Performance of Indium Phosphide Radiation Detectors for X-ray imaging applications

P.J. Sellin, H. El-Abbassi and S. Rath
Department of Physics
University of Surrey

R. Fornari
Instituto MASPEC-CNR, Parma

K. Zdansky
Czech Academy of Sciences, Praha

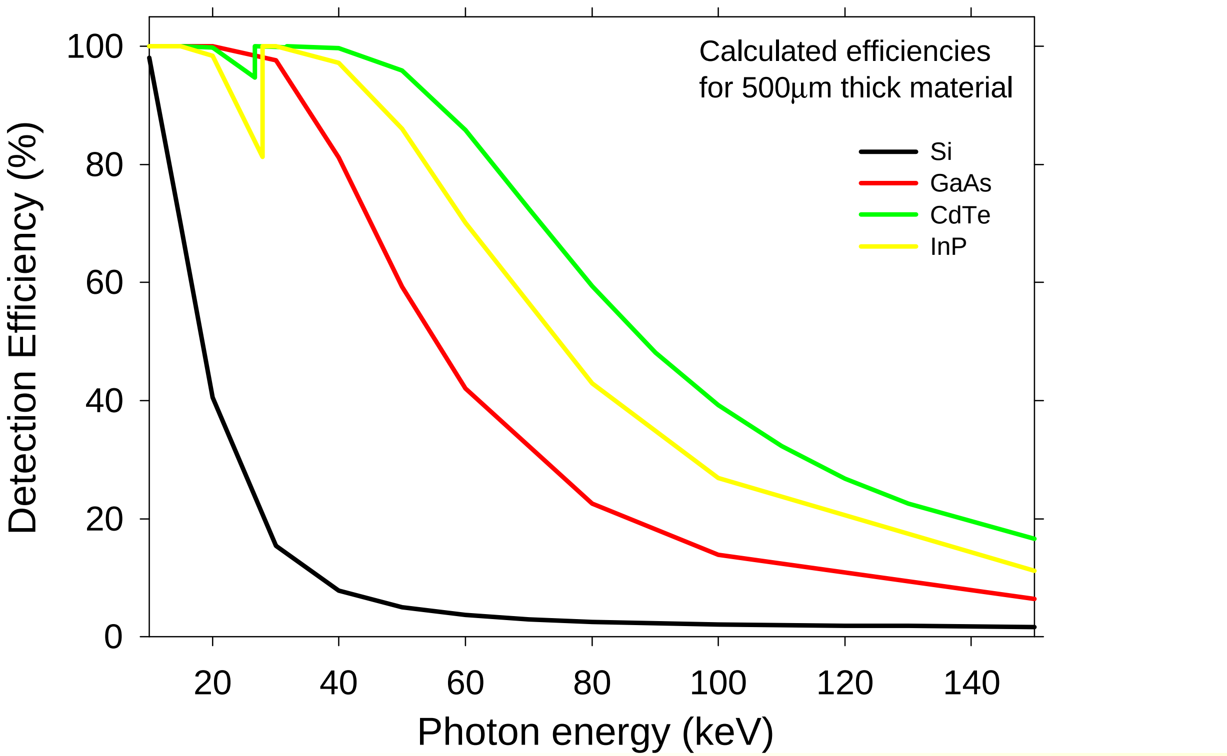
Introduction

- We have investigated the performance of 3 types of semi-insulating InP material for possible use in X-ray imaging applications
- InP potentially offers an alternative to GaAs or CdZnTe for X-ray detection in the 10 - 100 keV energy range
- Semi-insulating material is achieved by compensation with a deep acceptor such as Fe - new fabrication methods offer the potential for low-Fe, high resistivity material
- We have measured mu-tau products in InP for electrons and holes as a function of temperature, and compared these with the spectroscopic performance of InP radiation detectors
- Photoluminescence imaging also gives a valuable insight into material uniformity of SI InP

Detection Efficiency of InP

InP is a material with very similar properties to GaAs:

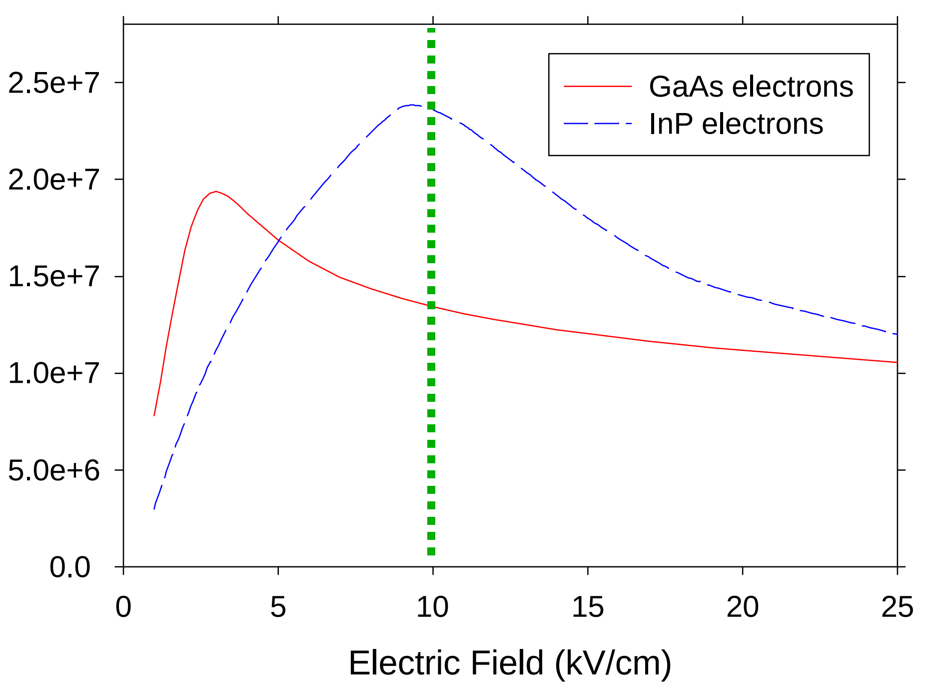
- atomic numbers of 49 and 15 produce a detection efficiency comparable to GaAs

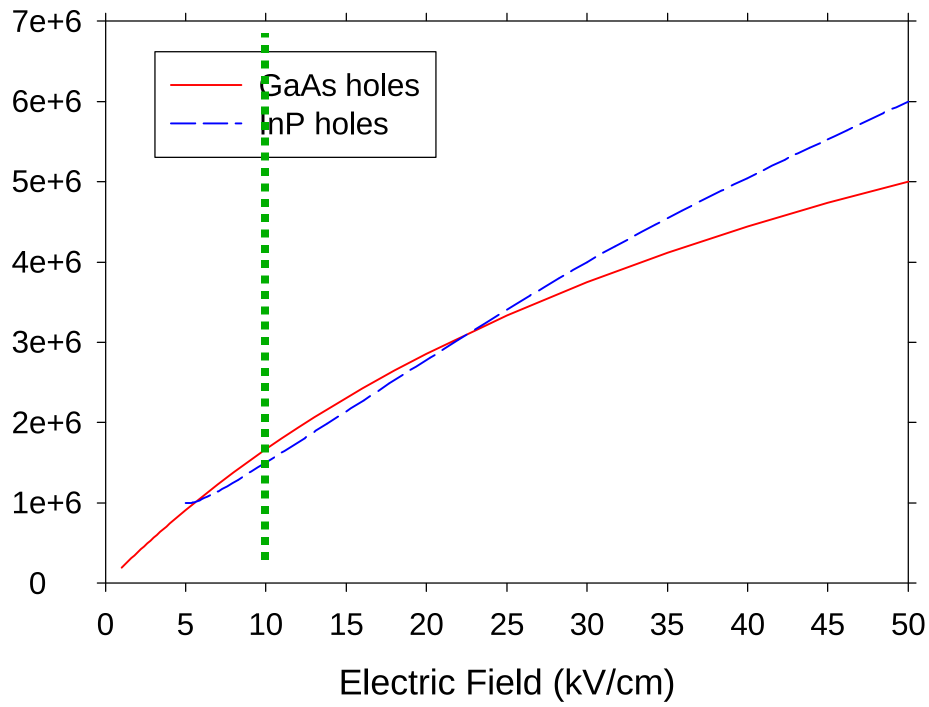


- material density is high (4.79 g/cm^3), and whole-wafer availability is good.

Electrical Properties

	E_G(eV)	W(eV/ehp)	$\rho_i(\Omega)$	$\mu\tau_{e/h}$ (cm^2/V)
Si	1.12	3.6	3×10^5	0.4 / 0.2
Ge	0.66	2.9	50	0.8 / 0.8
CdTe	1.47	4.7	10^9	10^{-3} / 10^{-4}
GaAs	1.42	4.3	3×10^8	10^{-5} / 10^{-6}
InP	1.34	4.2	9×10^7	10^{-5} / 10^{-5}





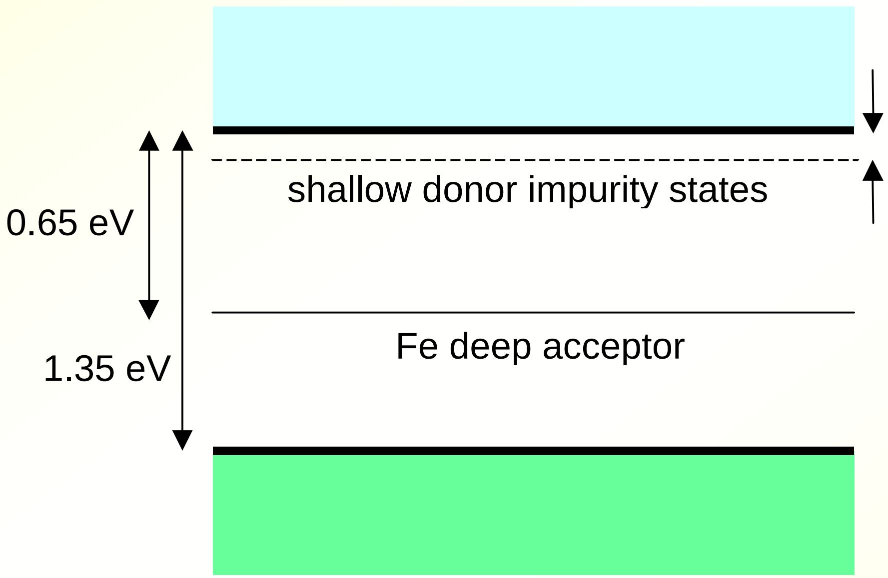
Resistivity

Nominally undoped bulk InP is n-type: $n_e \sim 10^{15}$ cm^{-3}, determined by residual donor impurity concentration

Room temperature mobilities ~4000 - 5000 cm^{2}V^{-1}s^{-1}

For Semi Insulating (SI) InP at 10^6-10^8 Ωcm, requires residual donor concentration to be reduced by ~10^6

Compensation is achieved using Fe as a deep acceptor: 0.65 eV below the conduction band edge.



Typical values for SI material:
- 10^{16} cm^{-3} Fe atoms
- 5 x 10^{15} cm^{-3} residual net donors
- resistivity of 1 - 3 x 10^7 Ωcm

Unlike GaAs (native EL2 defect acts as a deep donor) there is no comparable native acceptor defect in InP

Possible sources of InP material

The use of Fe-doped compensated SI InP requires:

- **high purity material**, to minimise residual impurity concentration
- **minimal Fe** doping to avoid over compensation
- well-controlled Fe doping, **uniform** over the wafer surface, and a controlled depth profile

In this work we have studied SI InP from three sources:

- commercial Fe-doped InP from **AXT** - grown by the Vertical Gradient Freeze technique
- LEC InP from **MASPEC** (Parma), with a special wafer-diffusion process to introduce well-controlled Fe doping
- Co-doped Zn, Fe InP from **Czech Academy** of Science (CAS, Prague)

In order to maximise the induced signal (CCE), both the field strength *E* and the mu-tau product $\mu\tau$ must be maximised:

$$CCE = \frac{Q}{Q_0} = \frac{l}{d} \qquad l = mtE$$

Material Growth - AXT

AXT has pioneered Vertical Gradient Freeze technology (VGF) for InP and GaAs crystal growth

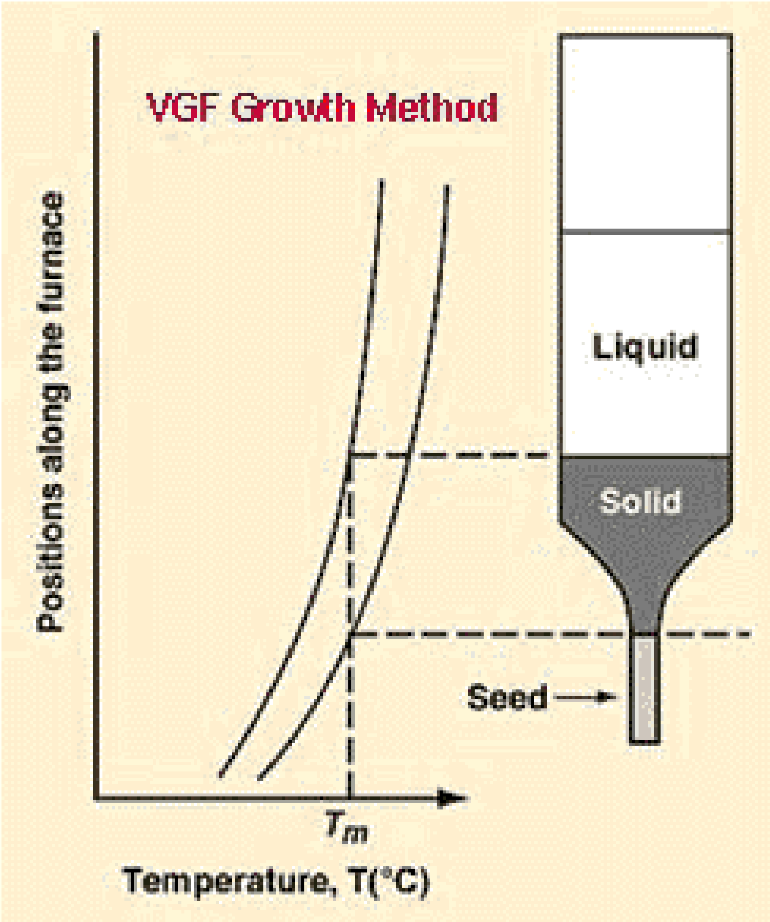
An enclosed crucible holds the melt, with a seed at the bottom. Furnace power is reduced to move the solidification front upwards

A lower temperature gradient than for the Liquid-encapsulated Czochralski (LEC) process: $\Rightarrow$ low dislocation density, low impurities, and uniform dopant concentrations

Nominal wafer properties - Fe-doped:

- resistivity 1 - 2x10^7 Ωcm
- Fe concentration: 1x10^{16} cm^{-3}
- thickness 350 ± 25 μm

American Xtal Technology



MASPEC Fe-diffused InP

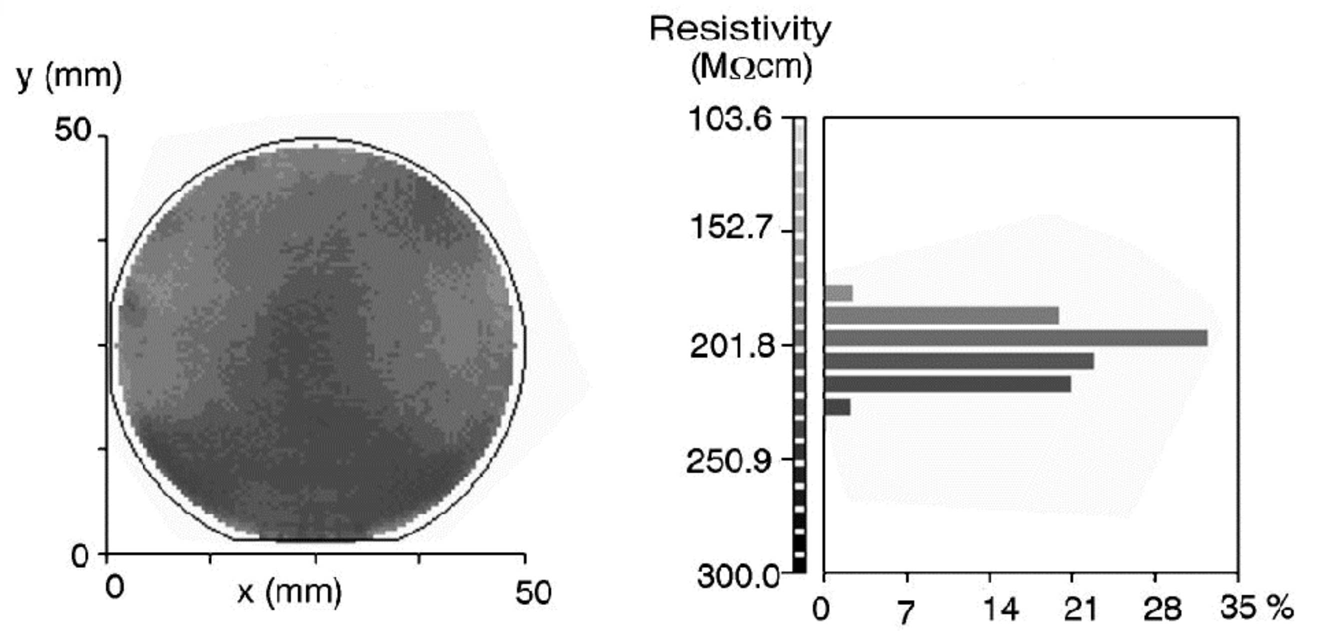
MASPEC perform a unique Fe-diffusion process on individual wafers: Fe deposition followed by annealing at 900C for 50 hours

Gives very uniform doping apart from surface layer - high mobility

Nominal wafer properties - Fe-doped:

- resistivity >10^7 Ωcm
- Fe concentration: $4x10^{15}$ cm^{-3}
- electron mobility 3000 - 4000 cm^2/Vs
- thickness 500 μm

R. Fornari et al,
JAP 88/9 (2000) 5225-5229



Zn+Fe co-doped InP

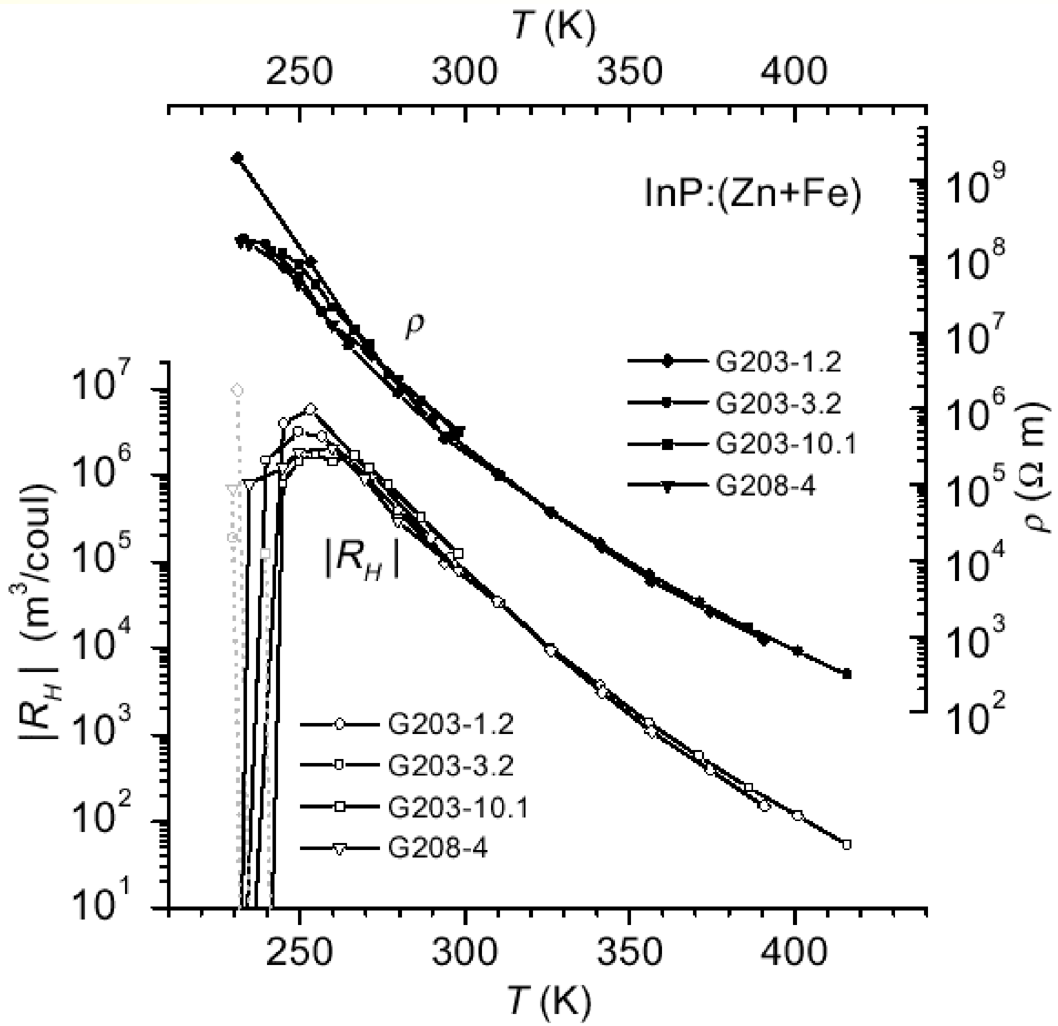
Grown at the Czech Academy of Sciences, pre-compensation is applied to the crystal using a shallow acceptor (Zn)

Fe is used to achieve high resistivity

Material has been observed to change from n-type to p-type at approximately -20C

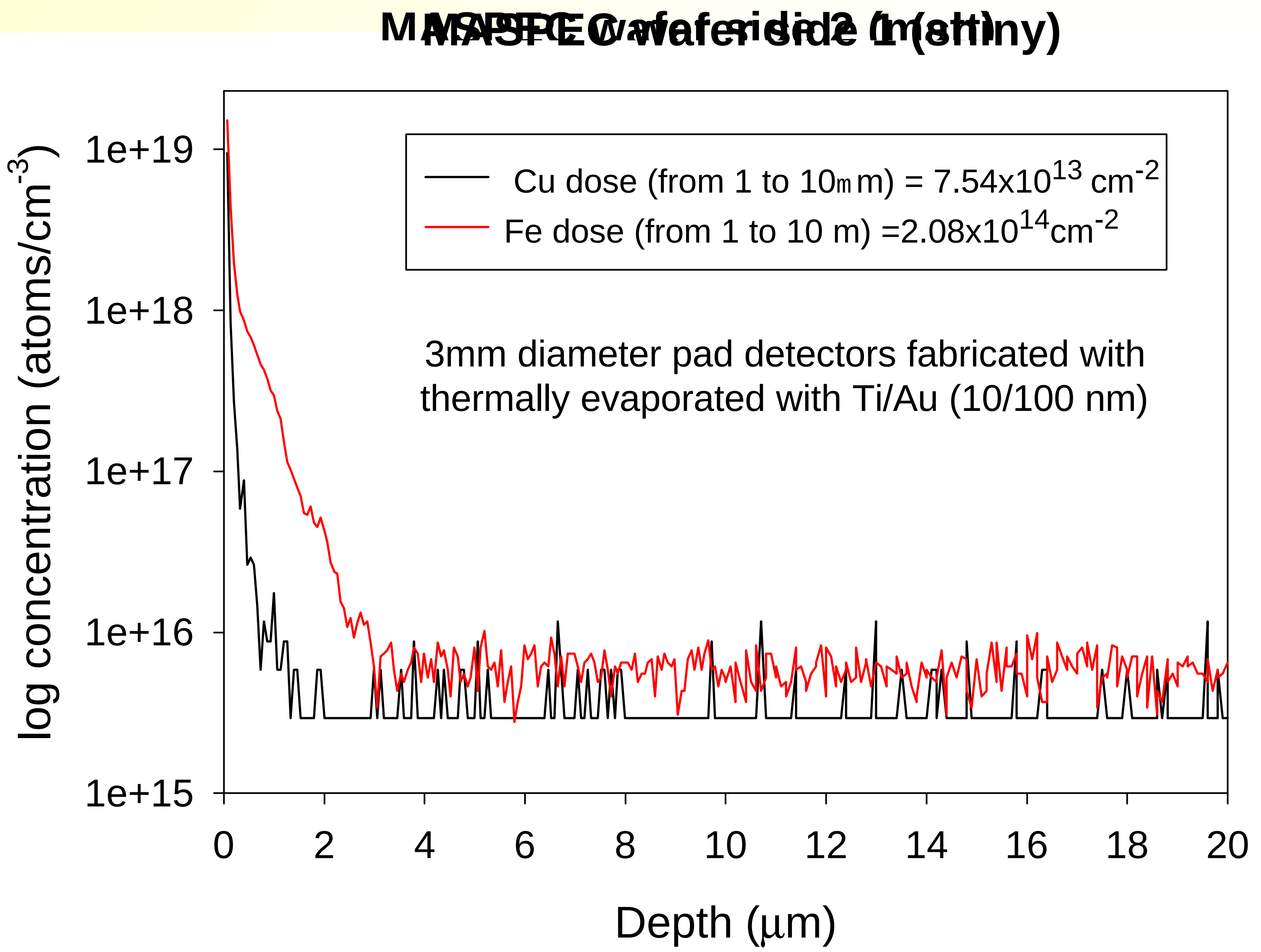
Nominal wafer properties:

- Fe concentration: $2x10^{16}$ cm^{-3}
- Zn concentration: $8x10^{15}$ cm^{-3}
- thickness 1 mm

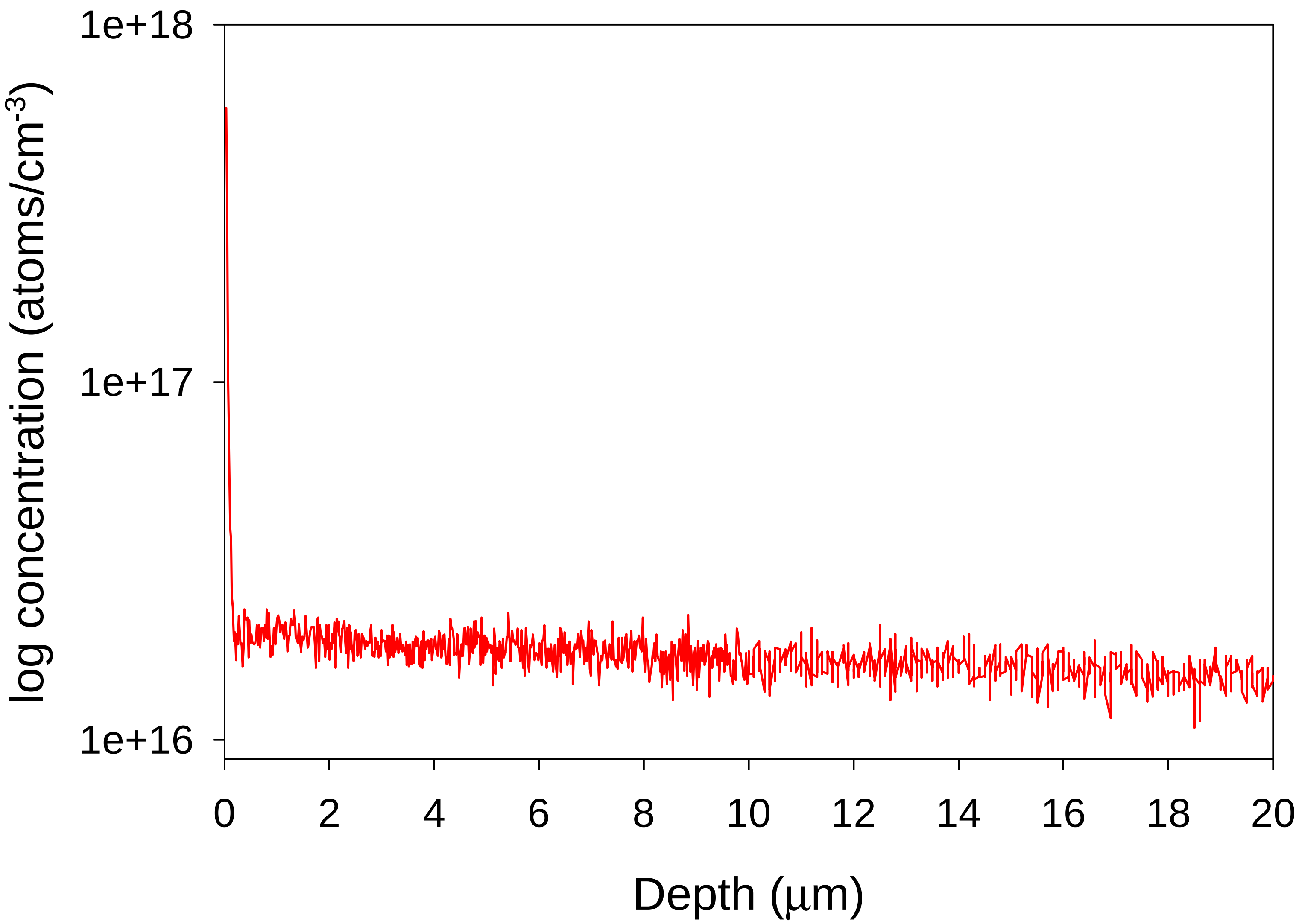


K. Zdansky et al,
Semi. Sci. Tech. 15
(2000) 297-300

Fe diffusion profiles by SIMS - MASPEC

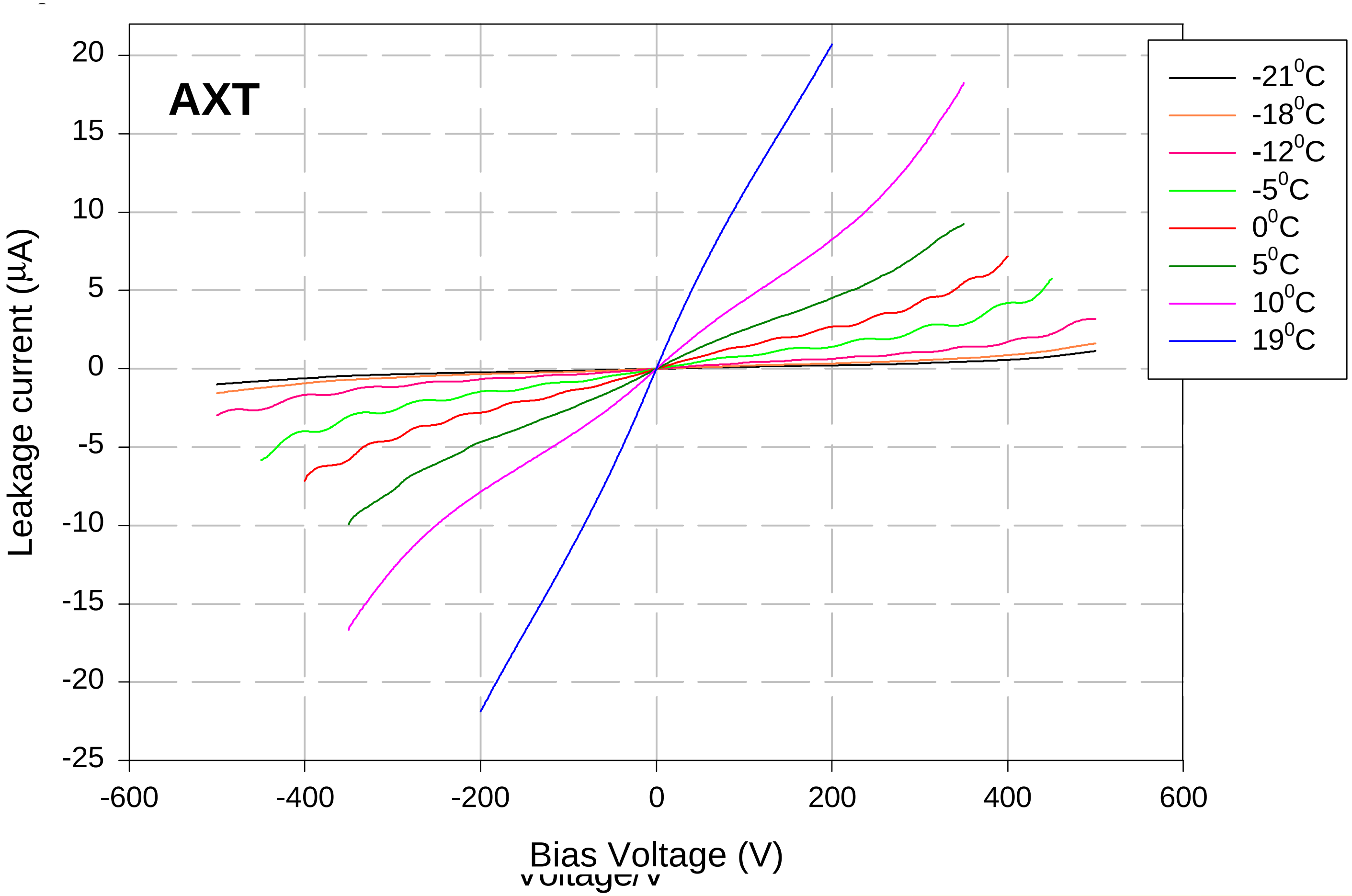


Fe diffusion profiles by SIMS - AXT



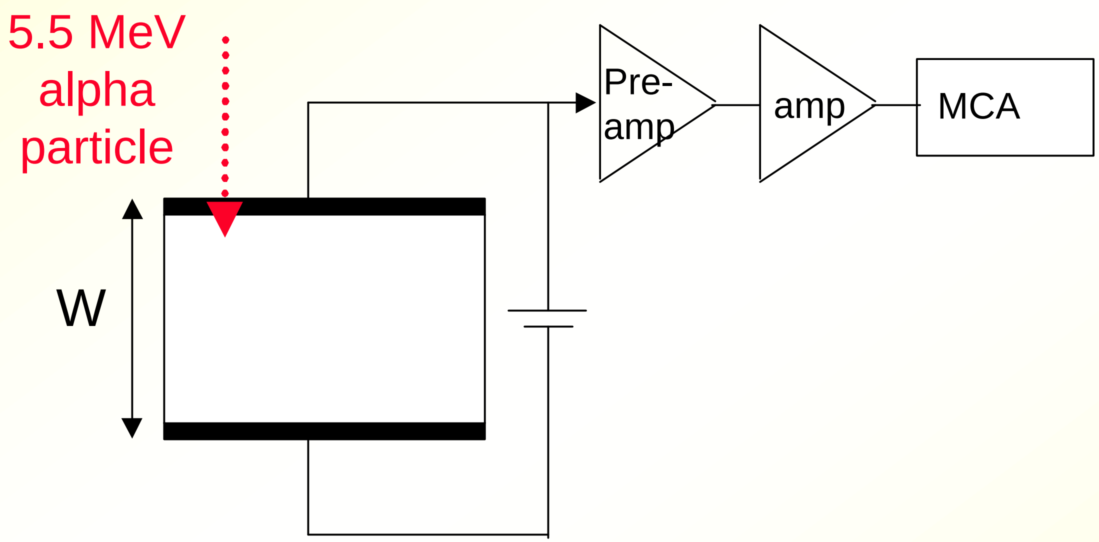
MASPEC I-V characteristics

IV characteristics of SI InP are strongly temperature dependent: thermal excitation of electrons from deep acceptor to conduction band. Eg: Δt = 30°C produced 1 order of magnitude change in current



Alpha particle Spectroscopy

Alpha particle measurements through the detector contact produces pulse height spectra sensitive to either holes or electrons:



A 3-stage Peltier cooler holds the detector at temperatures down to -60C.

Alpha particle peak position gives Charge Collection Efficiency (CCE) as a function of applied field: fitting to Hecht formula gives $\mu\tau$ product

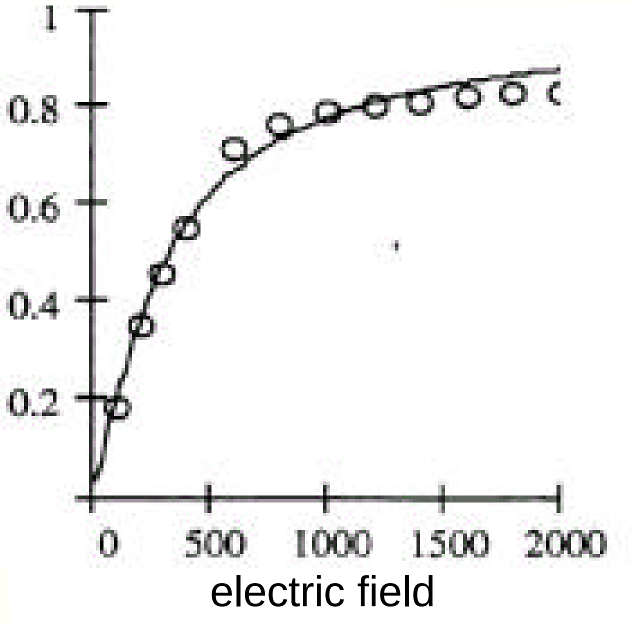
Mobility-Lifetime products

Mobility-lifetime products are calculated for the 3 devices using the Hecht relation applied to alpha particle peak positions

Generally: $$CCE = \frac{Q}{Q_0} = (\mu_e \tau_e + \mu_h \tau_h)E$$

For cathode irradiation with alphas:

$$CCE = \frac{Q}{Q_0} = \frac{\mu_e \tau_e V}{d^2}\left[1 - \exp\left(\frac{1 - \frac{x}{d}}{\frac{\mu_e \tau_e V}{d^2}}\right)\right]$$



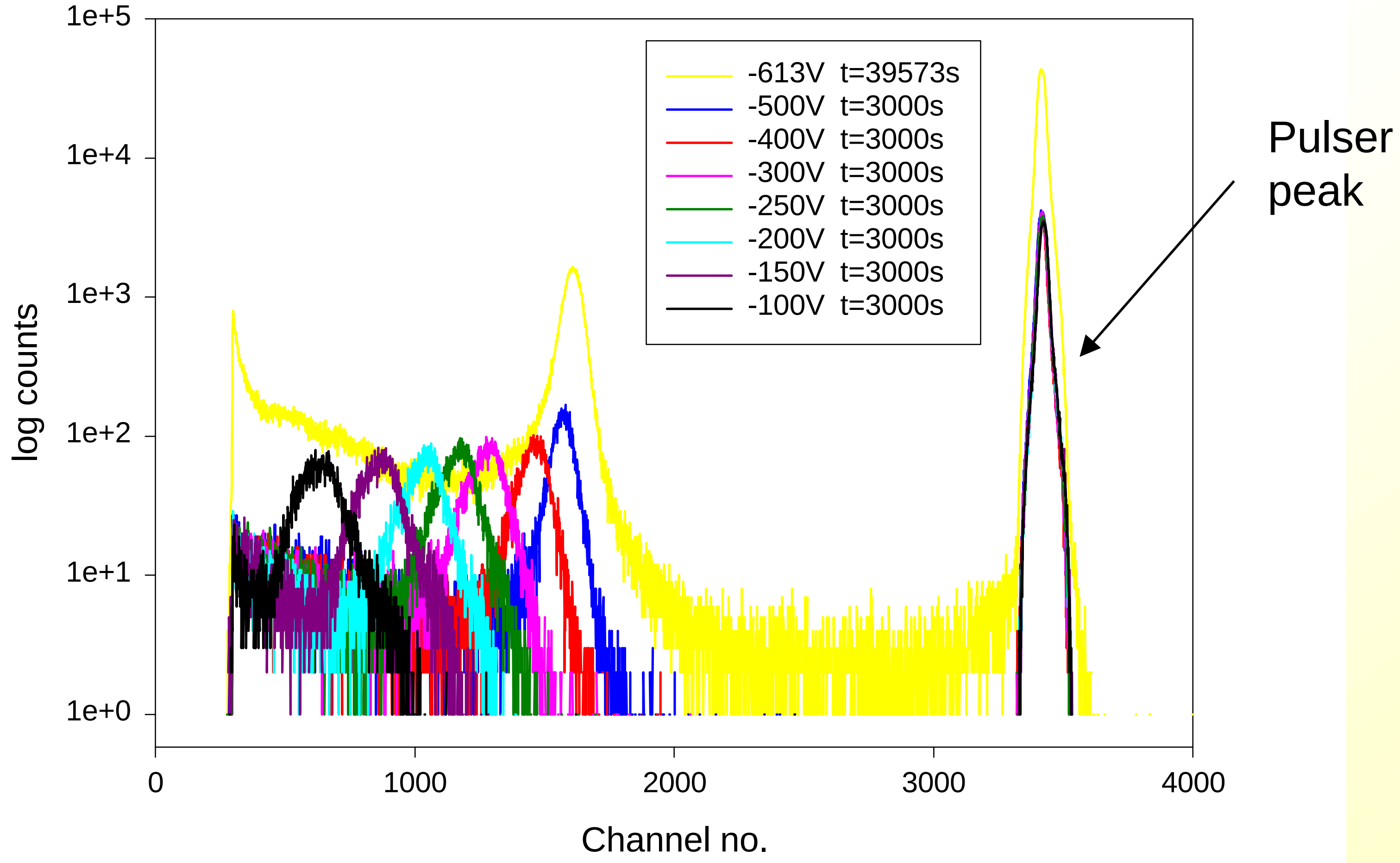
Hence fitting relative peak position as a function of electric field extracts $\mu_{e,h}\tau_{e,h}$ for cathode and anode irradiation respectively

Unlike in CdZnTe, electron and hole transport in InP is approximately equal

Alpha particle spectra

MASPEC detector, T = -60C (gain 100x)

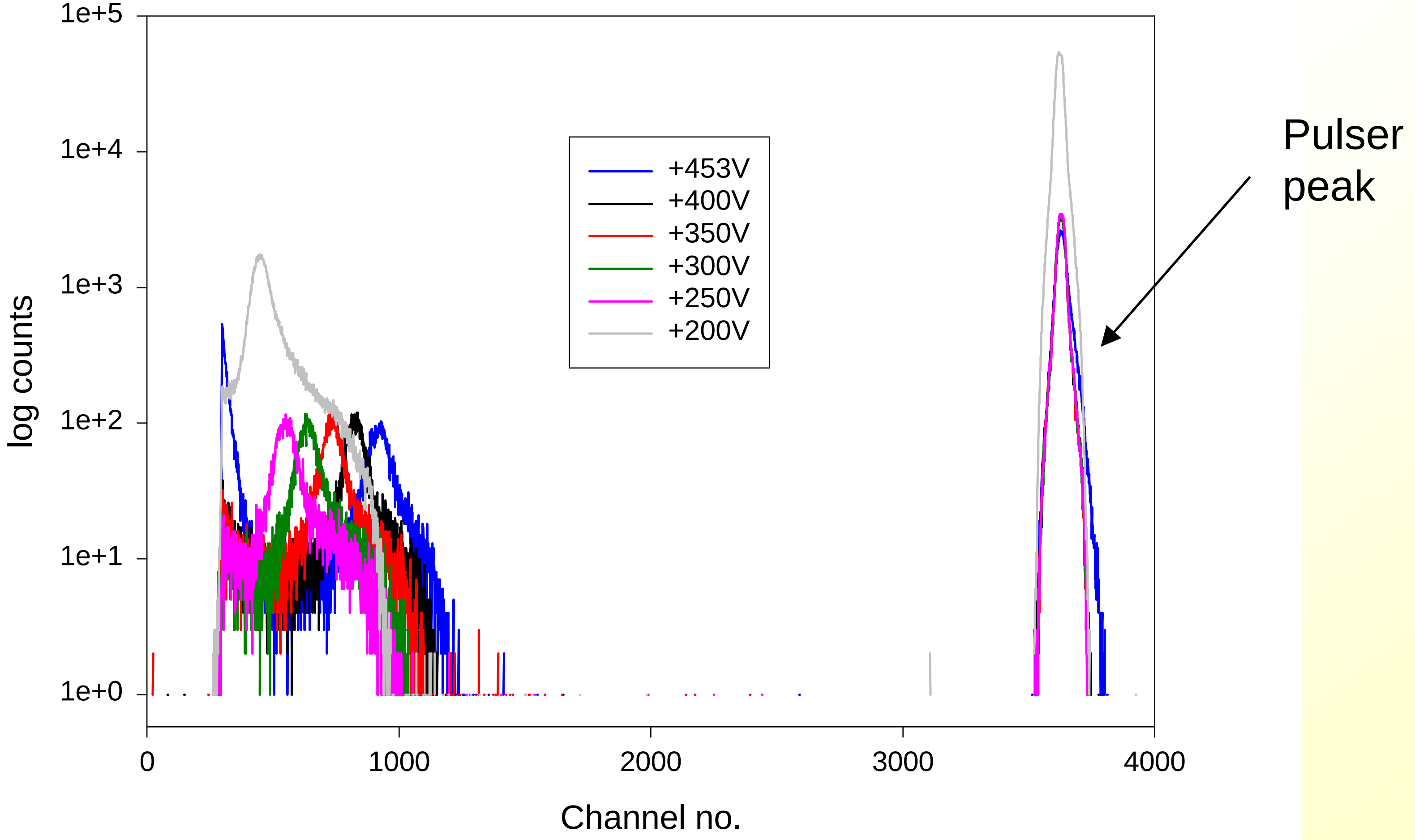
Alpha particles incident onto the cathode (electron signal)



Alpha particle spectra (2)

MASPEC detector, T = -60C (gain 100x)

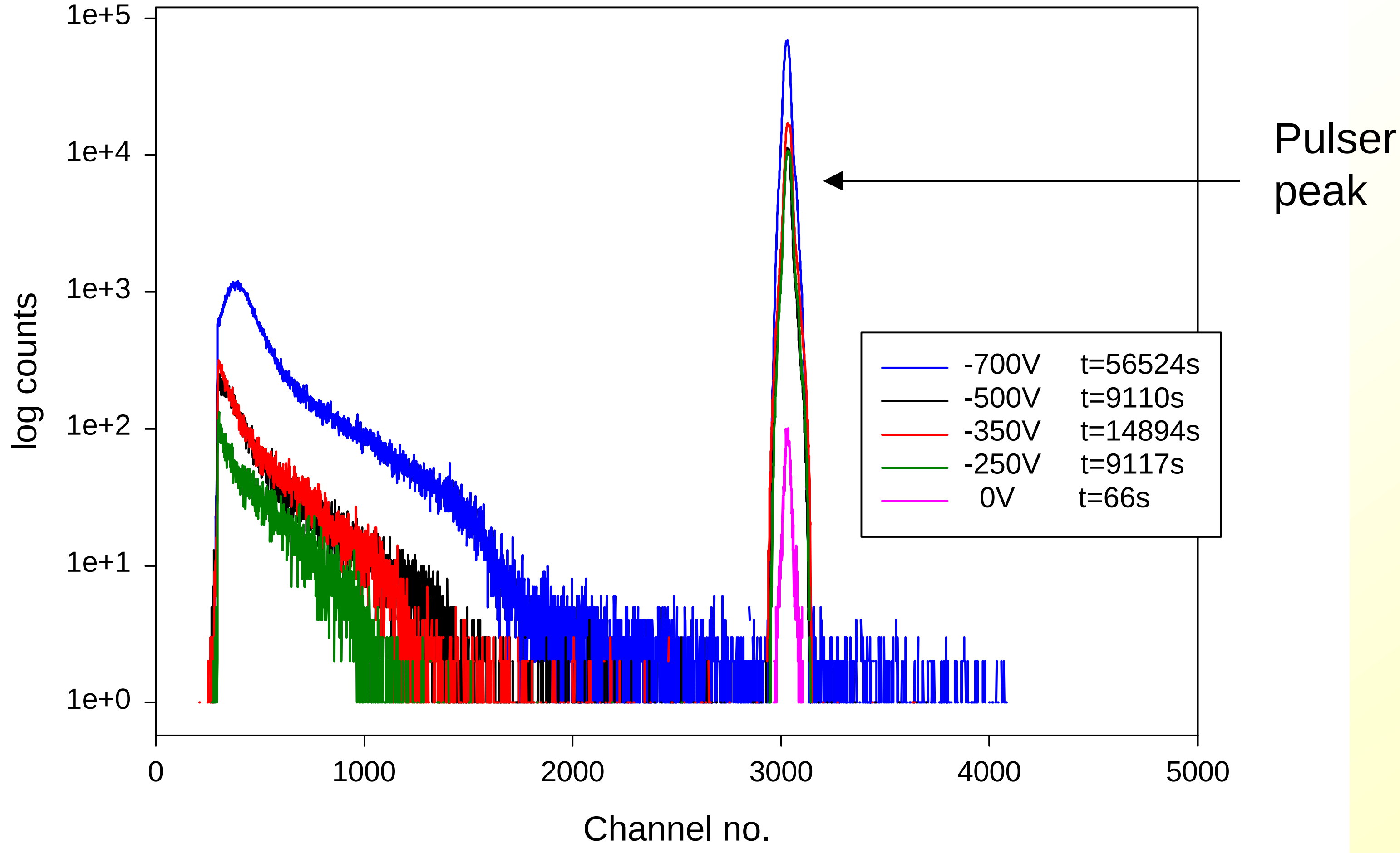
Alpha particles incident onto the anode (hole signal)



Alpha particle spectra (3)

CAS detector, T = -55C (gain 200x)

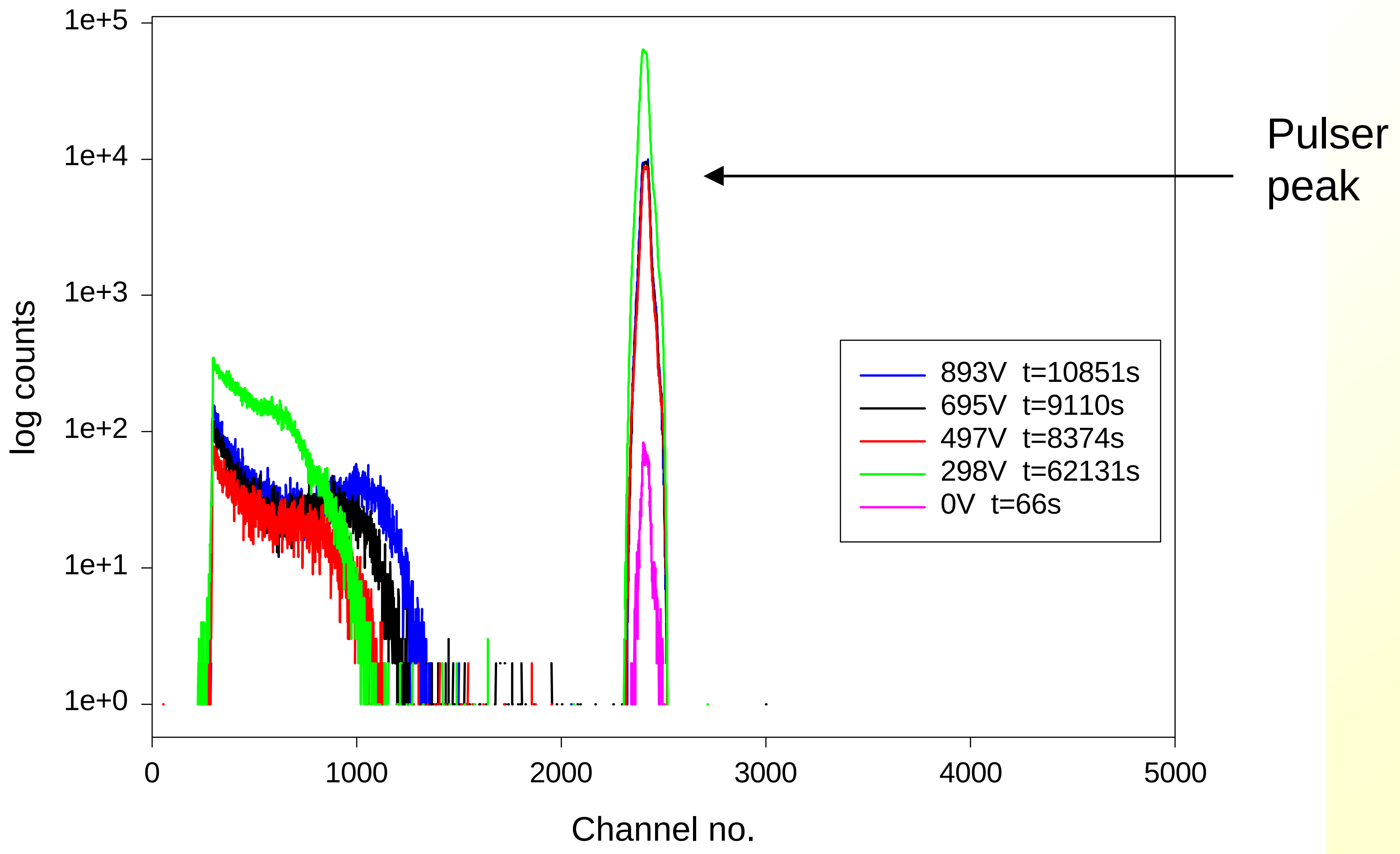
Alpha particles incident onto the cathode (electron signal)



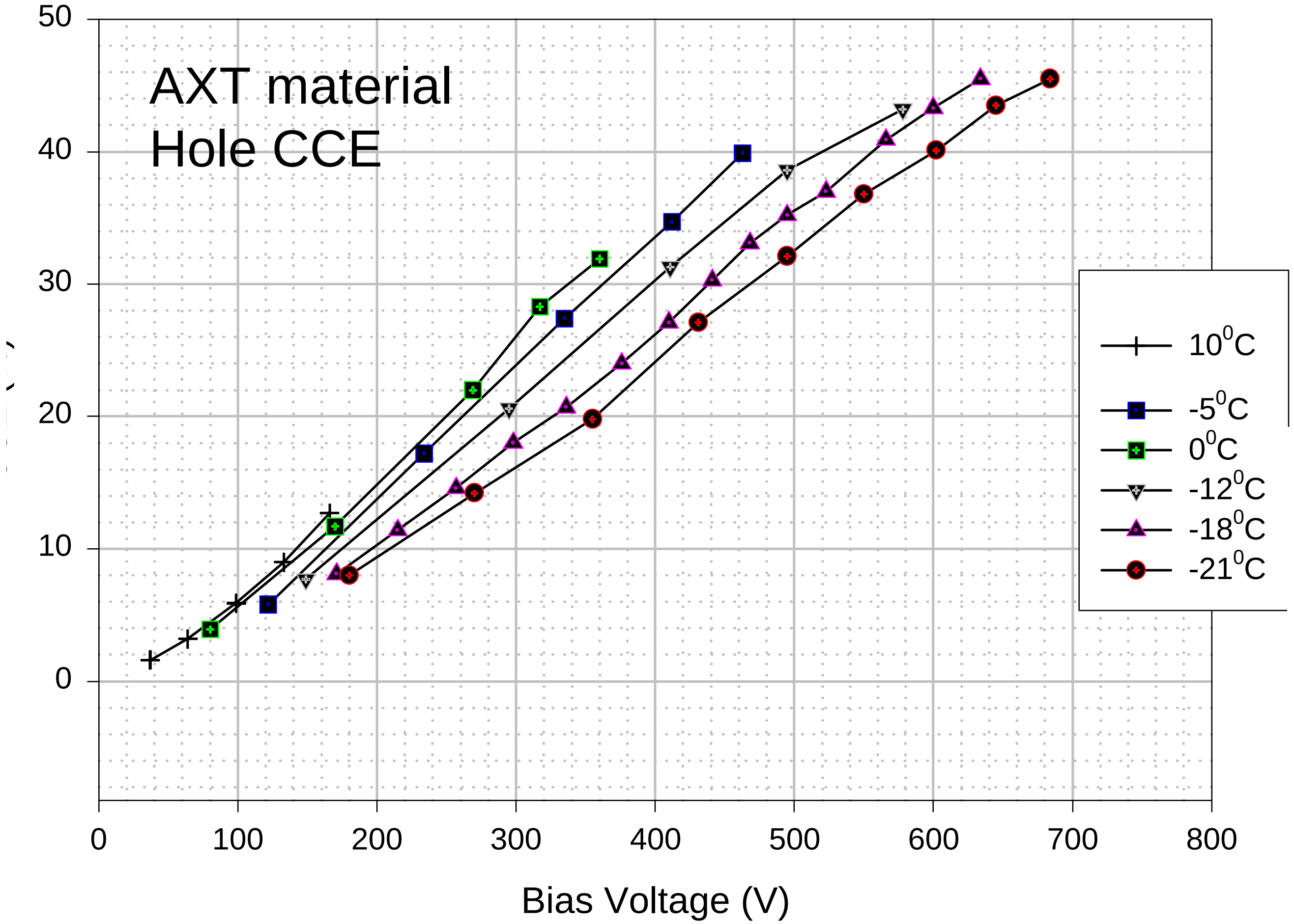
Alpha particle spectra (4)

CAS detector, T = -55C (gain 200x)

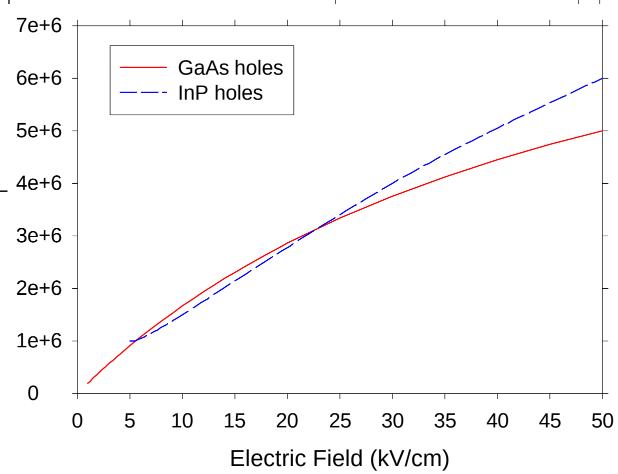
Alpha particles incident onto the anode (hole signal)



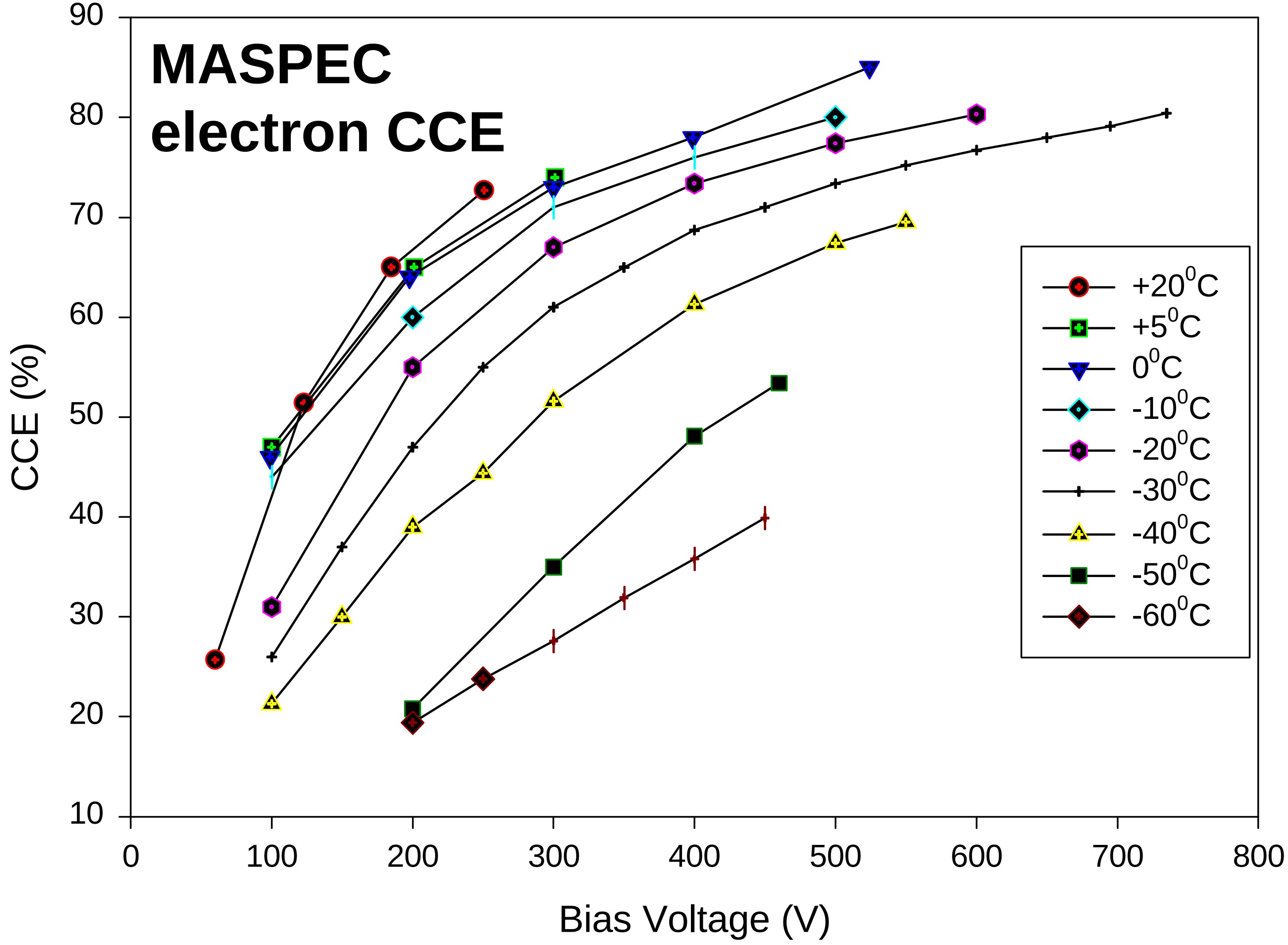
Alpha particle CCE - AXT material



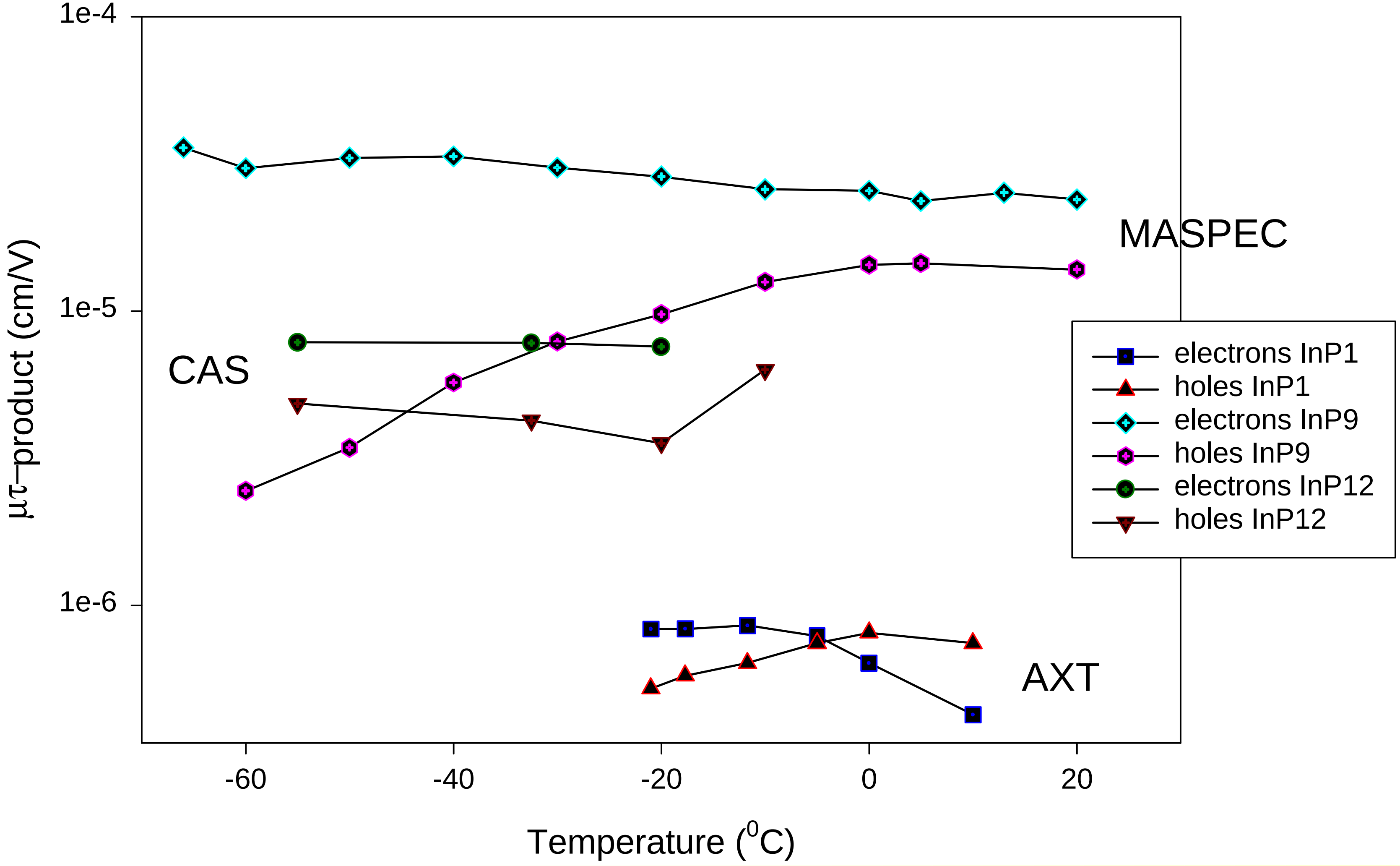
electron mobility
hole mobility



Alpha particle CCE - MASPEC



mu-tau product vs Temperature



MASPEC exhibits μτ values >50x greater than AXT material

CAS material is ~10x better performance than AXT

UniS Department of Physics University of Surrey

Paul Sellin, Radiation Imaging Group

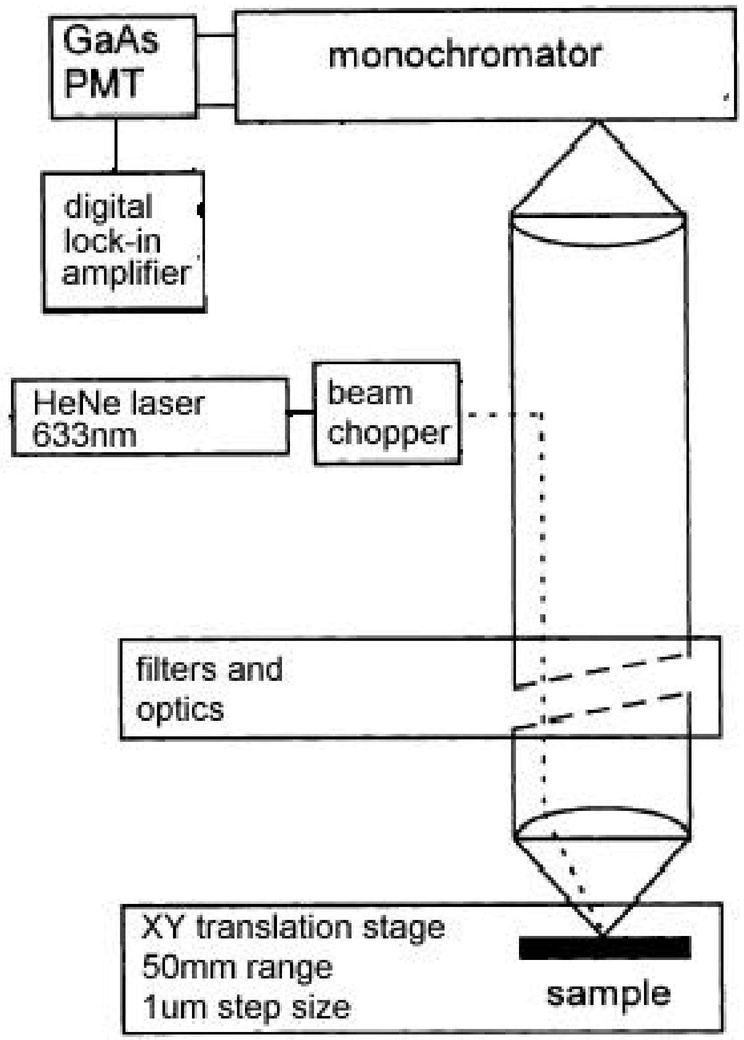
Photoluminescence imaging

Photoluminescence microscopy is used as a non-contacting technique to study the uniformity of defects in semiconductor wafers.

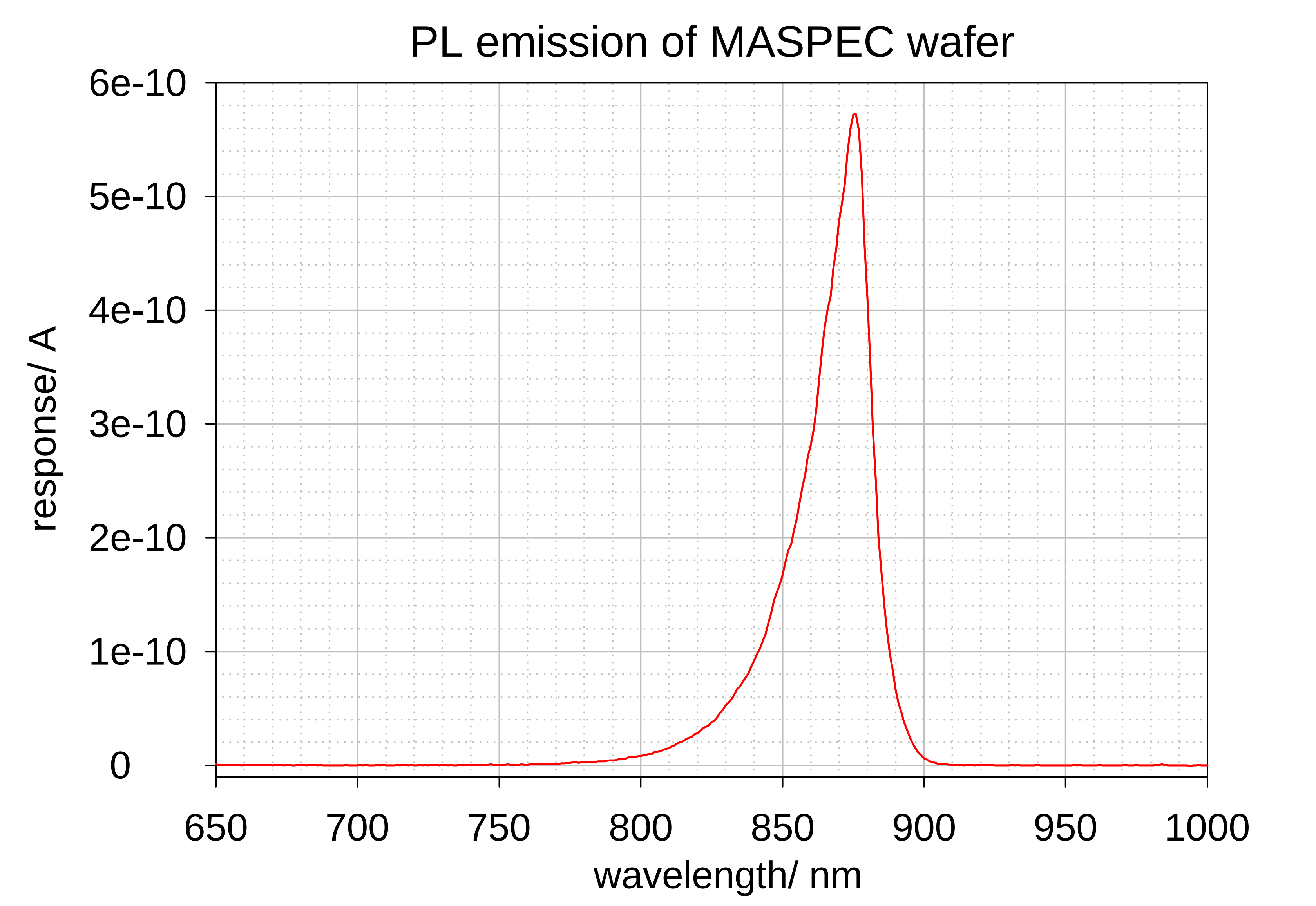
For example, does Fe-doped SI InP suffer from the same defect non-uniformity as SI GaAs?

We use a room temperature wafer-scanning technique, with a 25 mW HeNe laser focussed to 50-100 μm spot size

A GaAs-PMT (sensitive to 930 nm) detects the luminescence after passing through a monochromator ($\Delta\lambda = \pm 2$ nm). Very weak signals are extracted using a digital lock-in amplifier



Room temperature PL

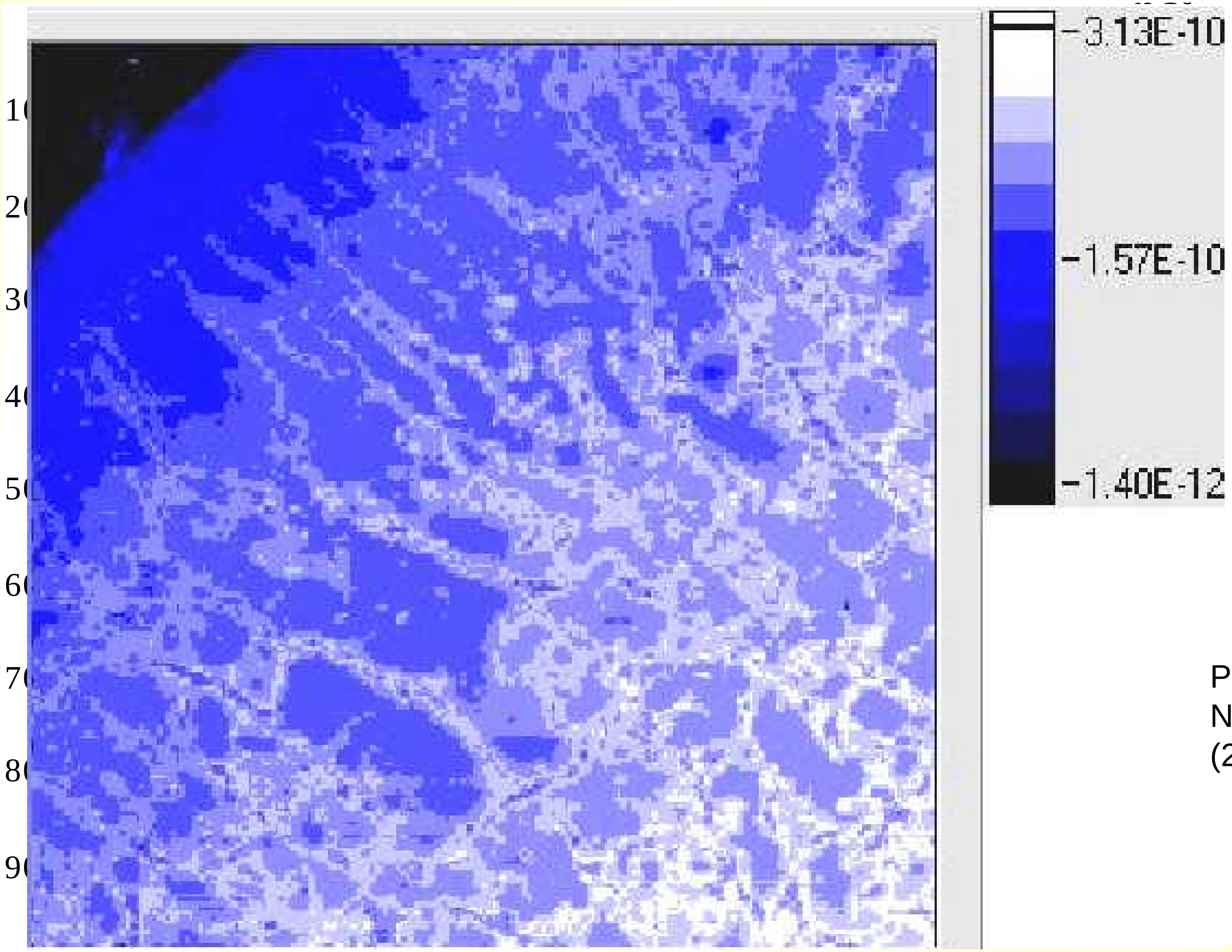


870

e is

s no
-
e
etc.

PL comparison with GaAs

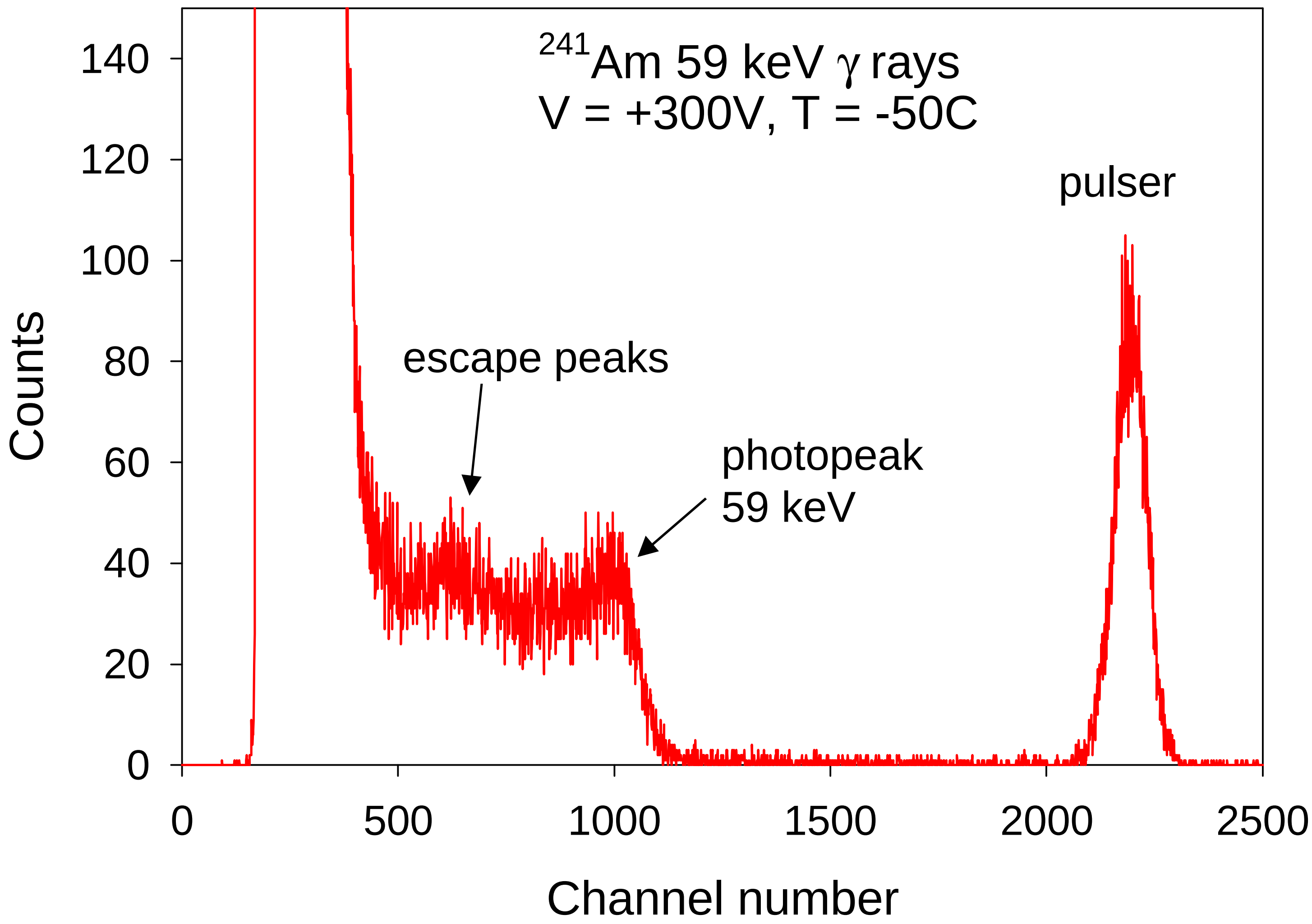


PJ Sellin et al,
NIM A460
(2001) 207-212

Growth-related defect distribution in SI GaAs (EL2)

Similar defect structure seen in SI GaAs pixel detectors with current integrating readout

Gamma ray spectroscopy at 59 keV



Department of Physics
University of Surrey

Conclusions

- SI InP material produced at MASPEC using wafer-based Fe-diffusion shows mu-tau products ~50x greater than commercial VGF-grown SI InP (typically **2×10^{-5}** cm^2V^{-1} for electrons, and **2×10^{-6} - 1×10^{-5}** cm^2V^{-1} for holes)
- PL mapping shows excellent material uniformity, unlike SI GaAs
- SIMS data confirms the low Fe concentration in the MASPEC material ($<5\times10^{15}$ cm^{-3}), compared to AXT VGF material ($\sim2\times10^{16}$ cm^{-3})
- Material co-doped with Zn and Fe shows conventional behaviour at temperatures to -60C, with performance better than VGF InP
- Detectors fabricated from MASPEC InP operating at T=-60C show a resolved photopeak at 59 keV, and evidence of escape peaks
- Material conductivity is still too high to allow room temperature operation of InP detectors. With advances in material purity prospects are good for higher resistivity material in the future

Acknowledgements

This work was partially funded by the UK's Engineering and Physics Science Research Council

We are very grateful to our collaborators at MASPEC and at the Czech Academy of Science for the supply of the InP material used in this study

^{241}Am spectrum from CdZnTe