6th International Workshop on Radiation Imaging Detectors
IWORID-2004,
July 25-29 , Glasgow (Scotland).

Prospects for Energy Resolving X-Ray Imaging with Compound Semiconductor Pixel Detectors

Giuseppe Bertuccio

Politecnico di Milano

Department of Electronics Engineering and Information Science and INFN

Milano - Italy

Outline

- GaAs and SiC X-Ray detectors

Outline

- GaAs and SiC X-Ray detectors
- The achieved results

Outline

- GaAs and SiC X-Ray detectors
- The achieved results
- Some related issues :
  - Leakage current
  - Electronic noise
  - Charge transport

Outline

- GaAs and SiC X-Ray detectors
- The achieved results
- Some related issues :
  - Leakage current
  - Electronic noise
  - Charge transport

Outline

- GaAs and SiC X-Ray detectors
- The achieved results
- Some related issues :
  - Leakage current
  - Electronic noise
  - Charge transport
- Prospects with GaAs and SiC pixel detectors

GaAs Radiation Detectors:

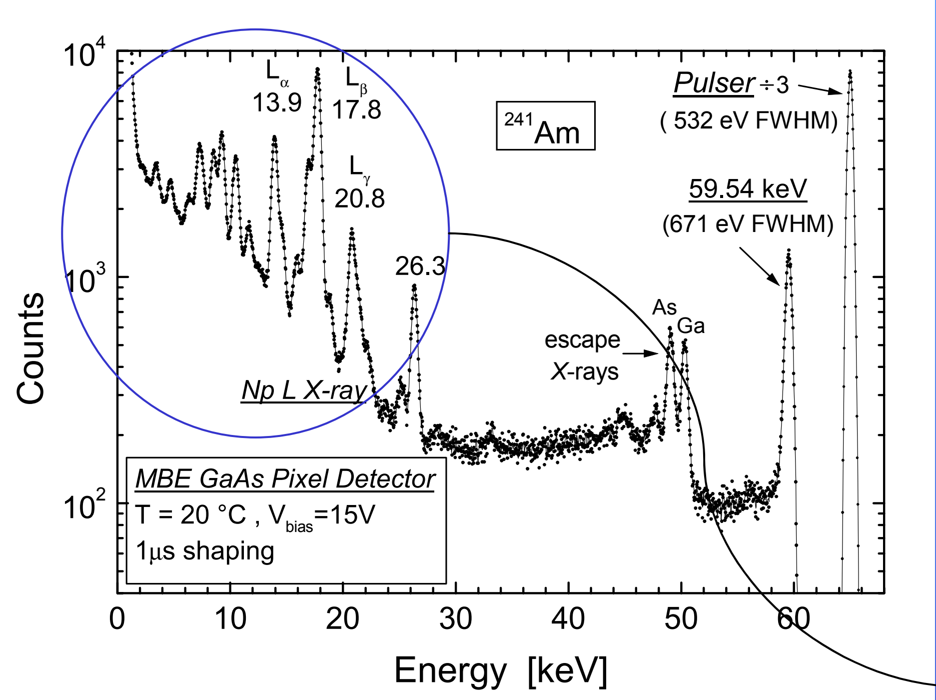
30 years of a fascinating history

- **1971-72** : Eberharth et al. (NIM-94), Kobayashi et al. (NIM-98)

1992 -1998:

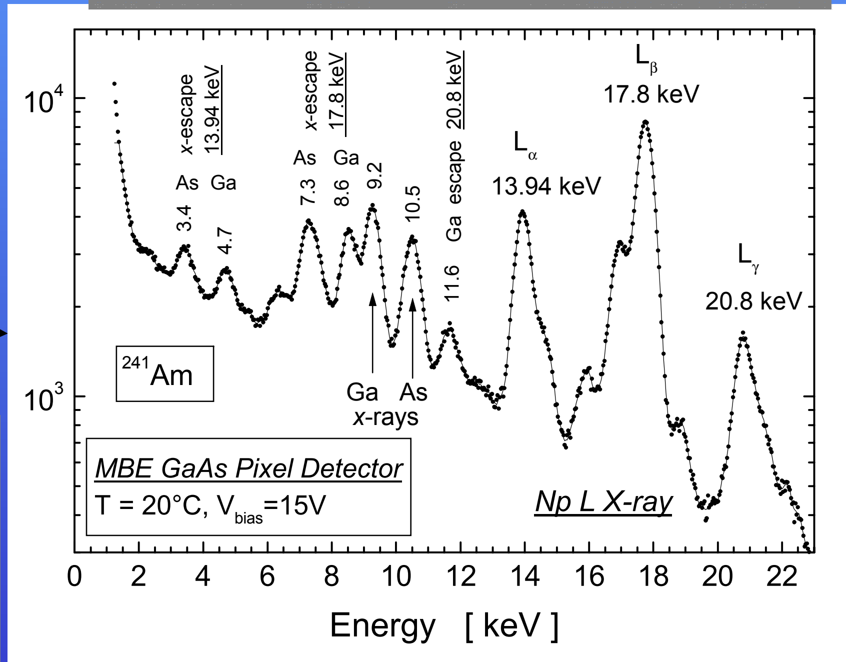
- **Europe**: Aachen, CERN, Freiburg, Glasgow, Imperial College, Lecce, Leicester, Milano, Modena, Pisa, Sheffield…
- **USA** : Michigan Univ., Sandia; UCLA, Livermore, Naval, Berkeley, Wright Univ.

1996 – GaAs single pixel GaAs



Politecnico di Milano – KFA Julich Collaboration

MBE GaAs - 5 µm thick
p-i-n structure ($3 \cdot 10^{14}$ cm^{-3})
pixel: 170 x 320 µm



Equivalent Noise Energies

@ 20 °C: 532 eV FWHM (53 e- r.m.s.)

@ -30°C: 373 eV FWHM (37 e- r.m.s.)

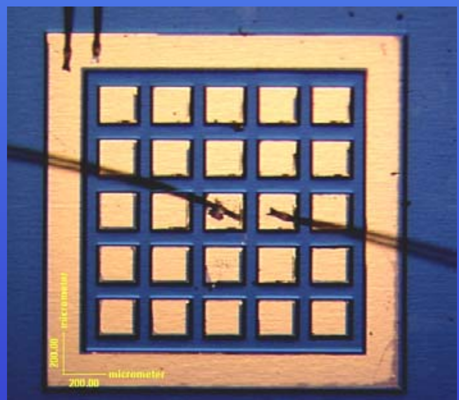
IEEE Trans. Nucl. Sci. 44, 1997

2002 - Pixel Array

A. Owen, M. Bavdaz, A. Peacock (ESA)

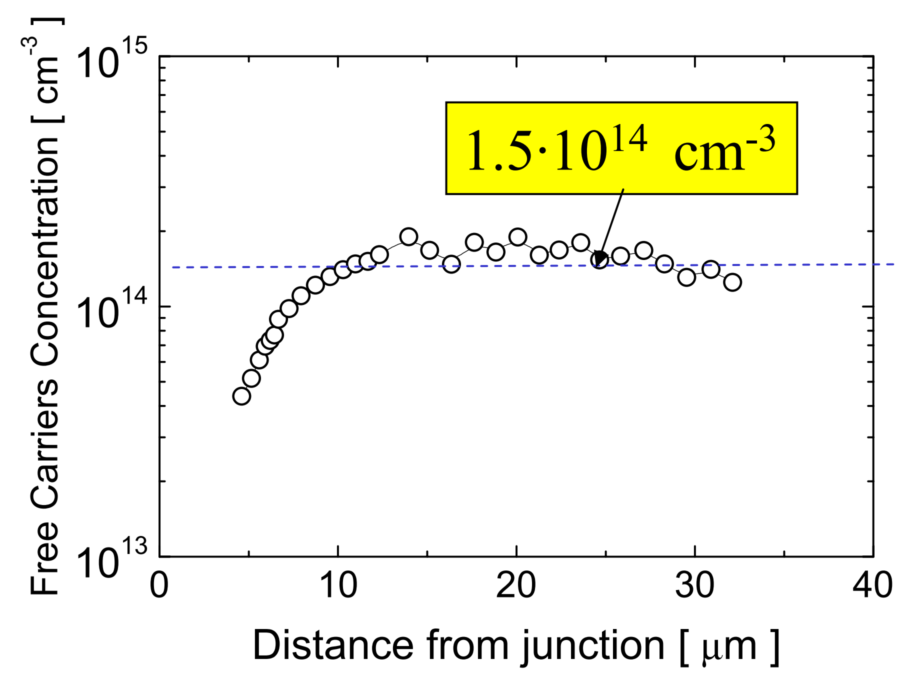
S. Nenomen, H. Anderson (Metorex)

G. Bertuccio, R. Casiraghi, D. Maiocchi (PoliMI)



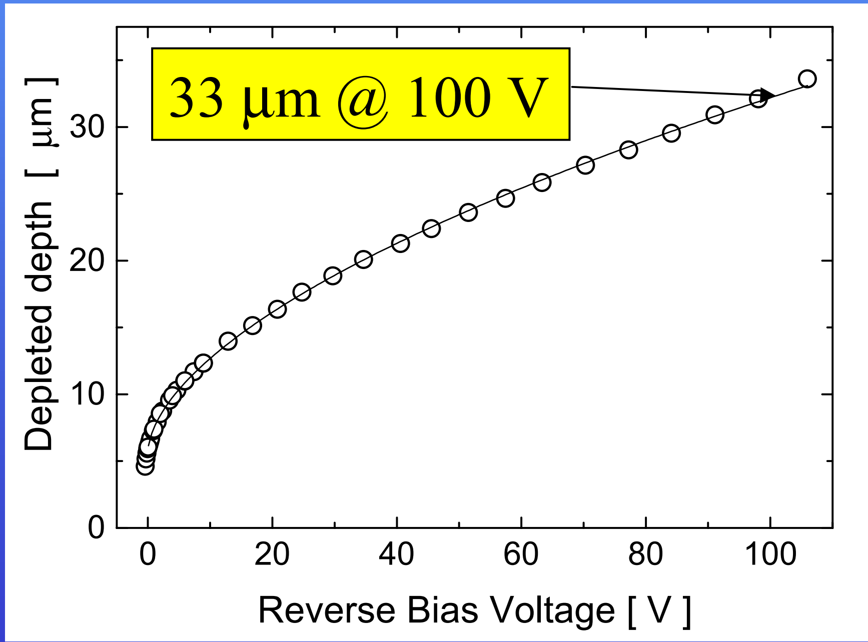
CVD GaAs - 40 µm thick
p^+n structure
Pixel size: 200 µm x 200 µm

Epitaxial Layer Characteristics

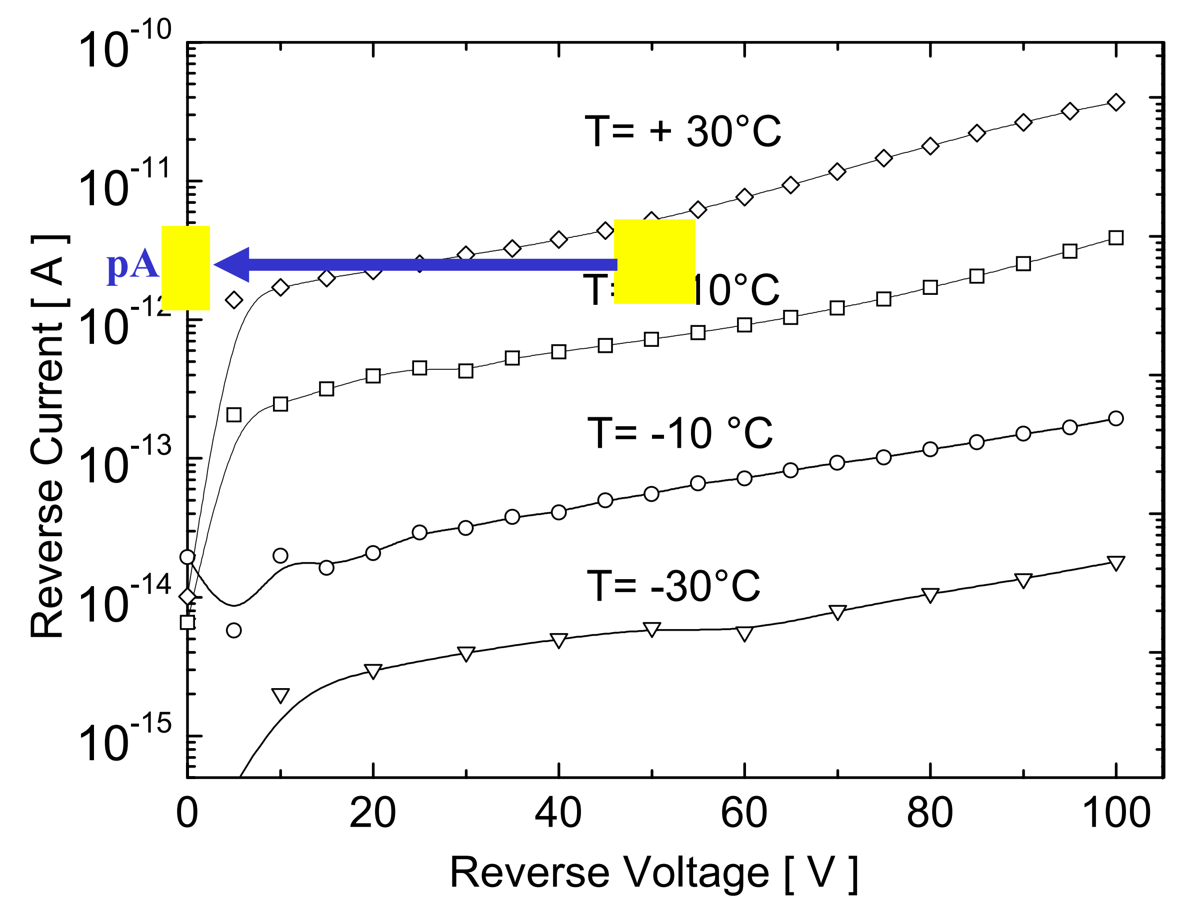


Equivalent to

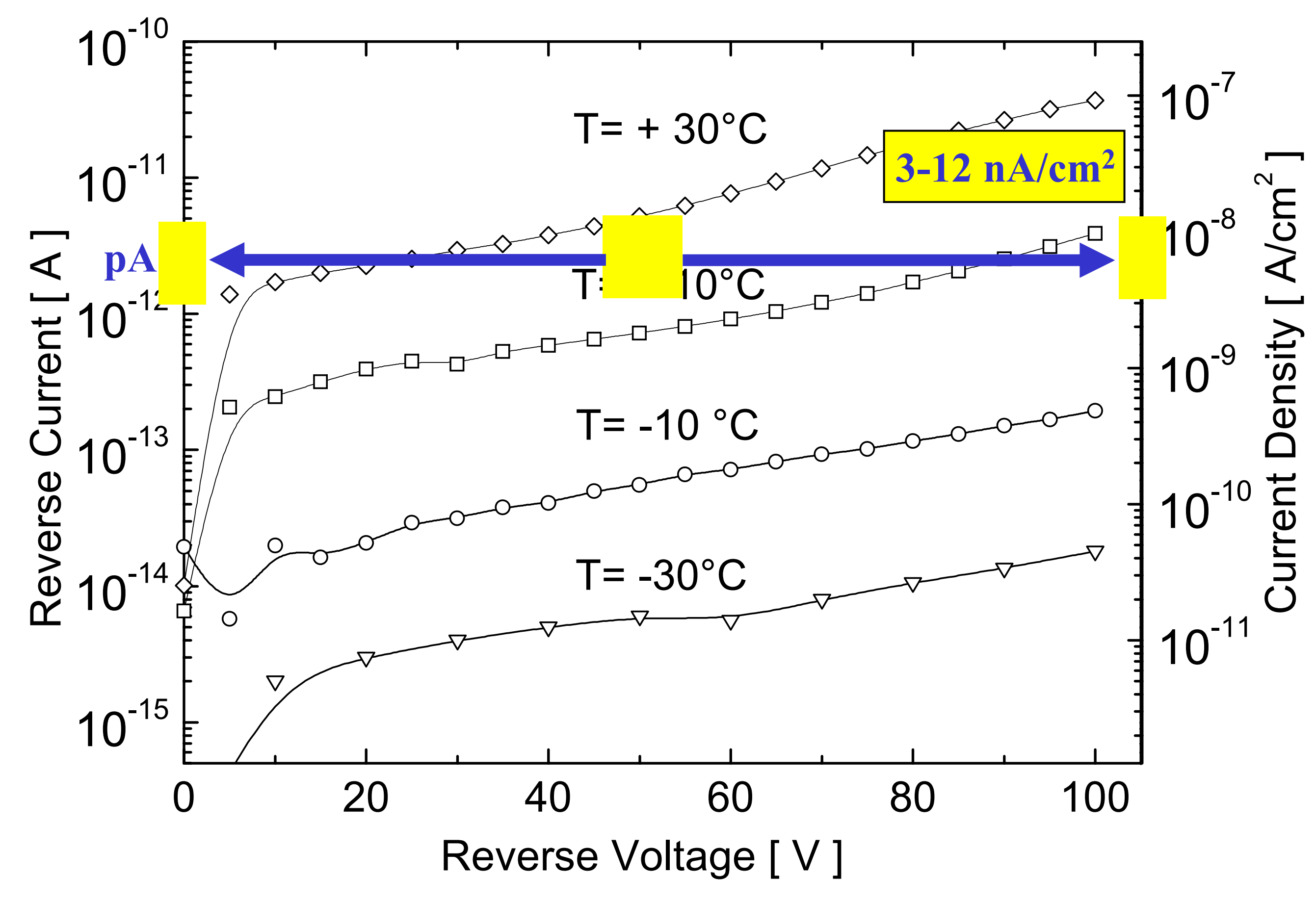
20 X Silicon thickness (650 μm)



Junction Leakage Current

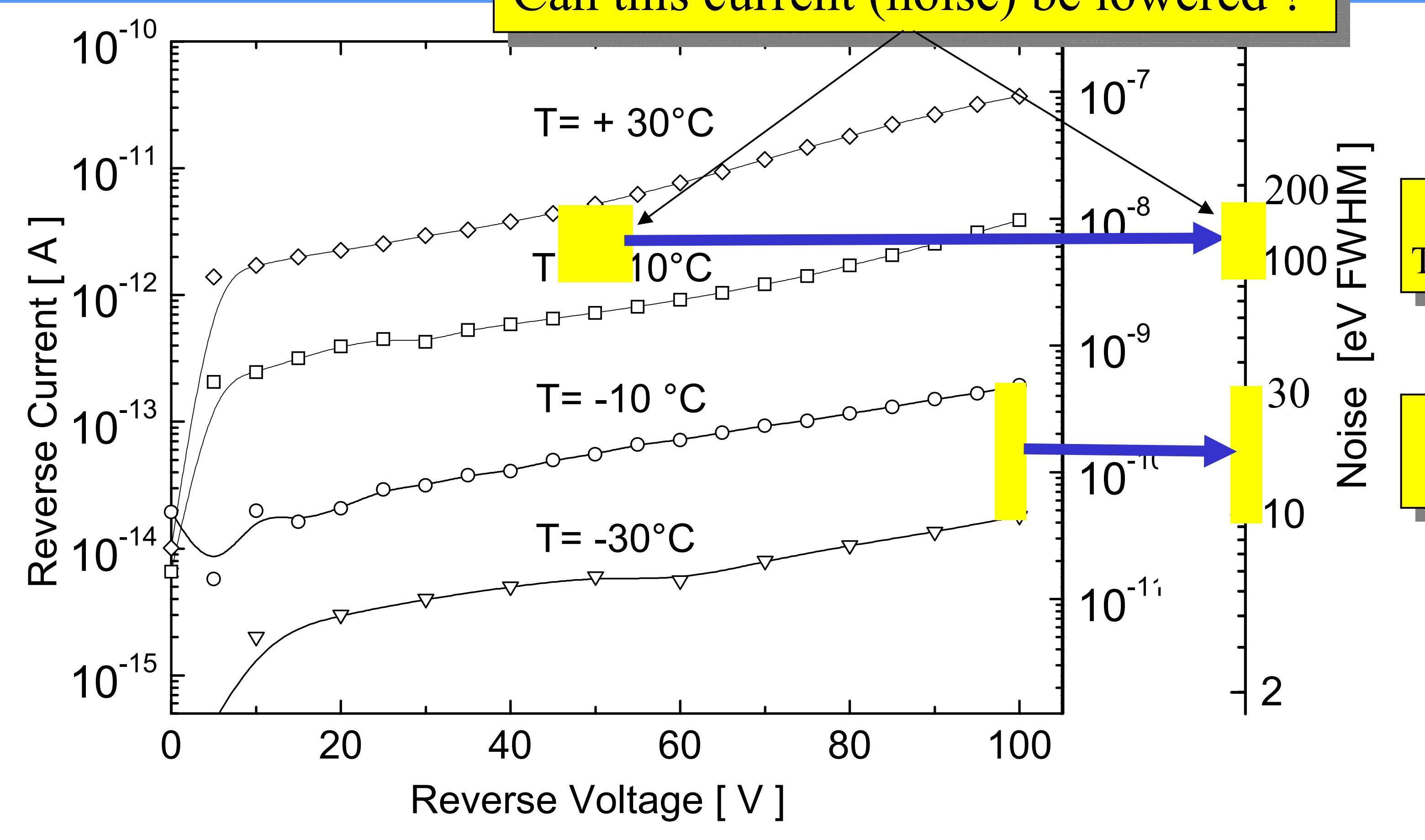


Junction Leakage Current



I_{leak} Equivalent Noise @ 5 µs

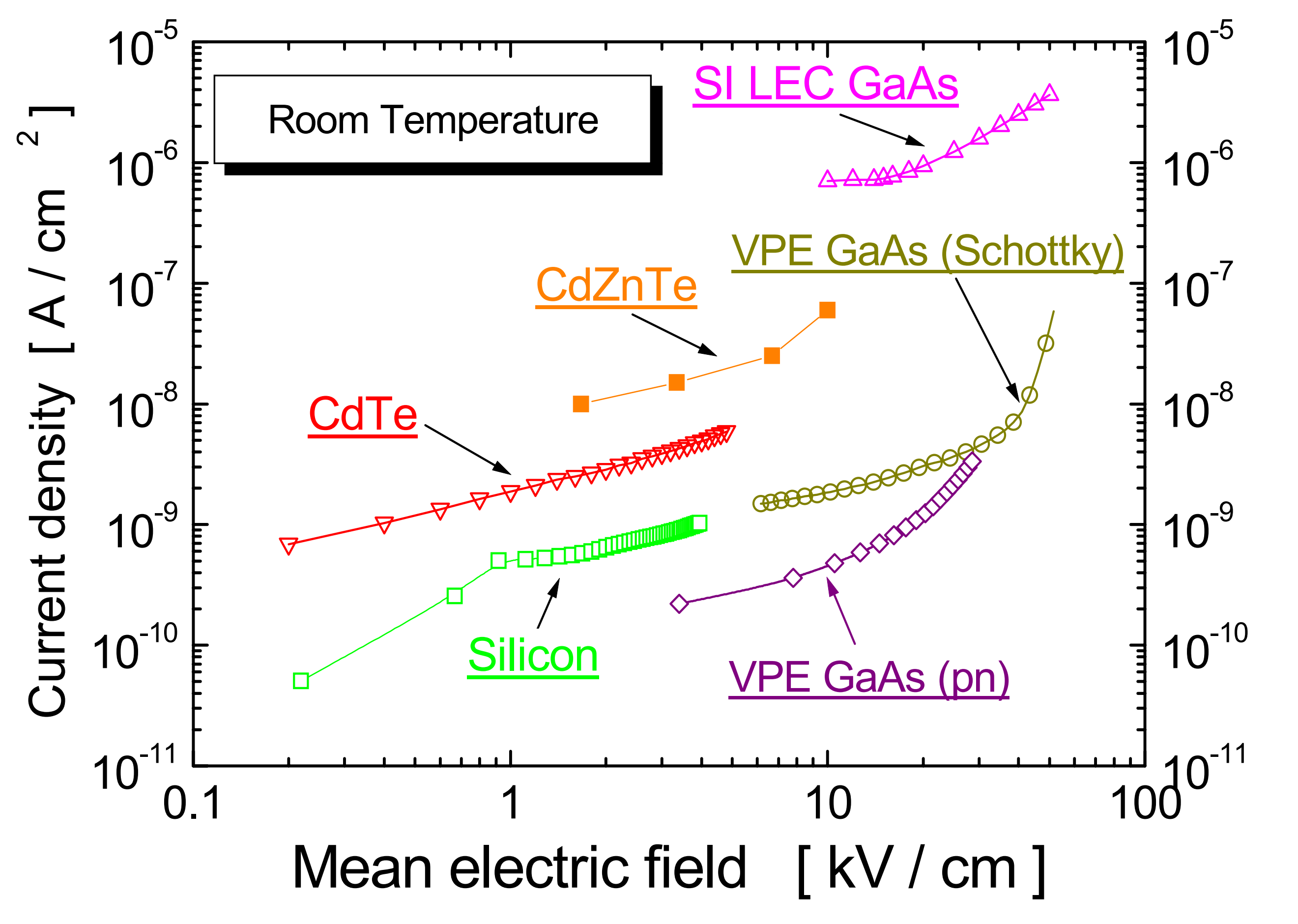
Can this current (noise) be lowered ?



Room Temperature

Soft Cooling

Leakage Current densities



Is the ultimate limit reached for J_{GaAs} ?

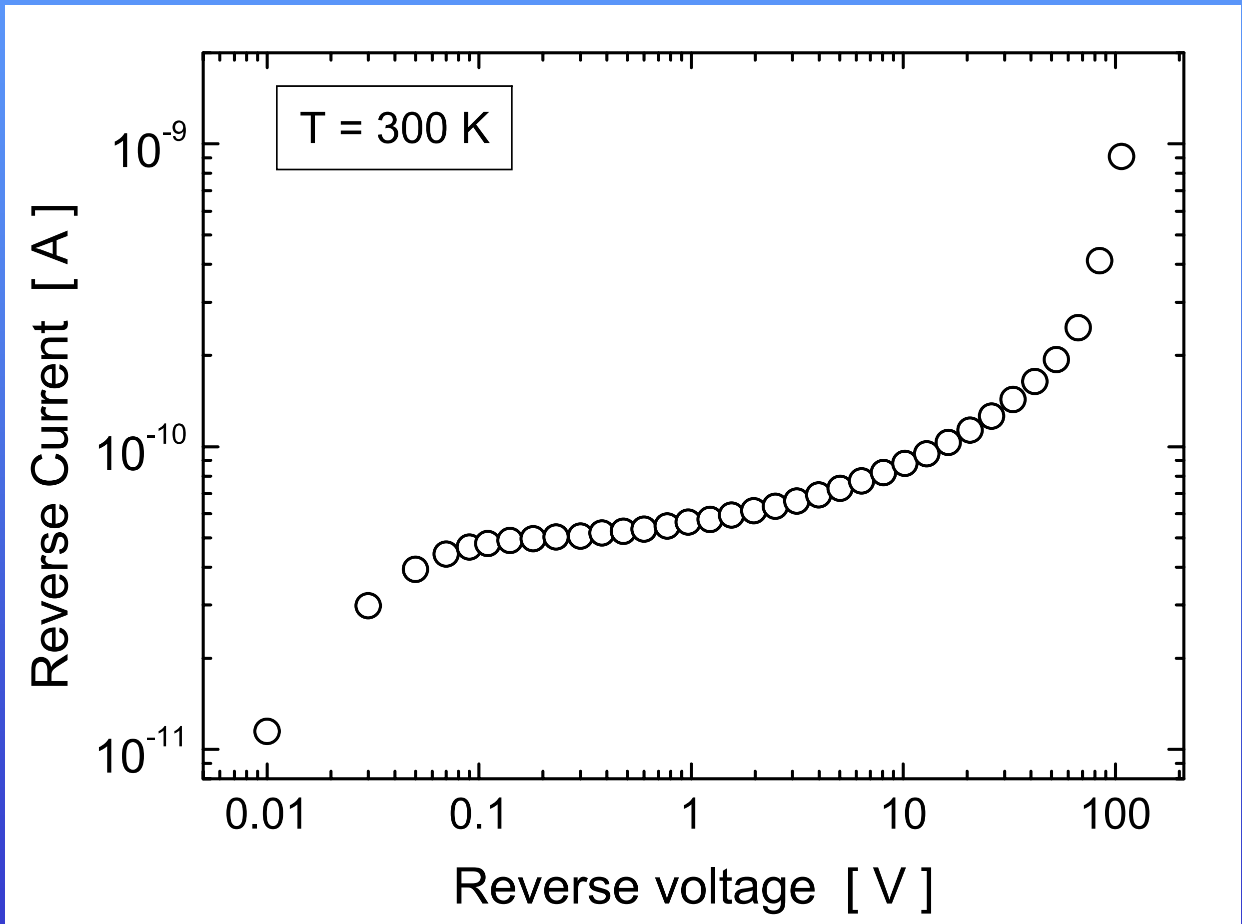
Investigation on

the leakage curent origin

in junctions on GaAs

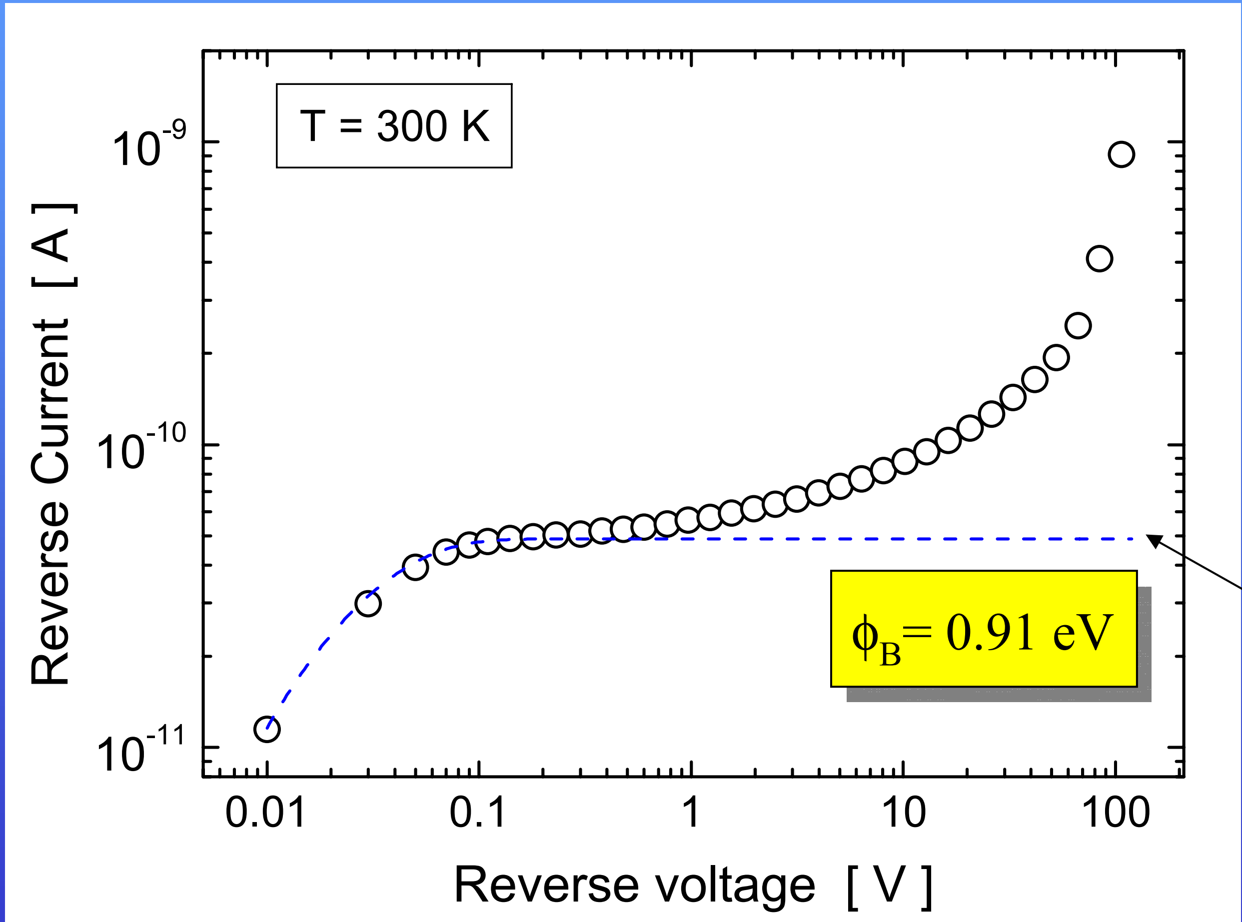
Leakage current origin in GaAs detectors

Schottky junction GaAs detectors



Leakage current origin in GaAs detectors

Schottky junction GaAs detectors

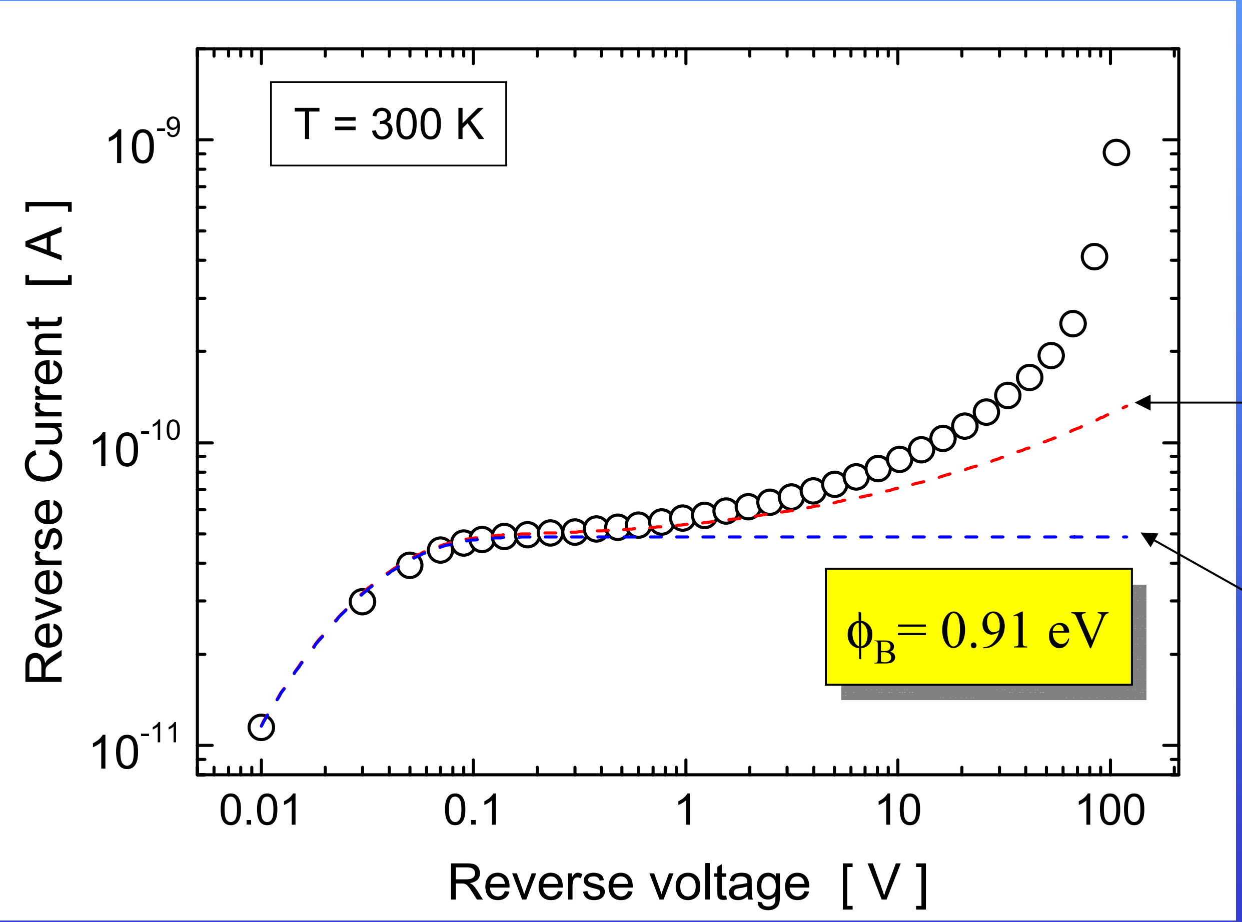


Thermionic emission

$$I_R = S A^* T^2 e^{-\frac{q\phi_B}{kT}} \left(1 - e^{-\frac{qV_R}{kT}}\right)$$

Leakage current origin in GaAs detectors

Schottky junction GaAs detectors



Barrier lowering

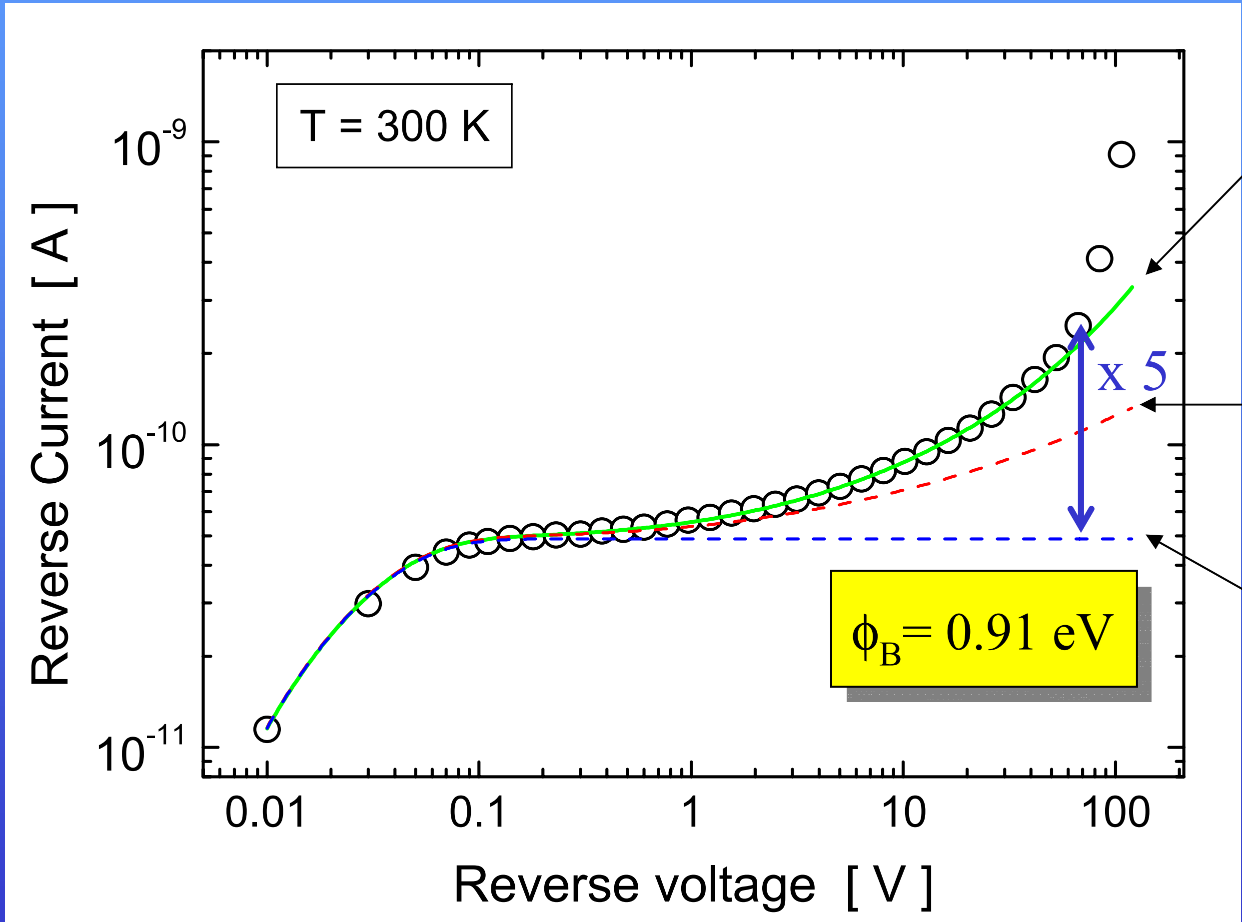
$$\phi_B = \phi_{B0} - \sqrt{\frac{qE_m}{4\pi\varepsilon_s}}$$

Thermionic emission

$$I_R = SA^*T^2 e^{-\frac{q\phi_B}{kT}}\left(1 - e^{-\frac{qV_R}{kT}}\right)$$

Leakage current origin in GaAs detectors

Schottky junction GaAs detectors



Barrier lowering + static

$$\phi_B = \phi_{B0} - \sqrt{\frac{qE_m}{4\pi\varepsilon_s}} - \alpha E_m$$

Barrier lowering

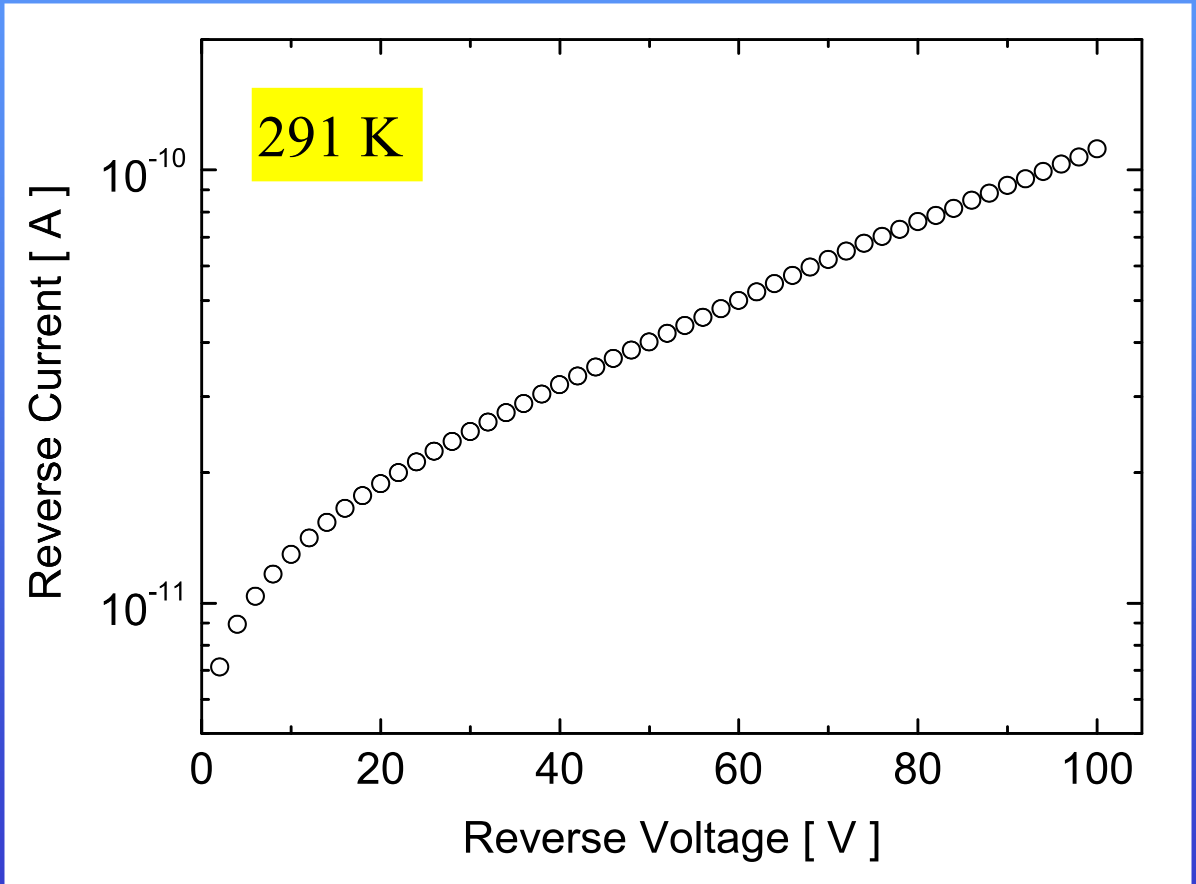
$$\phi_B = \phi_{B0} - \sqrt{\frac{qE_m}{4\pi\varepsilon_s}}$$

Thermionic emission

$$I_R = SA^*T^2 e^{-\frac{q\phi_B}{kT}}\left(1 - e^{-\frac{qV_R}{kT}}\right)$$

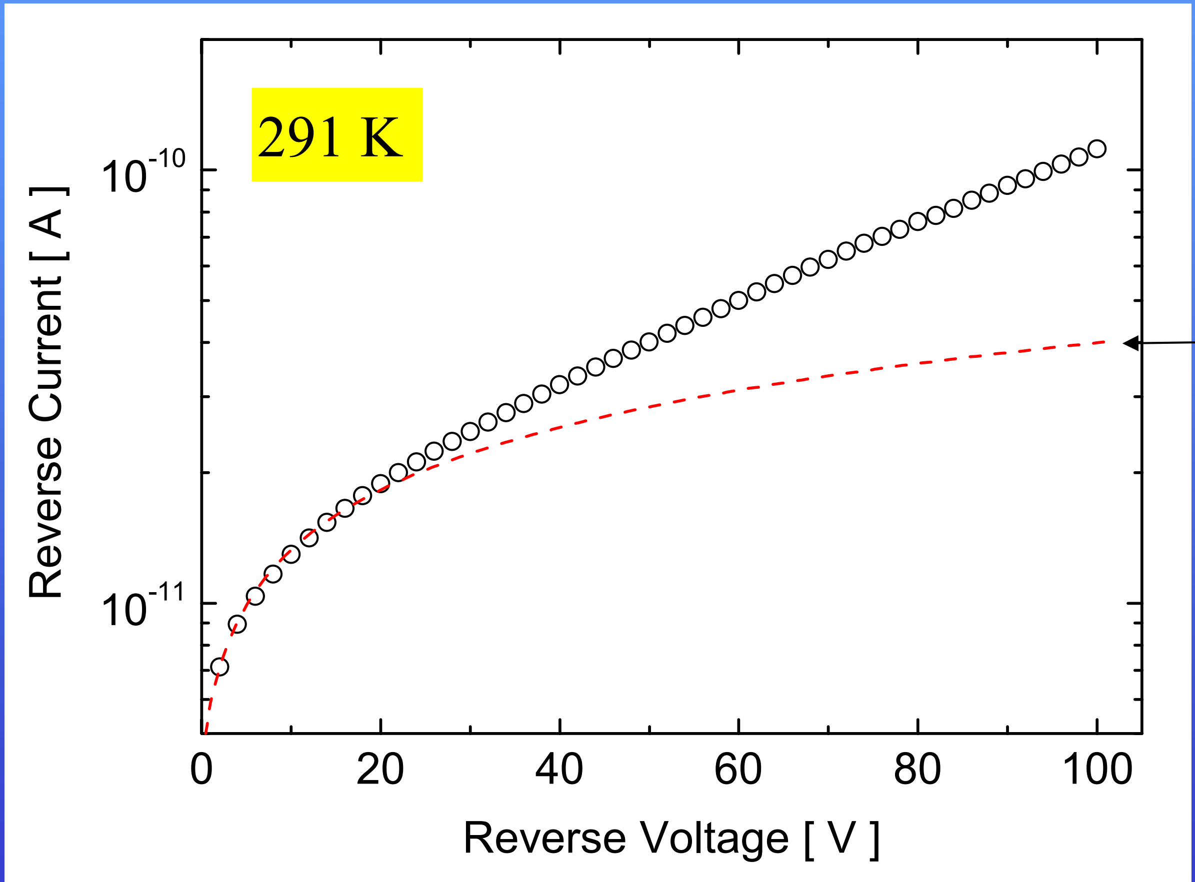
Leakage current origin in GaAs detectors

p^+n junction GaAs detectors



Leakage current origin in GaAs detectors

p^+n junction GaAs detectors



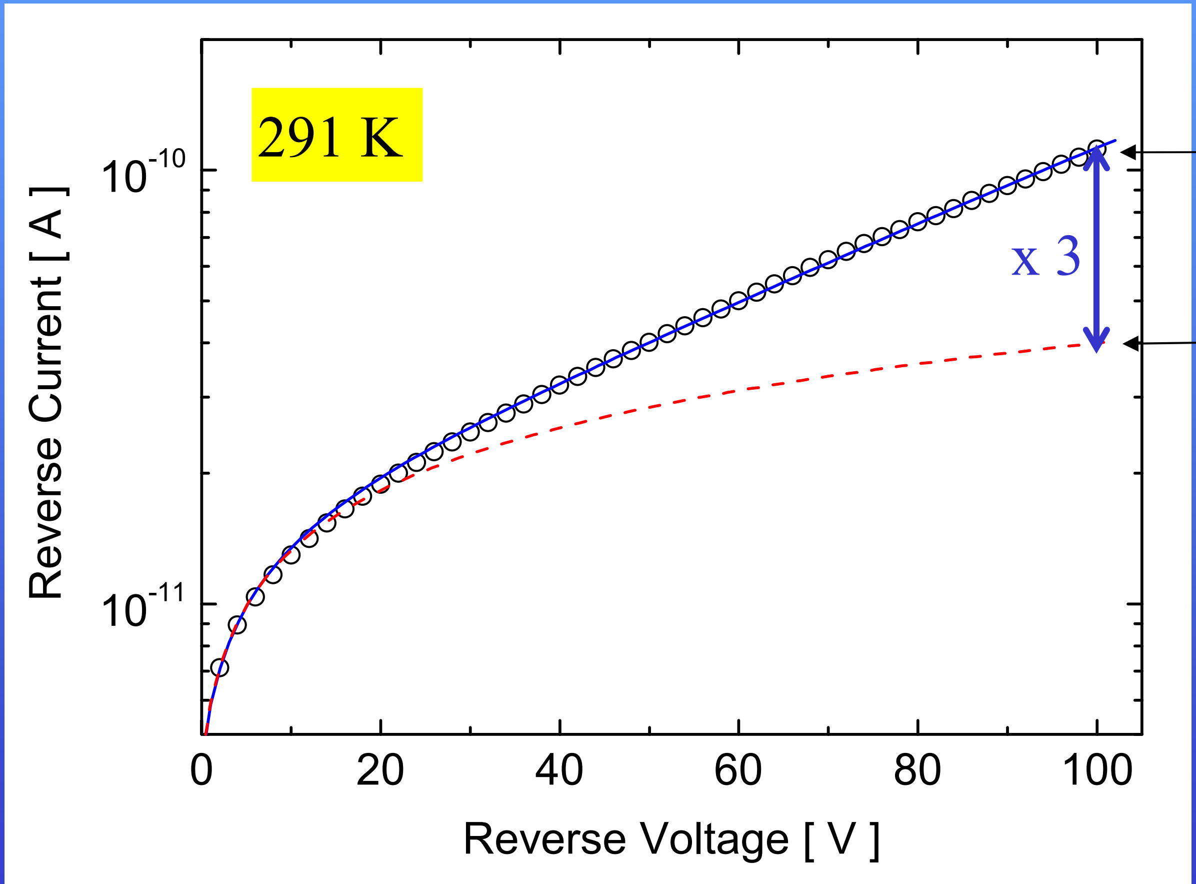
Thermal Generation

$E_A = 0.7$ eV

$\tau_G = 1\ \mu s$

Leakage current origin in GaAs detectors

p^+n junction GaAs detectors



Thermal gen. +

Poole Frenkel effect

Thermal Generation

$E_A = 0.7$ eV

$\tau_G = 1\mu s$

Leakage current in GaAs: conclusions

- Current densities $\leq$ 10 nA/cm^2 @ 290 K

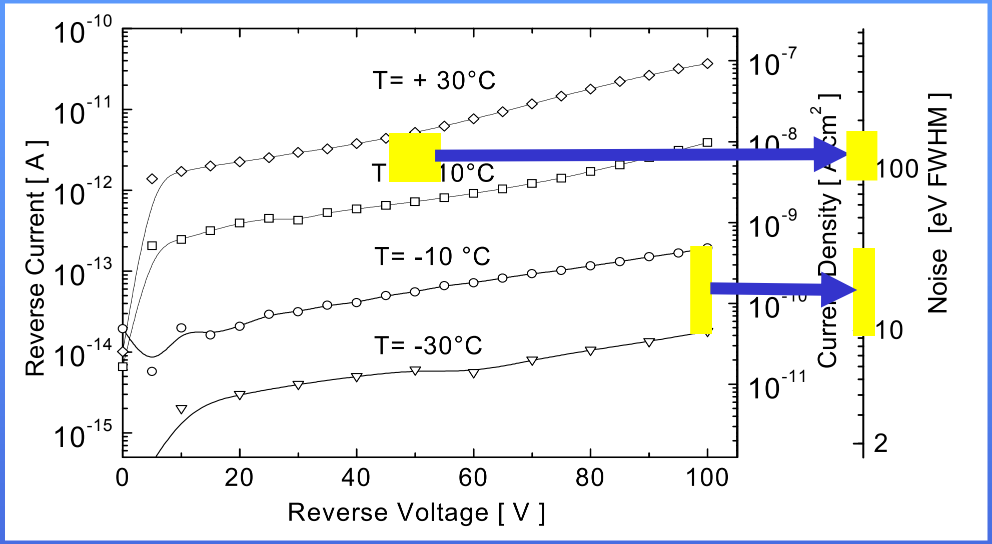
Leakage current in GaAs: conclusions

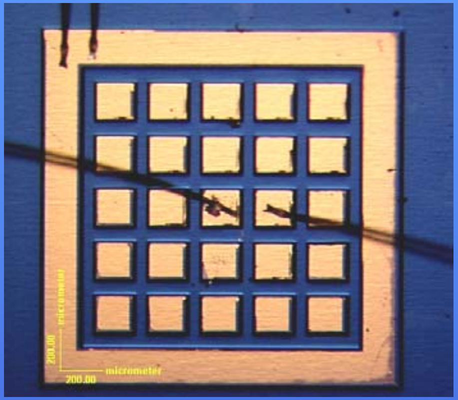
- Current densities ≤ 10 nA/cm^2 @ 290 K
- Schottky junction:
  - Barrier height $\phi = 0.9$ eV
  - Significant barrier lowering effects
  - Higher barrier, lower doping (smaller E_m) required

Leakage current in GaAs: conclusions

- Current densities ≤ 10 nA/cm^2 @ 290 K
- Schottky junction:
  - Barrier height $\phi = 0.9$ eV
  - Significant barrier lowering effects
  - Higher barrier, lower doping (smaller E_m) required
- p+n junction:
  - Generation current ($\tau_G = 1 \mu s$; $E_A = 0.7$ eV)
  - Poole-Frenkel effect observed
  - Higher purity, lower doping (smaller E_m) required

Prototype GaAs pixel array





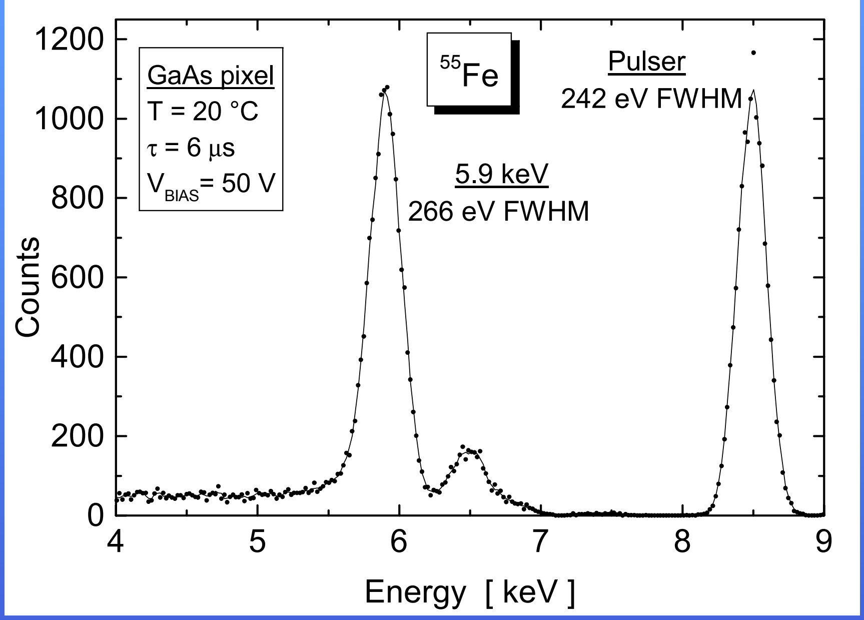
Test with discrete front-end electronics

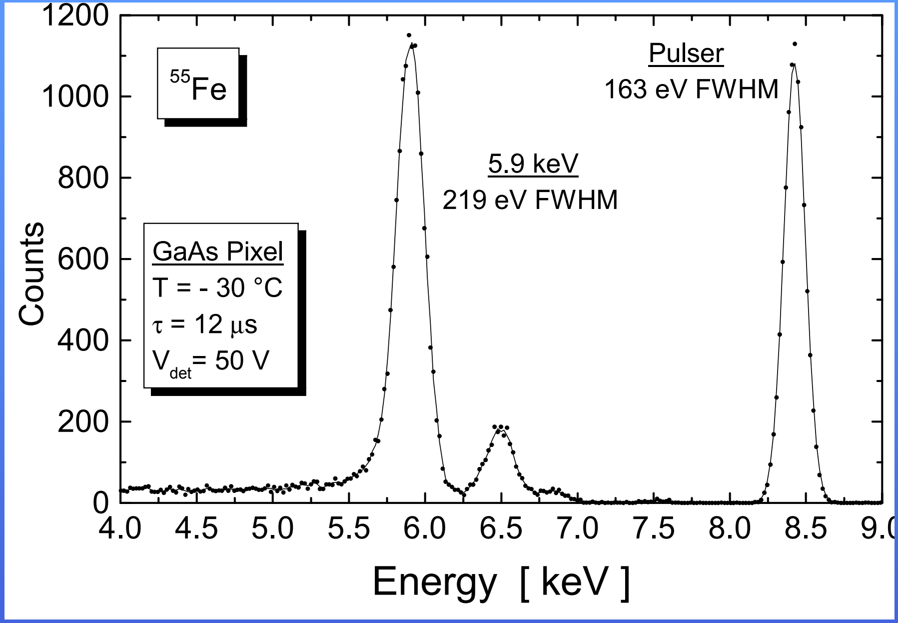
16 electrons r.m.s. at +20°C

14 electrons r.m.s. at -30°C

Which are the limits ?

Can we hope higher resolution ?





Room temperature (20°C)

242 eV FWHM (24 e^- r.m.s.)

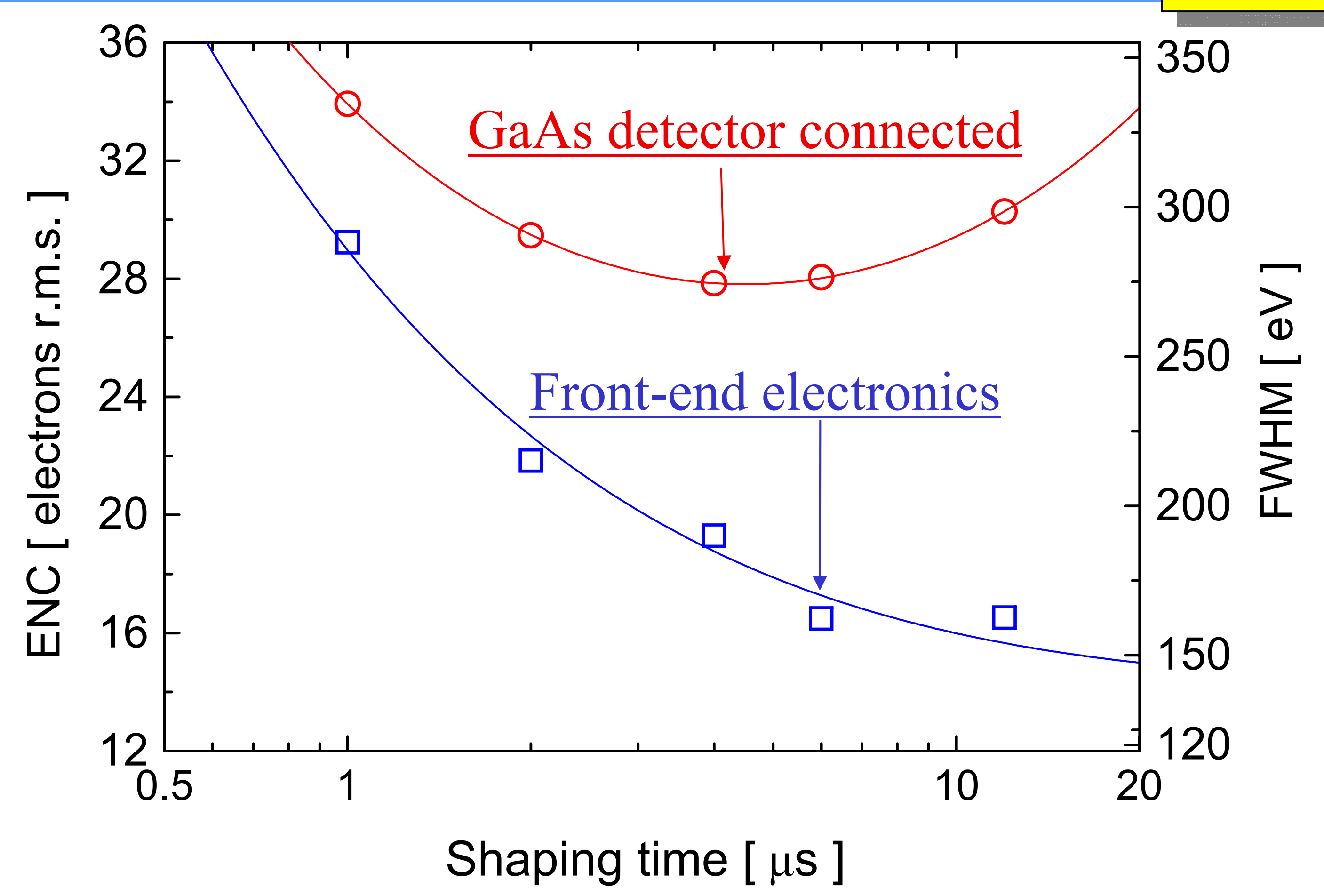
Thermoelectric cooling (-30°C)

163 eV FWHM (16 e^- r.m.s.)

Trans. Nucl. Sci. 50, 2003

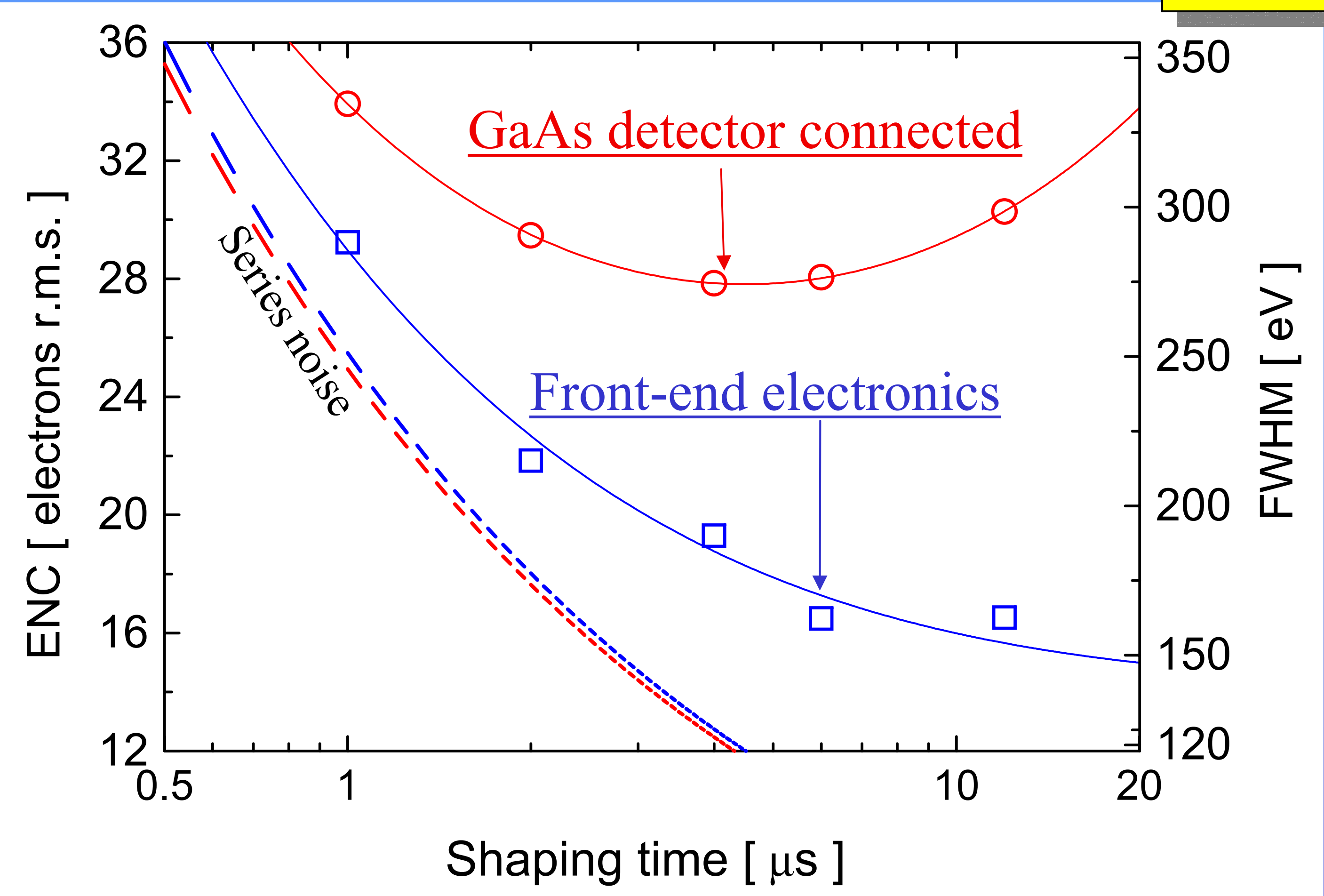
Noise Components Analysis

20 °C



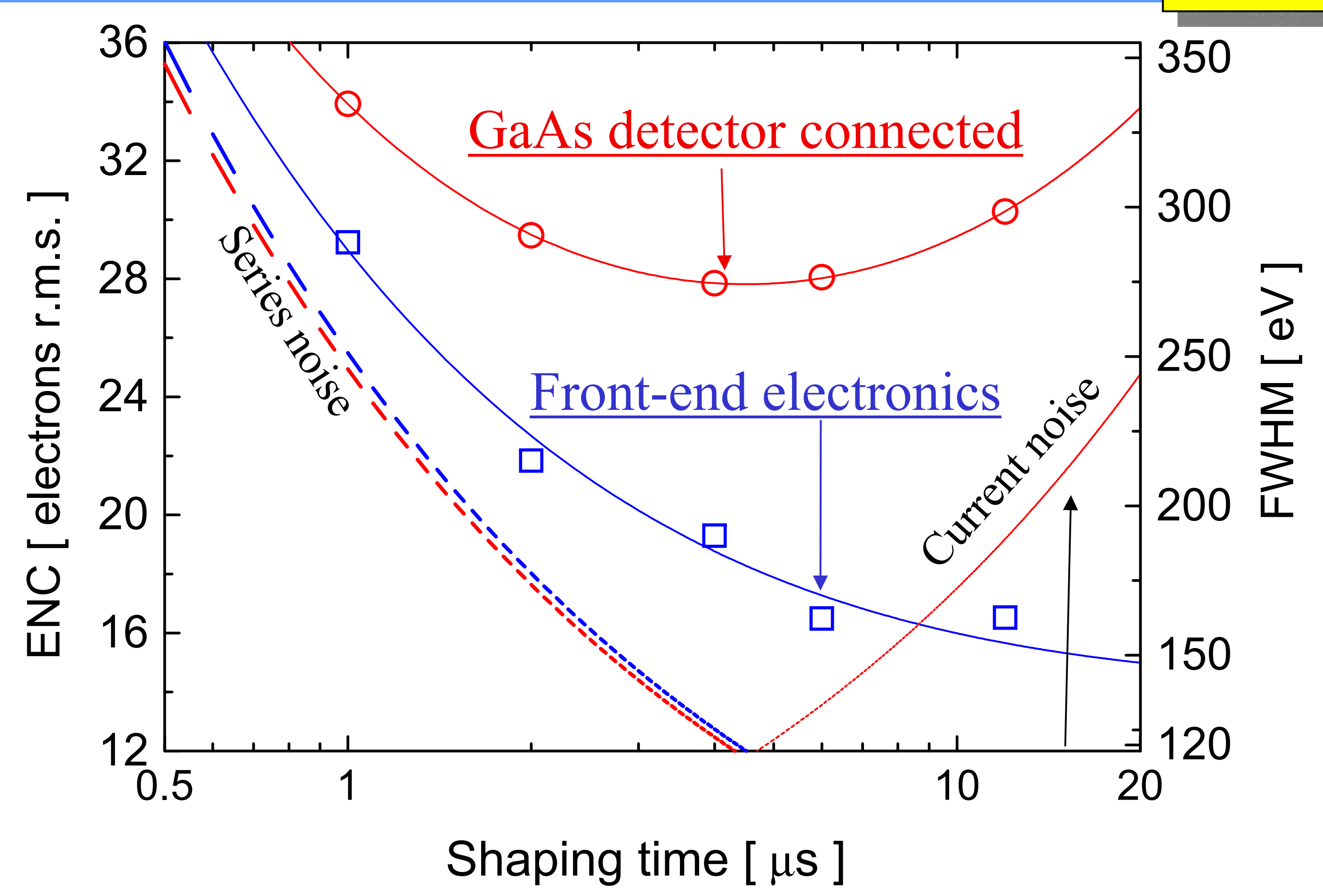
Noise Components Analysis

20 °C



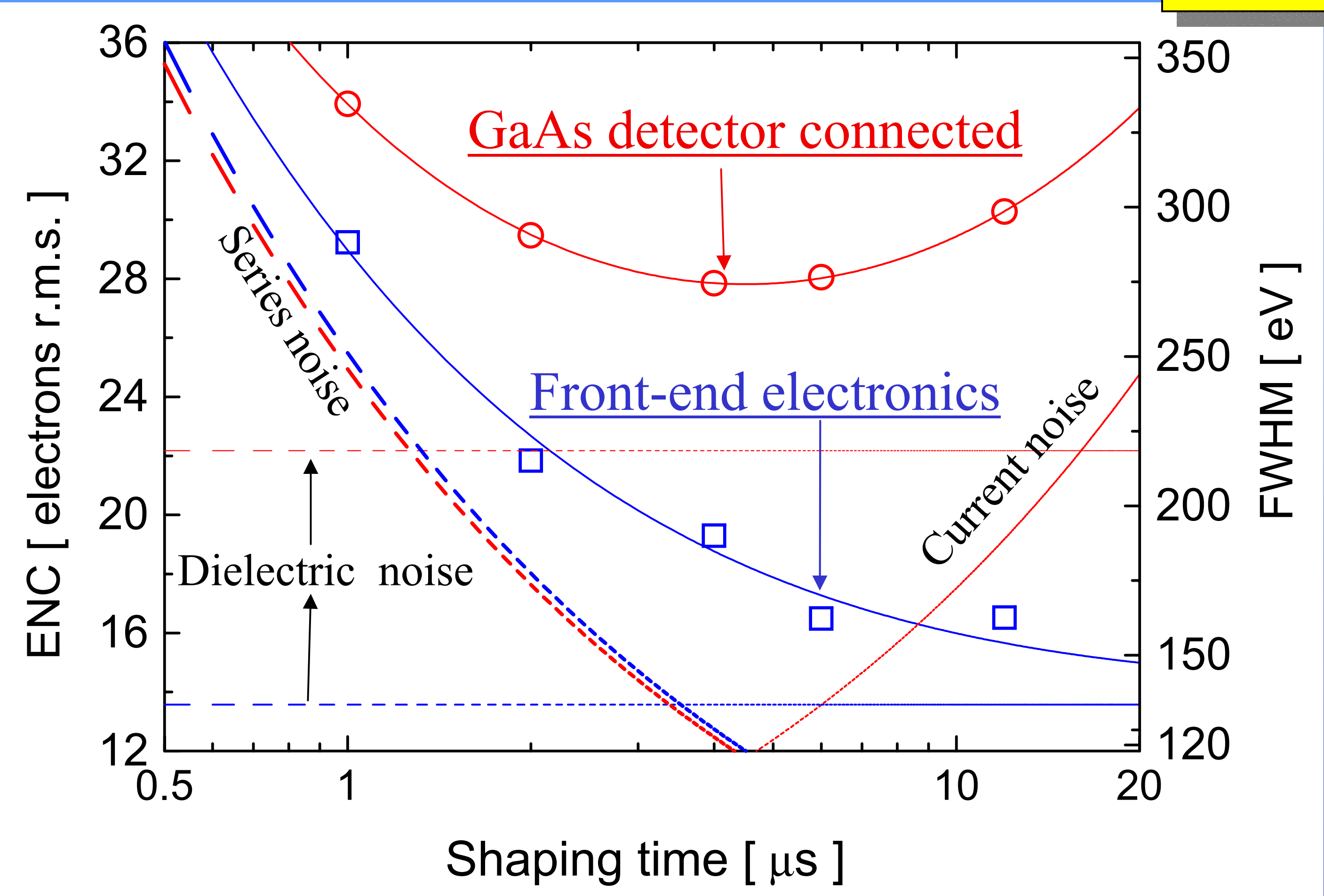
Noise Components Analysis

20 °C



Noise Components Analysis

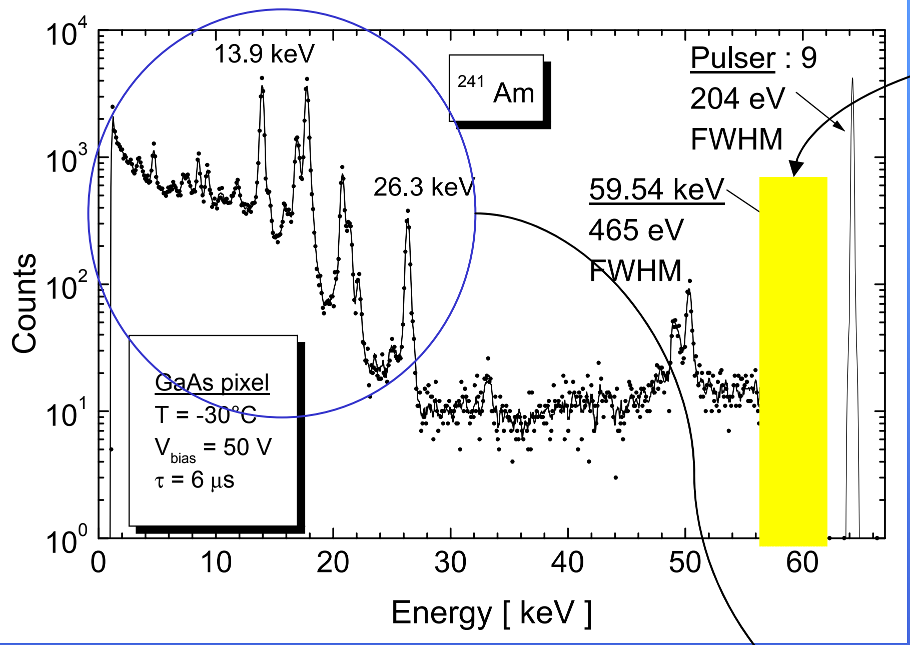
20 °C



X-γ Ray Spectroscopy with epi-GaAs pixels detectors

Results

X-γ Ray Spectroscopy with GaAs



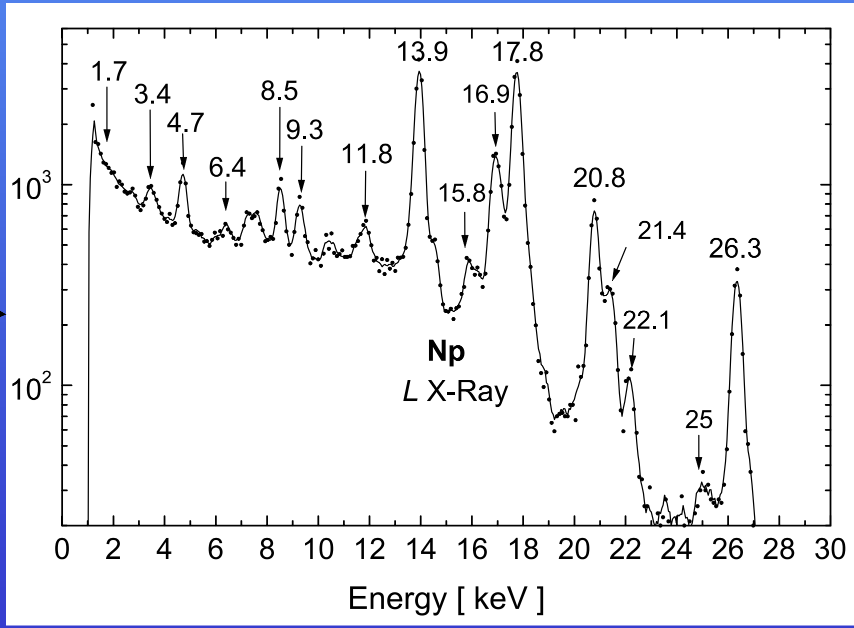
465 eV FWHM @ 59.5 keV

(Fano limit: 410 eV FWHM)

T = -30°C

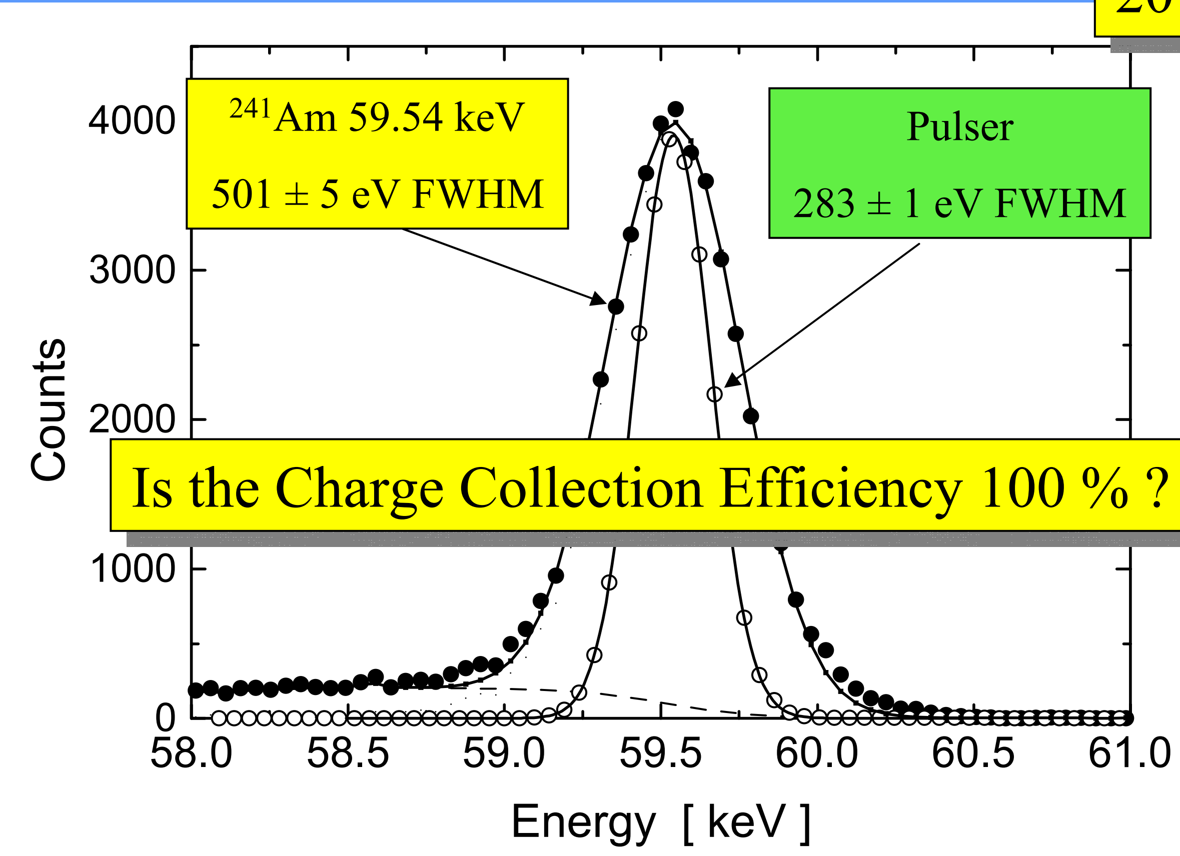
ENE = 204 eV FWHM

(20 e- r.m.s.)



59.5 keV line analysis

20 °C



Is the Charge Collection Efficiency 100 % ?

- No significant charge trapping
- Fano factor : F = 0.124 ± 0.004

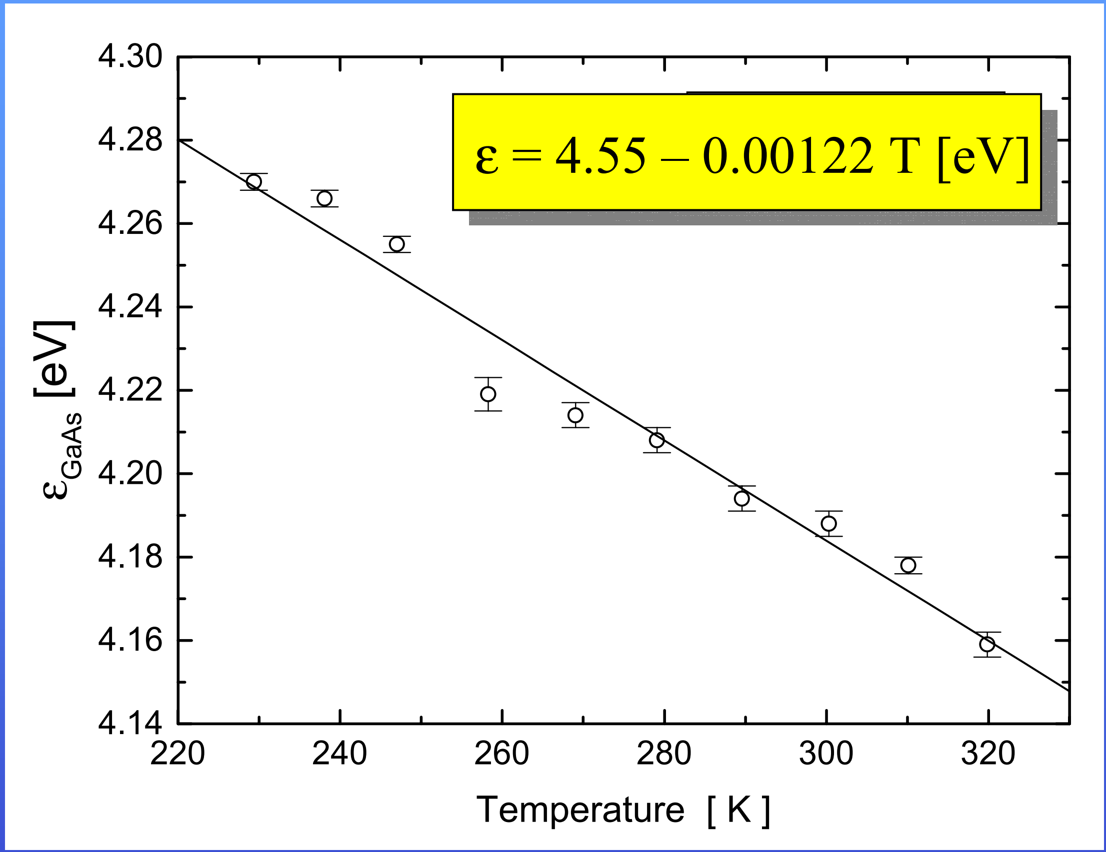
Charge trapping in GaAs detectors

$$CCE = \frac{Q_{\text{ind}}}{Q_{\text{gen}}}$$

$$Q_{\text{gen}} = \frac{E_{\text{ph}}}{\varepsilon}$$

Accurate knowledge
of the electron-hole pair generation energy
required

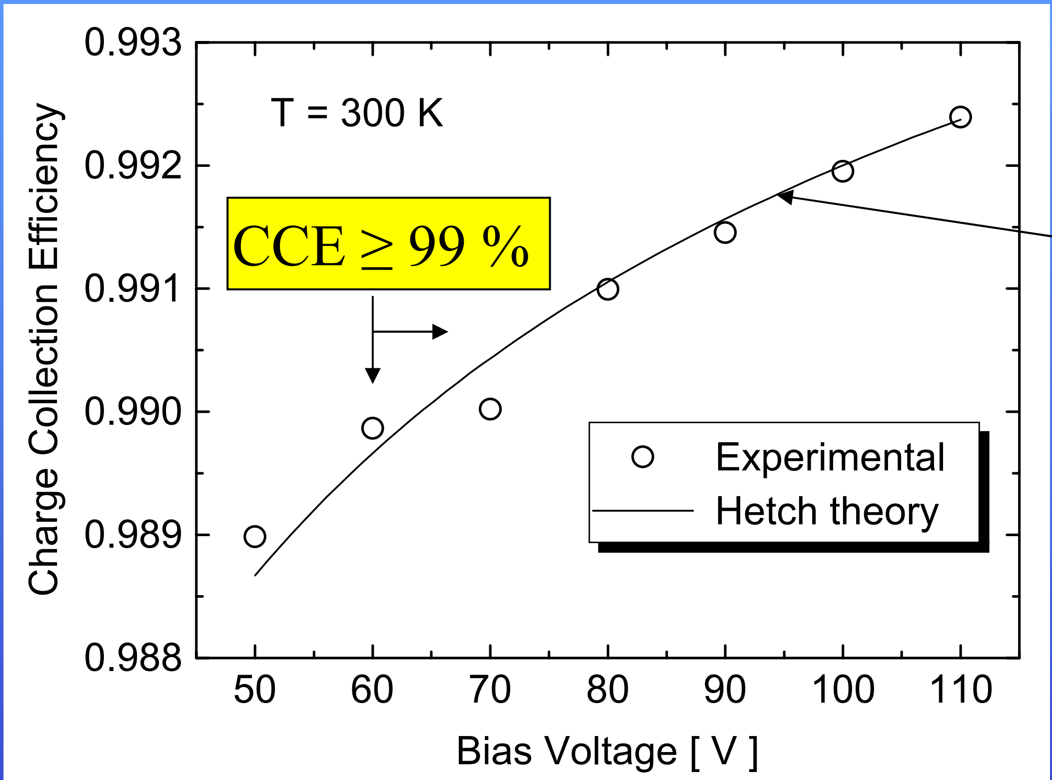
Generation Energy in GaAs



300 K : $\varepsilon = 4.18 \pm 0.02$ eV

Bertuccio, Maiocchi, JAP 92, 2002

Charge Collection Efficiency



$$CCE = \frac{\lambda_e + \lambda_h}{W}\left(1 - e^{-\frac{W}{\lambda_e + \lambda_h}}\right)$$

$$\lambda_e + \lambda_h = 1400\ \mu m\ @\ 110\ V$$

Conclusions on tested GaAs pixel

- High resolution with epi-GaAs pixels
  - 242 eV FWHM @ 20°C
  - 163 eV FWHM @ -30°C

Conclusions on tested GaAs pixel

- High resolution with epi-GaAs pixels
  - 242 eV FWHM @ 20°C
  - 163 eV FWHM @ -30°C
- Main noise component: dielectrics (with discrete electronics)

Conclusions on tested GaAs pixel

- High resolution with epi-GaAs pixels
  - 242 eV FWHM @ 20°C
  - 163 eV FWHM @ -30°C
- Main noise component: dielectrics (with discrete electronics)
- Leakage current density: $\leq$ 10 nA/cm^2 @ 20°C

Conclusions on tested GaAs pixel

- High resolution with epi-GaAs pixels
  - 242 eV FWHM @ 20°C
  - 163 eV FWHM @ -30°C
- Main noise component: dielectrics (with discrete electronics)
- Leakage current density: $\leq$ 10 nA/cm^2 @ 20°C
- Mean drift length: up to 1.4 mm (CCE>99 % for 30 μm)

Conclusions on tested GaAs pixel

- High resolution with epi-GaAs pixels
  - 242 eV FWHM @ 20°C
  - 163 eV FWHM @ -30°C
- Main noise component: dielectrics (with discrete electronics)
- Leakage current density: $\leq$ 10 nA/cm^2 @ 20°C
- Mean drift length: up to 1.4 mm (CCE>99 % for 30 μm)
- Limits: depletion layer depth (detection efficiency)
  - residual doping 10^{14} cm^{-3}
  - Epi layer thickness: 40 μm

GaAs pixel detectors

Status

- Good Schottky and p^+n junction detectors exists !
- Epitaxial thickness >300 μm has been grown (Poster: Glasgow-Paris)

GaAs pixel detectors

Status

- Good Schottky and p^+n junction detectors exists !
- Epitaxial thickness >300 μm has been grown (Poster: Glasgow-Paris)

Prospects

- Energy resolution of 180 eV FWHM are reachable at 20°C
- Residual doping $\leq 10^{13}$ cm^{-3} required
- Integrated spectroscopic-grade front-end electronic required

GaAs pixel detectors

Status

- Good Schottky and p^+n junction detectors exists !
- Epitaxial thickness >300 µm has been grown (Poster : Glasgow-Paris)

Prospects

- Energy resolution of 180 eV FWHM are reachable at 20°C
- Residual doping $\leq 10^{13}$ cm^{-3} required

Integrated spectroscopic-grade front-end electronic required

A Finmeccanica Company

Large Format Detector Readout ASIC

D. Martin, A. Owens

EUROPEAN SPACE AGENCY, ESA-ESTEC - Noordwjik (NL)

Supervision

P. Bastia, I. Cappelluti, F. Ferrari, N. Ratti

ALENIA SPAZIO s.p.a. - LABEN - MILANO (I)

Readout system & coordination

P. Malcovati, F. Borghetti, V. Ferragina

PAVIA UNIVERSITY (I)

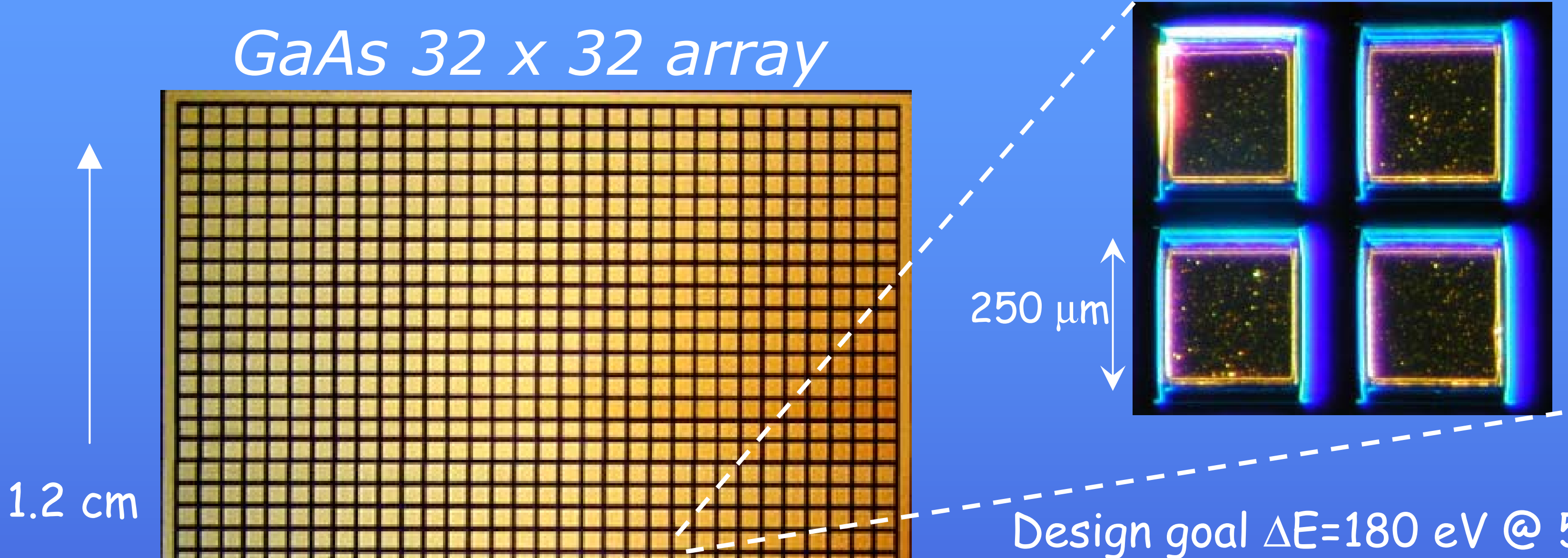
Back-end design

G. Bertuccio, S. Caccia, D. Maiocchi, A. Pullia

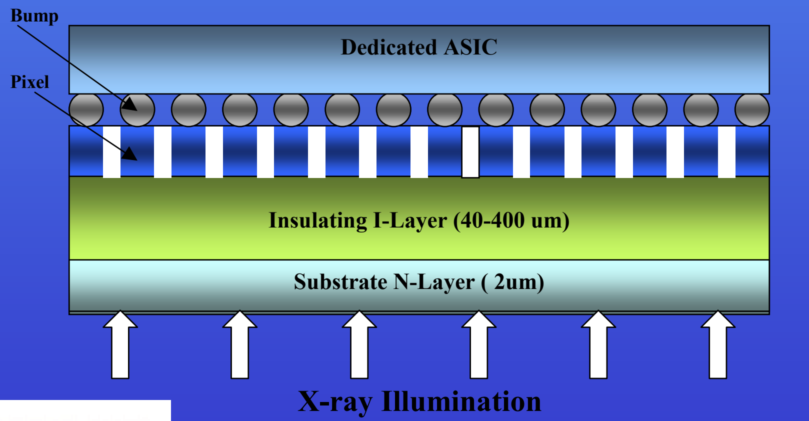
POLITECNICO DI MILANO (I)

Front-end design

LFDR ASIC for GaAs Pixels



Design goal ΔE=180 eV @ 5.9 keV



esa metorex

A Finmeccanica Company

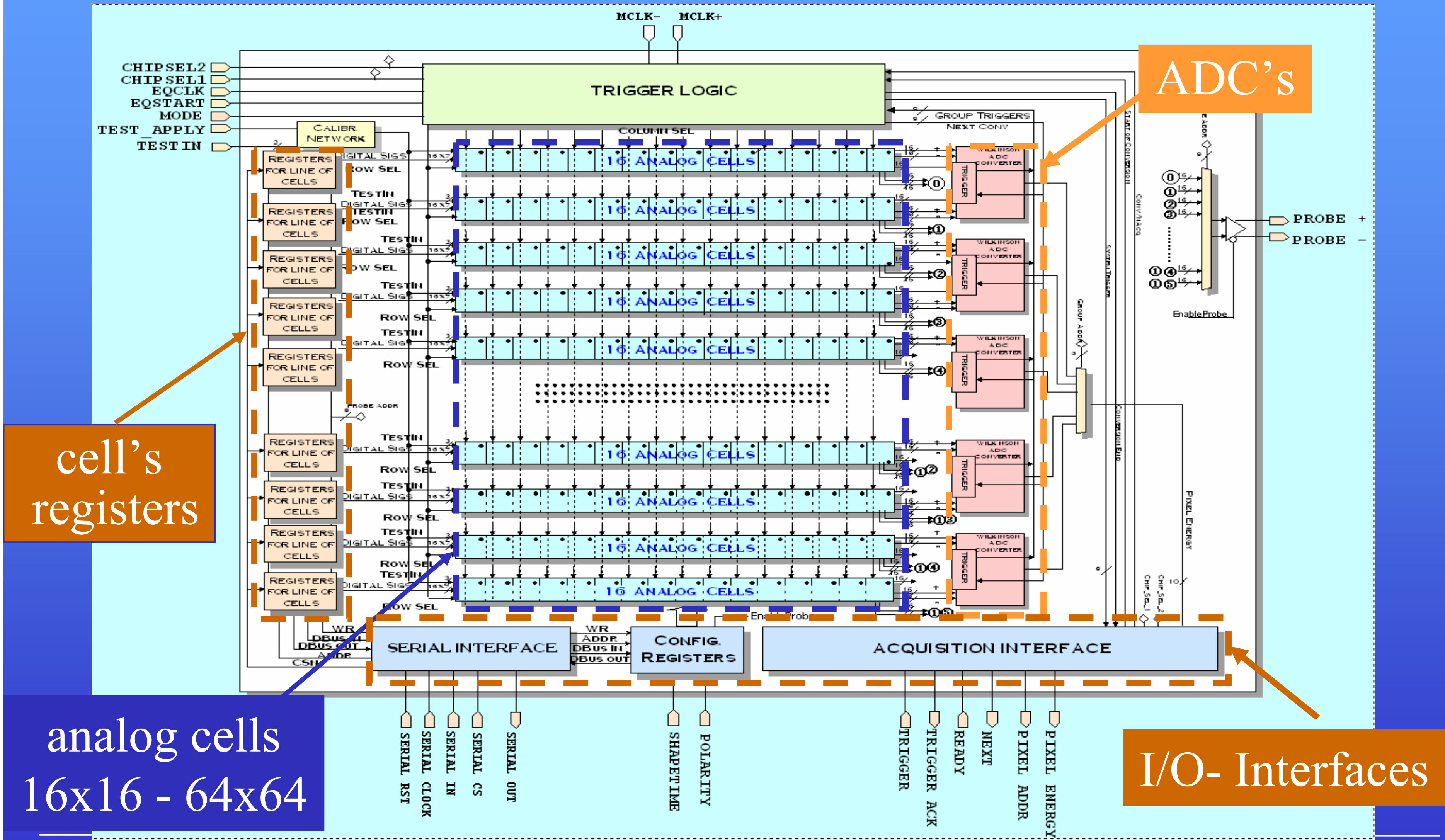
POLITECNICO DI MILANO

UNIVERSITÁ DEGLI STUDI DI PAVIA

LFDR ASIC (designed – in production)

- 0.35 µm CMOS (AMS)
- 16 x 16, 32x32, 64x64 pixel channels
- 300 x 300 µm^2 channel size
- Complete: Preamplifier → ADC
- Spectroscopic grade - 500 µW/channel (simulated)
- 30 electrons r.m.s. @ 20°C (simulated)

LFDR : ASIC Block diagram



G. Bertuccio

"Prospects for Energy Resolving X-ray Imaging with Compound Semiconductor Pixel Detectors"
6th International Workshop on Radiation Imaging Detectors - IWORID-2004, July 25-29 , Glasgow (Scotland).

Silicon Carbide

X-Ray Detectors

Silicon Carbide

X-Ray Detectors

- Introduction on SiC

Silicon Carbide
X-Ray Detectors

- Introduction on SiC
- Prototype detectors

Silicon Carbide
X-Ray Detectors

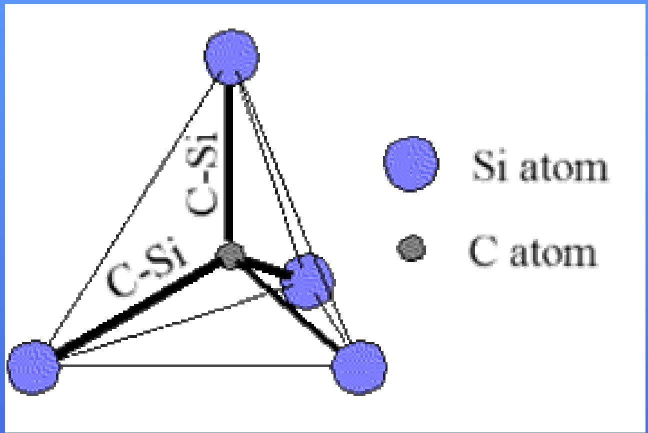
- Introduction on SiC
- Prototype detectors
- X-ray spectroscopy at room temperature…and above

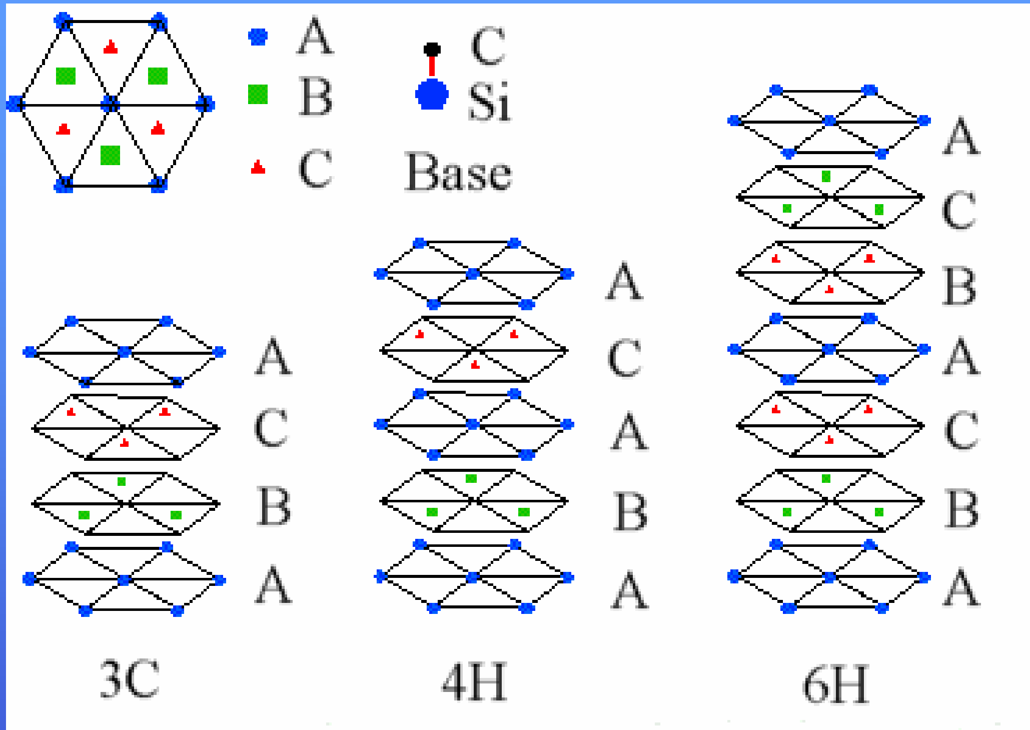
Silicon Carbide

X-Ray Detectors

- Introduction on SiC
- Prototype detectors
- X-ray spectroscopy at room temperature…and above
- SiC Pixel detectors: a *sub-electron* electronic noise device

SiC politypes





3C-SiC (E_G = 2.2 eV)

4H-SiC (E_G = 3.3 eV)

6H-SiC (E_G = 3 eV)

SiC properties

Wide Bandgap

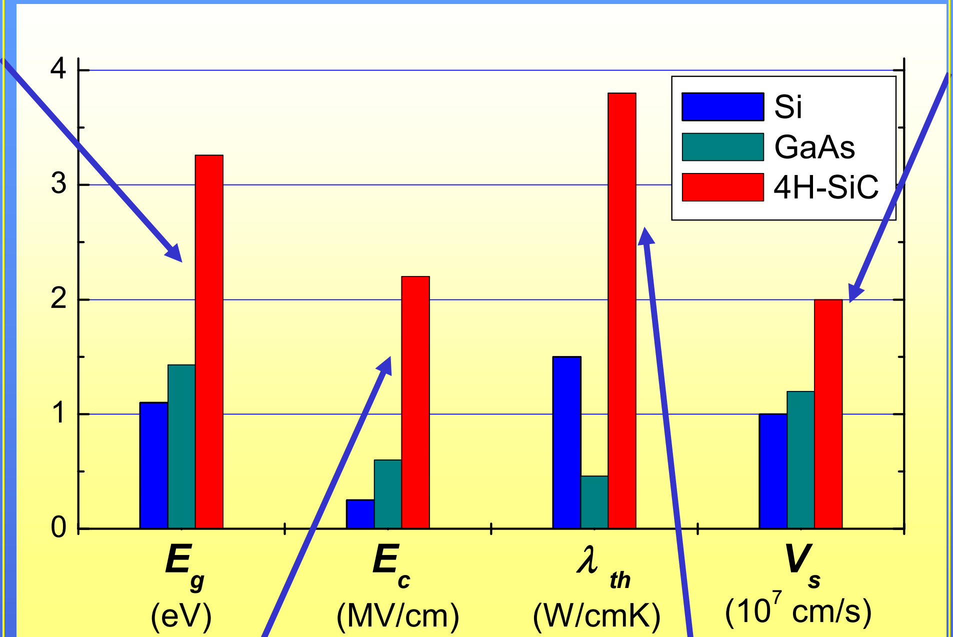
E_G=3.2 eV

⇓

Low thermally generated currents

⇓

Room temperature operation



High saturation velocity

v_S = 200 µm/ns

⇓

High frequency/speed devices

⇓

Short transit time

Low trapping probability

High Critical Field

E_C = 2 MV/cm

⇓

High Voltage devices

High thermal conductivity

⇓

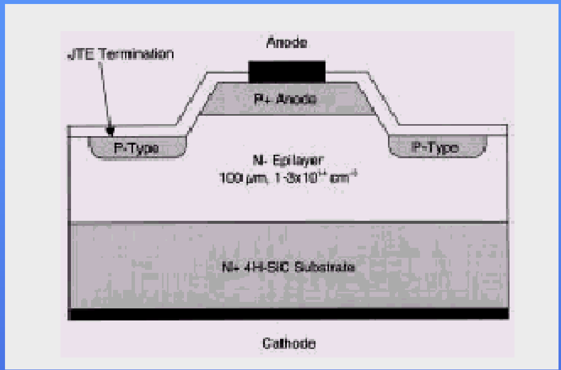
High Power devices

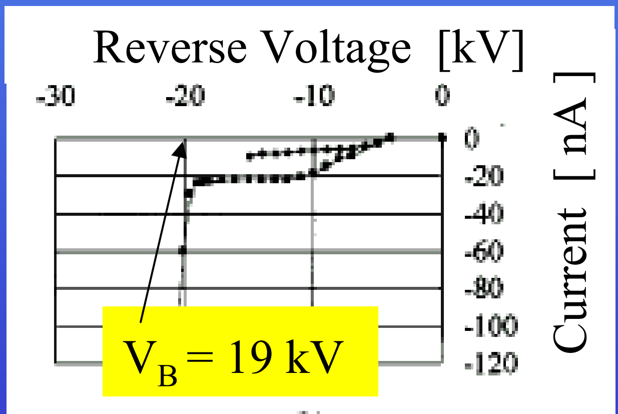
SiC High Performance Electron Devices…

...a reality

SiC High Performance Electron Devices

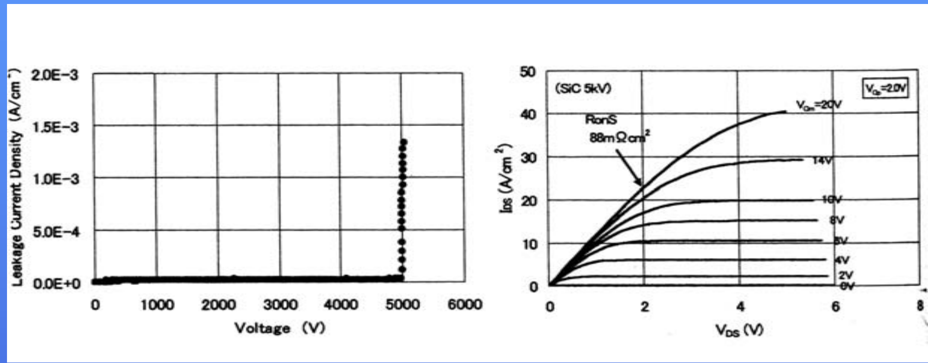
The highest V_B diode



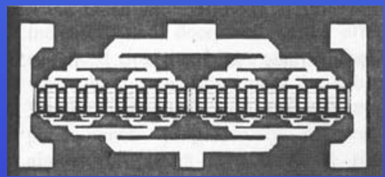


$V_B = 19$ kV

Power MOSFET: 5 kV - 88 mΩ cm^2



High Power X-Band MESFET



f_T=14.5 GHz, f_{MAX}=38 GHz

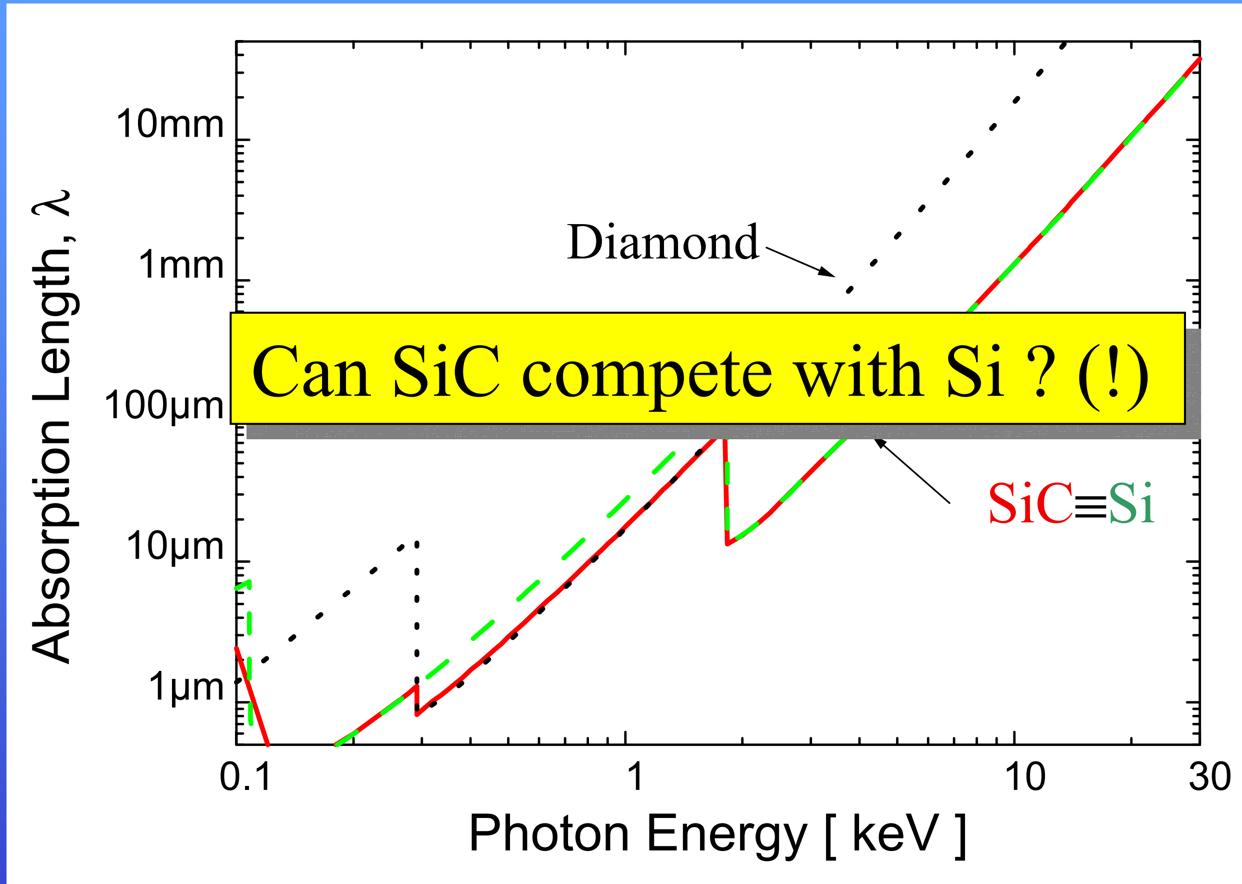
I_{Dmax}= 400 mA, V_{DSmax}=150V

Gain: 16 dB @ 2 GHz

Would SiC be advantageus

for X-Ray Spectroscopy and Imaging ?

Soft X-ray Absorption length



$$\lambda_{SiC} \leq \lambda_{Si}$$

Electron-hole pairs : Signal !

$$Q = E_{ph} / \varepsilon$$

Semiconductor	E_{GAP}	ε	e-h pairs @ 10 keV
Ge	**0.7**	**3.0**	**3.3 k**
Si	**1.1**	**3.7**	**2.7 k**
GaAs	**1.4**	**4.2**	**2.4 k**
CdTe	**1.5**	**4.5**	**2.2 k**
4H-SiC	**3.3**	**7.8**	**1.3 k**

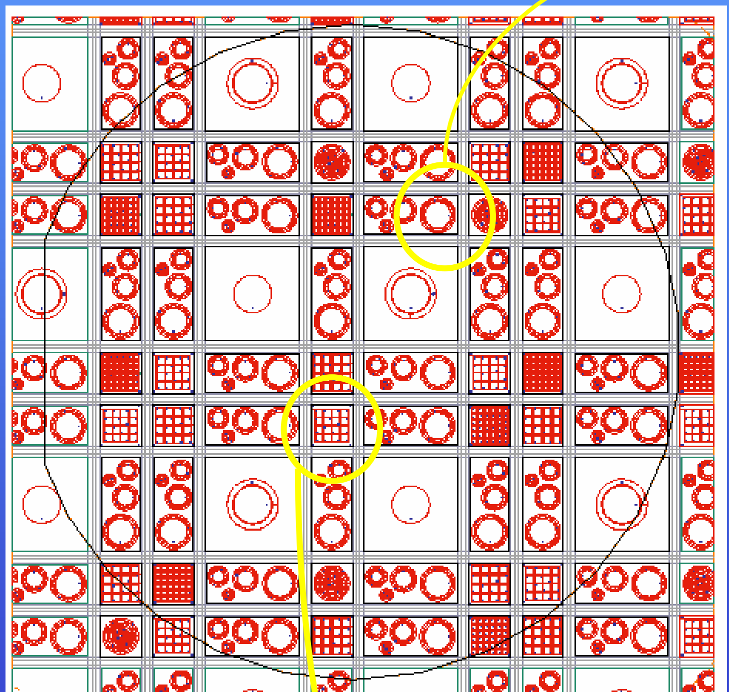
What about the SiC detector noise ?

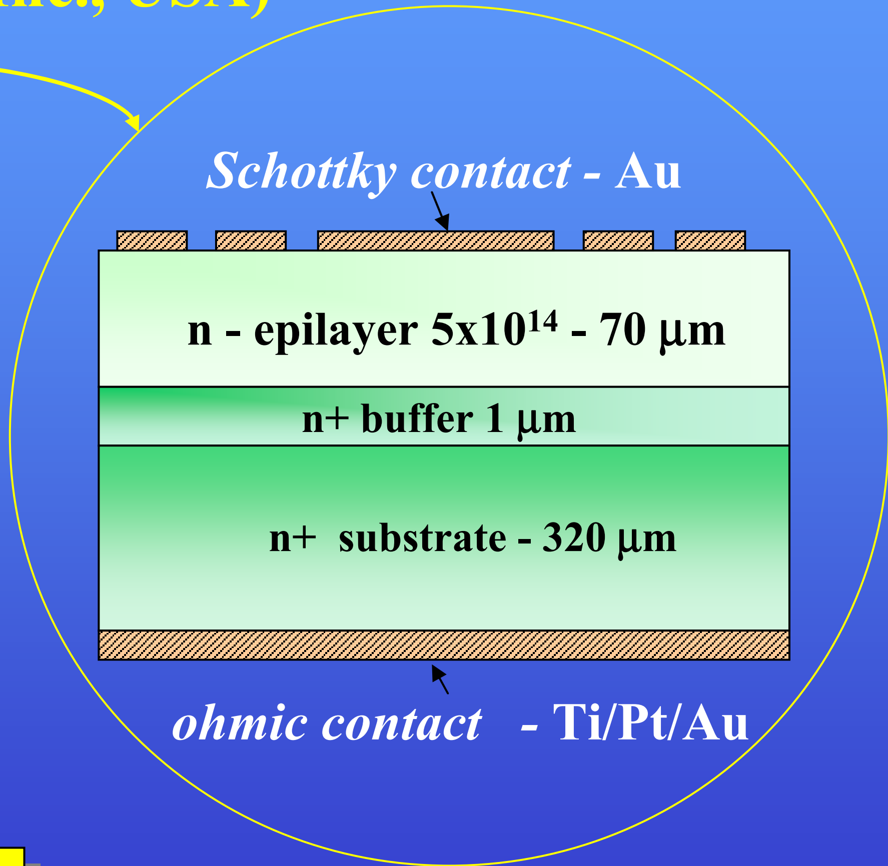
Detector noise sources

- Leakage current
- Carriers trapping phenomena
- Dielectric noise
- [Charge collection process (balistic deficit → signal reduction)]

Run of SiC X-Ray Detectors

(Technology: *Alenia Marconi Systems - Rome*)
(SiC wafers: CREE Inc., USA)

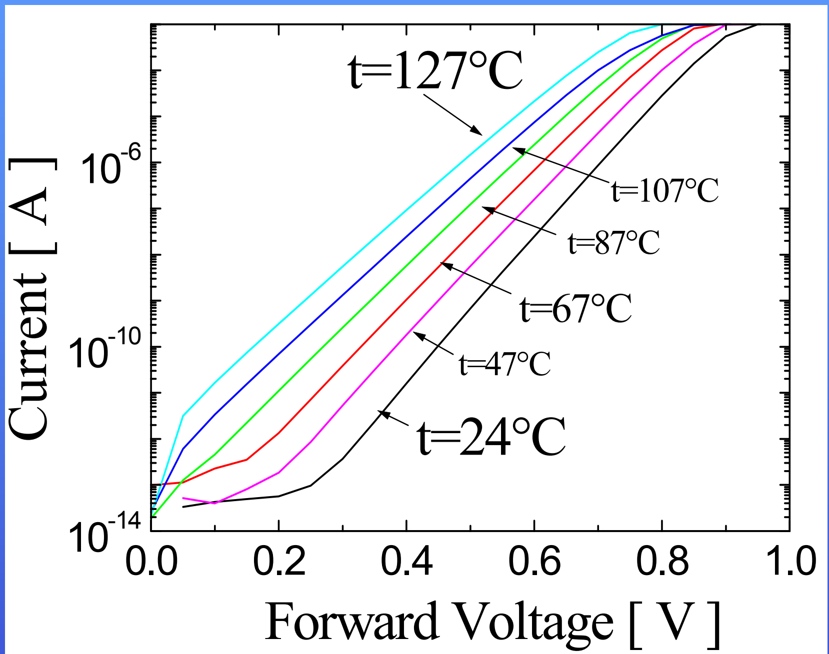




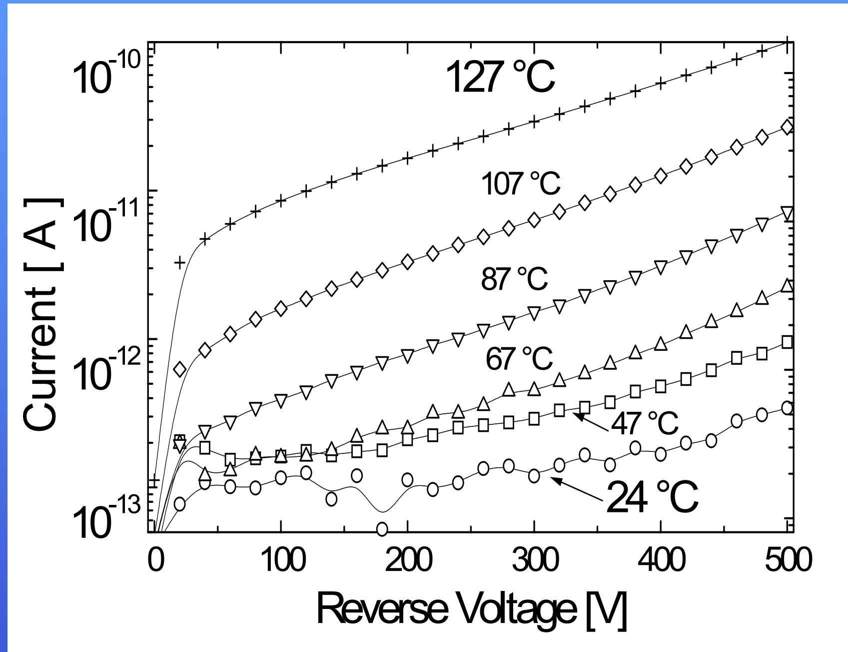
Array of pixels

I-V Characteristics

Forward bias



Reverse bias

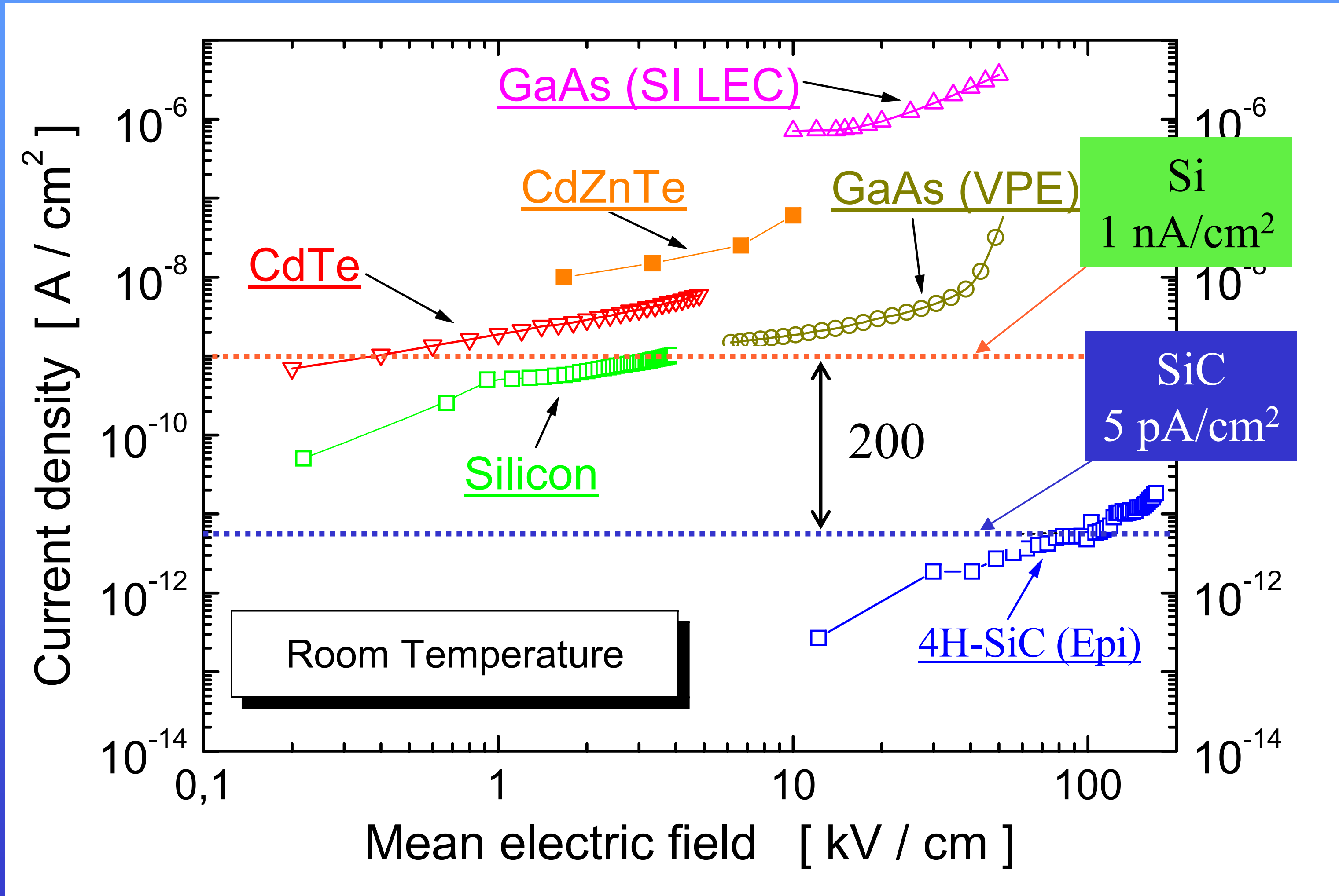


Schottky Barrier Height : Φ_b=1.16 eV

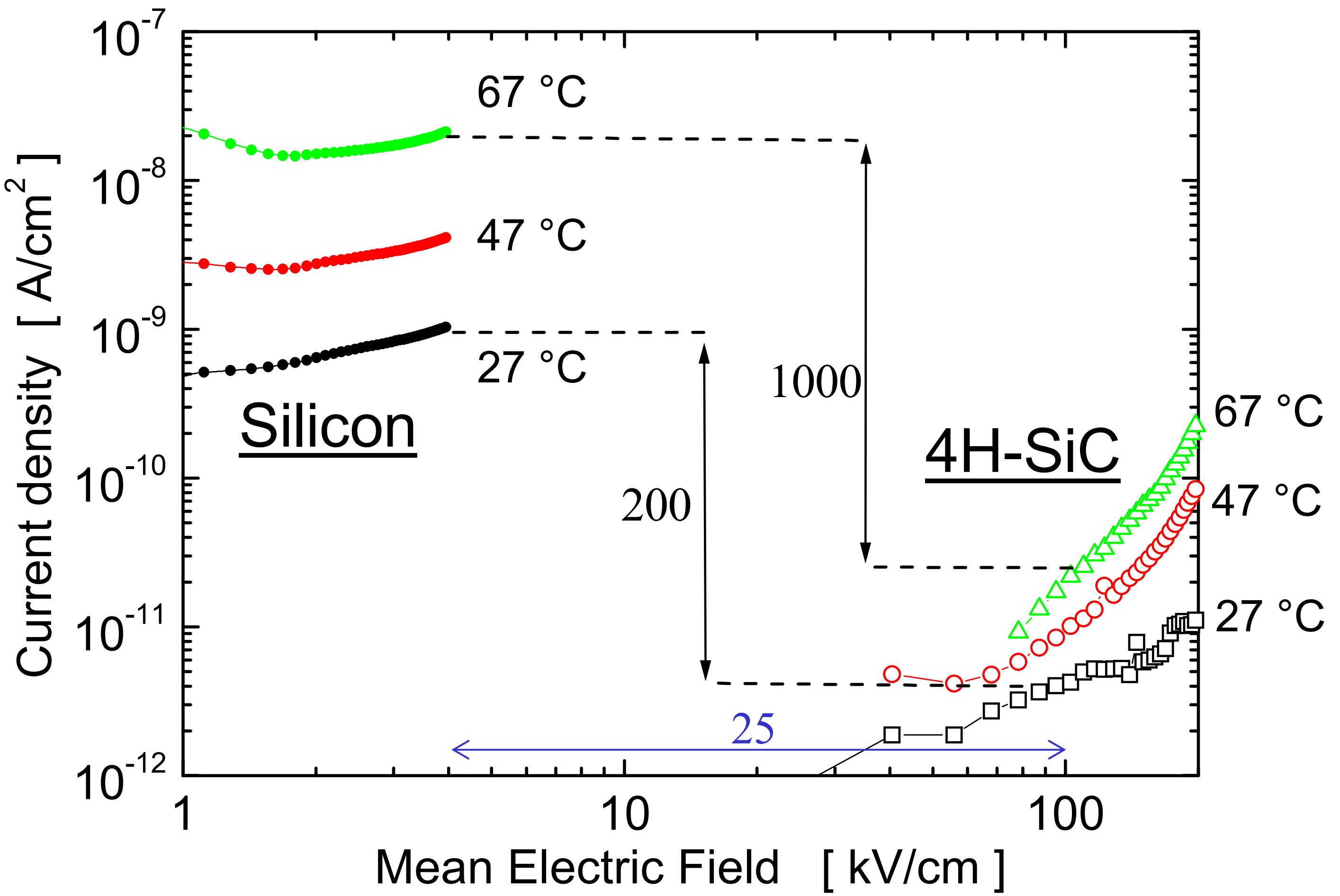
!!

Leakage Current Density

State of the art detectors



Temperature effect: SiC vs. Si



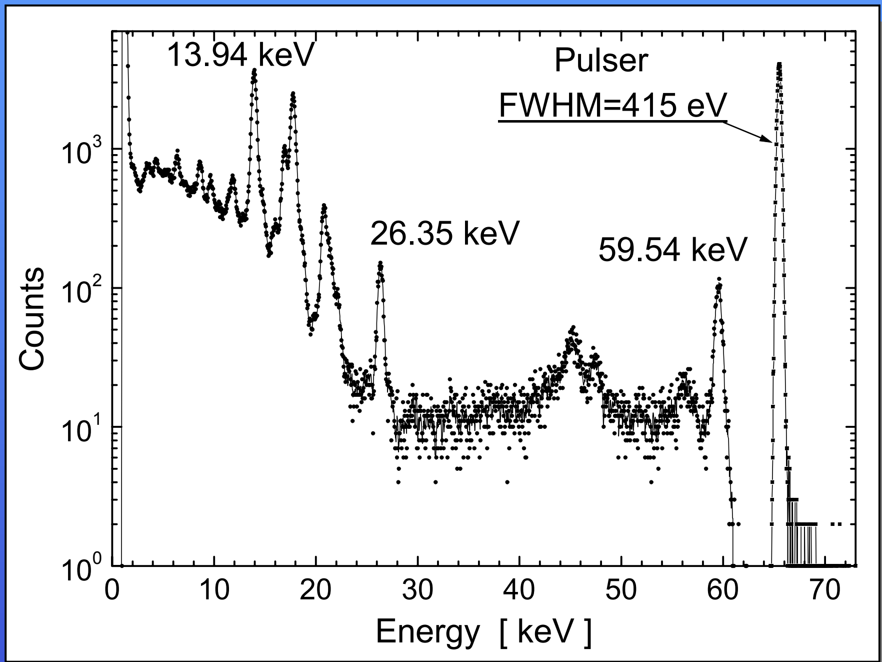
Experimental Results on SiC Detectors

Tested devices

- Pixel detector: area=0.03 mm^2 ; capacitance: 0.17 pF
- Pad detector : area= 0.3 mm^2 ; capacitance : 1.7 pF

SiC detectors at 27 °C (300 K)

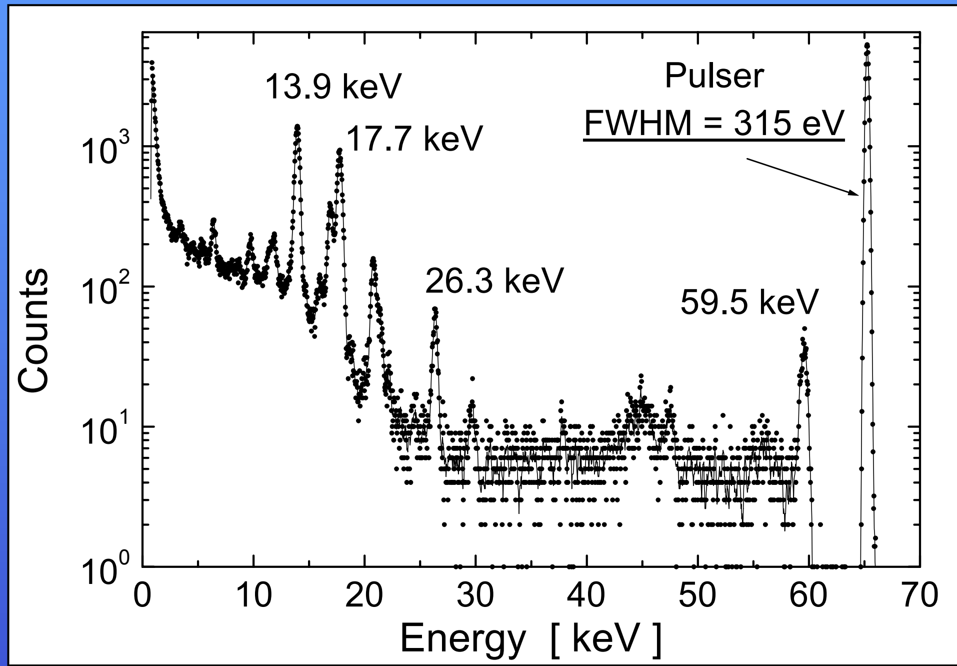
Pad : A=0.3 mm²



Energy resolution

415 eV FWHM (22 e⁻ r.m.s.)

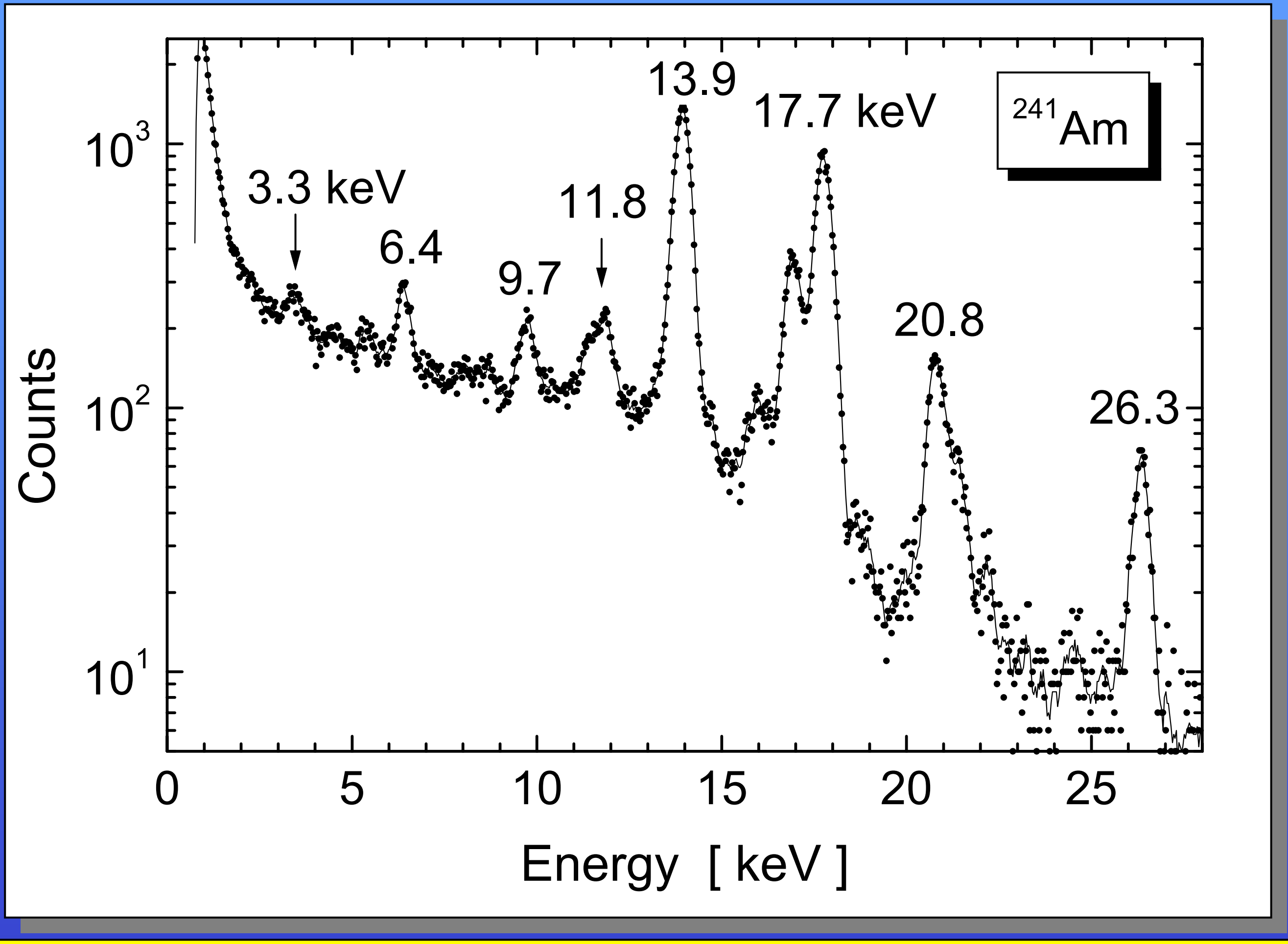
Pixel : A=0.03 mm²



Energy resolution

315 eV FWHM (17 e⁻ r.m.s.)

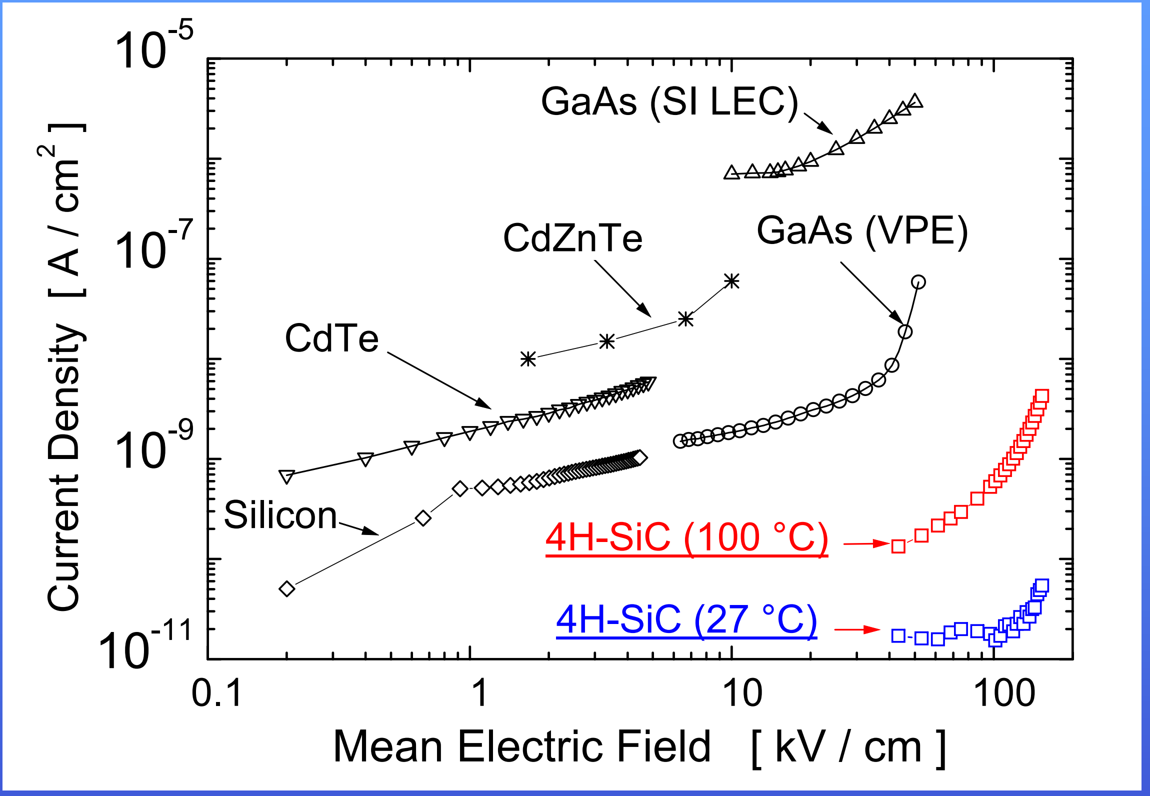
SiC pixel at 27 °C (300 K)



Energy resolution: 315 eV FWHM (17 e^- r.m.s.)

Beyond Room Temperature...

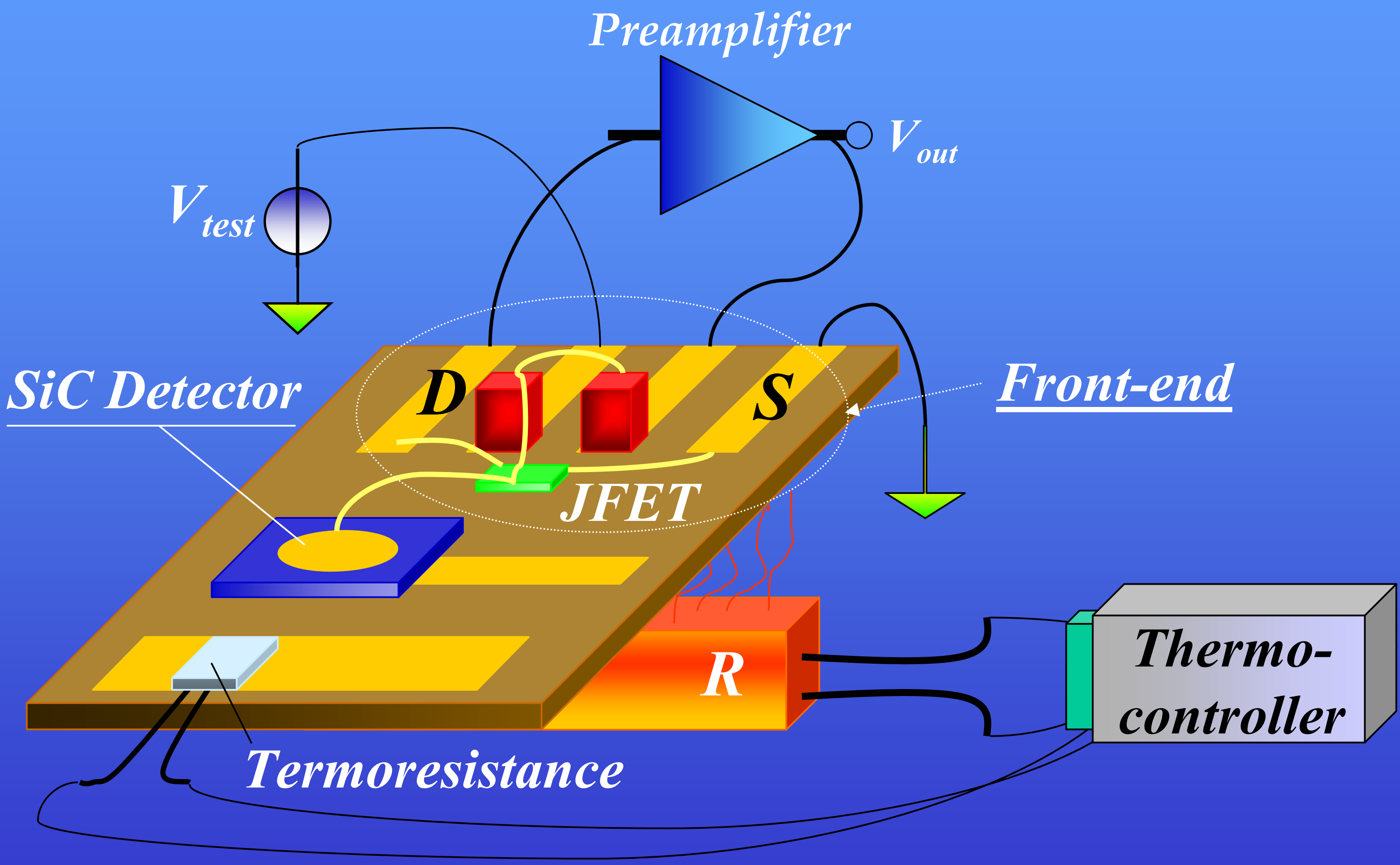
Operation beyond room temperature ?



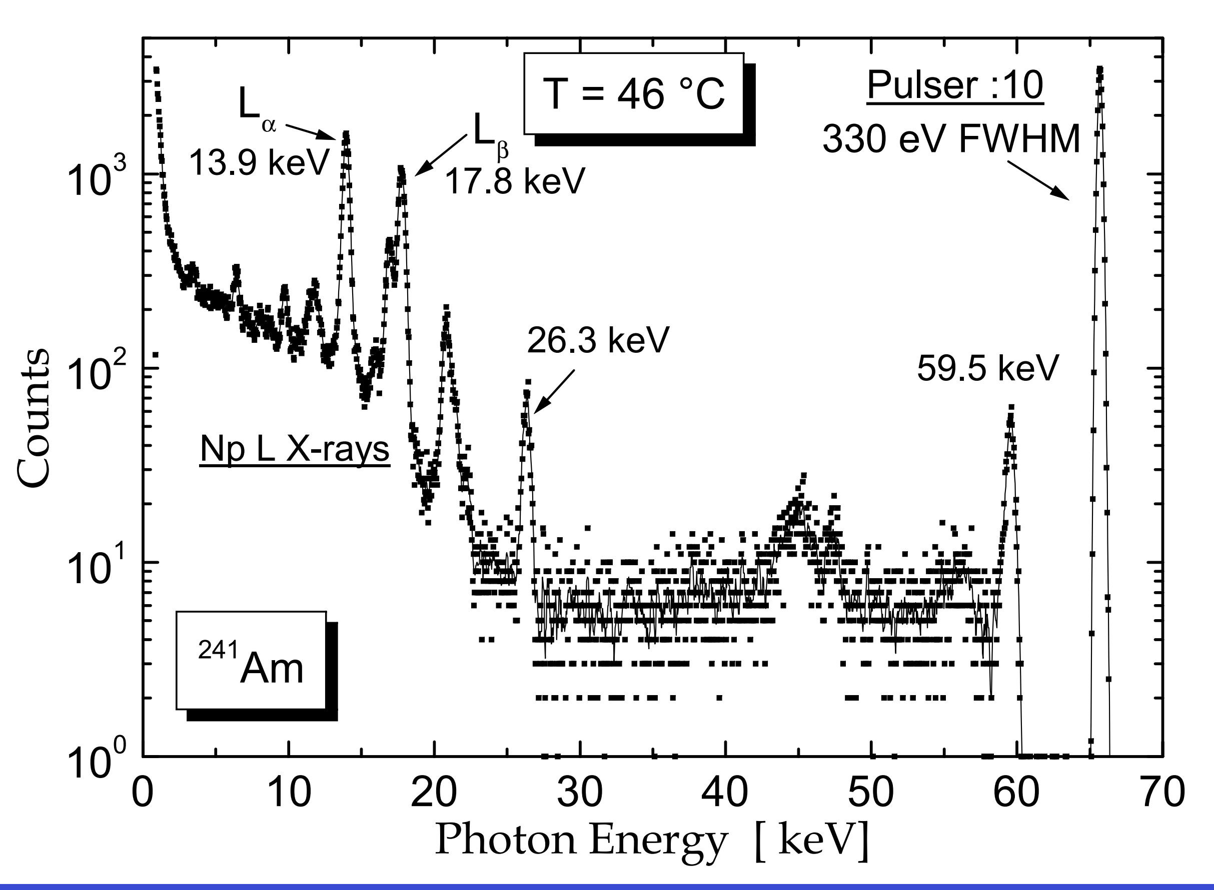
E= 100 kV/cm , T = 27 °C → J_R = 14 pA/cm^2

T = 100 °C → J_R = 0.5 nA/cm^2

High temperature set-up

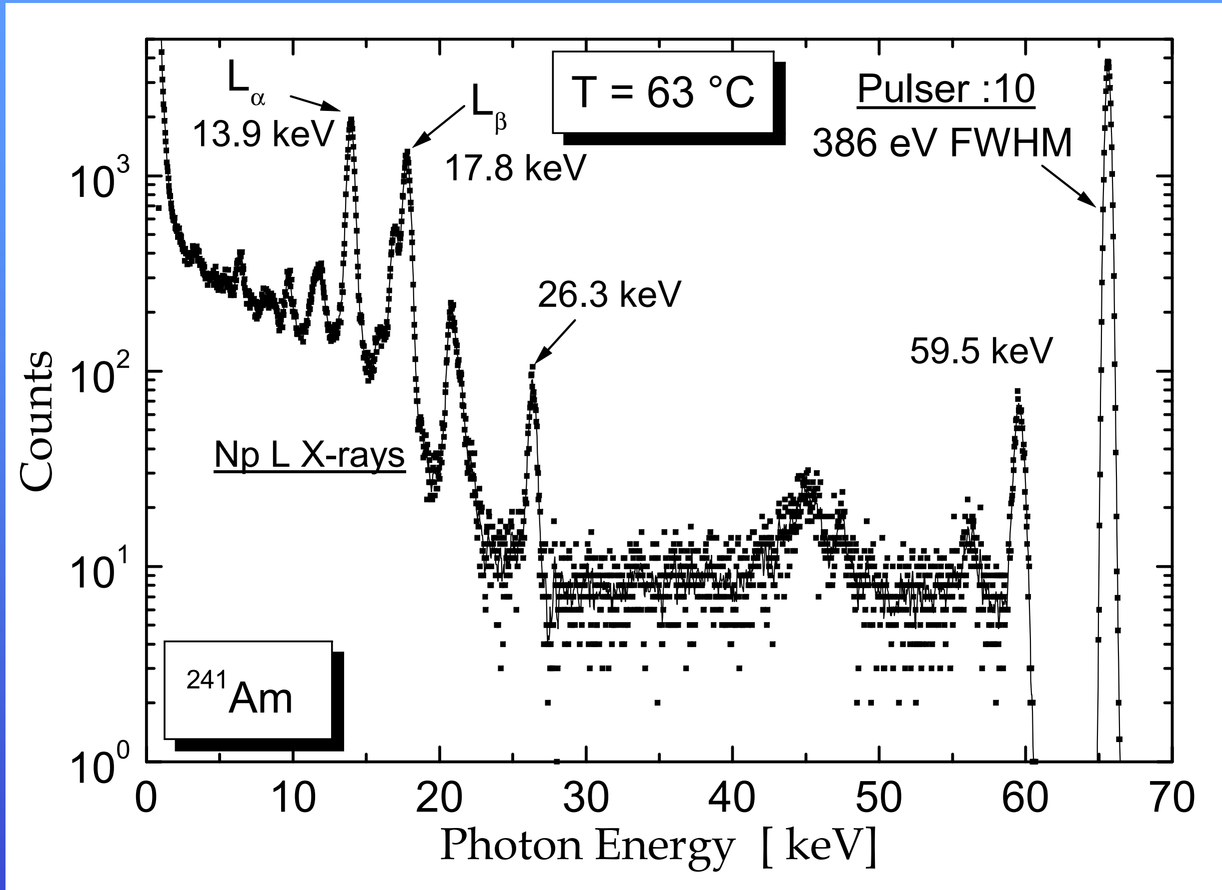


46 °C (319 K - 115 F)



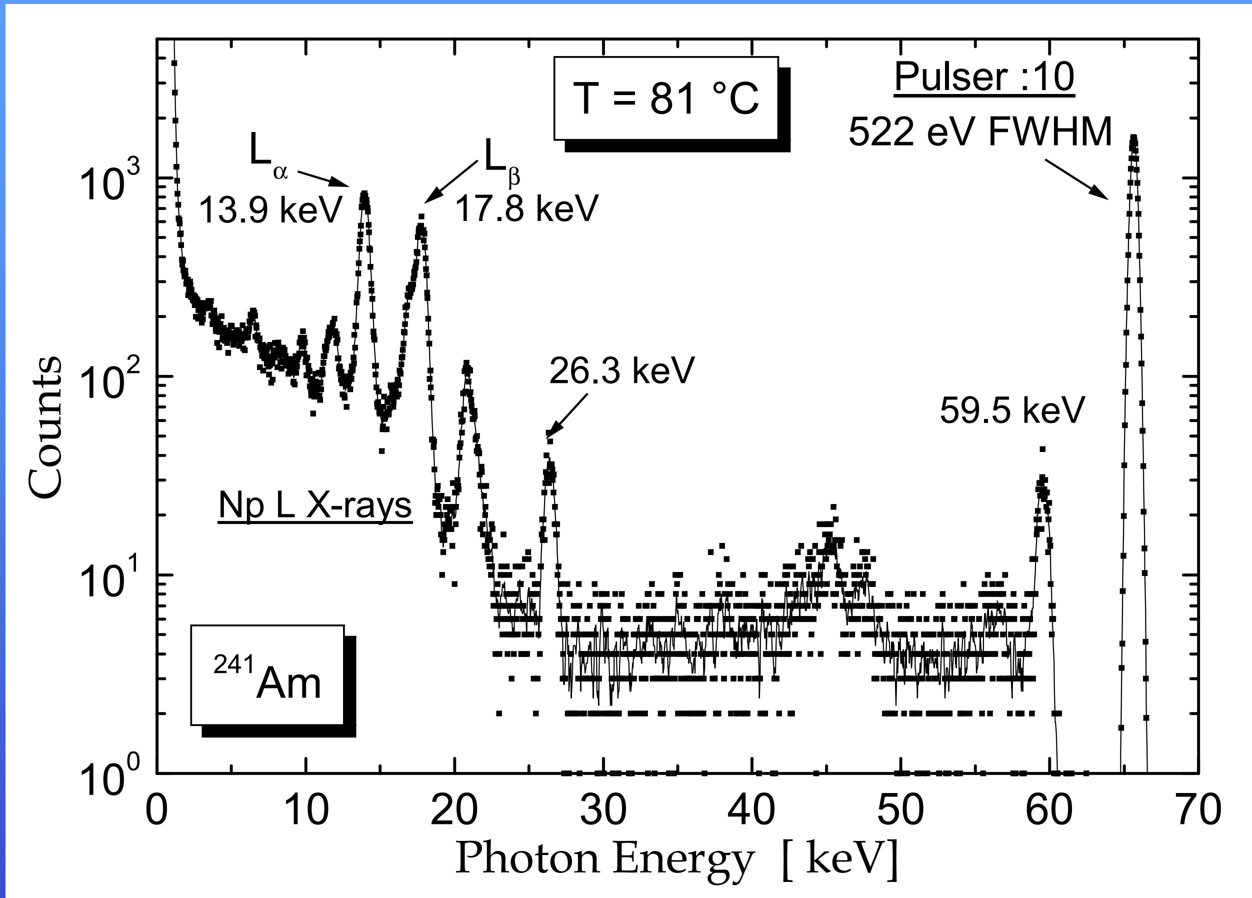
Energy resolution : 330 eV FWHM (18 e^- r.m.s.)

63 °C (336 K - 145 F)



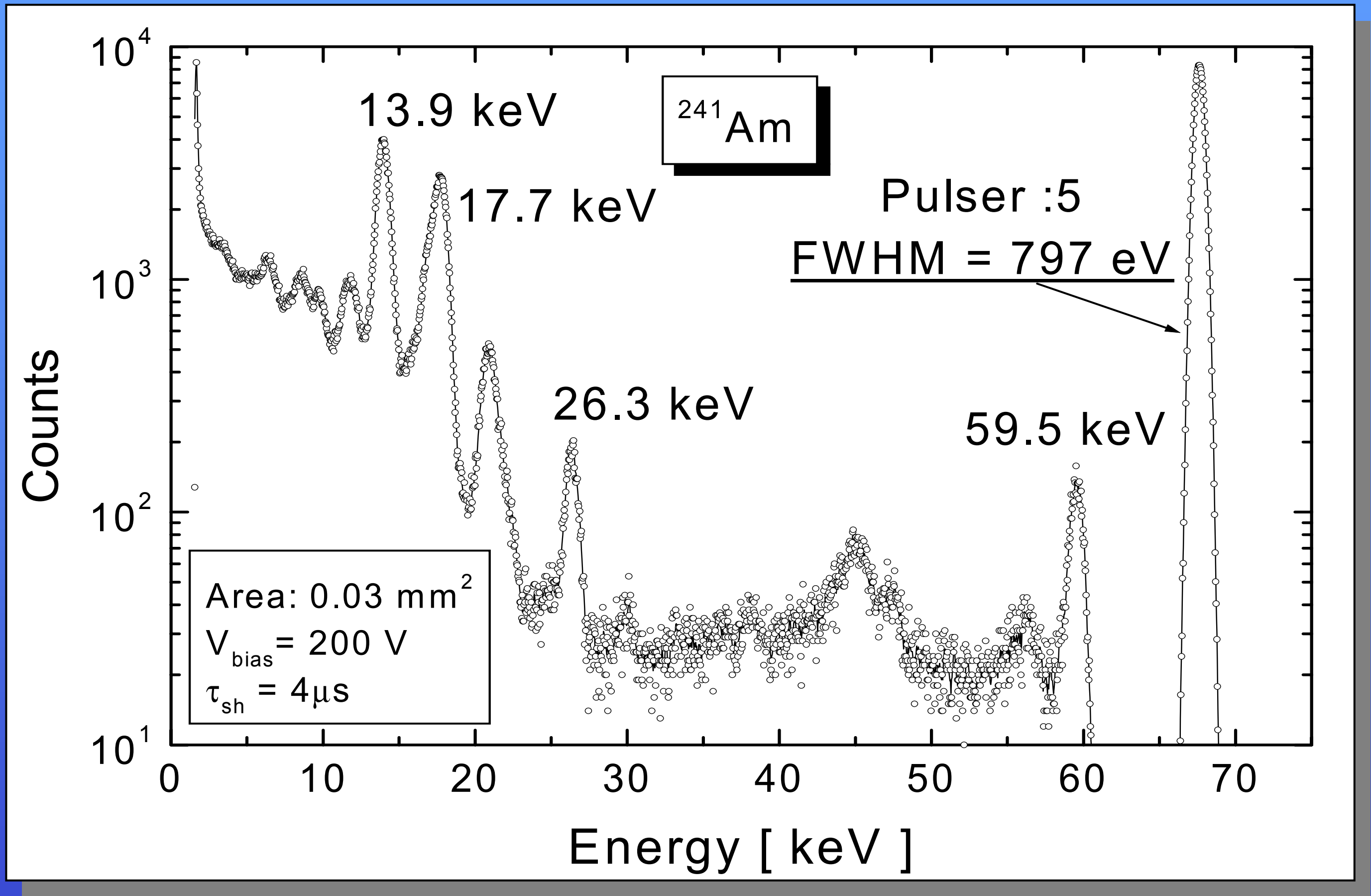
Energy resolution : 386 eV FWHM (21 e^- r.m.s.)

81 °C (354 K - 178 F)



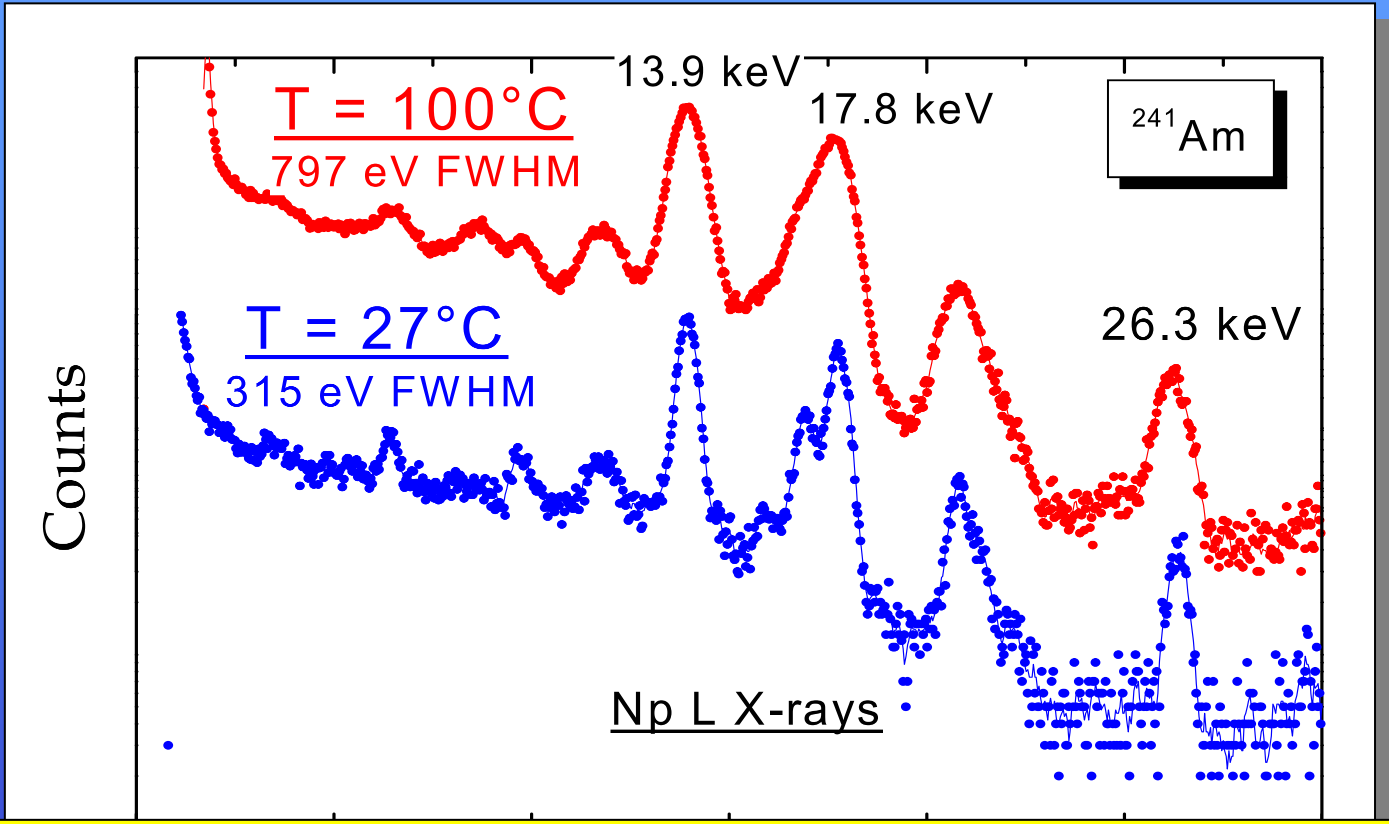
Energy resolution : 522 eV FWHM (28 e⁻ r.m.s.)

100 °C (473 K - 212 F)



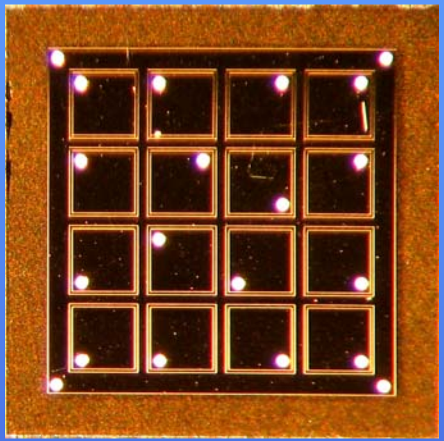
Energy resolution : 797 eV FWHM (43 e^- r.m.s.)

SiC pixel detector: from 27 °C to 100°C

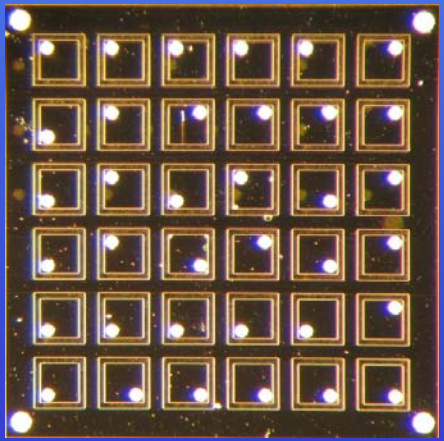


At high T the resolution is limited by the Front-end, NOT by the detector

Prototype of SiC Pixel Matrix

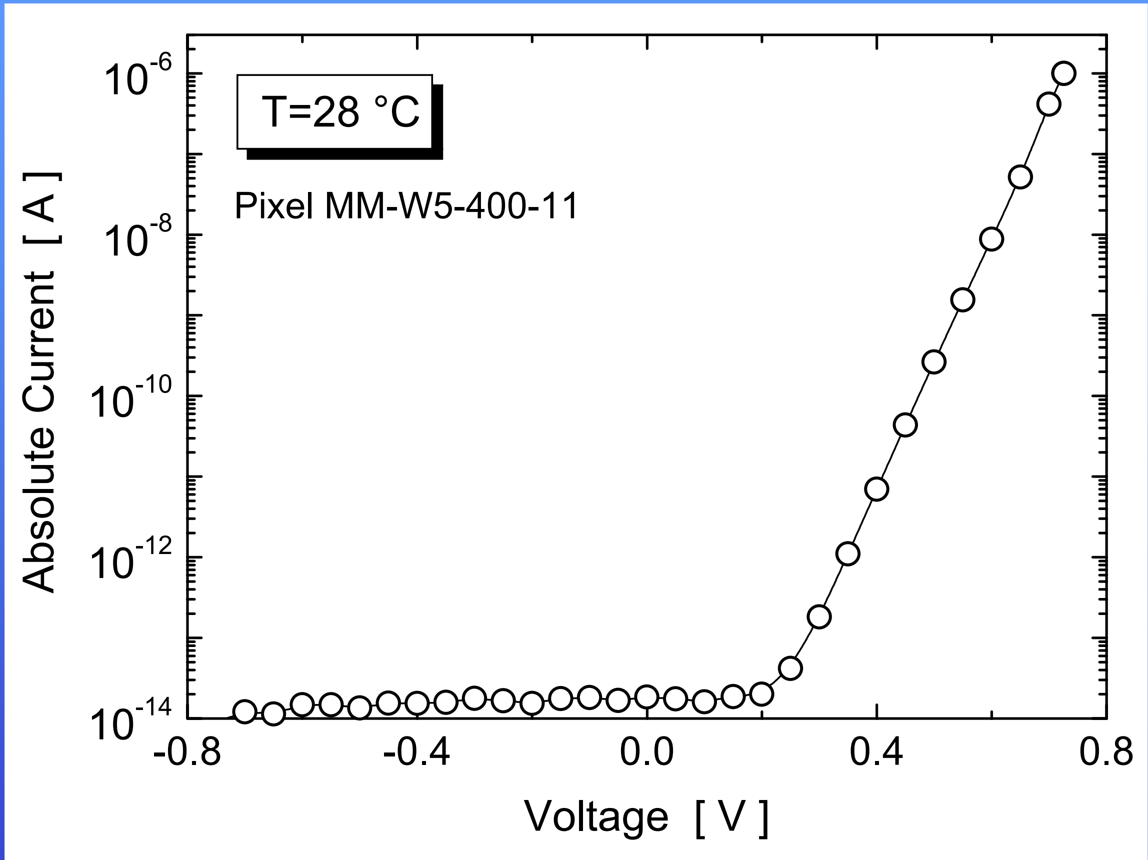


- 4 x 4 matrix
- Pixel size: 400 μm x 400 μm



- 6 x 6 matrix
- Pixel size: 250 μm x 250 μm

Pixel Forward Bias Characteristic



Saturation current

$I_s = 3.5 \cdot 10^{-18} A$

Ideality factor

$n = 1.06$

Measurement of the Pixel Leakage Current

The problem…

SiC Pad detectors : $J_{SiC} = 5 – 15\ pA/cm^2$

Current density of a pixel ?

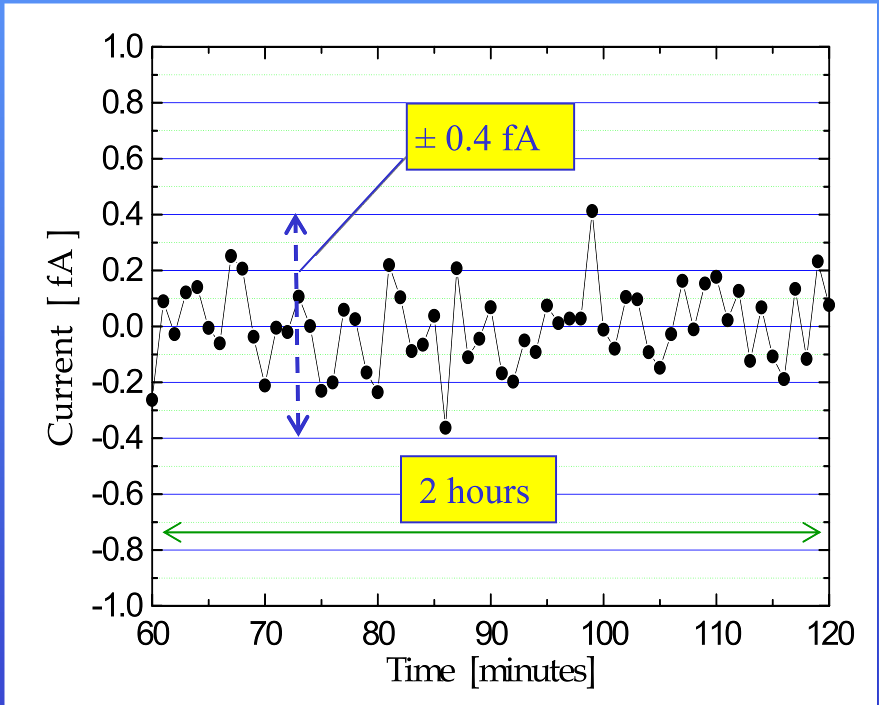
$J = 5 - 100\ pA/cm^2$, $Area = 400 \times 400\ \mu m^2$

$$\Downarrow$$

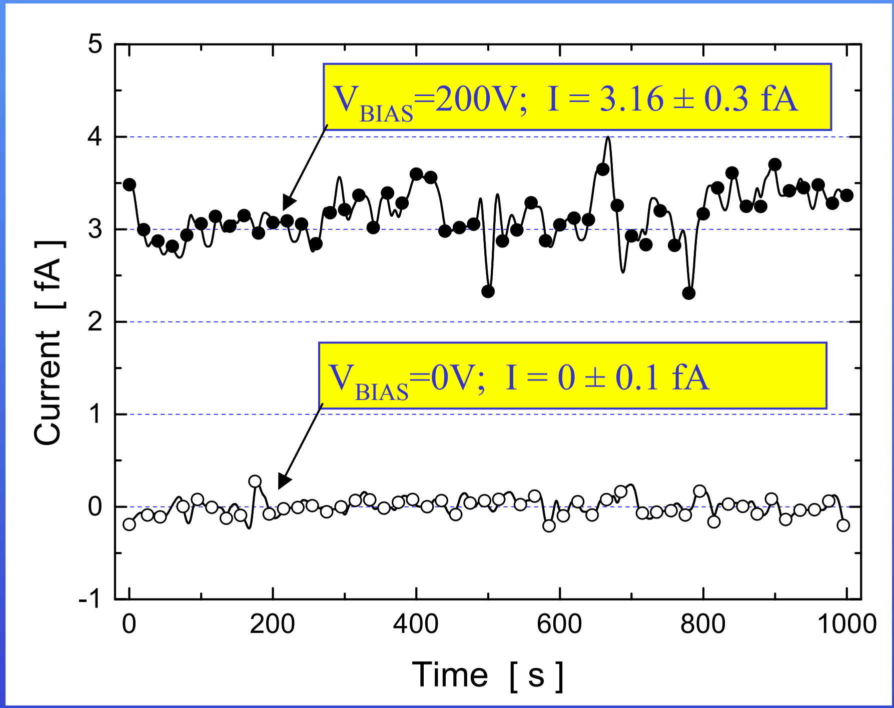
$I_{REV} = 8\ fA - 160\ fA$!!!

Instrumention and device noise

Electrometer noise

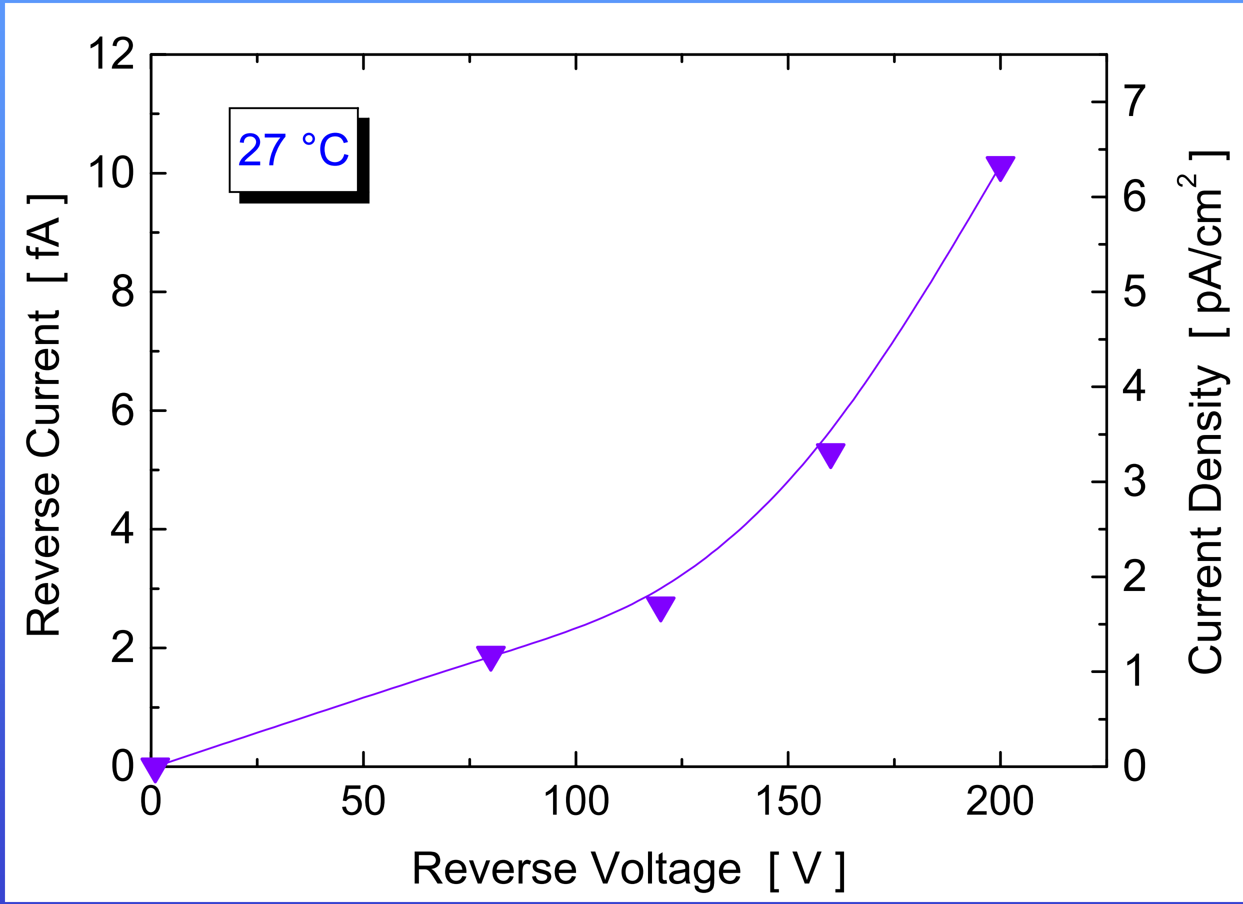


Test-fixture /device

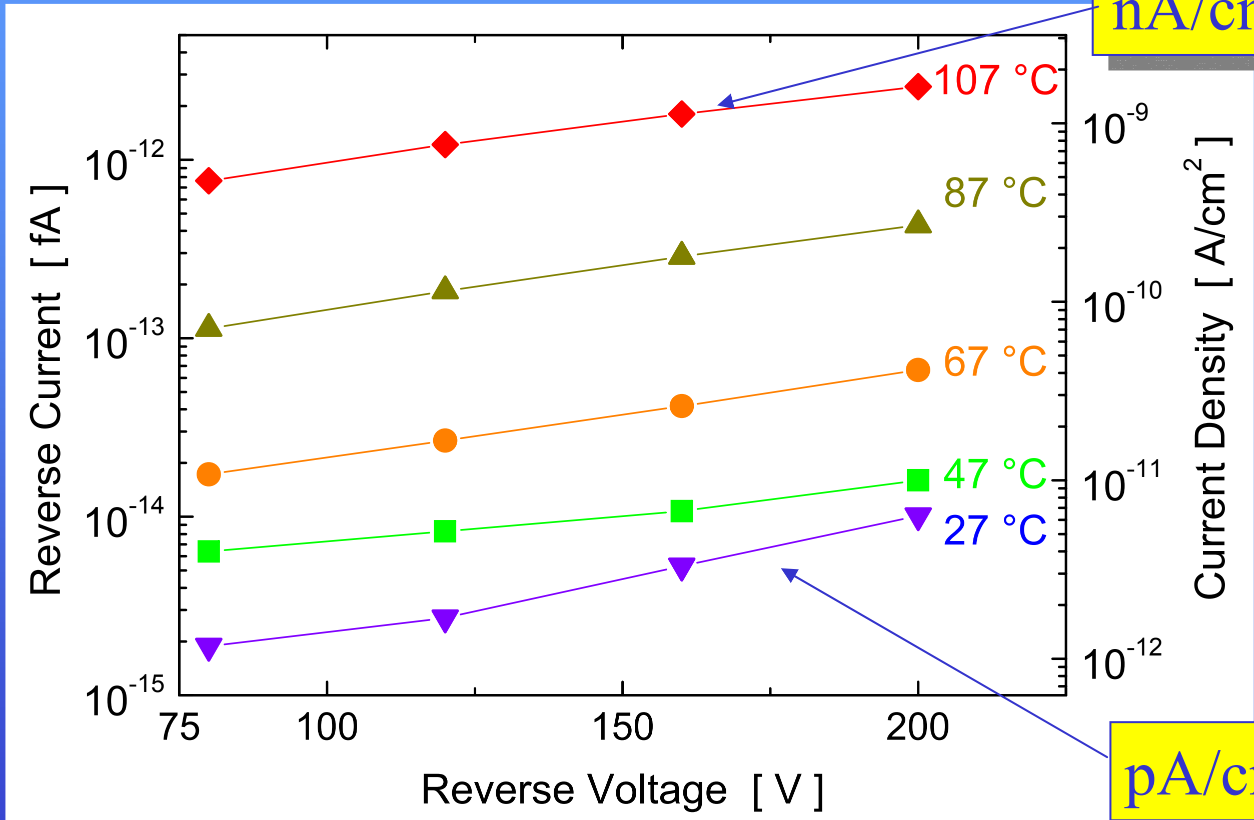


Pixel Reverse Bias Characteristic

Room Temperature



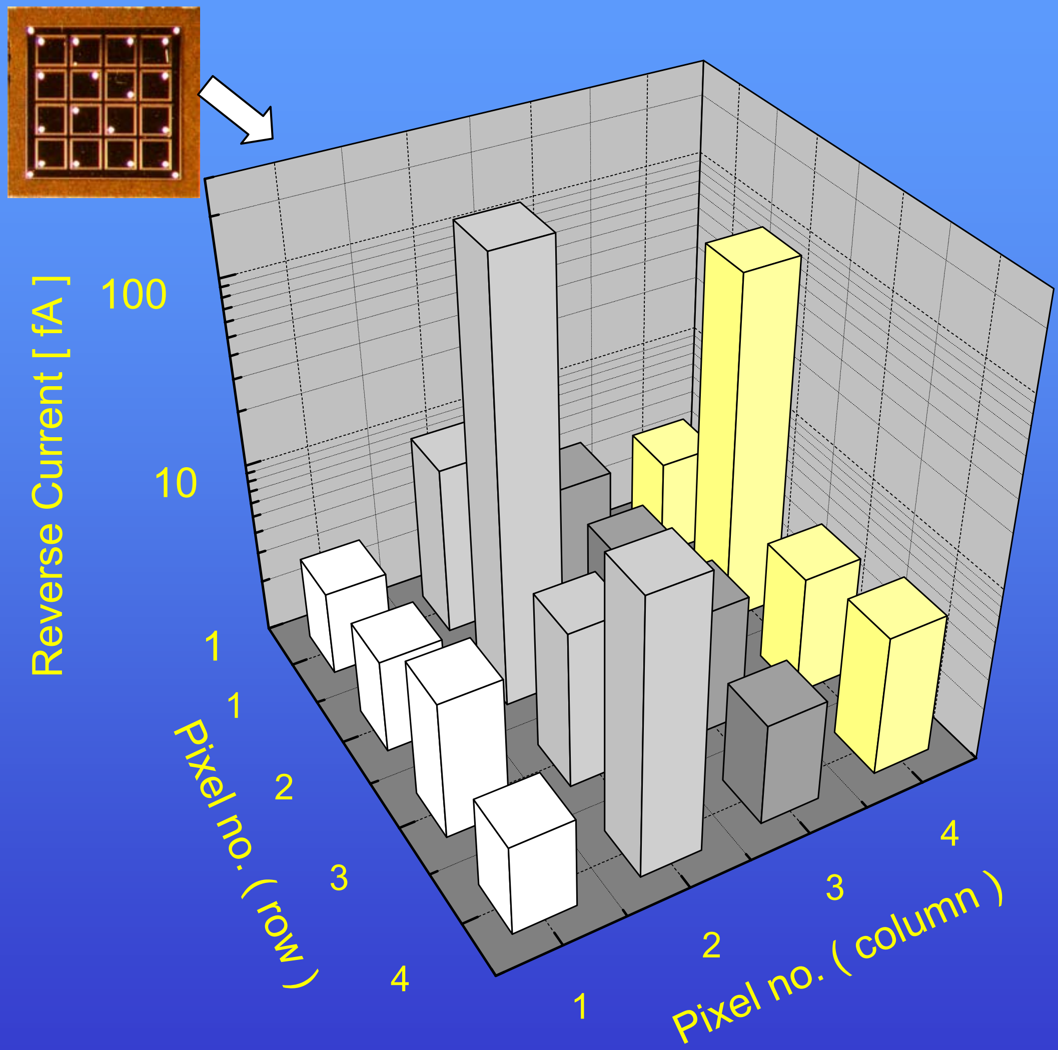
SiC Pixel
Reverse Bias Characteristic



nA/cm^2 @ 100 °C

pA/cm^2 @ 27 °C

Reverse Current Map



Leakage Current @ 27 °C		E.N.C. @ 10µs
I = 274 fA	: 1 pixel	= 5.8 e-
I = 98 fA	: 1 pixel	= 3.5 e$^-$
I = 36 fA	: 1 pixel	= 2 e-
I < 10 fA	: 12 pixel	< 1 e- r.m.s.

Summary

- **SiC has the same absorption length as Si**

Summary

- **SiC has the same absorption length as Si**
- **SiC can give superior resolution at certain T and Areas**

Summary

- SiC has the same absorption length as Si
- SiC can give superior resolution at certain T and Areas
- Pixel and pad detectors have been fabricated and tested

Summary

- SiC has the same absorption length as Si
- SiC can give superior resolution at certain T and Areas
- Pixel and pad detectors have been fabricated and tested
- Leakage currents: 5 - 14 pA/cm^2 @ 27 ° C

  500 pA/cm^2 @ 100°C

Summary

- SiC has the same absorption length as Si
- SiC can give superior resolution at certain T and Areas
- Pixel and pad detectors have been fabricated
- Leakage currents: 5 - 14 pA/cm^2 @ 27 ° C

  500 pA/cm^2 @ 100°C
- SiC pixel detector: 315 eV FWHM @ 27 ° C

  797 eV FWHM @ 100 °C

Summary

- SiC has the same absorption length as Si
- SiC can give superior resolution at certain T and Areas
- Pixel and pad detectors have been fabricated
- Leakage currents: 5 - 14 pA/cm^2 @ 27 ° C

  500 pA/cm^2 @ 100°C
- SiC pixel detector: 315 eV FWHM @ 27 ° C

  797 eV FWHM @ 100 °C
- SiC pixel : toward sub-electron (Fano limited) noise

Prospects for SiC detectors: Limits and needed...

- Thicker epi-SiC layers : t >100 μm (now: 50-70 μm)
- Ultra-low doping and pure SiC: $N \leq 10^{13} cm^{-3}$ (now: $> 5\ 10^{13}$)
- High purity semi-insulating SiC (?)
- Ultra low noise front-end at room and high temperature

Acknowledgements

Prof. Emilio Gatti - Politecnico di Milano

Prof. Claudio Canali - University of Modena

Prof. Filippo Nava – University of Modena

Dr. Antonio Cetronio - Alenia Marconi Systems

Dr. Claudio Lanzieri - Alenia Marconi Systems

Dr. Roberto Casiraghi – ST Microelectronics

Dr. Diego Maiocchi – University of Milano

Dr. Stefano Caccia – Politecnico di Milano

Dr. Enzo Mallardi – Politecnico di Milano

Dr. Marco Mandena – Politecnico di Milano