Polarization effects in radiation damaged scCVD Diamond detectors

Sergej Schuwalow, DESY Zeuthen

4th NoRHDia Workshop @ GSI
Contents

- Why do we need Diamond Detector @ ILC?
- BeamCal challenge
- Diamond properties
- Charge collection
  - Ideal crystal, Radiation damaged crystal
- Polarization creation, model
- Experimental studies:
  - CCD vs Dose, CCD time dependence
  - Future plans
- Summary
The International Linear Collider

Parameters:
- 500 GeV (1 TeV upgrade possible)
- $2 \times 10^{34}$ cm$^{-2}$sec$^{-1}$
- electron polarization $\sim 80\%$
- positron polarization $\sim 30\%$ (60\%)
- beam sizes: $\sigma_x \approx 600\text{nm}$, $\sigma_y \approx 6\text{nm}$, $\sigma_z = 300\text{\mu m}$
Design of the Forward Region

Solenoid
HCal
ECal
Low Z Mask
TPC or Si Tracker
IP Chamber
Detectors
LumiCal
BeamCal
GamCal
~185m
Steel Yoke
Antisolenoid
FD Cry.

09.06.2008 Radiation Hard Sensors
BeamCal Design

- Compact em calorimeter with sandwich structure:
  - 30 layers of 1 $X_0$
  - 3.5mm W and 0.3mm sensor
- Angular coverage from ~5 mrad to ~45 mrad
- Molière radius $R_M \approx 1$ cm
- Segmentation between 0.5 and 0.8 x $R_M$

W absorber layers

Radiation hard sensors with thin readout planes

Space for readout electronics
The Challenges for BeamCal

Creation of beamstrahlung at the ILC

- $e^+e^-$ pairs from beamstrahlung are deflected into the BeamCal
- 15000 $e^+e^-$ per BX
  => 10 – 20 TeV total energy dep.
- $\sim 10 \text{ MGy per year}$ strongly dependent on the beam and magnetic field configuration
  => radiation hard sensors
- Detect the signature of single high energetic particles on top of the background.
  => high dynamic range/linearity.

$\approx 1 \text{ MGy/a}$
$\approx 5 \text{ MGy/a}$

09.06.2008 Radiation Hard Sensors
Diamond properties

- Density $3.52 \text{ g cm}^{-3}$
- Dielectric constant 5.7
- Breakdown field $10^7 \text{ V cm}^{-1}$
- Resistivity $>10^{11} \Omega \text{ cm}$
- Band Gap 5.5 eV
- Electron mobility $1800 (4500) \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$
- Hole mobility $1200 (3800) \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$
- Energy to create e-h pair 13.1 eV
- Average signal created 36 e $\mu\text{m}^{-1}$

* High-purity single crystal CVD
Sensors

sc CVD diamond from Element 6 (provided by GSI, Darmstadt)

Thickness 326 µm, active area 3 mm in diameter

2 sensors, one is irradiated up to 5 MGy dose at the 10 MeV electron beam in 2007
'Ideal' crystal charge collection

Charge collection efficiency depends on $E$

$HV=0$

Recombination

$HV\neq 0$

Charge collection

CCD vs HV, not irradiated sample

$E$, V/\mu m

CCD, \mu m
Radiation damaged crystal

- Radiation causes local damages of the lattice structure.
- These local damages (traps) are able to capture free charge carriers and release them after some time.

- Assumptions:
  - Trap density is uniform (bulk radiation damage)
  - Traps are created independently (linearity vs dose)
Irradiation of single crystal CVD Diamond

After absorbing 5 MGy:

CVD diamonds still operational.

- Very low leakage currents (~pA) after the irradiation.
- Decrease of the charge collection distance with the dose.
- Generation of trapping centers due to irradiation. Traps release?
- Strong polarization effects!!!
Irradiation of single crystal CVD Diamond

**After absorbing 5 MGy:**

- After absorbing 5 MGy:
  - Switching HV off after signal stabilization: strong signal of opposite polarity is observed.
  - Signal time behavior depends on the MIPs rate.
  - Dynamic polarization!

**Measurements at $^{90}$Sr-source setup:**

- After switching HV on signal drops with time.
- Dynamic polarization!
Model of sCVD Diamond Polarization

**Polarization Model**

- Radiation damage – uniformly produced traps
- MIP signal – uniformly produced e–h pairs
- +Electric field → NONUNIFORM space charge

Change of the electric field
- e–h Recombination if the field is low
- Release of trapped charges (decay time)

Change of the space charge distribution

**Steady state POLARIZATION**

Dependent on trap density, applied voltage and signal rate
Model of sCVD Diamond Polarization - 1

Space charge

Steady state field

Low field, recombination

Change of signal shape

To be confirmed

Effective charge collection regions

09.06.2008 Radiation Hard Sensors
Model of sCVD Diamond Polarization - 2

Space charge

HV -> 0!

'Switch OFF' field

Steady state

Change of signal shape and POLARITY !!!

So14_04 sample model
Model of sCVD Diamond Polarization - 3

Space charge

$HV = 0$

$E \approx 0$

Change of signal size
Diamond sCVD sensor after 5 MGy

\[ CCE_0 = \frac{2}{aD} \left( 1 - \frac{1 - \exp(-aD)}{aD} \right) \]

\[ a = \frac{\pi R_{trap}^2 \cdot n_{free}}{l_0 \cdot N} \]

CCD at t=0 allows to extract \( n_{trap} R_{trap}^2 \) value

Steady state CCD is sensitive to \( n_{trap} \), \( T_0 \) and signal rate

Curve shape depends on the rate, trap properties and trap density.
CCD vs time dependence, low rate

So14-04 Diamond Sample (5 MGy)

- **HV polarity changed every 10 sec**
- **Constant HV polarity**
- **HV = 200 V, Low irradiation rate**

Trigger rate about 12 Hz, old trigger counters, $h_{\text{Source}} \sim 36$ mm
CCD vs time, different HV

“High rate” data

CCD dependence on HV in case of switching polarity is NOT yet in the model. What is E-field dependent: trap release time, capture probability?
Irradiated single crystal CVD Diamond

Regular change of HV polarity to avoid polarization: almost uniform E-field

Filled traps

\[ n_{\text{traps}} = k \text{Dose} + n_0 ? \]

More experimental studies needed
Uniformly distributed free traps

Charge absorption probability for the thin layer:

\[ P_l = 1 - \exp \left( -\pi R_{\text{trap}}^2 \frac{l}{l_0} \frac{n_{\text{free}}}{N} \right) = 1 - e^{-al} \]

\[ a = \frac{\pi R_{\text{trap}}^2}{l_0} \frac{n_{\text{free}}}{N} \]

In case when free traps are uniformly distributed:

Charge collection efficiency could be calculated analytically. For the detector of thickness D:

\[ CCE_0 = \frac{2}{aD} \left( 1 - \frac{1 - \exp(-aD)}{aD} \right) \]
Summary

- Strong polarization effect is observed in the radiation damaged scCVD Diamond detector.
- It was shown that the polarization significantly decreases the detector charge collection efficiency.
- A simple model is developed in order to understand and describe observed phenomena.
- Method of routinely switching HV polarity is proposed to suppress polarization. Large improvement of CCE is observed experimentally.
- More work is needed to understand CCD dependence on the signal rate and details of polarization development.
- It is desirable to continue test beam studies up to higher doses (approx 50 MGy) and measure sensor CCD @ ILC-like conditions.
Thank you...

Special thanks to GSI team: CVDD sensors, test beam etc.
Uniformly (partly) filled traps

Allowed reduction of the flux keeping $\varepsilon$ efficiency:

$$r = \frac{\Phi_{\varepsilon}}{\Phi_{\text{nom}}} = \frac{1}{R_{\text{nom}}^q} \cdot \frac{Q}{T_0 \cdot Q_{\text{absorb}}} \cdot \left( t - \frac{n_{\text{free}}^\varepsilon}{R_{\text{trap}}} \right) ; t - \text{detector operation time}$$

Alternating HV polarity + + stable particle flux = = XXL radiation hardness

Charge collection efficiency could be kept at high level for a very long time if particle flux is maintained stable.

Leakage current ??? Crystal destruction ???

sCVD Diamond Sensor

Allowed rate drop

CCE=0.95

D = 100 $\mu$m
D = 340 $\mu$m
D = 500 $\mu$m

CCE=0.9

Operation time, years

10^{-1} 1 \times 10^{2}