Institute of Electrical Engineering
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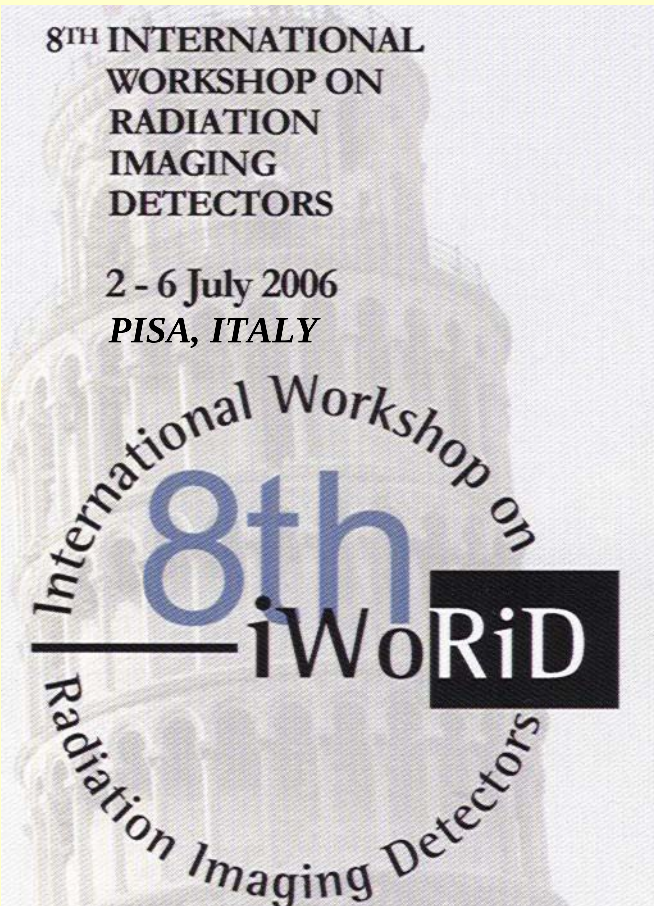
Performance of semi-insulating GaAs-based radiation detectors: Role of key physical parameters of base material



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OUTLINE

- **MOTIVATION**
- **RADIATION DETECTOR CHARACTERISTICS**
    - Key detector-grade material aspects
- **APPLICATIONS**
    - Monolithic LEC SI GaAs strip line in edge-on configuration
    - Line concept of SI GaAs chip
    - First “quantum” X-ray images
    - “Quantum” X-CT: preliminary
- **GaAs MATERIAL FOR RADIATION DETECTORS**
    - Key material characteristics
    - Characteristics summary
    - Performances of fabricated detectors
- **CONCLUSIONS**

Motivation I: New applications of semiconductor monolithic array detectors in X- and gamma-ray detection

NEW DETECTOR APPLICATIONS

• BASIC KNOWLEDGE: *Experiments in physics*
X-ray astronomy….
^{115}InP: Solar neutrino astrophysics

• MEDICINE *Digital X-ray radiology (stomatology, mammography), XCT*
Positron emission tomography

• NONDESTRUCTIVE ON-LINE CONTROL *Material defect and process control*

•SECURITY
Contraband inspections: cargo control
Detection of drugs and plastic explosives
Cultural heritage's study

• MONITORING
Environmental control and radioactive waste management
Metrology (testing of radioactive sources, spectrometry...)

IMPROVEMENTS IN X-RAY DIGITAL RADIOLOGY USING SEMICONDUCTOR DETECTORS

• *LOWER DOSE TO PATIENT*

• *MUCH BETTER RESOLUTION IN CONTRAST*
(more than 2 orders of magnitude)

• *DETERMINATION OF THE OBJECT DENSITY*
(Dual X-ray or "colour" imaging technique)

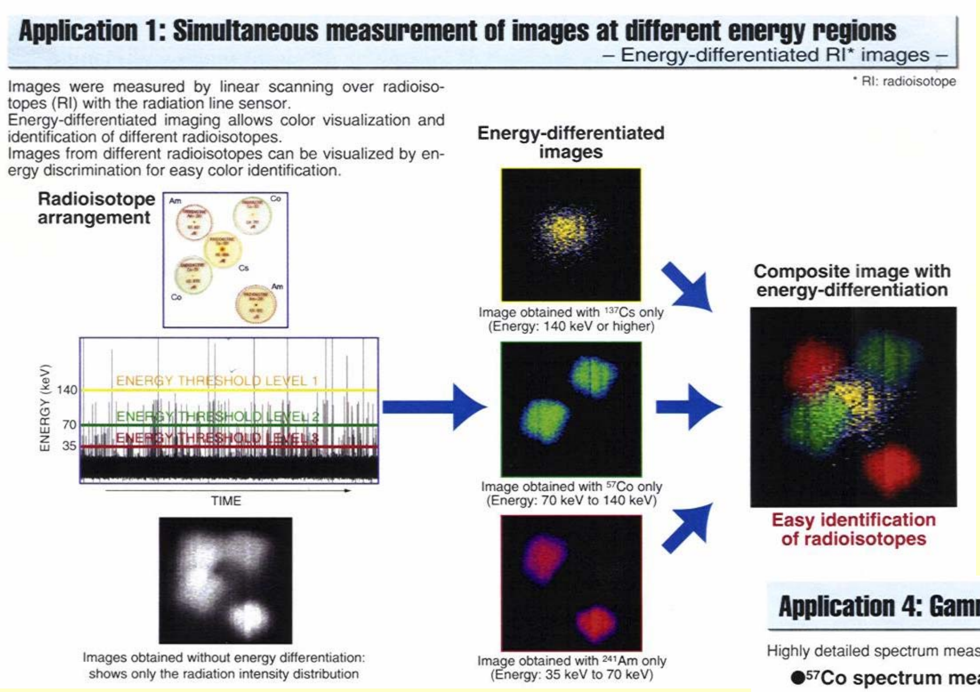
• *3-D IMAGE POSSIBLE USING CT METHOD*

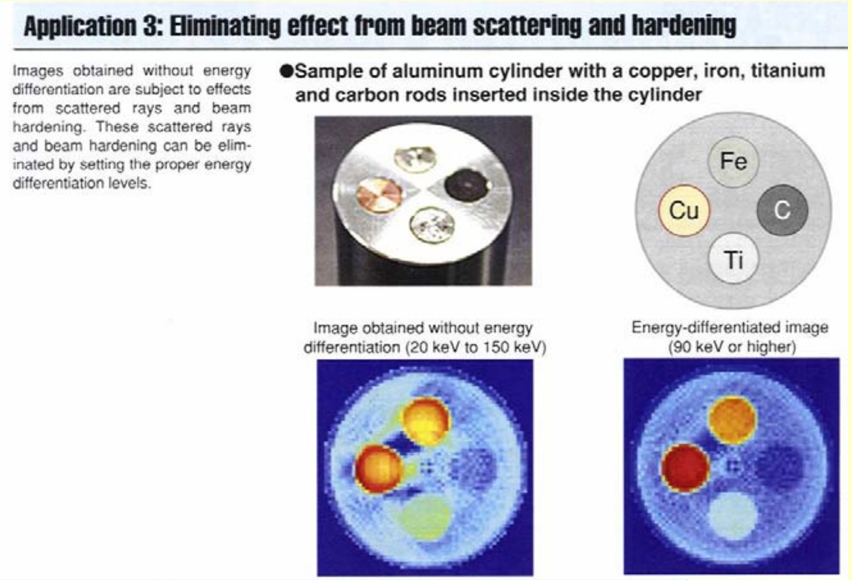
•*NO POLUTION DUE TO CHEMICAL PROCESSING*
(Necessary in the case of film application)

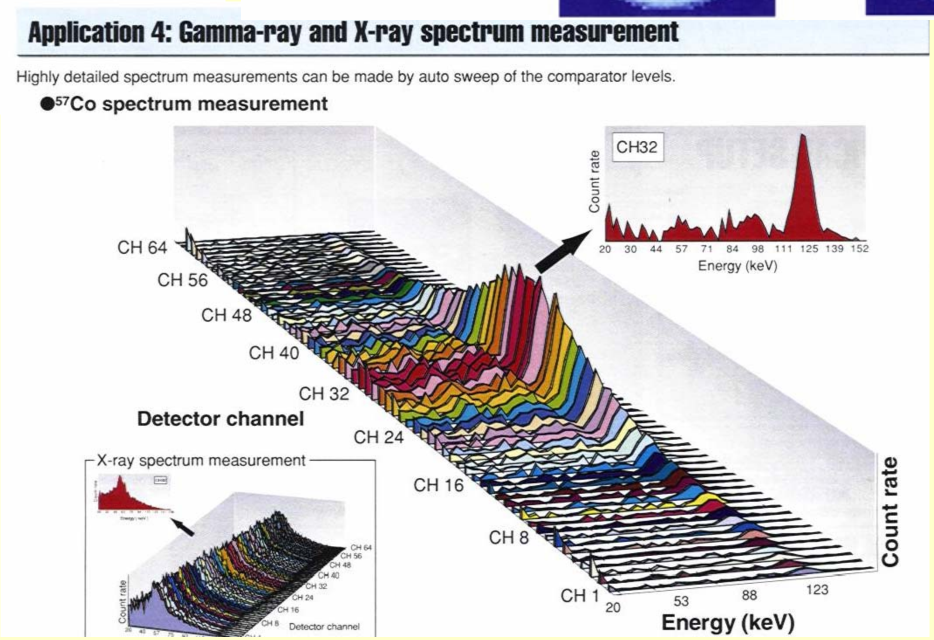
• *SIMPLE AND SPACE SAVING STORAGE OF DIGITAL DATA*

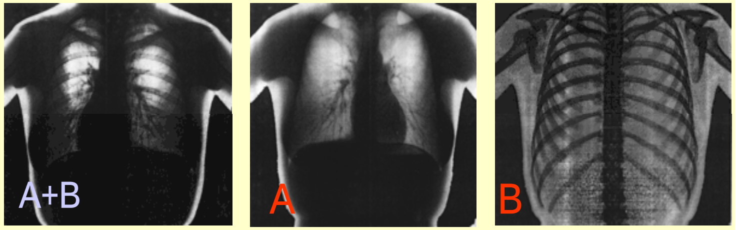
• *ON-LINE PROCESS CONTROL & DIAGNOSTICS*
OTHERS...???

„COLOUR IMAGING“ in digital radiography









A, B: *Dual energy digital radiographs*

MOTIVATION II

SI GaAs MATERIAL PROPERTIES

- ✓ **Radiation hard**
- ✓ ***Low cost***
- ✓ **Fast**
- ✓ **Wide band gap allows operation at RT**
- ✓ ***Highly developed technology processing***
- ✓ ***Easily commercially available***
- ✓ ***Bulk material – no limitation in thickness***
- ✓ ***HIGH QUALITY!!***

LINE (2D) SCANNING TECHNIQUE IN RADIOGRAPHIC IMAGING

Quantum XCT

- ✓ **Technical simplest imaging solution**
- ✓ ***Lowest cost***
- ✓ **Useful for fast testing of detector applicability in X-ray imaging**
- ✓ ***High quality of X-ray image (good scattered photons rejection)***
- ✓ ***Useful in many industrial, medical and security applications***
- ✓ **Applicable in basic and space research**

Key semiconductor material and detector characteristics

REQUIREMENTS TO SEMICONDUCTOR DETECTOR-GRADE MATERIAL

$Z > 30$; $E_G > 1.3$ eV, τ, ρ (RT), high v_d, μ_d

high homogeneity, low density of structural, space-charge and point defects, fast reaction

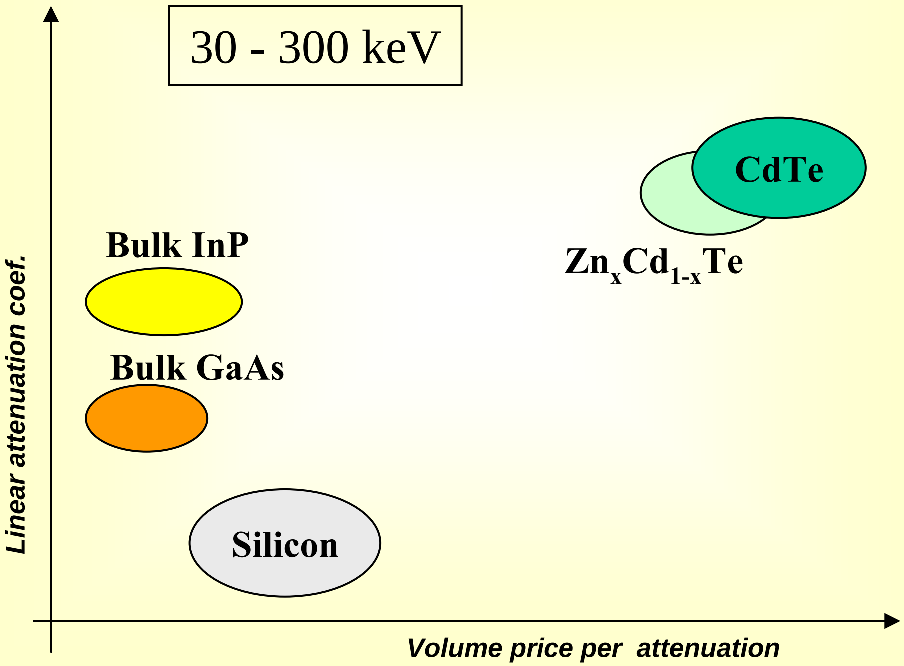
LOW COST

CANDIDATE SEMICONDUCTORS

II-VI: ***CdTe, CdZnTe, HgI$_2$,…***

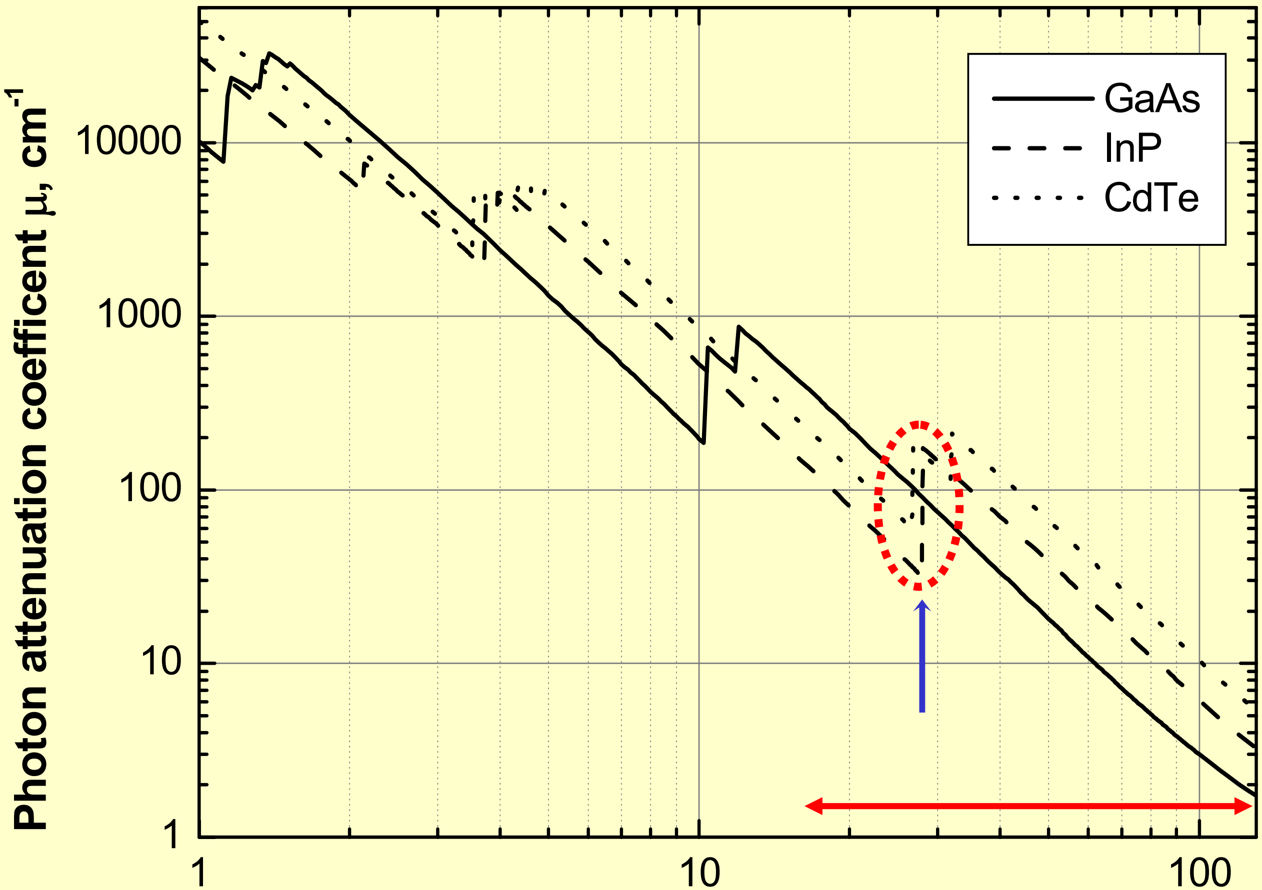
III-V: ***GaAs, InP, ?? GaP, GaN,…***

OUT OF INTEREST: ***Si, Ge***



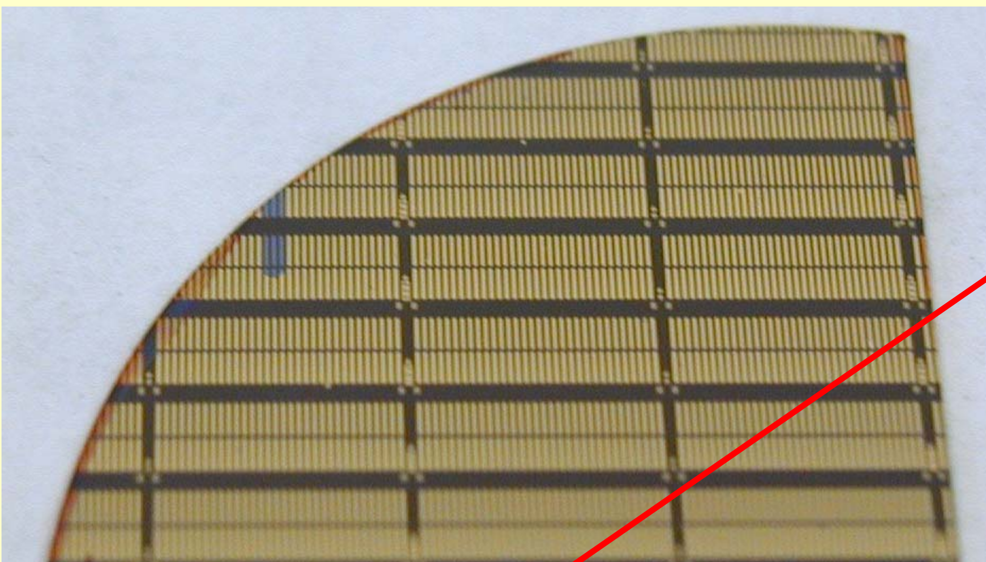
Important material aspect: Attenuation coefficient

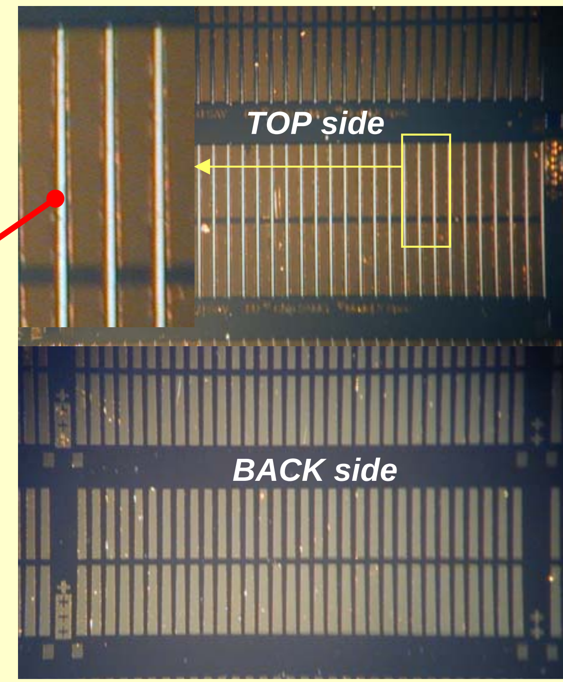
$A \sim Z^{4 \div 5}$

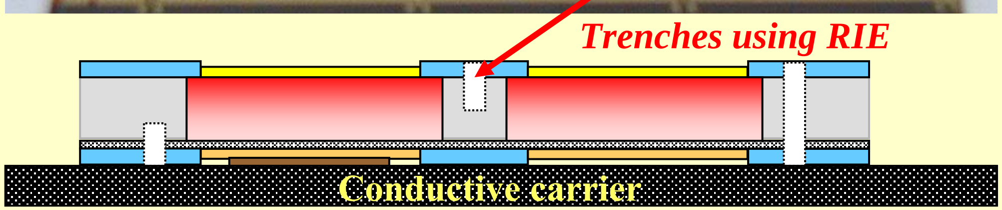


SI GaAs X- and gamma ray line detector: *New topology 2003*

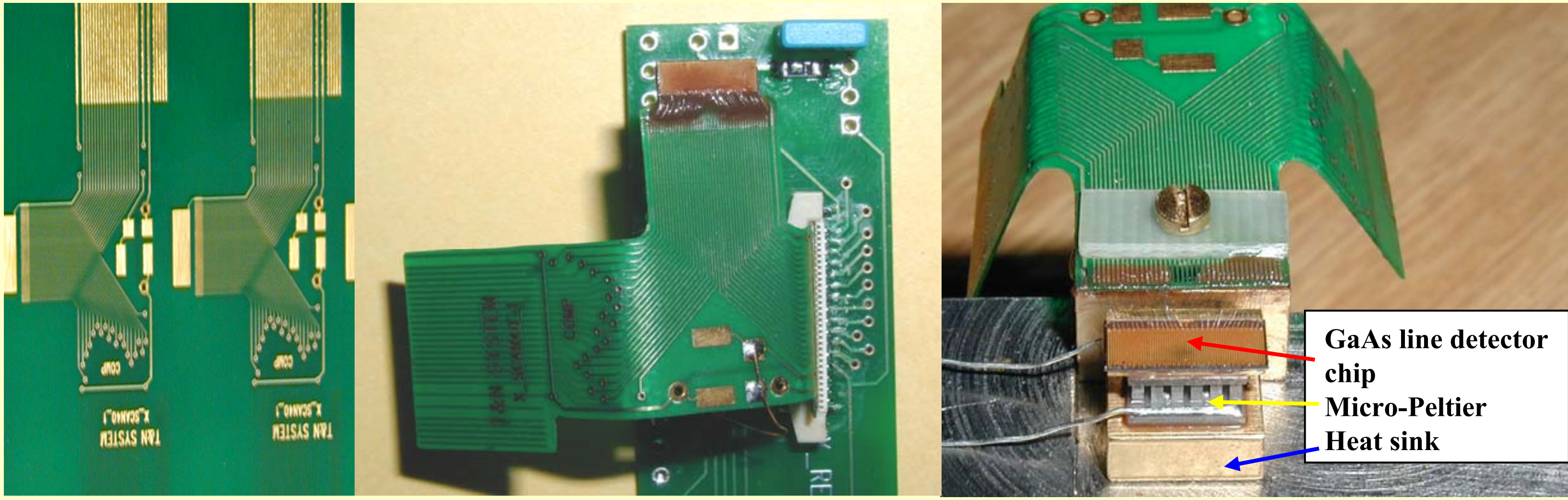
Type of developed line SI GaAs detector	Number of strips in line	Pitch, mm	Absorption length, mm	Chip dimensions, mm	Effective absorption volume of strip, mm^3	Maximal thickness of substrate base, mm
SAMO X	**32** **64** **128**	**0,25** **0,125/0,25*** **0,125**	**2,5**	**16x3,5** **16x3,5/32x3,5*** **32x3,5**	**0,06** **0,04/0,08** **0,04**	**0,12 – 0,18**
SAMO XS	**32**	**5.9**	**1,25** **2,5****	**8x3,5**	**0,1** **0,18**	**0,2 – 0,3**



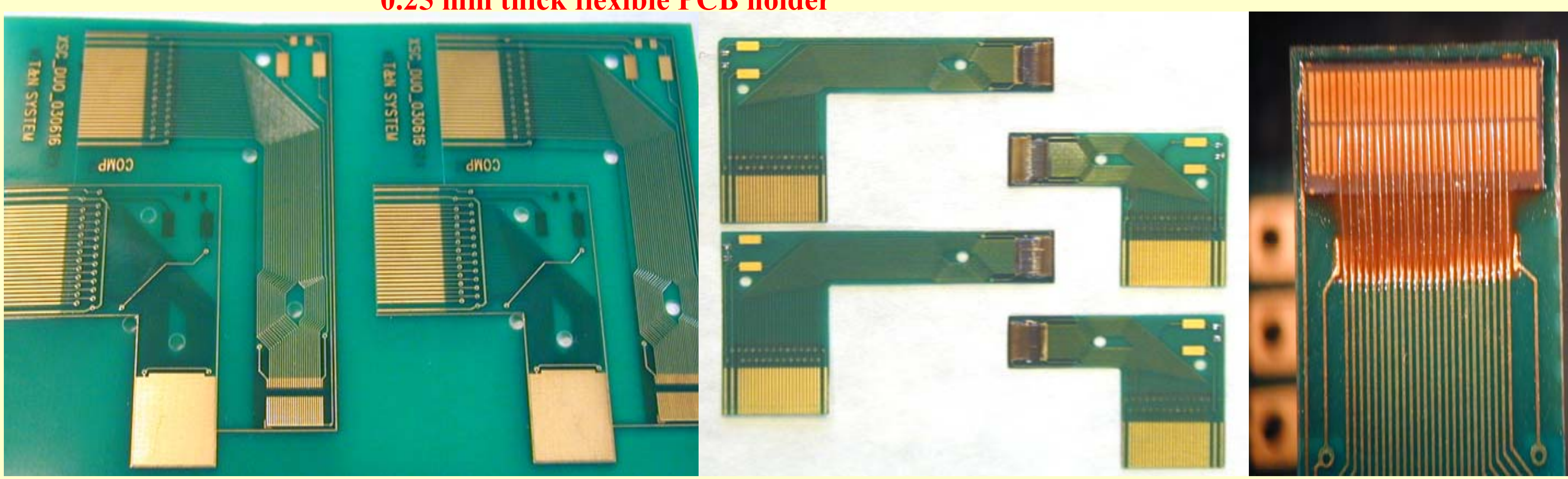




SI GaAs line X-ray detector chip mounted onto flexible PCB carrier:
Original concept (top), final arrangement (down)



0.25 mm thick flexible PCB holder



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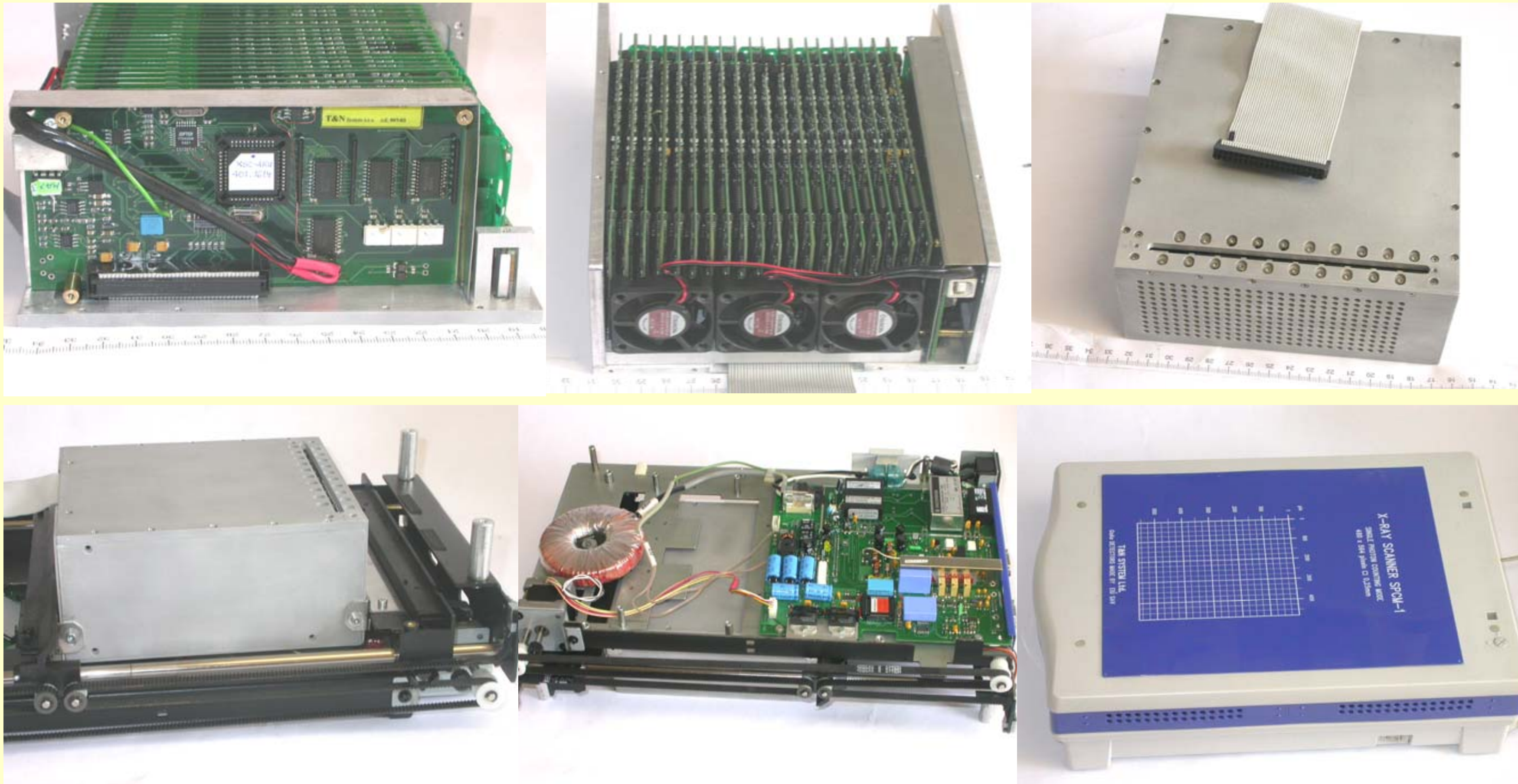
SI GaAs DETECTOR APPLICATIONS

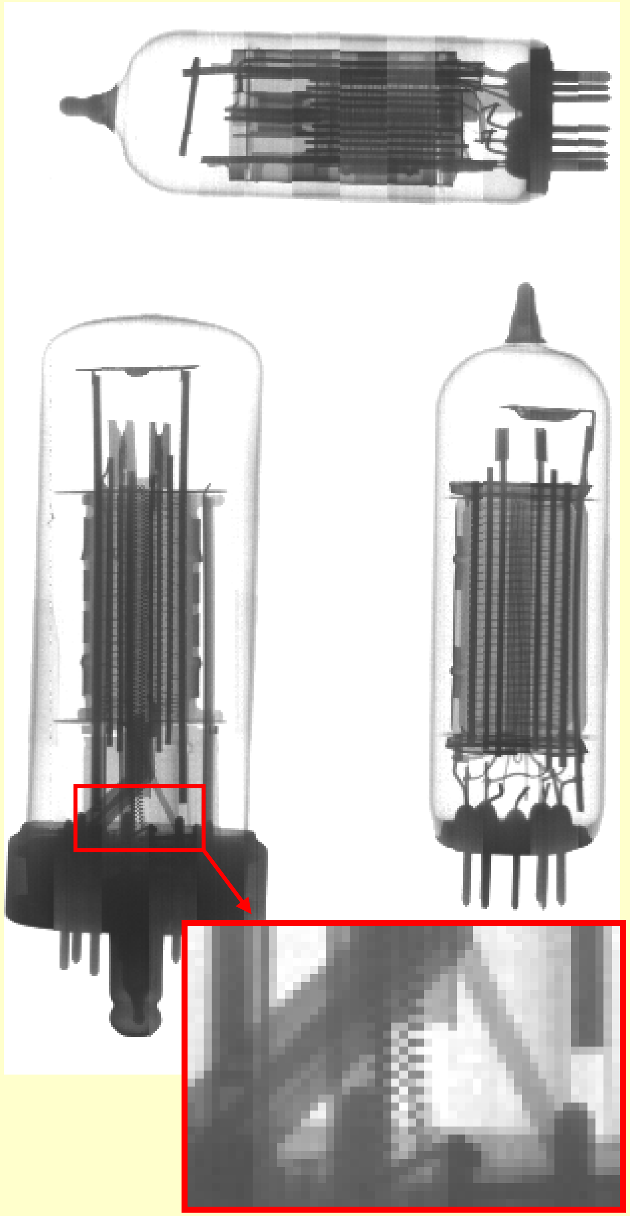
SINGLE PHOTON COUNTING =
QUANTUM X-RAY SCANNER
QUANTUM X-CT: *FIRST EXAMPLE*

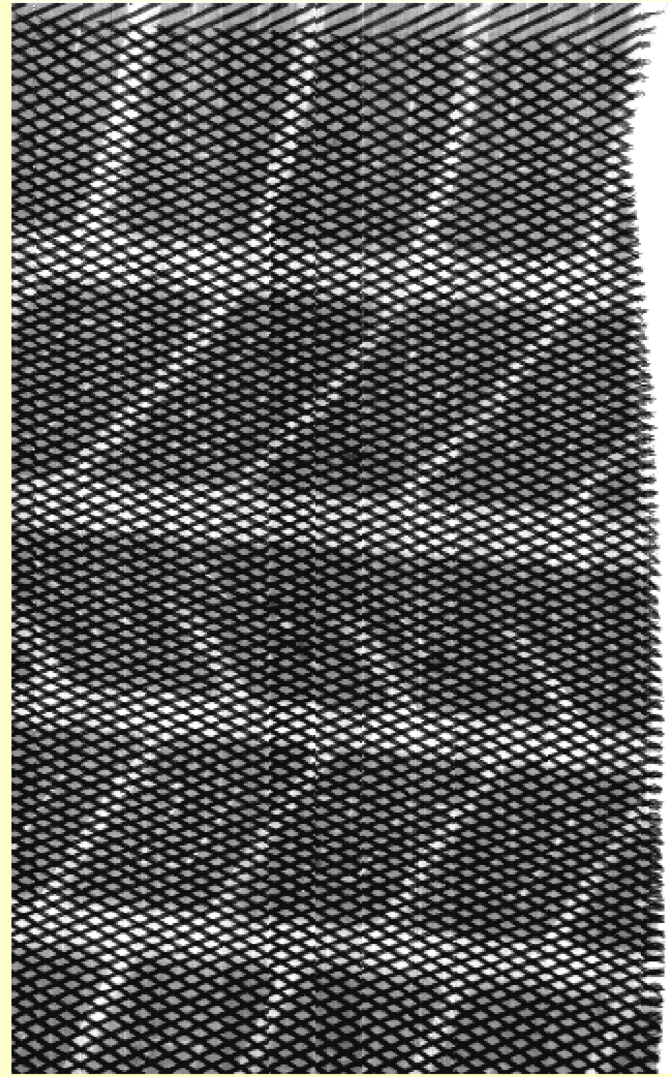
Portable digital X-ray scanner based on SI GaAs radiation detectors:
Final set-up consists of 480 channels line, position control and communication



Photos of various selected test objects

“QUANTUM” X-ray digital images of test objects





LINE STEP: 0.25 mm

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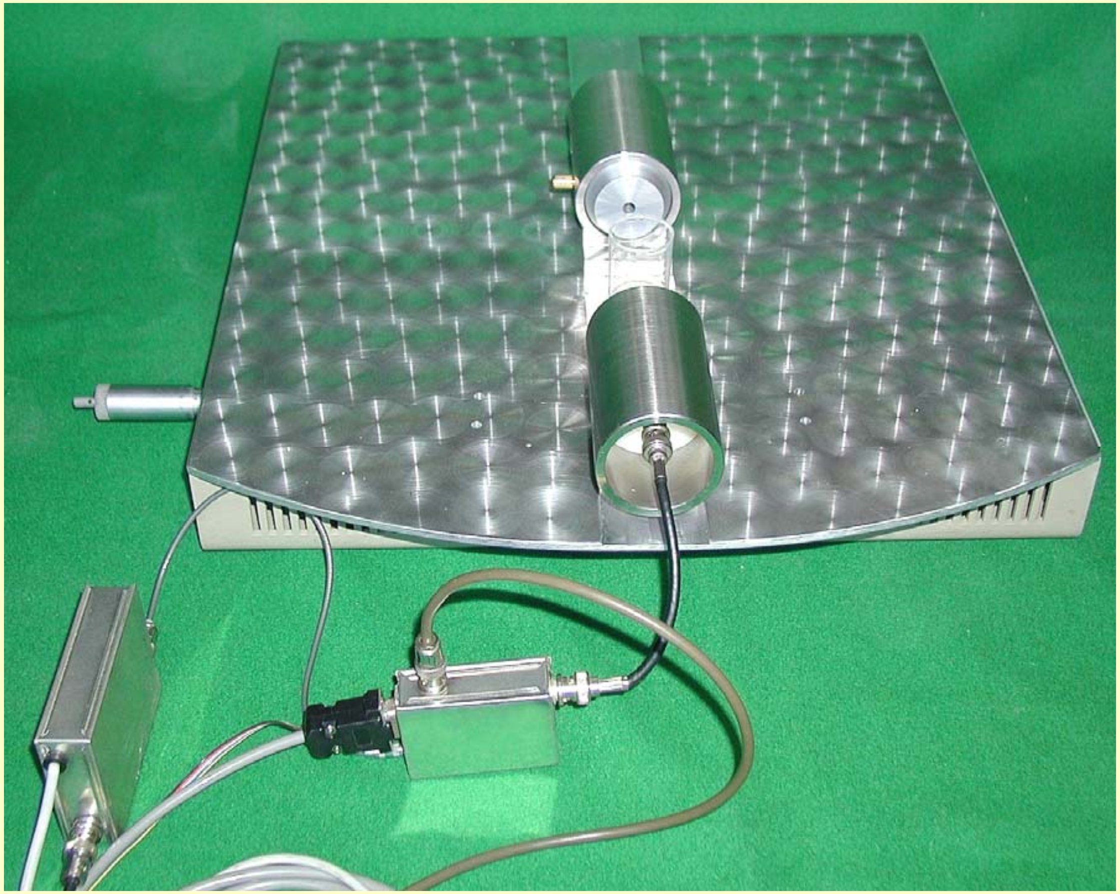
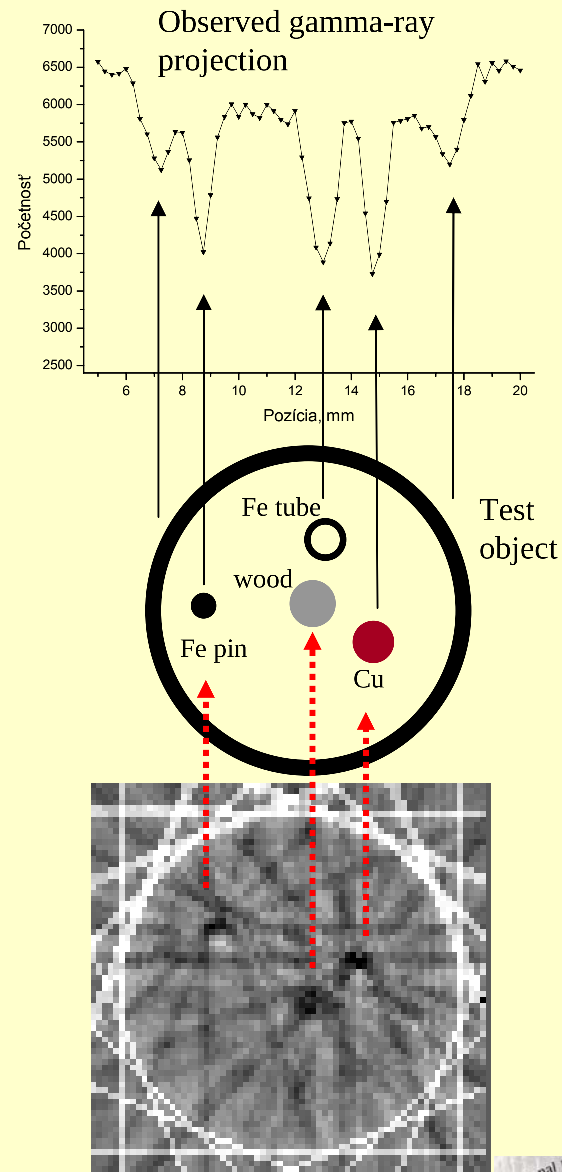
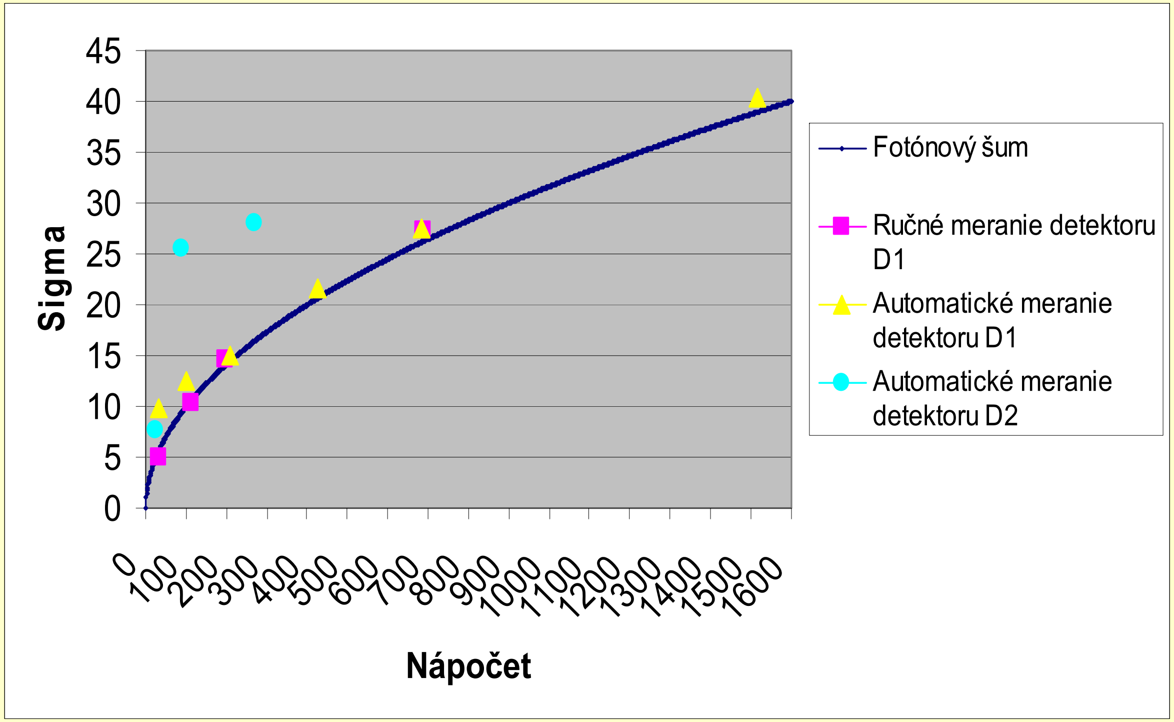
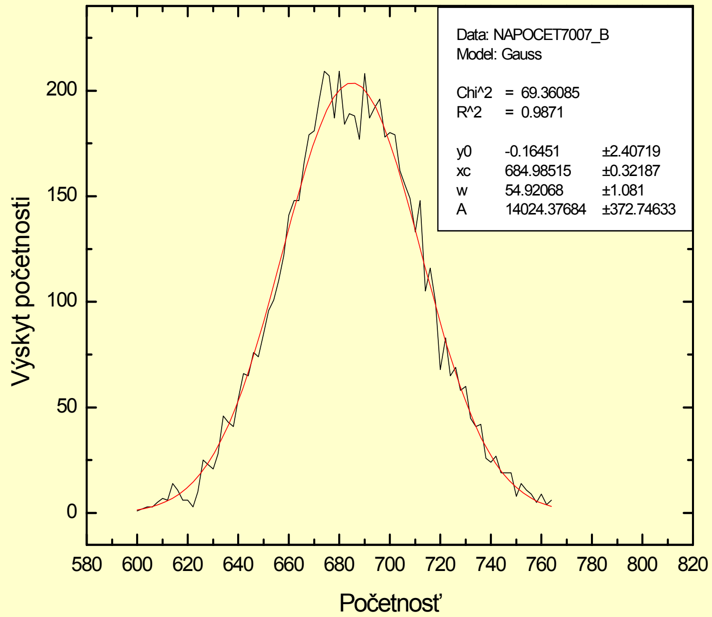
Testing X-CT platform





GaAs detectors testing: *fluctuations in counting – FPN*





Requirements to SI GaAs detectors based on "detector grade" materials

***From the point of view statistical fluctuations*:**

Poisson's limit: $S/N = (n)^{1/2}$

Other goals:
- **production yield**
- **stability in long-term operation**
- **high homogeneity**

SI GaAs

Role of key physical parameters of base materials

GDMS analysis: *SI GaAs materials*

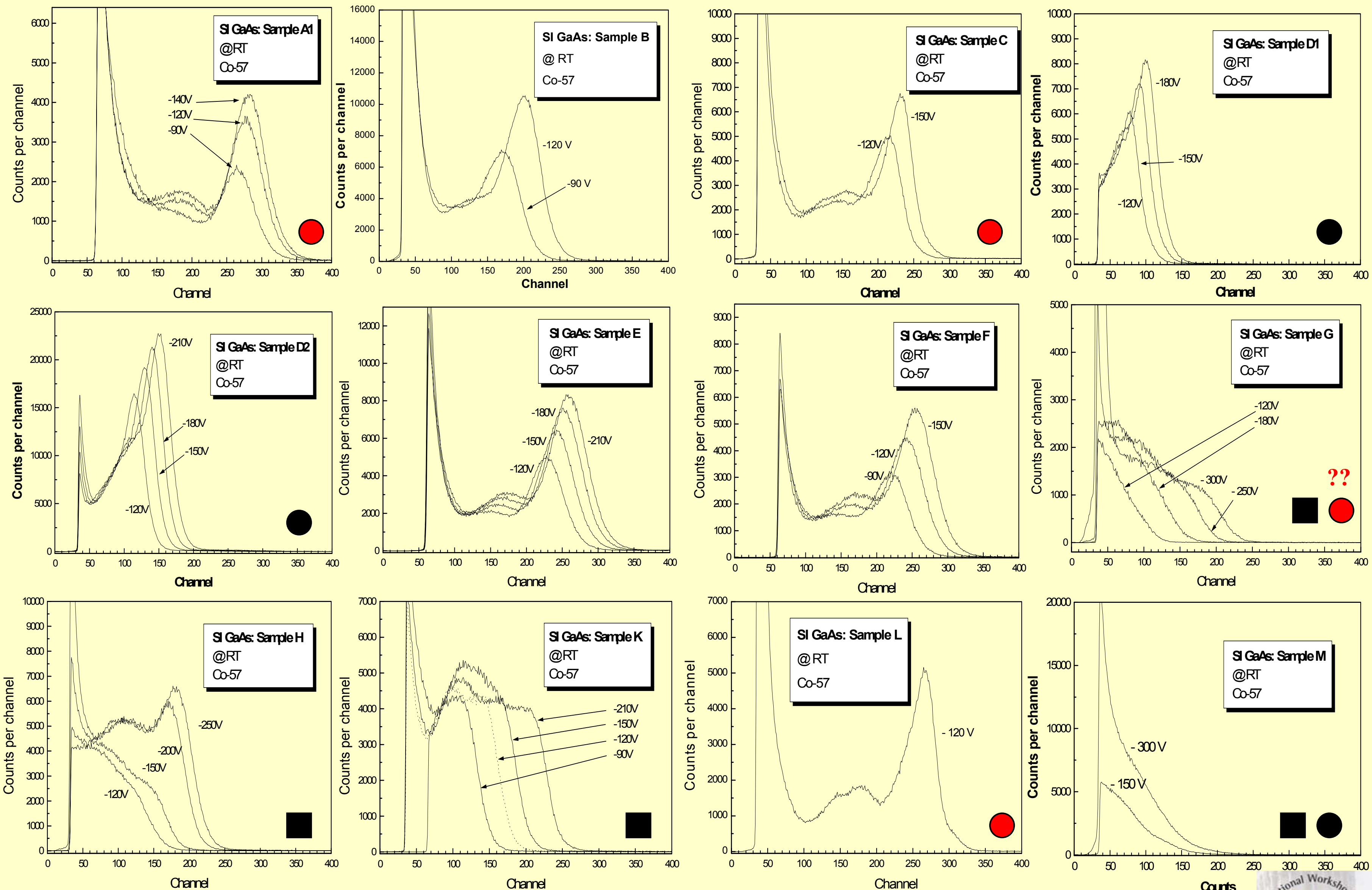
Element	Sample label											
	A1	B	C	D1	D2	E	F	G	H	K	L	M*
B	**190**	**303**	**51**	**1041**	**966**	**271**	**301**	**71**	**470**	**n/a**	**20**	**5600**
Na	**<1.5**	**<2**	**<1.7**	**4**	**<2**	**8**	**3**	**<2**	**4**		**<1.5**	**3**
Mg	**<2**	**<2**	**<2**	**<2**	**<2**	**4**	**<1.9**	**<1.9**	**5**		**<1.5**	**<2**
Al	**<1**	**3**	**<1**	**14**	**<1.4**	**13**	**3**	**2**	**3**		**<1**	**9**
Si	**<3**	**11**	**<3**	**142**	**4**	**212**	**5**	**20**	**11**		**<3**	**445**
P	**<3**	**<3.5**	**4**	**11**	**<2.8**	**12**	**<3**	**12**	**20**		**<3**	**110**
S	**<3**	**21**	**9**	**7**	**12**	**25**	**10**	**10**	**102**		**<3.5**	**77**
Cl	**14**	**13**	**9**	**13**	**16**	**<25**	**12**	**4**	**13**		**7**	**11**
Ti	**<0.4**	**2**	**<0.4**	**3**	**<0.5**	**<0.5**	**1**	**<0.4**	**1**		**<0.4**	**<0.4**
Cr	**<1.2**	**<1.2**	**<1.2**	**<1**	**<1**	**<1**	**<1.2**	**<1.2**	**70**		**<0.9**	**<1.5**
Fe	**<0.4**	**1**	**<0.5**	**1.8**	**0.7**	**1.4**	**1.5**	**0.8**	**0.8**		**<0.4**	**8**
Cu	**<2.5**	**<3**	**<2.5**	**26**	**8**	**<3**	**<3**	**<2.5**	**<3**		**<2.5**	**<2.7**
Total:	<447	<594	<312	<1515	<1258	<806	<576	<360	<953		<257	>6655

Following impurities were obtained in all samples under given detection limit: F<25, Li<6, Be<5, K<25, Ca<20, Mn<0.5, Ni<1.1, Zn<4, Ge<40, Se<13, Mo<1.8, Cd<0.5, In<100, Sn<4, Te<2, Sb<2, Pb<0.5, Bi<0.5.

NOTICES: In the analysis there are not included C, N_2, O_2 as the background contaminants in GDMS and host atoms, Ga and As.

****Content of other important impurities (ppb at.) in the sample M is following: F 35, Mn 5, and Te 32.***

Detection performance: *SI GaAs detectors*



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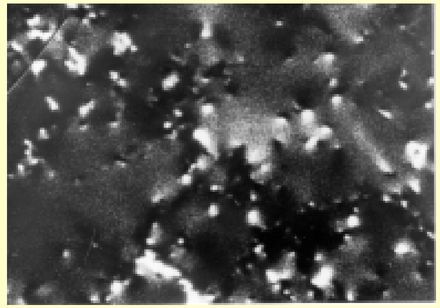
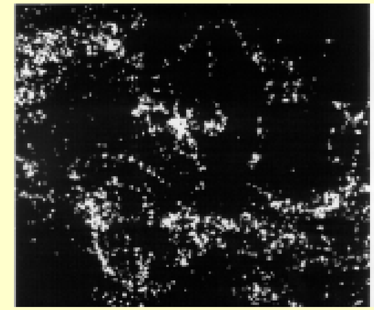
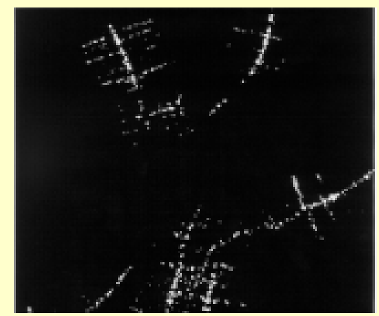
High resolution DCT and LST: *SI GaAs materials*

a) SI GaAs: LEC (B) and VGF (D1) grown materials.

Ma-terial	FWHM DD, **cm^{-2}**	DCT	PD, **cm^{-3}**	LST
B LEC ●	**7.2** **2x10^{4}**	(image 1)	**n/a**	(image 2)
D1 VGF ●	**6.2** **4x10^{3}**	(image 3)	**4.3x10^{7}**	(image 4)







Capacitance study: *SI GaAs detectors*

Measured capacitance	Sample label											
										N/A ??		
T=400 K V_b=0 f<1 kHz	A1	B1	C	D1	D2	E	F	G	H	K	L	M
	780	1050	580	16	22	200	800	10	850	220	260	<10

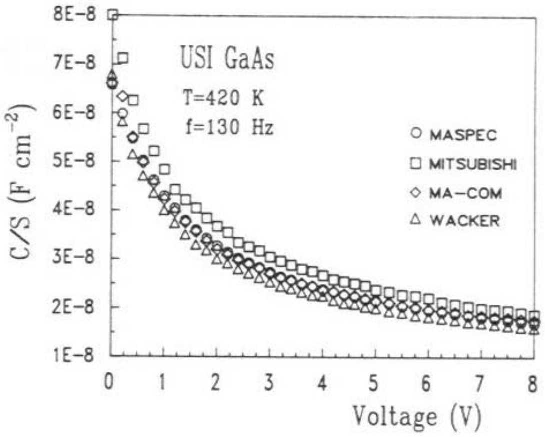


Figure 3. Measured dependences of the capacitance per unit area on voltage of the back-to-back Schottky barrier structres in undoped semi-insulating GaAs from four different manufacturers measured at 420 K and frequency 130 Hz.

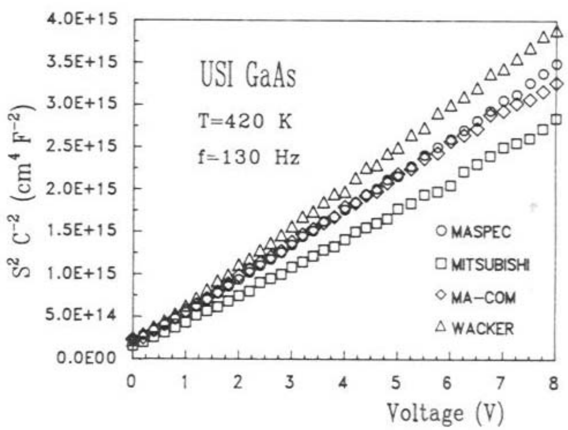
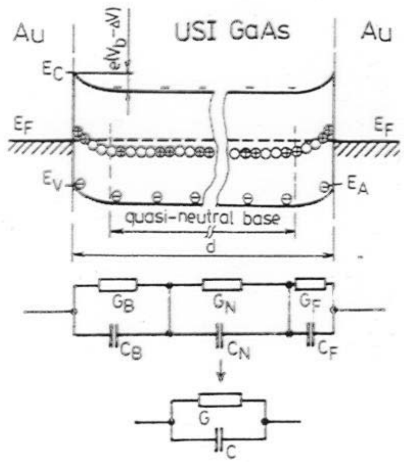


Figure 4. Calculated dependences of S^2C^{-2} on voltage of the back-to-back Schottky barrier structures in undoped semi-insulating GaAs from four different manufacturers measured at 420 K and frequency 130 Hz.



$$C_{\rm Bif} = \frac{\Delta Q}{\Delta V_{\rm B}} = S\sqrt{q\epsilon N_{\rm ef}/2(V_b - \Delta V + V_{\rm B})}$$

$$N_{\rm ef} = \left(\frac{2}{q\epsilon S^2}\right)\left(\frac{\partial V_{\rm B}}{\partial C_{\rm Bif}^{-2}}\right)$$

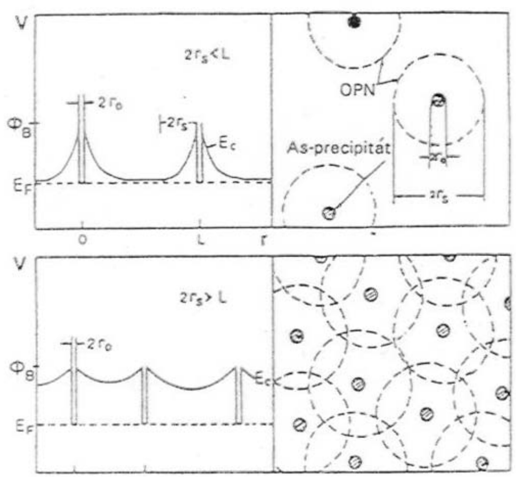
$$N_{\rm ef} = N_{\rm EL2} - N_{\rm net} + N_{\rm TD} - N_{\rm TA}.$$

$$\omega^2 C_{\rm B}^2/G_{\rm N}^2 \ll 1$$

$$C_{\rm B}G_{\rm N}^2/C_{\rm N}G_{\rm B}^2 \gg 1$$

$$G_{\rm B} \ll G_{\rm N}$$

F. Dubecky, et al., *Semicon. Sci. Technol.* 9 (1994) 1654



A.C. Warren, et al., *Appl. Phys Lett.* 57 (1990) 1331

$2r_0 = 3 \div 10$ nm $N_p = 10^{17} \div 10^{18}$ cm^{-3}

P. Gall, et al., *J. Appl. Phys.* 64 (1988) 5161

$2r_0 = 20 \div 100$ nm $N_p = 10^{6} \div 10^{8}$ cm^{-3}

Basic electrical and material characteristics and detectors performances:

SI GaAs materials SUMMARY

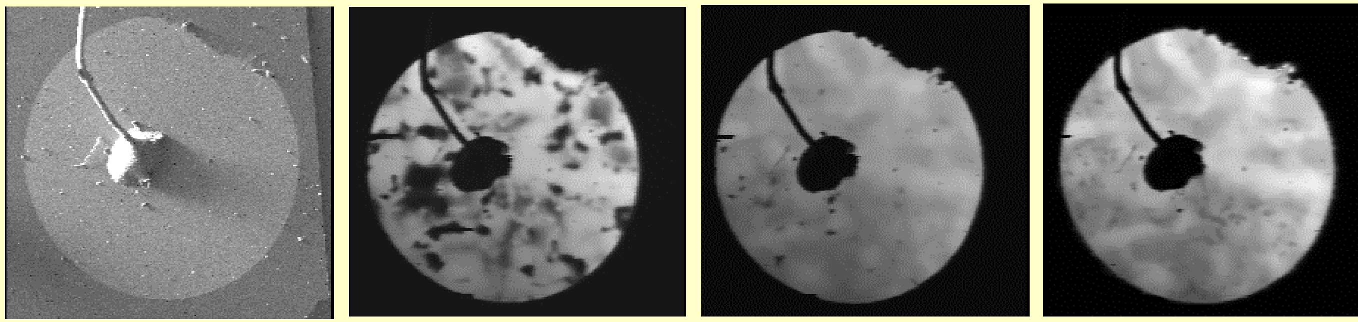
Tabe 1. Information about bulk SI GaAs wafers and detection performances to 122 keV γ-radiation.

Sample label	Growth Method	Doping, contamination	EPD cm^{-2}	Resistivity Ωcm (RT)	Hall mobility cm^2/Vs (RT)	Detection performances (RT) CCE, %	HWHM, %	P/V	
A1	**LEC**	**Non**	**$<6x10^4$**	**$3.9x10^6$**	**7464** ●	**79**	**18.5**	**4.2**	●
B	**LEC**	**Non, Ti**	**$<4x10^4$**	**$1.15x10^7$**	**7227** ●	**59**	**24**	**2.5**	
C	**LEC**	**Non**	**$<4x10^4$**	**$2.44x10^7$**	**6040**	**65**	**14**	**2.6**	
D1	**VGF**	**Non, Cu, Fe, Ti**	**$<5x10^3$**	**$8.8x10^7$**	**5400** ●	**28**	**35**	**2**	● ■
D2	**VGF**	**Non, Cu, Fe**	**$<4x10^3$**	**$4.63x10^7$**	**6203**	**43**	**21**	**2.5**	● ■
E	**HP LEC**	**Non**	**$<6x10^5$**	**$2.95x10^6$**	**6940** ●	**73**	**22.5**	**2.9**	
F	**LP LEC**	**Non**	**$<2x10^5$**	**$1.06x10^7$**	**5816**	**72**	**21.6**	**2.6**	
G	**LEC**	**Non**	**$<8x10^4$**	**$2.8x10^8$**	**5122** ●	**42**	**no photopeak detected**		● ■
H	**LEC**	**Cr**	**$<1x10^5$**	**$1.2x10^8$**	**5770** ●	**51**	**25**	**1.4**	■
K	**LEC**	**Non**	**$<2x10^5$**	**$9.65x10^6$**	**7517** ● ??	**57**	**no photopeak detected**		■
L	**LEC**	**Non**	**$<6x10^4$**	**$2.6x10^7$**	**6915** ●	**72**	**12.5**	**3.8**	●
M	**LEC**	**Non**	**$<8x10^5$**	**$1.4x10^8$**	**4830** ●	**32**	**no photopeak detected**		■

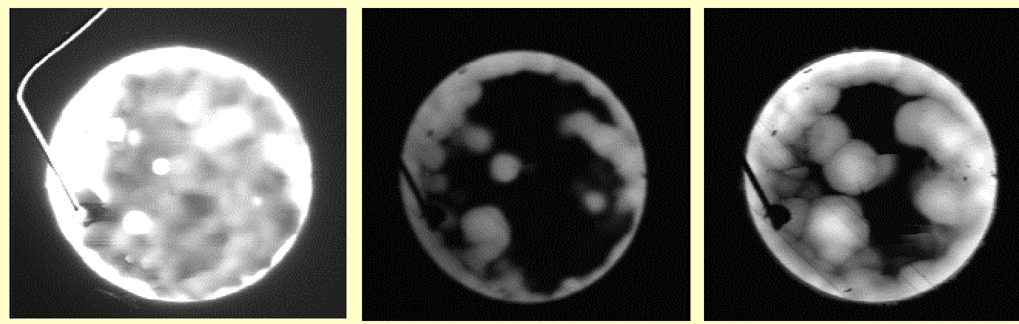
EBIC: *SI GaAs*

SE *Bias voltage: 0* *-30 V* *-60 V*

E: M/A COM
HP LEC SI GaAs



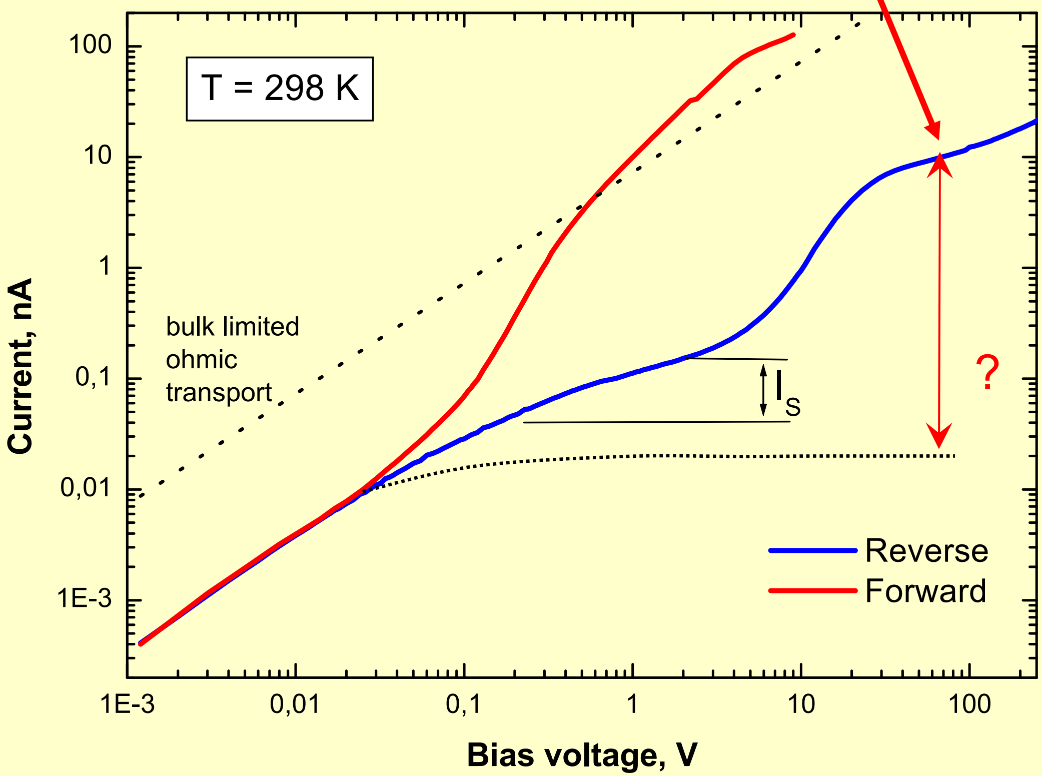
F: M/A COM
LP LEC SI GaAs

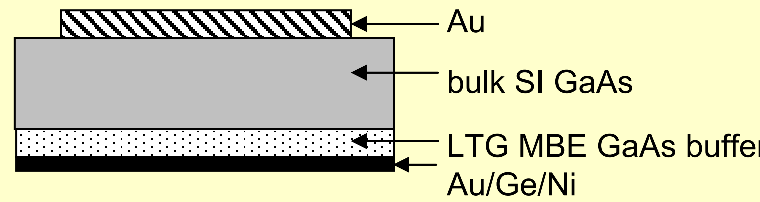


Detector contact: 2 mm diameter
Base thickness: 200 μm

I-V characteristic of SI GaAs detector
with the Schottky barrier

?? Explanation of the second current saturation region observed at the reverse I-V characteristics





Thermiionic emission current via Schottky barrier

$$I = I_S\left[e^{\frac{q(V-IR_S)}{nkT}} - 1\right]$$

Saturation current

$$I_S = AA^{**}T^2 e^{-\frac{q\phi_B}{kT}}$$

I-V characteristics of SI GaAs detectors
with the Schottky barrier (2 mm diameter)

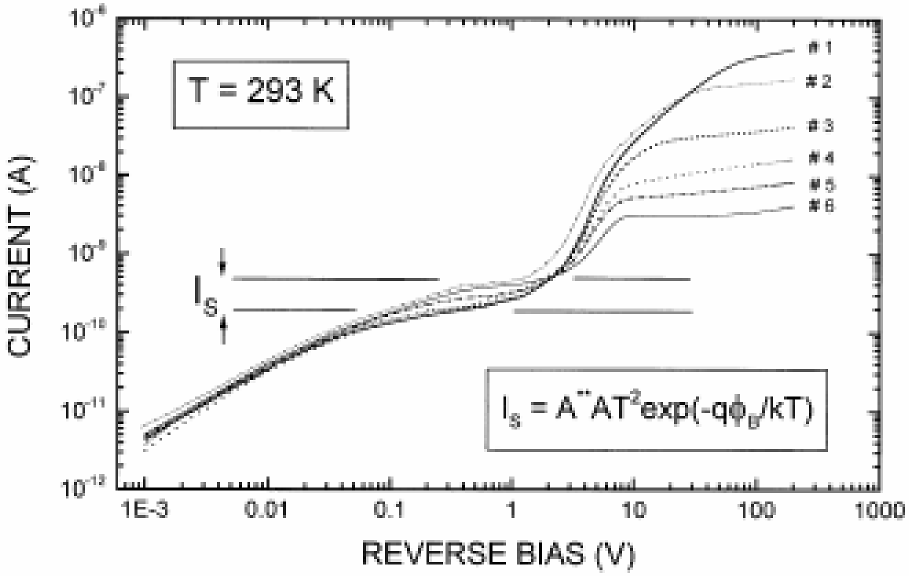


Fig. 2. A detailed reverse current behaviour from low voltages, 1×10^{-3} V, to 200 V, with the saturation current, I_s, range indicated.

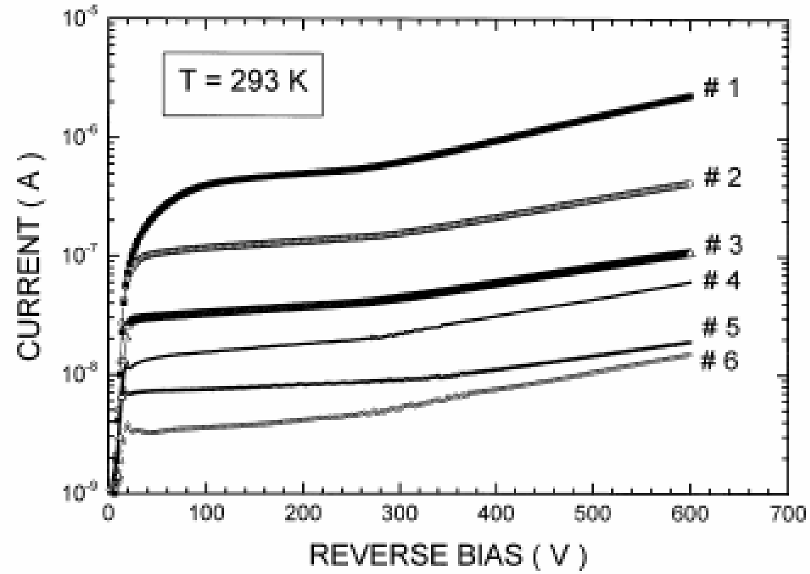
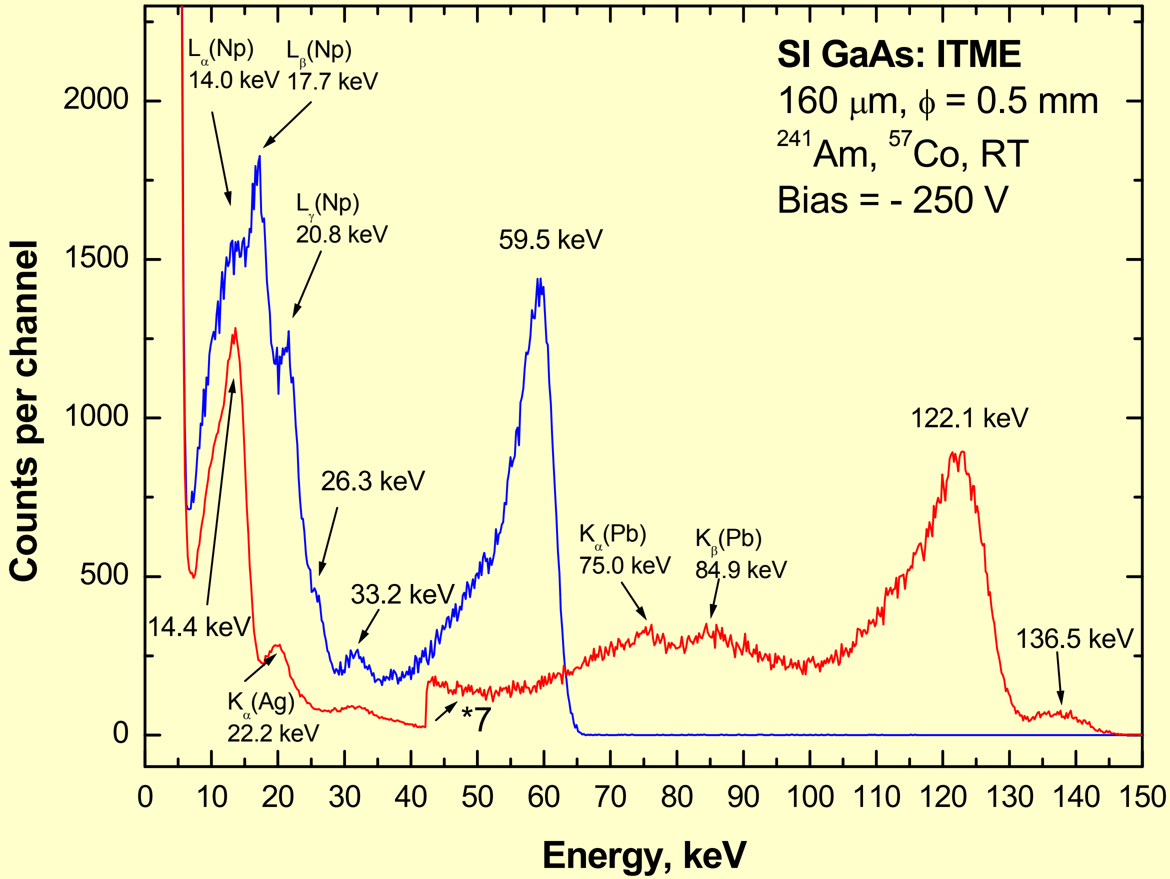


Fig. 1. Room-temperature I–V characteristics versus reverse bias voltage for SI LEC GaAs detectors at different acceptor dopant concentrations, N_a, as reported in Table 1.

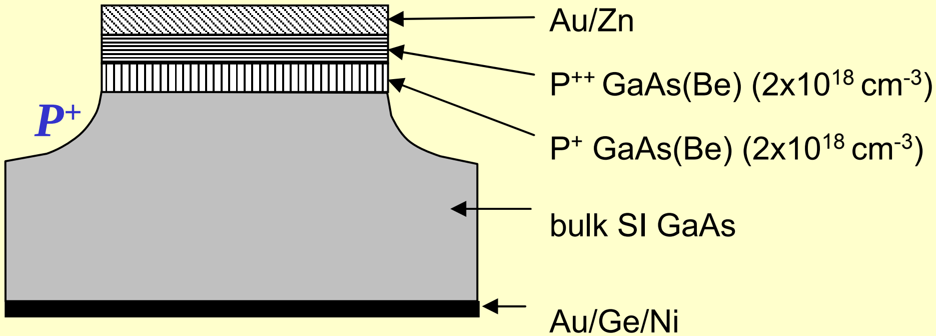
Baldini, R., et al., NIM A 449 (2000) 268

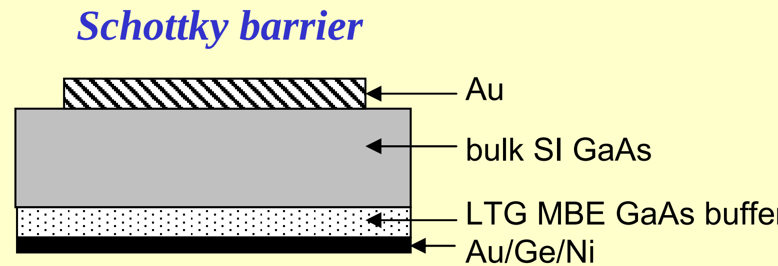
Pulse-height spectra of ^{241}Am and ^{57}Co detected by "dedicated" SI GaAs PAD detector



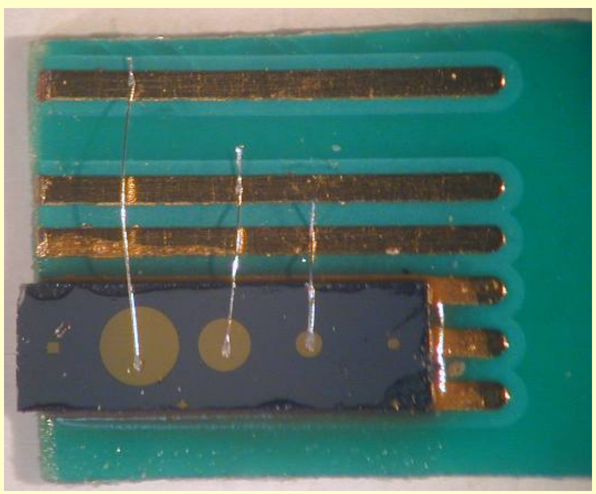
B. Zaťko at al.: Nucl. Instr. Meth. A (2004)

SI GaAs detectors structure

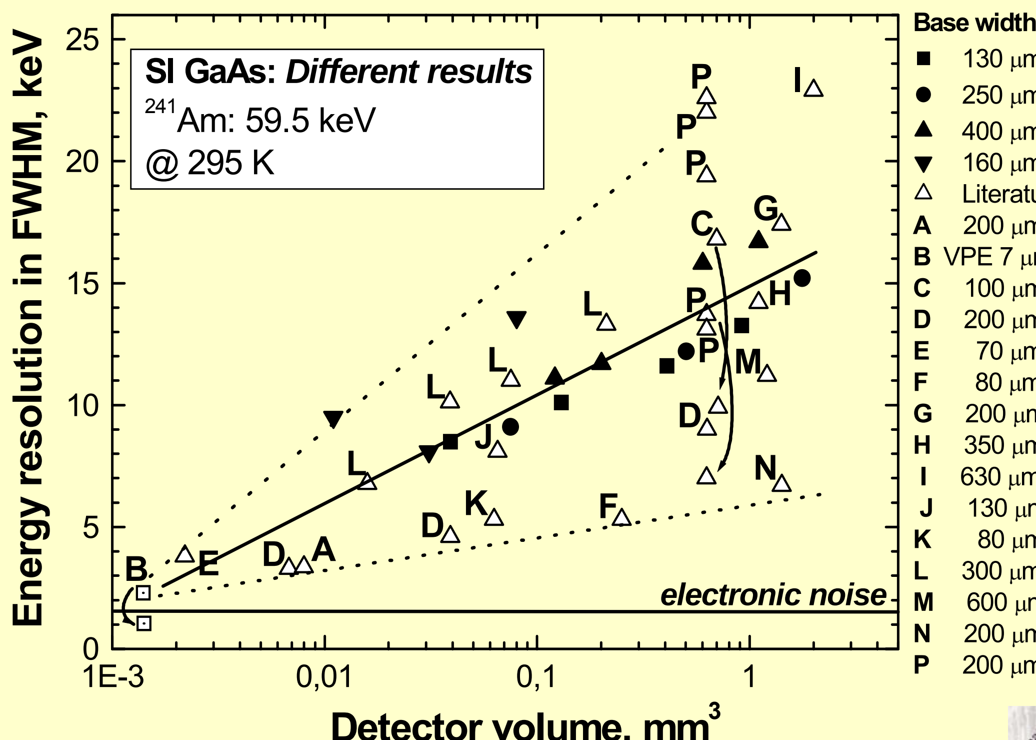




Optimization of the ohmic and blocking SI GaAs detector contacts



Zaťko, B., et al., NIM A531 (2004) 111



Conclusions

- **Bulk SI GaAs: Radiation detector-grade material is available on the market!**
- **Key material characteristics: - preferable VGF, low dislocation density**
  - high chemical purity (GDMS)
  - RT Hall mobility > 6500 cm^2/Vs
  - RT resistivity (0.8 – 3)e7 ohm cm
- **Following material evaluation tools: X-ray topography, LST, PL, …**
- **Detector evaluation tools: I-V, C-V, EBIC, pulse height spectra,...**
- **Detector electrodes: Must be optimized for required performance**
- **Schottky back-to-back electrode technology: Potential improvement must be investigated in more details!!**
- **PERSPECTIVE APPLICATIONS: *Quantum X-RAY IMAGING, Quantum X-CT,…***
- **BASIC & SPACE RESEARCH: *PLASMA DIAGNOSTIC IN NUCLEAR FUSSION***

THANK YOU

FOR YOUR ATTENTION!!!