Development of NTD Ge sensors for low temperature thermometry

(for Neutrinoless Double Beta Decay)

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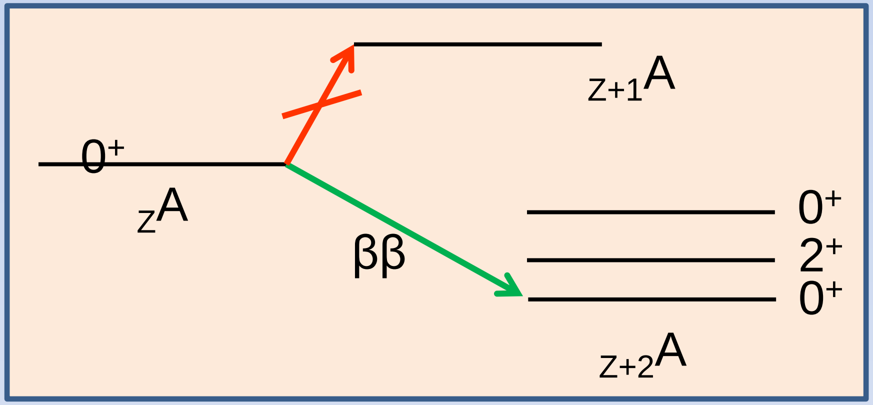
Plan of the talk

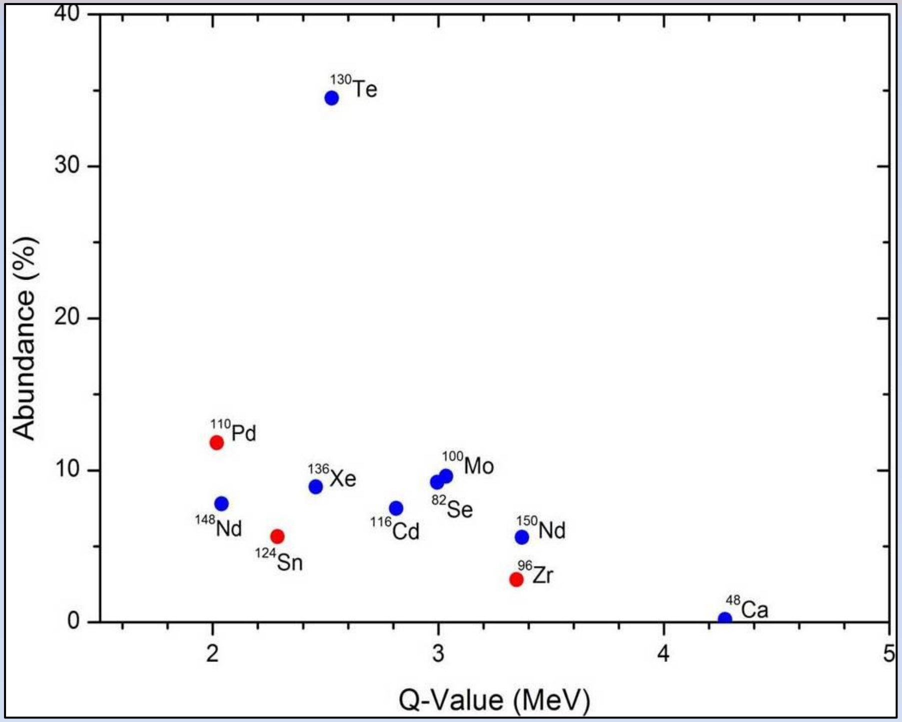
- Cryogenic bolometer for Neutrino less Double Beta Decay (NDBD)
- NTD Ge sensor development for bolometer
- Hall Effect Measurement – carrier concentration
- Defect studies in NTD Ge
    - Positron Annihilation Lifetime Spectroscopy (PALS)
    - Channeling
- Low temperature resistance measurement of NTD Ge sensor
- Summary

Search for NDBD in ^{124}Sn

- 2νββ : 2nd order weak interaction
- Normal beta decay (βν) suppressed by Q-value or J^{π}
- ^{124}Sn is one of the nuclei which undergoes ββ decay



A typical level diagram for ββ decay



Various isotopes which can undergo ββ decay

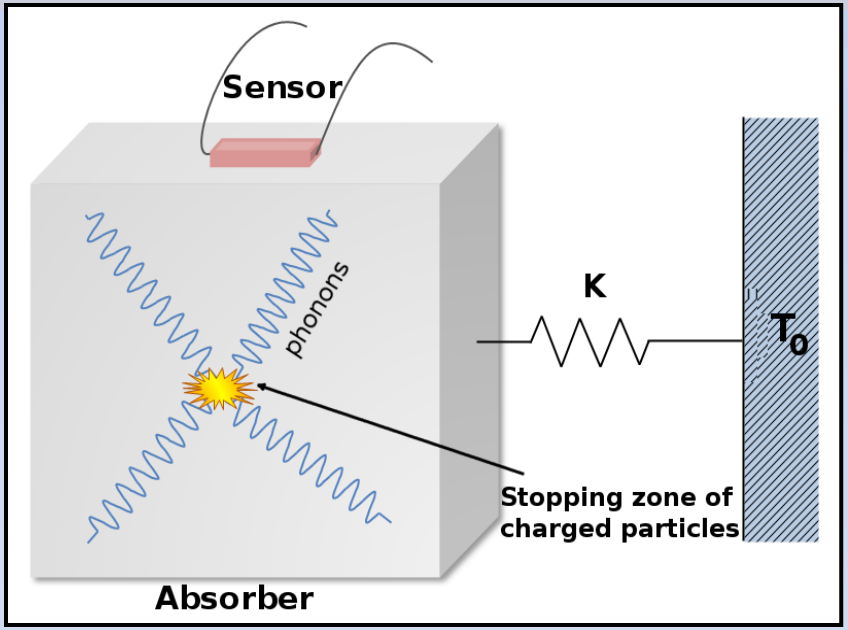
Significance of 0νββ:

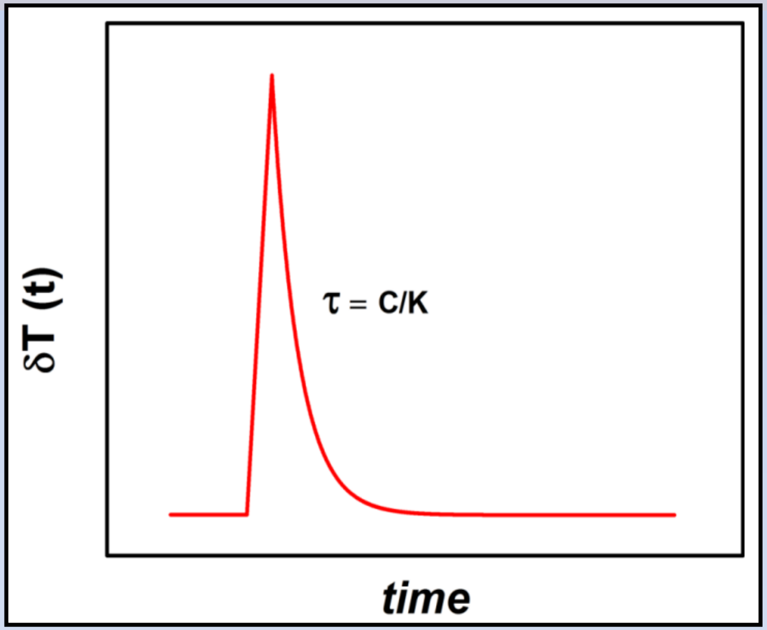
- Only experiment which can tell whether neutrino has its own antiparticle (Majorana particle) or not (Dirac particle)

Experiments will look at:

- Constancy of sum energy of two simultaneously emitted electrons, which requires high energy resolution and large scale detector

Schematic of bolometer





- When DBD occur, energy of electrons heats the crystal
- Thermalization leads to rise in the crystal temperature T+δT
- The detector will be operated at an optimum temperature of 10mK, in order to get a reasonable δT.

NTD Ge sensor development

- Low neutron capture cross-section - homogenous doping. Melt-doped Ge with large concentration will be inhomogeneous and can have different characteristics
- Dopant concentration can be controlled by changing the neutron dose
- Low specific heat, fast rise time are essential to detect bolometer pulse.

Dopant details of irradiated Ge

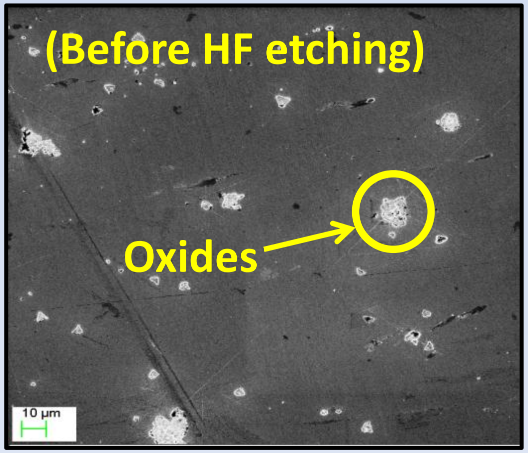
Isotope	Products formed (half-life)	Decay into(decay mode)	Type
^{70}Ge	^{71}Ge* (11.43 d)	^{71}Ga(e^- capture)	p
^{72}Ge	^{73}Ge (stable)	^{73}Ge	-
^{73}Ge	^{74}Ge (stable)	^{74}Ge	-
^{74}Ge	^{75}Ge* (82.78min)	^{75}As (β-decay)	n
^{76}Ge	^{77}Ge* (11.3,38.8hrs)	^{77}As*,^{77}Se (β, β-decay)	n

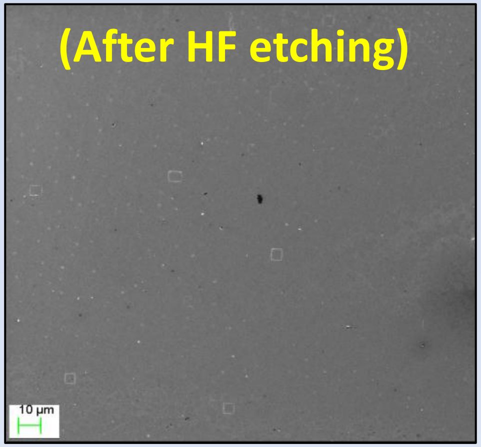
- For a natural Ge, the neutron doping results in p-type due to its isotopic abundance and the thermal neutron capture cross section.

Irradiation details of NTD Ge

- Ge sample irradiated with thermal neutron fluence at **Dhruva reactor, BARC, Mumbai**.
- Samples exposed to both **thermal and fast neutrons**.
- **Fast neutron induces damage to the crystal lattice**.
- The samples are etched with HF to remove oxide layers.
- Scanning Electron Microscope (SEM) and Energy Dispersive X-ray Analysis (EDAX) are done before and after etching.
- Etched samples are free of oxides.

Sample	Values
Plane	<100>
Thickness (mm)	1.0
Resistivity (Ωcm)	>35
Thermal neutron fluence (<0.625eV) from the reactor data	7×10^{18} /cm^2
Fast neutron fluence (.625eV - 0.821 MeV) from the reactor data	1.2×10^{18}/cm^2
Calculated carrier concentration/cm^3 (Acceptor – Donor)	1.7×10^{17}/cm^3





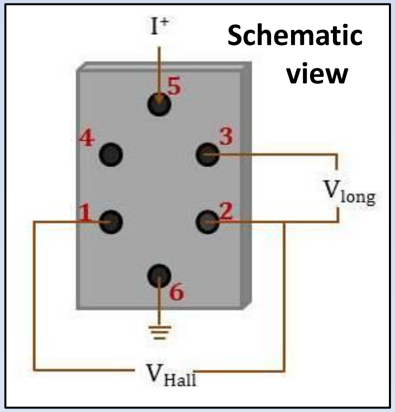
SEM images of NTD Ge sample

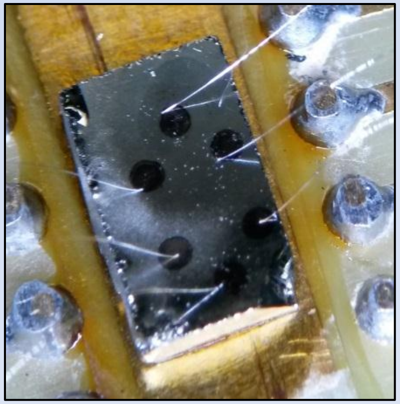
Hall Effect Measurement

- For Hall effect measurement six Au (88 %) – Ge (12 %) were made using standard Vander Pauw method.
- The samples were rapid thermally annealed at 400°C for 2 min.
- Electrical connections were made by wedge bonding 25 µm Al wires to the contact pad.
- The Hall voltages were measured at both 77 K and at 300 K.
- The hall voltage is measured with 100µA current in the varying magnetic field of -1 to 1 tesla.
- Both Hall voltage and longitudinal voltage were measured simultaneously with two lockin amplifiers.
- The carrier concentration were estimated by assuming single carrier approximation using the following formula:

$$V_H = \frac{B_z . I_x}{n. e. t}$$

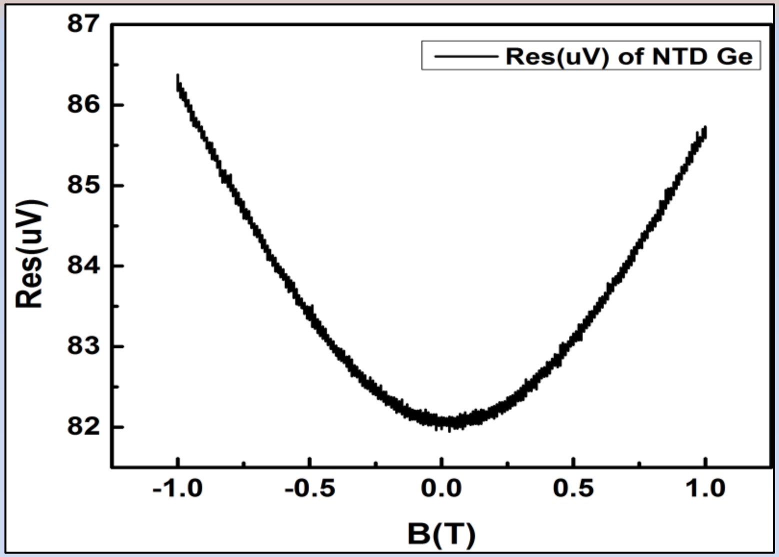
V_H = Hall voltage
B_z = Applied Mag field
I_x = Supplied current
t = thickness of sample
n = carrier concentration
e = charge

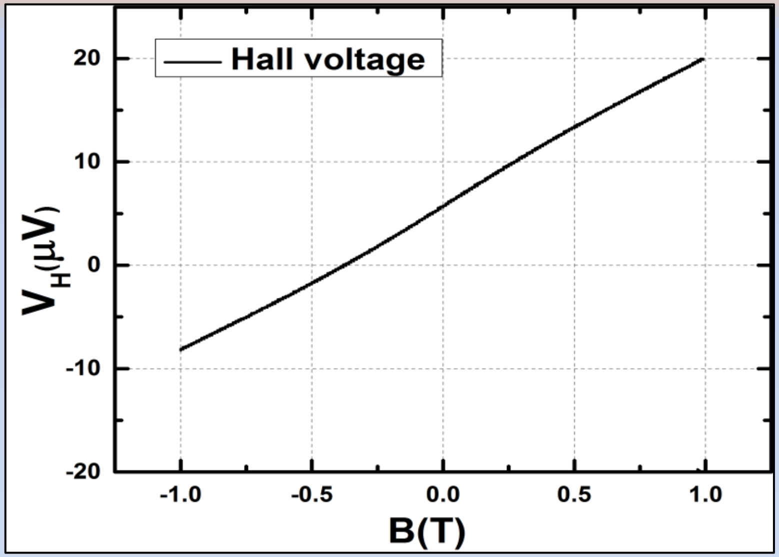




Actual sample

Hall Effect Measurement cont..





- Carrier concentration was estimated using the Hall voltage value.
- The contribution of magneto-resistance was taken into account during estimation.
- The Hall factor (Hall mobility / Hall conductivity) is close to unity [1] below 100K.
- Hall effect measurement can be used as tool to estimate thermal neutron dose by estimating the carrier concentration at 77K.
- Estimated thermal neutron fluence is about **4.6 x 10^{18}/cm^2.**

Sample	Carrier concentration (x 10^{17}/cm^3)		
	77K	300K	Calculated using neutron dose
NTD Ge	1.11	2.13	1.70

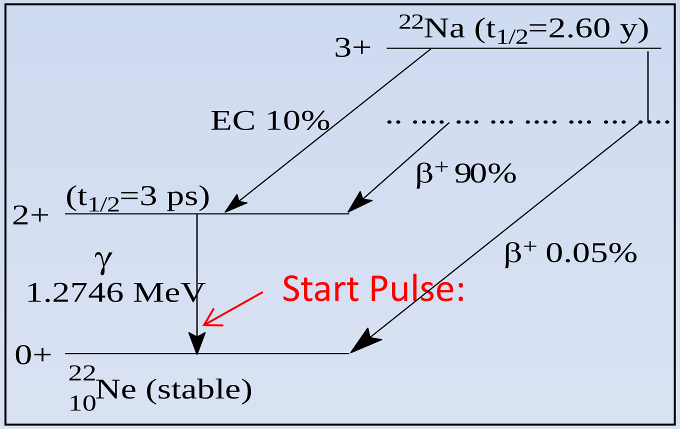
- At 300K the intrinsic carriers due to thermal agitation can participate in conductivity, hence the values are higher than the actual dopant concentration.

[1] F.J.Morin, Physical Review, **93** (1954) 62.

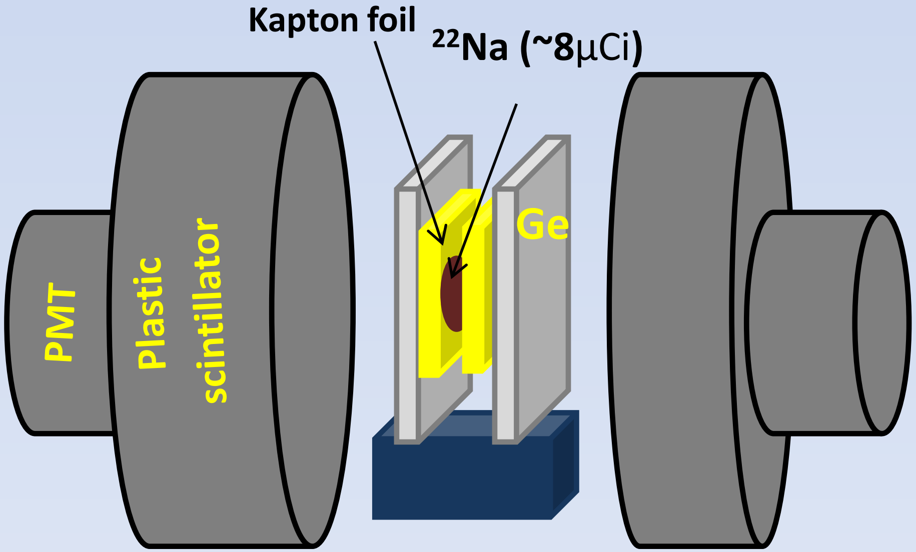
Defect studies – Positron Annihilation Lifetime Spectroscopy

- PALS will quantify the defect size through the positron lifetime measurement
- A positron is allowed to interact with the sample, where it experiences both attractive (due to e^-s) as well as the repulsive force (due to core ions)
- In a defect free crystal, the positron interacts with the valance electron and two γ rays of 511 keV are generated as a result of annihilation. This positron lifetime gives the bulk lifetime
- When a positron interacts with a crystal having defects, it is more likely to be trapped in the defect due to repulsive force of ions. This will lead to increase in lifetime of positron. Thus larger the defect, longer will be the lifetime of the positron

Decay scheme of a ^{22}Na nucleus



Stop Pulse: 511keV (γ-ray resulting from annihilation in the crystal)



- **Counts:** ~ 3 x 10^6 events
- **Count rate:** ~ 50 cps

PALS Results

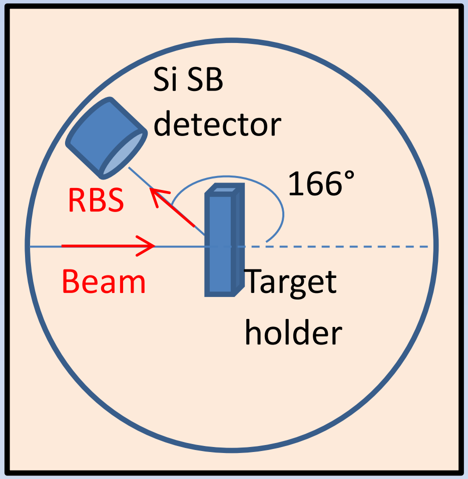
- Irradiated sample, irradiated-annealed at 600°C for 2hrs (in vacuum sealed quartz tube) and virgin sample are studied using PALS at **RCD, BARC, Mumbai**.
- PATfit software is used for acquiring and analysing data
- The irradiated sample shows **monovacant defects and vacancy clusters**.
- The annealed samples had the positron lifetime close to that of the un-irradiated (bulk) lifetime.

Samples	ϕ_{th} (n/cm^2)	$T_{\beta+}$ (ps)	Ref (ps) [2]
Virgin Ge	-	232 ± 0.3	228 (Bulk)
Irradiated Ge	4.57×10^{18}	294 ± 0.3	293 (Monovacant)
		401 ± 30	401 (Vacancy Clusters)
Annealed NTD Ge	4.57×10^{18}	233 ± 0.4	228 (Bulk)

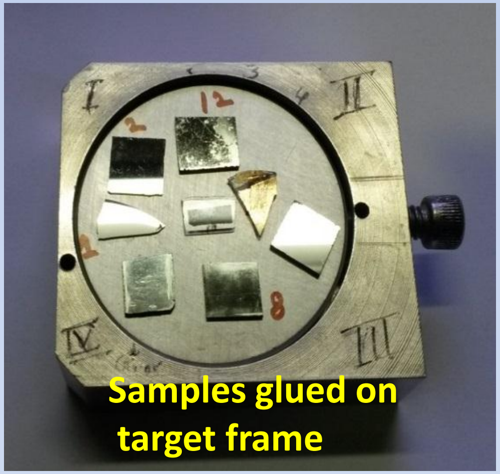
[2] Reinhard Krause-Rehberg, Hartmut S. Leipner, *Positron Annihilation in Semiconductors: Defect Studies*, Springer, 1998.

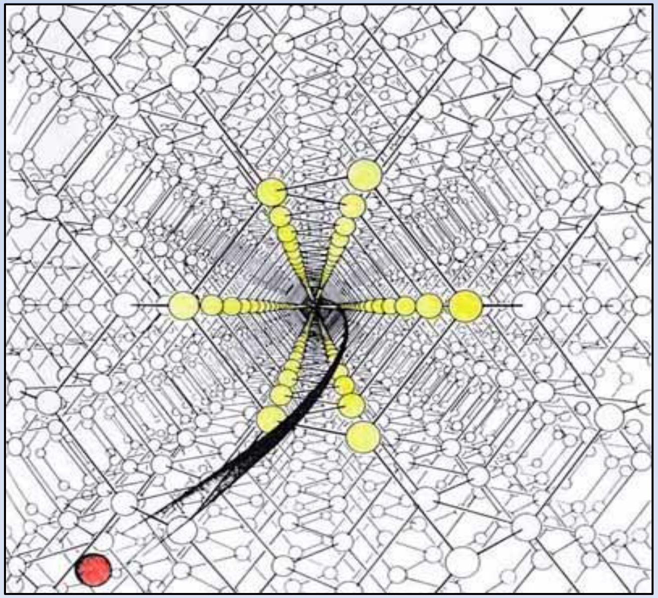
Channeling studies

- NTD Ge crystal probed with an energetic alpha beam (~2MeV) along the axial direction at **PARAS facility, IUAC, New Delhi.**
- Defects lead to dechanneling of the beam, results in higher Rutherford Back Scattering (RBS) yield
- Minimum current – avoids damage produced during measurement.

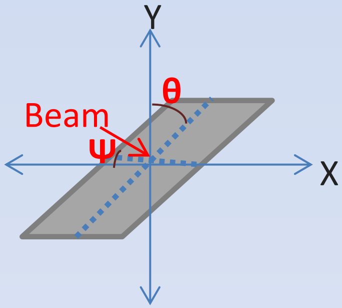


Schematic diagram

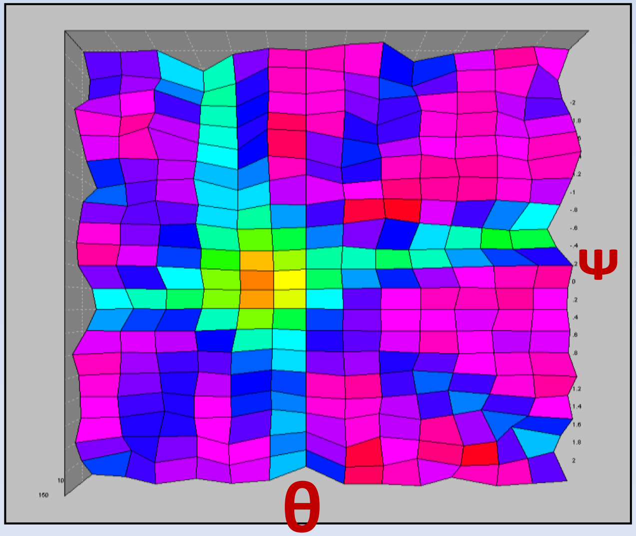




Artist view of ion channeling along the crystal axis



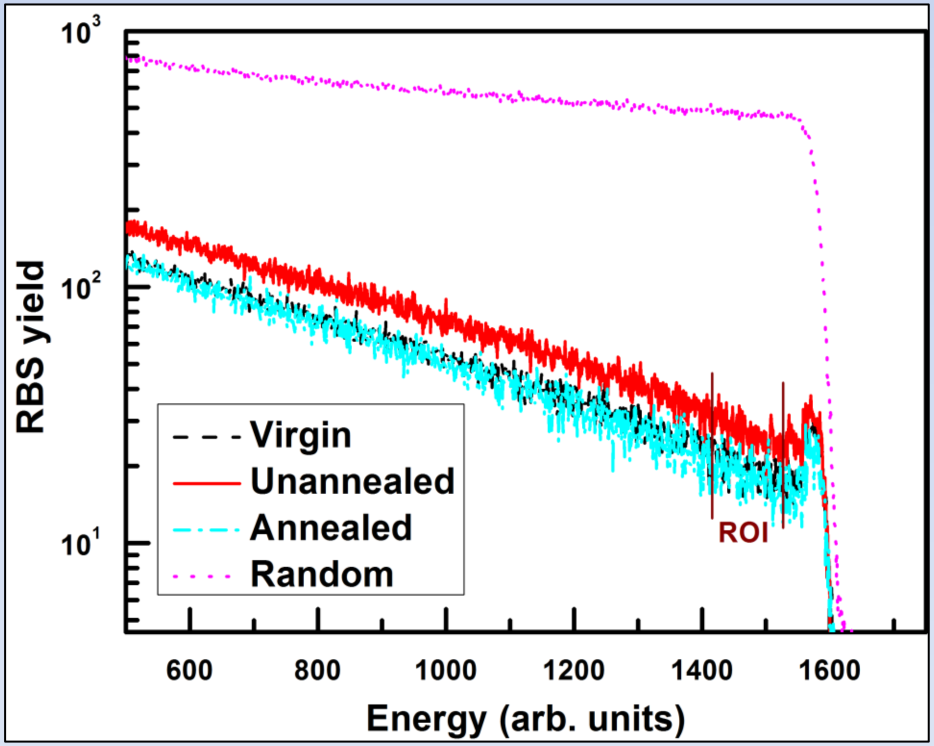
5-Axis Goniometer



2D Image of Ge crystal <100> cleavage plane

Channeling results

- The irradiated sample – higher RBS yield compared to virgin sample
- Annealed sample – close to virgin sample.
- Indicates recovery of the defects in the crystal after annealing.
- Defect density calculated to a depth of 316nm just below the surface



Channeled spectra and random spectrum of NTD Ge sample

- The defect density is calculated by,

$$N_D = N\left(\frac{\chi_{min}^{irr} - \chi_{min}^{0}}{1 - \chi_{min}^{0}}\right)$$

Where χ_{min} = channelled RBS/random RBS

Samples	316 nm
Virgin	0.042 ± 0.001
Irradiated	0.058 ± 0.001
Annealed	0.040 ± 0.001
N_D (/cm^3)	**(7.3 ± 0.4) x 10^{20}**

Low temperature resistance measurement in dilution refrigerator

Gas Handling system along with the dilution unit

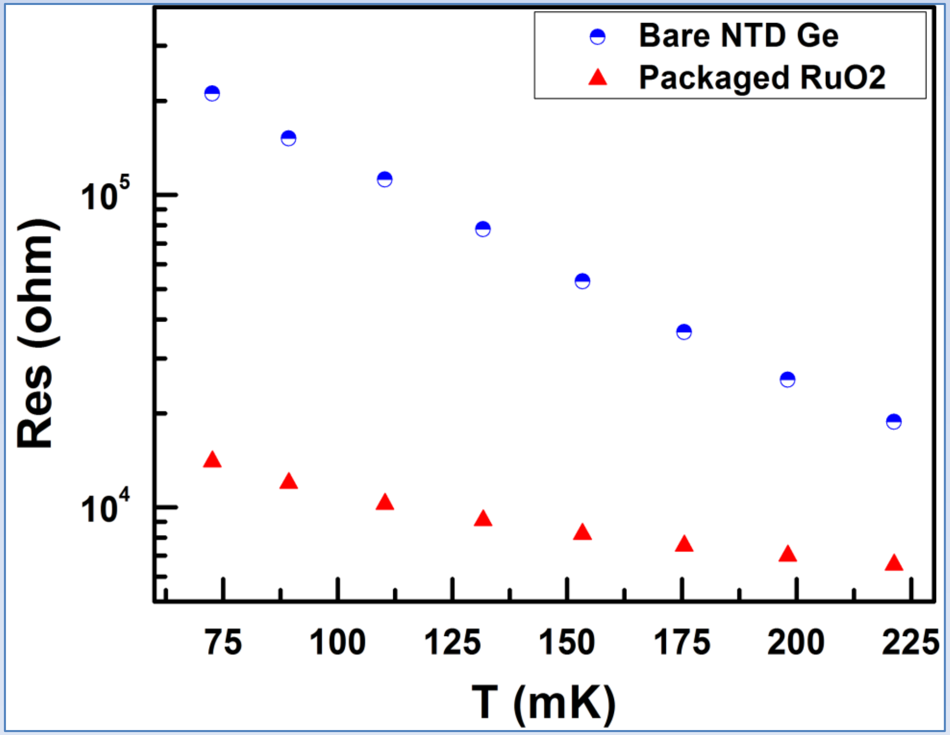
Inset of dilution unit

Probe setup

V. Singh, S. Mathimalar, N. Dokania, V. Nanal, R. G. Pillay, S. Ramakrishnan, Pramana 81 (2013) 719.

Low temperature resistance measurement cont..

- The samples used in Hall probe measurement were tested for low temperature resistance measurement.
- The resistance values are compared with that of commercial RuO_2 sensors.
- Clearly the NTD Ge sensor showed higher dR/dT compared to RuO_2.
- The dR/dT is about ~2.3k Ω/mK at 100mK.
- Below 75mK the NTD Ge shows saturation, which might be due to thermal link or due the noise.



- Logarithmic sensitivity $\alpha = \left|\frac{d(\log R)}{d(\log T)}\right|$
- For a semiconductor thermistor will range between 1 to 10.

Samples	Logarithmic sensitivity at 100mK
NTD Ge	1.7
RuO_2	0.7

- Clearly the figure of merit is higher for NTD Ge as compared to that of RuO_2.

Summary

- Ge wafers are doped by neutron transmutation doping technique.
- Hall probe measurement was done in order to verify the carrier concentration formed due to doping.
- From the estimated carrier concentration at 77K, the neutron dose has been recalculated.
- Samples were studied for the defects due to fast neutron during irradiation.
- Both PALS and Channeling confirmed that annealing the irradiated samples at 600°C for 2hrs in a sealed quartz tube can reduce the defects.
- Low temperature resistance measurement showed better dR/dT compared to that of the commercial RuO_2.

Collaborators

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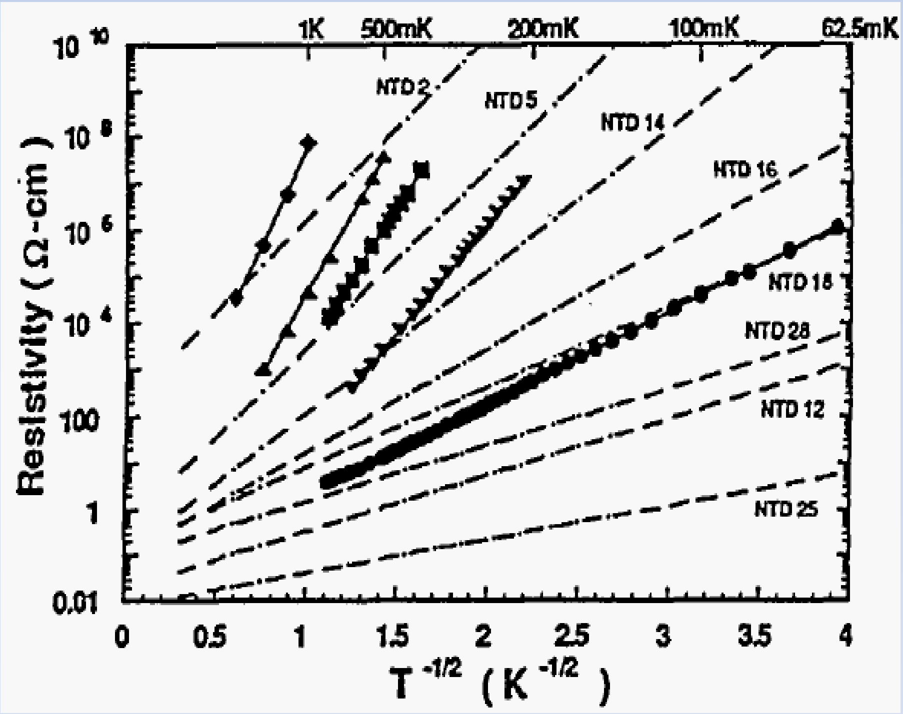
Ms. Sudipta Dubey
Mr. Abhishek Singh
Mr. Harshad S Surdi
Mr. Kiran Divekar

Thank you

Back ups



Sample	Hole Conc. ($x10^{16}cm^{-3}$)	K	ρ_0 (Ω cm)	T_0 (K)
NTD 2	0.03	0.32	200	82.9
NTD 5	1.5	0.32	0.47	77.6
NTD 14	2.7	0.32	0.11	49.0
NTD16	4.2	0.32	0.1	26.5
NTD 18	5.3	0.32	0.15	15.9
NTD 28	6.3	0.32	0.09	7.84
NTD 12	6.8	0.32	0.02	7.84
NTD 25	8.6	0.32	0.008	2.74
^{70}Ge-3.30	3.02	<0.001	0.34	364.8
^{70}Ge-2.98	8.00	<0.001	0.0074	247.6
^{70}Ge-1.90	9.36	<0.001	0.0019	201.4
^{70}Ge-1.65	14.5	<0.001	0.0006	100.3
^{70}Ge-2.15	17.7	<0.001	0.0215	20.7