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Diamond as the future material for High Energy Physics Experiments

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Outline

- Properties of tracking detectors
- Simulation for Charge created by MIP (GEANT)
- Multiple Scattering
- Comparison of Radiation damage
- MPCVD System designing
- Growth of diamond film and Characterization
- Summary and Future Plan

Properties of tracking detectors

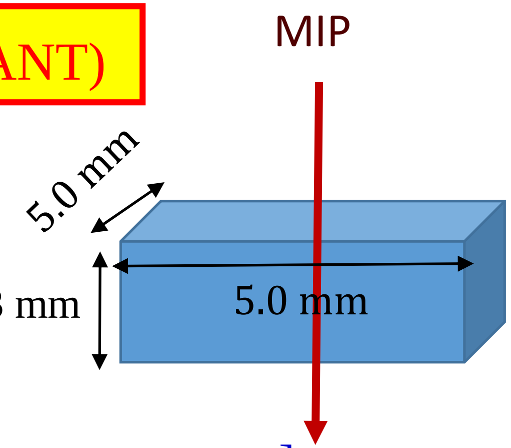
- High precision tracking and vertexting ⇒ Semiconductor detectors
- Typical choice of semiconductors are Si, Ge, GaN and Diamond
- Material should have following properties:

1. High signal to noise ratio for good position resolution
2. Low material budget for less multiple scattering
3. Fast pulse timing for less pile up
4. Low radiation damage
5. Particle Identification capabilities

In this talk we will compare Si, Ge, GaN and Diamond and will try to figure out the suitable material for High energy and high luminosity experiments

Simulation for Charge created by MIP (GEANT)

$\epsilon = 3.6$ eV, 2.96 eV, 8.9 eV and 13.6 eV for Si, Ge, GaN and Diamond



$\boldsymbol{\epsilon = 2.73\ E_g + 0.55\ eV}$

Ref: Electron-Hole-Pair Creation Energies in Semiconductors , PRL, Volume 35, Number 32

Intrinsic Signal to Noise ratio for Sensors ($5.0 \times 5.0 \times 0.3\ mm^3$)

$\sigma = q(n_e\mu_e + n_h\mu_h)$ for Intrinsic material $n_e = n_h = n_i$ [Room temperature]

Material	MPV Signal	$\rho\ (\Omega\ m)$	$\mu_e\ \left(\frac{cm^2}{Vs}\right)$	$\mu_h\ \left(\frac{cm^2}{Vs}\right)$	Noise (e)
Silicon	23220	640	1450	505	3.8×10^8
Germanium	55740	0.46	3900	1800	1.5×10^{11}
GaN	23460	$\frac{1}{6} \times 10^{-2}$	1000	350	7.0×10^{13}
Diamond	9826	10^{13}	1800	1600	0.14

Intrinsic Signal to Noise ratio for Si ($\approx 10^{-4}$), Ge ($\approx 10^{-6}$), GaN ($\approx 10^{-9}$) and diamond ($\approx 10^5$)

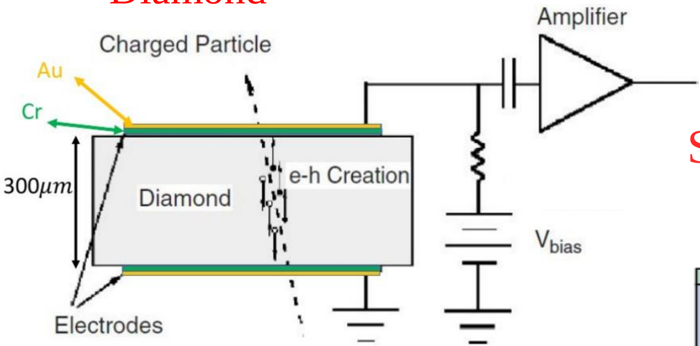
No p-n junction required for diamond while for others It is necessary

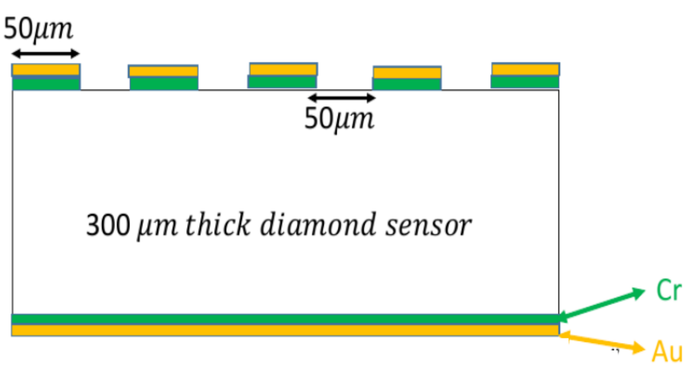
p-n junction reduces intrinsic noise (example for Si)

Silicon sensor reverse biased: $5.0 \times 5.0 \times 0.3\ mm^3$ Just rough numbers

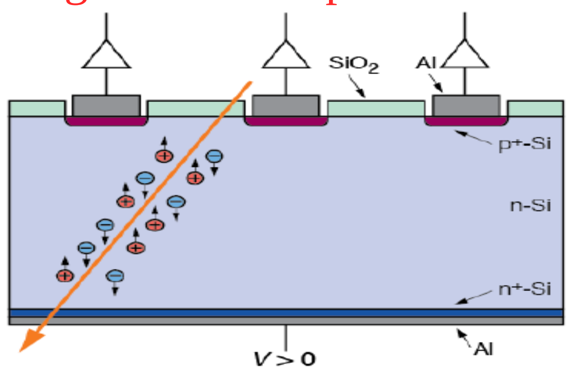
Material	Voltage	Current	$\rho\ (\Omega\ m)$	Noise (e)	Signal/Noise
Silicon	300 V	$1\ \mu A$	2.5×10^7	9591	2.365
Silicon	300 V	$1\ nA$	2.5×10^{10}	10	2268

Diamond



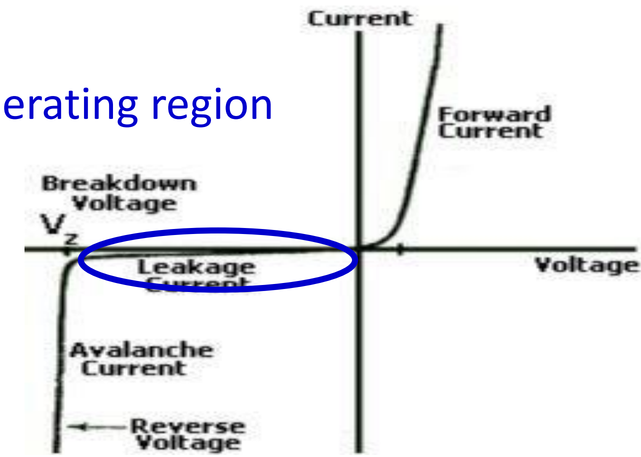


Single Sided Strip detector

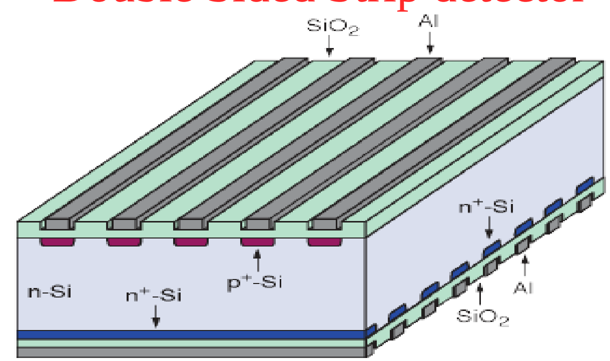


Si, Ge and GaN same concept

Operating region



Double Sided Strip detector



Signal to Noise ratio with electronics and also trick to increase ratio (Back up Slide)

Multiple Scattering

$\rho_{Si} = 2.33\ g/cm^3\ (X_0 = 9.37\ cm)$

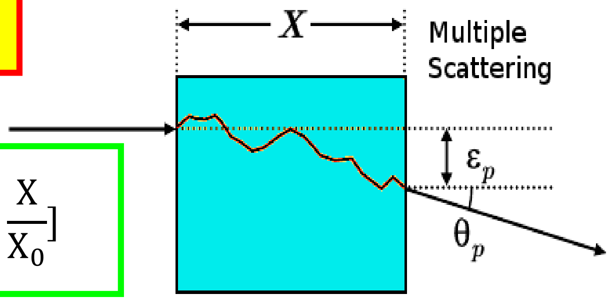
$\rho_{Ge} = 5.323\ g/cm^3\ (X_0 = 2.3\ cm)$

$\rho_{GaN} = 6.1\ g/cm^3\ (X_0 = 1.5215\ cm)$

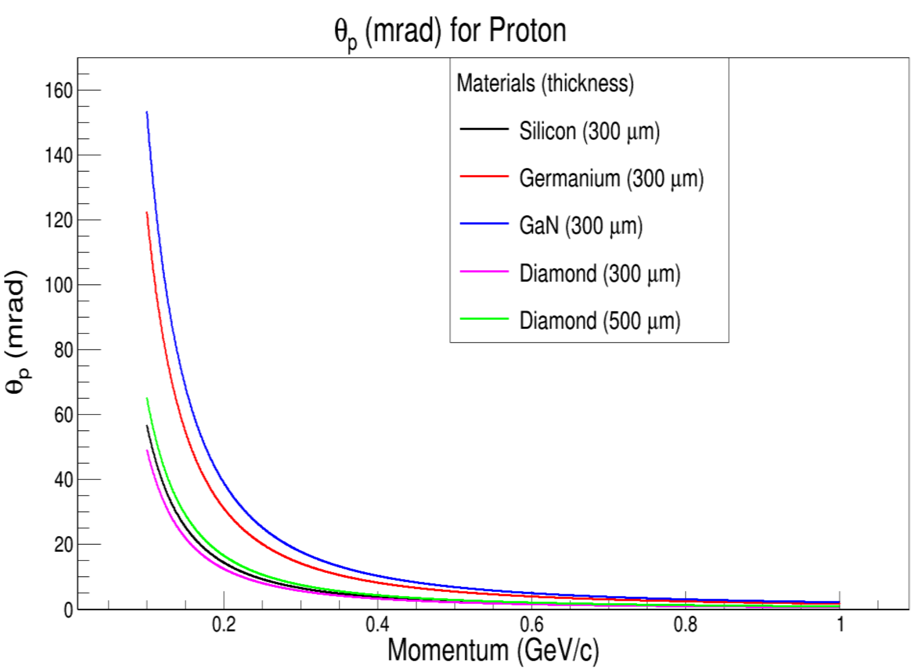
$\rho_{Di} = 3.52\ g/cm^3\ (X_0 = 12.14\ cm)$

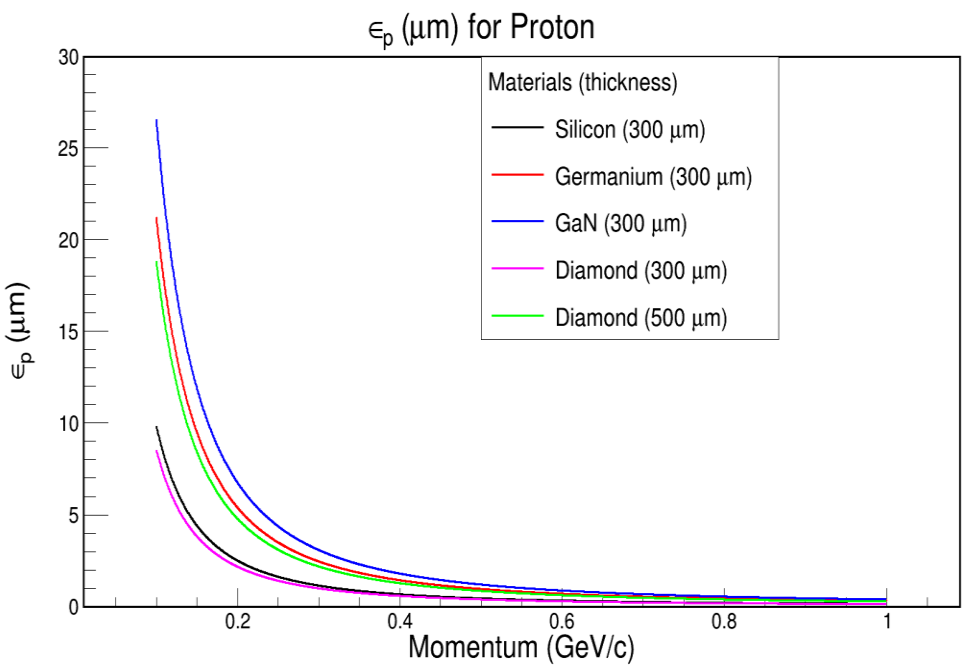
$$\theta_p = 13.6 \frac{MeVz}{\beta cp} \sqrt{\frac{X}{X_0}} \left[1 + 0.038 \ln \frac{X}{X_0}\right]$$

$$\epsilon_p \approx \frac{1}{\sqrt{3}} \theta_p X$$



Ref: "Particle Detectors", C. Grupen and B. A. Shwartz





Diamond has low multiple scattering than others for same thickness

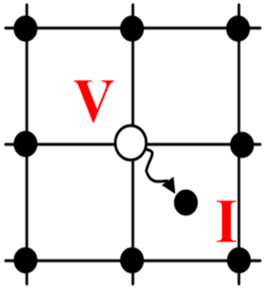
Comparison of Radiation damage

- Surface damage: Ionizing energy loss due to electron stopping [DOSE Equivalent]
- Bulk damage: Non-Ionizing energy loss due to Nuclear stopping [Si1MeVNeutronEquivalent]

Both types of damage reduces Signal to Noise ratio ≤ 10 is critical value

$$E_{min} = \frac{1}{2}\left[E_{rec} + \sqrt{E_{rec}^2 + 4\,m_p^2 + 2\,E_{rec}\,M_{atom} + \frac{2\,E_{rec}\,m_p^2}{M_{atom}}}\right] - m_p$$

"Study of radiation effects on prototypes of the PANDA Micro Vertex Detector", Ilaria Balossino, et al. , pages 36-37, Anno Accademico (2012-2013)



Frankel Pairs:
Vacancy + Interstitial

Table 1. E_{min} **of incident particles in eV**

Particles	Silicon	Germanium	Diamond
Electron	255915	457390	199668
Muon	1560	3212	1176
Pion	1184	2434	896
Kaon	344	695	269
Proton	187	371	153
Neutron	187	370	153

$$S = S_{electronic} + S_{nuclear}$$

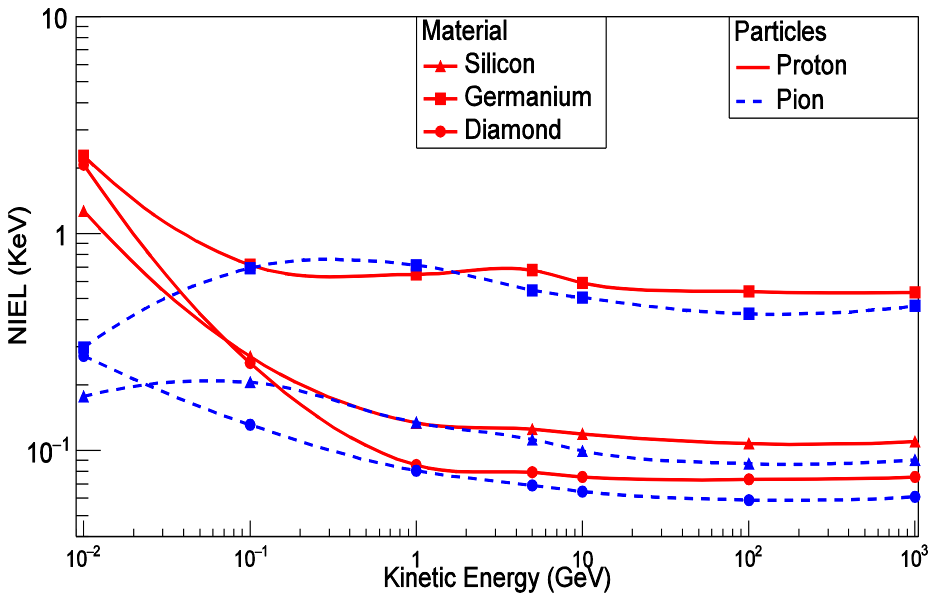
$$\mathbf{E_{th} = 25\ eV\ (Si)}$$
$$\mathbf{E_{th} = 20\ eV\ (Ge)}$$
$$\mathbf{E_{th} = 43.6\ eV\ (Di)}$$
$$\mathbf{E_{th} = 73.2\ eV\ (Ga)}$$
$$\mathbf{E_{th} = 32.4\ eV\ (N)}$$

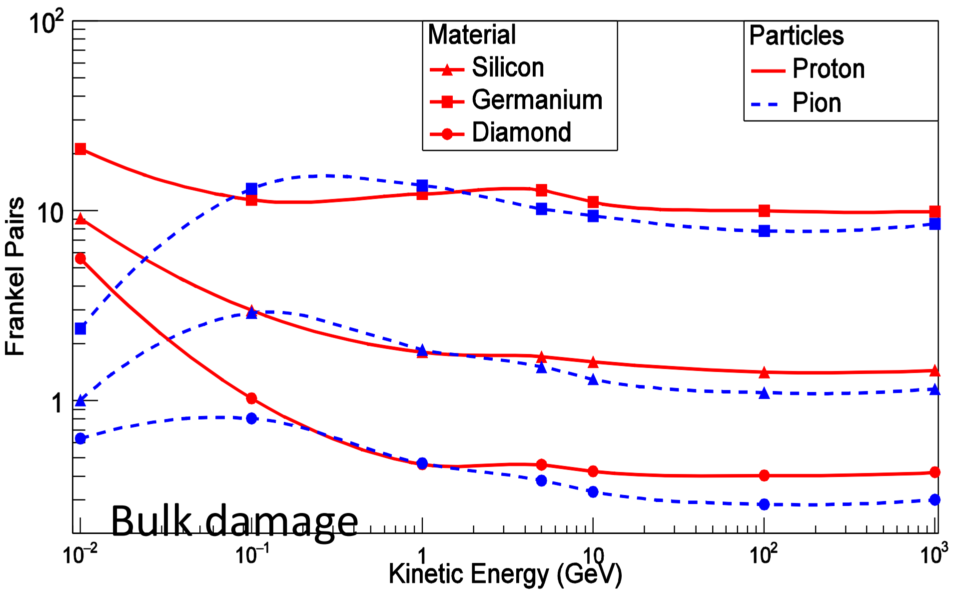
$$D(E) = \sum_k \sigma_k(E) \int dE_R\, f_k(E, E_R)\, P(E_R)$$

$DPA = \frac{1}{\rho}\sum_i N_i N_F^i$ = Displacement Per Atom

SEU: Single Event Upset (Random in time) may cause loss of data but temporary

FLUKA Simulations





In diamond, there will be no surface damage , bulk damage will be smallest and also less number of Single Event Upset (simple concept of detector as compared to Si, CMOS, LGAD)

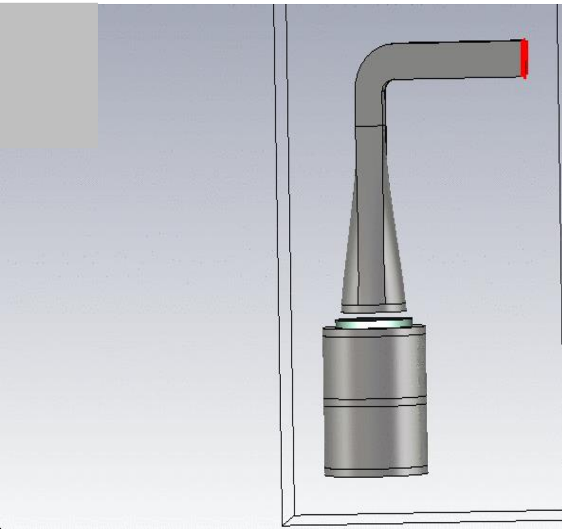
MPCVD System designing

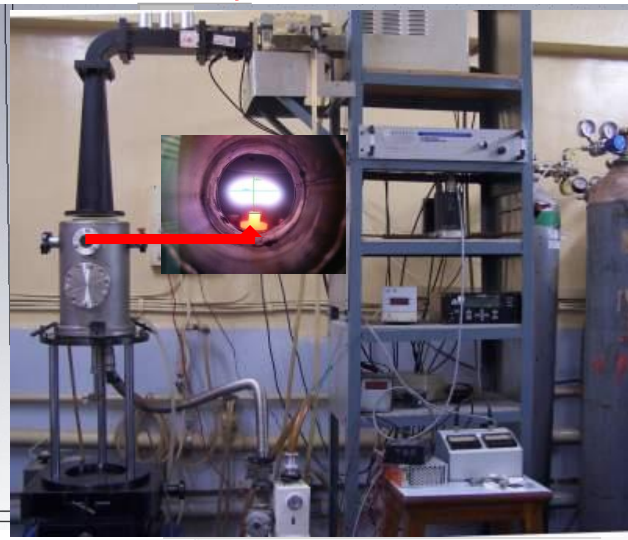
Computer Simulation Technology

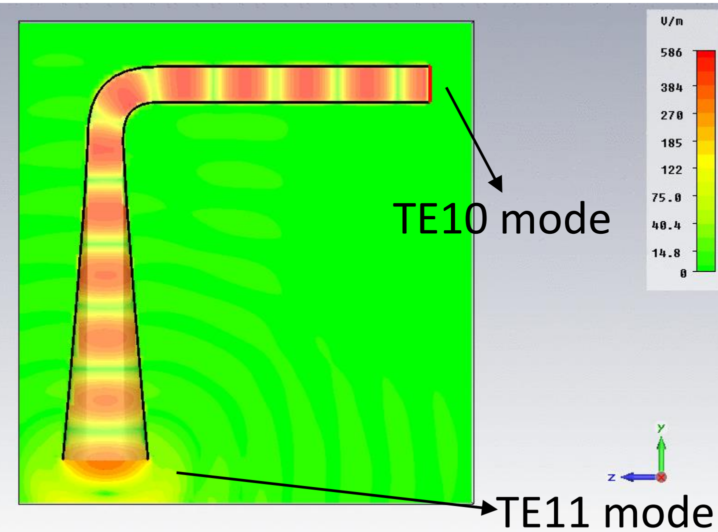
Used also in accelerator designing

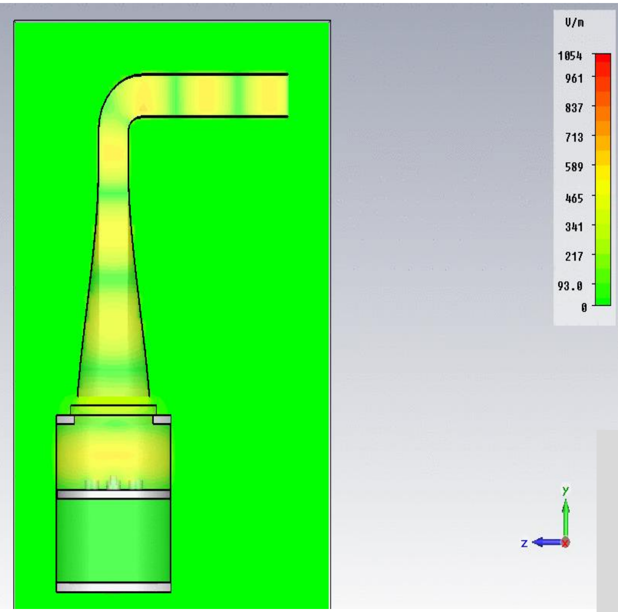
MPCVD : Microwave Plasma Chemical Vapour Deposition System & Resonant Cavity

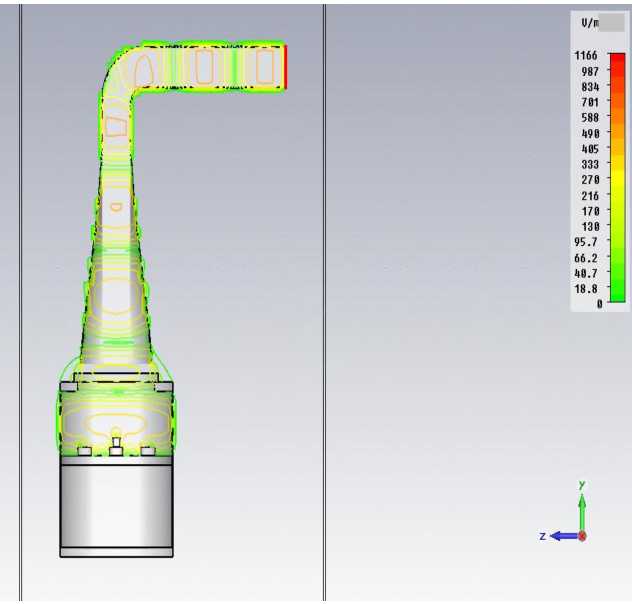
Real System in Lab



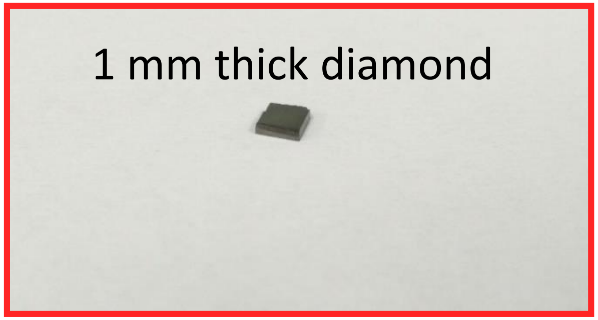








Growth of diamond film and Characterization



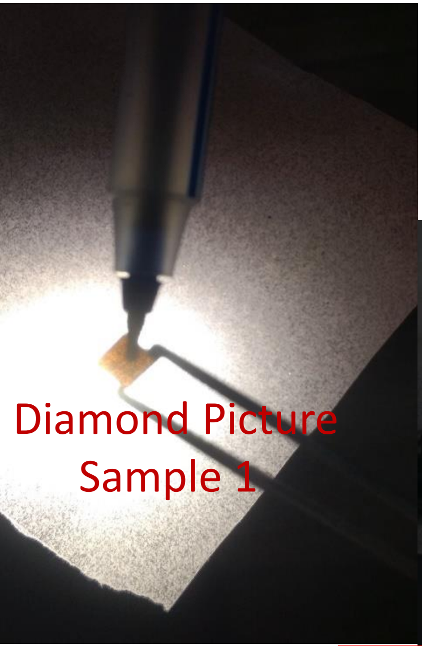
❖ Growth Parameters of Diamond film:

- ➢ HPHT diamond (100) substrate
- ➢ Hydrogen=250 sccm and Methane=2.0 sccm
- ➢ Pressure 90-91 torr (atmospheric pressure=760 torr)
- ➢ Temperature =916-938 °C
- ➢ Power Input = 0.7 kW
- ➢ Power reflected = 0 kW

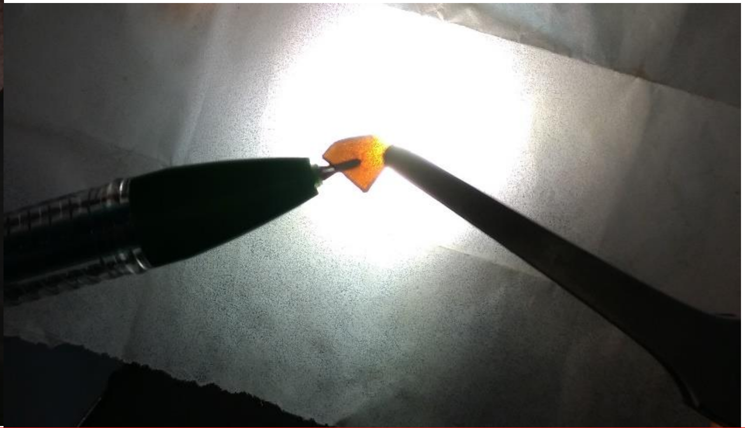
Thanks to Aman Bajaj, Sushant Raniwala, Krishna Chaitanya and Nilormi (summer student) [Sample1]

Diamond looking yellow due to Nitrogen content

Deposition time=198.5 hrs
Thickness 1 mm [Sample1]



Deposition time=168 hrs
Thickness 250 μm [Sample2]



Thanks to Amarendra and Bilal [Sample2]

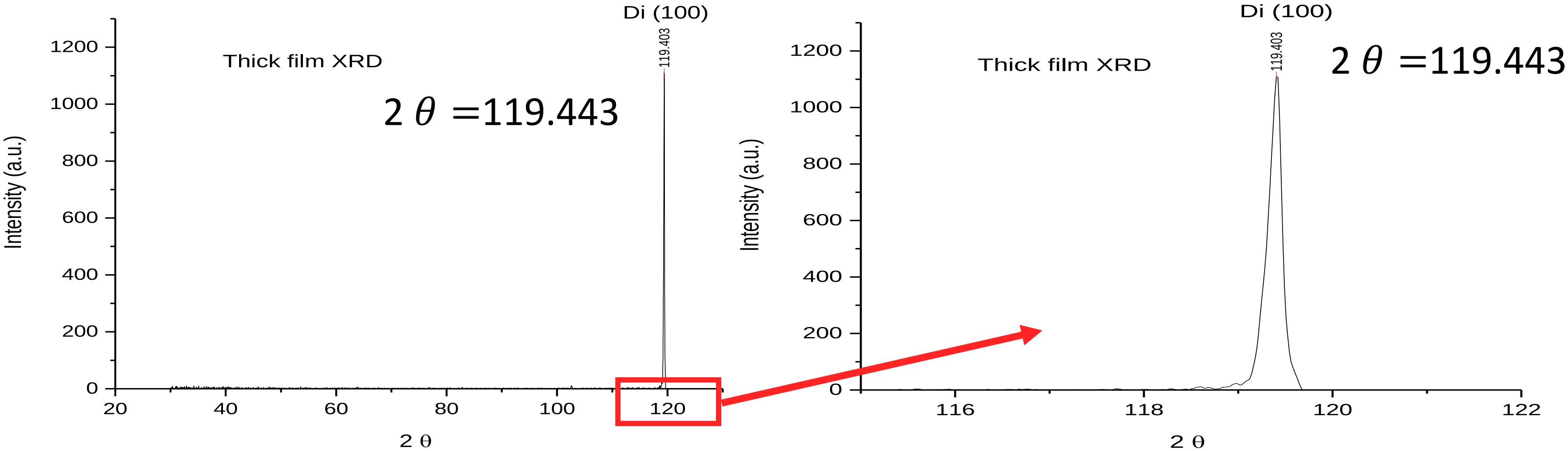
Range of G Band ~ 1500-1600 cm^{-1}

Range of D Band ~ 1300-1400 cm^{-1}

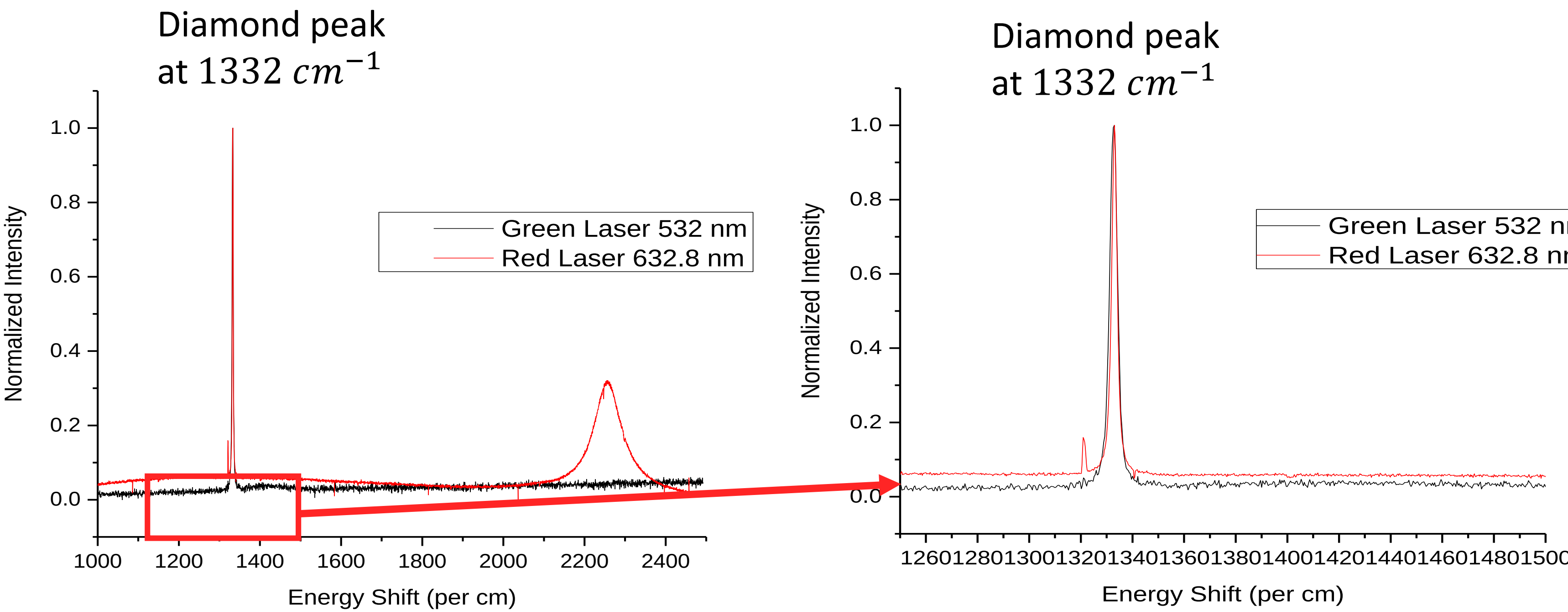
2D Band ~ 2650-2700 cm^{-1}

Electronic grade diamond has Nitrogen in Parts per billion level (ppb)

Diamond film shows the good XRD and Raman spectrum



High Resolution XRD @ Department of Physics IIT Bombay



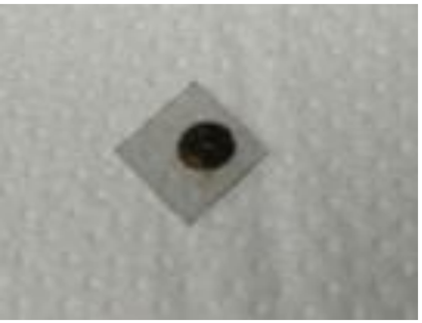
Raman Spectroscopy @ CRNTS, IIT Bombay

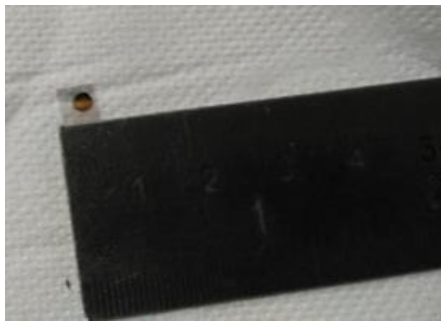
<u>I-V looking promising</u>

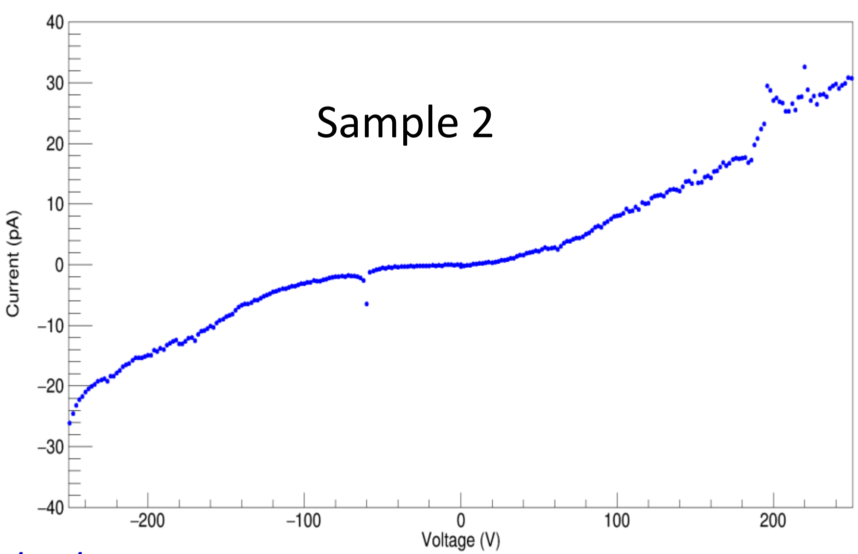
- Ohmic Contact: Thermal Evaporation (Both side)
- Cr/Au: 20 nm/100 nm
- Slow Annealing of the sample up to 605 K

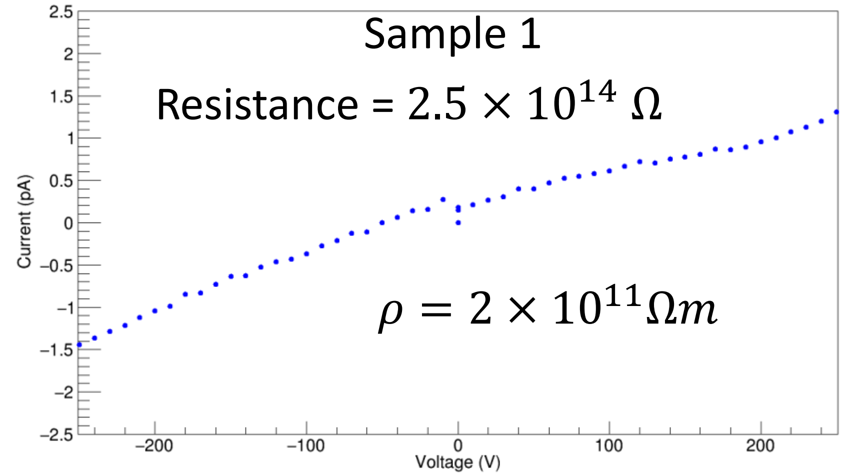
Contact made @ CEN, IIT Bombay

Sample 407 : $5.0 \times 5.0 \times 0.4\ mm^3$



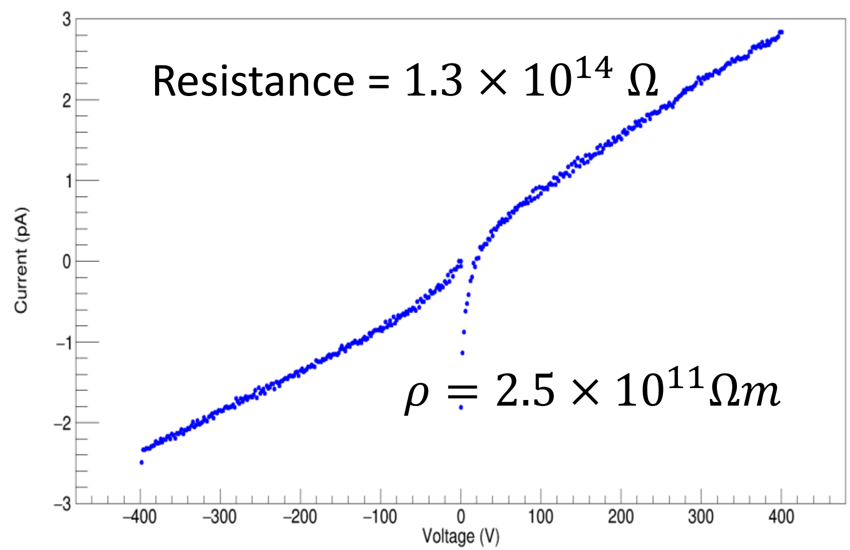






I-V done at BARC, Thanks to Amit and Dr. Anita Topkar (Electronics division BARC)

Sample 407
Commercial



Transient Current Technique (TCT) measurement for diamond

$[Am^{241}$- α source, 5.486 (MeV)]

- **Silicon**
  - IEL ≈ 5485.9 KeV
  - NIEL ≈ KeV
  - Signal=5485900/3.6

  = 1523861 e-h pairs

- **Germanium**
  - IEL ≈ 5485.8 KeV
  - NIEL ≈ KeV
  - Signal=5485800/2.96

  = 18,53311 e-h pairs

- **Diamond**
  - IEL ≈ 5485.9 KeV
  - NIEL ≈ KeV
  - Signal=5485900/13.6

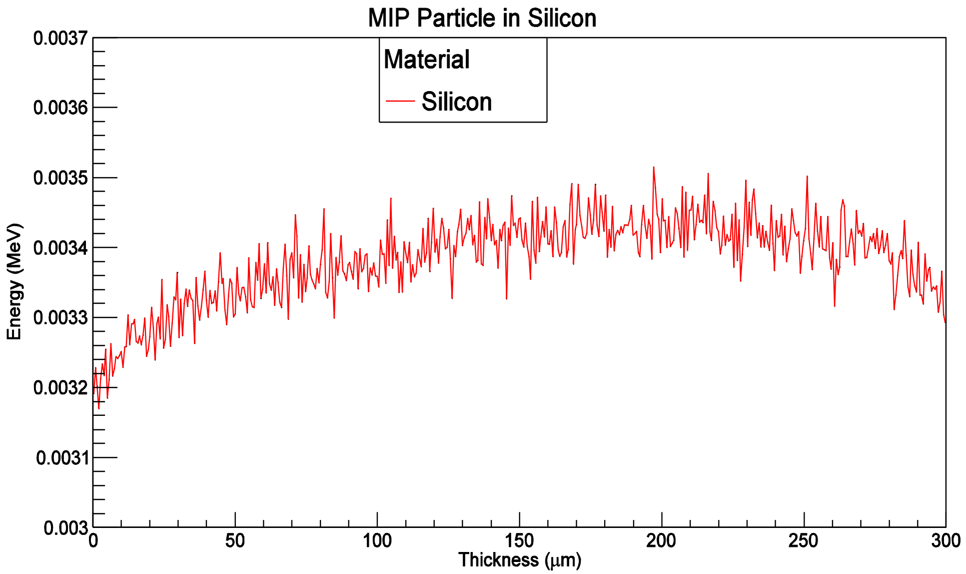
  = 403375 e-h pairs

- **GaN**
  - IEL ≈ 5485.9 KeV
  - NIEL ≈ KeV
  - Signal=5485900/8.9

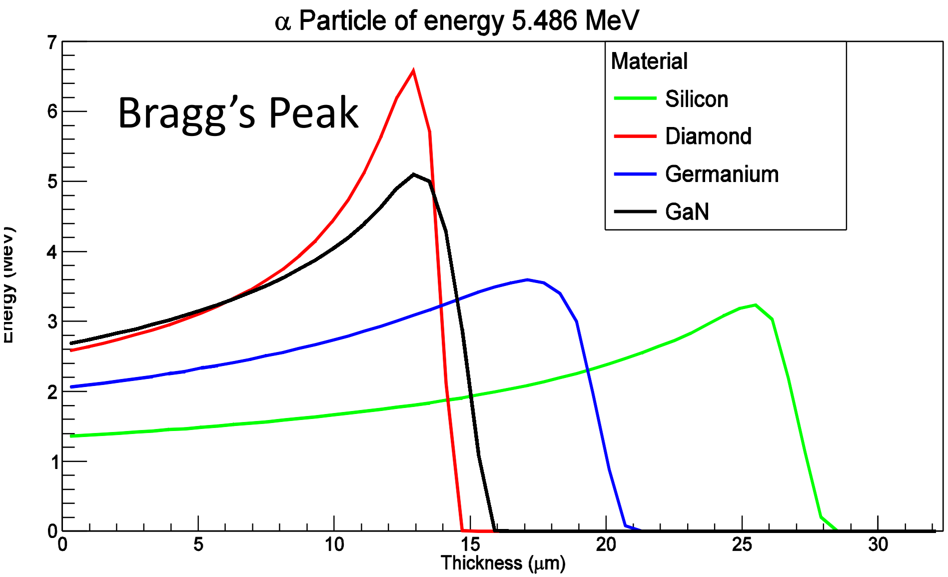
  = 616393 e-h pairs

MIP Creates very smaller signal than α and it just deposit small amount of energy

MIP in Silicon: Fluka simulation

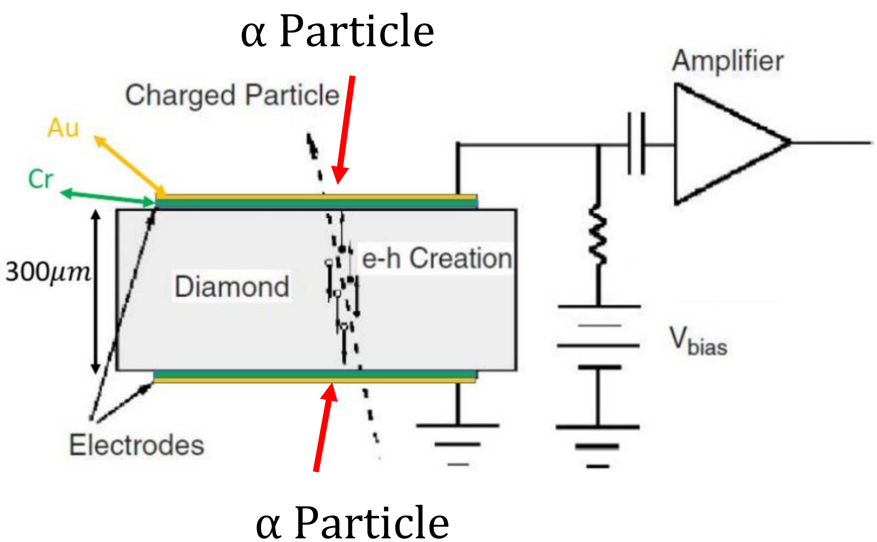


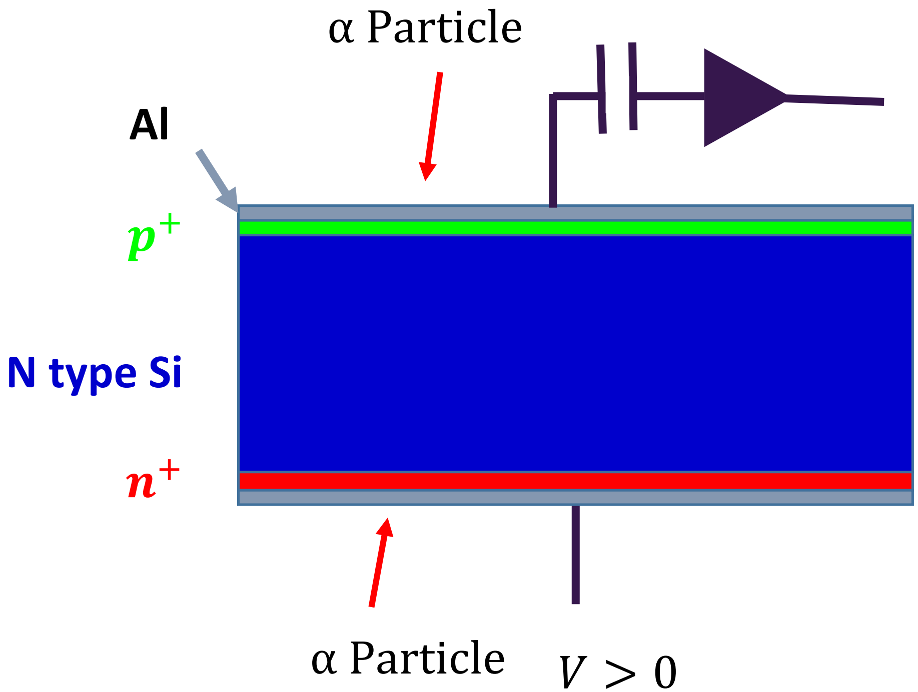
Range of α in Material: Fluka simulation



Note: Direction of α is very important in case of Si, Ge, GaN but not for diamond

Diamond: α will not make any difference either from Top or Bottom (Uniformity of Electric field)





Alpha spectroscopy with Silicon (TCT also):

Case1: If detector is fully depleted then It will be no difference from top and Bottom

Case2: If detector is not fully depleted then If we have depletion width of 30 μm the α from top will deposit all the charge in depletion region and will get full signal but If you through from below you will get no signal

Gain of cividec amplifier= +40 dB => $\frac{v_{out}}{v_{in}} = 100$

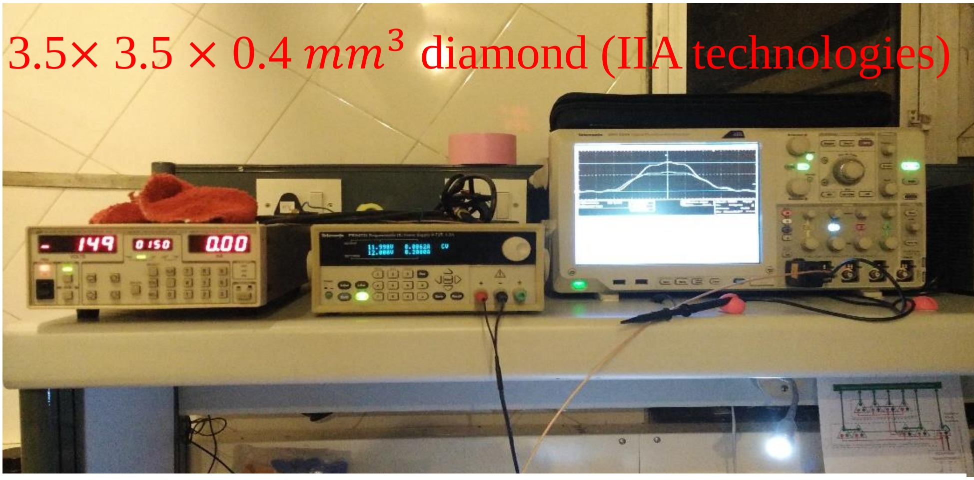
$$v_{out} = 100\, v_{in} = 100 \times 50\,\Omega \times I_{in}$$

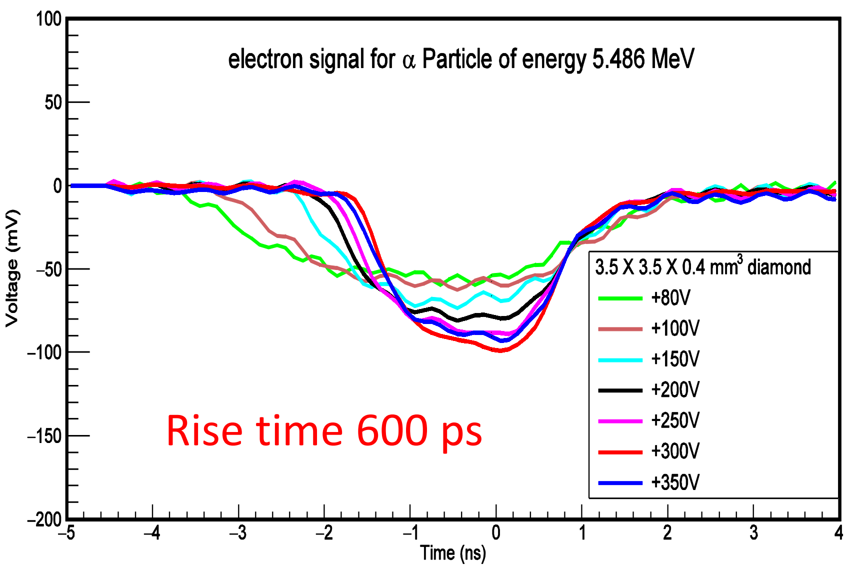
$$I_{in}(mA) = \frac{v_{out}\,(mV)}{5000}$$

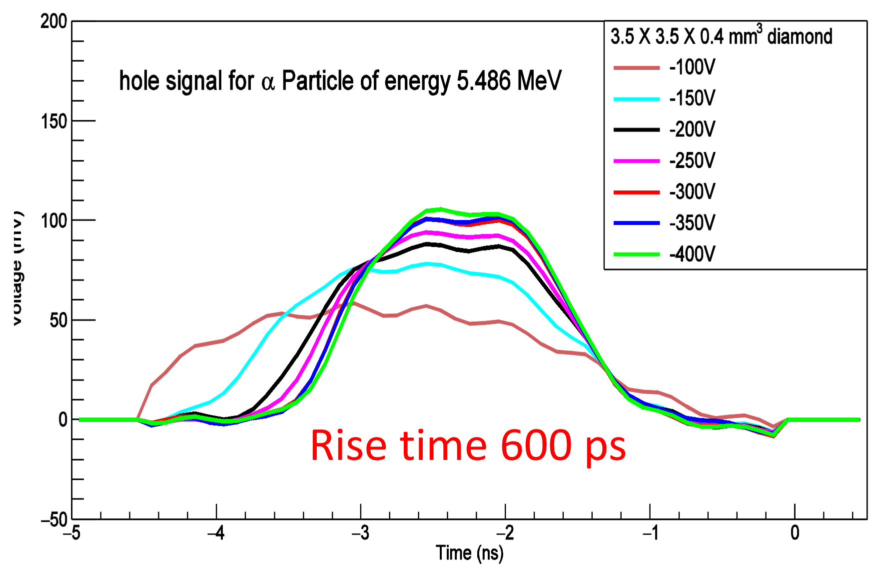
Timing of diamond pulse of the order of ns

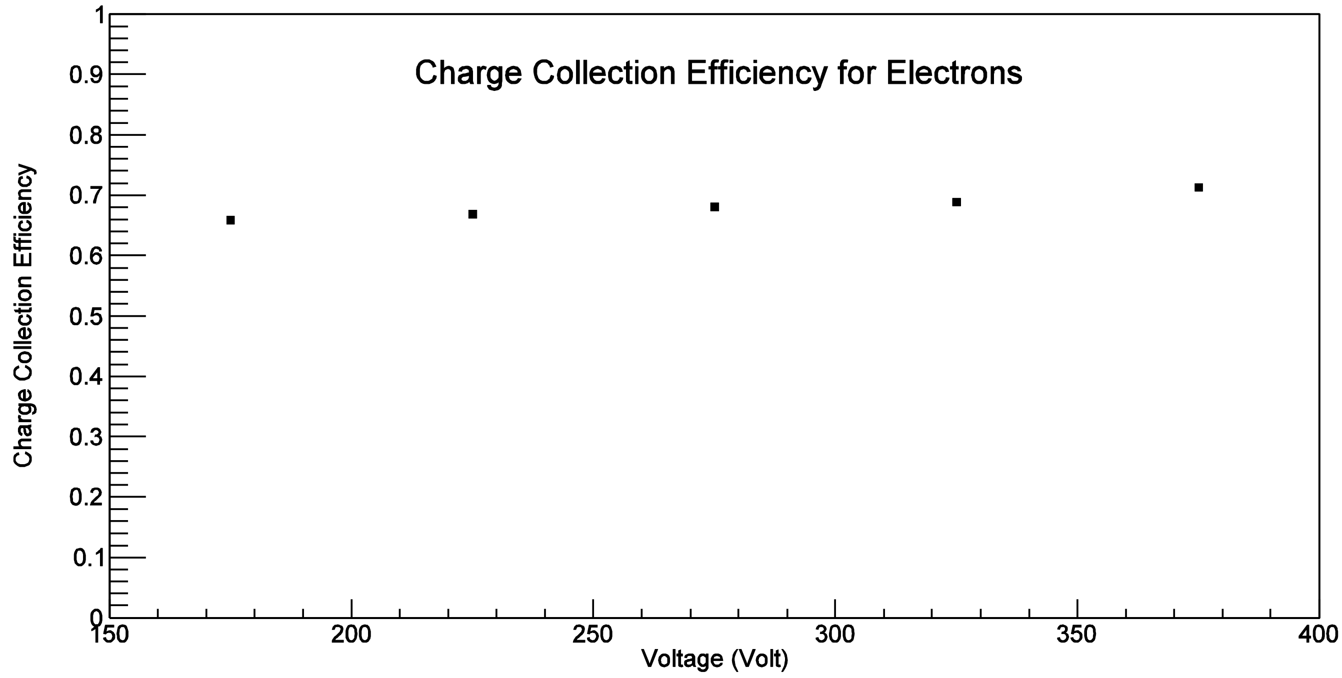
$$Q_{collected} = \int I_{in}\, dt$$

$$CCE = \frac{Q_{collected}}{Q_{created}} \times 100 = \frac{Q_{collected}}{403375} \times 100$$

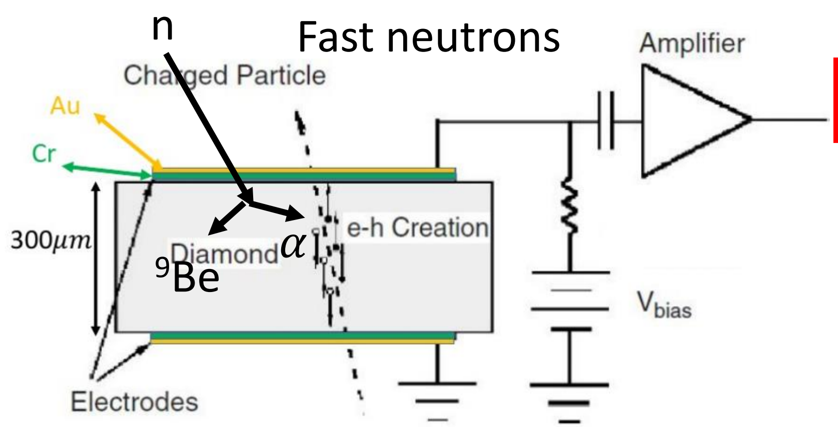








Applications:



14.1 MeV n, with α and
^{9}Be having a total energy of 8.4 MeV

Neutron detection at High temperature (300^{0}C)

Si, Ge can not be used at this High temperature

n directly interact with carbon ^{12}C

$$n + ^{12}C \rightarrow \alpha + ^{9}Be - 5.7MeV$$

1. ITER Experiment

2. Beam Condition Monitors ATLAS Experiment

Summary and Future Plan

- Diamond has good signal to noise ratio, fast timing, low material budget, low radiation damage and no cooling required so it will be a good choice for HEP experiments
- Diamond has large e-h pair creation energy so less disturbance in charge center of gravity
- Diamond can also detect fast neutrons at High temperature
- We have grown self supporting diamond film which shows good I-V characteristic
- We have also tested good quality diamond from IIA technologies
- The only problem with diamond we don't have large area high quality diamond, cost is high and different diamond shows different results
- Still working on growing high quality diamond basically try to reduce nitrogen

FLUKA Simulation used Ref : "FLUKA: a multi-particle transport code" A. Ferrari, P.R. Sala, A. Fasso`, and J. Ranft,
CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773

Thank You !!!

Thanks for discussion and help:

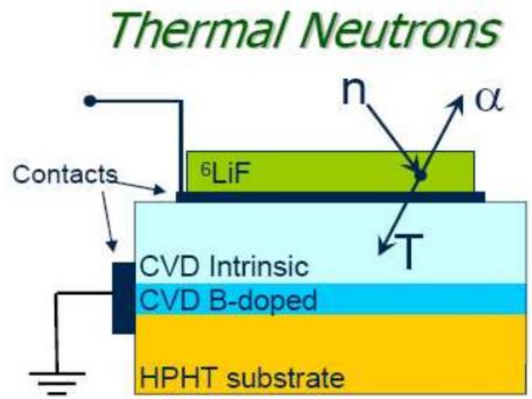
- ❖ Michael Moll (RD50, CERN)
- ❖ Moritz Guthoff, (CMS, CERN)
- ❖ Harris Kagan (RD 42, CERN)
- ❖ William Trischuk (RD42, CERN)
- ❖ Shaun Roe (ATLAS, CERN)
- ❖ Hartmut Hillemanns (ALICE, CERN)
- ❖ CERN-FERMI School 2017 at CERN

Ref:

https://indico.cern.ch/event/586317/contributions/2465762/attachments/1413709/2172626/Advancedetector_Shyam.pdf

Back Up Slides

Diamond as Neutron detectors



n interacts with ^6Li in 6LiF layer (95%)

$$n +^6 Li \rightarrow Tritium + \alpha + 4.8\ MeV$$

Tritium (2.73 MeV) and α $(2.06\ MeV)$ emitted at 180^0C, only α or Tritium is detected

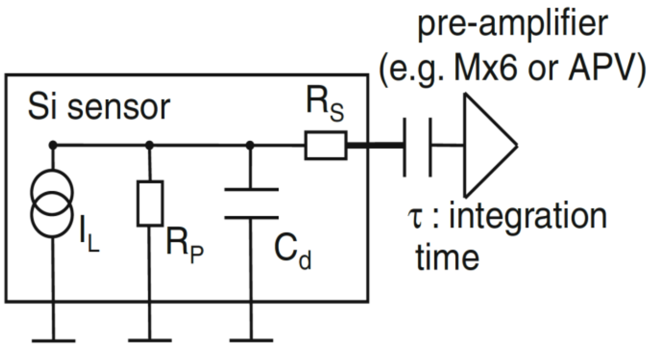
Ref: CVD Diamond Neutron Detectors, Arnaldo Galbiati

Diamond Pulse time Estimation $(d = 400\ \mu m\ thick)$ at E field = $1V/\mu m$:

$$t_e = \frac{d}{v} = \frac{d^2}{\mu_e \mathrm{V}} = \frac{16 \times 10^{-8}}{0.18 \times 400} = 2.2\mathrm{ns} \qquad t_h = \frac{d}{v} = \frac{d^2}{\mu_e \mathrm{V}} = \frac{16 \times 10^{-8}}{0.16 \times 400} = 2.5\ \mathrm{ns}$$

Experimental $t_e \approx 3.2\ ns\ and\ t_h \approx 3.2\ ns$

Signal to Noise Ratio: Expressed in terms of **ENC (Equivalent Noise Charge)**



$$ENC(e) = \sqrt{ENC_{I_L}^2 + ENC_C^2 + ENC_{R_p}^2 + ENC_{R_s}^2}$$

1. Shot Noise due to I_L: $$ENC_{I_L} \approx 107\sqrt{I_L(nA)t_p(\mu s)}$$

2. Parallel thermal noise: $$ENC_{R_p} \approx 44.5\sqrt{\frac{T(K)t_p(\mu s)}{R_p(M\Omega)}}$$

3. Series thermal noise from metal strip resistance: $$ENC_{R_s} \approx 0.025\, C_d\,(pF)\sqrt{\frac{T(K)R_s(\Omega)}{t_p\,(\mu s)}}$$

4. Preamplifier noise: $ENC_C = a + b\, C_d(\mathrm{pF})$, a and b preamplifier design parameters

❖ For making the small noise design follow the below specification:

➢ Small load capacitance C_d=C_{strip}

(~ depends on strip dimension) to minimize ENC_{R_s} and ENC_C

➢ low leakage current I_L to minimize $\mathrm{ENC_{I_L}}$

➢ high parallel resistance R_{bias} to minimize $\mathrm{ENC_{R_p}}$

➢ small series resistance R_{strip} to minimize ENC_{R_s}

Ref: Evolution of Silicon sensor technology in Particle Physics: pages: 27-28
Frank Hartmann

❖ ENC Silicon: (DELPHI microvertex)

$t_p = 1.8\ \mu s$, $I_L = 0.3\ nA$, $R_p = 36\ M\Omega$, $R_s = 25\ \Omega$,
$C_d = 9\ pF\ (Strip), a = 340, b = 20, T = 20^0C$

$\boldsymbol{ENC_{I_L} = 78\ e}$

$ENC_{R_P} = 170\ e$

$ENC_{RS} = 14\ e$

$\boldsymbol{ENC_C = 520\ e\ (\mathbf{Preamplifier})}$

$\boxed{\text{Total } \boldsymbol{ENC = 553\ e}}$

➢ $For\ 300\ \mu m\ thickness \Rightarrow \frac{Signal}{ENC} = \frac{22680}{553} = 41$

❖ ENC Diamond: (Estimation)

$t_p = 5.0\text{ ns}$, $I_L = 1\ pA$, $R_p = 36\ M\Omega$, $R_s = 25\ \Omega$,
$C_d = 2\ pF$, $T = 20^0C$

Low Noise Viking Amplifier: $ENC_C = 135 + 13\ C_d$

$\boldsymbol{ENC_{I_L} = 0.24\ e}$

$ENC_{R_P} = 9\ e$

$ENC_{RS} = 61\ e$

$\boldsymbol{ENC_C = 161\ e}$

Ref: First measurements with a diamond microstrip detector, NIM, Research A 354 (1995) 318-327

$\boxed{\text{Total } \boldsymbol{ENC = 172\ e}}$

$For\ 300\ \mu m\ thickness \Rightarrow \frac{Signal}{ENC} = \frac{9645}{172} = 56$

➢ Impact Parameter IP: for short lives particles , If life time τ is $10^{-13} - 10^{-11}\ sec$ => Impact parameter 30-3000 μm $(c\tau)$

❖ Binary Readout:

➢ Limited position resolution $\propto \frac{Pitch}{\sqrt{12}}$ or $\frac{Pitch}{2\sqrt{12}}$

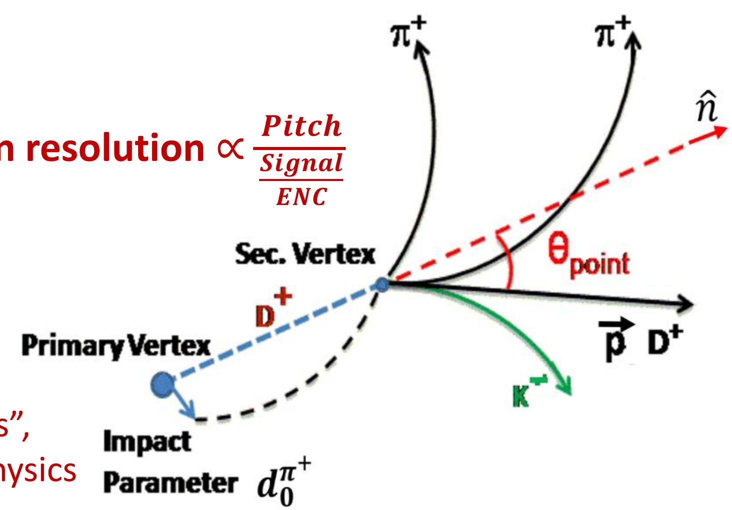
❖ Analogue Readout:

➢ Nonlinear Eta Algorithm- For small track angles where diffusion is large

➢ Simple linear Analogue Head Tail algorithm- For large angle tracks

➢ Charge Centre of gravity method- For middle range of angles

Best Position resolution $\propto \frac{Pitch}{\frac{Signal}{ENC}}$



Ref: "Spatial resolution of silicon microstrip detectors", R. Turchetta, Nuclear Instruments and Methods in Physics

Thickness enhances Signal to Noise ratio !!!

For 300 μm:

Silicon

$$\frac{Signal}{ENC} = \frac{23220}{553} = 41.9$$

Diamond

$$\frac{Signal}{ENC} = \frac{9826}{172} = 57$$

For 400 μm diamond:

$$\frac{Signal}{ENC} = \frac{9826 \times 4/3}{172} = \frac{13101}{172} = 76$$

For 500 μm diamond:

This will increase Multiple scattering

$$\frac{Signal}{ENC} = \frac{9826 \times 5/3}{172} = \frac{16377}{172} = 95.21$$

Is there any other way to enhance Signal to Noise ratio?

Creating Internal Gain

❖ Diamond (300 μm)

1. If gain is 10 , then Signal=98260 e and ENC_{I_L}=0.76 e (It is less than other contributions)

$$\frac{Signal}{ENC} = \frac{98260}{172} = 570$$

2. If gain is 100 , then Signal=982600 e and ENC_{I_L}=2.4 e (It is less than other contributions)

$$\frac{Signal}{ENC} = \frac{982600}{172} = 5700$$

❖ Silicon (300 μm)

1. If gain is 10 , then Signal=232200 e and ENC_{I_L}= 247 (It is more than other contributions)

$$\frac{Signal}{ENC} = \frac{232200}{951} = 244$$

2. If gain is 100 , then Signal=2322000 e and ENC_{I_L}= 780 (It is more than other contributions)

$$\frac{Signal}{ENC} = \frac{2322000}{1484} = 1565$$

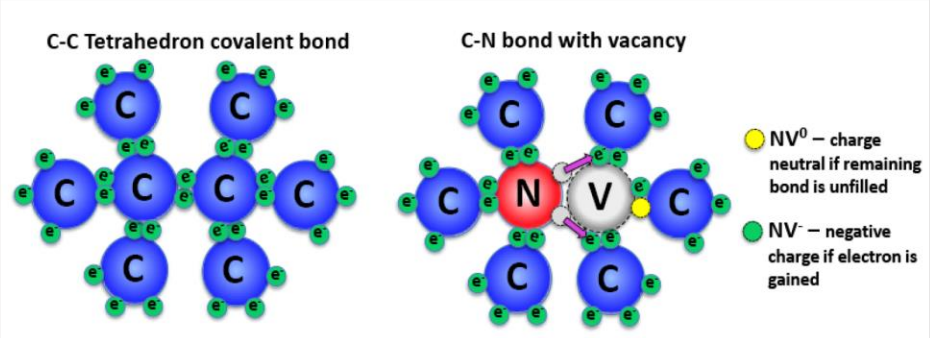
Internal gain can also enhance the signal to noise ratio, larger in diamond than Silicon (LGAD)

Characterization techniques

- ➢C-DLTS: Capacitance Deep Level Transient Spectroscopy
- ➢XPS (X-ray photoelectron spectroscopy): For elemental composition
- ➢I-DLTS: Current Deep Level Transient Spectroscopy

Ref. Diamond nitrogen vacancy impurity ppt, April 2013, physics 6530, Stefan Thonnard

- ➢TSC: Thermally Stimulated Currents
- ➢RL: Recombination Life-time Measurements
- ➢PC: Photo Conductivity Measurements
- ➢PL –Photoluminescence

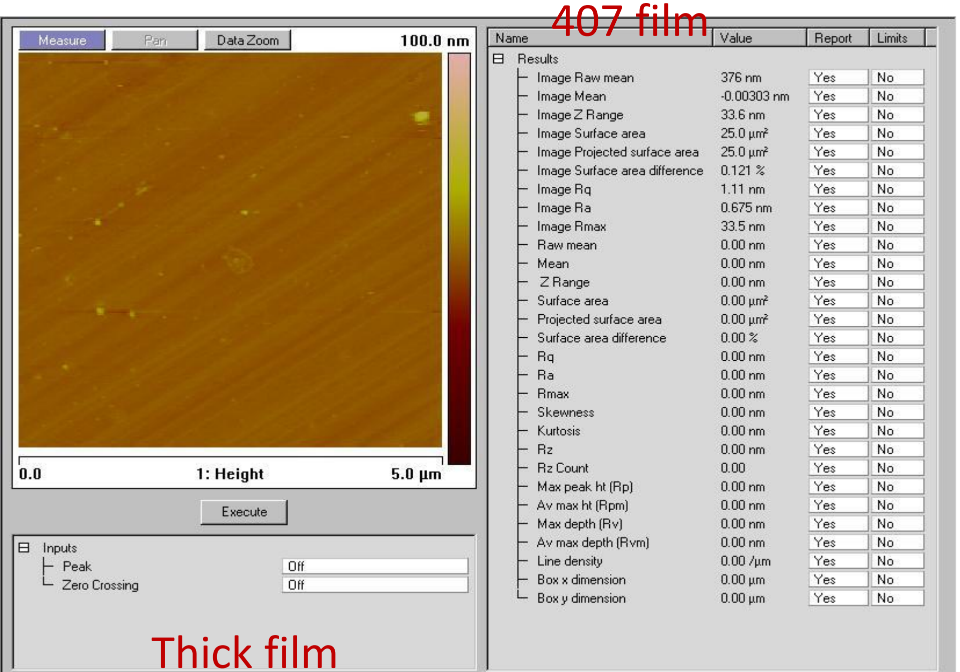


N-V Center reduces CCE

- ➢Raman Spectroscopy
- ➢IV-CV Characteristics: For leakage current and capacitive noise determination
- ➢Atomic Force Microscopy (AFM)
- ➢Transient current technique (TCT): For electron and hole mobility determination
- ➢HRXRD: High Resolution X-ray Diffraction

Atomic force Microscopy (AFM) [Polishing of 407 is compared to thick film]

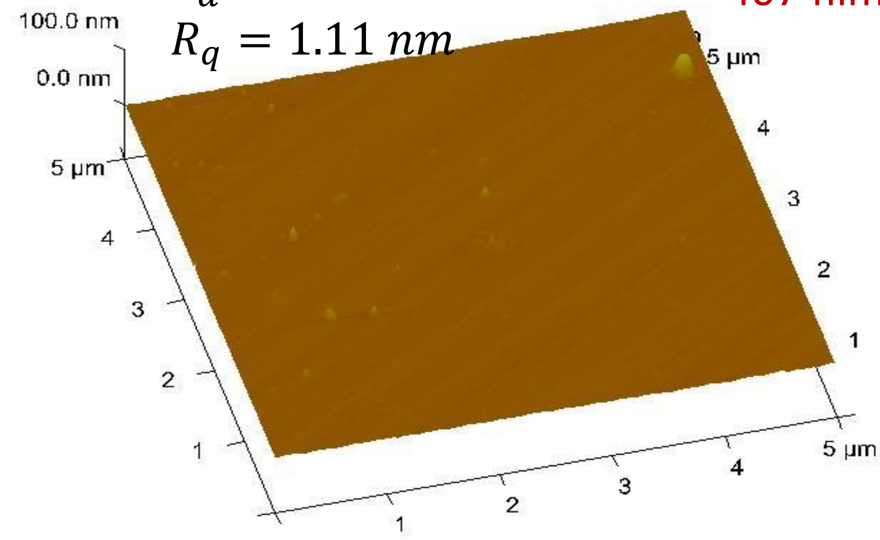
407 film



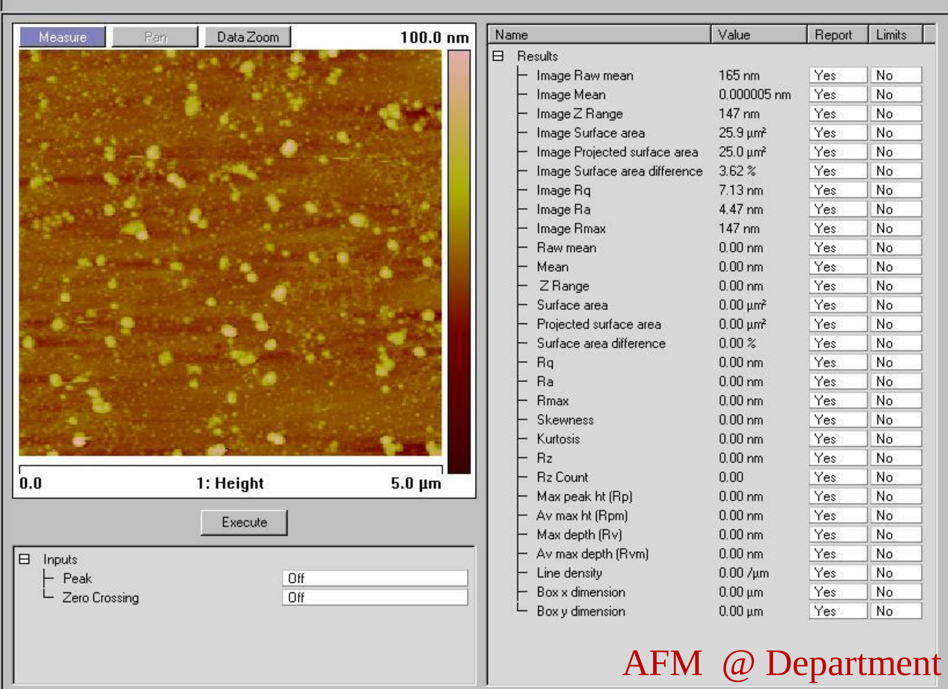
$R_a = 0.675\ nm$

$R_q = 1.11\ nm$

407 film



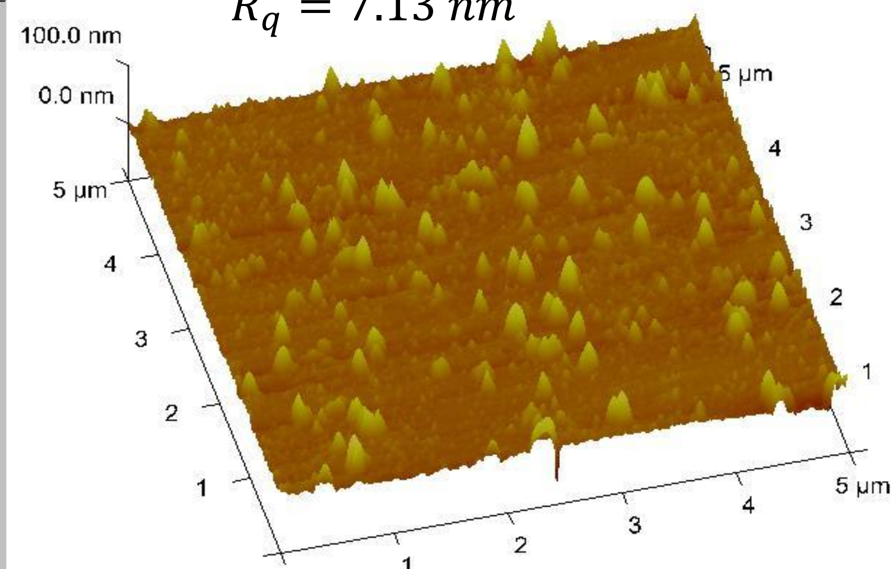
Thick film



$R_a = 4.47\ nm$

$R_q = 7.13\ nm$

Thick film



AFM @ Department of Physics IIT Bombay

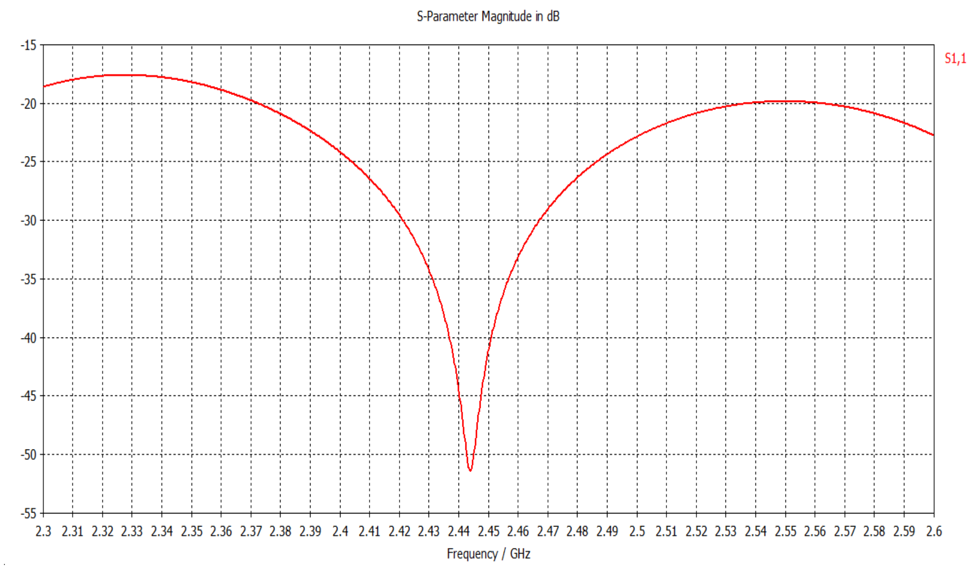
TE10 to TE11 mode converter simulation

Single Port S_{11} – reflection coefficient,
For two Ports S_{11}, S_{12}, S_{21} *and* S_{22}

Frequency= 2.45 $\pm$ 0.020 GHz

Decibel-milliwatts (dBm)= Decibel watt (dBW) +30

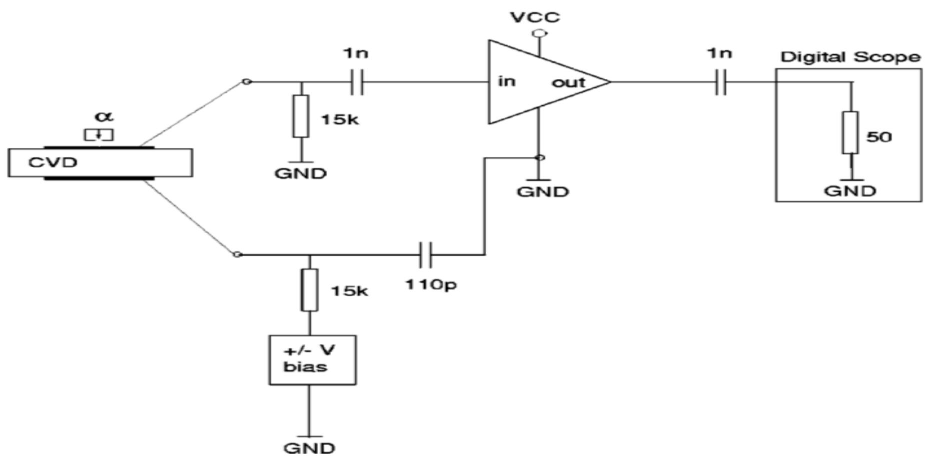
S parameter ≈ -50 dBW = -20 dBm=10 μW



MPCVD : Advantages

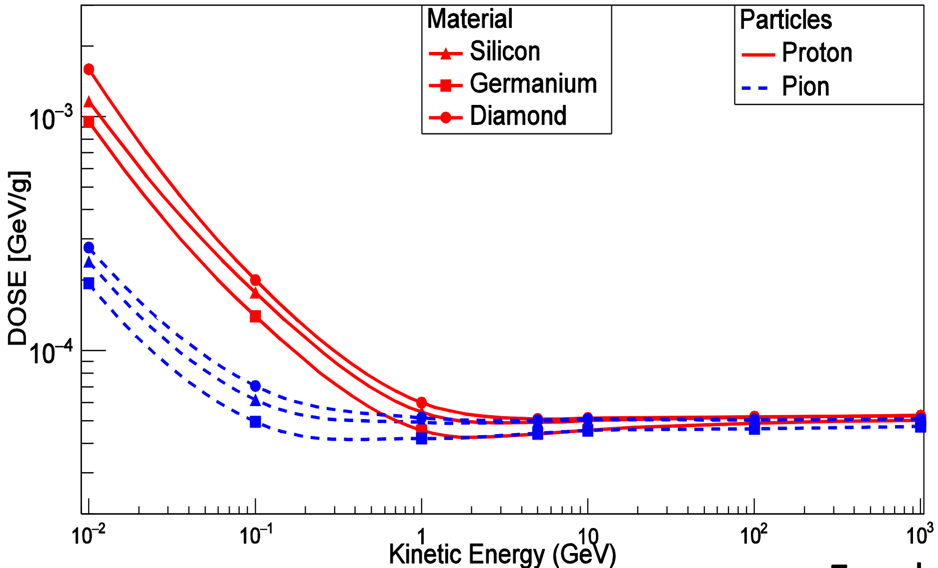
- Electrode less process=> No Plasma sheath formation take place
- Plasma density is high
- Stability of Plasma up to many days
- Ability to scale up the process over large substrates
- Quality of film grown is high

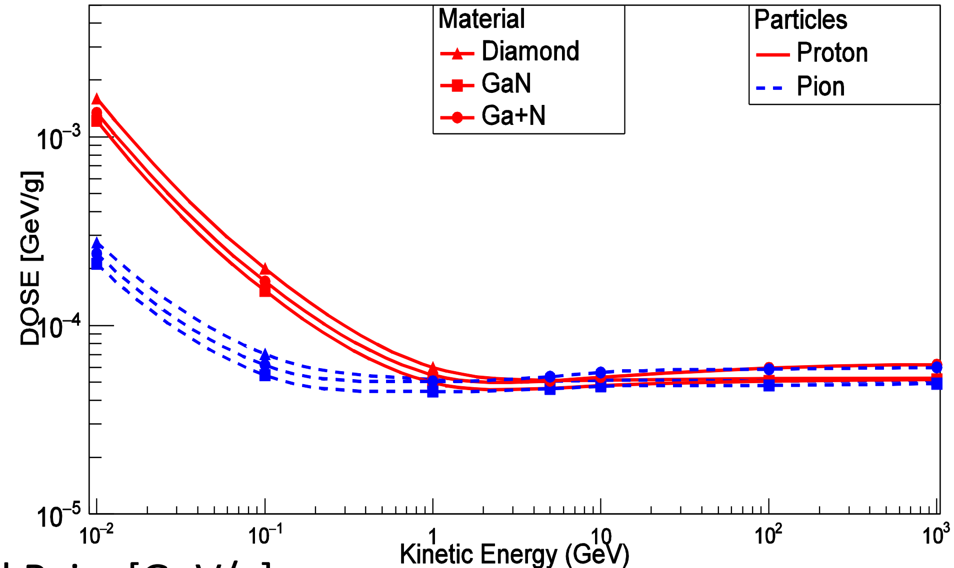
TCT circuit diagram



Ref. Charge-carrier properties in synthetic single-crystal diamond measured with the transient-current technique by H. Pernegger et al., JOURNAL OF APPLIED PHYSICS 97, 073704 (2005)

Dose [GeV/g]





Frankel Pairs [GeV/g]