ADAMAS 1st Workshop

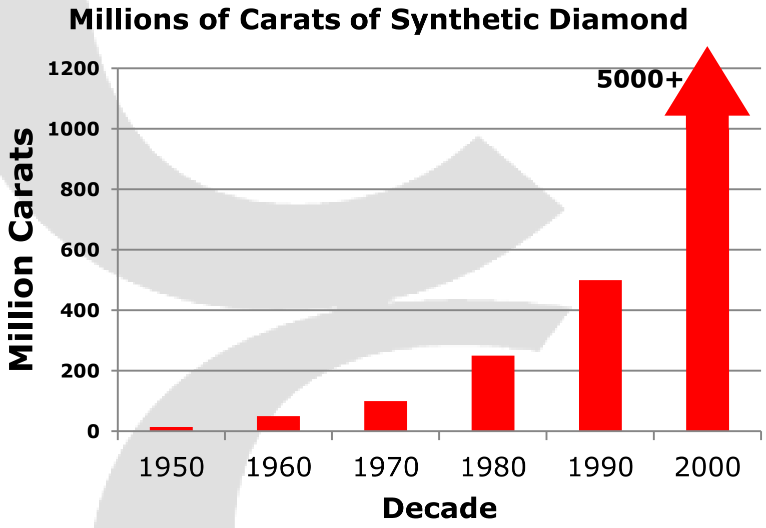
Diamond Material for Radiation Detectors

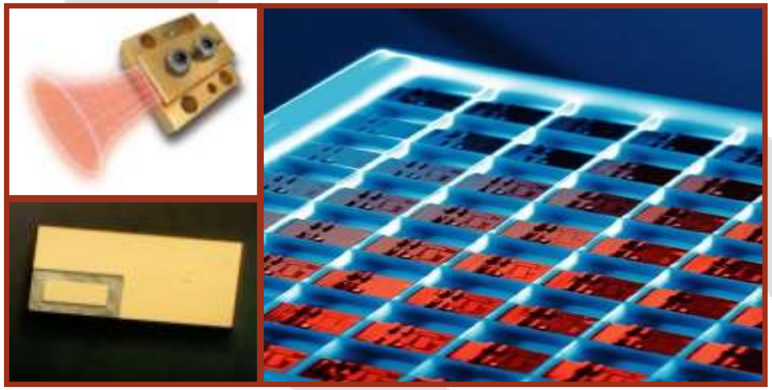
Monday 17th December 2012

Simon Mathias – Product Manager
Joe Dodson - Senior Scientist

Element Six today

- **World's leading supplier** of synthetic diamond and related super materials
- **Manufacture synthetic diamond from carbon**
  - using high pressure high temperature (**HPHT**) synthesis
  - chemical vapour deposition (**CVD**)
- **Processing and manufacturing** facilities in Ireland, Germany, South Africa, UK, Sweden, Isle of Man, China and **US**
- **2,500 employees** worldwide and sales of **~$500 million**
- Supply **~20,000 unique products** for our **~3,000 global customers**





Element Six Divisions

Abrasives

Oil & Gas

HPHT synthesis of polycrystalline diamond cutters

Global leader for Oil and Gas drilling

Advanced Materials

HPHT synthesis of synthetic diamond and cubic boron nitride (CBN) grits, powders and polycrystalline discs

Precision Grinding, Precision Machining, and Construction and Extraction applications of synthetic diamond

Hard Materials

Tungsten carbide sintering for hardmetal tooling applications

Carbide tools for the Road Restoration, Mining and Wear parts markets

Technologies

CVD diamond for applications beyond hardness

Global leader in synthesis of higher quality synthetic diamond exploiting the material’s many other extreme properties

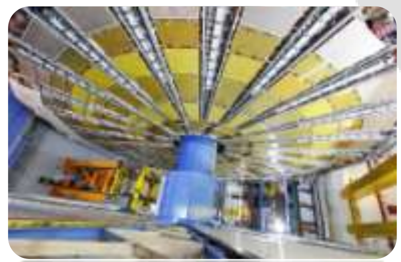
CVD diamond applications

Thermal

Thermal / Power Management

Sensors

Electrochemical / Radiation Detectors



Copyright CERN

Magnetometers

CURRENT APPLICATIONS → **EMERGING APPLICATIONS** → **FUTURE APPLICATIONS**

Optical Transmission

High Power Laser Windows, IR Imaging

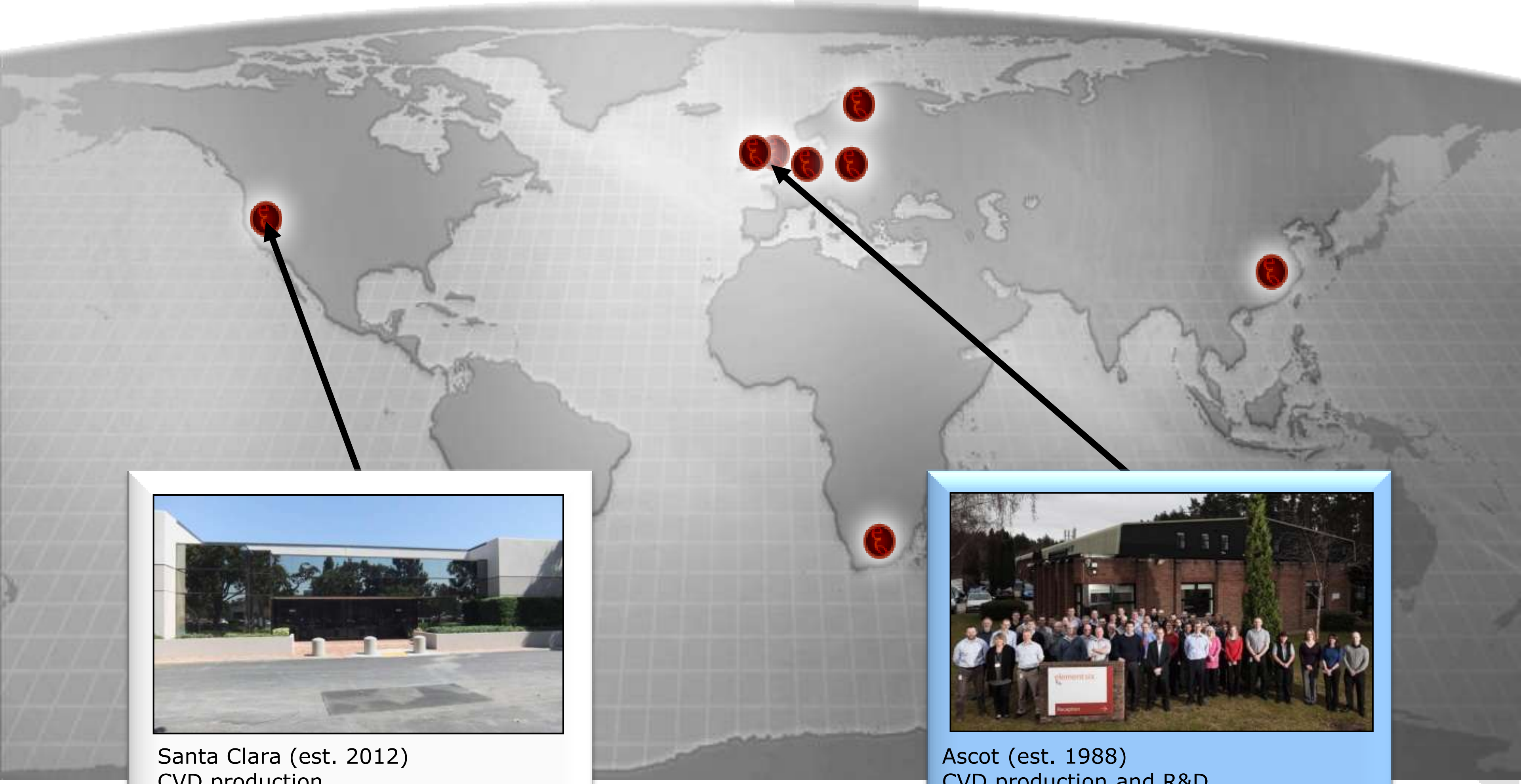
Water & Environment

Water Treatment, Ozone Generation

Quantum Computing

Quantum Information Processing

E6 Technologies sites



Santa Clara (est. 2012)
CVD production
and Business Development
Close proximity to silicon valley

Ascot (est. 1988)
CVD production and R&D
50 staff
ISO9001 (since 1993)

The world's largest and most sophisticated synthetic diamond R&D facility

- Investing in a Global Innovation Centre to continue our innovation
  - Harwell, Oxfordshire
- $30m investment in a 16,000sq ft building
- Consolidates global R&D teams
- 100 top engineers, scientists and technicians
- Facilities includes CVD synthesis lab

Product Strategy – Electronic Grades

- Electronic Grade Product and Material Strategy:
  - Supply material in standard dimensions/thicknesses for detector applications:
    - Single Crystal (ELSC)
      - 2x2, 3x3, 4.5x4.5mm @ 300/500microns
    - Polycrystalline (EL+)
      - 5x5, 10x10, 20x20 @ 300/500microns
- Demand and Orders
  - Build relationship with detector community to understand technical, material and product requirements
  - Additional demand through 2012-2013/14, require input from detector community
  - New thicknesses, sizes
- Important to obtain early notice as lead times are long

Questions from July 2012

DISCUSSION

1. Quality of DG materials as regards structural defects (especially problematic for applications with DC current readout

2. Quality of materials as regards residual trace contaminations, dangling bonds etc. : if some application do not require < 5 ppb EG but 10 or 50 ppb ?

3. Sizes: why always squares? Octagons and hexagons may give larger active areas.

4. Urgently required option (= standard): marked corner and surface for the orientation identification.

5. What thicknesses will be prepared from E6 for commercial supply ?

6. How to define the ‚surface quality' ?

7. What kind of final post processing will be done from e6.

Detector grade production

- Production methods and philosophy
  - Thickness
  - Lateral dimensions – sizes and shapes
  - Orientation marking
  - Surface finishes
- Quality
  - Interaction of bulk and surface
  - Lattice imperfections
  - Higher defect densities for less demanding applications
- Questions for discussion

Production methods and philosophy

- Batch process
- Site operates at high volumes
  - *Part X: 15 mm polycrystalline, 300 units / month*
  - *Part Y: 4 mm single crystal plates, 500 units / month*
- Fixed production routes to ensure consistency and cost management
  - Standard part sizes and methods for current set of Detector materials

Production route

Synthesis

Processing

- Achieve thickness
- Create surface finish

Processing

- Lateral dimensions

Production route – Electronic grades

Synthesis
- Optimised for 500 µm product

Processing
- Achieve thickness
- Create surface finish

Processing
- Lateral dimensions

Both Polycrystalline and Single Crystal

Production route – Electronic grades

Synthesis

- Optimised for 500 µm product

Both Polycrystalline and Single Crystal

Processing

- Achieve thickness
- Create surface finish

Standard thickness
Thinned plates

Standard surface finish
Post processing

Processing

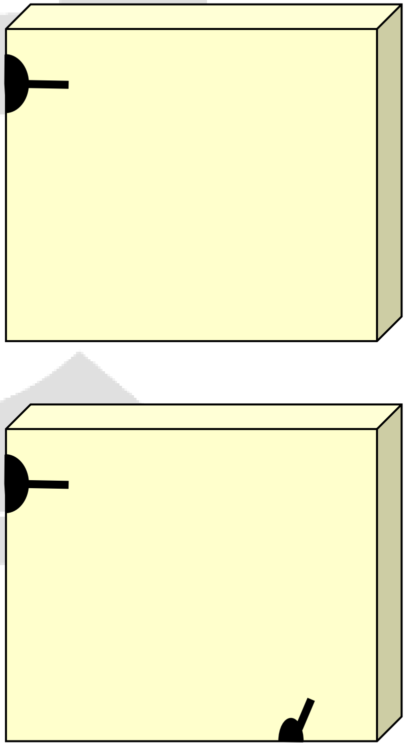
- Lateral dimensions

Shapes – squares
Marking for sides

Processing – thickness and surfaces

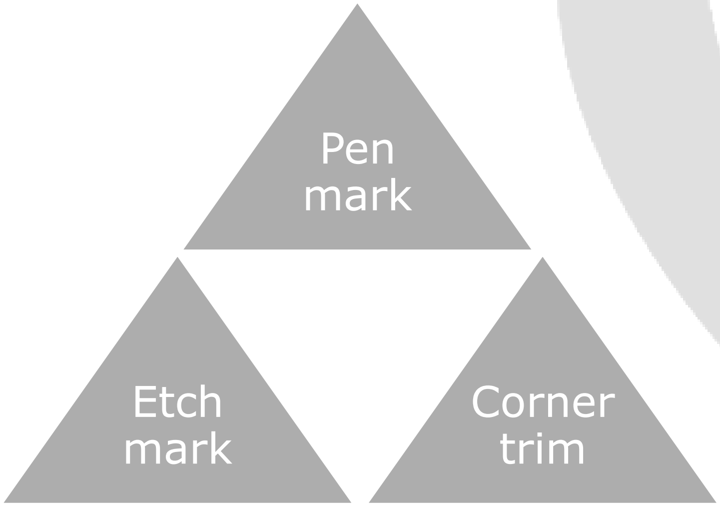
- Processing to thickness
  - 500 micron product is historic standard thickness
  - 300 micron thickness now standard variant
  - *Is there an ideal thickness in range 10-100 micron?*
- Surface finish
  - Mechanical polishing for both polycrystalline and single crystal grades
  - Emphasis is on minimised "sub surface damage"
    - Polycrystalline method as developed for CERN RD42 (2005)
    - Single crystal method internally developed
  - *Lowest damage is not necessarily flattest surface*
    - *Flatness, surface form, parallelism?*

Processing for lateral dimensions



- Laser cutting
  - Normally finish with laser trim
    - ➢ Remove cracks / edge damage
  - Assessment to make standard sizes
    - ➢ Squares simplest to maximise product size

- Markings to identify side
  - Bespoke requests: will always be additional operation

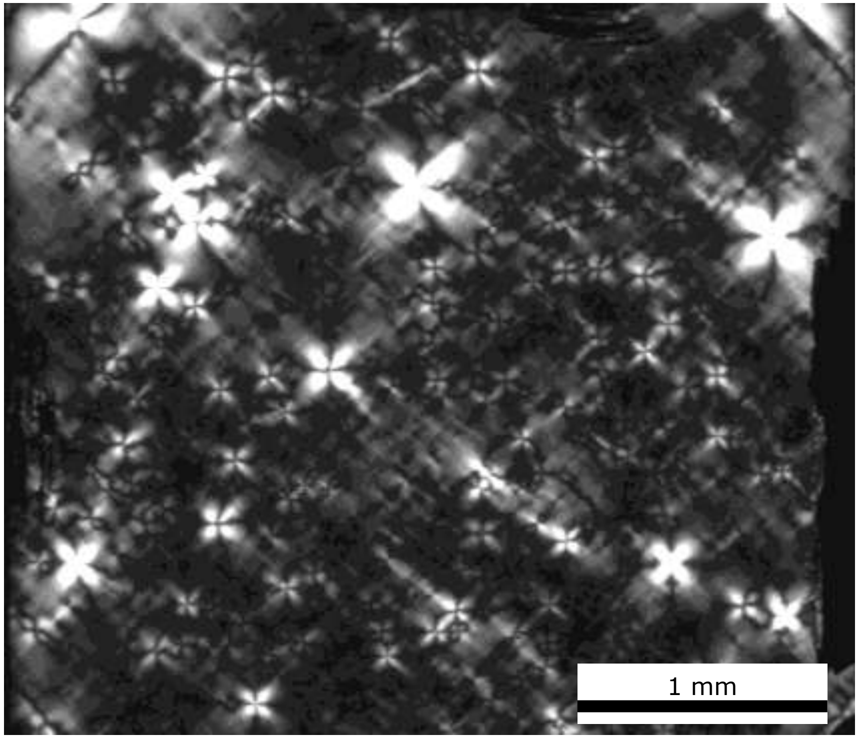


Detector grade production

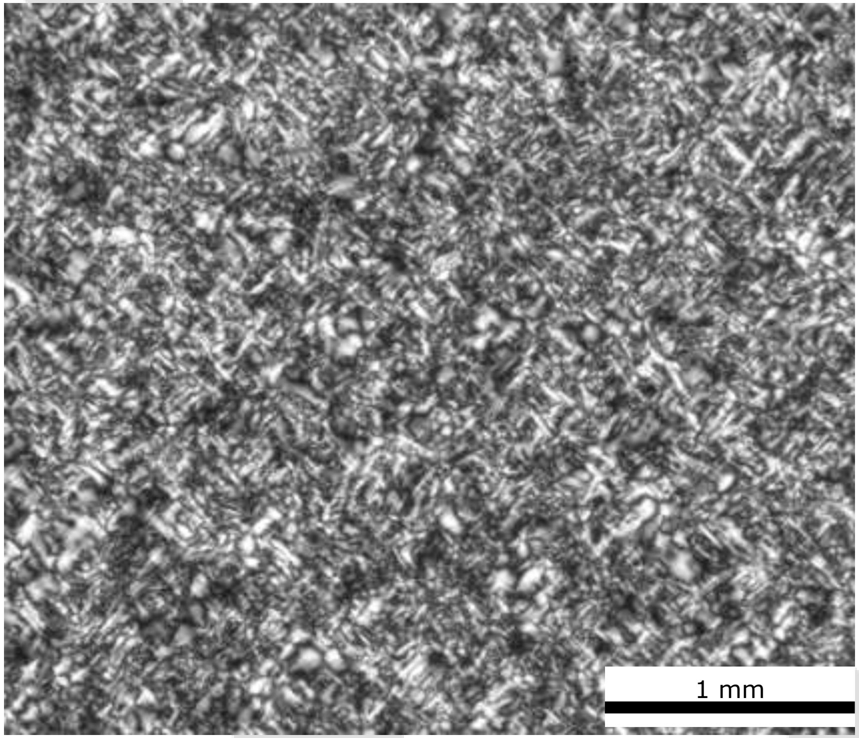
- Production methods and philosophy
  - Thickness
  - Lateral dimensions – sizes and shapes
  - Orientation marking
  - Surface finishes
- Quality
  - Interaction of bulk and surface
  - Lattice imperfections
  - Higher defect densities for less demanding applications
- Questions for discussion

Surfaces and bulk defects

Crossed-polar microscopy shows stress birefringence



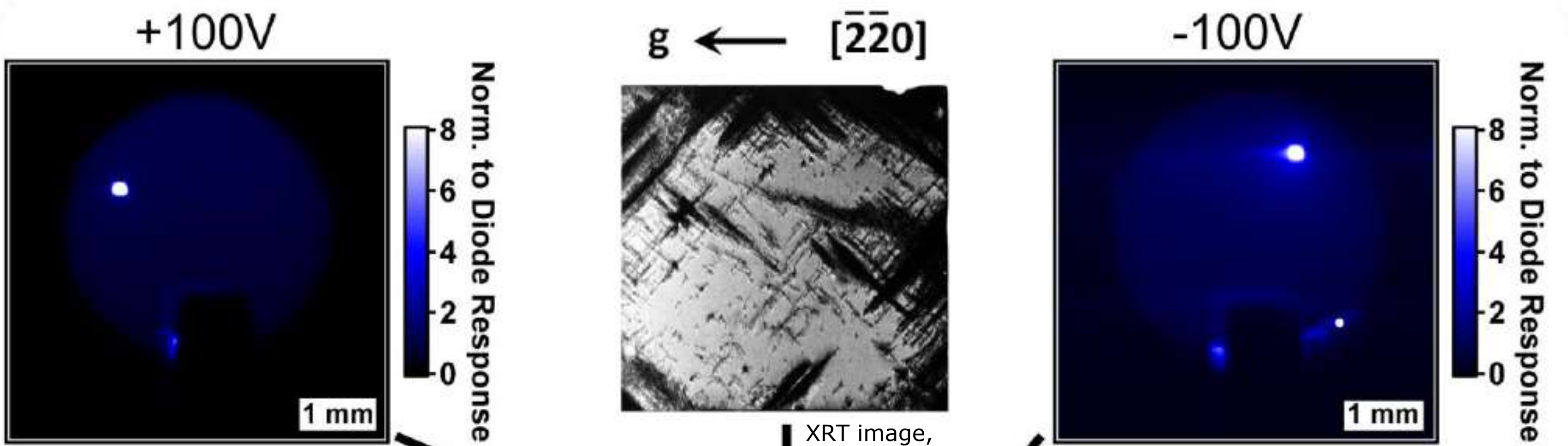
Historic single crystal *c*2006

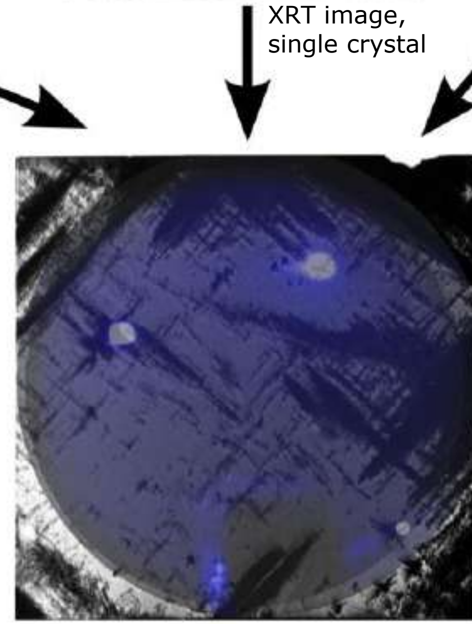


EL poly sample – historic and current

Despite high levels of stress visible in polycrystalline samples, performance can be excellent

Polarity dependent location





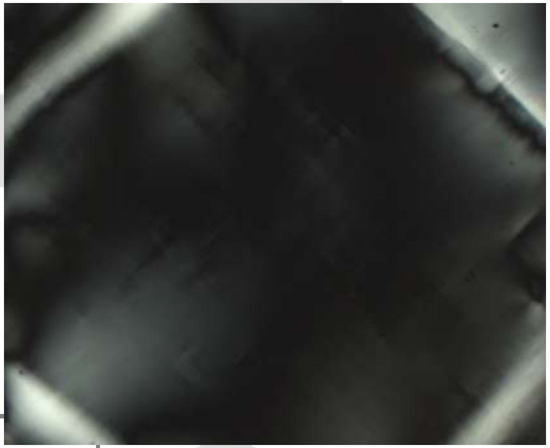
Metallised diamond in focussed white x-ray beam

Current response map under different polarities shown normalised to Si reference diode

- Hotspots map on to three defects
  - Defects only active in one polarity
  - **Interaction of defect with surface**

Brookhaven National Lab.
Smedley and co-workers

Improved bulk and surfaces?



Recent research grade single crystal sample under cross-polar microscopy

Improve material	Ongoing: modified recipe modified structure
Improve polishing	Internal development Increase capacity
Add in post processing	Various etches known; not E6 standard offering

- Will always need to be combination of material, surface and contacts to get best performance

Alternatives to Detector grades

- Electronic grades are at lowest defect extreme
  - Bulk of E6 diamond sold has more defects

CVD Polycrystalline Diamond Grades

Grade		Key Properties		Key defects
Boron Doped	**Mechanical**	B conc	Typ. 10^{21} cm^{-3}	B conc.
	Electrochemical		Typ ~10^{21} cm^{-3}, 10^{-3} Ω.m	Impurities (e.g. N)
Mechanical	**CDM, CDD**	Thermal Conductivity	Typ > 1000 $W.m^{-1}.K^{-1}$	Intrinsic defects
		High wear resistance	F_n(grain size)	Nitrogen
		Fracture strength	500 - 1100 Mpa, F_n(grain size)	Grain size/boundaries
		Youngs Modulus	1050 Gpa	
Thermal	**TM100 to TM200**	Thermal Conductivity	1000 - 2200 $W.m^{-1}.K^{-1}$	All point defects
		CTE	1.0 ppm K^{-1}	Grain size (< 5 µm)
Dielectric	**RF grade**	Loss tangent (145 GHz)	$<10^{-4}$	Intrinsic defects
		Relative permittivity	5.7	Surface contamination
Optical	**Standard**	Absorption	< 0.07 cm^{-1} at 10.6 µm	Intrinsic defects
		Integr. forward scatter	< 0.7% at 10.6 µm	Black spots
		dn/dT	9.6×10^{-6} K^{-1}	Strain
Electronic	**Detector**	CCD	300 µm possible	Intrinsic defects
		Chemical purity	[N] < 50 ppb, [B] < 0.5 ppb	Nitrogen/impurities
		Radiation hardness	50% original CCE for 6×10^{15} p cm^{-2}	Grain size
	Quantum	T2 (NV^- decoher. time)	> 0.5 ms	All defects, via spin or strain

Decreasing impurities/ defects

CVD Single Crystal Diamond Grades

Grade		Status	Key Properties	
Boron Doped	**Mechanical**	R&D	B conc:	Typ. 10^{17} - 10^{21} cm^{-3}
	Electrochemical			High concentration uniformity
Mechanical		Commercial	Thermal Conductivity:	> 2000 $W^{-1}.m^{-1}.K^{-1}$
			Youngs Modulus:	1050 Gpa
			Wear:	High wear resistance
			Reactivity:	Chemically inert
Optical	**Standard**	Commercial	Absorption:	< 0.02 at 1.064 µm
			Birefringence:	< 5 x 10^{-4}
			Integr. forward scatter:	< 0.6% at 1.064 µm
	Low birefringence	Commercial	Birefringence:	< 1 x 10^{-5} (to < 1 x 10^{-7})
			Raman gain:	15 $cm.GW^{-1}$
Electronic	**Detector**	Commercial	CCD:	>> 400 µm (limited by dim.)
			Chemical purity:	$[N_s^0]$ < 5 ppb, [B] < 0.3 ppb
			X-ray sensitivity:	> 300 $nC.Gy^{-1}.mm^3$ (~ 6 x nat.)
	Device structures	R&D	Electron mobility:	4500 $cm^2.V^{-1}.s^{-1}$
			Hole mobility:	3800 $cm^2.V^{-1}.s^{-1}$
Quantum		R&D	Isotopic purity:	> 99.95% ^{12}C
			Chemical purity:	$[N_s^0]$ < 1 ppb
				[NV] < 10^{10} cm^{-3}
			T2 (decoherence time):	> 15 ms

Decreasing impurities/ defects

Alternatives to Detector grades

- Electronic grades are at lowest defect extreme
  - Bulk of E6 diamond sold has more defects
- Polycrystalline
  - Optical, Thermal and Mechanical grades
    - Sizes match or exceed EL
    - Limited quantitative data on CCD / timing performance
    - Range of variation of performance not controlled
- Single Crystal
  - Optical and Mechanical grades
    - Sizes match or exceed EL
    - Indicative CCD data -> 50-150 μm (500 μm sample) at 2 V/μm
    - Improved optical grade in R&D (not yet commercial)

For discussion

- Standard thicknesses 300, 500 micron
  - A “thin” standard thickness as well?
- Surface finishes vs damage
  - How important is flatness?
- Shapes and marking
  - Appropriate corner marking method?
- Improving quality
  - Bulk / surface interactions
- Your needs and requirements