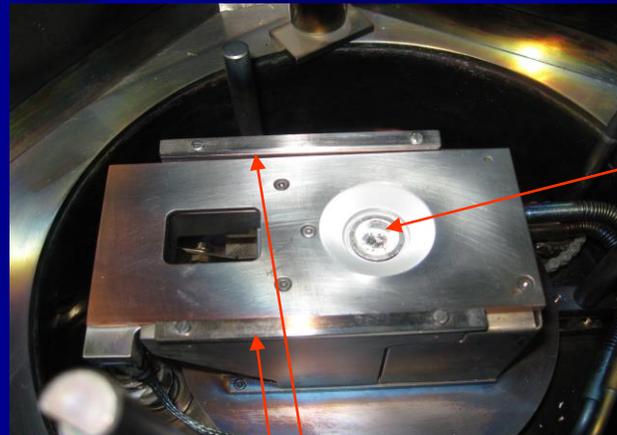
Crucible

Magnet

Electron-beam evaporator.

Deposited material

Front   Front (used)   Back

Quartz oscillators
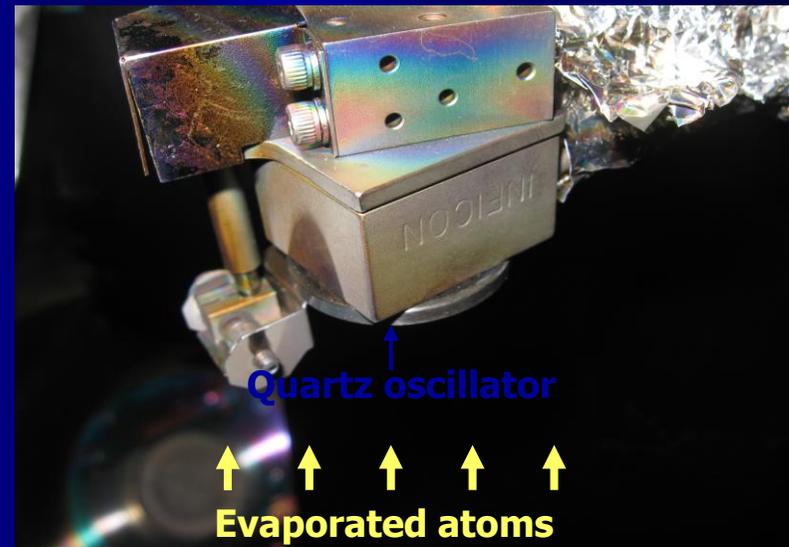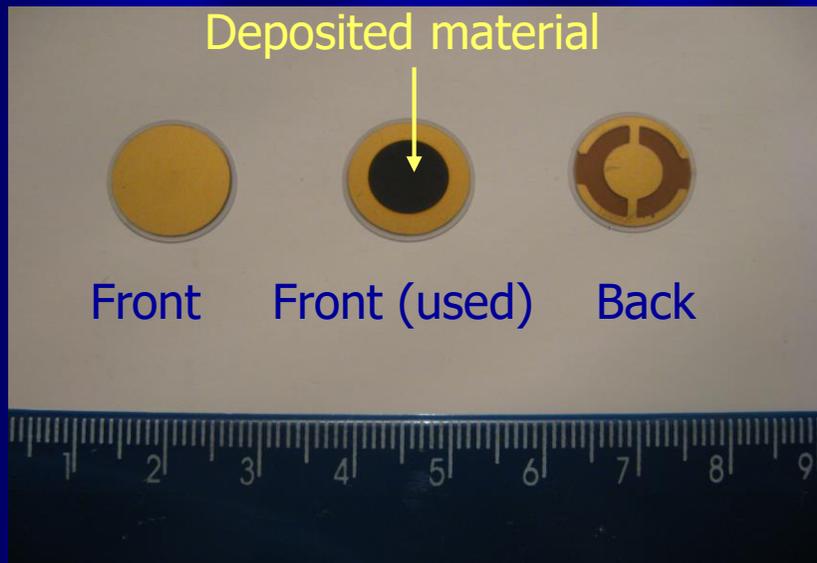
Quartz oscillator

Evaporated atoms

Monitor head
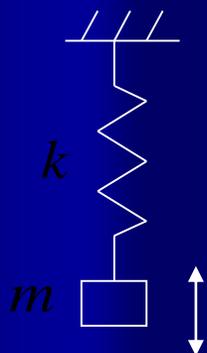
$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

k

m

Quartz deposition rate monitor.

What physics is in all this ?

- thermodynamics and kinetics
  - phase transition - gas condenses to solid
  - nucleation
  - growth kinetics
  - activated processes
    - desorption
    - diffusion
  - allowed processes and allowed phases
- solid state physics
  - crystallography
  - defects
  - bonding
- electricity and magnetism
  - optics
  - conductivity - resistivity
  - magnetic properties
- mechanics
  - stresses in films
  - friction and wear

IBAD Method
Ion Beam Assisted Deposition

Substrate

Intermixed Layer

New Material

In
Evaporated Atoms

N$^+$
Ions Accelerated
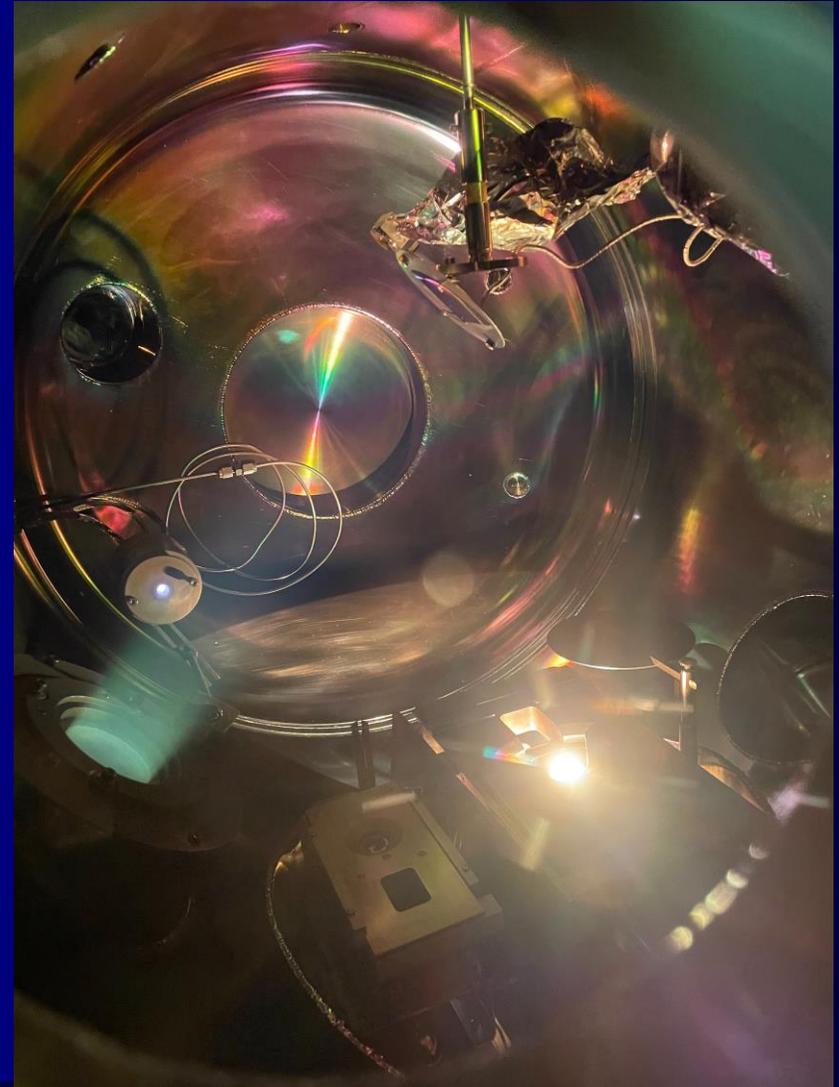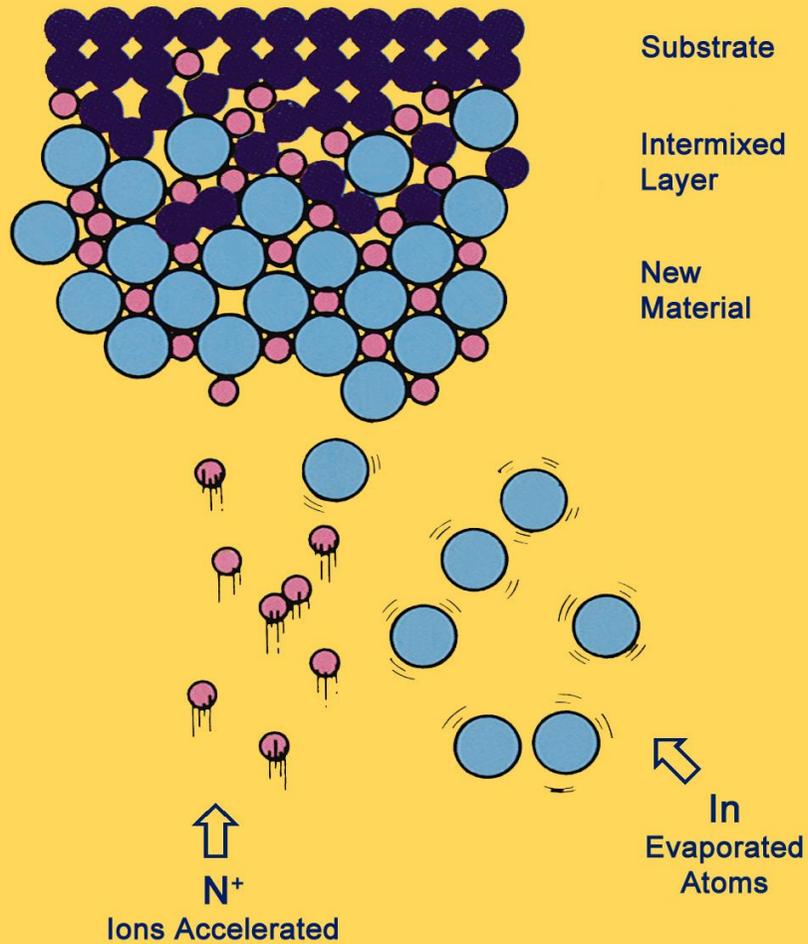
Atomic Layer-by-Layer Growth
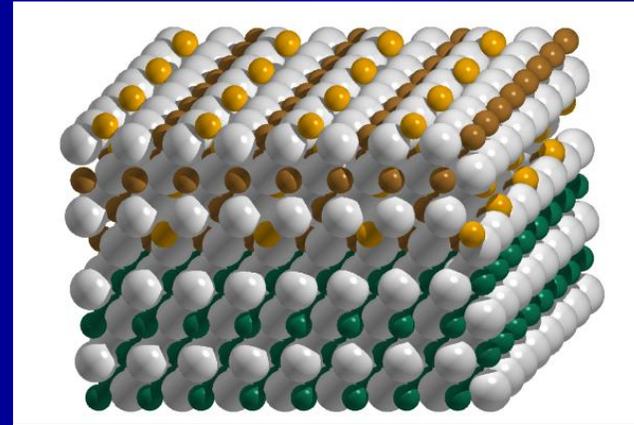
Ultimate goal:

Epitaxial growth of perfect thin layers with atomic precision onto (selected parts of) *a single crystalline substrate, in order to manipulate materials properties* (or to design ultrathin devices).

IBAD system: Details

Cathode
Grids

Neutralizer
filament

← 5 cm →
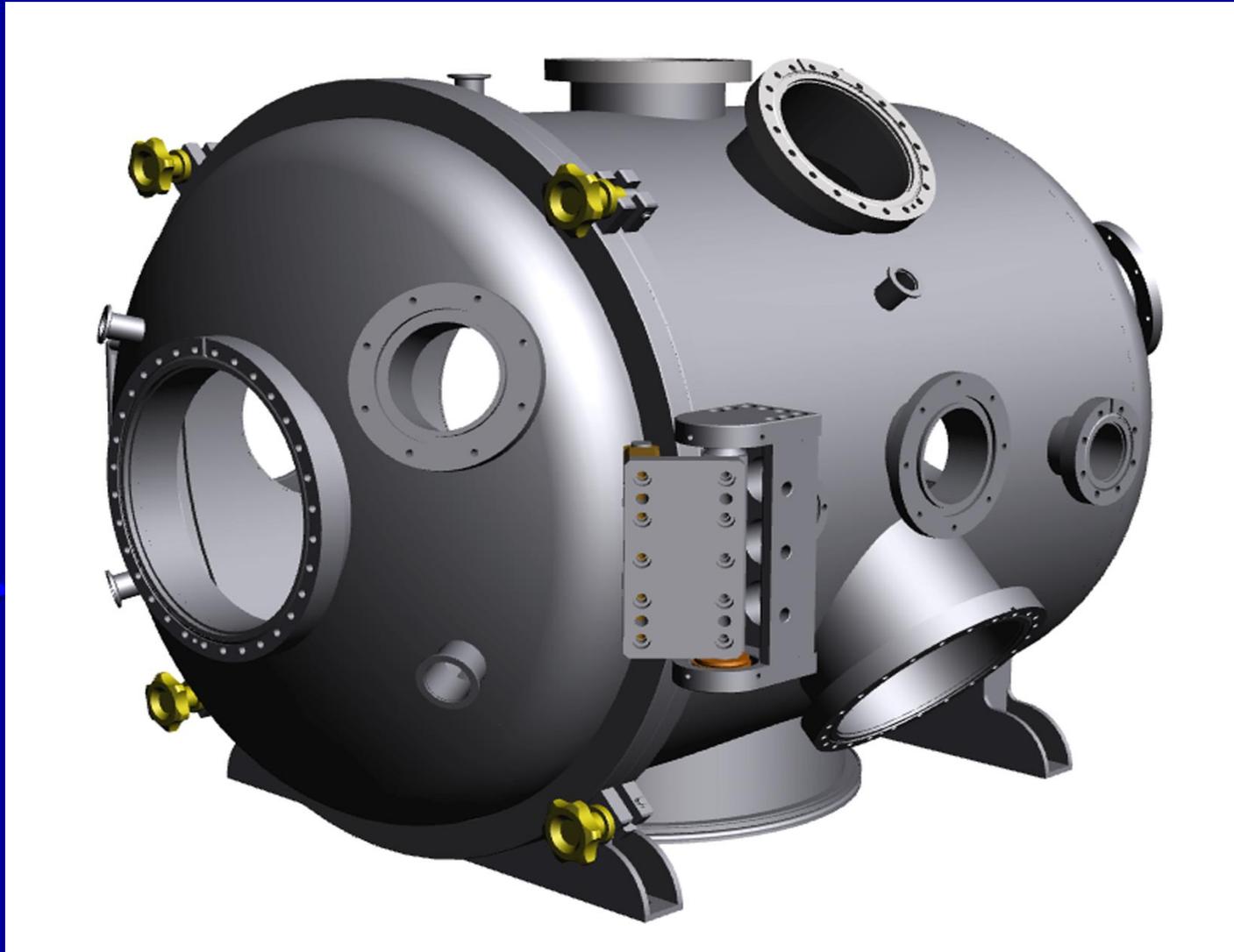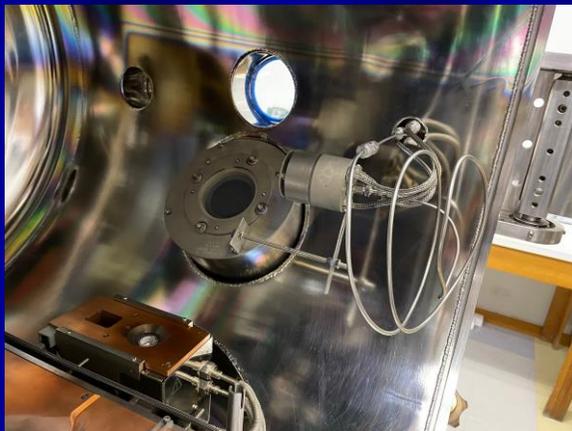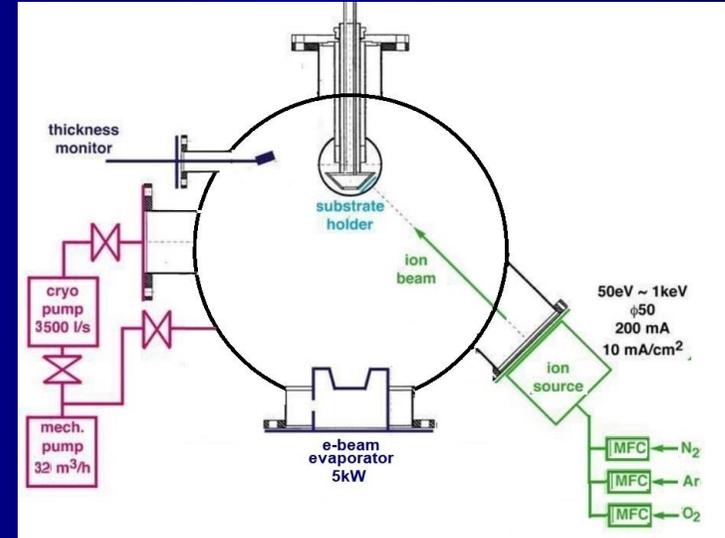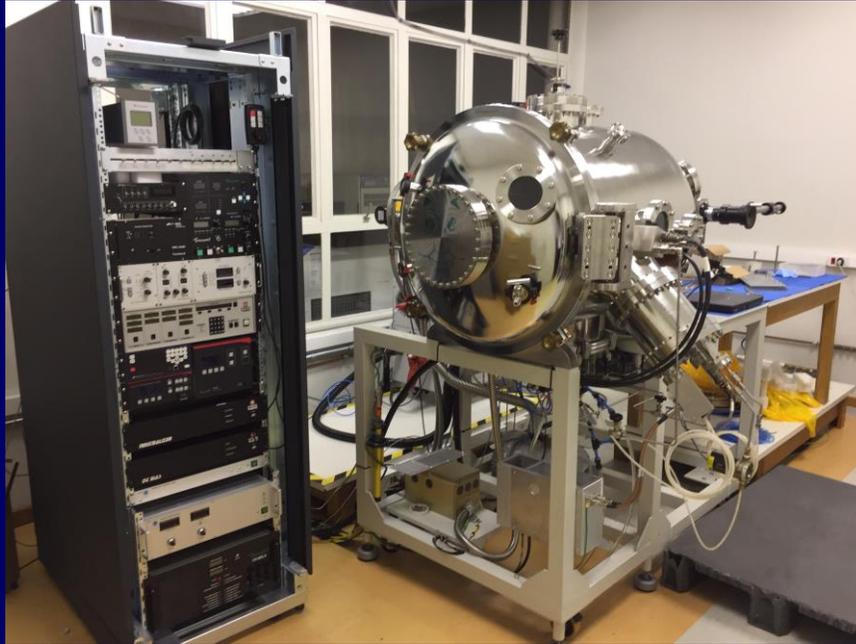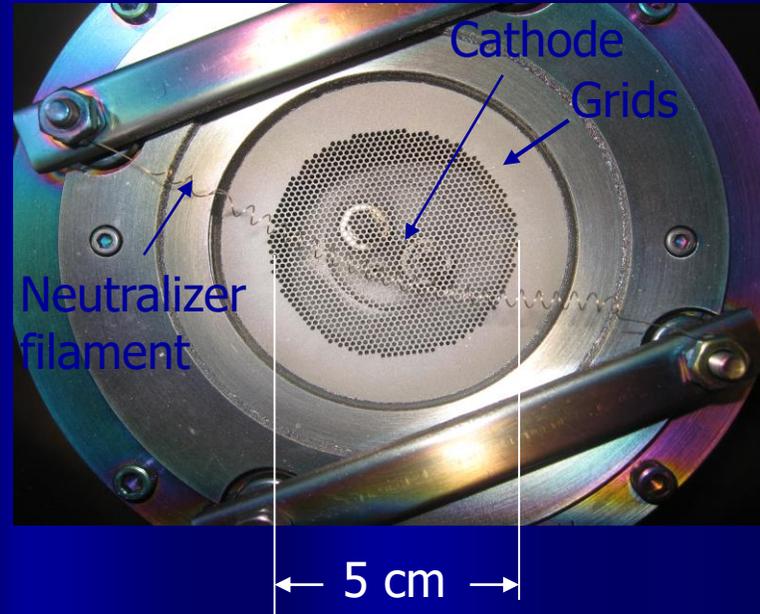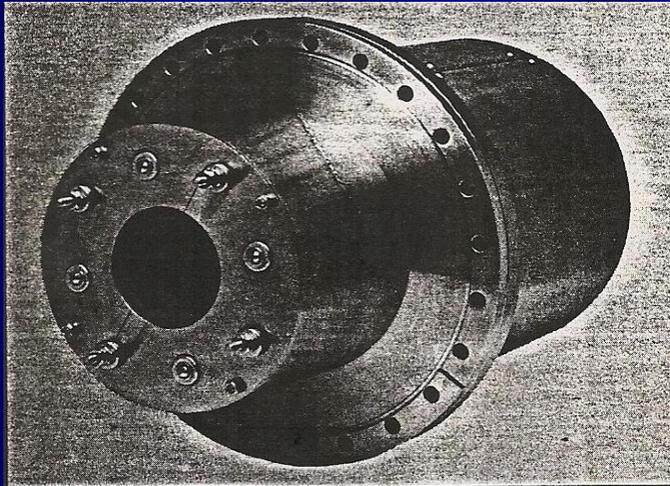
Front view

Fig. 3.5. Ion beam source.

HAYABUSA

26 August 2011 | $10

Science

HAYABUSA
Dust from Itokawa

AAAS

低利得アンテナ
Low-Gain Antenna

高利得アンテナ
High-gain Antenna

サンセンサ
Sun-Sensor

イオンスラスタ
Ion Thruster

サンプル採集装置
Sampler

© JAXA
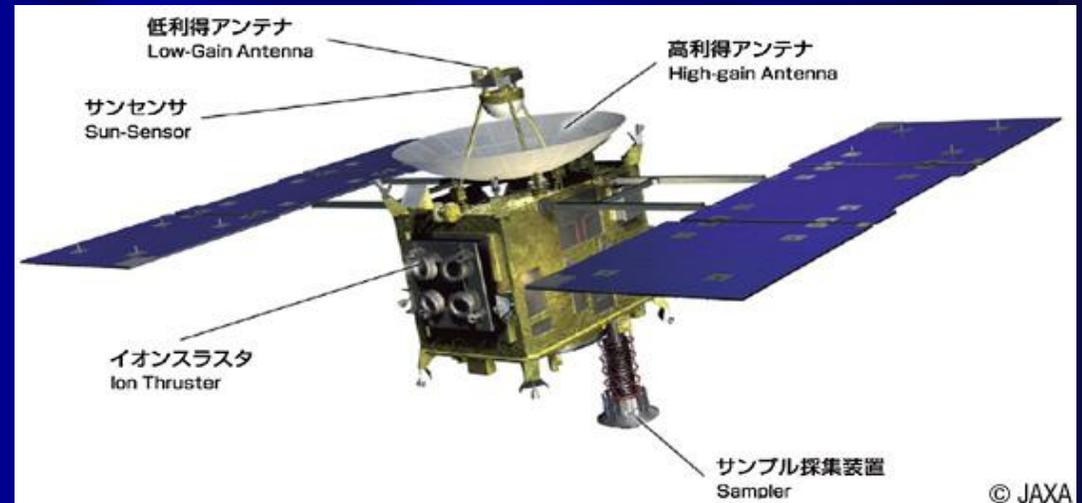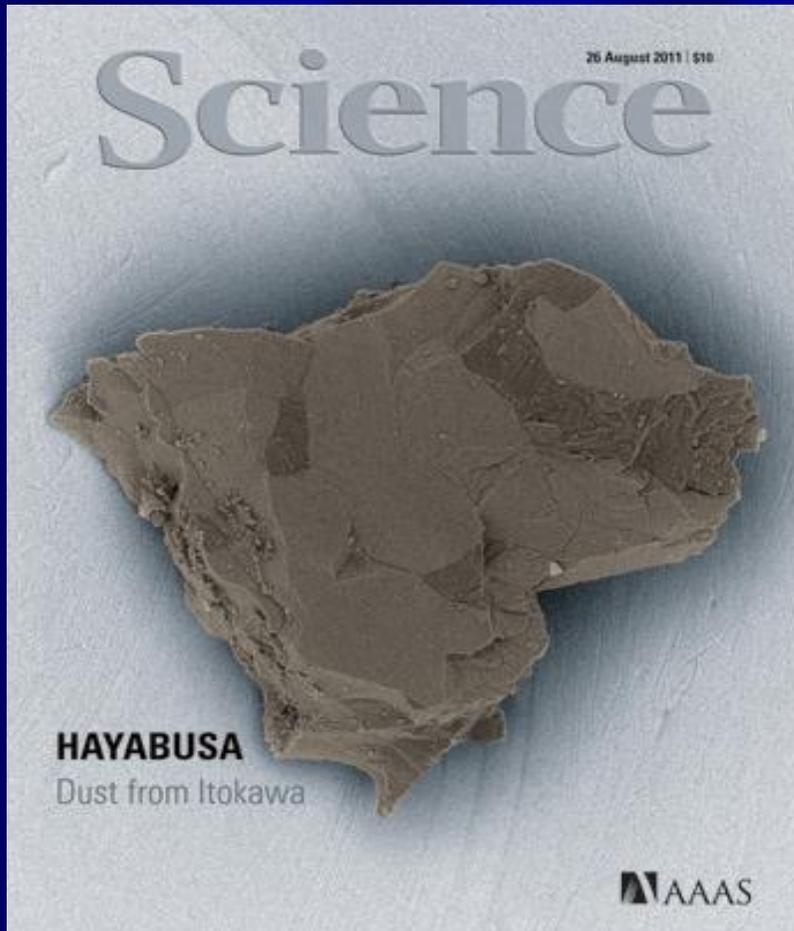
Itokawa
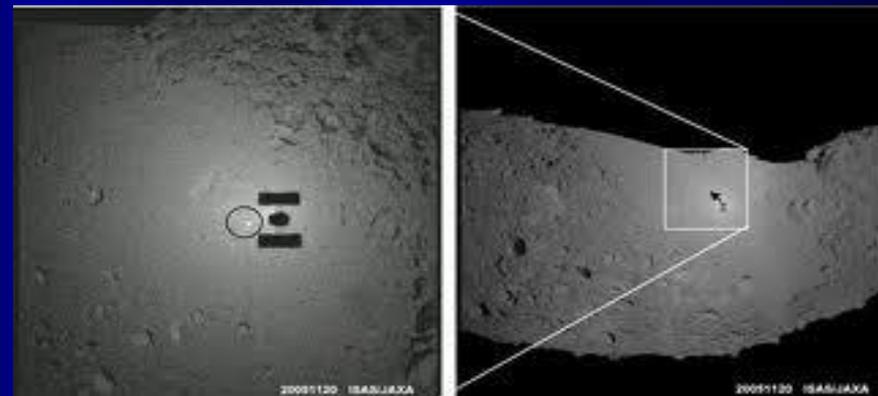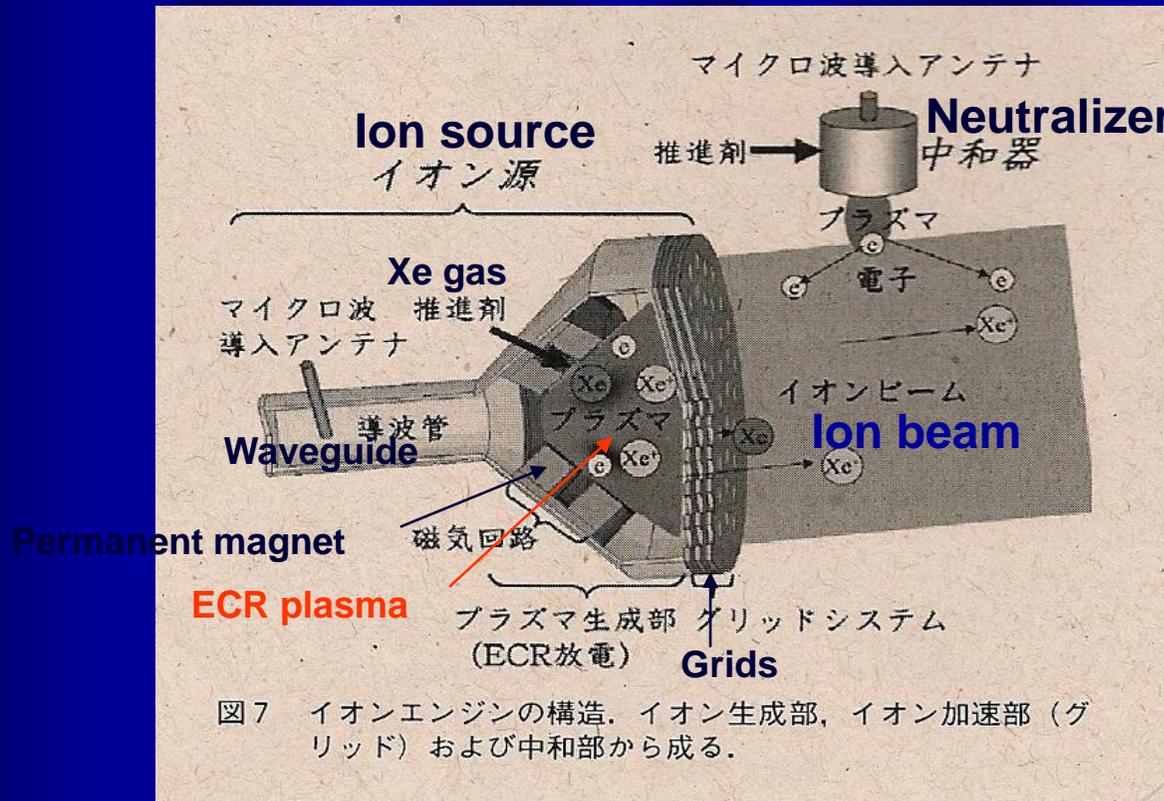
Total weight = 510 kg
Weight of LXe = 66 kg
E = 1.5 keV
F = 4.2 GHz
B = 0.15 T

$F = \Delta p / \Delta t$
$E = p^2 / m$
Rare gases:
He, Ne, Ar, Kr, Xe, Rn, Ku

Ion engine of the asteroid explorer HAYABUSA.
From: J. Plasma Fusion Res. **86**, 282 (2010).

Analysis Systems

**Spectrophotometer
Cary 7000**

**Spectrofluorimeter
Horiba Fluorolog 3**

**EPR Spectrometer MiniScope
MS5000 – Magnettec -
Freiberg**

OBJETIVOS

- **Deposição e caracterização de óxidos com alta constante dieléctrica, tais como HfO_2, Al_2O_3, Ga_2O_3, GaGdO sobre diferentes substratos por deposição assistida por feixe de íons (IBAD);**

- **Fabricar filmes até espessura de 500 nm de ferroeléctricos como $Ba_xSr_{1-x}TiO_3$;**

- **Otimizar a deposição de filmes finos para deposição de camadas com alta qualidade para a fabricação de dispositivos.**

Materials, Deposition Conditions & Analysis Methods

- Al 99.99% ingots
- O_2 99.999%
- Substrates:
  - Si(100)
  - A-plane sapphire
  - C-plane sapphire
  - R-plane sapphire
  - GaN/A-plane sapphire
- Ion beam energy:
  - 100 eV
- Film thickness (Al):
  - 500 Angstrom
- Arrival rate ratio ARR(O/Al):
  - 0.8 and 5.5
- Substrate temperature:
  - Room Temp. (R.T.), 100, 200, 300, and 450ºC

- SEM   (JEOL,2010)
- Surface Profilometer
    (Slon, Dektak 3030)
- XRD   (Rigaku, Rint 2100)
- XPS   (Kratos, XSAM HS,
        $h\nu$= 1486.6 eV)
- Raman (Renishaw,
        Raman 2000)

Al$_2$O$_3$ films
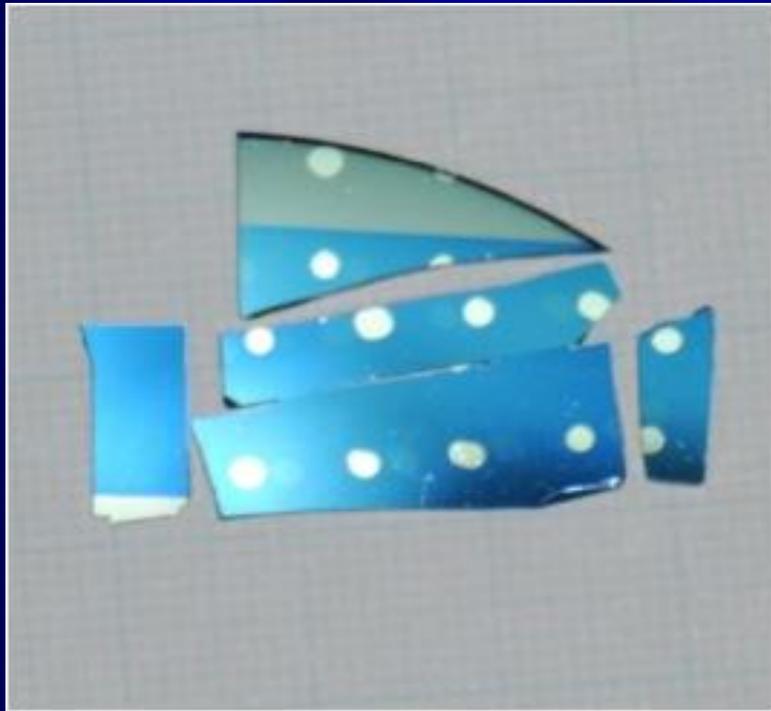
Al$_2$O$_3$ film produced with 300 eV ion beam energy and 100 nm of thickness on Si(100).
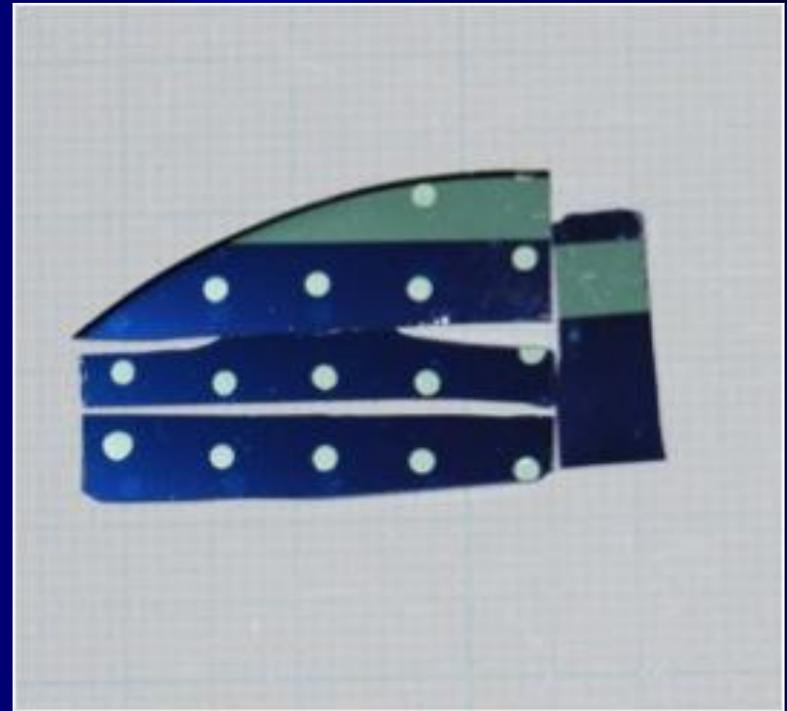
Al$_2$O$_3$ film produced with 800 eV ion beam energy and 100 nm of thickness on Si(100).

Optical Absorption %R
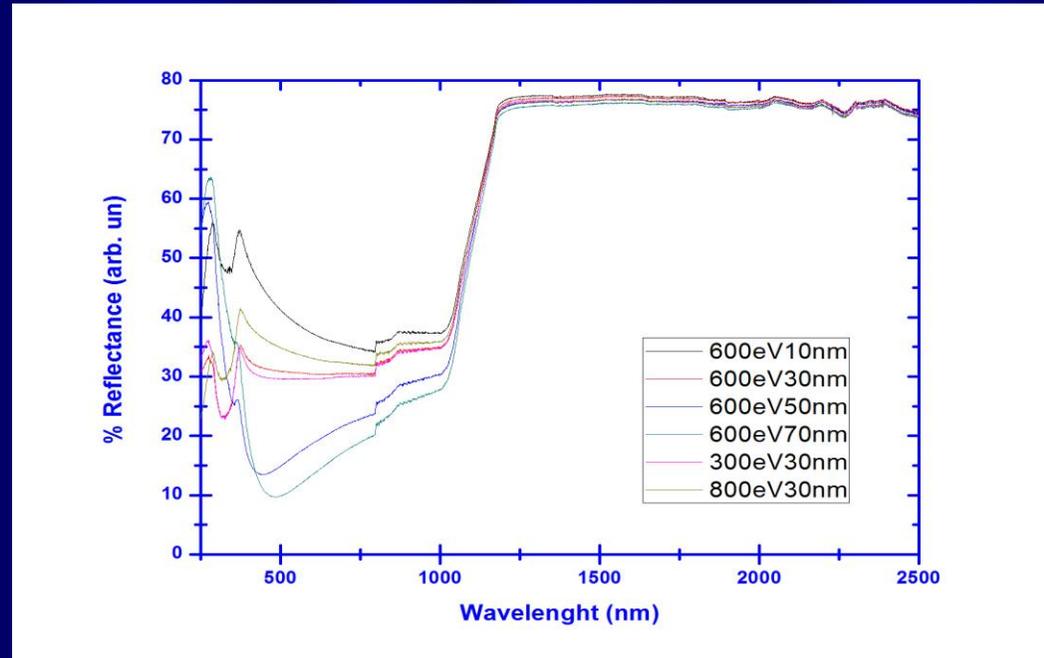
Figure 3: %R spectra from the aluminum oxide film prepared on silicon substrate at an ion beam energy of 800 eV.

%Reflectance
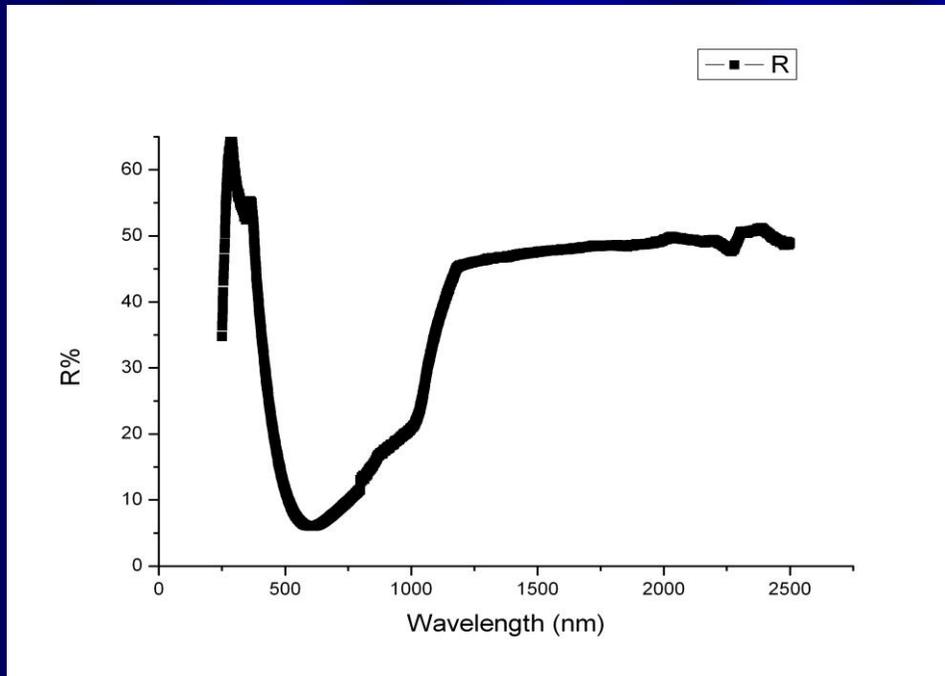
Figure 1: %R spectra from the aluminum oxide film prepared on silicon substrate at an ion beam energy of 300 eV.
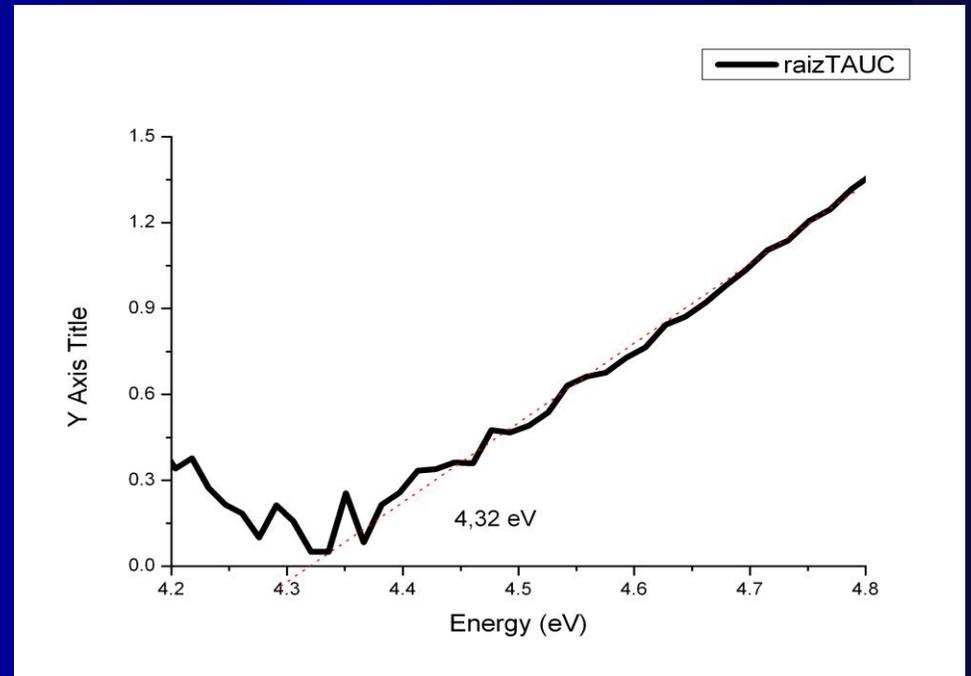
Figure 2: %R spectra from the aluminum oxide film prepared on silicon substrate at an ion beam energy of 300 eV. The X and Y data was converted into energy and Tauc equation to estimate the optical band gap.

%Reflectance
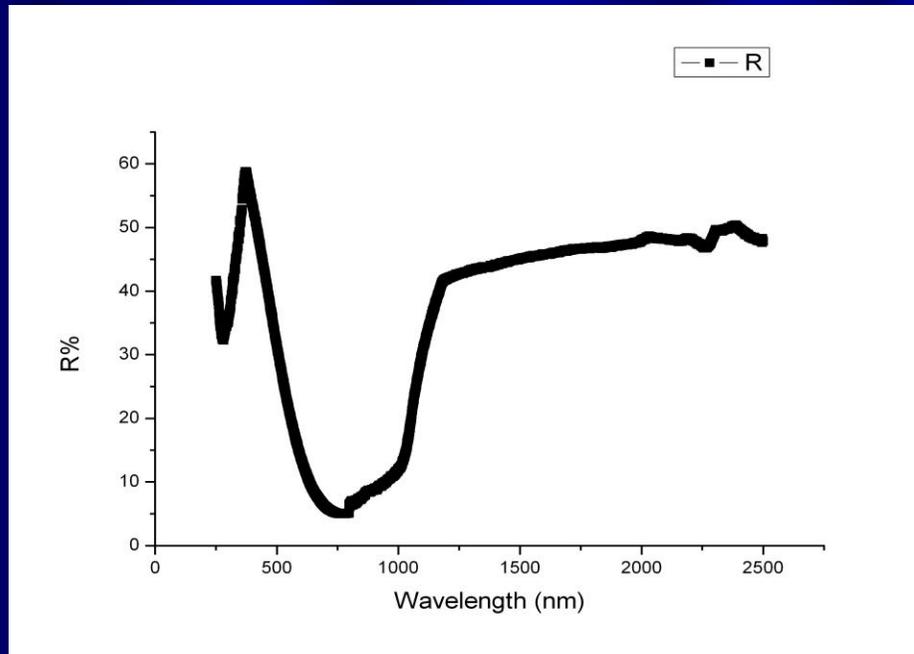
Figure 3: %R spectra from the aluminum oxide film prepared on silicon substrate at an ion beam energy of 800 eV.
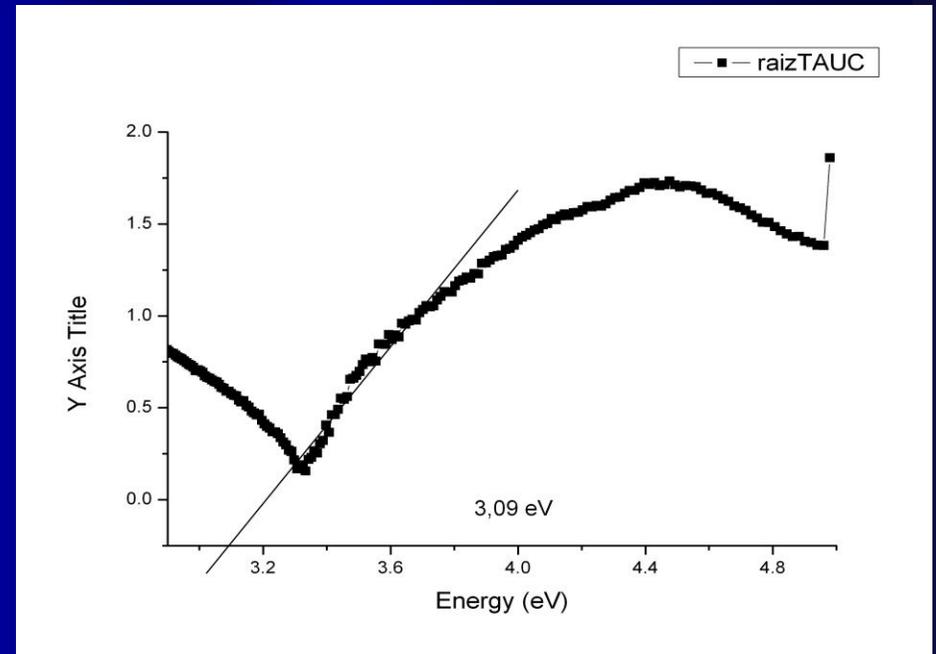
Figure 4: %R spectra from the aluminum oxide film prepared on silicon substrate at an ion beam energy of 800 eV. The X and Y data was converted into energy and Tauc equation to estimate the optical band gap.

Optical Absorption
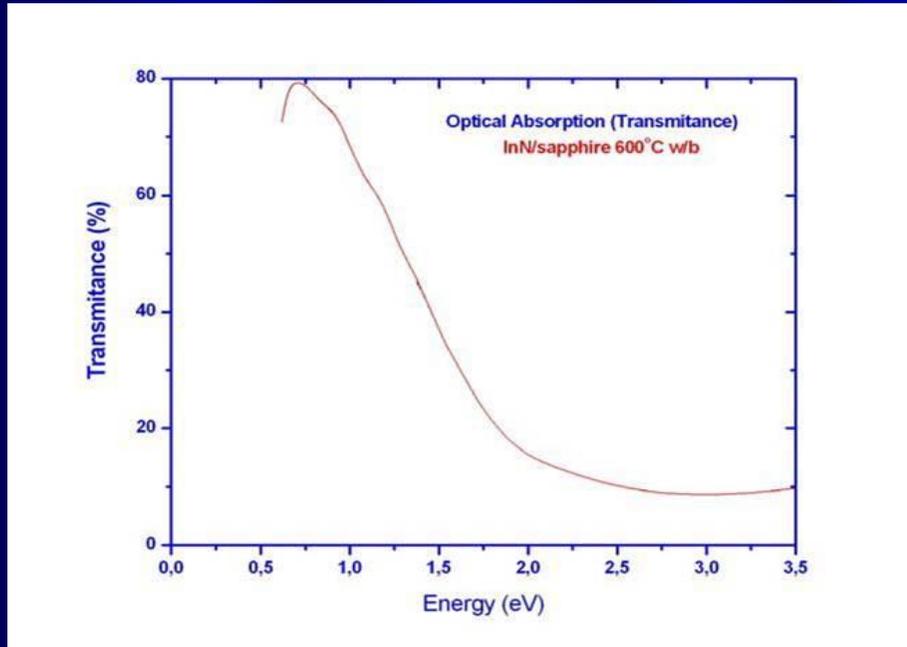
Transmission spectrum of InN/sapphire film produced at 600ºC, E = 0.8 keV and ARR(N/In) = 5.3
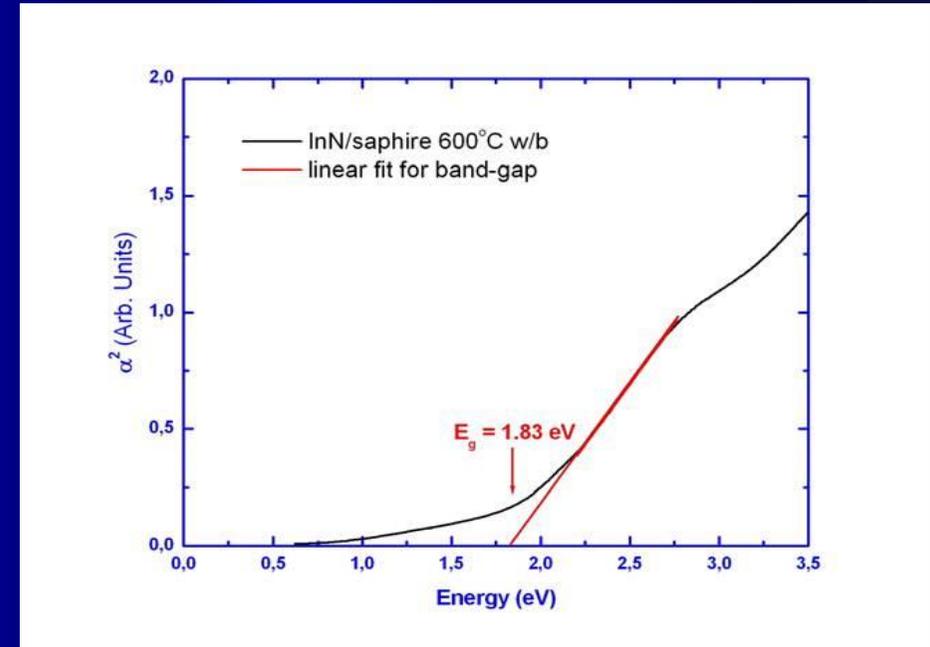
Band-gap determination of InN/sapphire film produced at 600ºC, E = 0.8 keV and ARR(N/In) = 5.3. Assuming that InN has a direct transition, $\alpha^2 = b(E - E_g)$.

CxV
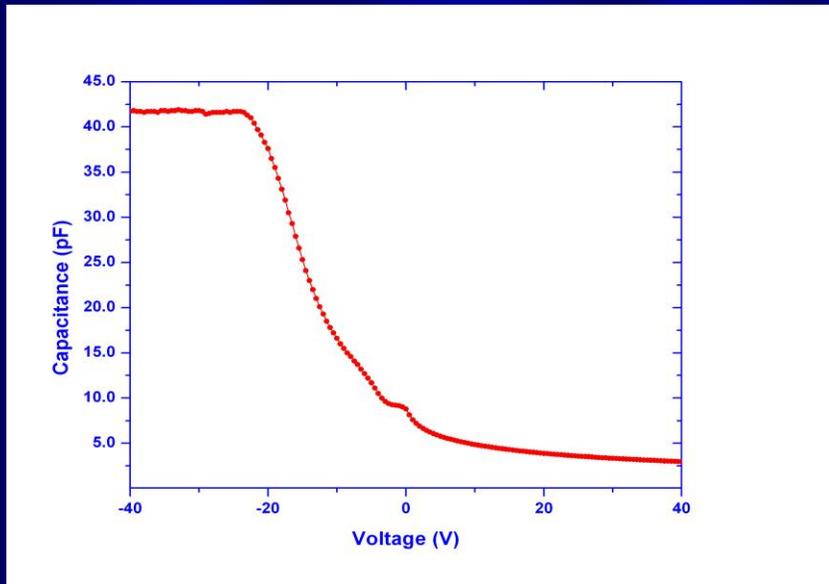
Figure 5: CxV measurement of the aluminum oxide film prepared on silicon substrate at an ion beam energy of 300 eV.
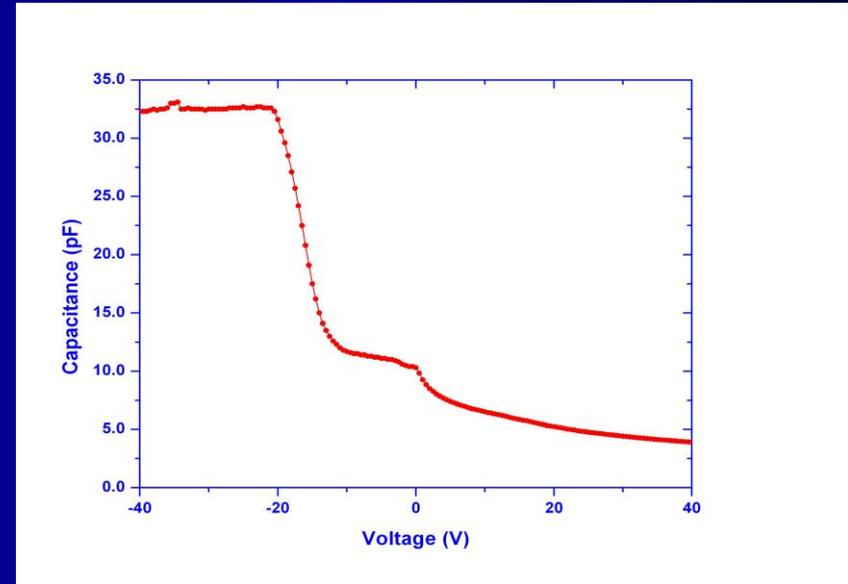
Figure 6: CxV measurement of the aluminum oxide film prepared on silicon substrate at an ion beam energy of 800 eV.

Al$_2$O$_3$ - XPS Composition Ratio O/Al = 1.87
Al$_2$O$_3$ - RBS Composition Ratio O/Al = 1.85

HfO$_2$ — RBS data under analysis
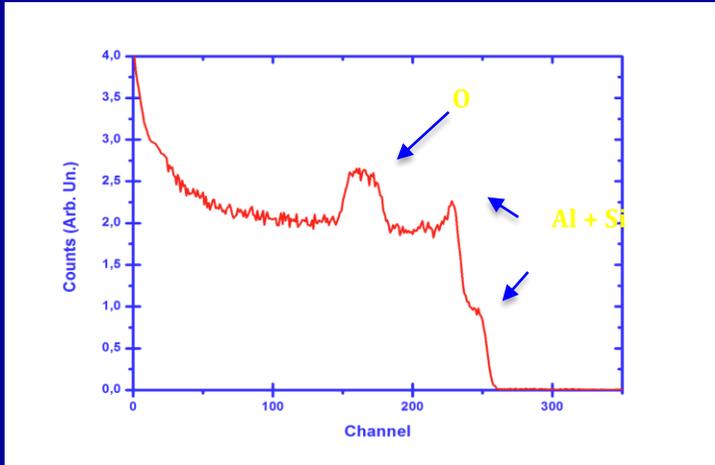
RBS Spectra of Al$_2$O$_3$
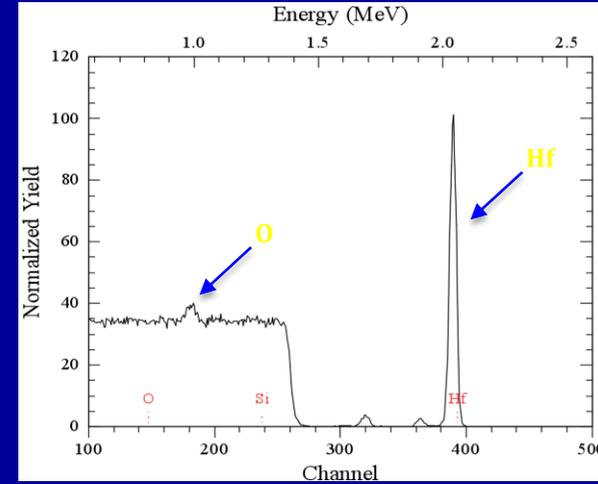
RBS Spectra of HfO$_2$
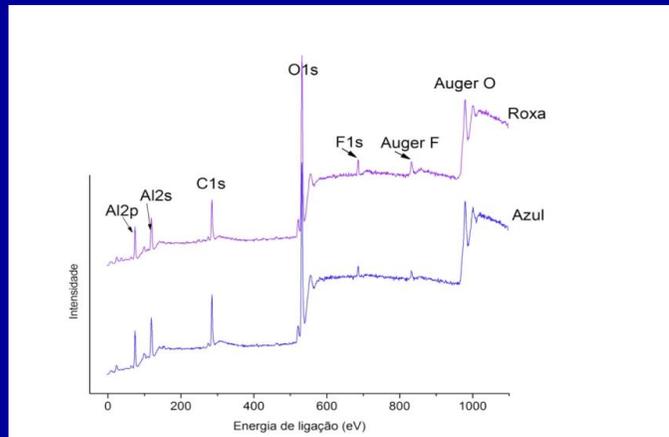
XPS Spectra of Al$_2$O$_3$

SEM Images – sample prepared at 300 eV

| 7/29/2010 | curr | HV | mag | WD | | 1 μm |
| 9:32:18 AM | 71 pA | 3.00 kV | 50 000 x | 10.3 mm | LSI by Adir Jose Moreira | |

| 7/29/2010 | curr | HV | mag | WD | | 500 nm |
| 9:47:10 AM | 0.57 nA | 10.0 kV | 80 000 x | 4.8 mm | LSI by Adir Jose Moreira | |
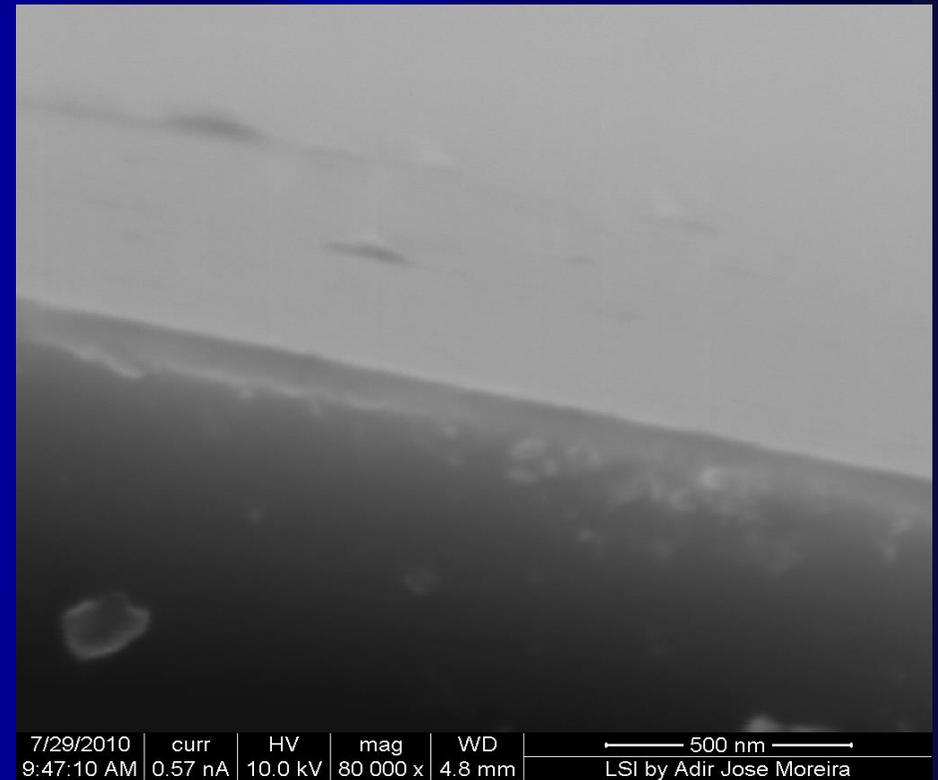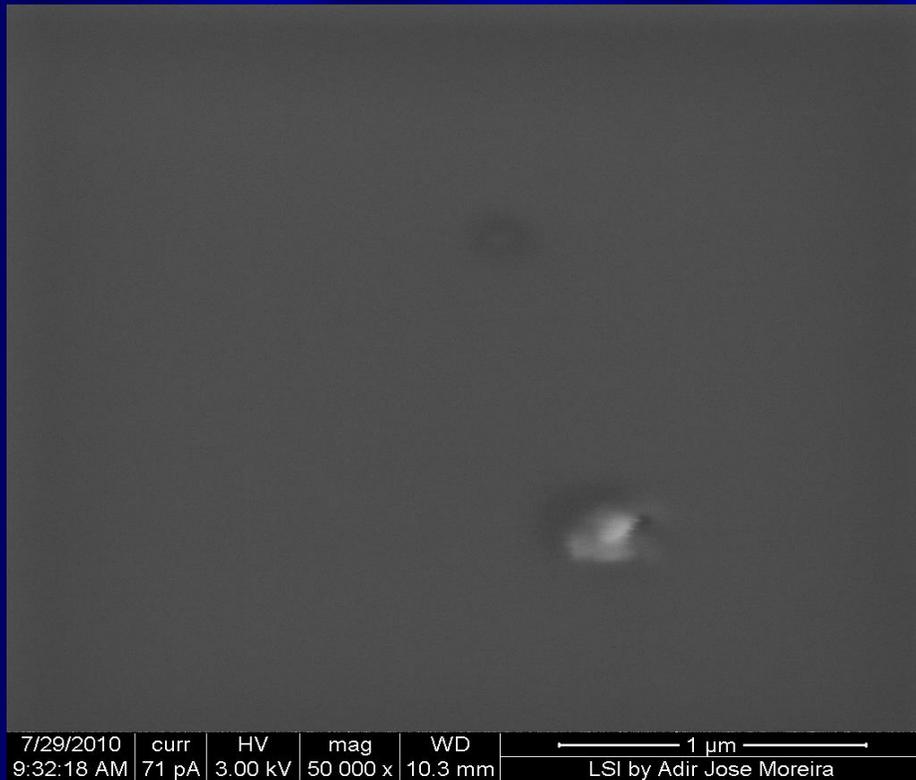
SEM –sample prepared at 800 V

118.0nm

7/29/2010	curr	HV	mag	WD		300 nm
10:49:42 AM	0.74 nA	30.0 kV	200 000 x	2.4 mm		LSI by Adir Jose Moreira

7/29/2010	curr	HV	mag	WD		500 nm
10:52:19 AM	0.74 nA	30.0 kV	100 000 x	2.4 mm		LSI by Adir Jose Moreira
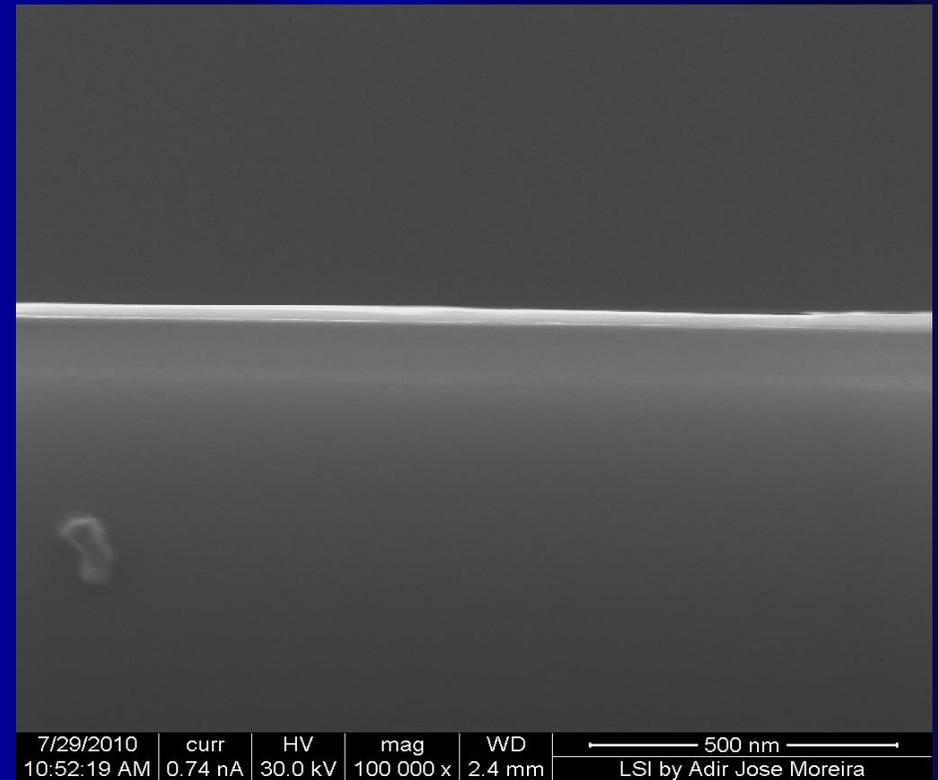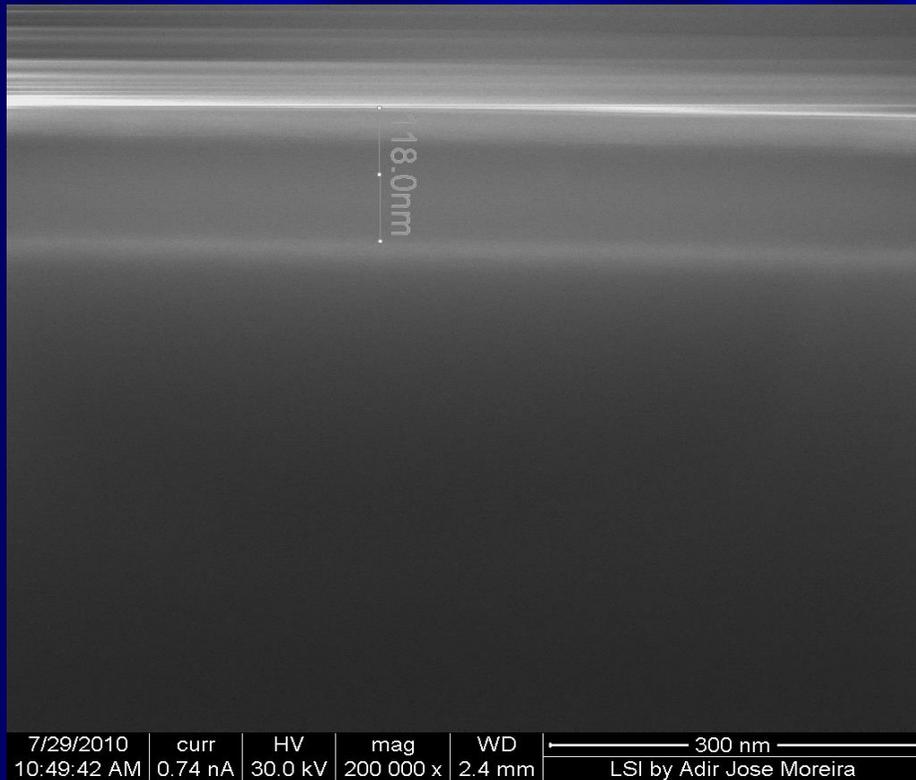
Cross–sectional SEM Microphotograph

Etch pits
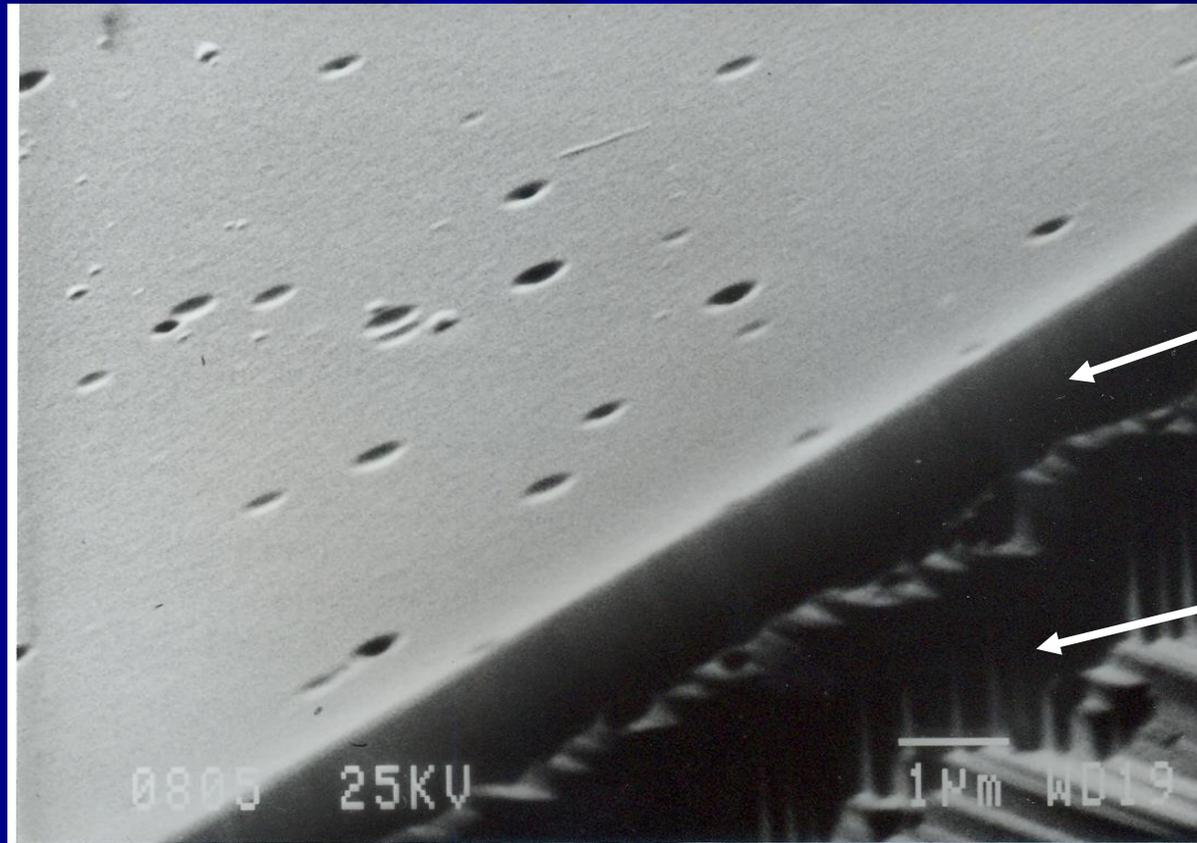
GaN

Sapphire

GaN/A-plane sapphire - 500 eV

SEM Microphotographs

Glass - R.T.
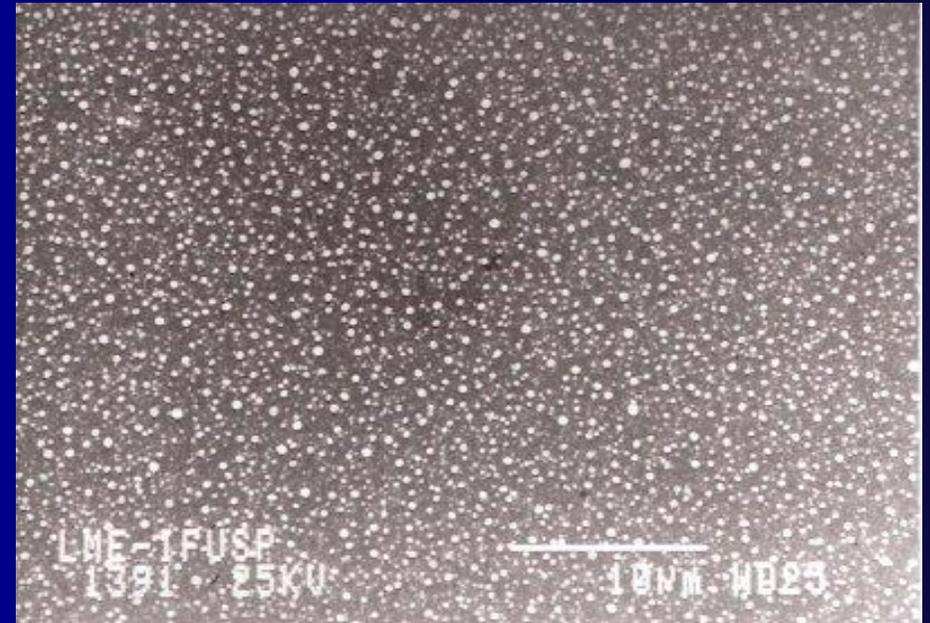
In droplets

Glass - 200ºC

SEM images
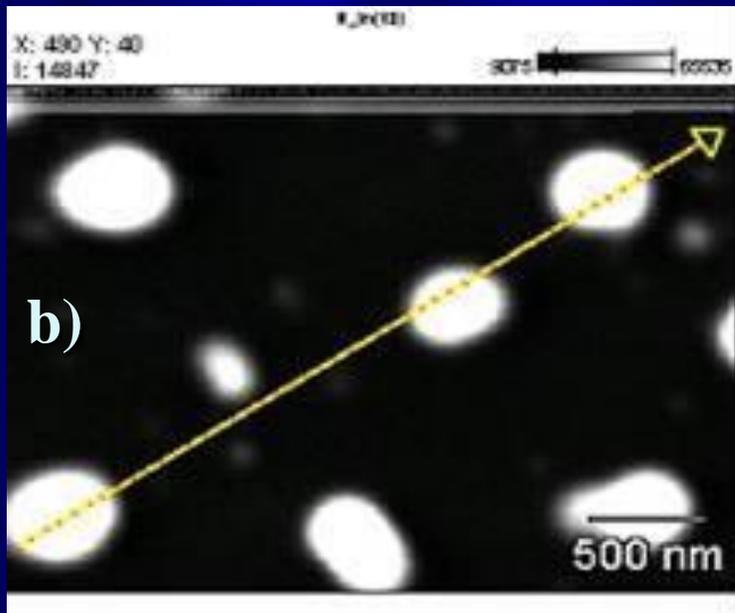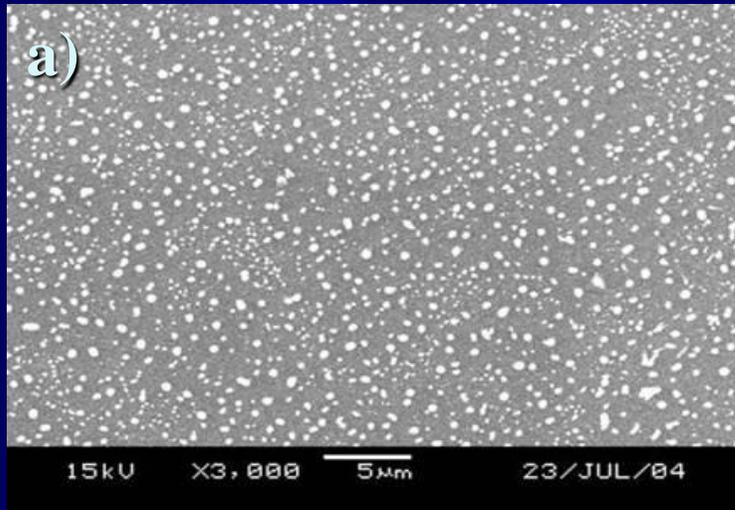
a) SEM micrography of an InN/Si(111) film produced at E = 0.8 keV, ARR(N/In) = 5.3, T = 520°C with a magnification of 3000x.

b) SEM micrography of the same film with a magnification of 35000x.

c) X-ray elemental profile through the line marked on figure b).

XRD

GaN/A-plane sapphire
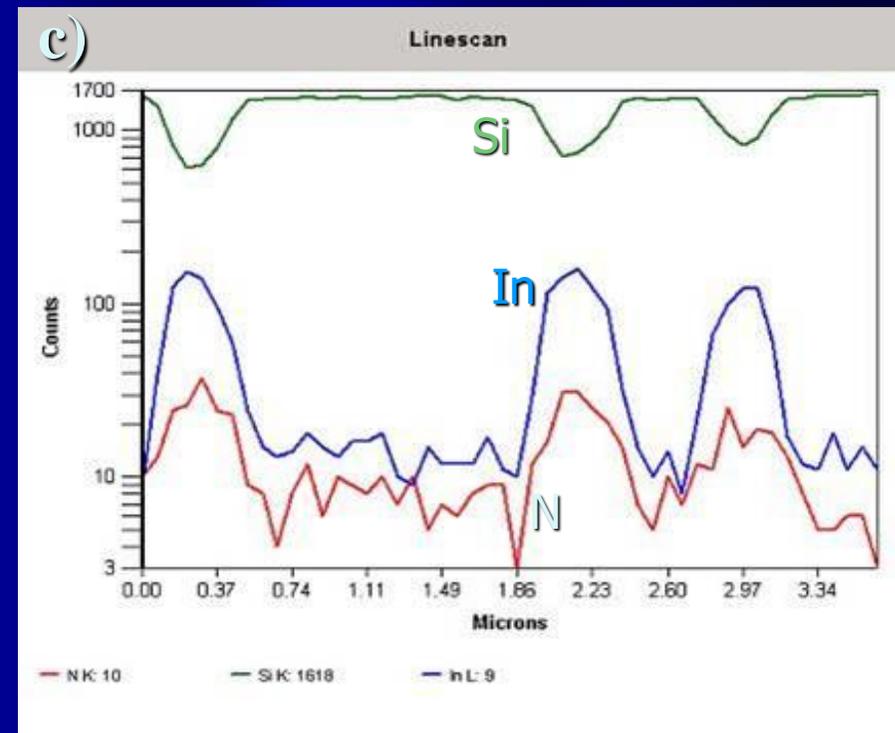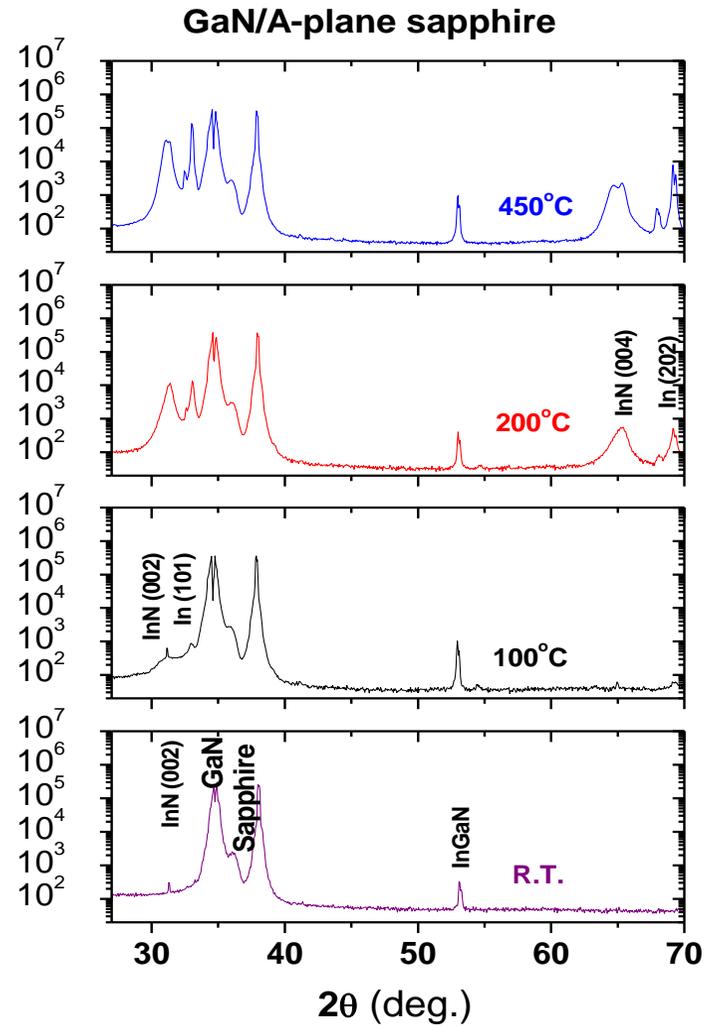
XRD
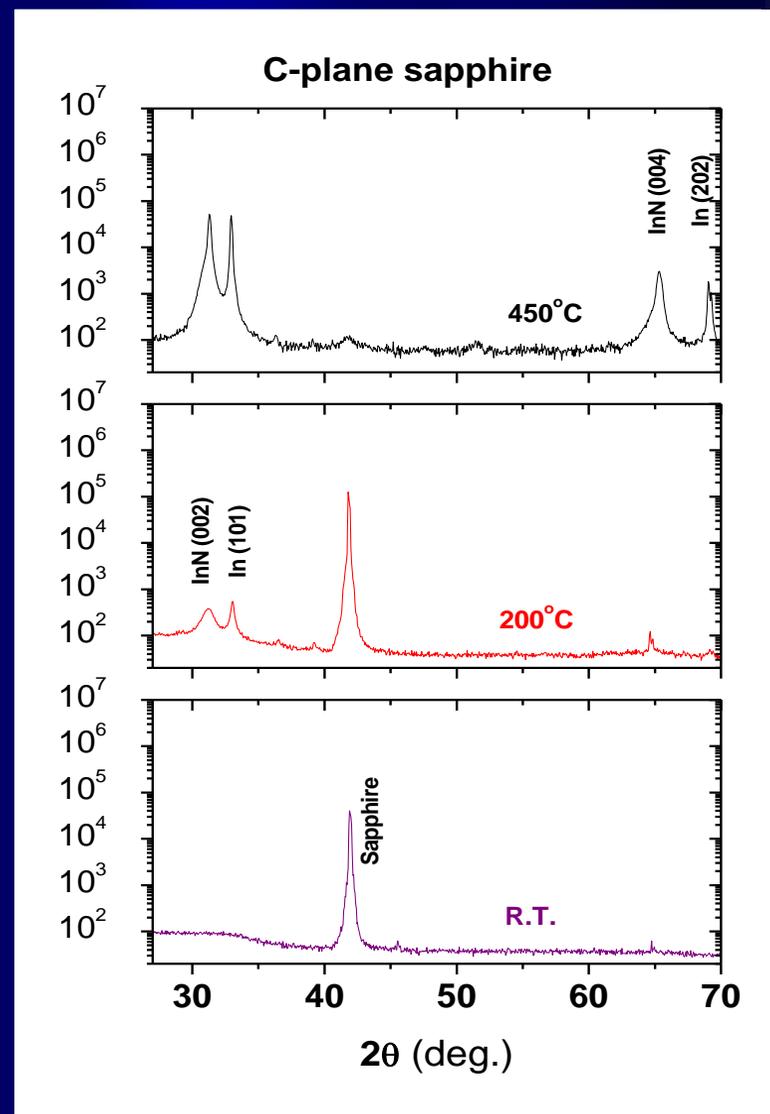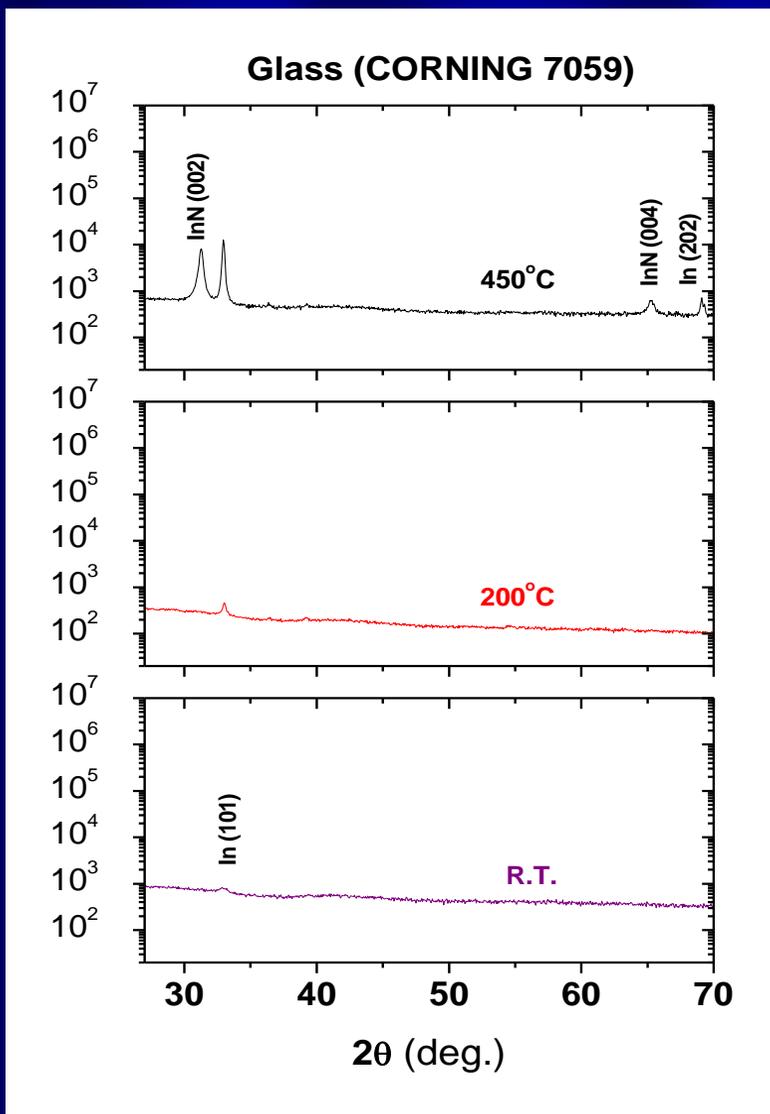
XRD
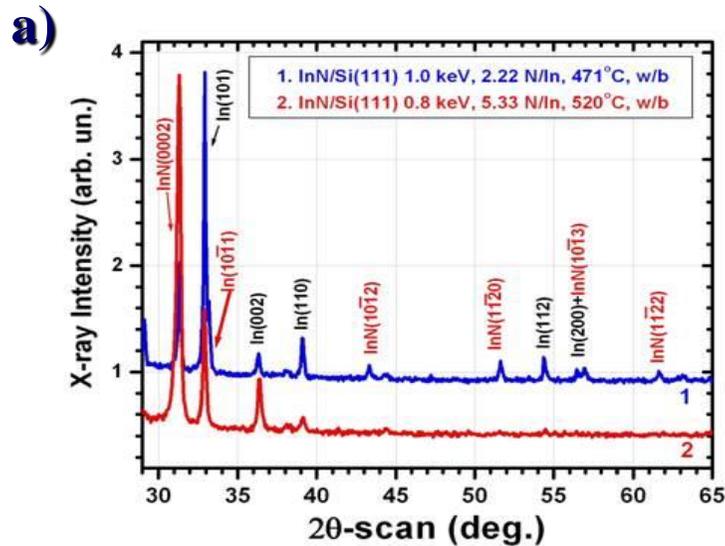
a) XRD patterns of InN/Si(111) without any buffer layer.

b) XRD pattern of InN/Si(111) with a buffer layer.

c) Dependence of the XRD pattern on temperature and substrate.
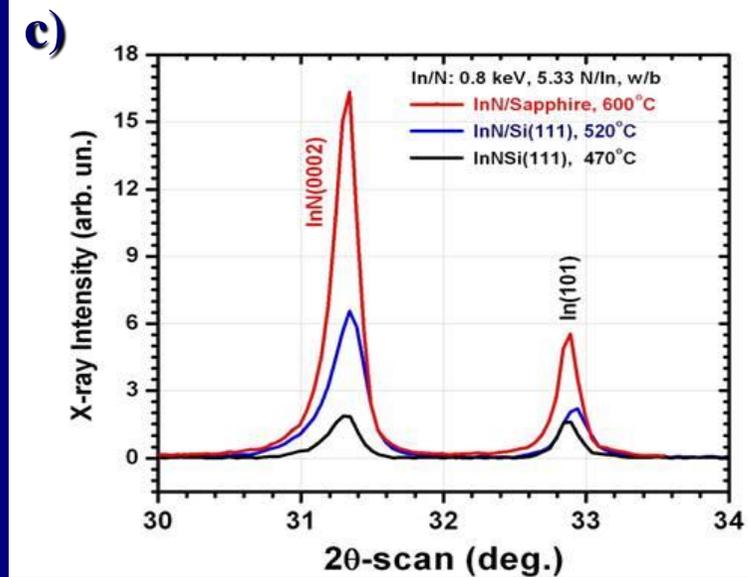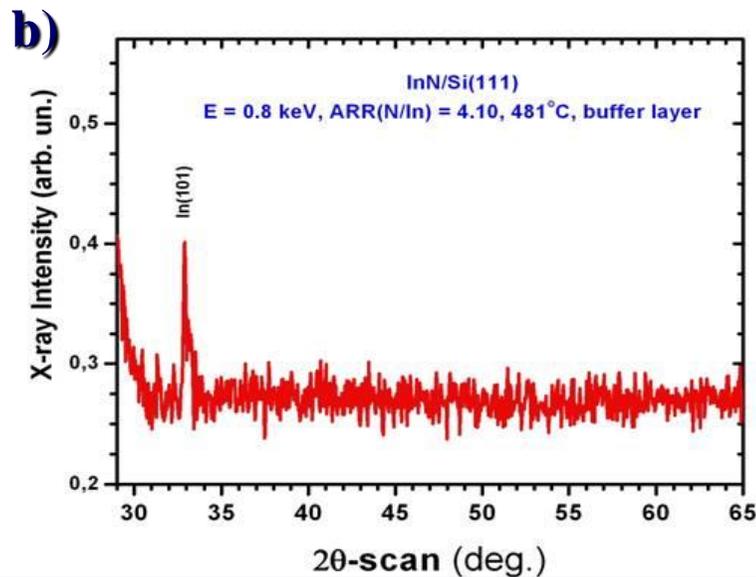
XPS spectra
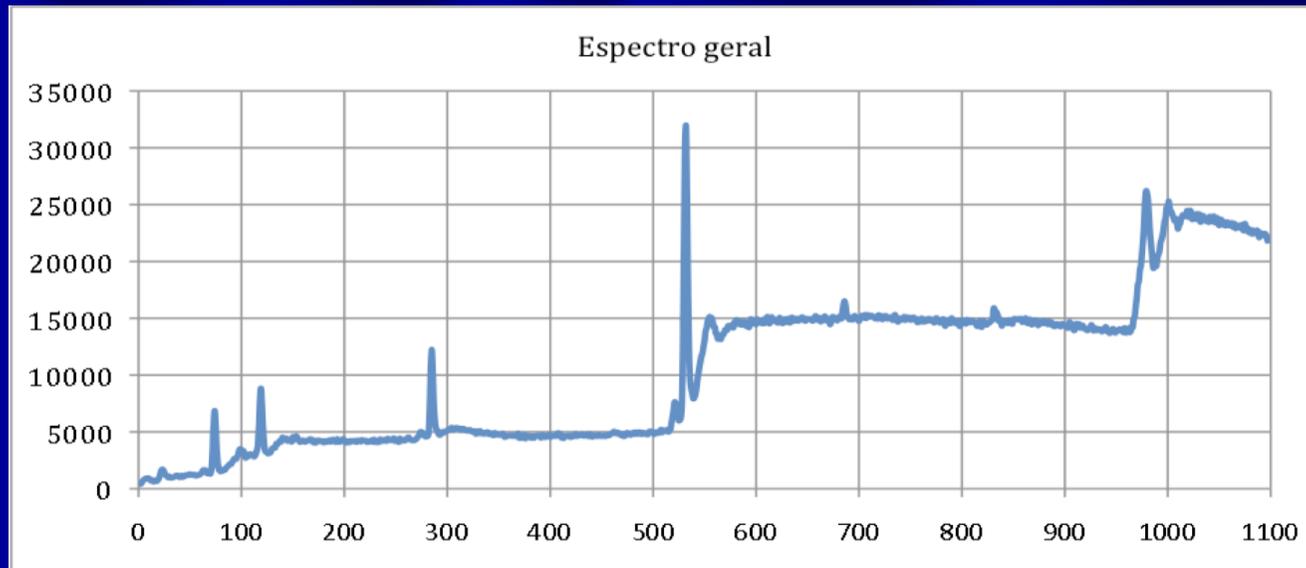
Figure 3: %R spectra from the aluminum oxide film prepared on silicon
substrate at an ion beam energy of 800 eV.

XPS
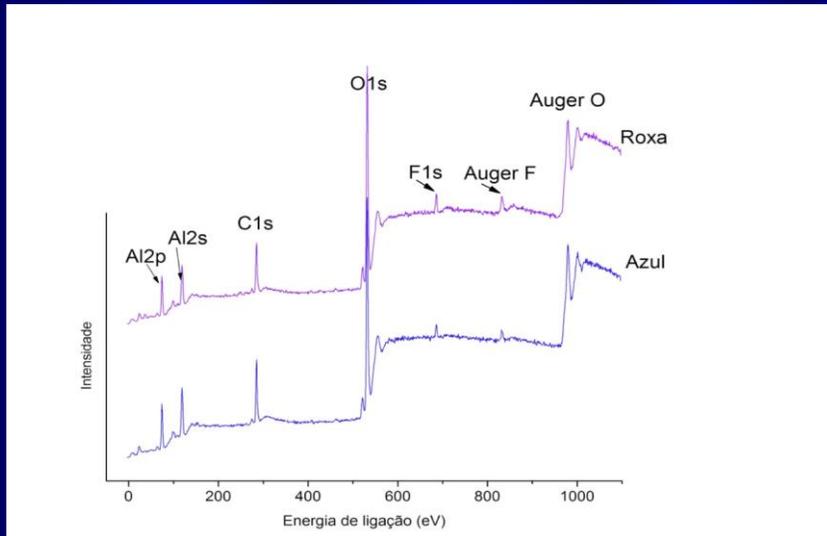
Fig. 3: Blue and Purple samples XPS Wide spectra (0-1100 eV)
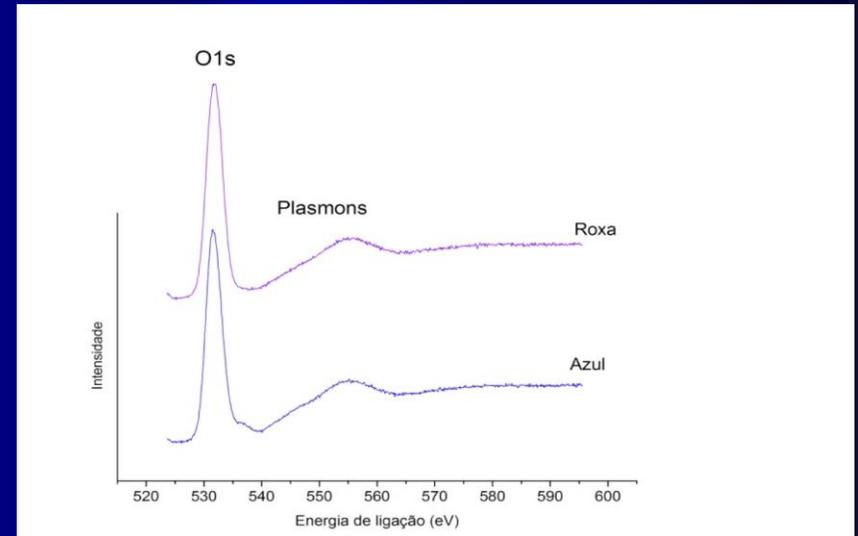
O1s spectra with plasmons.

XPS - In 3d with surface cleaning by Ar ion etching

C-plane sapphire - R.T.

$3d_{3/2}$

$3d_{5/2}$

In_2O_3?

Glass - R.T.

InN

In

GaN/A-plane sapphire - R.T.

InN

Glass - 450ºC

In

InN
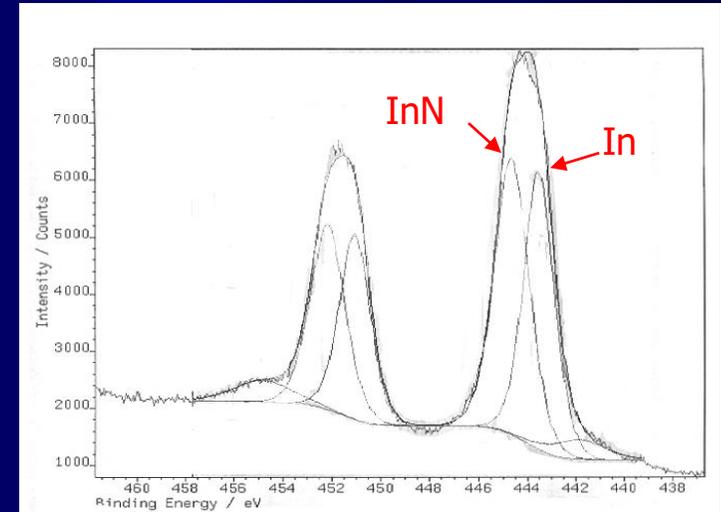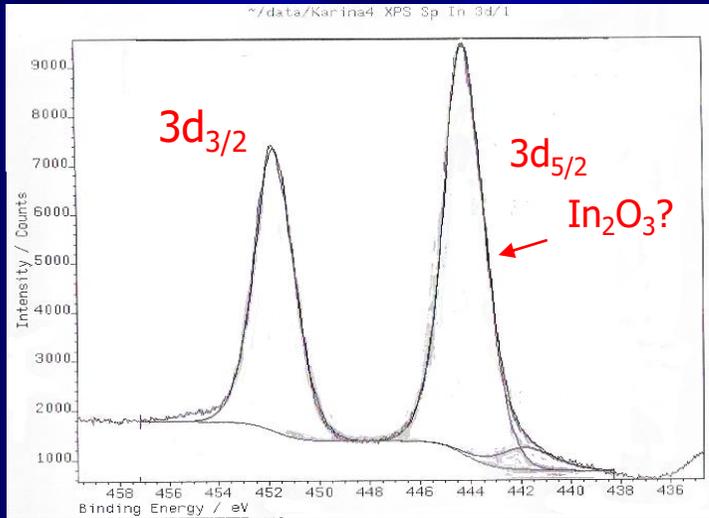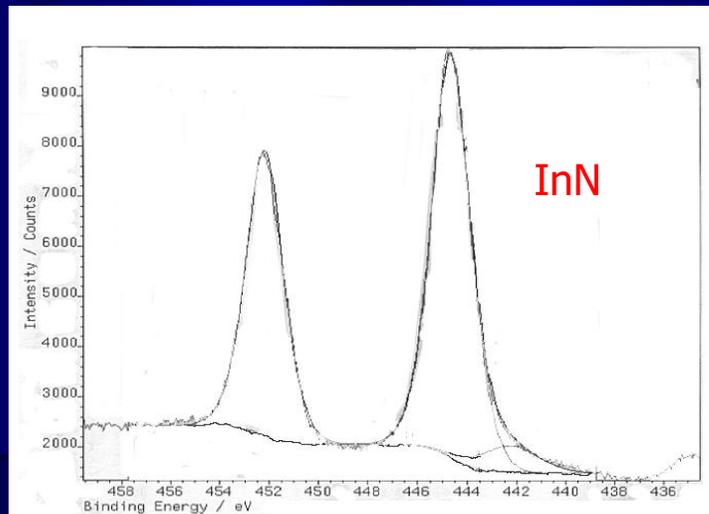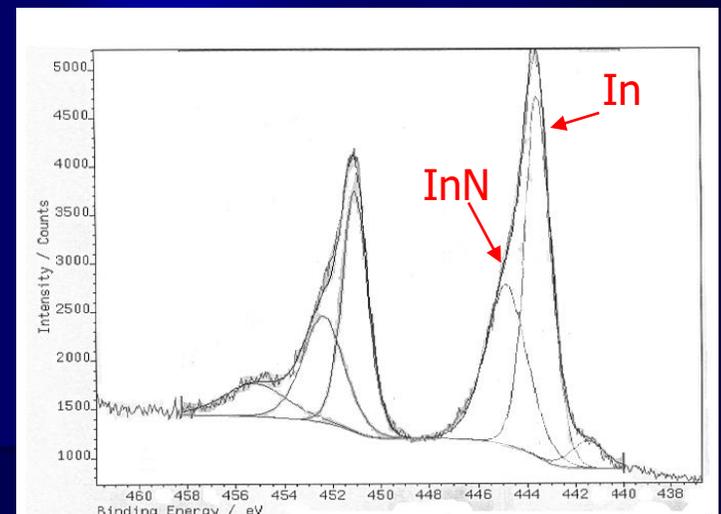
XPS - N 1s with surface cleaning by Ar ion etching

C-plane sapphire - R.T.

InN
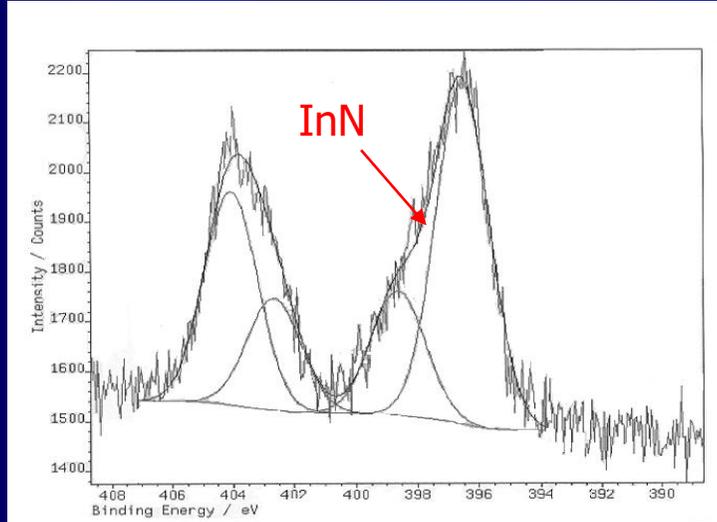
N 1s
In 3d

0.50

Glass - R.T.

N-O

InN

InN

N-O N-H

Atomic N
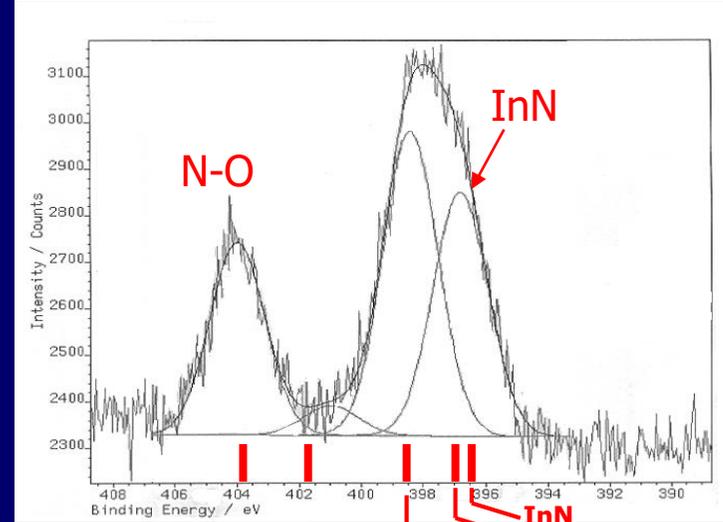
N 1s
In 3d

0.50

GaN/A-plane sapphire - R.T.

Auger electrons:
Ga $L_2M_{4,5}M_{4,5}$

1.66

Glass - 450ºC

InN
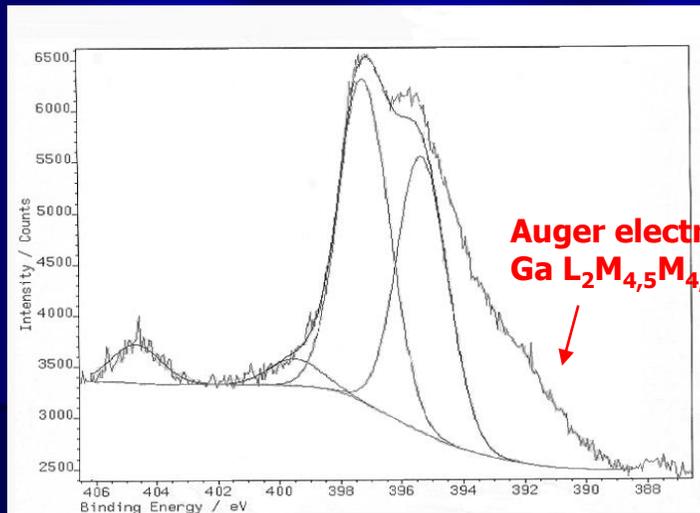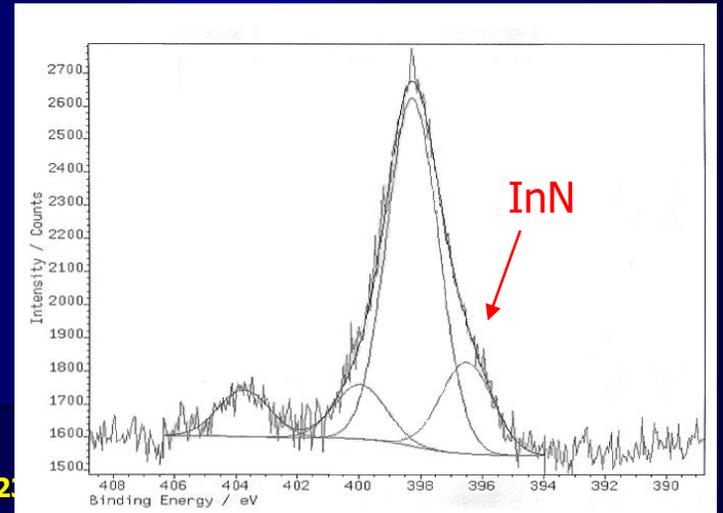
1.30

Raman Spectroscopy
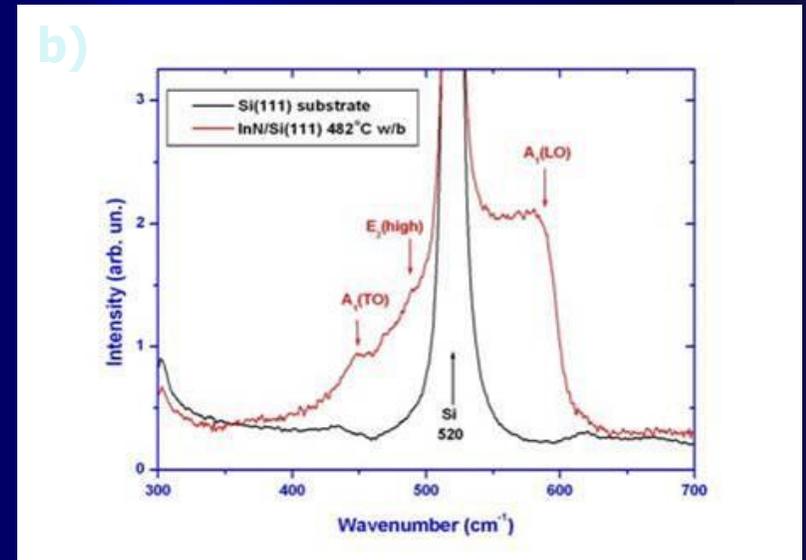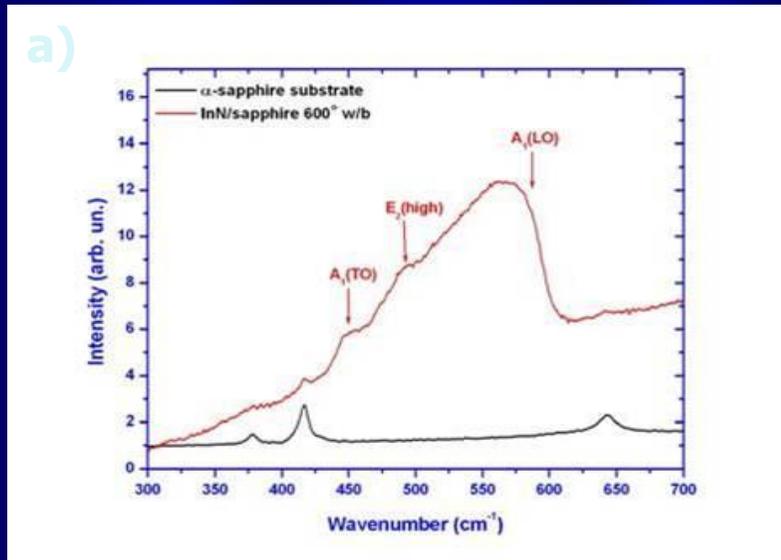
a) Raman spectrum for the InN/sapphire film. Three phonon modes for wurtzite-type InN are observed. The spectrum of the sapphire substrate is shown.

b) Raman spectrum for the InN/Si(111) film. Three phonon modes for wurtzite-type InN are observed. The peak of Si(111) substrate can be also observed.

c) Raman spectra for the InN/Si(111) film showing an anisotropy of the InN A_1(LO) at 590 cm^{-1} after three sequential readings turning the sample by 30º.
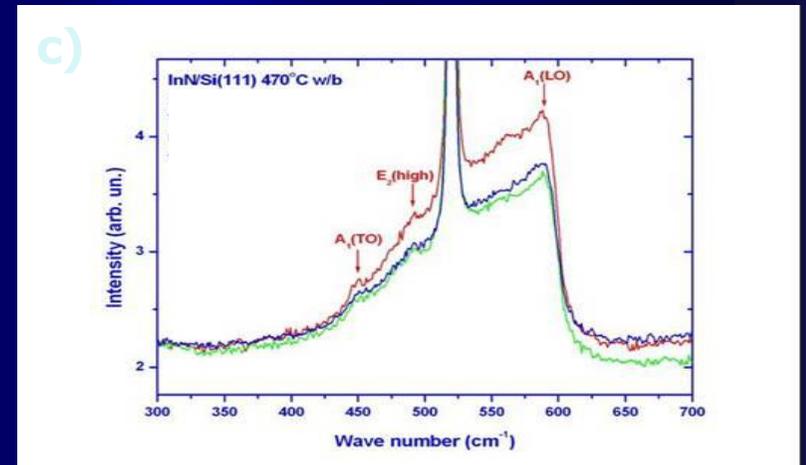
RBS
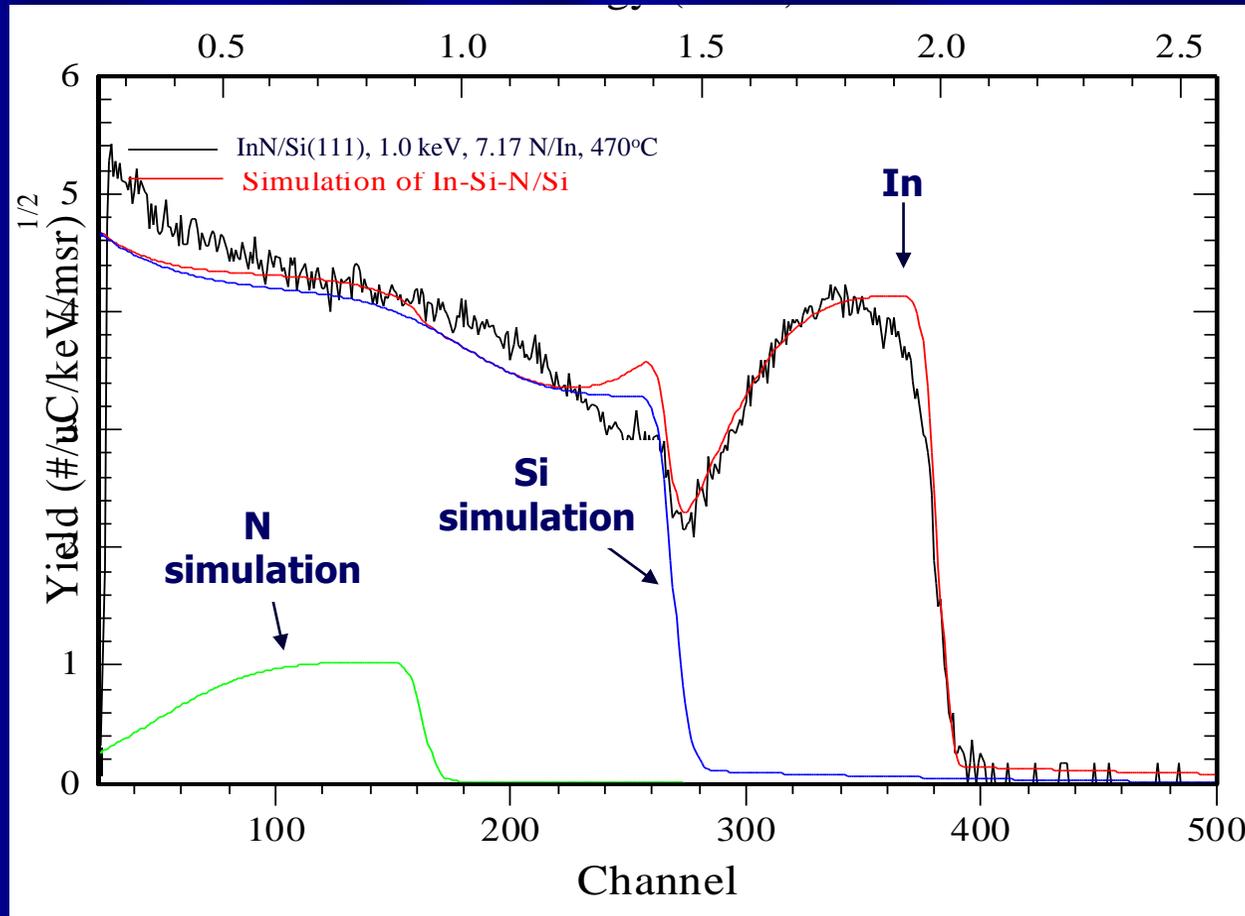
RBS spectrum of an InN/Si(111) showing a predominant presence of In over N on the surface of the film. This sample showed a poor crystallization characteristic.

Capacitance-Voltage Measurements on IBAD HfO₂ Films

Capacitor thickness = 1057Å

➢ HfO₂ film deposited by IBAD

➢ 100 µm diameter dot
   k = 12.3

➢Hysteresis indicates charge
   trapped within the oxide
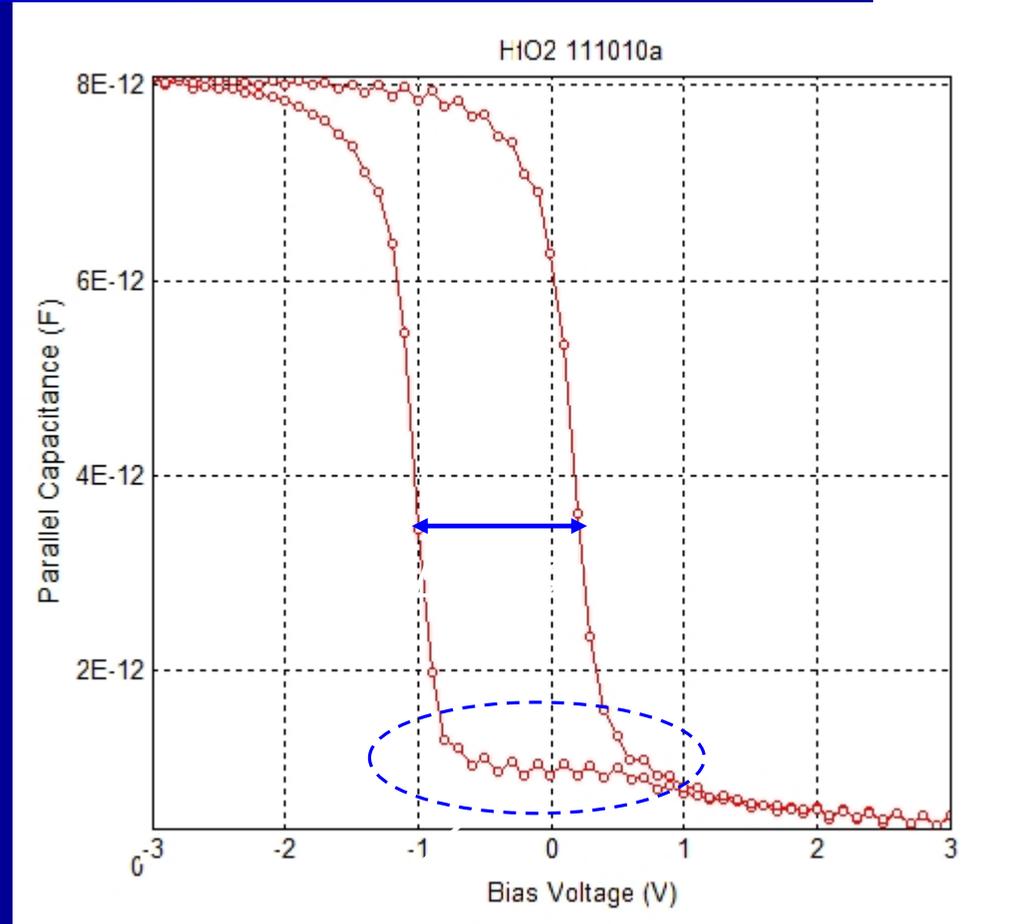
Interface trapped charges

Gallium Oxide - Ga_2O_3

- *It is a wide band gap semiconductor, between 4.5 eV - 4.9 eV*

- *Ga_2O_3 single crystals have α, β, δ, ε and γ, polymorphs with free energy of formation in the order of $\beta<\varepsilon<\alpha<\delta<\gamma$*

- *Among the different Ga_2O_3 polymorphs, the β-phase is the most stable crystalline phase with a monoclinic structure*
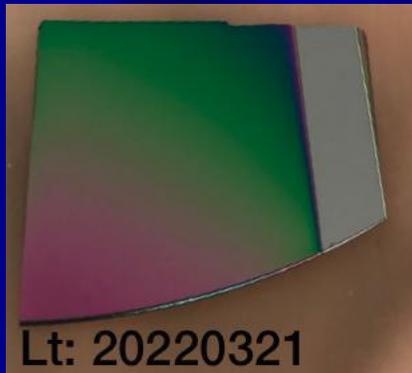
Gallium Oxide - Ga_2O_3

Crystallographic structure of gallium oxide phases
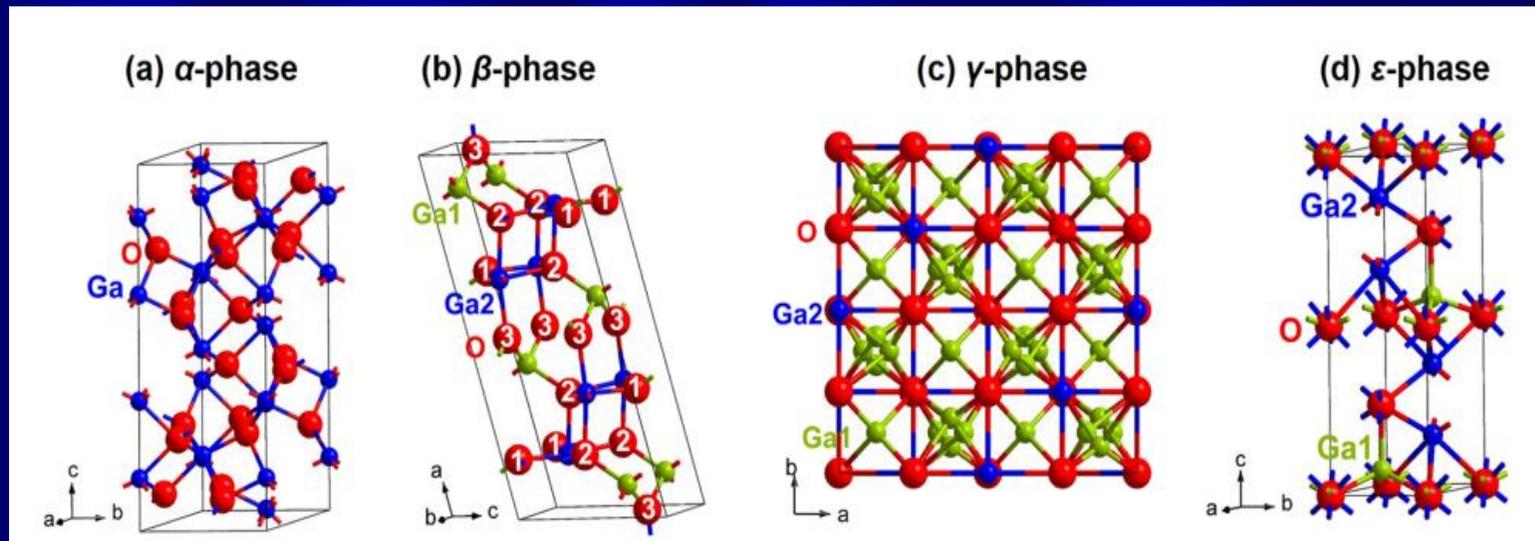
Deposition on Si(100) substrates

Sample	Substrate	Temperature	d.d.p.	Beam
GaO1	Si p	20 °C	500 V	50 mA/500 V
GaO2 blue	Si p	20 °C	500 V	50 mA/500 V
GaO2 red	Si p	20 °C	500 V	50 mA/500 V
GaO4	Si p	400 °C	500 V	50 mA/500 V
GaO5	Si p	800 °C	500 V	50 mA/500 V

Ga$_2$O$_3$ films
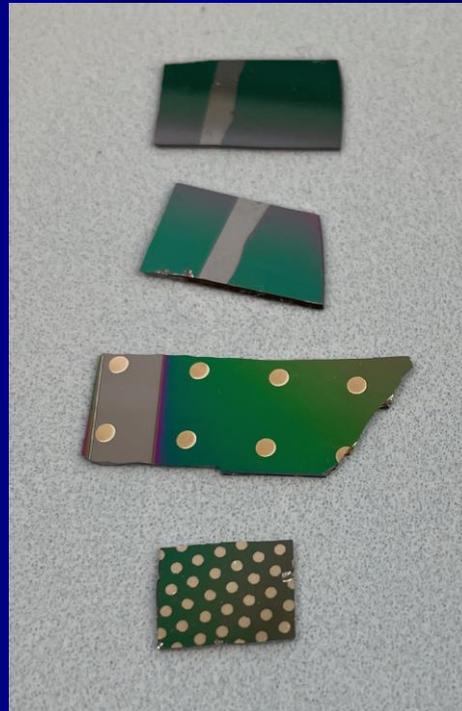
Ga$_2$O$_3$ film deposited on Si(100), with 500 eV ion beam energy

Testing Device Assembly

For electrical measurements, testing devices were manufactured on thin Ga_2O_3 films

Film morphology: SEM

Sample	T (ºC)
GaO-01	20
GaO-02 blue	20
GaO-02 red	20
GaO-04	400
GaO-05	800

GaO1
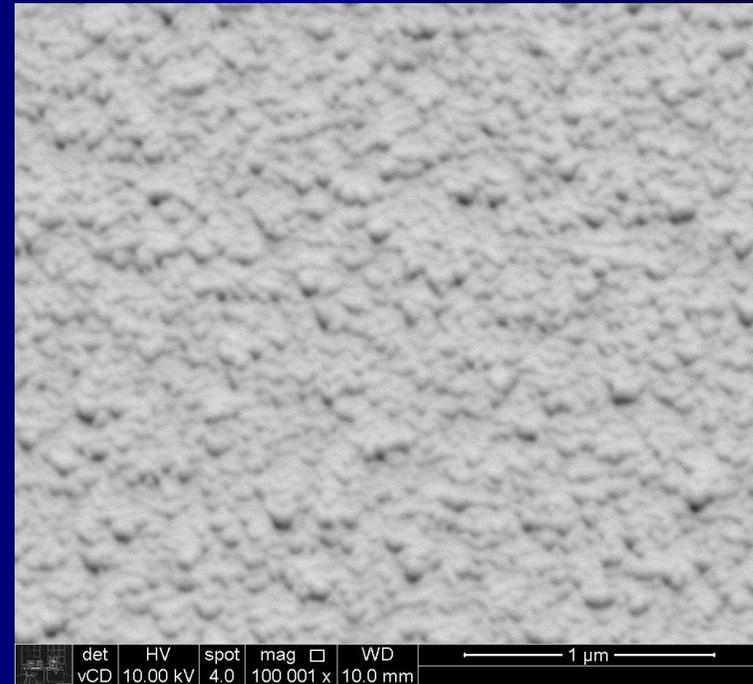
GaO2 blue

Film morphology: SEM

Sample	T (ºC)
GaO-01	20
GaO-02 blue	20
GaO-02 red	20
GaO-04	400
GaO-05	800

GaO4

GaO4

Film morphology: SEM

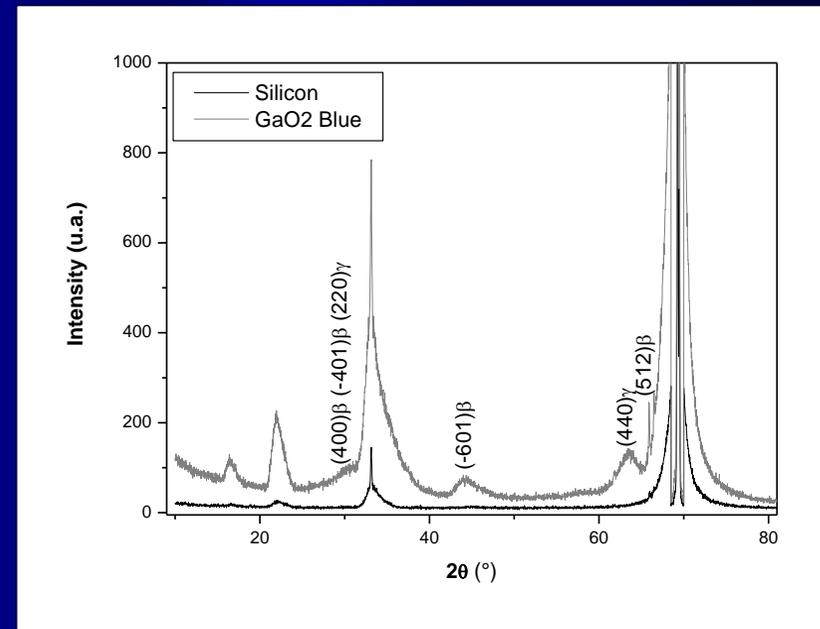| Sample	T (ºC)
GaO-01	20
GaO-02 blue	20
GaO-02 red	20
GaO-04	400
GaO-05	800

GaO4

GaO4

Structural property: XRD

Sample	T (ºC)
GaO-01	20
GaO-02 blue	20
GaO-02 red	20
GaO-04	400
GaO-05	800

Structural property: XRD

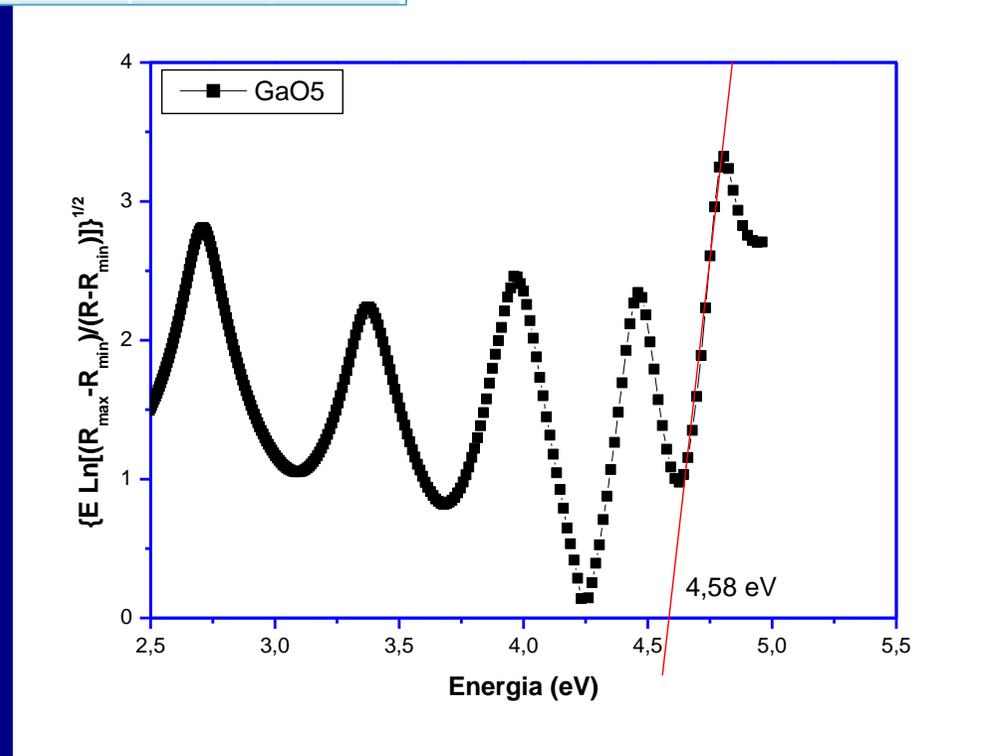| Sample	T (ºC)
GaO-01	20
GaO-02 blue	20
GaO-02 red	20
GaO-04	400
GaO-05	800

Optical Absorption %R
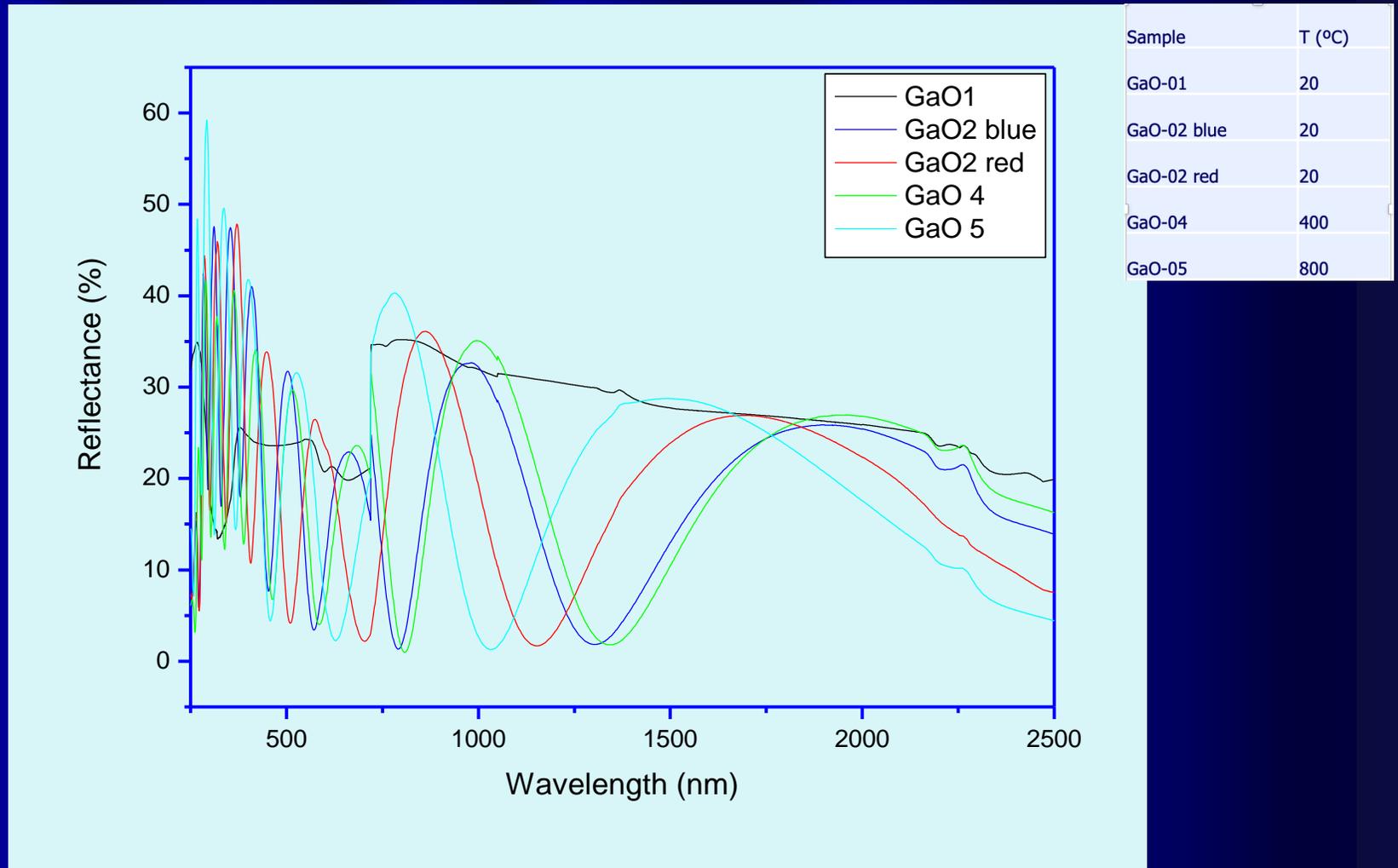
%R spectra from the gallium oxide films prepared on silicon substrate at different temperatures.
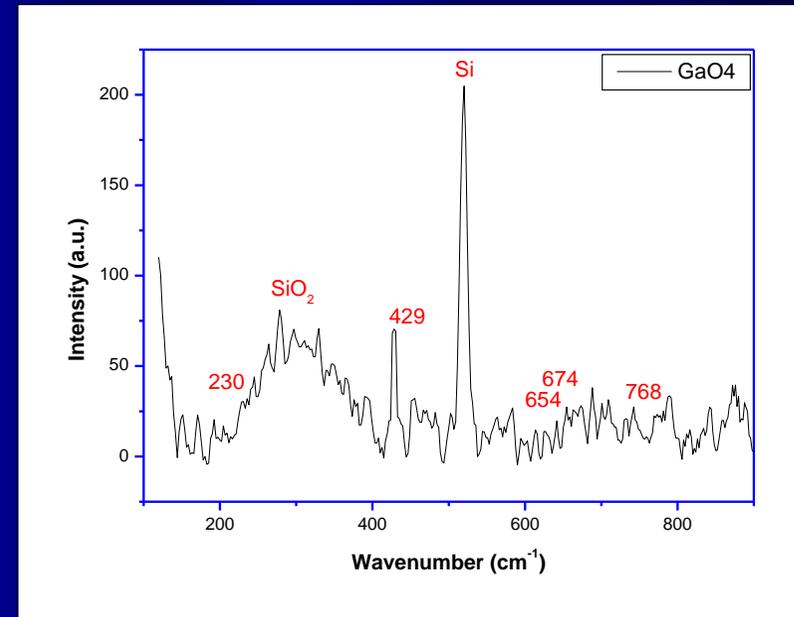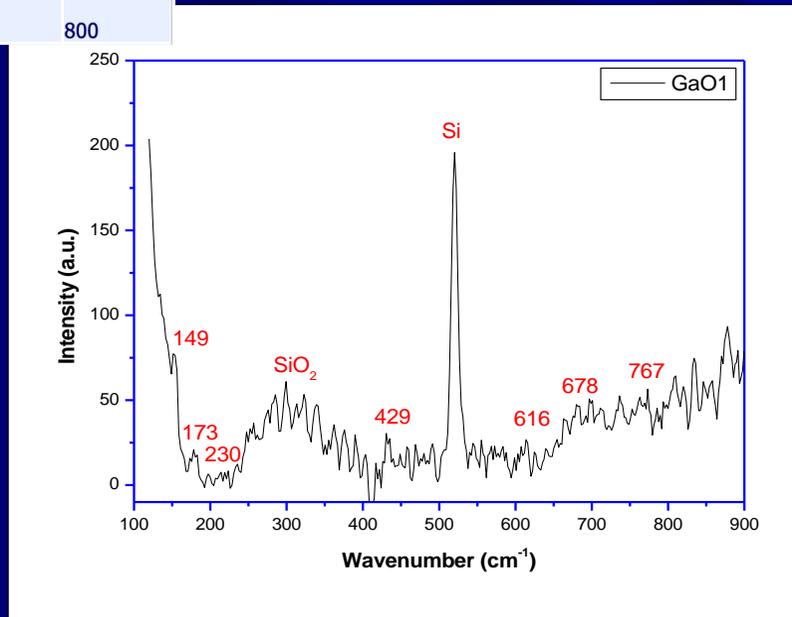
Band Gap values

Amostra	Espessura (nm)	Band Gap (eV)
GaO1	150	4,54
GaO2 Blue	639	4,35
GaO2 Red	552	4,33
GaO4	524	4,50
GaO5	358	4,58

Sample	T (ºC)
GaO-01	20
GaO-02 blue	20
GaO-02 red	20
GaO-04	400
GaO-05	800

Raman spectrum of Ga$_2$O$_3$/Si(100)

Sample	T (ºC)
GaO-01	20
GaO-02 blue	20
GaO-02 red	20
GaO-04	400
GaO-05	800

IxV from Ga$_2$O$_3$/Si(100)

Sample	T (ºC)
GaO-01	20
GaO-02 blue	20
GaO-02 red	20
GaO-04	400
GaO-05	800

negative to positive
— without light
— with light

IxV from Ga$_2$O$_3$/Si(100)

Sample	T (ºC)
GaO-01	20
GaO-02 blue	20
GaO-02 red	20
GaO-04	400
GaO-05	800

IxV from Ga$_2$O$_3$/Si(100)

Sample	T (ºC)
GaO-01	20
GaO-02 blue	20
GaO-02 red	20
GaO-04	400
GaO-05	800

IxV from Ga$_2$O$_3$/Si(100)

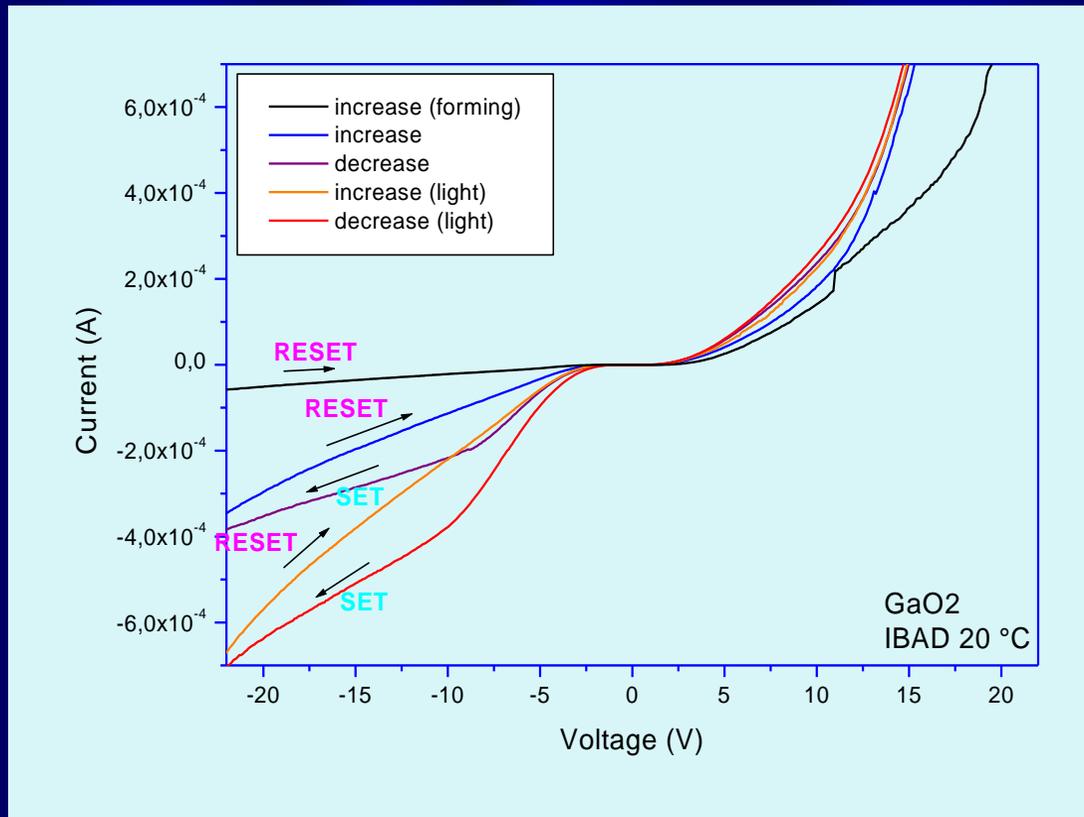| Sample	T (°C)
GaO-01	20
GaO-02 blue	20
GaO-02 red	20
GaO-04	400
GaO-05	800
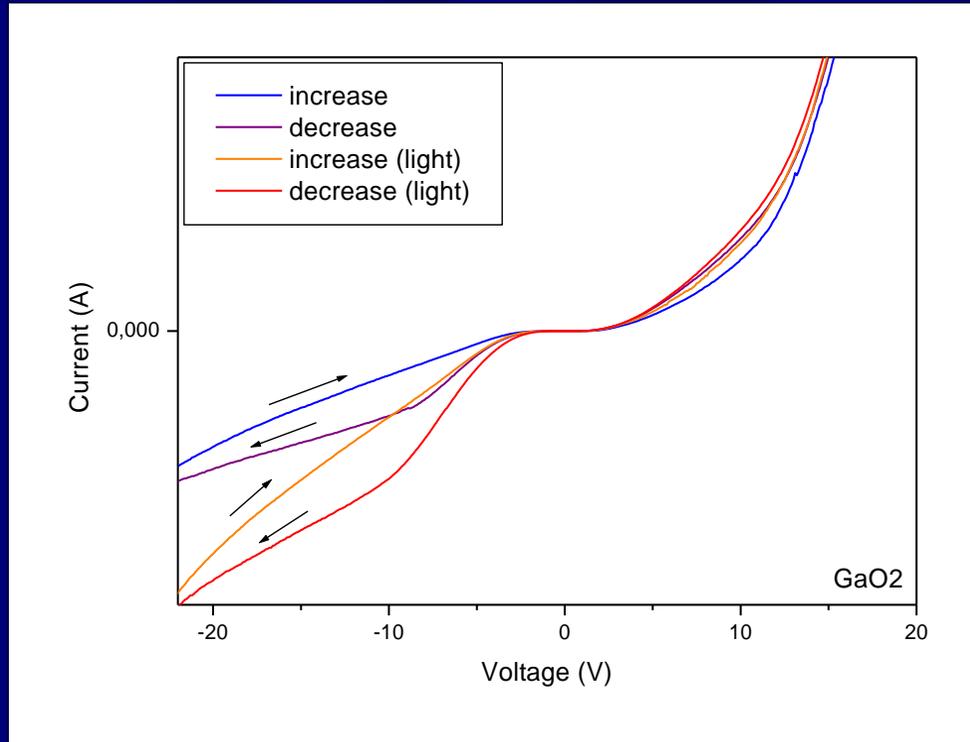
This figure shows the photoresistive memory behavior.
The curves shows different response for illuminated situation.
In the region around 0 volts there are the indication of resistance state change.
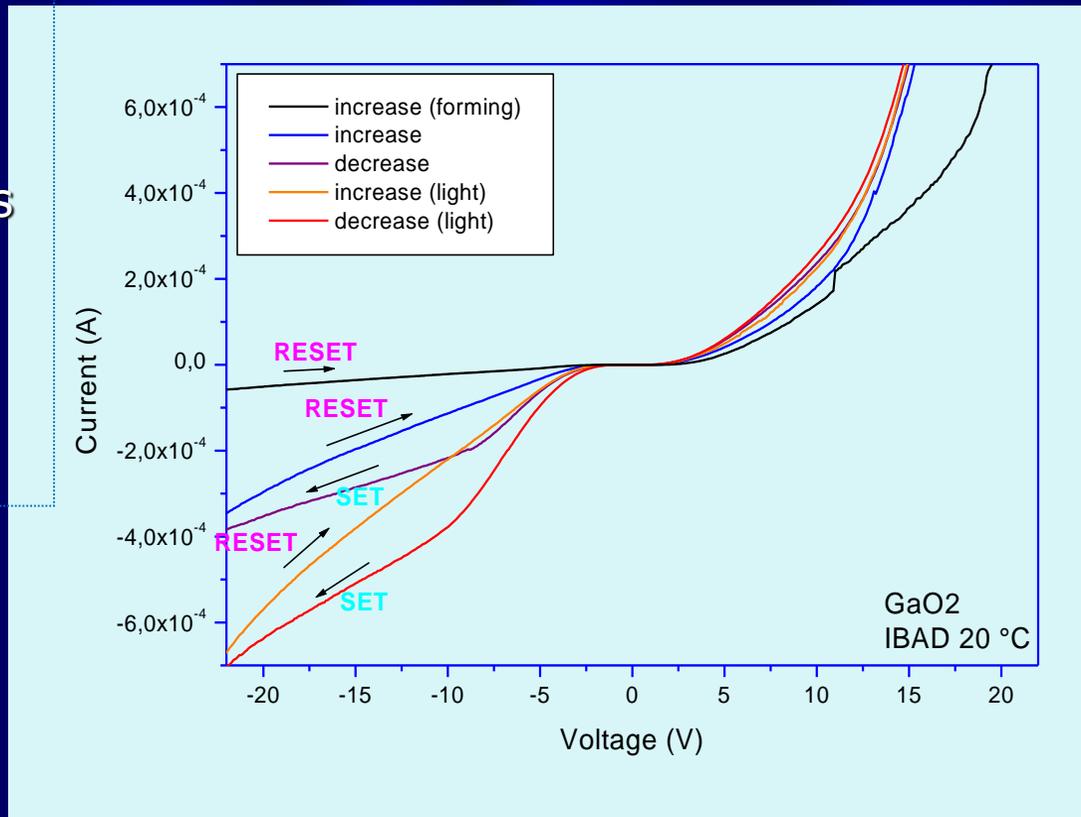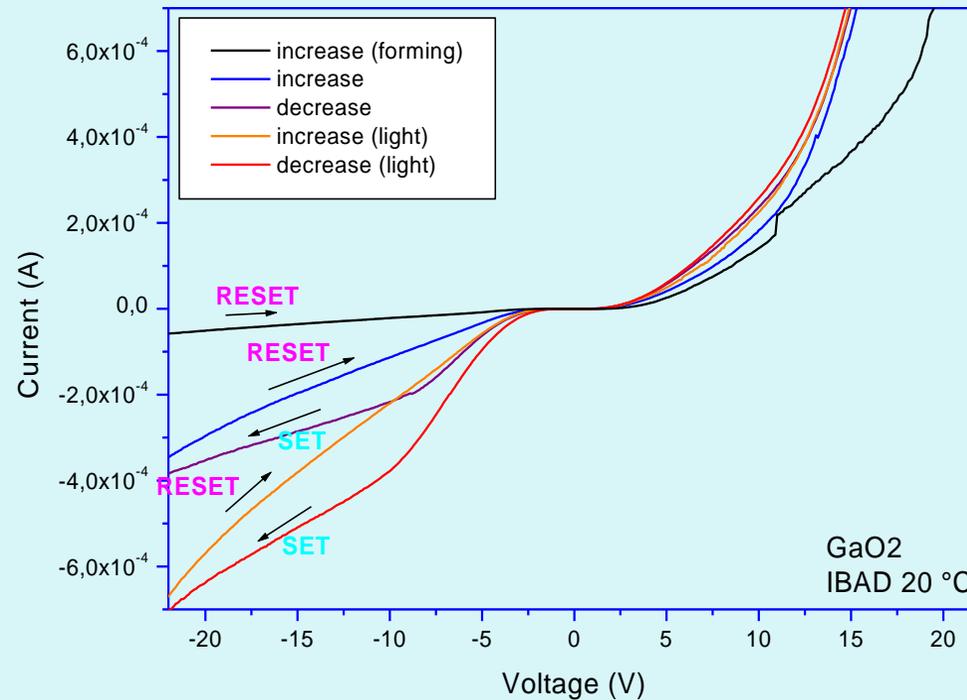
ReRAM de GaO

GaO2
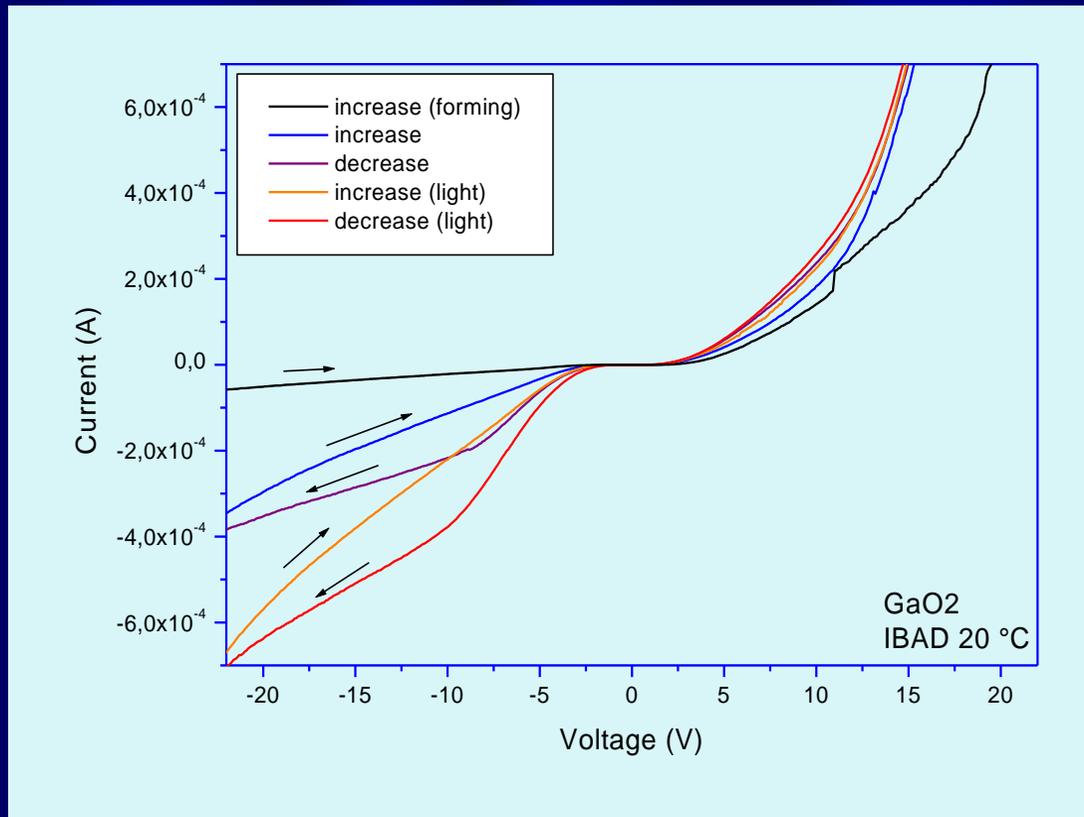
GaO2

GaO2

RESET

All devices present

same behavior when the resistance makes the transition from the low resistance state to the high resistance state.
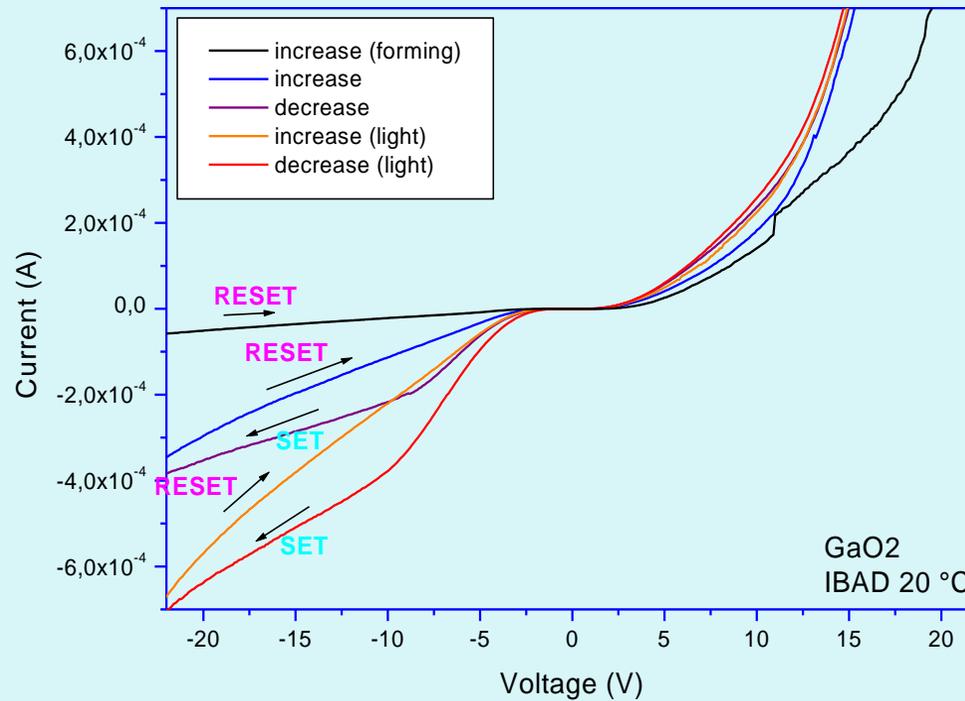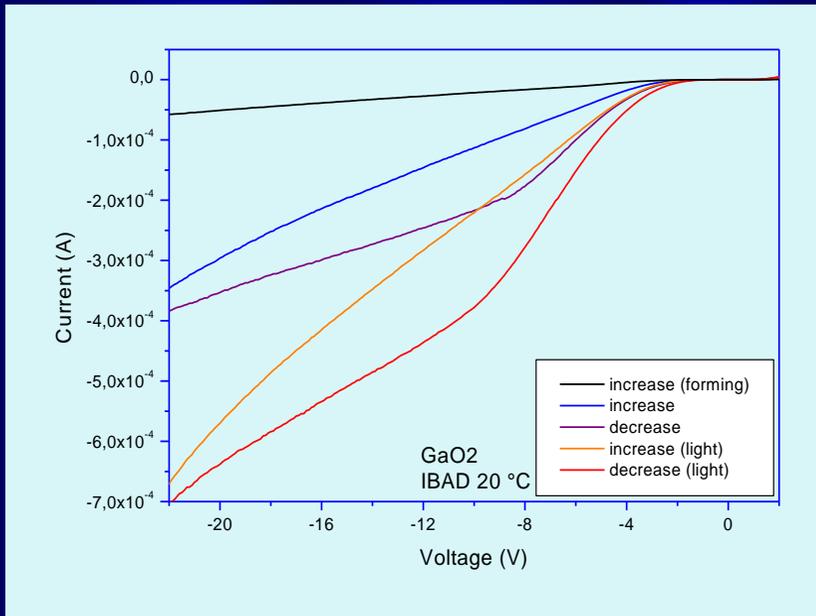
GaO2

SET

The same can be said when resistance goes the other way.

GaO2

It is possible to say that all resistive memories are unipolar

GaO2

	Voltage (V) Reference: -1x10^{-5} A
Increase (forming)	-5.6
Increase	-3.4
Decrease	-2.8
Increase (light)	-3.0
Decrease (light)	-2.4

	Voltage (V) Reference: 1x10^{-5} A
Increase (forming)	3.8
Increase	3.0
Decrease	2.6
Increase (light)	2.7
Decrease (light)	2.6

GaO4

GaO4

GaO4

GaO4
IBAD 400 °C

	Voltage (V) Reference:- 1x10^{-5} A
Increase (forming)	-8.3
Increase	-6.8
Decrease	-2.7
Increase (light)	-3.9
Decrease (light)	-2.6
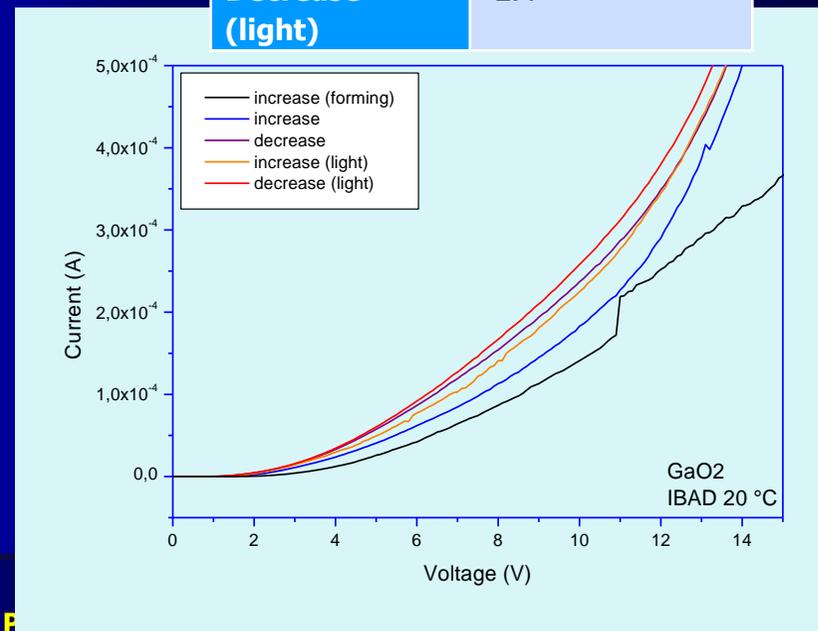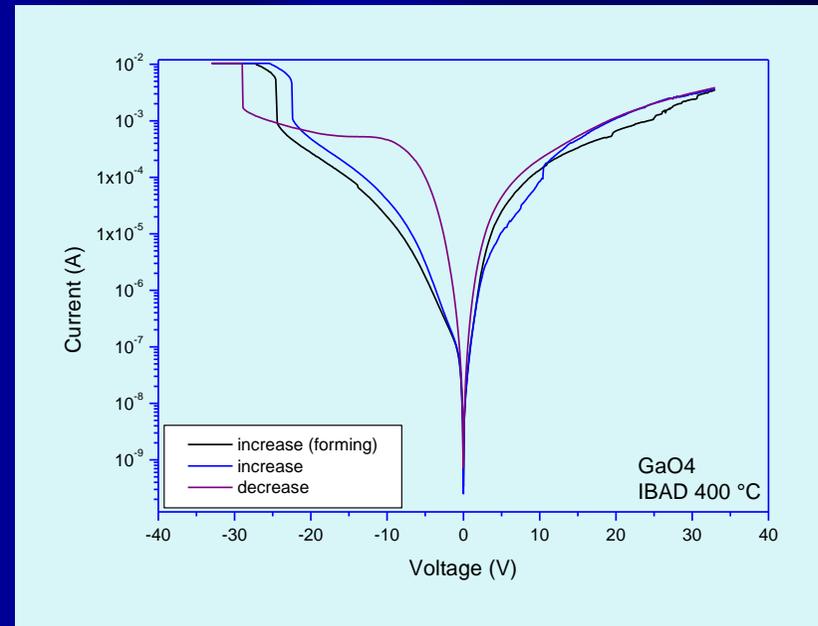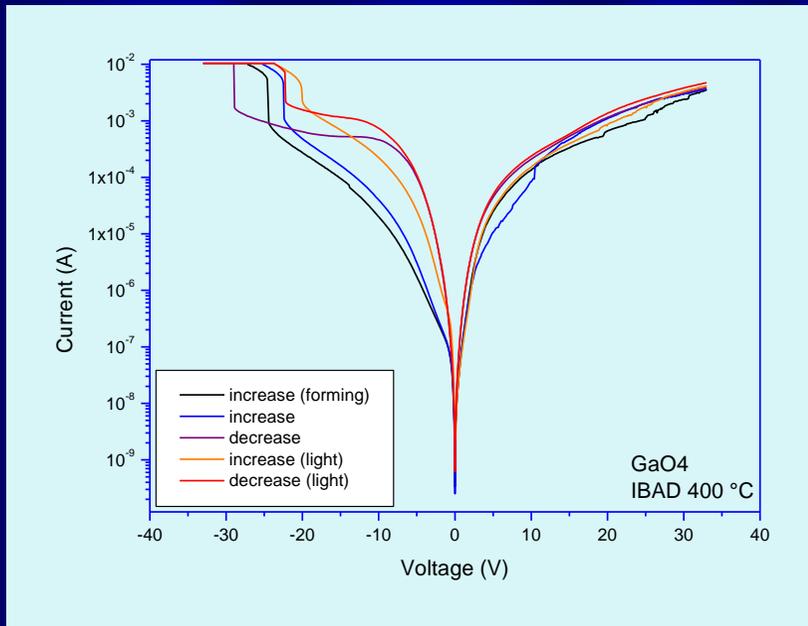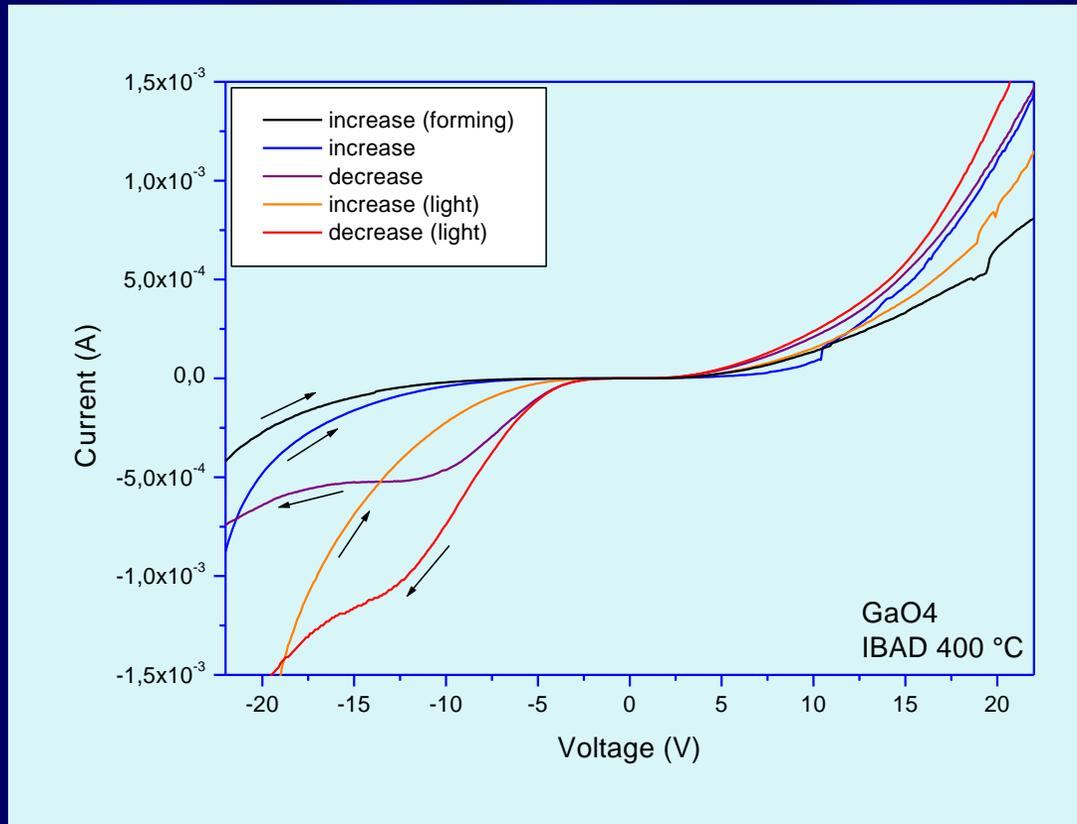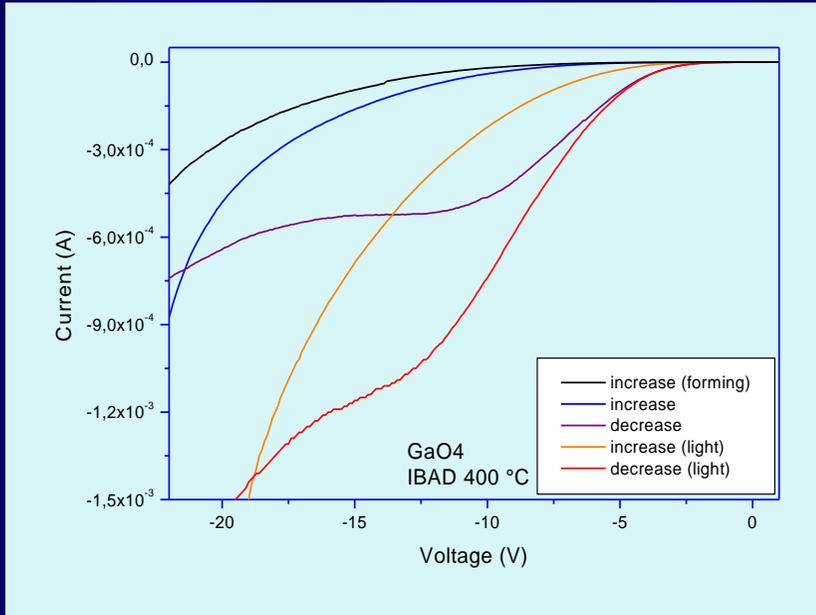
	Voltage (V) Reference: 1x10^{-5} A
Increase (forming)	3.7
Increase	4.9
Decrease	2.9
Increase (light)	3.6
Decrease (light)	2.9

GaO4
IBAD 400 °C
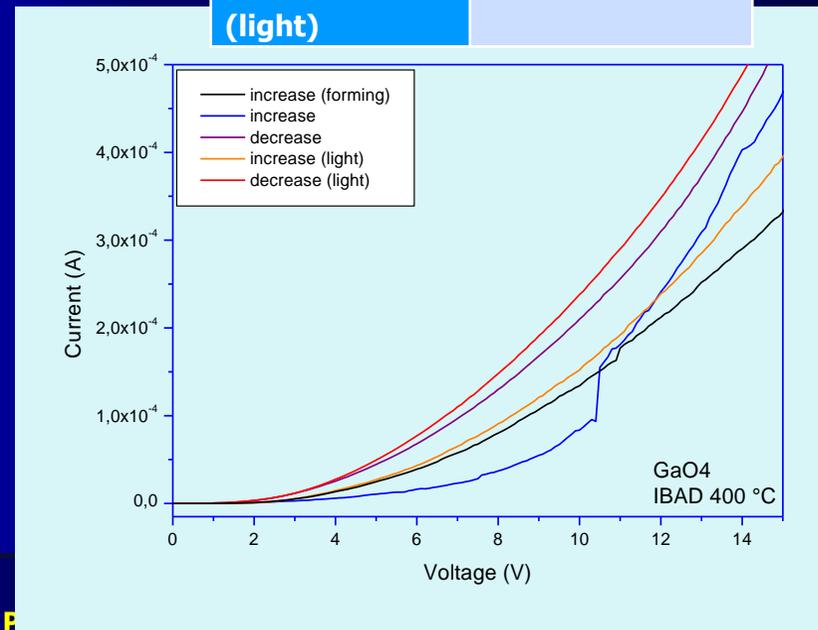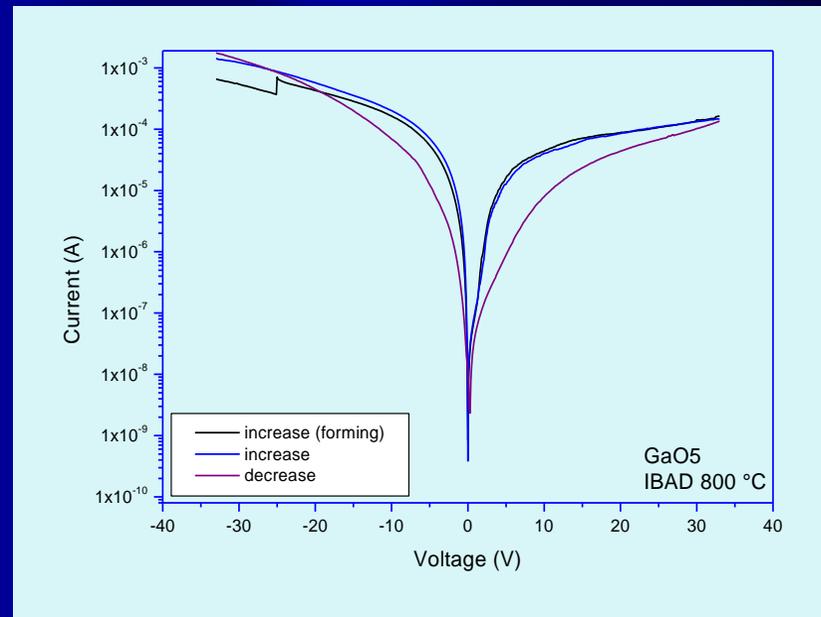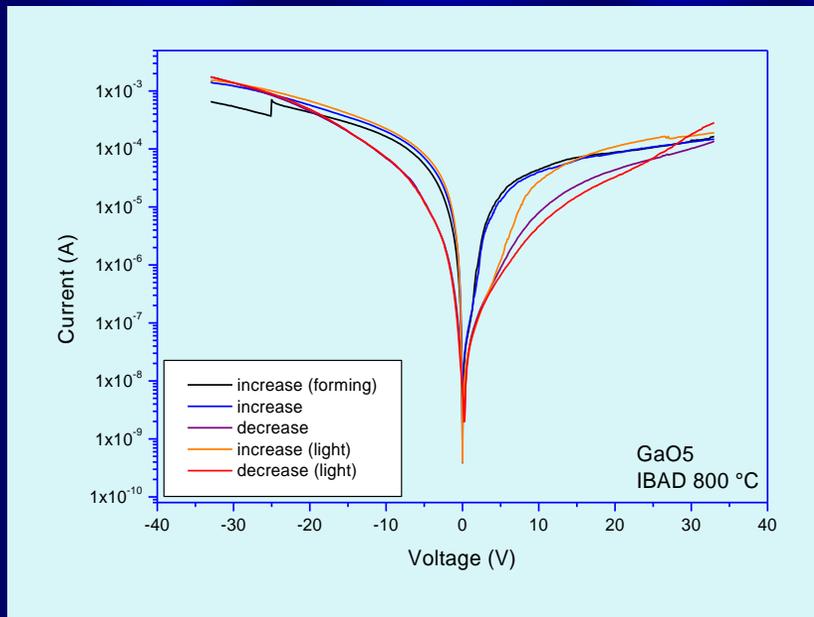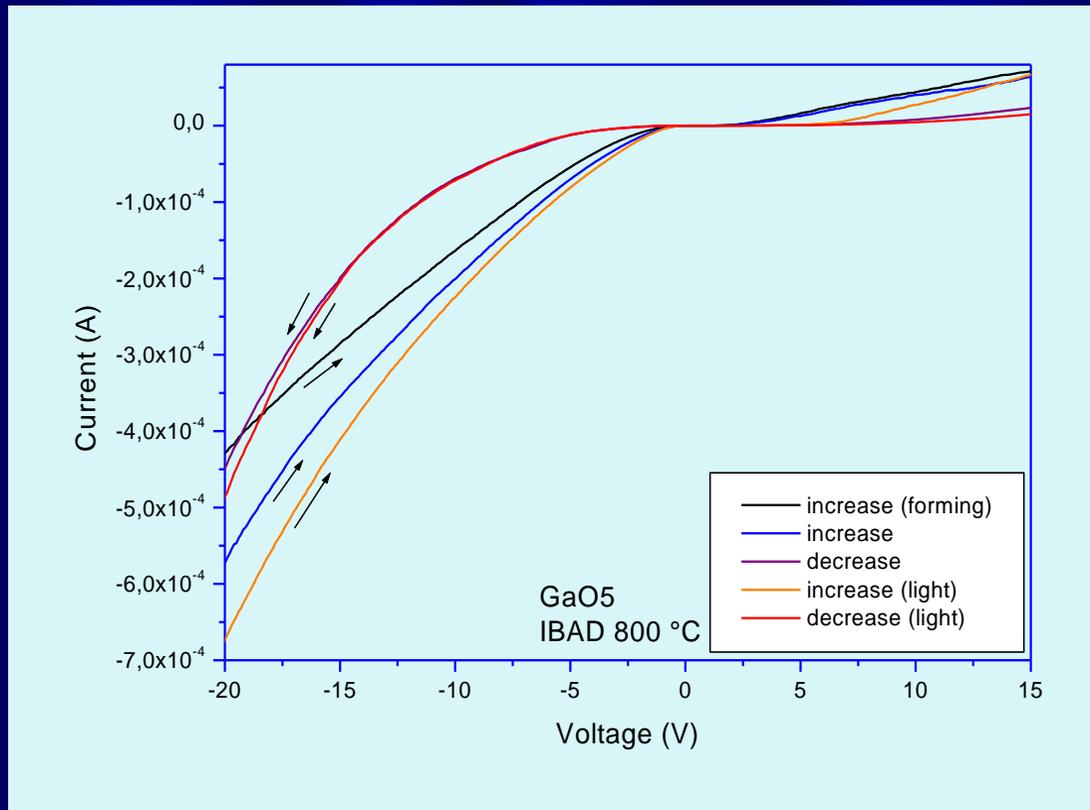
GaO5

GaO5

GaO5
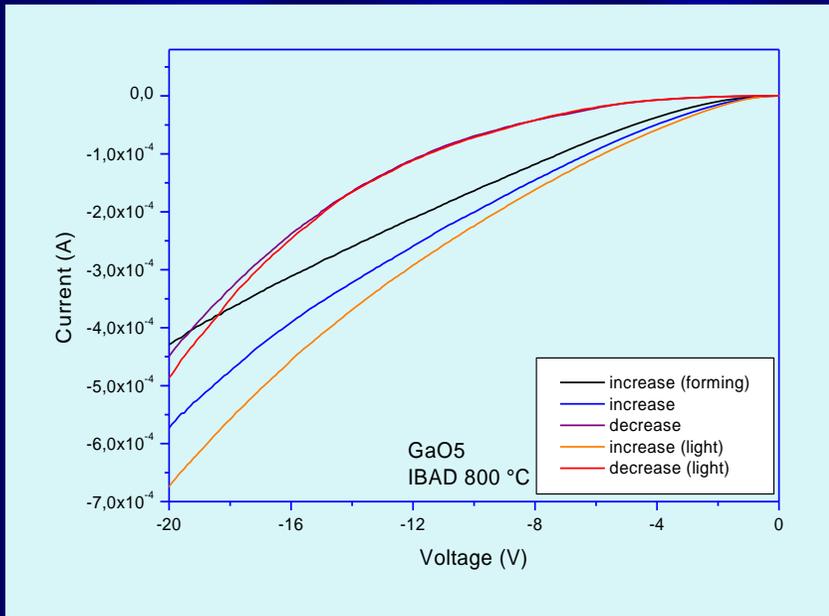
	Voltage (V) Reference: -1x10^{-5} A
Increase (forming)	-2.1
Increase	-1.6
Decrease	-4.6
Increase (light)	-1.5
Decrease	-4.7

	Voltage (V) Reference: 1x10^{-5} A
Increase (forming)	4.0
Increase	4.4
Decrease	10.9
Increase (light)	7.7
Decrease (light)	13.1
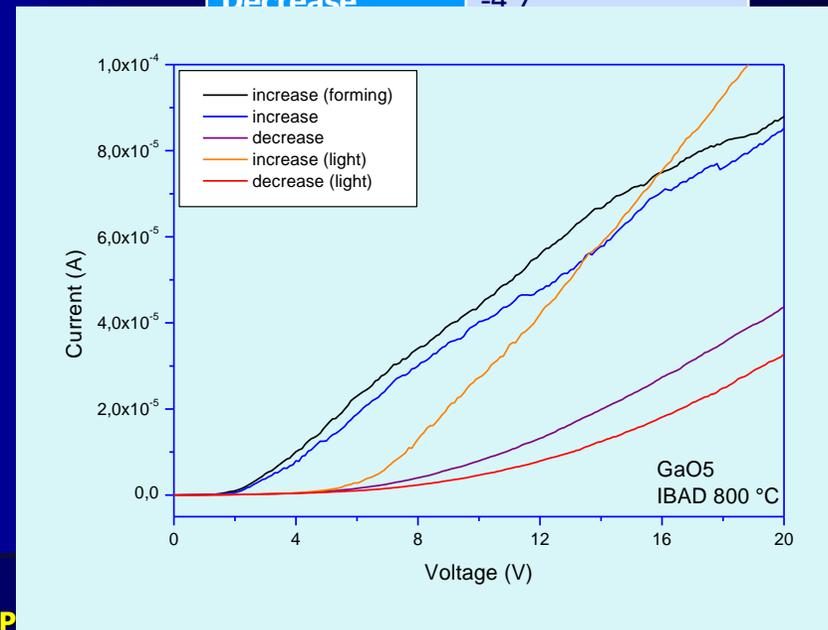
Com grafeno, brasileira da USP cria memória que pode revolucionar a tecnologia

Patente foi desenvolvida utilizando óxido condutor transparente com grafeno como memória resistiva

Rodrigo Mozelli | ⊙ 07/02/2023 02h30, atualizada em 07/02/2023 20h37

Com grafeno, brasileira da USP cria memória que pode revolucionar a tecnologia
Novos chips são 100 vezes mais rápidos que as memórias Flash atuais: eles são do tipo resistivo...
olhardigital.com.br

https://olhardigital.com.br/2023/02/07/ciencia-e-espaco/pesquisadora-cria-memoria-para-pcs-que-pode-substituir-as-de-silicio/
12:22

Inovação na USP

Uma nova maneira de fabricar memórias como essas foi criada por cientistas da **USP** e teve o pedido de registro aceito pelo **INPI** (Instituto Nacional da Propriedade Industrial) em novembro de 2022. Marina Sparvoli, pós-doutoranda do Instituto de Física (IF) da USP, em colaboração com outros pesquisadores, desenvolveu um mecanismo de memória baseado nos **memristores**, a partir de materiais jamais combinados.


Material inédito

O professor José Fernando Chubaci, que supervisiona Marina no pós-doutorado, conta que a aplicação de Iton a memórias resistivas nunca foi feita antes.

"Esse é um projeto na fronteira do conhecimento mundial, que terá aplicação no mercado internacional daqui a dez, 15 ou 20 anos. A doutora Marina conseguiu criar memórias resistivas usando grafeno com o Iton, ampliando espaço de pesquisa na área e trazendo conhecimento ao nosso laboratório."

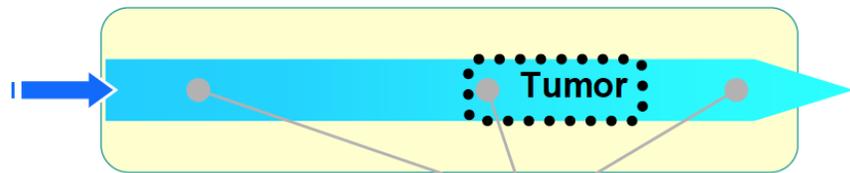*José Fernando Chubaci, professor do Instituto de Física da USP*

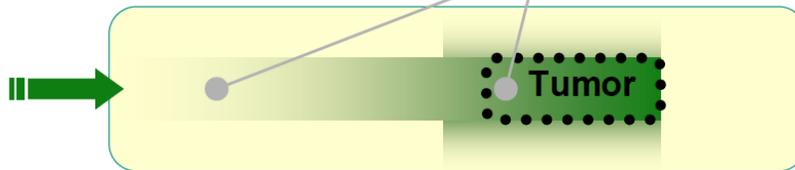**Instituto de Física – USP – São Paulo – 23 de outubro de 2023**

Perspectivas

Perspectivas

NIRS

HIMAC
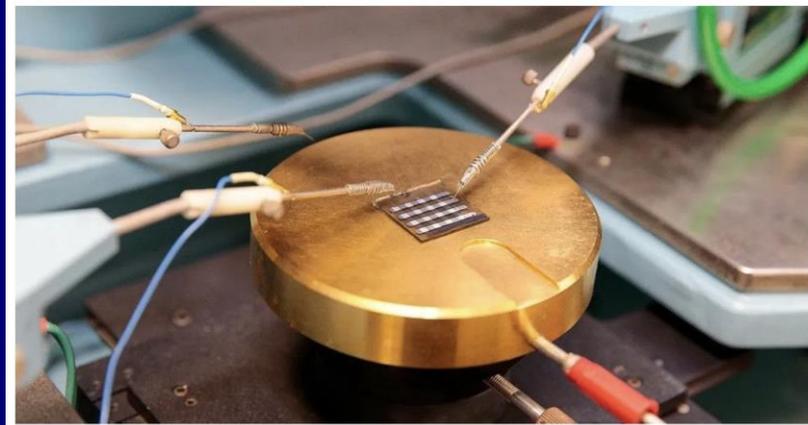
1. History of the heavy ion radiotherapy

HIMAC project

Requirements
Ion species: He to Si (to Ar for research)
Range: 25cm
Irradiation size: 15 x 15 cm (22cm dia.)
Dose rate: 5Gy/min.

1984   **Project was funded**
1988   **Start of construction**
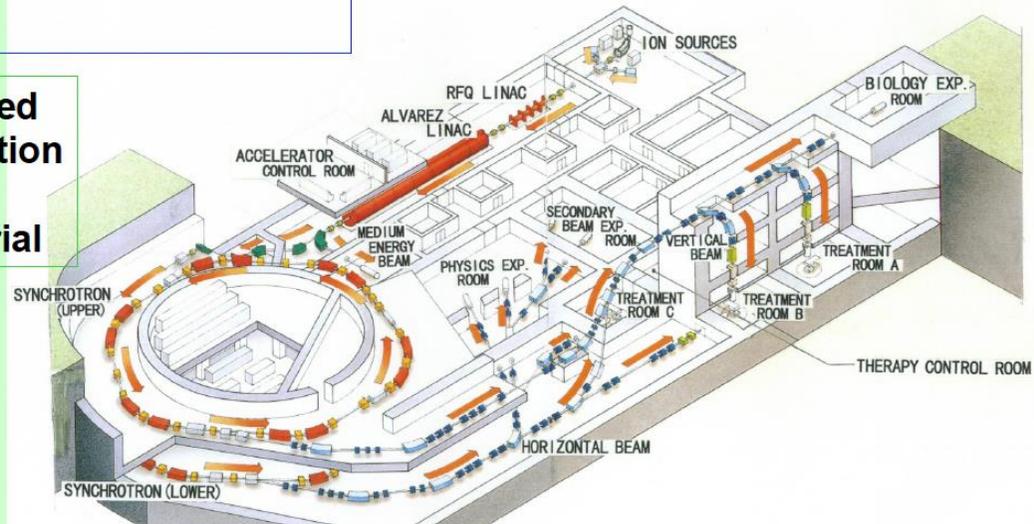1993   **Complete**
1994   **Start of clinical trial**

Size:
    60 x 120 m
Construction cost:
    32.6GJPY
    (Building 14.6GJPY)
    (machine 18.0GJPY)

ION SOURCES
BIOLOGY EXP. ROOM
RFQ LINAC
ALVAREZ LINAC
ACCELERATOR CONTROL ROOM
SECONDARY BEAM EXP. ROOM
MEDIUM ENERGY BEAM
VERTICAL BEAM
TREATMENT ROOM A
PHYSICS EXP. ROOM
SYNCHROTRON (UPPER)
TREATMENT ROOM C
TREATMENT ROOM B
THERAPY CONTROL ROOM
HORIZONTAL BEAM
SYNCHROTRON (LOWER)

HIMAC (Heavy Ion Medical Accelerator in Chiba)

Y. Hirao *et al.*, Nucl. Phys. A 538, 541c (1992).

Perspectivas

√ Produção de materiais especiais como óxidos e nitretos;

√ Aplicação dos sistemas de caracterização por feixes iônicos nos materias produzidos;

√ Geral:

  √ aplicação de caracterização por feixeis de íons em outras áreas;

  √ Aplicação de feixe de íons em radioterapia.

IBAD system: Details

Base Pressure = 7.0×10^{-5} Pa
Working Pressure = 2.0×10^{-2} Pa