Surface and nano science research prospects using ANURIB

- Ion beam in surface & nano science
- Tailoring of material properties by ion beam
- Ion beam and radioactive ion beam for material investigation
- Research prospects using ANURIB

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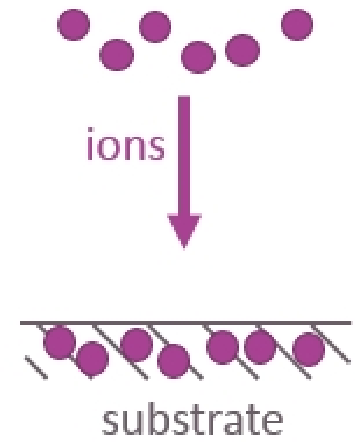
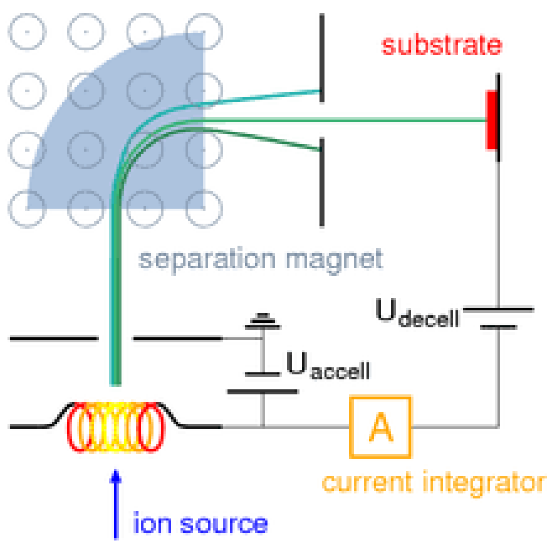
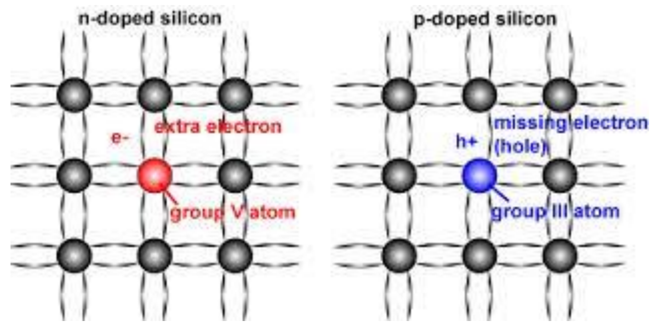
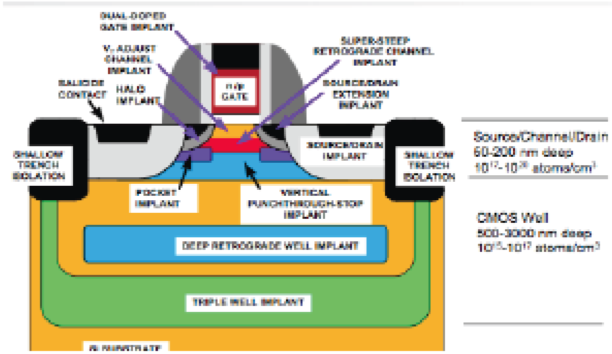
Ion beams for semiconductor devices

Energetic ion implantation is a critical and universal tool for the fabrication of transistors in semiconductor devices and the various forms of electronic, photovoltaic and photonic materials.









CMOS (complimentary metal oxide semiconductor)

Ion beams for surface, interface and nano materials

Surface interface and nanomaterials
electronic, opto-electronic, magnetic devices, sensors and detectors are developed by playing with the surface, near surface and interface (junction) properties of the materials.

Example: solar cell, LED, sensors, magnetic memory, all thin film,catalysts.

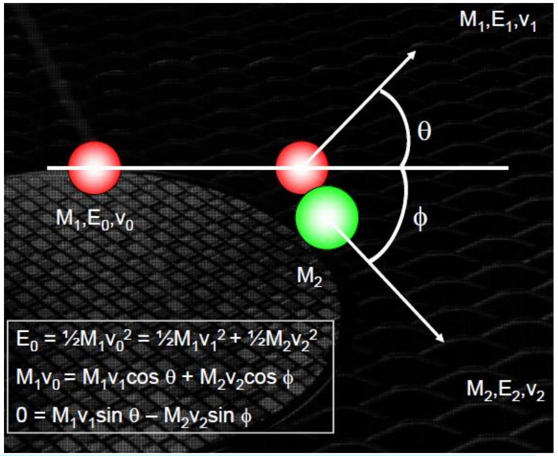
Atoms at thermal energy (~25 meV- eV) used for film deposition, surface/ interface and nanostructure development (no need of ion accelerator)

Why energetic ion beam is important ?

Precise manipulation by selected atom (mass/charge) at definite depth (energy) with specific quantity(fluence),

What we do with ion beam?

Transfer energy and momentum to the host atoms and finally implant the projectile atom into the host material

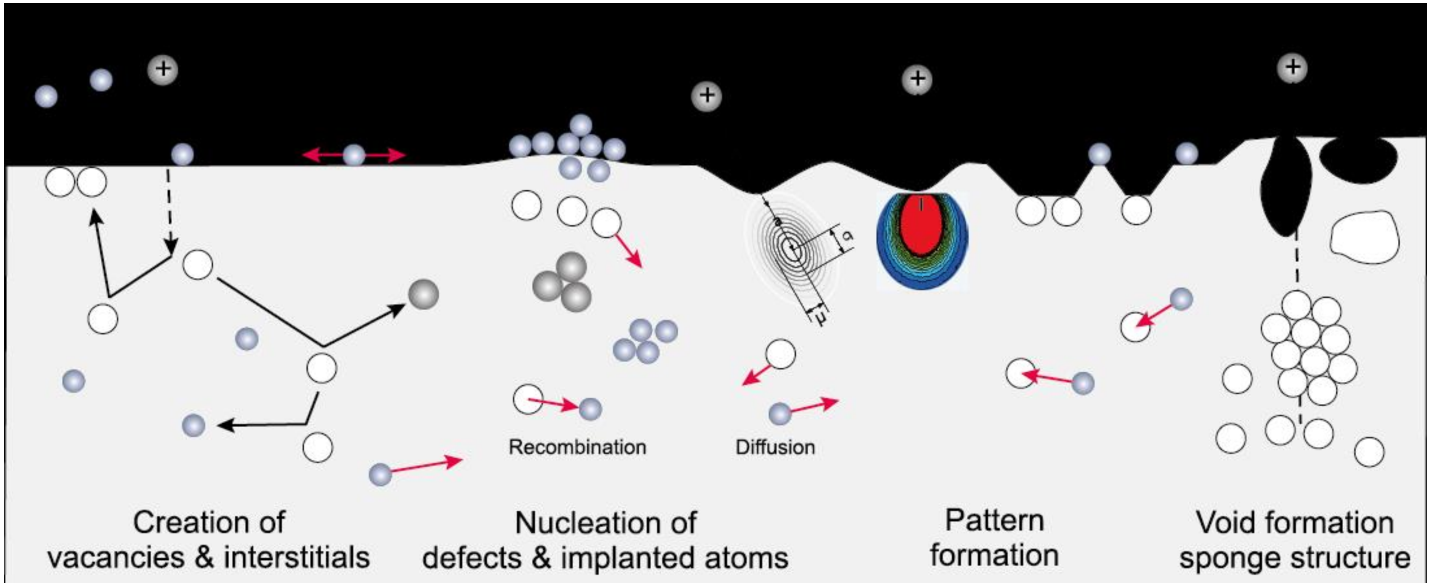


Atom rearrangement, impurity deposition, defect creation, amorphization, recrystallization.

Localize energy deposition in hadron therapy.

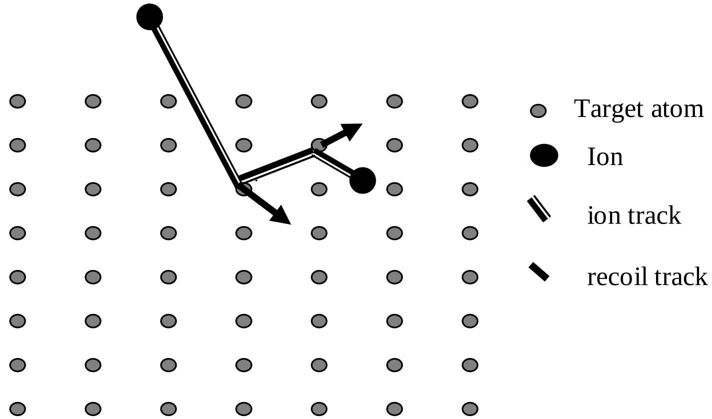
$$V(r) = \left(\frac{Z_1 Z_2 e^2}{r}\right)\chi(r)$$

Interatomic potential

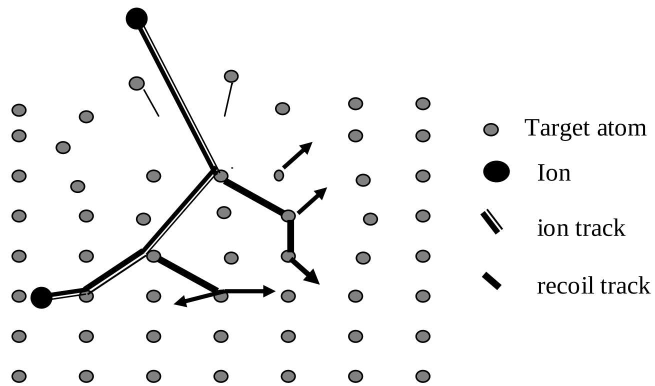


Dependence on projectile species and energy

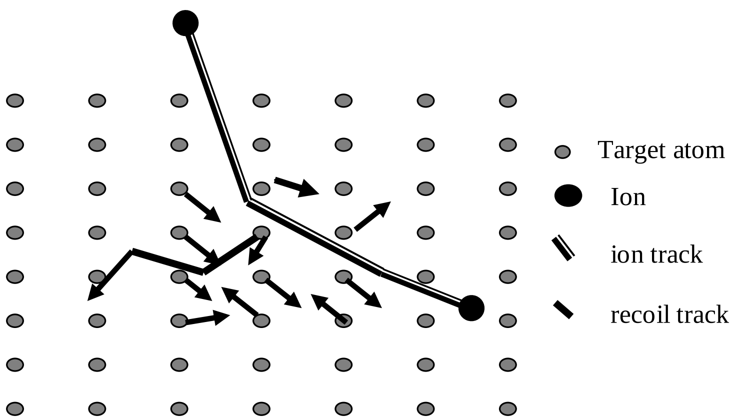
Formation of collision cascade



Single collision (Light ions at low energy)

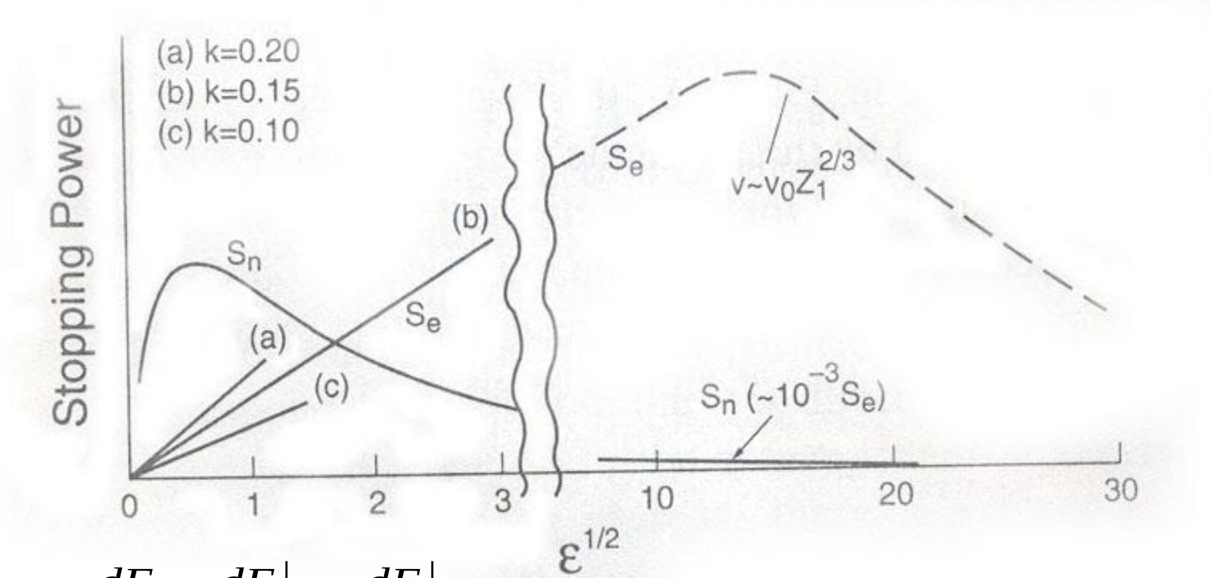


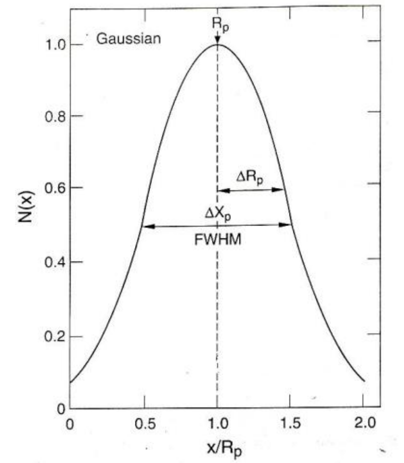
Linear Collision (Medium energy)



Thermal spike (High energy heavy ions)

Stopping and range of atoms





$$\frac{dE}{dX} = \left.\frac{dE}{dX}\right|_n + \left.\frac{dE}{dX}\right|_e$$

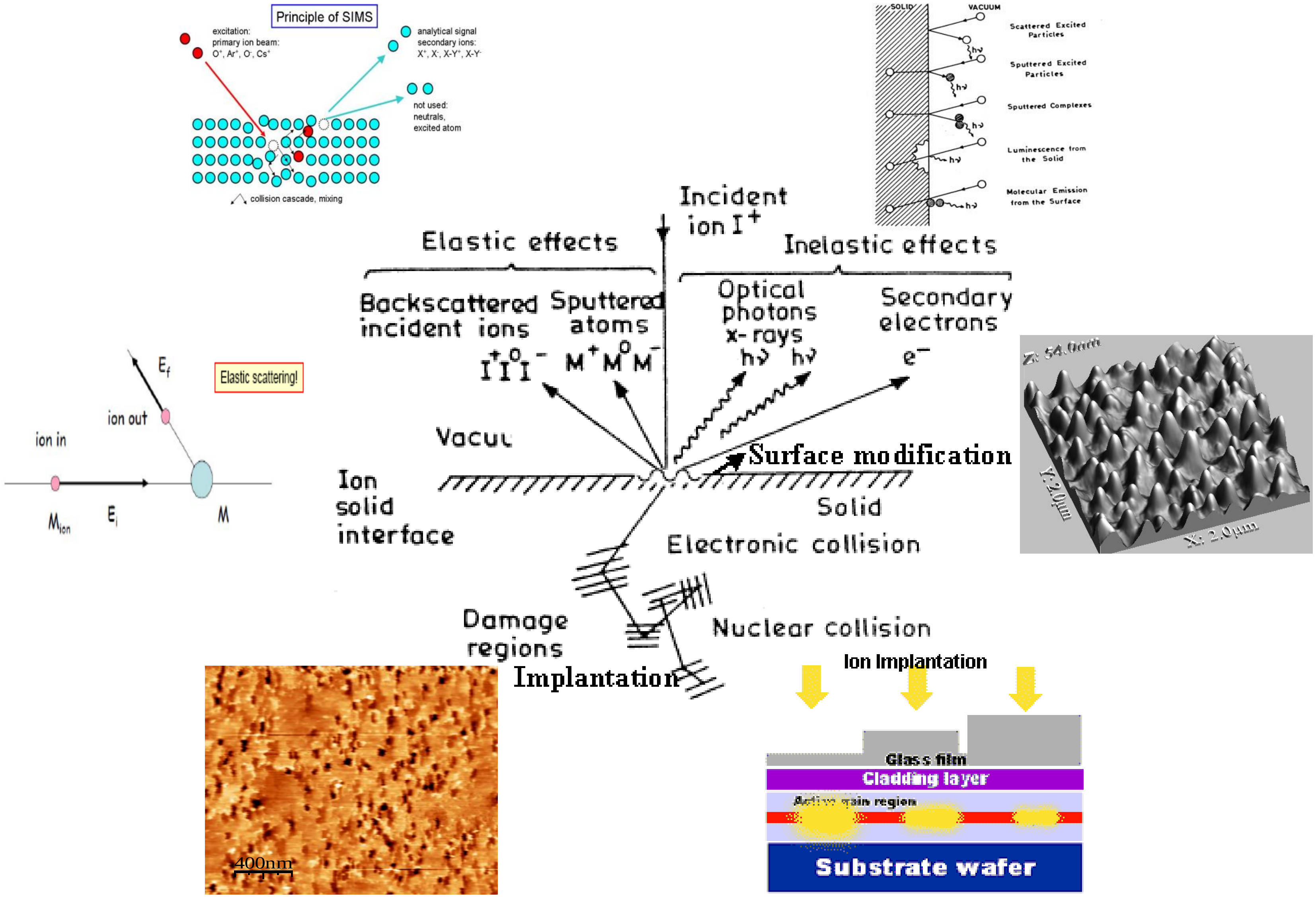
$$\boxed{\varepsilon = \frac{0.03255E(eV)}{Z_1 Z_2 \left(Z_1{}^{2/3} + Z_2{}^{2/3}\right)^{1/2}} + \frac{M_2}{M_1 + M_2}}$$

$$\boxed{R = \int_{E_0}^{0} \frac{1}{dE/dX} dE}$$

$$\boxed{S = \frac{1}{n}\frac{dE}{dX}}$$

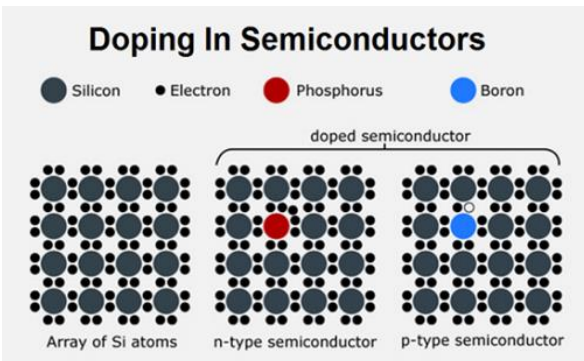
Stopping power = energy loss per unit path length

Stable Ion Solid Interactions

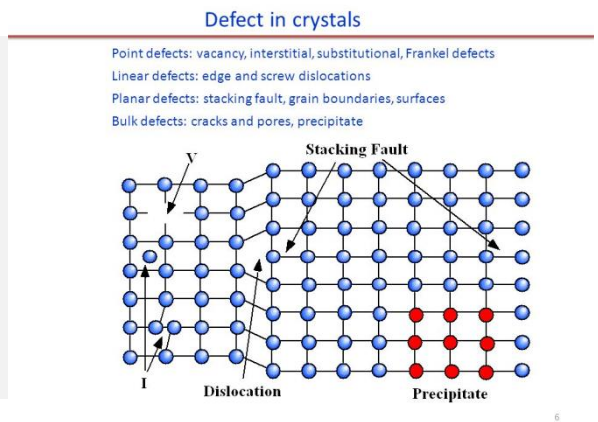


Modification and characterization of material properties

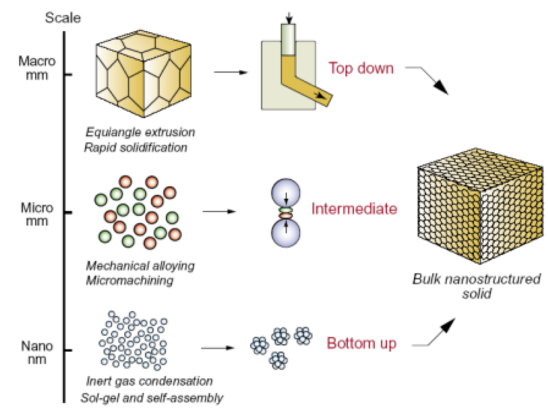
Material properties depends on local structure and electronic functionality (electric, magnetic, optical etc.)



Incorporate impurity



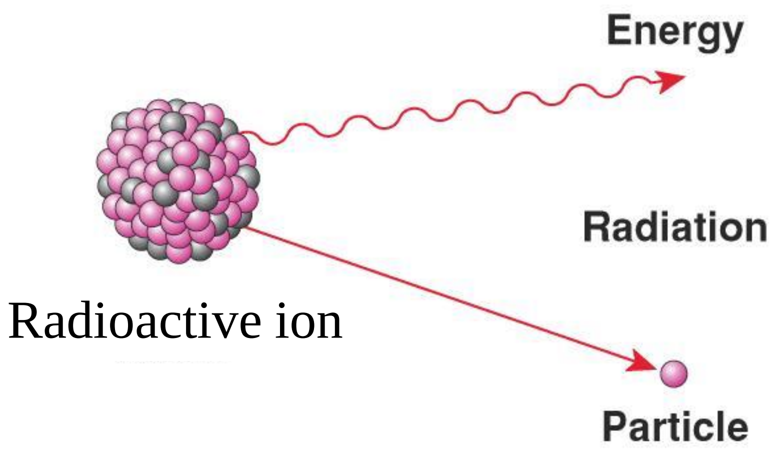
Create defects



Dimensional change

Ion scattering (LEIS, MEIS, RBS)
Ion induced electron and photon emission
Ion microscopy, Auger electron spectroscopy,
Proton induced X ray emission

Radioactive Ion Solid Interactions



Radioactive ion implantation on surface and near surface adds possibilities of modification and characterization in sub atomic scale.

Spectroscopic study of emitted radiations

In material science: Probe the host materials at sub atomic resolution when nuclear properties of the implanted nuclei is known.

In nuclear physics: Explore the properties of exotic nuclei when properties of host material are known.

The use of radioactive low energy ion beams in Surface Science and Nuclear physics

- ➢**Perturbed Angular Correlation (PAC)**
- ➢**Beta Nuclear Magnetic Resonance (β-NMR)**
- ➢**Mössbauer Spectroscopy (MS)**
- ➢**Emission Channeling lattice location**
- ➢**Nuclear spectroscopy**

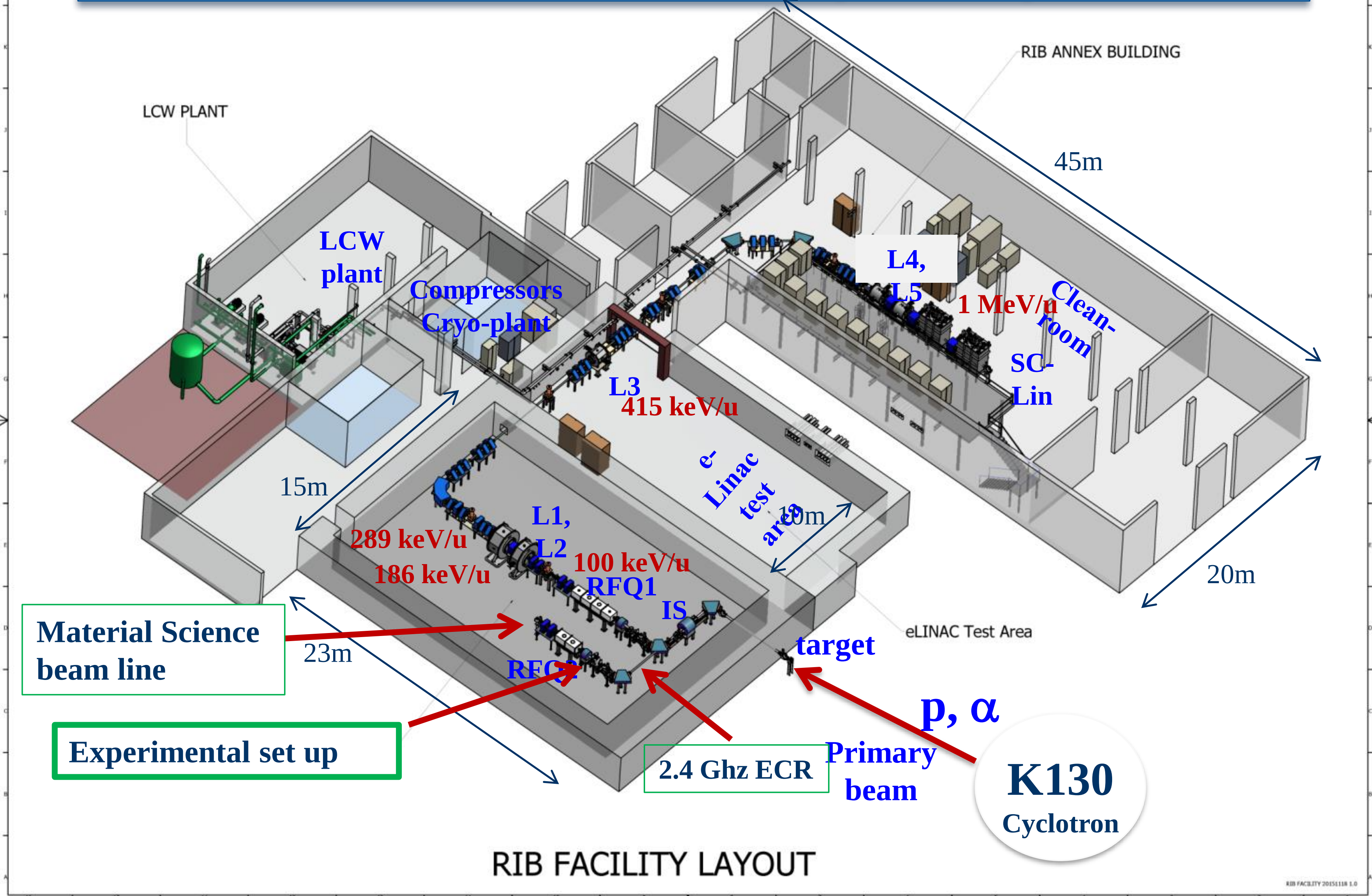
Benefits over other characterization techniques

✓**Nuclear radiation can easily be detected with high sensitivity, i.e. very low concentrations of radioactive implant atoms are required.**

✓**Local probe at sub atomic resolution**

✓**Non destructive**

Radioactive Ion Beam facility birds eye view



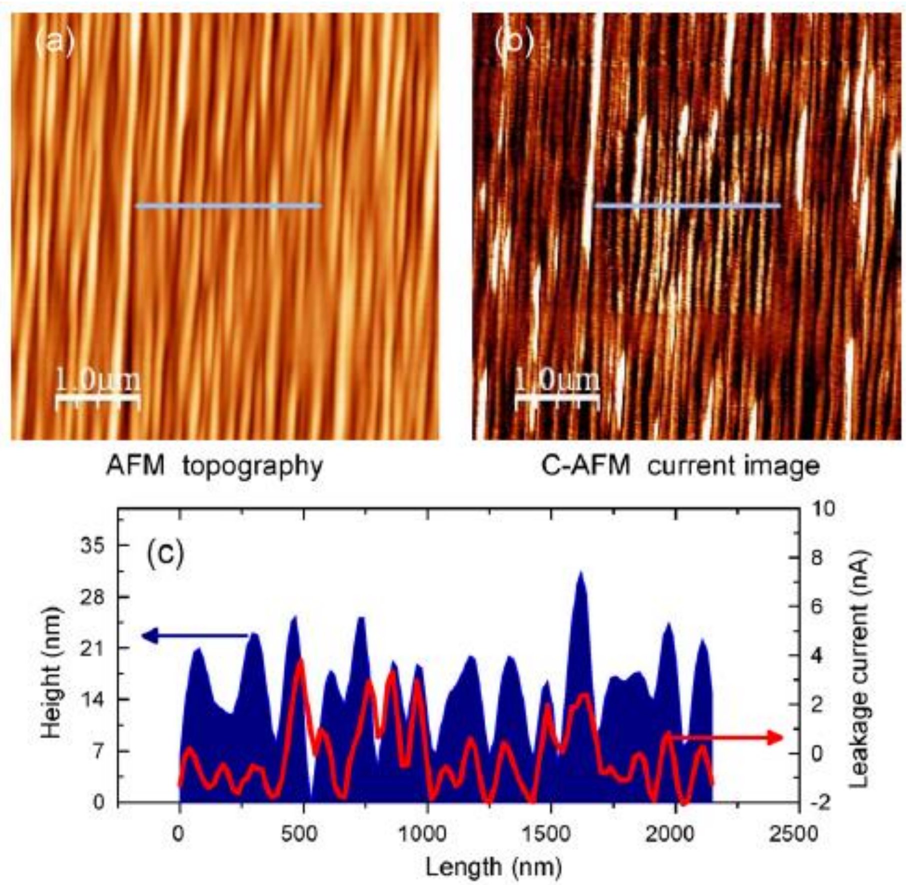
List of stable ion beams developed

Species	Beam Energy(keV)	Beam Intensity/ cm^2
$^{1}H^{+}$	15	1-200 uA
$^{1}H_2^{+}$	15	1-200 uA
$^{4}He^{+}$	12	1-100 uA
$^{11}B^{+}$	10	160 nA
$^{6}C^{+}$	5-12	1.5-10 uA
$^{14}N^{+}$	5-14	6-50 uA
$^{14}N_2^{+}$	5-14	6-60 uA
$^{16}O^{+}$	5-14	5-50 uA
$^{16}O_2^{+}$	5-14	5-50 uA
$^{20}Ne^{+}$	10	1-10 uA
$^{40}Ar^{+}$	8-12	9-60 uA
$^{40}Ar^{2+}$	24	30 uA
$^{58}Ni^{+}$	10	800 nA
$^{64}Zn^{+}$	8	10 nA
$^{66}Zn^{+}$	8	5 nA
$^{68}Zn^{+}$	8	3 nA
$^{107}Ag^{+}$	6	240 nA

List of radioactive ion beams developed

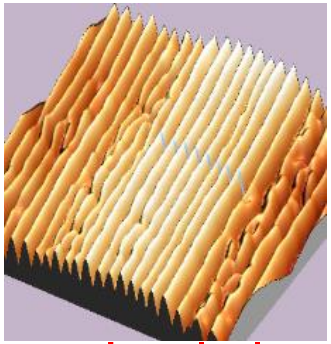
RIB	*Prod. route*	*T1/2*	*I(pps) before RFQ*	*I(pps) after RFQ*	*Study/Applications*
^{14}O	$^{14}N(p, n)$	71 s	5.0×10^3	3.2×10^3	super-allowed beta decay, test of standard model
^{42}K	$^{40}Ar(\alpha,pn)$	12.36 hr	2.7×10^3	-	radio tracer
^{43}K	$^{40}Ar(\alpha,p)$	22.3 hr	1.2×10^3	-	Radio tracer
^{41}Ar	$^{40}Ar(\alpha,2pn)$	109 min	1.3×10^3	-	tracer used in engineering ; wear studies
^{111}In	$^{nat}Ag(\alpha,xn)$	2.8 days	1.0×10^4	-	Perturbed angular correlation spectroscopy, wear studies

Parallel Pt nano wires formed by 16 keV Ar+ ion bombardment at grazing incidence

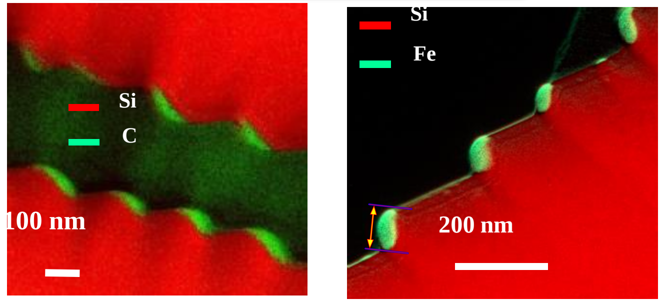


P. Karmakar, Appl. Surf. Sci. 258, 4125 (2012)

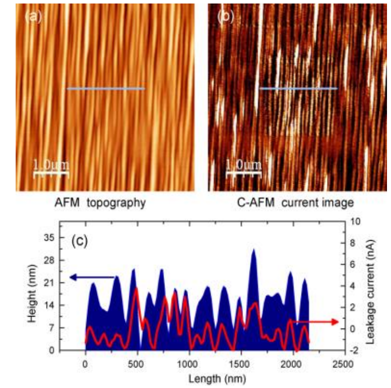
Nano wires on Si



Germanium ripple



Nano wire of Fe and SiC



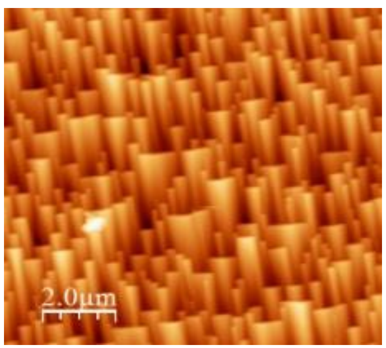
Platinum nano wires on Si

P. Karmakar et .al, Appl. Phys. Lett. 104, 231601 (2014)

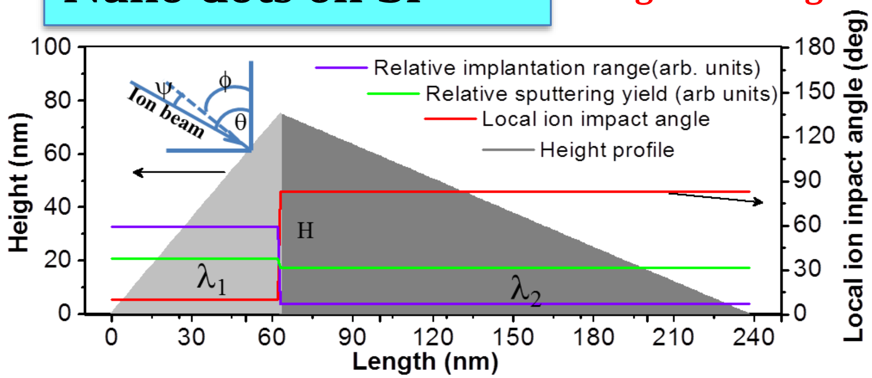
P. Karmakar, Appl. Surf. Sci. 258, 4125 (2012)

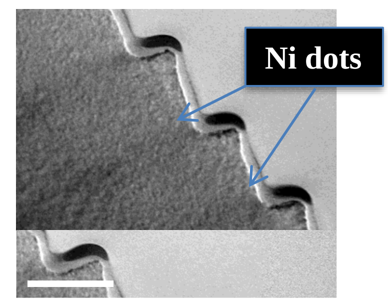
Nano dots on Si

Large area single step Ni nano dot formation



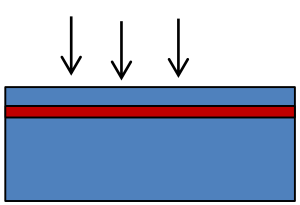
Si conical structure

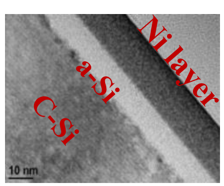




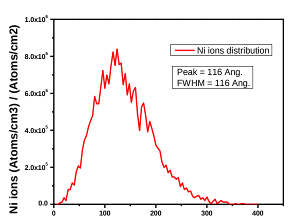
TEM Cross sec view

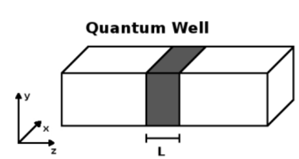
Buried layer (quantum well structure) formation



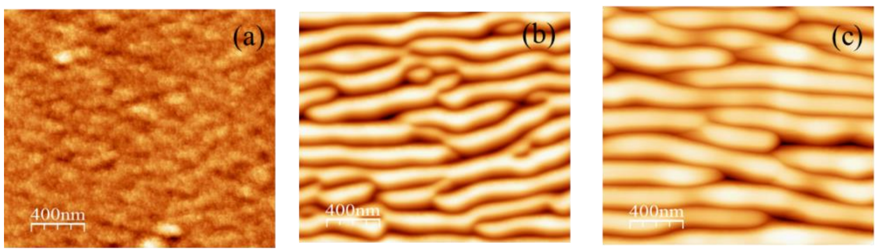


TEM Cross sec view

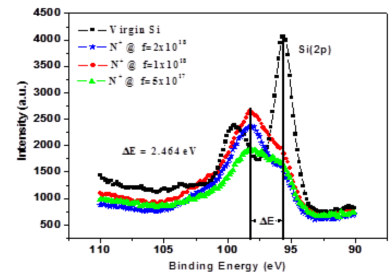


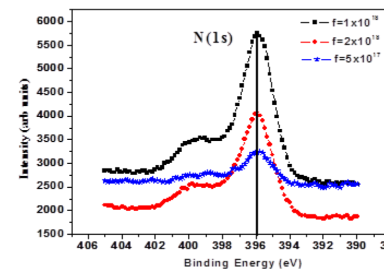


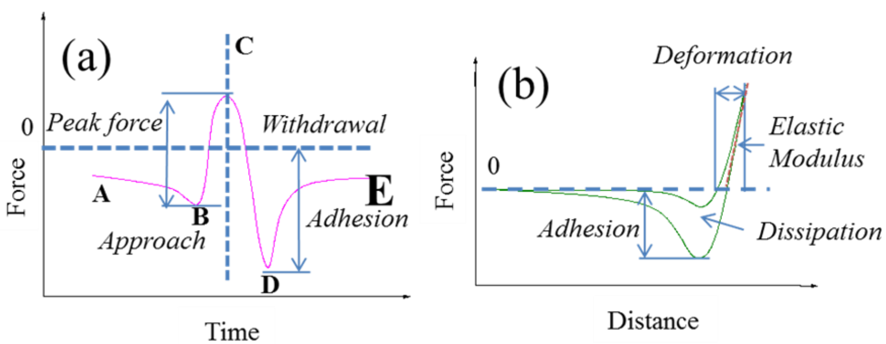
Quantitative nano mechanical property study of Si ripple

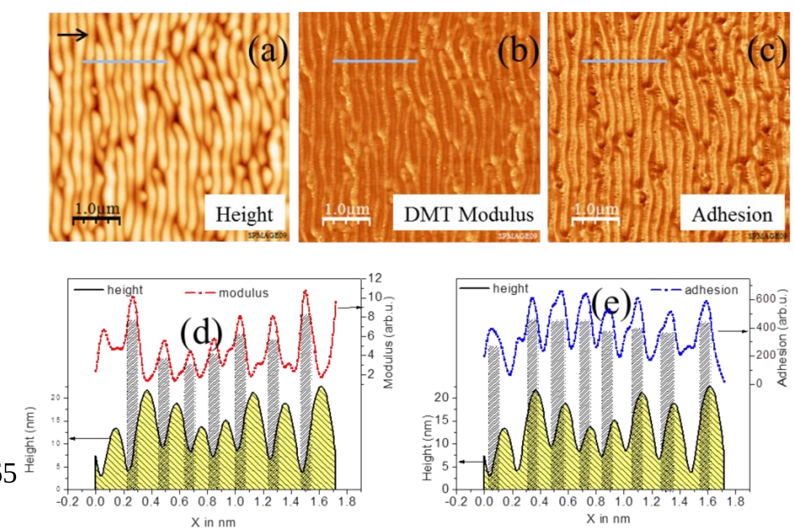


5 x 10^{17} ions/cm^2 1 x 10^{18} ions/cm^2 2 x 10^{18} ions/cm^2



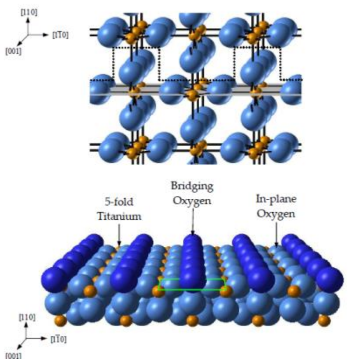




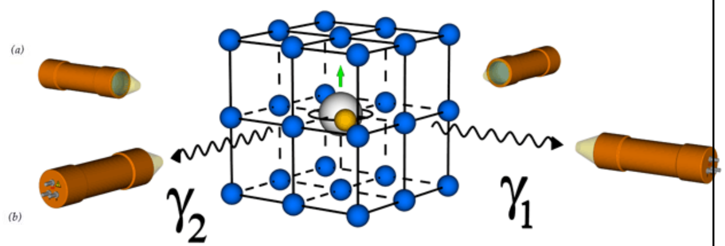


S. Bhattacharjee, et al. and **P. Karmakar**, Thin Solid Films **645** (2018) 265

Atomic scale study of ion impact modification of TiO_2(110) crystal

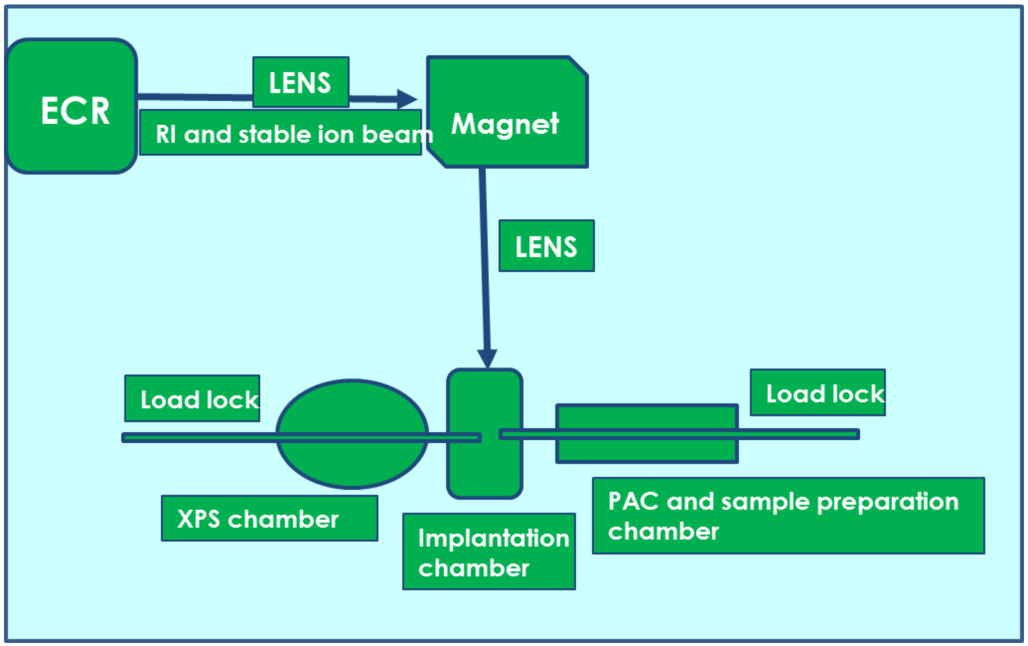


TiO_2 bulk structure

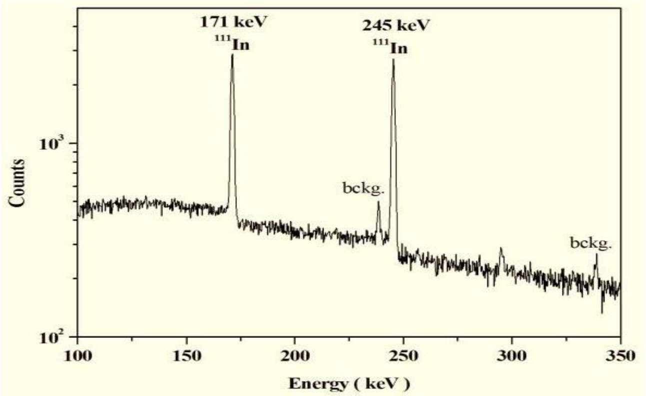


Perturbed angular correlation spectroscopy

- ^{1111}**In RIB** : produced in ^{nat}Ag(α,xn) with 30 MeV, alpha beam from K-130 cyclotron
- keV energy mass analyzed ^{111}In beam is developed using ECR plasma sputtering of chemically separated ^{111}In Cl $_3$
- ^{111}In implantation on TiO_2(110) surface at fluence > 10^{10} ions/ cm^2
- Perturbed Angular Correlation (PAC) spectroscopy measurement for the study of ion impact induced crystal modification in atomic scale.



Proposed extension of Experimental set up at RIB cave



Previous gamma-ray spectrum of implanted ^{111}In ions

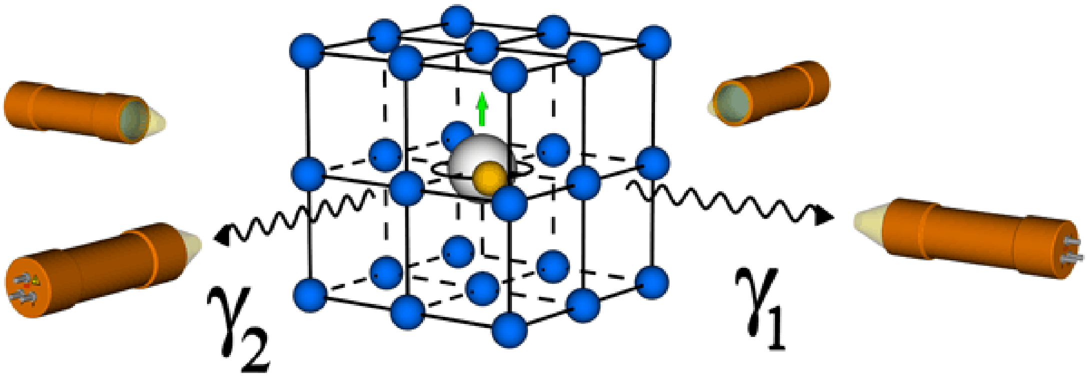
What new in ANURIB

- More stable and radioactive ion species
- **More intensity** of stable and radioactive ion beams
- Various energy
- Multiple experimental station
- Well equipped characterization laboratory
- More collaboration with institutes, universities and industry

Proposed beam lines and facilities for material science research

1. Multiple experimental station for stable and radioactive ions of few eV to MeV energy.

2. *In situ* and *ex citu* Perturbed Angular Correlation spectroscopy

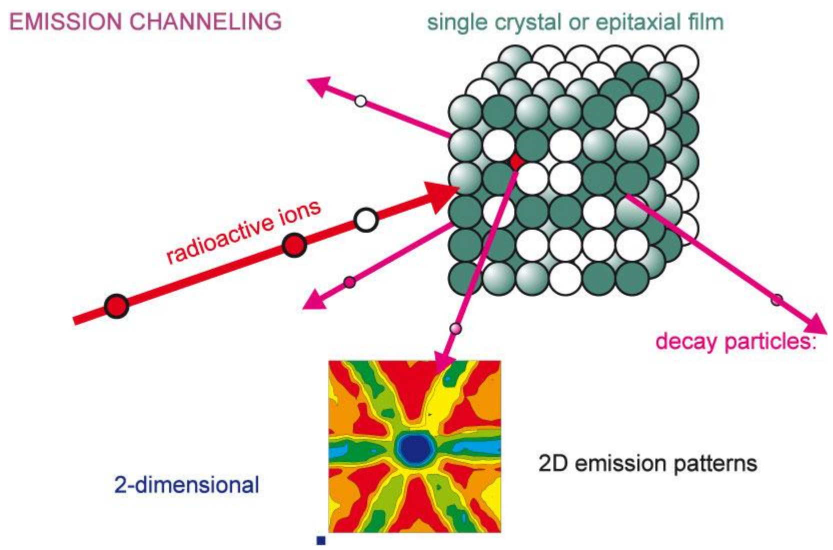


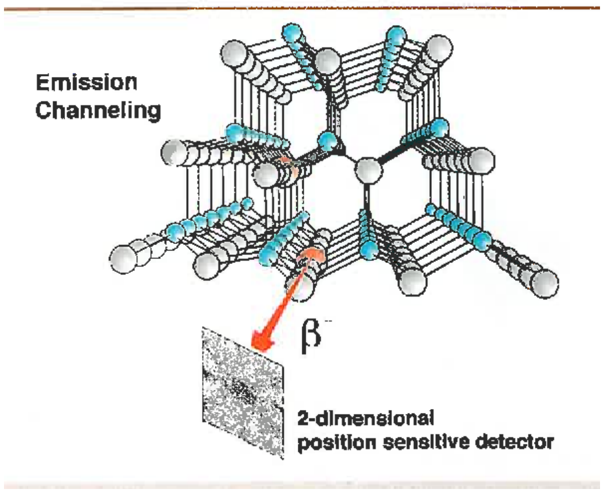
Perturbed angular correlation spectroscopy

Emission channeling by radioactive ion implant

Emission channeling determines the lattice location of radioactive impurities in crystalline solids at very low impurity concentrations of typically 10^{17} cm^{-3} by measuring the channeling effects of electrons, positrons or α-particles emitted in the nuclear decay.

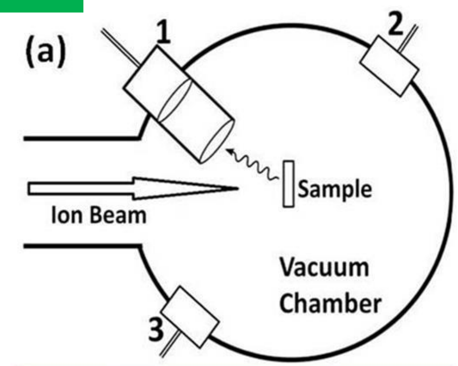
Lattice sites of ion implanted dopants in semiconductors and subsequent recovery of implantation defects can be studied after implantation without amorphizing the lattice.



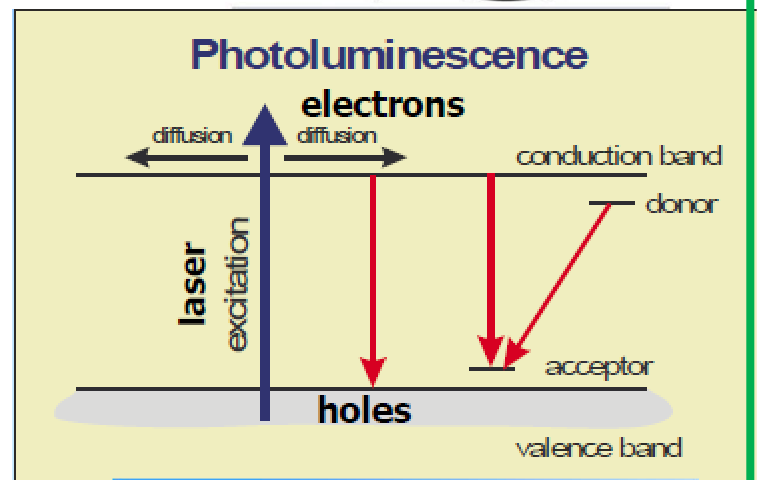


Detection of interstitial or substitutional position of the implanted atoms
Ion induced defect detection.
Which are important for fundamental understanding as well as control of physical and chemical properties

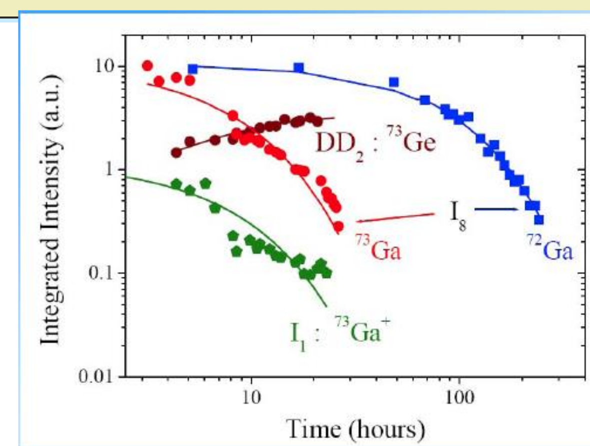
Photoluminescence Radioactive impurity



- Change of chemical nature of the implant with time.
- change in the character of impurity
- distinguish the origin of photoluminescence
- Change of color center with time



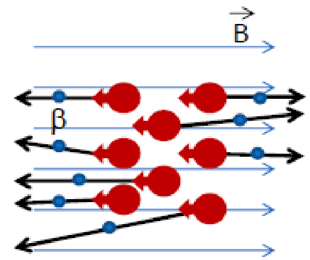
Photoluminescence (PL) in ZnO:
^{73}Ga (4.8 h) → ^{73}Ge and ^{72}Ga (14 h) → ^{72}Ge



Proposed Beta detected NMR facility for ANURIB

Weak interaction doesn't conserve parity

- Anisotropic emission of beta particles from decay of polarized nuclei
- NMR resonance: destruction of asymmetry, observed as decrease in beta-decay asymmetry



Angular distribution of beta-radiation:

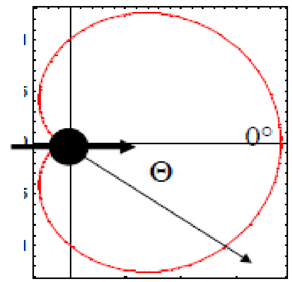
Velocity of beta-particle (v/c close to 1)

Angle between beta-particle emission and direction of spin polarization

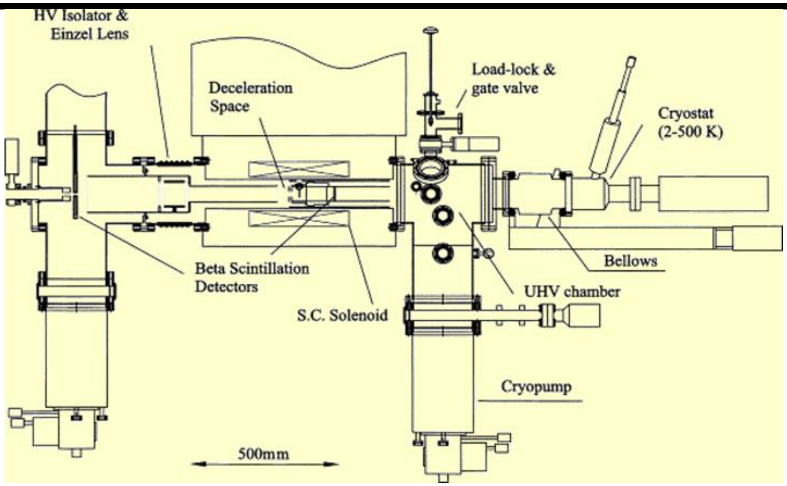
$$D(\Theta) = 1 + a\frac{v}{c}\frac{\langle I_z \rangle}{I}\cos(\Theta)$$

Asymmetry factor (-1,1), depends on details of beta decay

PI (0-100%): degree of spin polarization



Measured b-decay asymmetry: $A = \frac{N(0^\circ) - N(180^\circ)}{N(0^\circ) + N(180^\circ)} = \frac{N_1 - N_2}{N_1 + N_2}$



Conventional versus beta-NMR

	Conventional NMR	Beta-NMR
Polarization	• << 1%: **Created inside** sample: (thermal occupation of levels in NMR magnetic field)	• 1%-100%: **Created outside** sample: (e.g. laser excitation)
Detection	• << 100% detection efficiency: Change of magnetization	• Up to 100% efficiency: Anisotropy of beta decay
Probe nuclei	• Stable or long-lived: ^{1}H, ^{13}C… • Need ~10^{17} in the sample	• Radioactive; ^{8}Li, ^{11}Be, ^{31}Mg, … • 10^{7} per resonance

10 orders of magnitude higher sensitivity than conventional NMR

Summary

- Existing RIB facility is being used to study the ion beam induced growth of various nano structures and ion implantation.

- Radioactive beam is implanted to probe atomic level defects and magnetic structures of solids.

- Stable and radioactive ion beams are being used for material science and nuclear spectroscopy experiments by VECC, SINP, BARC, Jadavpur University, Amity University, IIT Kharagpur UGC-DAE-CSR Kolkata etc.

- Looking forward for development and utilization of ANURIB facility for applied research with more numbers of stable and radioactive ion beams of few eV to MeV energy with higher beam intensity.
- New beam lines and equipments for atomic scale modification and characterization of materials and devices

Thank You!