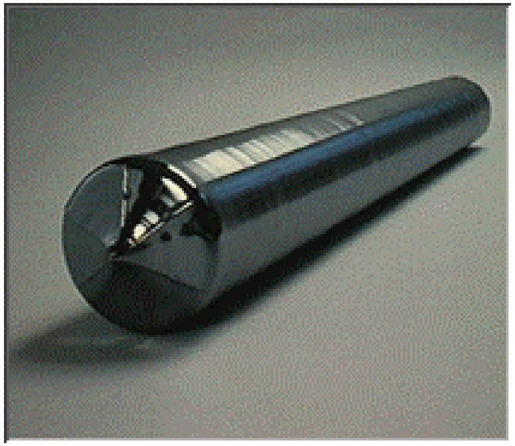
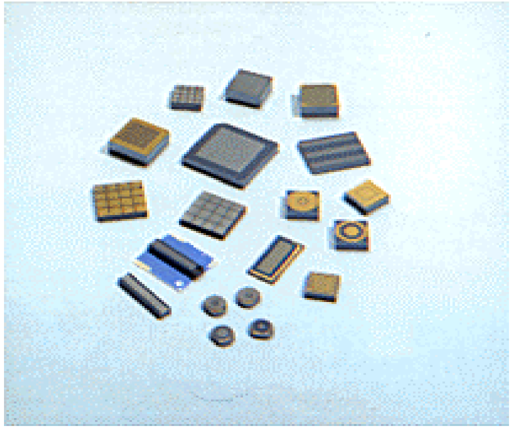
New semiconductor materials

Workshop on X-ray Detectors, ESRF February 13-14, 2003

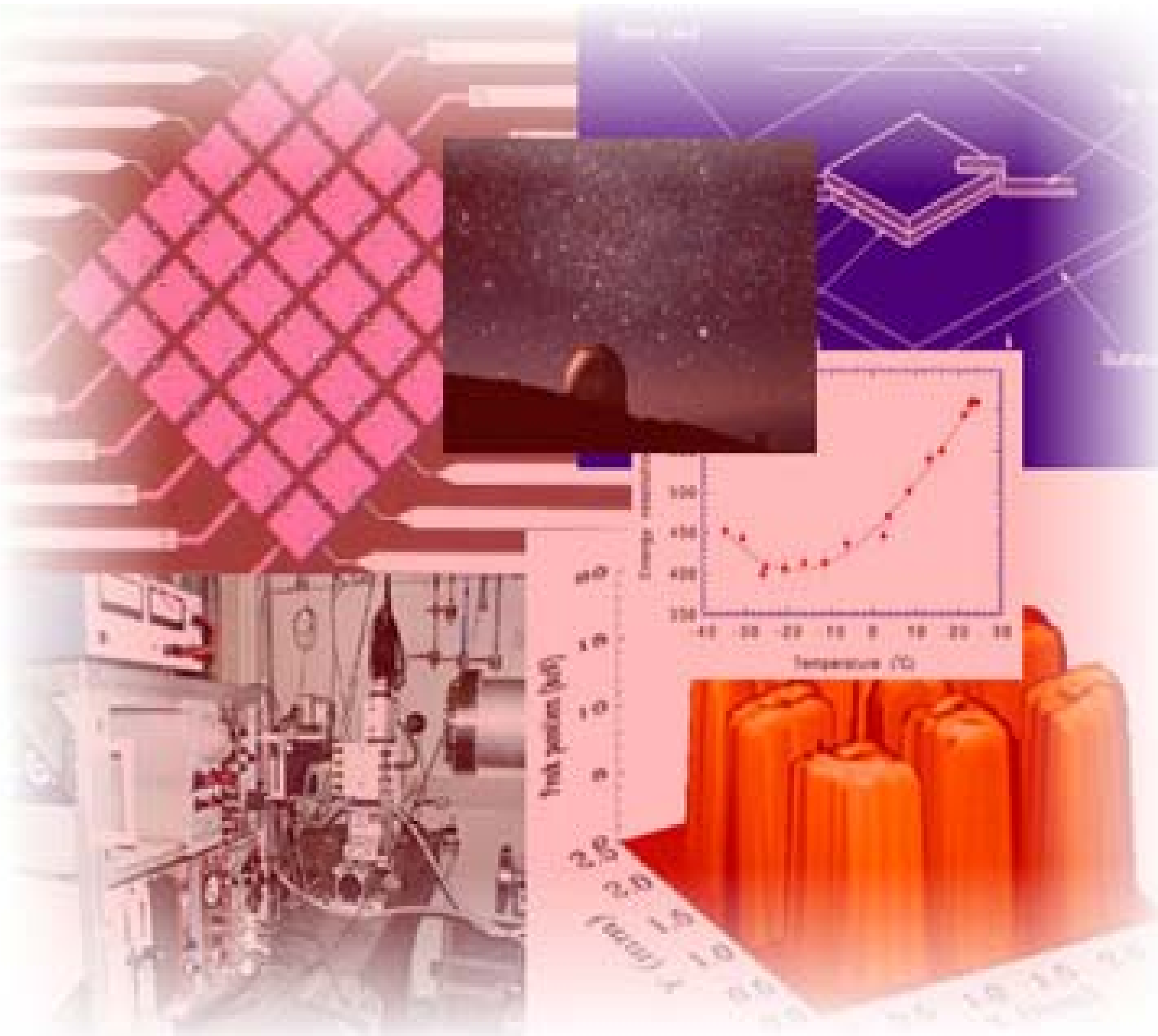
Alan Owens

Science Payloads and Advanced Concepts, ESA/ESTEC, 2200AG Noordwijk, The Netherlands





SCI-A Laboratory program



Experimental goals

Produce Fano-limited hard X-ray imagers

- sub-keV energy resolution
- 0.5-200 keV energy range
- room temperature operation
- micron spatial resolution
- low power and bias

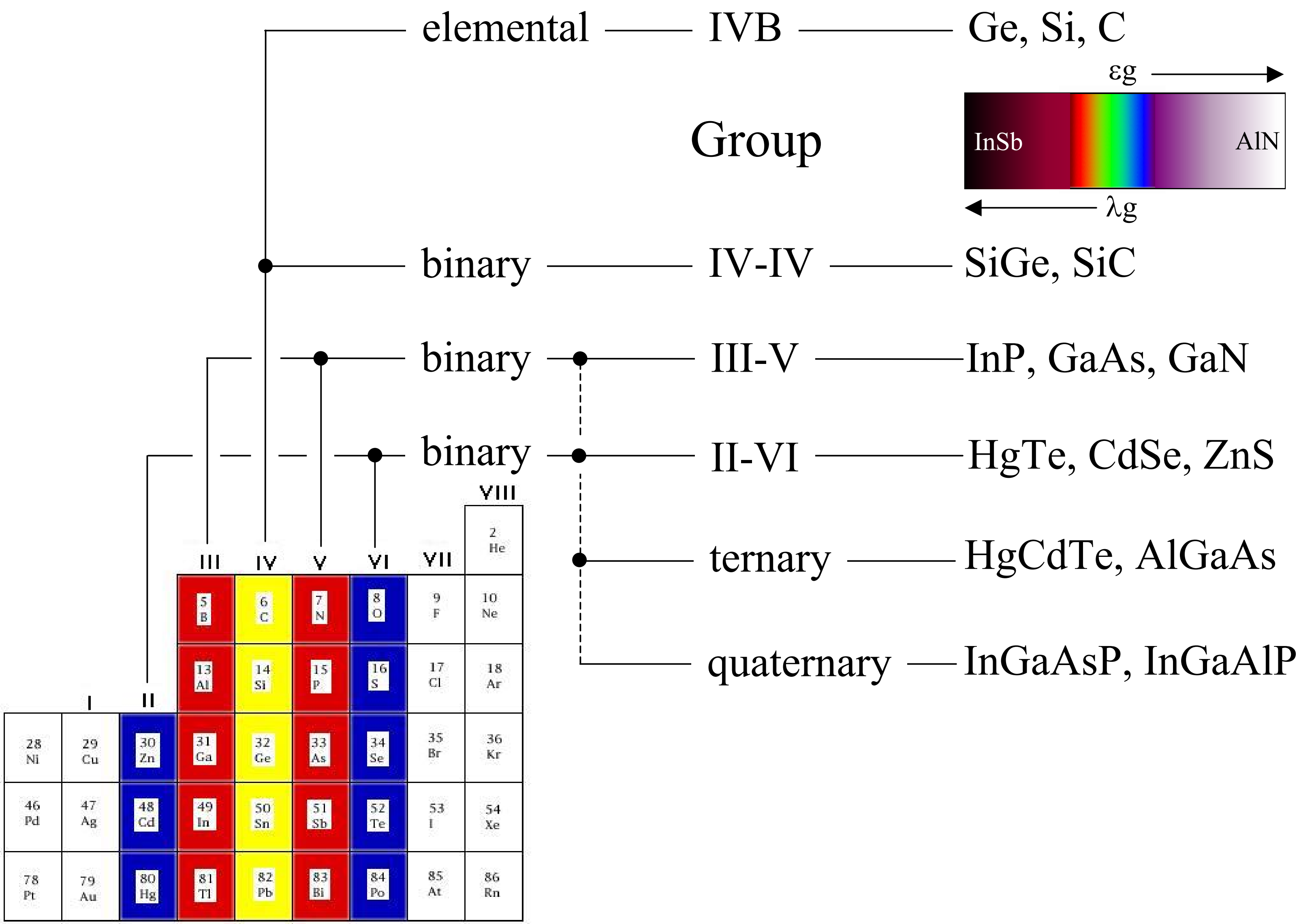
Produce light weight hard X-ray focussing optics

- energy range matched to detection plane
- arc-second psf's
- short focal lengths
- low replication costs

Research areas

- monolithics
- arrays
- Wolter-type nested shells
- micro-pore optics

What are compound semiconductors?

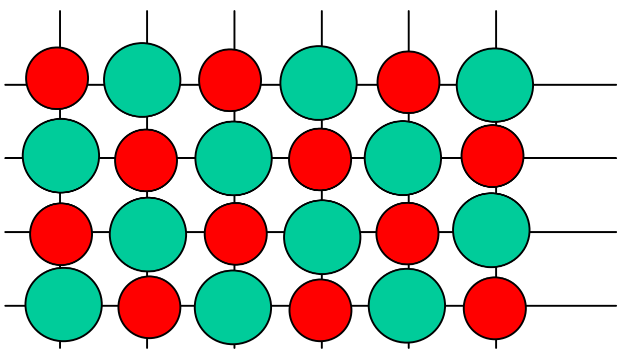


Alloying: atoms mixed on a lattice
Solid Solutions and Ordered Compounds

Ordered Substitutional and Interstititials Compounds

Substitutional

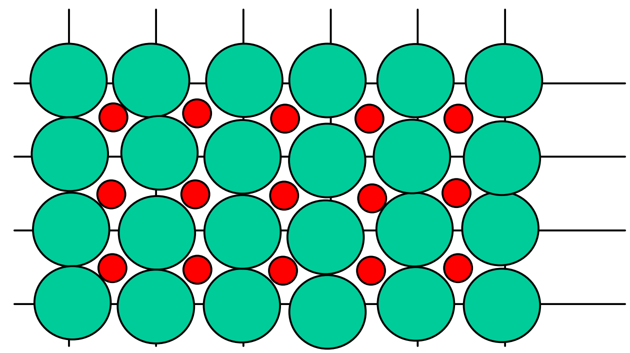
'an element replaces host atoms in an orderly arrangement'



***e.g.*, Ni_3Al (hi-T yield strength), $Al_3(Li,Zr)$ (strengthening)**

Interstitial

'an element goes into holes in an orderly arrangement'



***e.g.*, small impurities, clays ionic crystals, ceramics.**

Hume-Rothery Rules

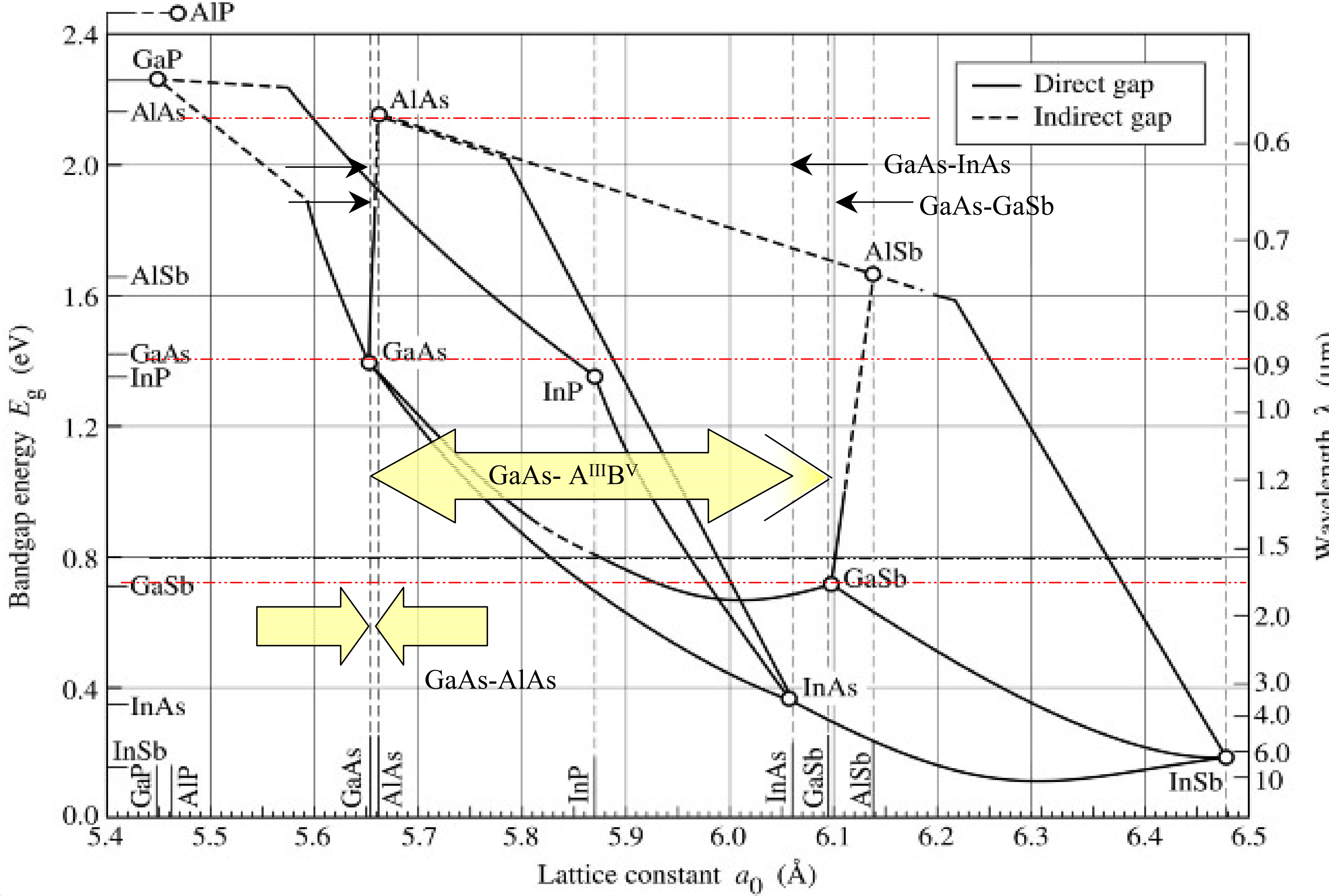
When a substitutional alloy is formed:

- The ***atomic radii*** of the different atoms involved must ***differ by <15%***
- The components must have the ***same crystal structure***
- The species must have ***similar valences***
- The components must ***have similar electronegativities***

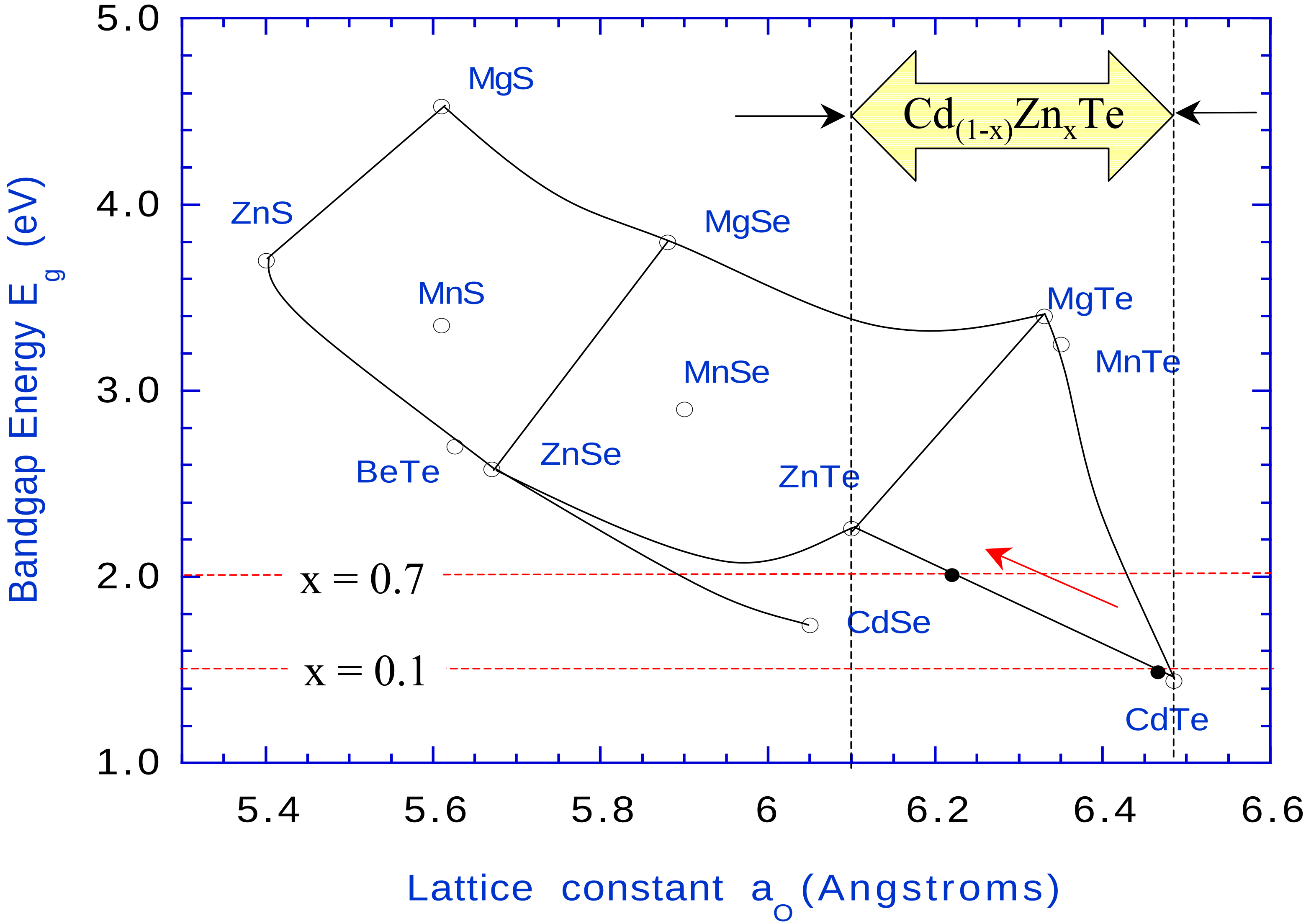
Rational behind Hume-Rothery Rules

- ***Atomic radii must be similar*** because if substituted atom is too large, ***considerable strain will develop in crystal lattice***
- ***The components must have similar crystal structure if solubility is to occur over all proportions***, *e.g.* Co/Ni system. However, this is less important if small proportions of solute being added such as in the doping of semiconductors.
- ***Similar valences and electronegativities*** indicates that components have ***similar bonding properties.***

Phase diagram III-V materials



Phase diagram II-VI materials



x=0.1 - Eg optimized for operation at ~-30°C; x=0.7 - Eg optimized for room temp. operation

Advantages of compound semiconductors

- Wide variety of compounds available

Band-gap energy (eV)	Elemental Group IVB	Binary IV-IV Compounds	Binary III-V Compounds	Binary II-VI Compounds	Binary IV-VI Compounds	Binary n-VIIB Compounds	Ternary Compounds
0.00-0.25	Sn		InSb	HgTe			HgCdTe
0.25-0.50			InAs	HgSe	PbSe, PbS,PbTe		
0.50-0.75	Ge		GaSb				InGaAs
0.75-1.00		SiGe					
1.10-1.25	Si						
1.25-1.50			GaAs, InP	CdTe			AlInAs
1.50-1.75			AlSb	CdSe			AlGaAs
1.75-2.00			BP, InN				CdZnTe,CdZnSe,InAlP
2.10-2.25		SiC	AlAs	HgS		HgI_2	CdMnTe
2.25-2.50			GaP, AlP	ZnTe, CdS		PbI_2	TlBrI, InAlP, $TlPbI_3$
2.50-2.75				ZnSe		TlBr	
2.75-3.00				MnSe			
3.10-3.25				MnTe			
3.25-3.50			GaN	MgTe, MnS			
3.50-3.75				MgSe, ZnS			
3.75-4.00							
4.10-4.25							
4.25-4.50				MgS			
4.50-4.75							
4.75-5.00							
5.10-5.25							
5.25-5.50	C						
5.50-5.75							
5.75-6.00			BN				
6.10-6.25			AlN				
6.25-6.50							
6.50-6.75							
6.75-7.00							

Advantages of compound semiconductors

- Wide variety of compounds available
- Compounds can be selected for specific environments or applications

  e.g., to operate in the high radiation fields of the LHC or Jupiter

  operation at elevated temperature e.g., solar probes, direct beam monitors

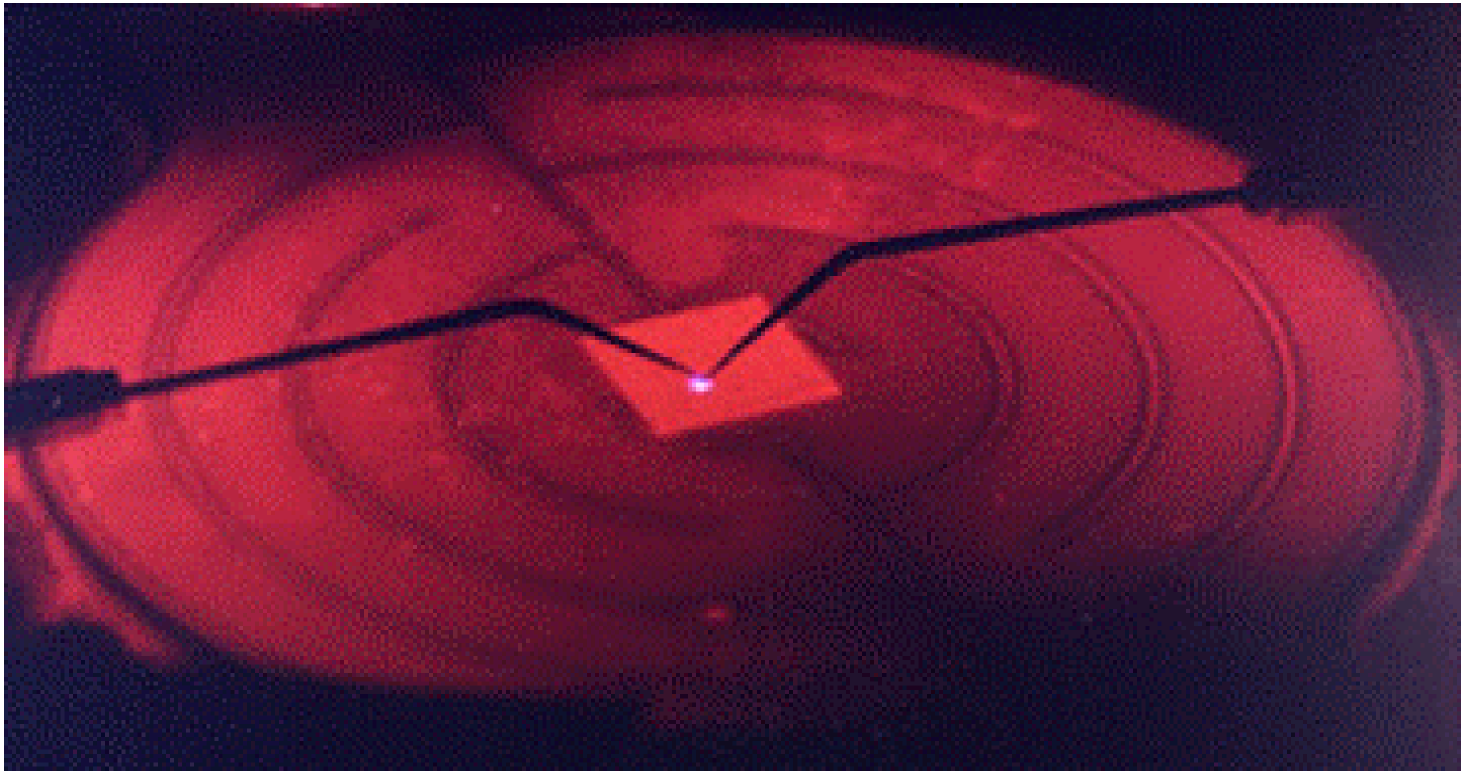
Table III. Suggested "top ten" compounds for future development. Apart from AlSb and CdMnTe, which could become the workhorses of room temperature X-ray and gamma-ray spectrometry, each material has great potential in a specific area. Even though diamond and TlBr are already under investigation, we include them here for future development because of their immaturity.

Material	Bandgap eV	Density g cm^{-3}	Comments	Space/medical/general applications
InSb	0.17	5.66	Narrow band gap, 3 times better energy resolution than Si	High resolution X-ray astronomy (He$_3$ temperatures), XRF
InAs	0.35	5.68	Narrow band gap, 2 times better energy resolution than Si	High resolution X-ray astronomy (He$_3$ temperatures), XRF
AlSb	1.62	4.26	Theoretically, the best all round performer	Room temperature Si replacement, compact planetary spectrometers,
PbO	1.9	9.8	Highest Z, gamma-ray detection	Compact gamma-ray planetary detectors/radio guided probes
BP zb	2.0	2.90	Neutron detection	Spacecraft in-orbit neutron monitor, neutron capture therapy
CdMnTe	2.1	5.8	Gamma-ray detection, inexpensive replacement for CdZnTe	γ-ray astronomy, low cost gamma-ray imagers/PET detectors, well logging
SiC	2.2	3.2	All round radiation detection (p,n γ) in extreme environments, rad hard	Planetary surface X-ray spectrometer, solar flare monitor, nuclear reactors
III-N			High temperature ceramics, chemically inert, stable, range of band-gaps	High temperature applications, planetary surfaces, solid state lighting
InN	2.0	6.81	high effective hole mass, high Z	Compact gamma-ray spectrometer for rovers
GaN	3.4	6.15	high mobility, high speed applications	Solar X-ray monitors. Penetrators, synchrotron applications
BN	6.0	3.48	neutron detection, extremely rad. hard	Planetary surface neutron monitor, nuclear pile detectors
AlN	6.2	3.25	widest bandgap, radiation hard	Solar blind X-ray monitors, well logging
TlBr	2.68	7.56	High Z, gamma-ray detection	Gamma-ray astronomy/ radio guided probes, well logging
Diamond	5.4	3.52	High temperature, hard, chemically inert, radiation hard, robust, stable	Detectors for hot corrosive, atmospheres, solar flare monitors, hadron therapy – tissue equivalent detectors

Owens (2003)

Advantages of compound semiconductors

- Wide variety of compounds available
- Compounds can be selected for specific environments or applications
  - e.g., high temperature operation

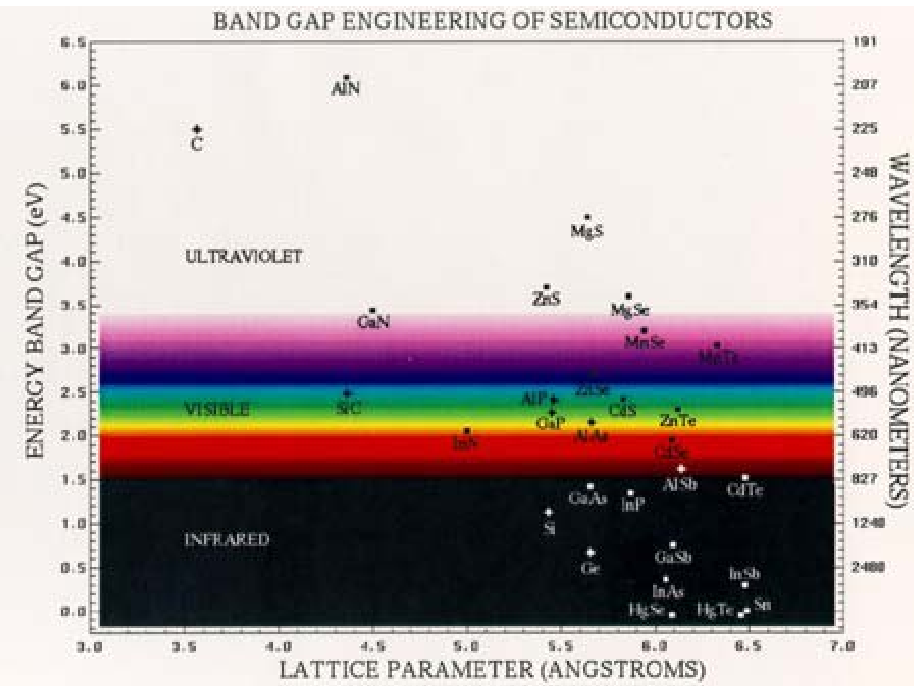


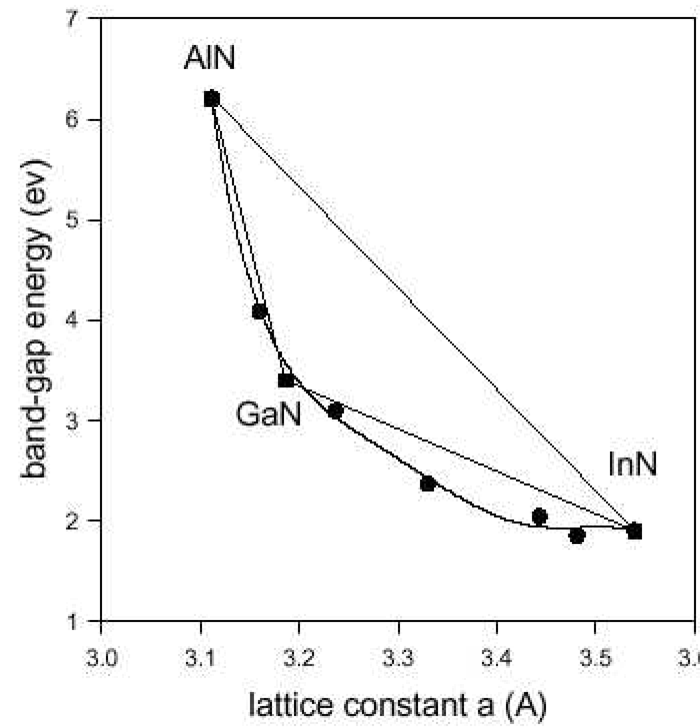
SiC blue photodiode (25mm^2) operating at 600^o C

Advantages of compound semiconductors

- Wide variety of compounds available
- Compounds can be selected for specific environments
- Materials can be <u>engineered</u> for specific applications

  bandgap or wavelength engineering, e.g., colored LEDs (NASDAQ display in Times Square)





Advantages of compound semiconductors

- Wide variety of compounds available
- Compounds can be selected for specific environments
- Materials can be engineered for specific applications

  e.g., photonic crystals, quantum wires

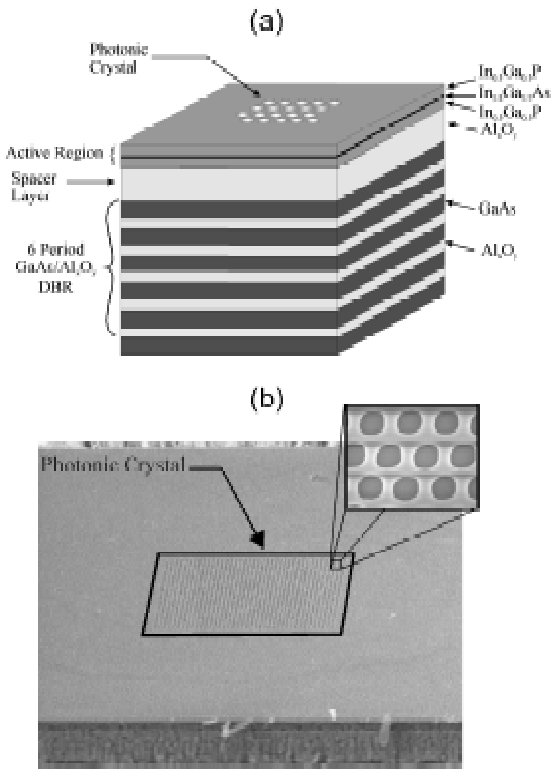
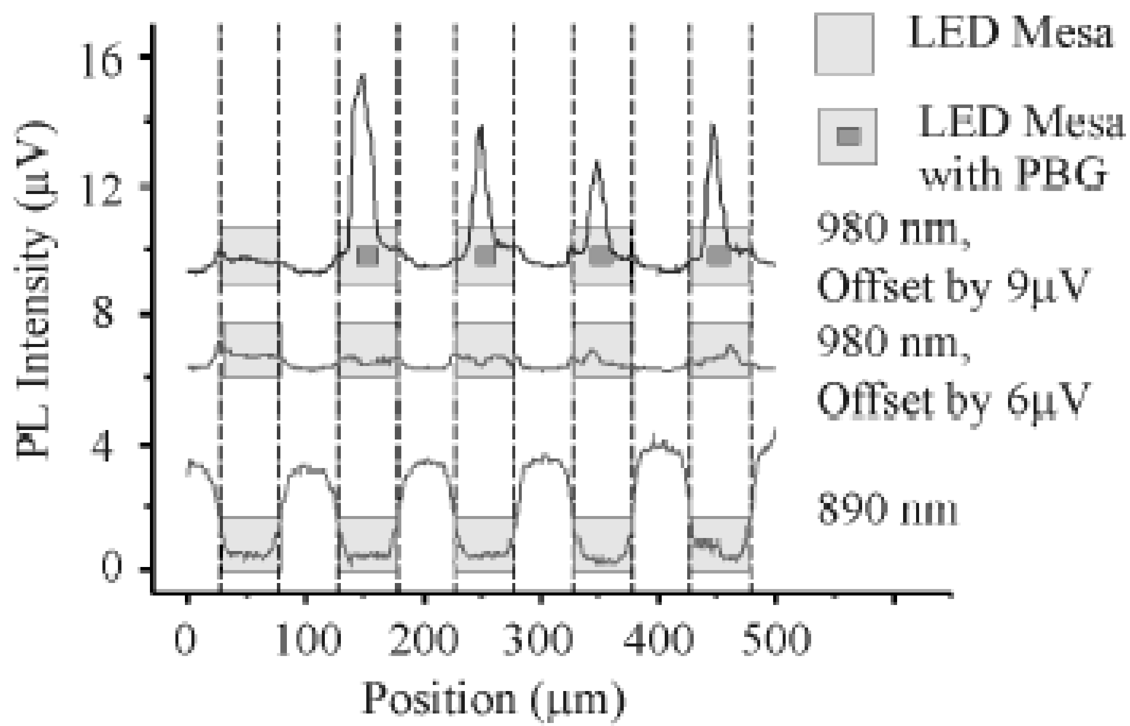


Figure 8. (a) The schematic of the 2-D PBG light emitting diode structure. (b) A scanning electron micrograph of the 2-D PBG light emitting diode.

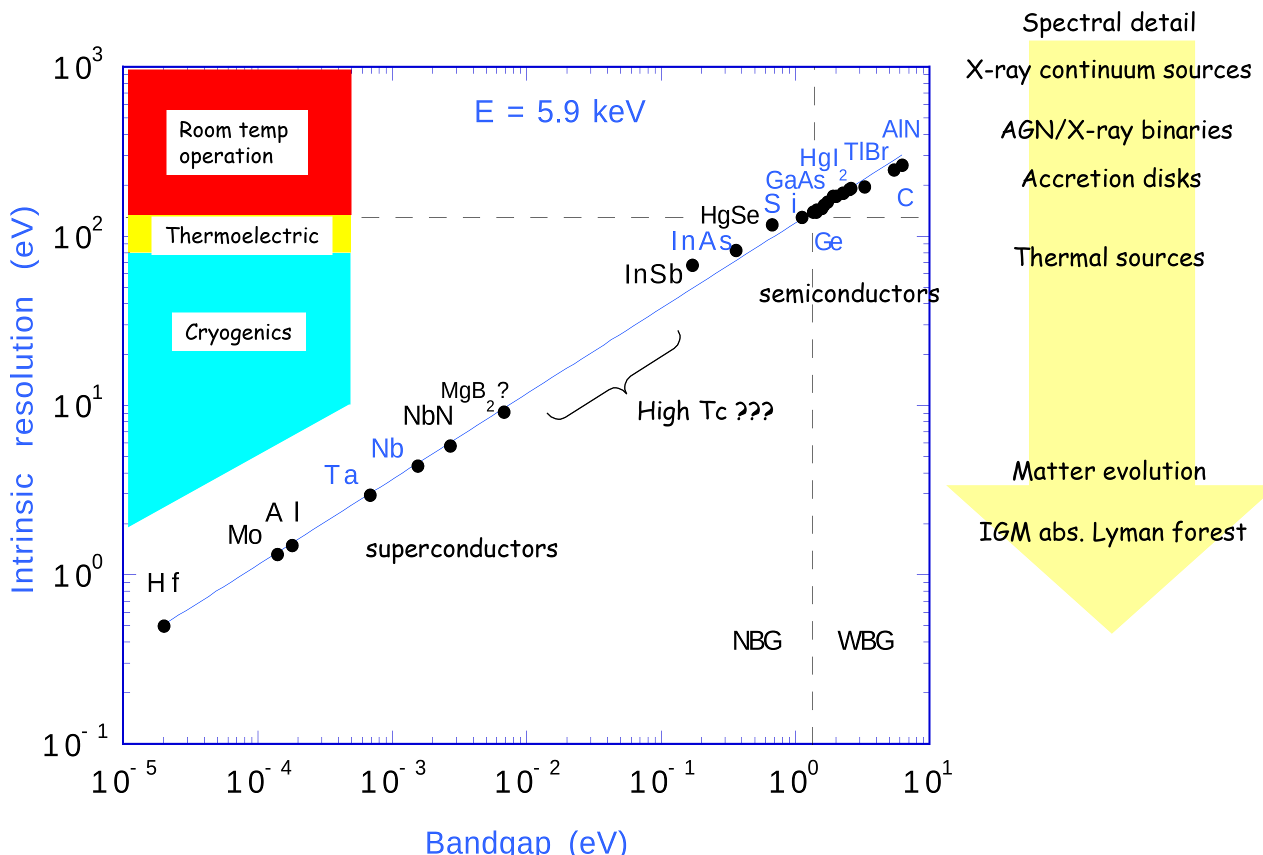


Spatially resolved photoluminescence

Advantages of compound semiconductors

- Wide variety of compounds available
- Compounds can be selected for specific environments
- Materials can be engineered for specific applications
- Ability to match response and energy resolution to an application

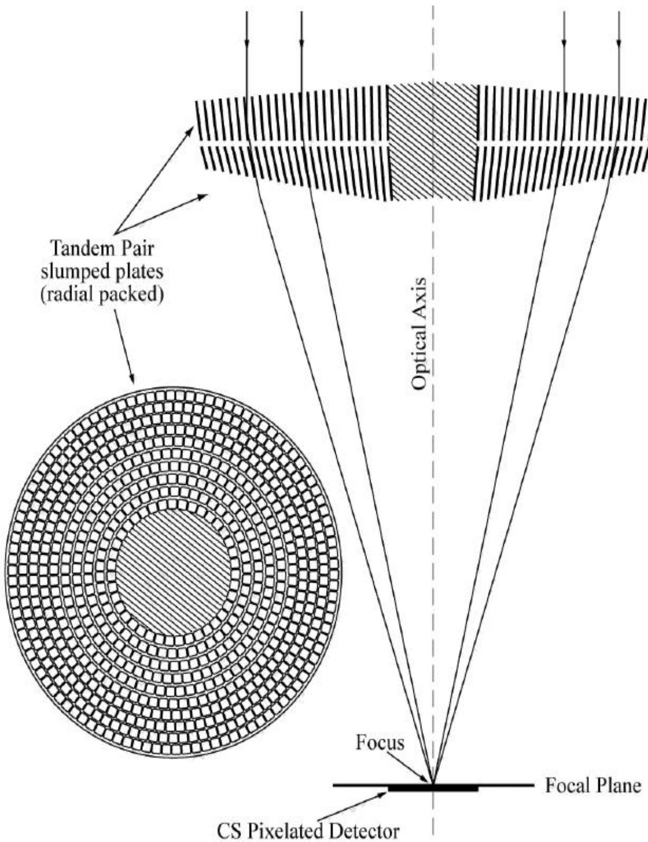
  e.g., detectors matched to science – e.g., low band gaps for XEUS (detect redshifts >4)

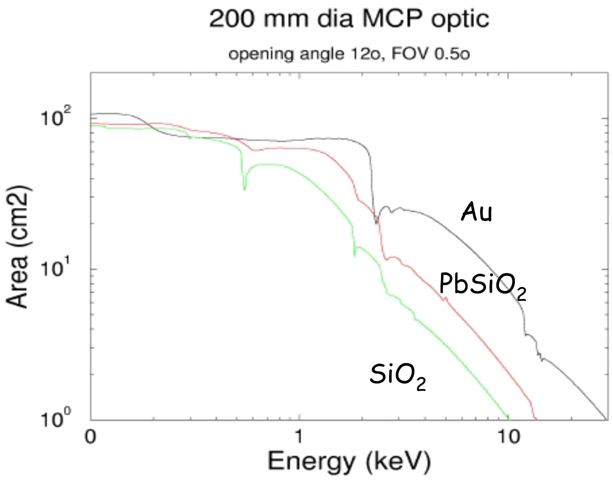


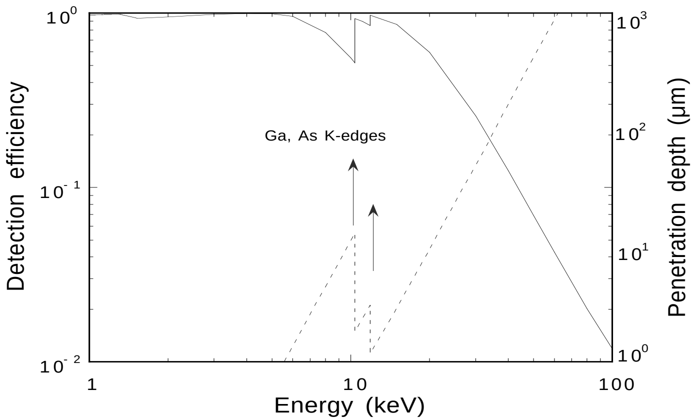
Owens *et al.*, Proc. SPIE, **4784** (2002) 244.

Advantages of compound semiconductors

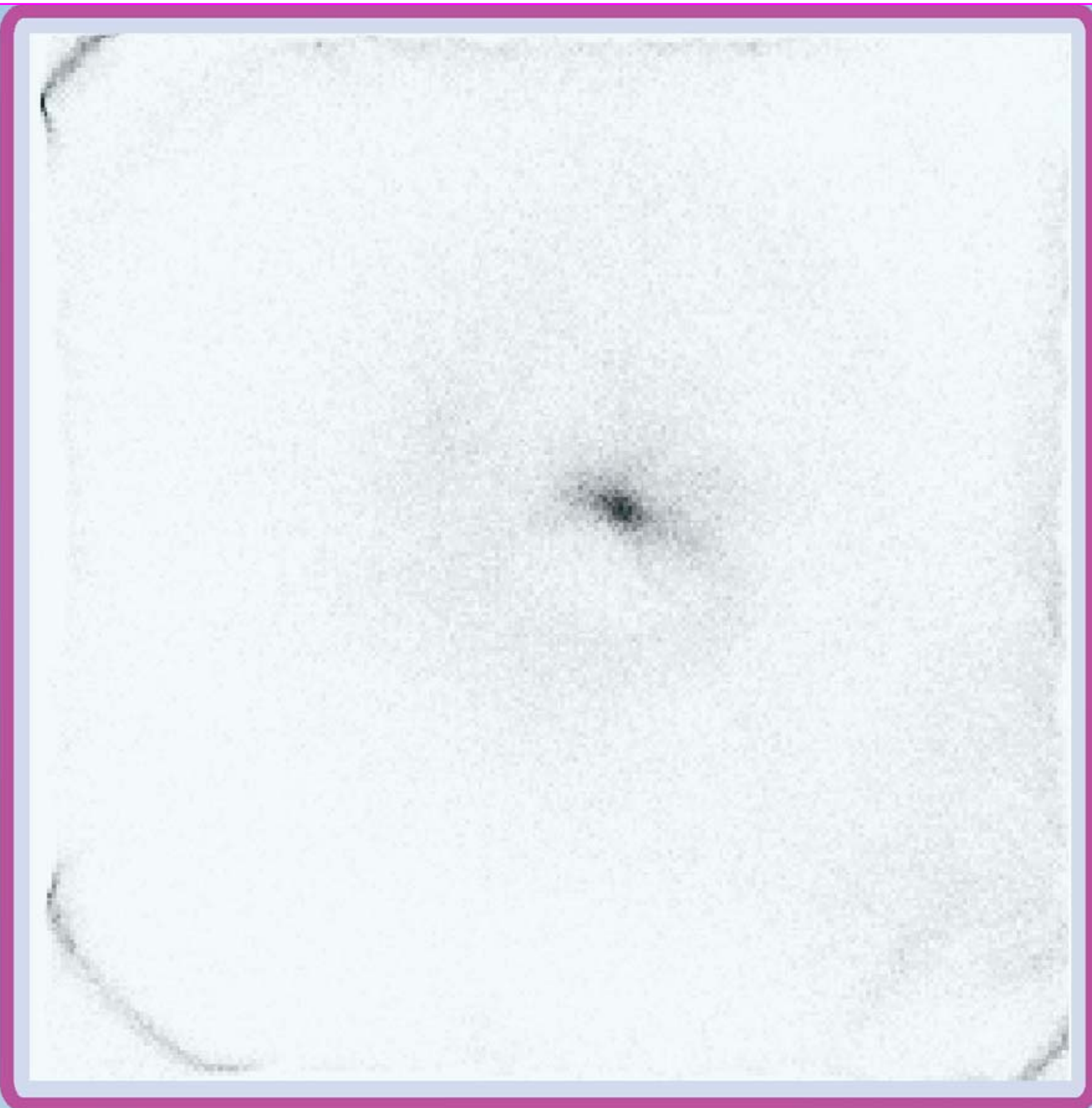
- Wide variety of compounds available
- Compounds can be selected for specific environments
- Materials can be engineered for specific applications
- Ability to match response and energy resolution to an application
  - e.g., GaAs detectors for planetary XRF, matched to an optic

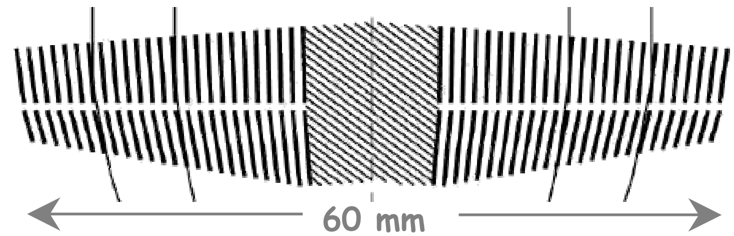






X-ray focusing test of prototype optic





X-ray radiation (8 keV) focussed by the glass X-ray lens. The source is located at a distance of 10 m from the lens. Half the focussed radiation falls within a circle with a diameter of 1.0 arc min diameter (0.017 degree). This is only a factor of 4 larger than the imaging resolution of ESA's X-ray satellite telescope XMM-Newton, which weighs a few hundred times more per unit of collecting area that can be achieved with this technology.

Advantages of compound semiconductors

- Wide variety of compounds available
- Compounds can be selected for specific environments
- Materials can be engineered for specific applications
- Ability to match response and energy resolution to an application
- Wide range of stopping powers
  mass and cost benefits for planetary spacecraft, surgical probes

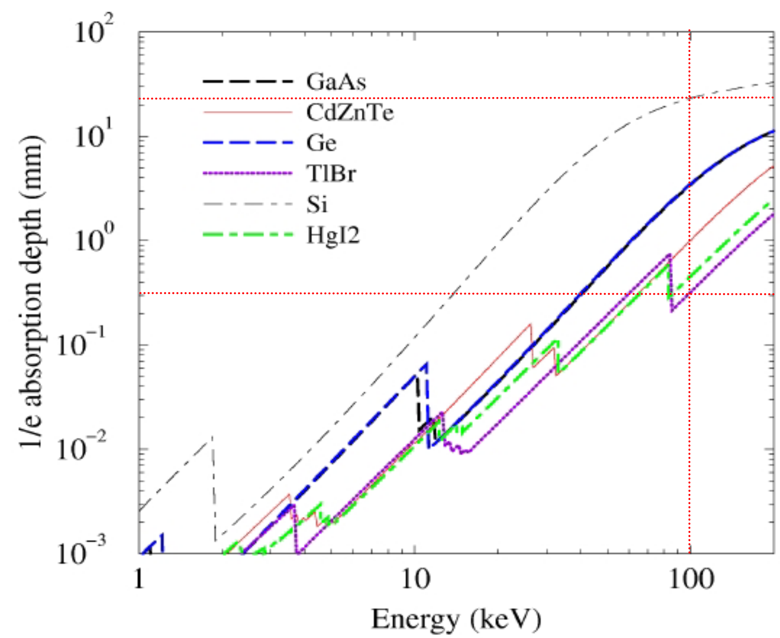
Material Properties

Summary of some material properties:

	Z	E_G (eV)	ω (eV/ehp)	r_i at RT (Ω)
Diamond	6	5	13	>10^{13}
SiC	6/10	3.3	8.4	10^{13}
Si	14	1.12	3.6	~10^{4}
Ge	32	0.66	2.0	50
GaAs	31/33	1.4	4.3	10^{8}
InP	49/15	1.4	4.2	10^{7}
CdTe	48/52	1.4	4.4	10^{9}
CdZnTe	48/52	1.6	4.7	10^{11}
HgI_2	80/53	2.1	4.2	10^{13}
TlBr	81/35	2.7	5.9	10^{11}

NB, wide range of stopping powers
available with similar energy resolutions

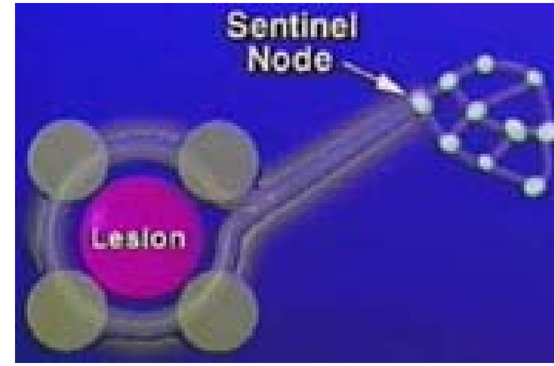
40μm of GaAs is equivalent to 500 μm Si – same resolution

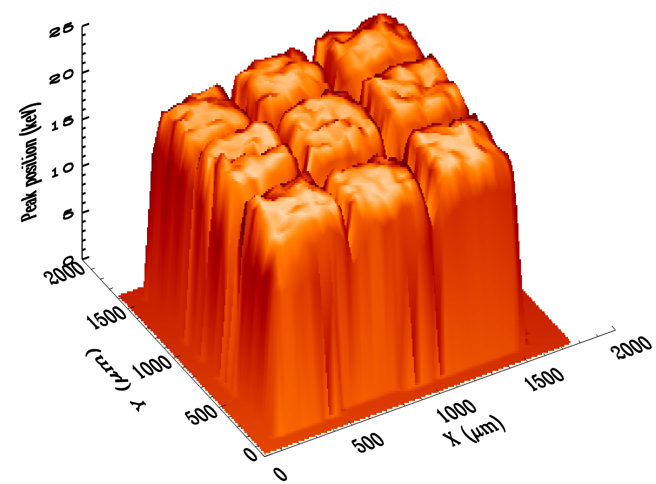


Advantages of compound semiconductors

- Wide range of stopping powers

surgical probes – small, efficient, 98.6°F operation



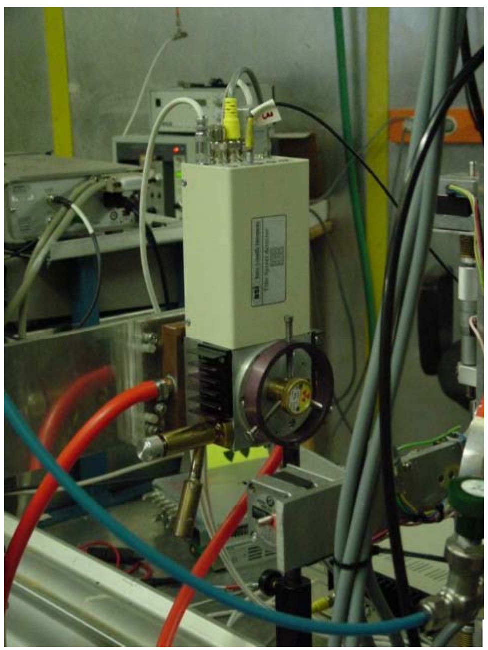


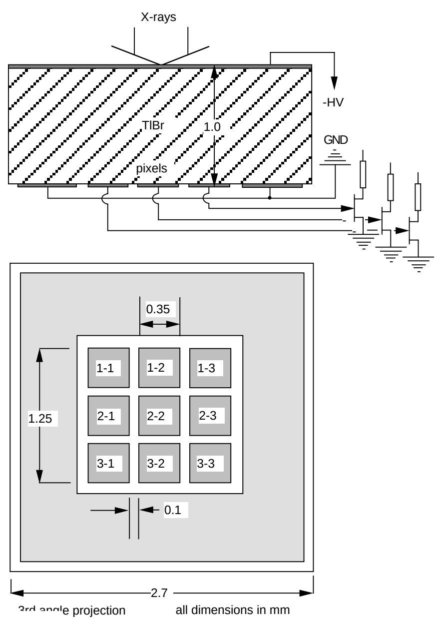
Advantages of compound semiconductors

- Wide variety of compounds available
- Compounds can be selected for specific environments
- Materials can be engineered for specific applications
- Ability to match response and energy resolution to an application
- Wide range of stopping powers
- Wide dynamic range in a single detector

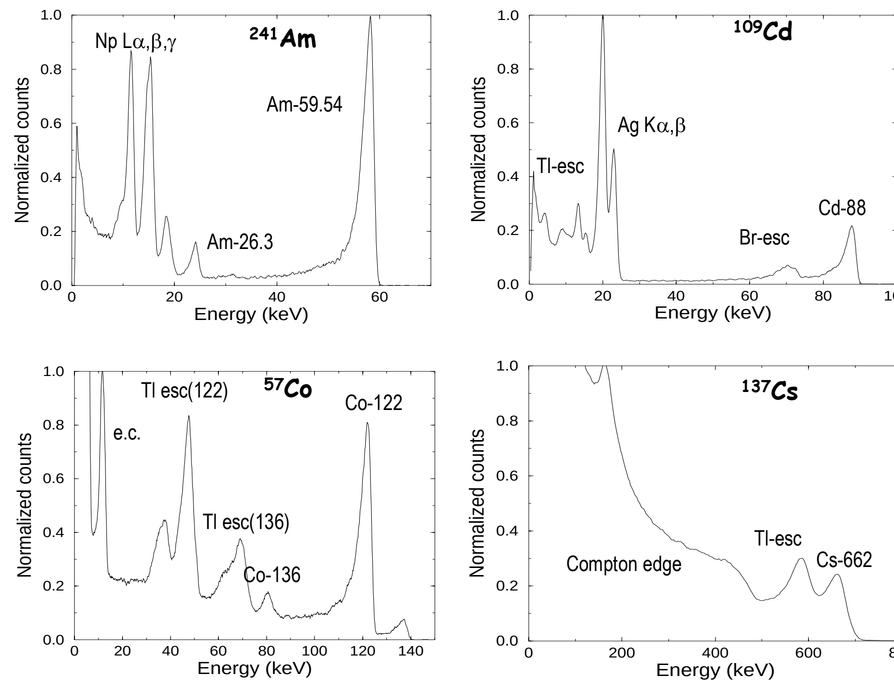
    detectors with good X- and gamma-ray response

TlBr array





TlBr array – spectral response



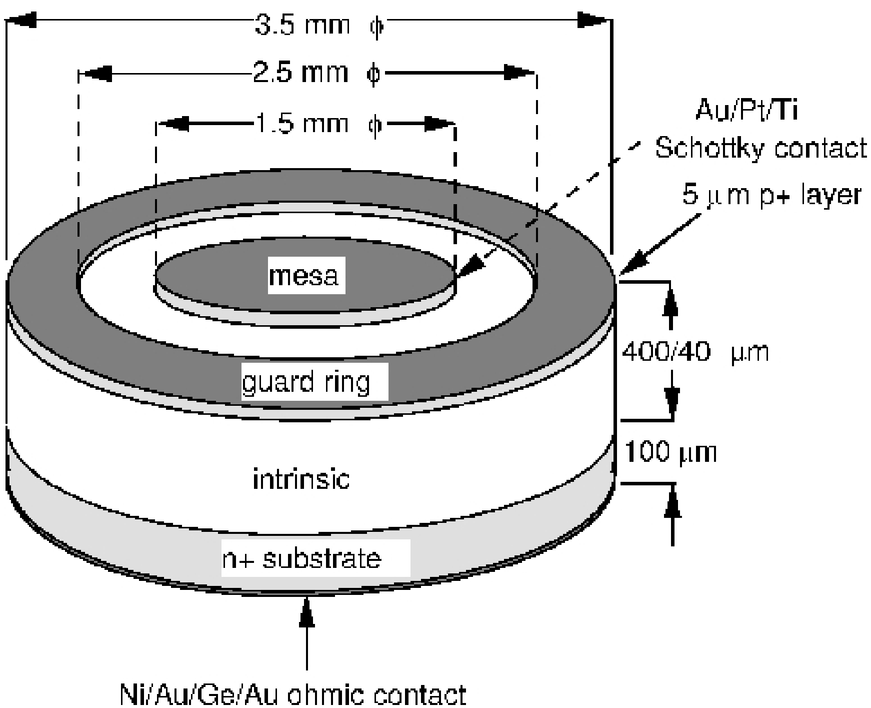
Owens *et al.*, Nucl. Instr. & Meth., **A497** (2003) 359.

Advantages of compound semiconductors

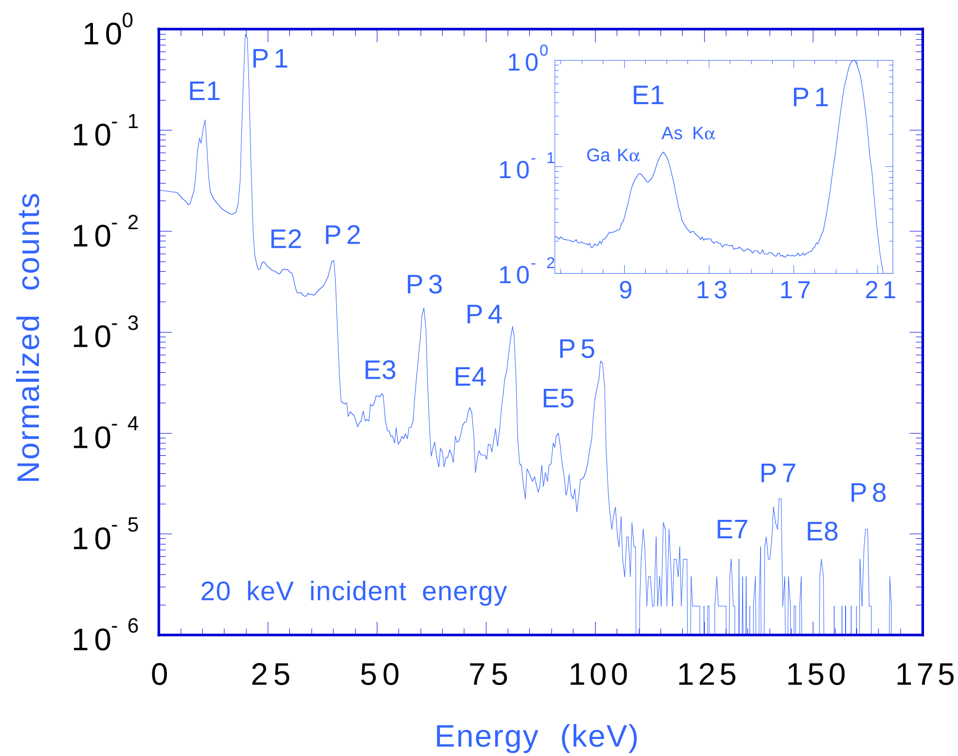
- Wide variety of compounds available
- Compounds can be selected for specific environments
- Materials can be engineered for specific applications
- Ability to match response and energy resolution to an application
- Wide range of stopping powers
- **Wide dynamic range in a single detector**

  detectors with good X- and gamma-ray response

1.68 μm², 400 μm thick, GaAs diode



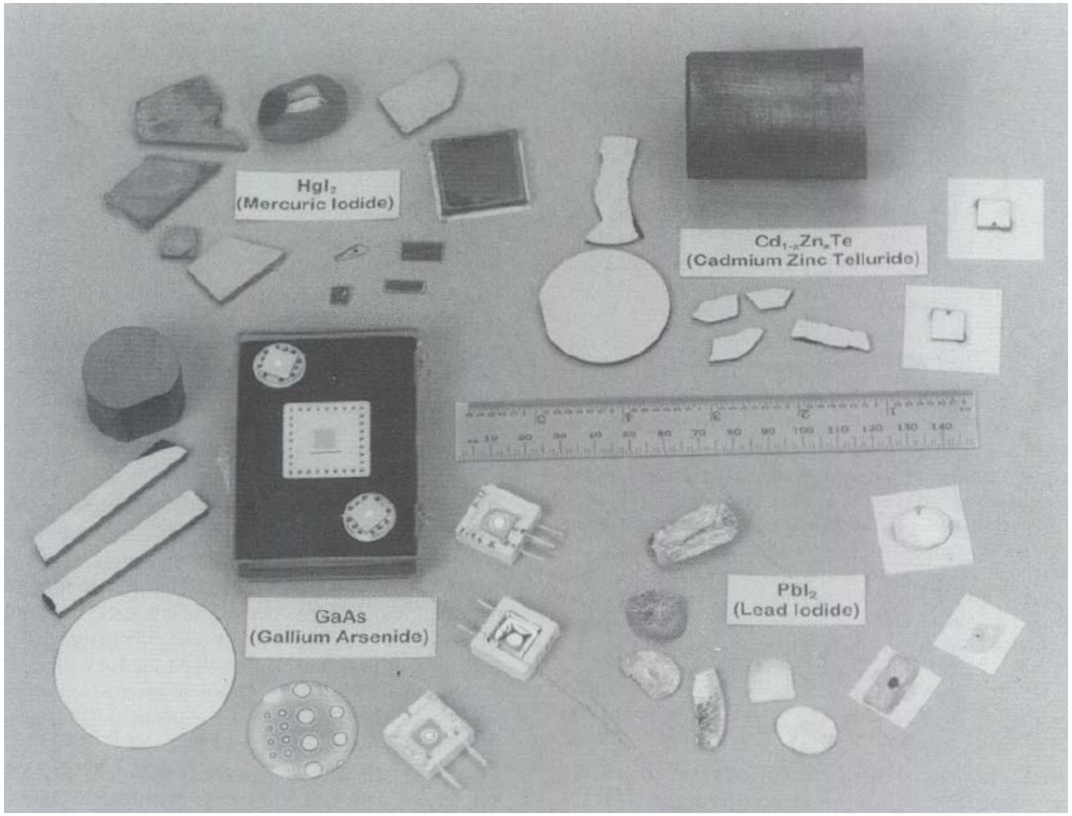
ESRF BM5 energy spectrum



Owens *et al.*, J. Appl. Phys., **86** (1999) 4341.

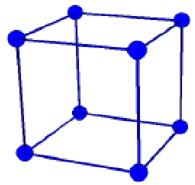
Compound semi-conductors under development

- GaAs
- TlBr
- CdZnTe
- HgI_2
- InP

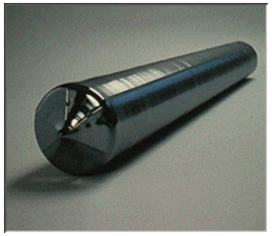


Pros and cons of current detector materials

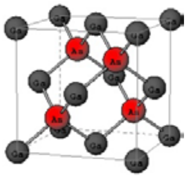
Si



- ✓ well developed technology
- ✓ heritage
- ✓ well matched to optics
- ✗ limited X-ray response
- ✗ not rad hard
- ✗ cooling issues

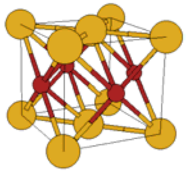


GaAs



- ✓ near Fano
- ✓ RT operation possible
- ✓ well matched to optics
- ✓ hard X-ray response
- ✓ rad hard
- ✗ development issues

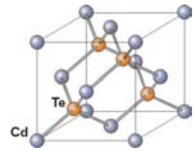
HgI_2



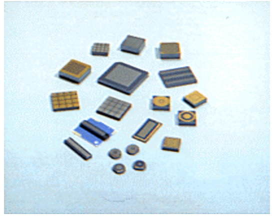
- ✓ near Fano
- ✓ RT operation
- ✓ hard X-ray response
- ✓ very rad hard
- ✗ difficult to work with
- ✗ soft

Pros and cons of current detector materials

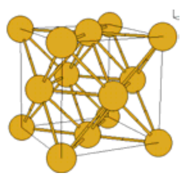
CdZnTe



- ✓ sub-keV energy resolution
- ✓ hard X-ray response
- ✓ seems rad hard
- ✓ RT operation
- ✗ expensive (HPB)

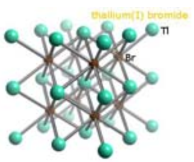


Ge



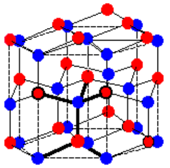
- ✓ Fano limited
- ✓ hard X-ray response
- ✗ not rad hard
- ✗ cryogenics
- ✗ fabrication problems

TlBr

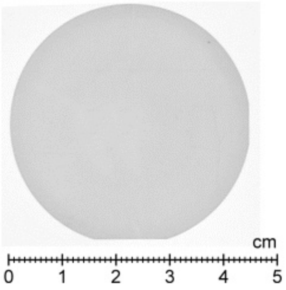


- ✓ sub-keV energy resolution
- ✓ hard X-ray response
- ✓ rad hard
- ✗ polarization effects
- ✗ difficult to work with
- ✗ toxic (genetic modifier)

SiC

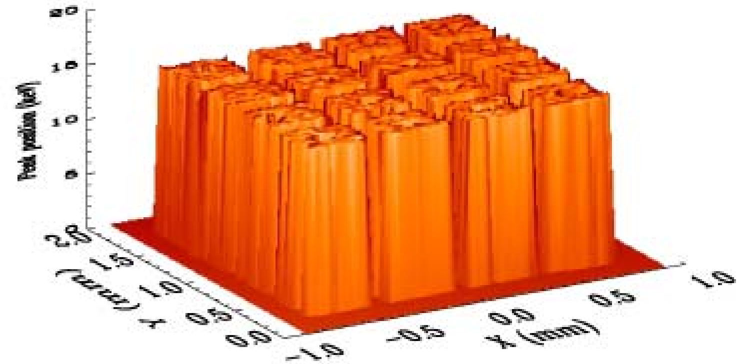


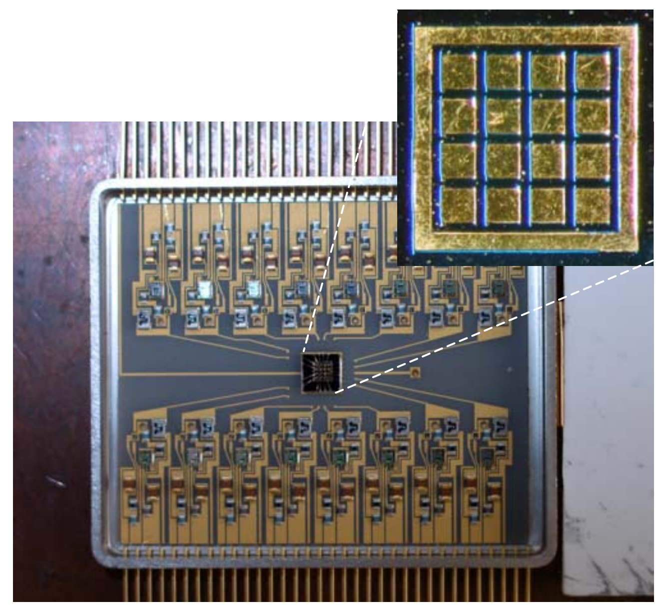
- ✓ kev energy resolution
- ✓ stable, chemically inert
- ✓ very rad hard
- ✗ poor transport properties



CSD detector development program

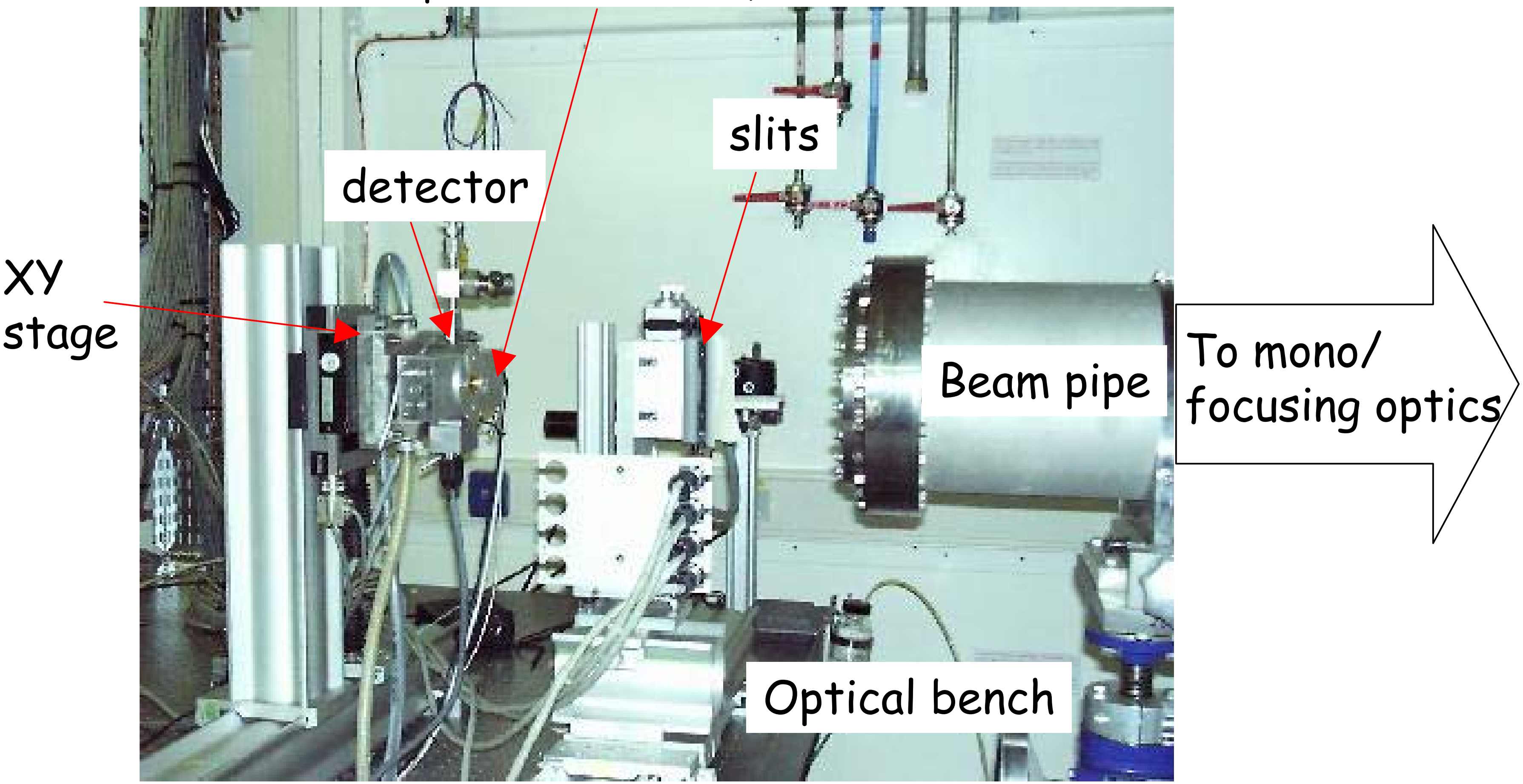
- 3 materials matured & detection systems fabricated
- 5 other materials under study
- technology development program in place & ongoing
- extensive testing program at the ESRF, HASYLAB and BESSY
- ESA close to Fano resolution limit for GaAs and CdZnTe
- immediate planetary and astrophysics applications
- clinical spin-offs





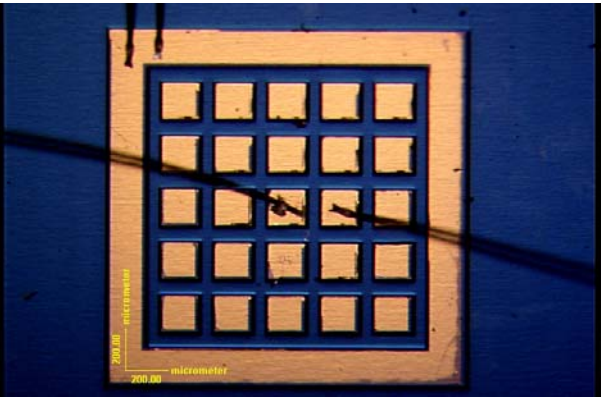
Synchrotron radiation measurements

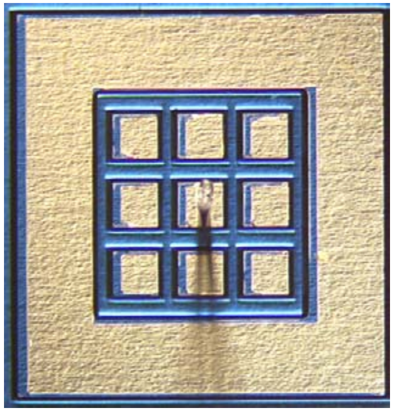
Beam profile ~$20 \times 20\ \mu m^2$, $E/\Delta E > 10^4$

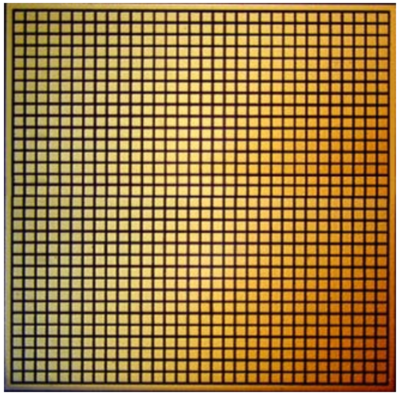


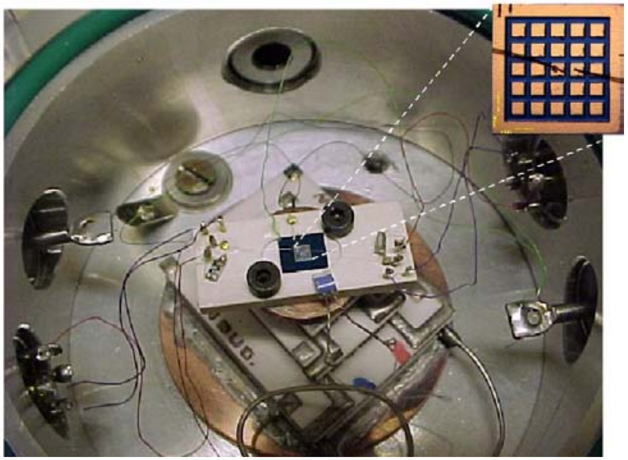
Beamline set-up

GaAs evolution : arrays

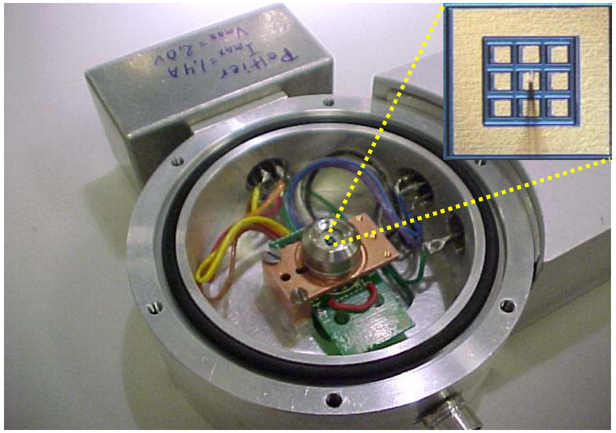




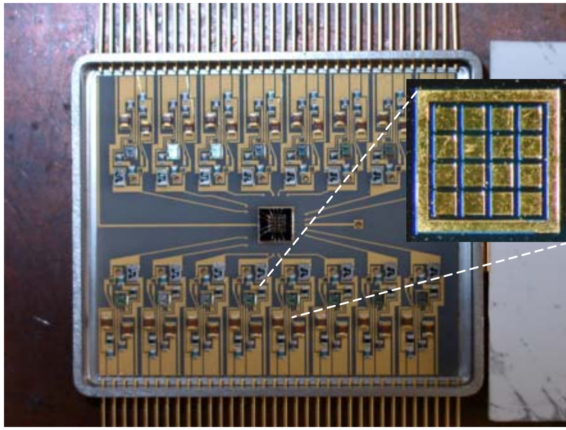




1999

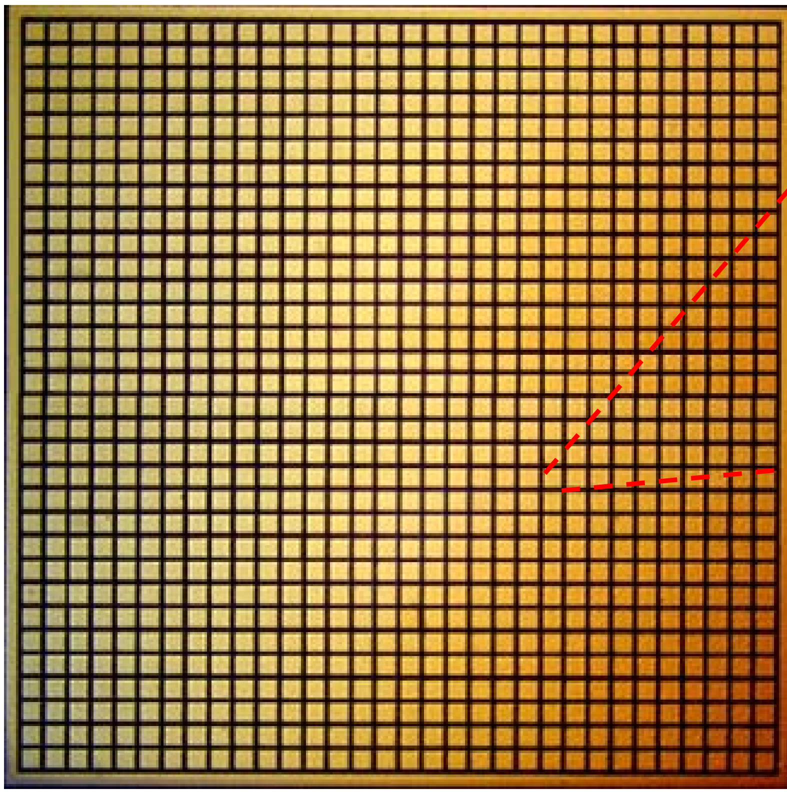


2000



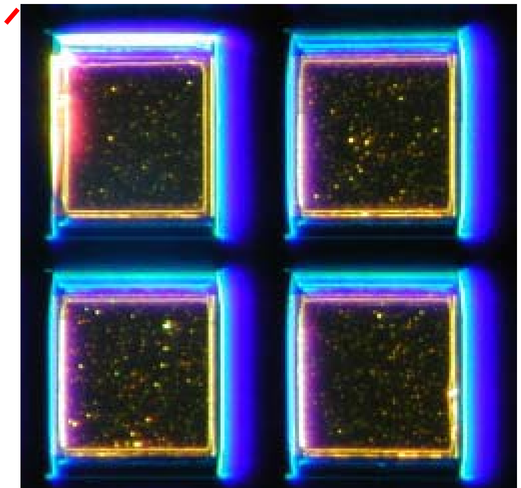
2001

GaAs 32 x 32 array



1.2 cm

1.2 cm



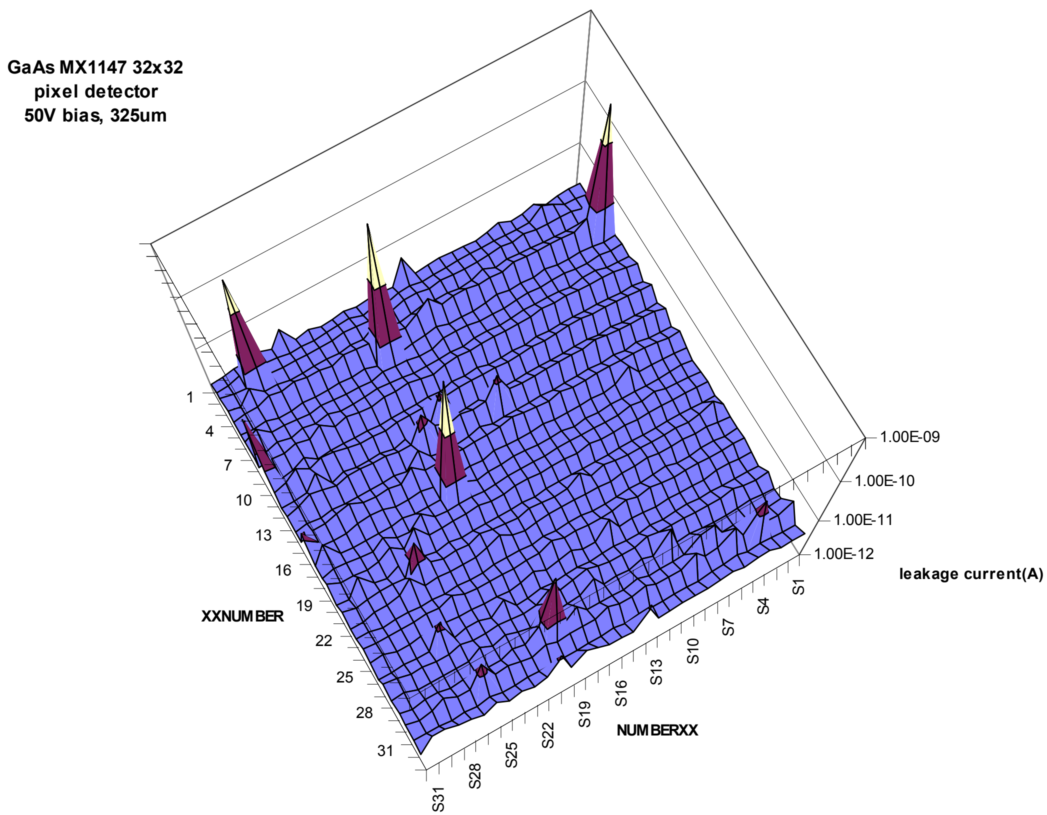
250 μm

Design goal ΔE=180 eV @ 5.9 keV

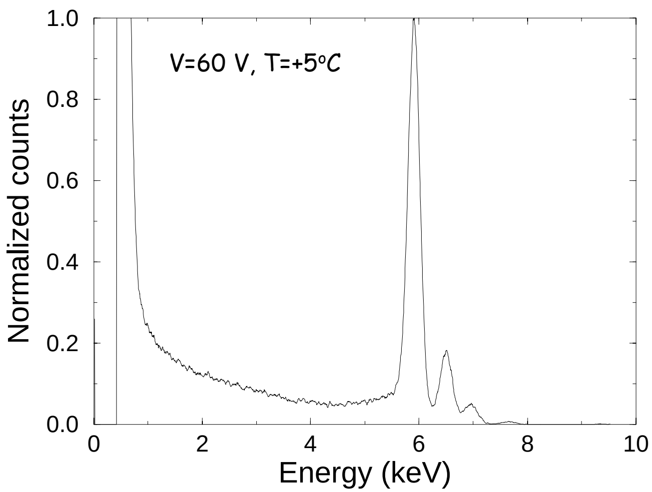
Pitch 300 μm, pixel size 250μm
Thickness 40 μm, 4 μm p^+, <1 μm n^+
Inter-pixel resistivity > $10^{10}\Omega$

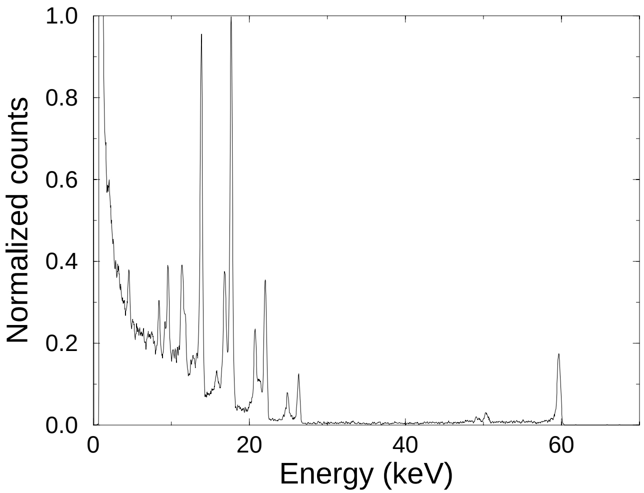
GaAs prototype 32 x 32 array - first results

Leakage current map at RT



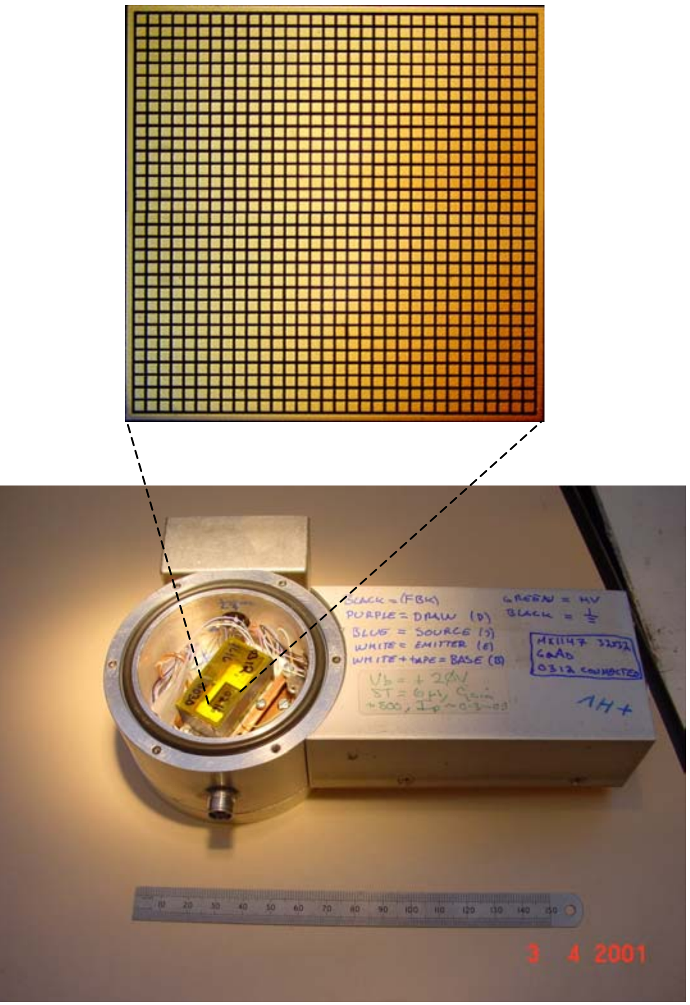
ΔE =250 eV @5.9 keV, 550 eV@59.54 keV

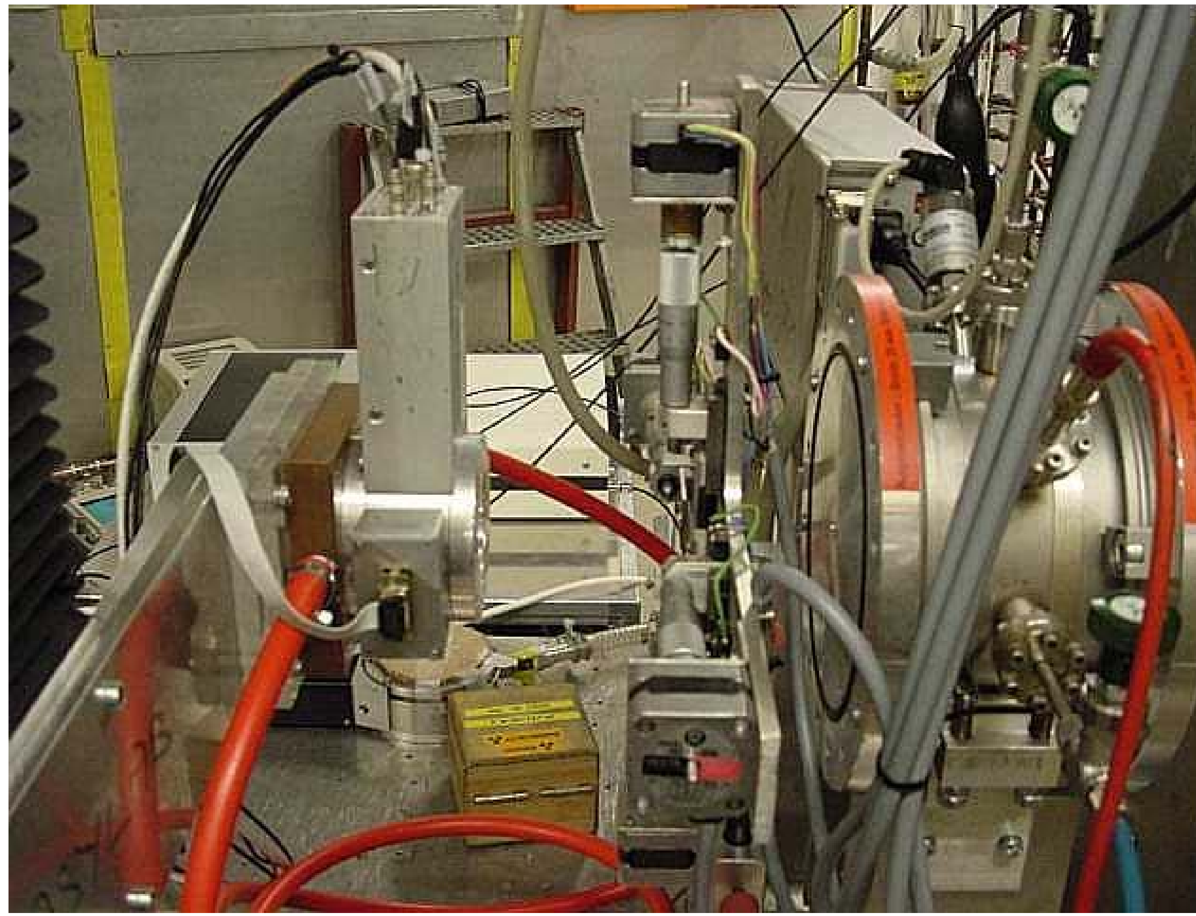




Demonstrated resolution of
ΔE=270 eV @ 5.9 keV at RT

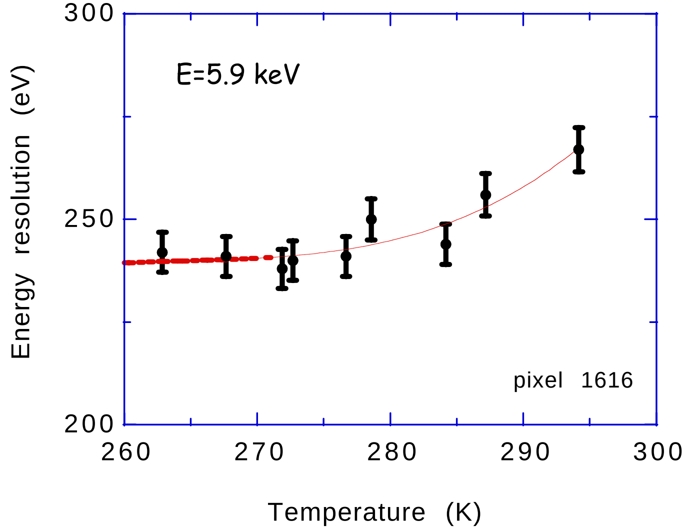
GaAs prototype 32 x 32 array - HASYLAB tests

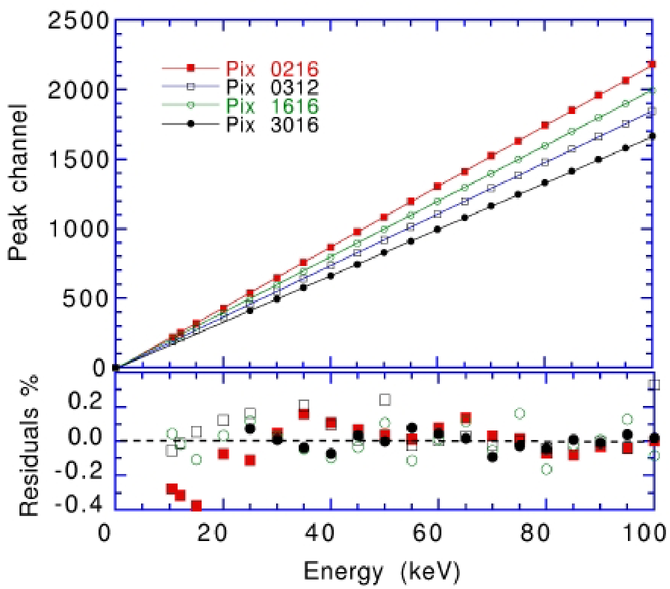


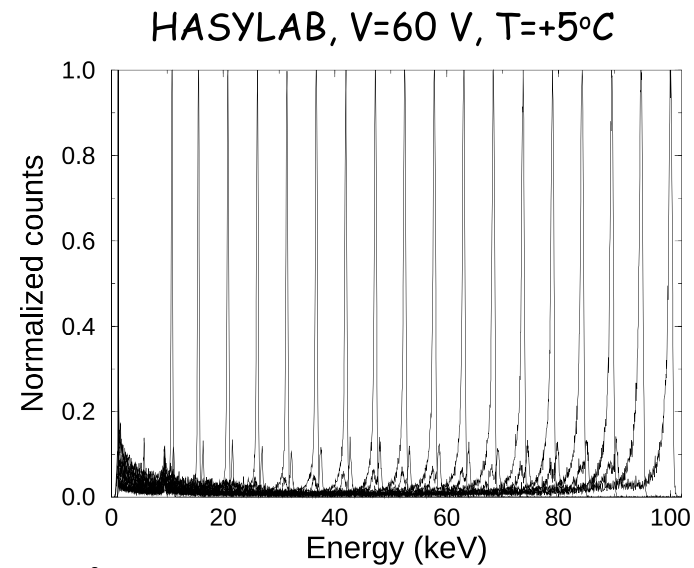


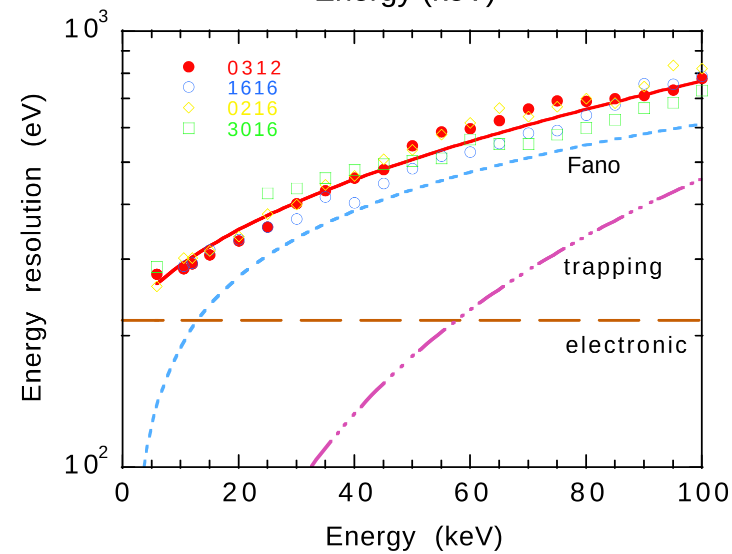
Beamline X-1

GaAs prototype 32 x 32 array - first results









Erd *et al.*, Nucl. Instr. and Meth **A487** (2002) 78.

32 x 32 pixel array, spatial distributions

E=15 keV, 20 x 20 μm^2 beam, 10 micron resolution

Pixel — 0312 — 0216 — 1616

Count rate

Centroid

Resolving power