SiC and diamond as radiation hard semiconductor detectors

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www.surrey.ac.uk
Department of Physics  ~  30 academics

Part of the Faculty of Engineering and Physical Sciences (FEPS)

• Soft condensed matter (SCM)

• Astrophysics

• Photonics & Semiconductor devices - Advanced Technology in collaboration with electronic engineering

• Centre for nuclear and radiation physics (CNRP)
  - Experimental & Theoretical Nuclear Physics
  - Medical and Radiation Physics
    - Medical Physics & Imaging
    - Radiation Detector development

2 academics and approx. 12 research students

Page 2
Talk outline

• Basic semiconductor detector operation

• Advantages of wide band gap semiconductors – Low Z Radiation hard materials SiC/D

• (General) Effects of Radiation damage on semiconductor detector operation

• Quantifying “radiation hardness”

• Identifying created defects

• Conclusion – Future work
The current signal is induced by the movement of the created charge carriers: the current is proportional to
• the number of carriers \( \propto \) lifetime \( \tau > \) transit time \( T_R \)
• the charge carrier velocity \( \propto \) mobility \( \mu \), electric field strength

\[
\vec{E} = \frac{V_{bias}}{d}
\]
Signal formation

\[ \bar{E} = \frac{V_{bias}}{d} \]

\[ V_{Bias} \]

\[ R_B \]

charge sensitive pre-amplifier

Induced current

Signal duration

Induced charge

Signal amplitude
Wide band gap semiconductor materials for room temperature radiation detector application

Application areas

• High energy and nuclear physics
• Neutron detection & monitoring in nuclear industry
• High energy X- and γ-ray detection for medical and security applications
• Photon science/Synchrotron instrumentation
• Medical dosimetry
• High fluence backgrounds and harsh environments
• ....

http://www.ptw.de/diamond_detector0.html

Commerically available PTW chambers based on natural diamonds
Two main groups of materials studied

High Z material for X/$\gamma$ spectroscopy and imaging

Cd$_x$Zn$_{1-x}$Te

HgI$_2$ & TlBr

http://www.contech.com/Mercuric_Iodide_Detectors.htm

Radiation hardness/
Tissue “equivalent”
Neutron detection, TOF

Diamond
SiC
polymers

Birefringence pattern
diamond

3 mm

3 mm

CdTe
CdZnTe
HgI$_2$
TlBr

3 mm
Diamond & SiC for sensor applications

- Large heat conductance
- Low Z (low absorption)
- Tissue equivalence*
- Wide band gap (solar blind)
- Fast charge transport *
- Tissue equivalence*
- (Radiation) hardness

UV sensor  Neutron detection  (X-ray) Dosimetry

(s)LHC  Beam monitor

* stronger advantage in diamond compared to SiC
Attractive properties for detector applications (II)

Large band gap
⇒ “solar blind” (UV detection)
⇒ (low intrinsic leakage currents)
high temperature operation

Large heat conductance (5 x copper)

Resilience
⇒ Chemically inert
⇒ Radiation hardness

80 μm thick pc CVD diamond detector with Al contact

1 μs bunches of $10^9$ of $^{208}\text{Pb}^{67+}$ ions (400 MeV/u = 83.2 GeV).
⇒ Stable signal (in the order of milliampere)

J. Bol et al., phys. stat. sol. (a) 204, 9, pp. 2997-3003 (2007)

Diamond radiation detectors may be forever!

H. Kagan

Department of Physics, Ohio State University, Columbus, OH 43210, USA
Available online 4 May 2006

On behalf of the RD42 Diamond Detector Collaboration
Challenges in the material synthesis

**Diamond is meta-stable:**
- High Temperature/High Pressure (HP/HT) limited volume, purity

**Chemical vapour deposition (CVD)**
- Heteroepitaxy (typically polycrystalline – large area possible)
  
  *Diamond on Iridium might be able to provide sufficiently thick, homogenous large areas in the future*
- Homoepitaxy (typically < 1 cm² area)

**Columnar growth**
- Increasing grain size towards the top

- 1 to 10 μm h⁻¹

**Several polytypes of SiC exist**
- Physical Vapour Transport (bulk – single crystal)

- Chemical vapour deposition (CVD)

**Common defects**
- Impurities, Vacancies, Interstitials, Dislocations, Grain boundaries, Stacking faults, Polytype inclusions
SiC – thick (350 μm) “bulk” material

Non-uniform response in polycrystalline material

![Diagram showing signal amplitude and comparison between polycrystalline and single crystalline materials.](image)
Electronic grade single crystal detector performance

Energy resolution similar to Silicon

Time resolution, time of flight: 28 ps

See Figure 8 and 9 in M. Pomorski et al. phys. stat. sol. (a) 203 (12), pp. 3152-3160 (2006) DOI: 10.1002/pssa.200671127

See Figure 22 in M.Ciobanu, IEEE TNS 58 (4), pp. 2073-2083 (2011) DOI: 10.1109/TNS.2011.2160282
Towards large area single crystals

Images from E. Berdermann et al, 3rd Carat Workshop at GSI, Dec 2011

Heteroepitaxial growth on Iridium – large area substrates possible
Main European player: M. Schreck et al in Augsburg/Germany

For illustrations see:

http://www-carat.gsi.de/CARAT03/CARAT03Talks/Berdermann_CARAT03.pdf

Slide 4 and 14

Continuously improvement in thickness, quality and area with time
Towards more radiation hardness

Images from B. Caylar et al, 1st Adamas Workshop at GSI, Dec 2012

For illustrations used see:

http://www-adamas.gsi.de/ADAMAS01/talks/caylar.pdf

Slide 5 and 19

Several groups have demonstrated working devices:

Full CCE reached at very low applied bias (operate detectors with a 9V battery is possible)
SiC – excellent Schottky diodes for Spectroscopy have been demonstrated

Figure 2 in Ruddy et al, Nucl. Instr. Meth. B 263 (2007) 163-168
doi:10.1016/j.nimb.2007.04.077
High Temperature spectroscopy in epitaxial SiC Schottky diodes developed by RD50)

Alpha emission energy spectrum broad with average energy at 5 MeV

(Due to encapsulation of source to be safe to use at elevated Temperature)

Figure 1 inC. Manfredotti et al., Nucl. Instrum. Meth. A 552 (2005) 131–137
doi:10.1016/j.nima.2005.06.018
High Temperature spectroscopy in SiC

![Graph showing CCE and FWHM vs. Negative bias (V) for different temperatures.]

- CCE (%)
- FWHM (Chn.)
- Temperatures: 300K, 350K, 400K, 450K, 500K

Negative bias (V) vs. CCE (%) and FWHM (Chn.) for different temperatures.
Stability tests under fast neutron and gamma irradiation at room temperature show that epitaxial and bulk SiC samples also exhibit good stability at 4.5 to 18.5 mSv/hour (AmBe Source, Co-60).
Created of defects due to irradiation

\[ E_k = 60 \text{ keV} \]

Energy transfer to the lattice atoms moves them from a substitutional to an interstitial site:

\[ \rightarrow \text{Creation of } [V - C_i] \]

(Frenkel pair)

Dissociation and diffusion then can lead to many more defect complexes…

Annealing can change the defect types and concentrations further.
Effect of damage on electrical properties

... changes the type/concentration of defects present in the material and hence introduces/removes energy levels in the band gap

\[
\begin{align*}
\text{In the absence of any dopants:} & \\
\text{n}^- &= n^+ \\
\text{E}_C &= E_V \\
\end{align*}
\]

- “Close” to $E_C / E_V$: Dopants
- Near “mid gap”: Recombination centres
Effect of damage on electrical properties

... changes the type/concentration of defects present in the material and hence introduces/removes energy levels in the band gap

Leakage current:

In an “ideal” intrinsic semiconductor, free charge carrier density is given by

\[ n \approx N_c \exp\left(\frac{E_G}{2k_B T}\right) \]

\( N_c \), density of states in the conduction band \( \sim 10^{19} \text{cm}^{-3} \)

Large \( E_G \) gives lower dark currents, but experimentally “intrinsic” leakage current dominated by free carriers from defect states in the band gap.
Effect of damage on electrical properties

- **increase leakage**
  - increase in effective doping

- **reduce leakage**
  - Compensation (reduction in doping)
  - Reduction in carrier life time (recombination)

**Signal acquisition:**

- Reduction in free carrier lifetime – possibly reduced signal
- Trapping/De-trapping – “slower” signal
- Reduction in active thickness (depletion thickness depends on doping in diodes)
Polarisation a contact problem?

Surface and temporary effects:
- “temporary” changes in space charge distribution (polarisation)
- increase in number of occupied traps – increase in lifetime (priming)

Inconsistencies as a function of contacting method also observed by W. DeFerme, Hasselt Diamond Workshop 2009
The challenge of quantifying radiation hardness for detector applications

The NIEL concept – assumes displacement damage cross-section $D$ (MeV mb) – assumes that lifetime scales with # displacements

Seems to work for protons/neutrons $> 0.1$ GeV

Damaging radiation and probing radiation penetrate through the device thickness.

(26 MeV $H^+$/ 20 MeV $n$/ MIPs)

Signal halves after

$p: 4.5 \times 10^{14}$ cm$^{-2}$

$n: 1.3 \times 10^{15}$ cm$^{-2}$

Figure 4 De Boer, phys. stat. sol. (a) 204, No. 9, 3004–3010 (2007)
DOI: 10.1002/pssa.200776327
The challenge of quantifying radiation hardness for detector applications

What if the damaging/probing radiation does not penetrate the whole device?

A. Lohstroh et al, phys. stat. sol. (a) 2008, 205(9); p.2211-2215

Damaged area not visible in Raman spectra
The challenge of quantifying radiation hardness for detector applications

What if the damaging/probing radiation does not penetrate the whole device?

A. Lohstroh et al, phys. stat. sol. (a) 2008, 205(9); p.2211-2215

Damaged area not visible in Raman spectra
TOF/TCT measurements ...

... confirms that damage does not have a strong effect on mobility compared to lifetime (in Diamond)

\[ \mu_0 = (1600 \pm 100) \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} \]

\[ v_{\text{sat}} = (1.20 \pm 0.05) \text{ V cm}^{-1} \]

S. Gkoumas, PhD thesis, University of Surrey 2012
Introducing a “corrected” Damage factor

- Assume that trapping probability increases linearly with radiation fluence
- Take into account damage profile (e.g. SRIM or other code)
- Ionisation profile of probing radiation (e.g. SRIM or other code)

\[ Z. \text{ Pastuovic et al, Proc. of SPIE Vol. 8725 87251A-1} \]

\[ \text{Figure 4,5, 6} \]

\[ \text{doi:10.1117/12.2015541} \]

\[ \text{Works well for “low level damage in Silicon”} \]

\[ \Rightarrow \text{Needs to be demonstrated in wider range of materials} \]

IAEA (CRP: F11016-CR-2)
Identifying defect levels that affect the detector signal

Defect characterisation in semiconductors

- **DLTS** not useful for high resistivity
- **PICTS** light source/limited time scale
- **Luminescence** not quantitative/cannot see non-radiative defects
- **Optical absorption** detection limits/sample size
- **EPR** sample size, only sensitive to paramagnetic
- **PAS** sample size
- ...
**TL - after annealing**

20 Gy pre-irradiation – 313 K to 650 K, 10 K/s

1 $\times 10^{12}$ $n$ cm$^{-2}$: 0.5 eV
   0.6 eV
   1.7 eV
   0.7 eV

2 $\times 10^{13}$ $n$ cm$^{-2}$: 0.6 eV
   0.6 eV
   1.8 eV
   0.6 eV

1 $\times 10^{16}$ $n$ cm$^{-2}$: 0.6 eV
   0.6 eV
   0.8 eV
   0.9 eV

In pc: 1.8 to 1.9 eV observed by

Gonon et al. (APL 70 (1997) 2996-2998) and
Benabdesselam et al. (DRM 10 (2001) 2084-2091)
(substitutional Nitrogen?)
3H and “3.188 eV” centre – also seen in neutron irradiation study
Almaviva et al
JAPP 106 (2009) 073501

CL – after annealing

![CL intensity graph with wavelengths and concentrations](image)

- **5RL or L-band system** 305 nm
- **Free exciton** 232.5 nm
- **TR12 vibronic band** 480 nm
- **Band A** 425 nm
- **575 nm vibronic band** 600 nm
- **Nitrogen-vacancy center ZPL 575 nm**
- **3H center ZPL 504.56 nm**

**Concentrations:**
- $1 \times 10^{16} \text{ cm}^{-2}$
- $2 \times 10^{13} \text{ cm}^{-2}$
- $1 \times 10^{12} \text{ cm}^{-2}$
### CL - summary

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<th>λ [nm]</th>
<th>E [eV]</th>
<th>0 \text{n}cm^{-2}</th>
<th>A: $1 \times 10^{12}$ \text{n}cm^{-2}</th>
<th>B: $2 \times 10^{13}$ \text{n}cm^{-2}</th>
<th>C: $1 \times 10^{16}$ \text{n}cm^{-2}</th>
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</table>

**Before annealing**

**After annealing**

- **Free Exiton**
- **5RL - self interstitial or L band**
- **Known as damage signature**
- **Band A - dislocations**
- **TR12**
- **3H - interstitial**
- **N-related**
- **[N-V]_0**

GR1 (single neutral vacancy)
Conclusion

• Estimating the operational lifetime of detectors needs more understanding of the effects of radiation induced damage on their characteristics – including self annealing

• In wide band gap semiconductors, separating priming/polarisation and structural damage is challenging

• “Radiation hardness” as a material property independent of radiation and probe is not trivial

• Improving our understanding of hardness and defect characteristic with the help of IAEA coordinated research programme
Thank you!

Questions?