

## HIGH ENERGY PHOTOEMISSION SPECTROSCOPY AS TOOL FOR THIN FILM SOLAR CELL CHARACTERISATION

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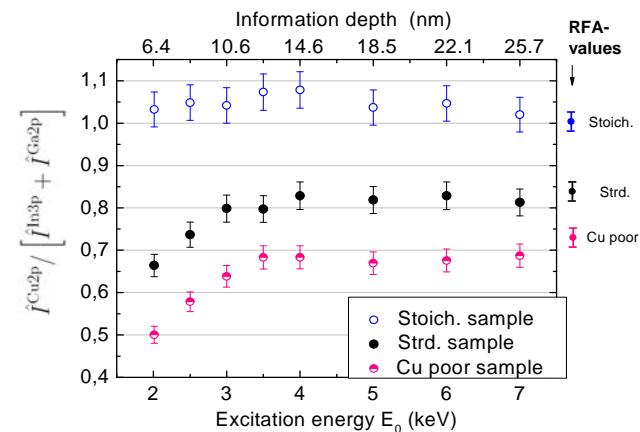
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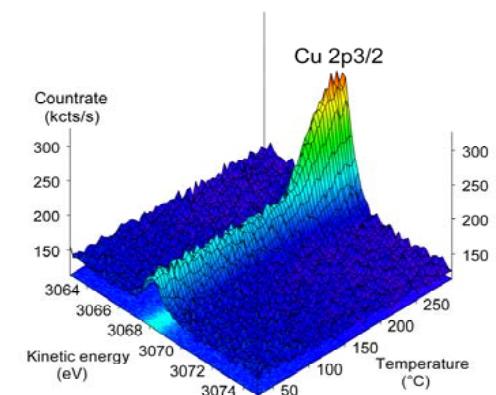
- Measurement of band bending in semiconductors
- Depth profiling using HAXPES

H. Mönig, C.H. Fischer, R. Caballero, C.A. Kaufmann, N. Allsop, M. Gorgoi, R. Klenk, H.W. Schock, S. Lehmann, M.C. Lux-Steiner, I. Lauermann, *Acta Materialia*, 57 (2009) 3645-3651



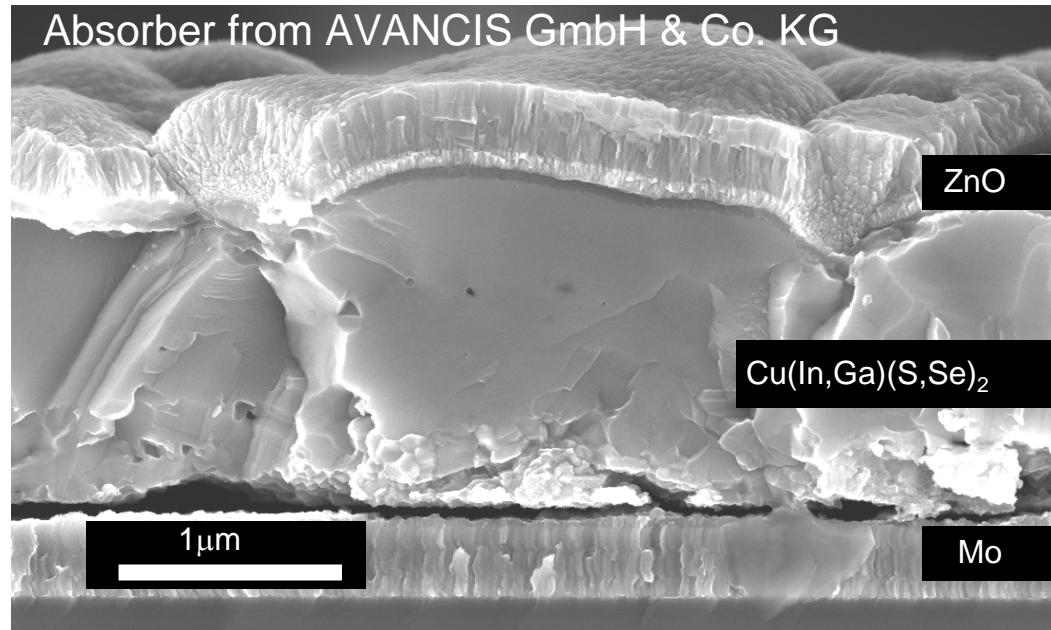
- In-situ monitoring of Cu-diffusion in  $\text{In}_2\text{S}_3$

P. Pistor, N. Allsop, W. Braun, R. Caballero, C. Camus, C.H. Fischer, M. Gorgoi, A. Grimm, B. Johnson, T. Kropp, I. Lauermann, S. Lehmann, H. Mönig, S. Schorr, A. Weber, R. Klenk, *Physica Status Solidi A*, 206 (2009) 1059-1062.



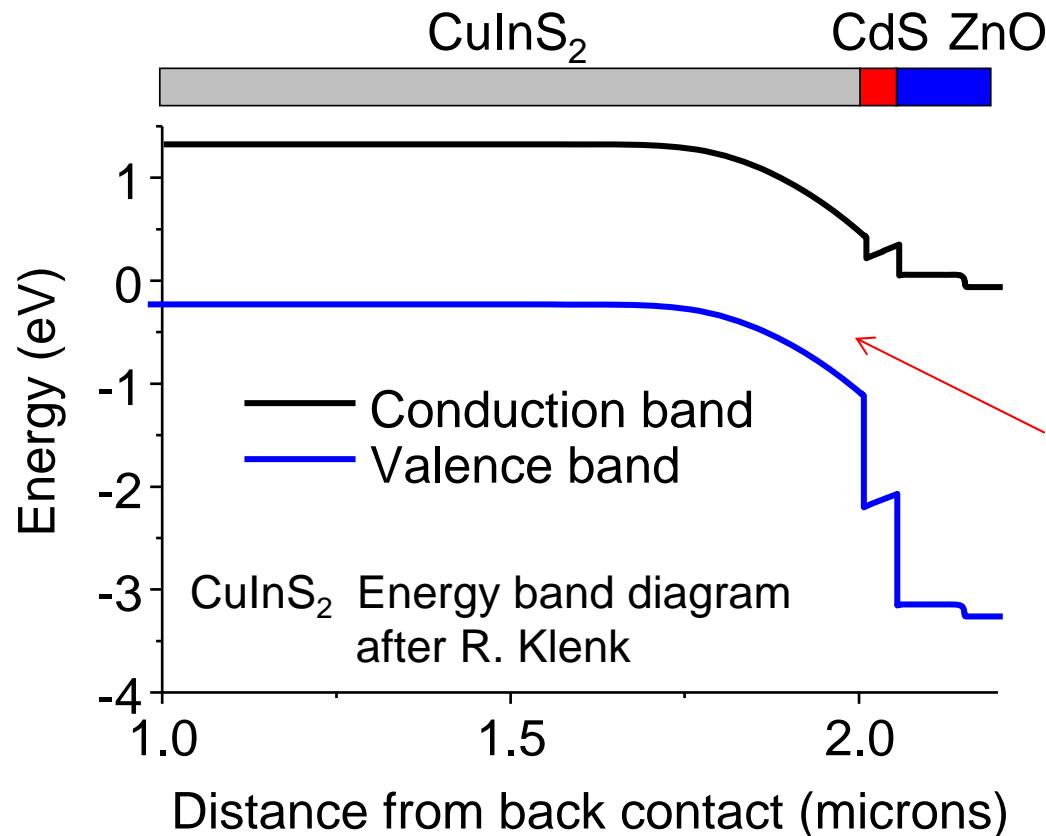
- Band bending in semiconductors and solar cells
- Experimental spectra from GaAs:Au samples
- Peak fitting and results
- Conclusions

# Motivation



- Thin film heterojunction solar cells are complex multilayer electronic devices
- Band lineup, doping density and interface charges crucial for device performance
- Multilayer structure with complex defect structures means that there is ambiguity in the usual capacitance based characterisation.

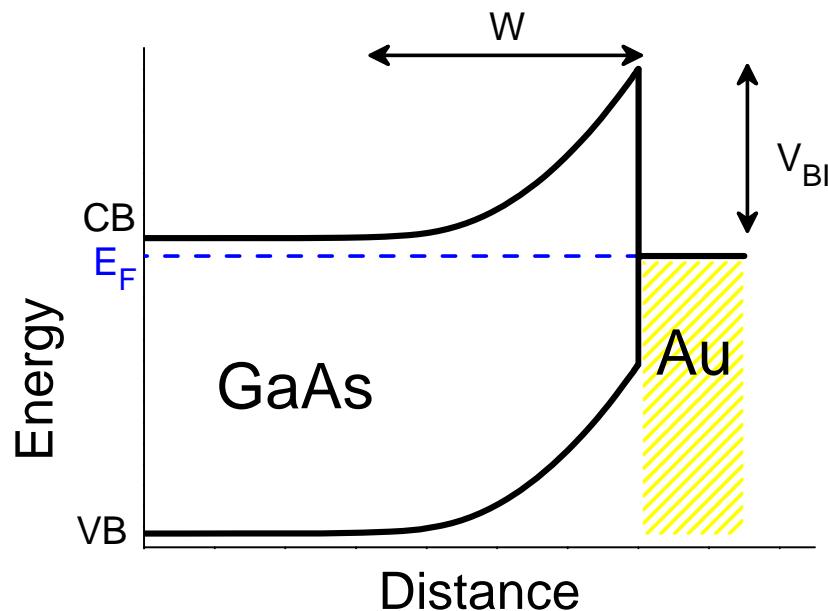
## Band bending in thin film solar cells



Critical interface has high interface charge and strong Fermi level pinning  
- Both effects are poorly quantified

Problem: Capacitance based measurements give ambiguous results

# Semiconductor junctions



$$\text{Depletion Width } W = \left( \frac{2 \epsilon V_{BI}}{e N_D} \right)^{1/2}$$

$$\text{Maximum Field } E_{\max} = \left( \frac{2 e V_{BI} N_D}{\epsilon} \right)^{1/2}$$

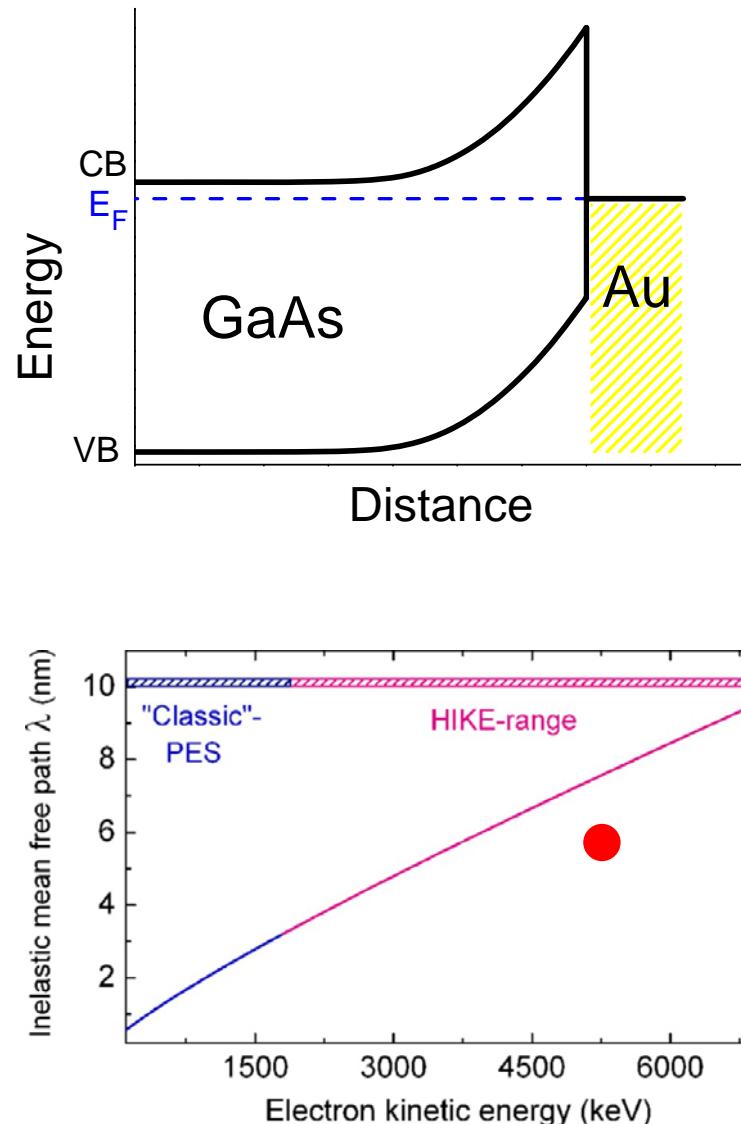
GaAs with  $V_{BI} = 1V$

$$N_D = 10^{16} \rightarrow W = 380\text{nm} \quad E_{\max} = 5.3 \text{ mV/nm}$$

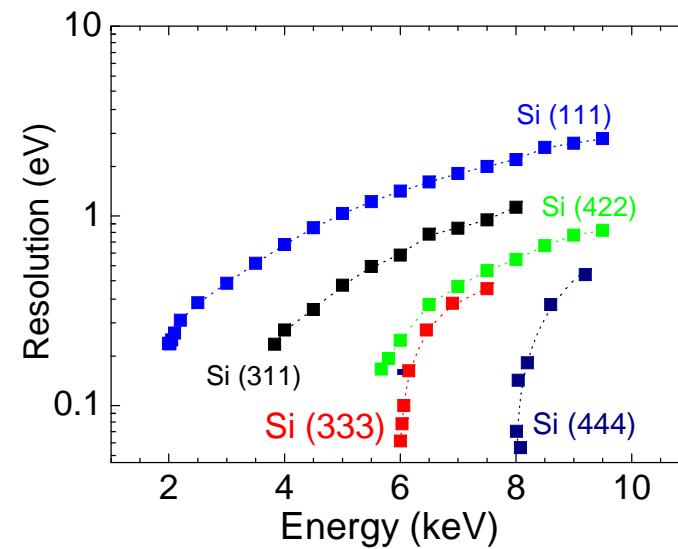
$$N_D = 10^{17} \rightarrow W = 120\text{nm} \quad E_{\max} = 16 \text{ mV/nm}$$

$$N_D = 10^{18} \rightarrow W = 38\text{nm} \quad E_{\max} = 53 \text{ mV/nm}$$

# Monitoring band bending with HAXPES in a model system



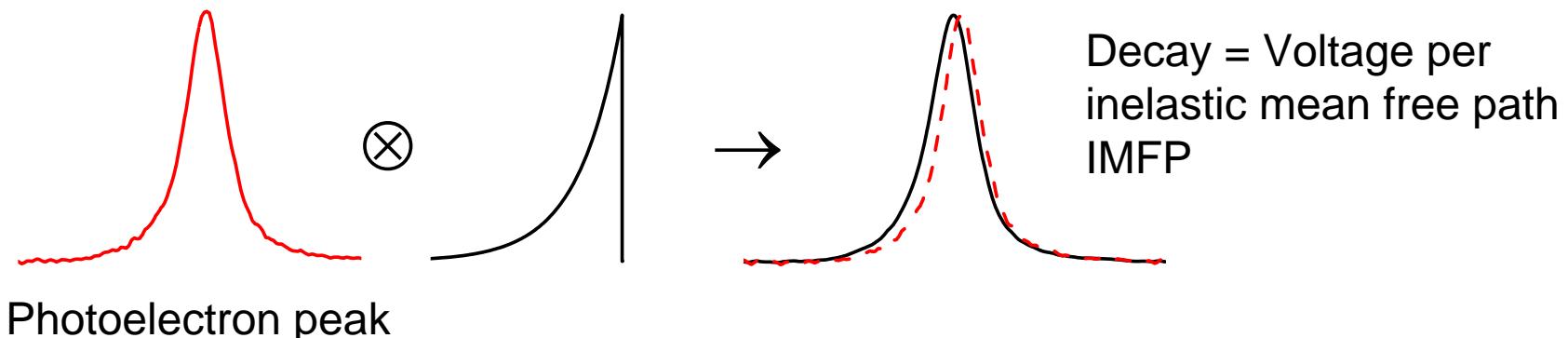
Model system: Schottky diode GaAs/Gold,  
excitation with 6 keV from KMC-1 @ BESSY II  
using HIKE-setup.



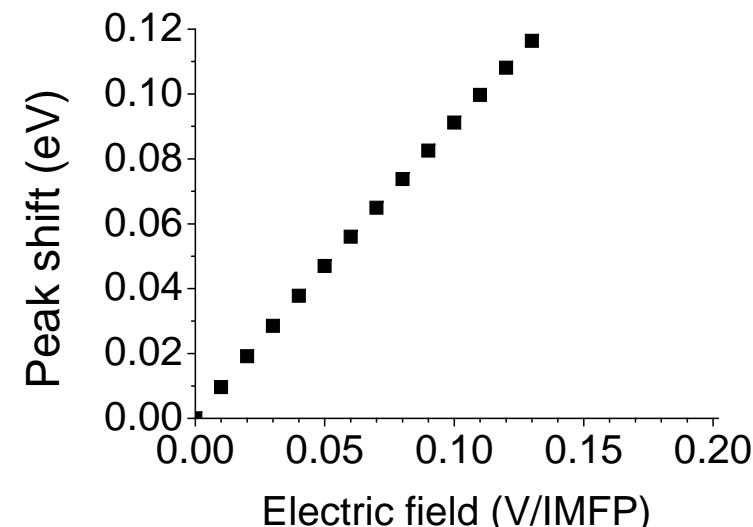
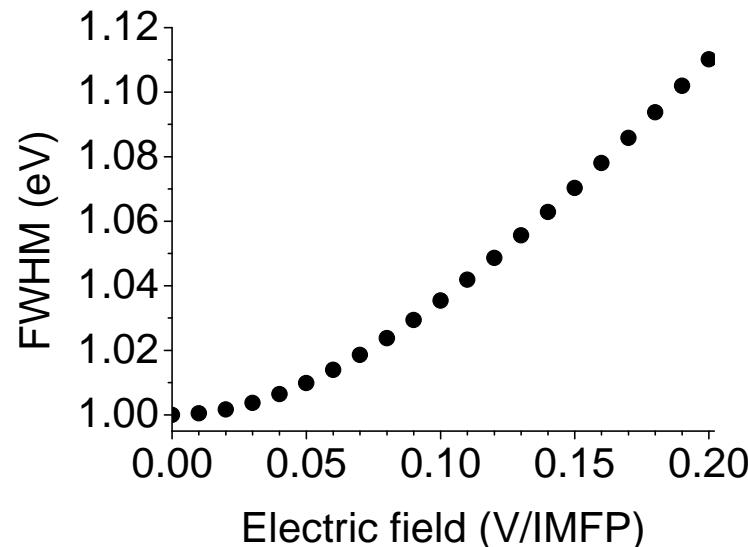
GaAs IMFP at 4900eV ~4.5nm  
Dallera et al. *J. Nucl. Inst. Meth. Phys. Res. A* 547 (2005) pp113

## The effect of an electric field

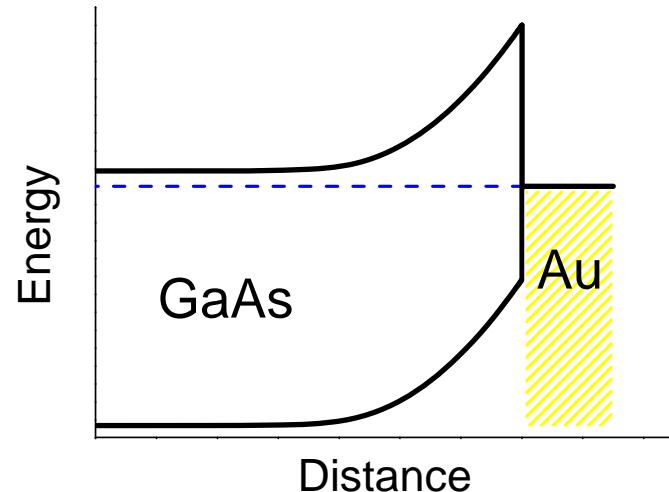
The effect of a linear electric field in an otherwise uniform sample is a convolution of the peak by an exponential decay function



See also G. Margaritondo et al. Phys. Rev. B, 47 (1993) pp 9907-9909

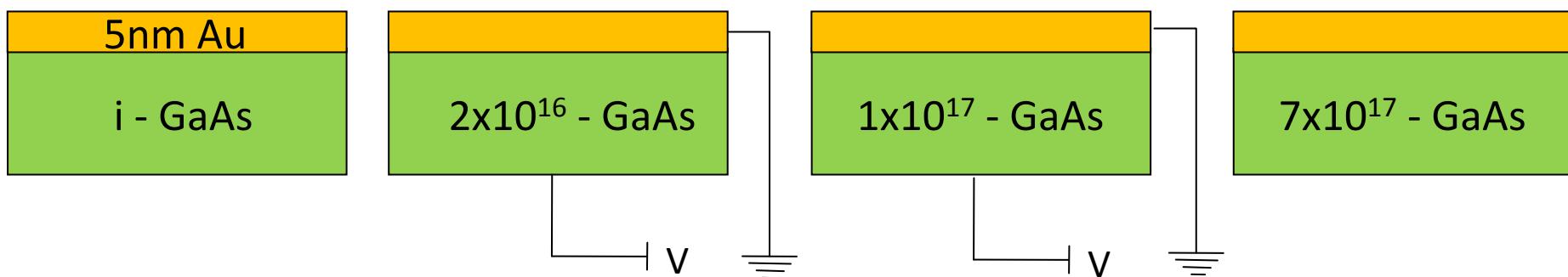


## GaAs - Au Schottky contact



High Energy PES allows GaAs peaks to be measured through a conductive ~5nm gold layer.

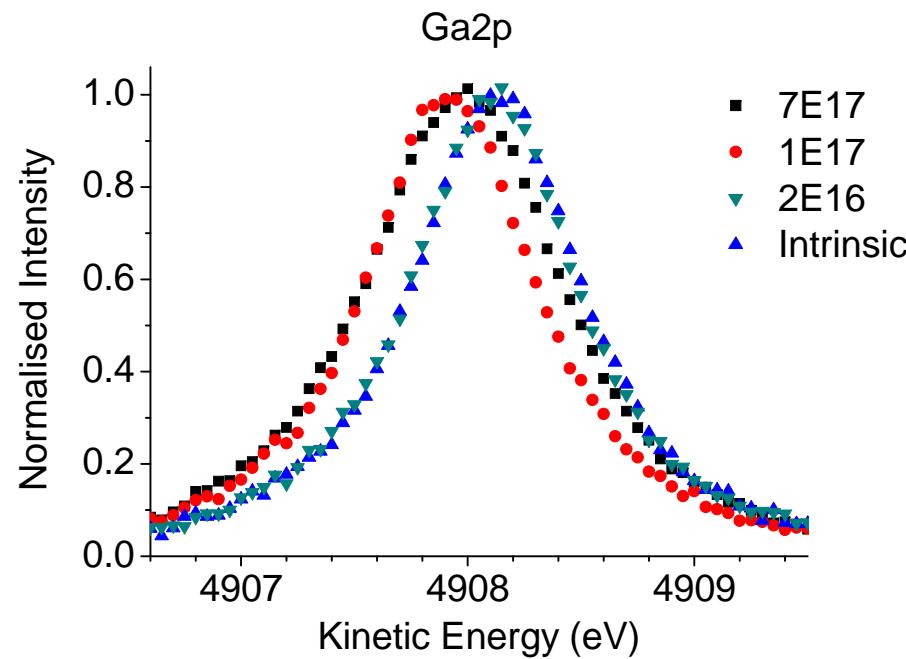
GaAs surface was sulfur terminated using ammonium sulfide treatment to give good Schottky contacts with gold.



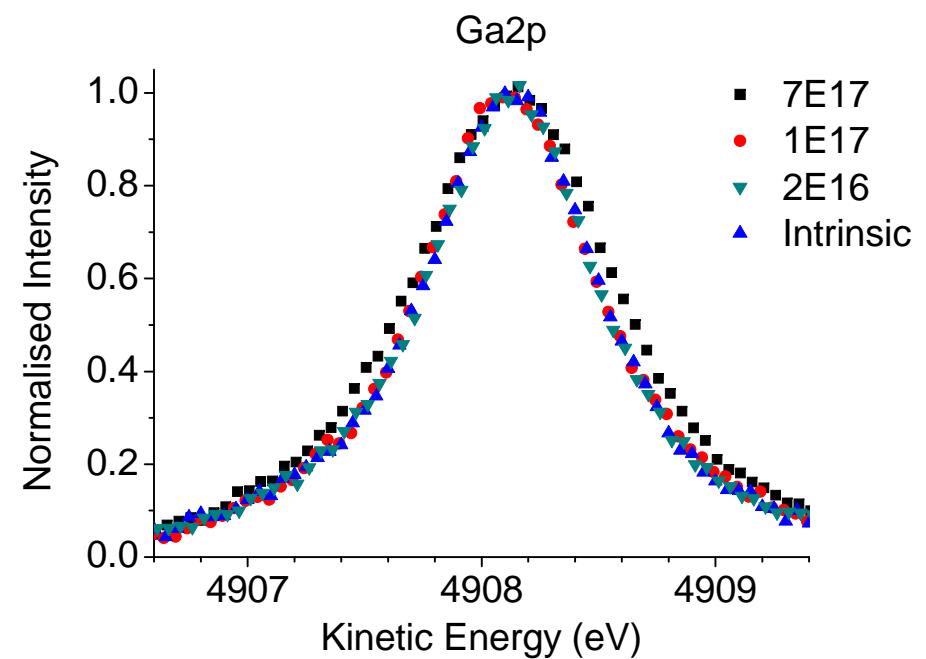
# Comparing doping concentrations

Ga2p spectra with different doping levels

As measured

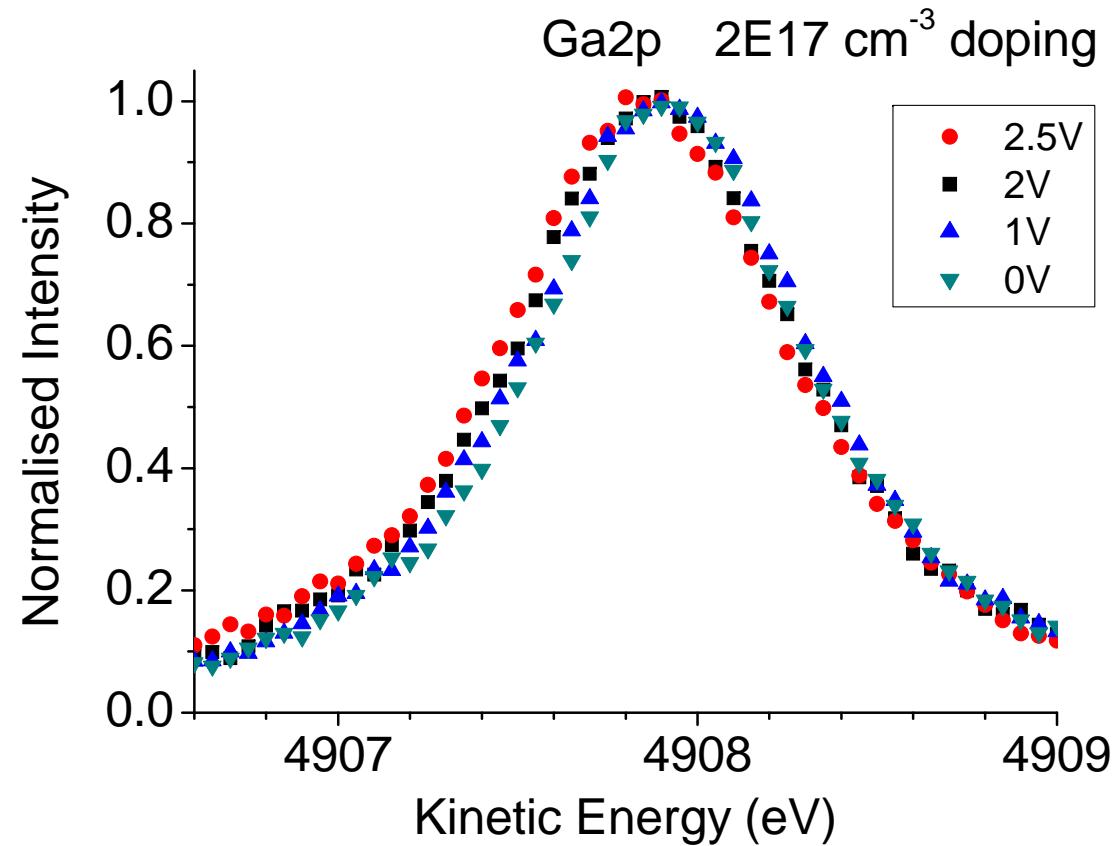


Aligned



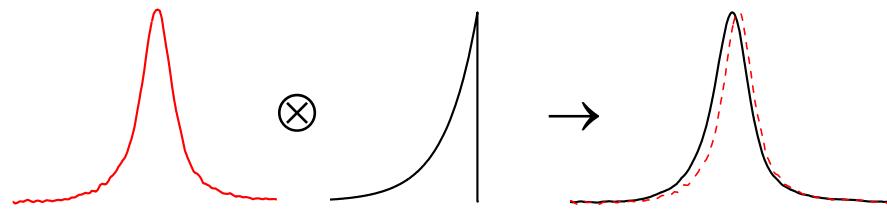
- Broadening clearly seen in the 7E17  $\text{cm}^{-3}$  doped sample.
- Broadening present but difficult to see in the lower doped samples
- Monitoring the shift between samples is not reliable – even using Au reference.

## Changing the field with an applied bias

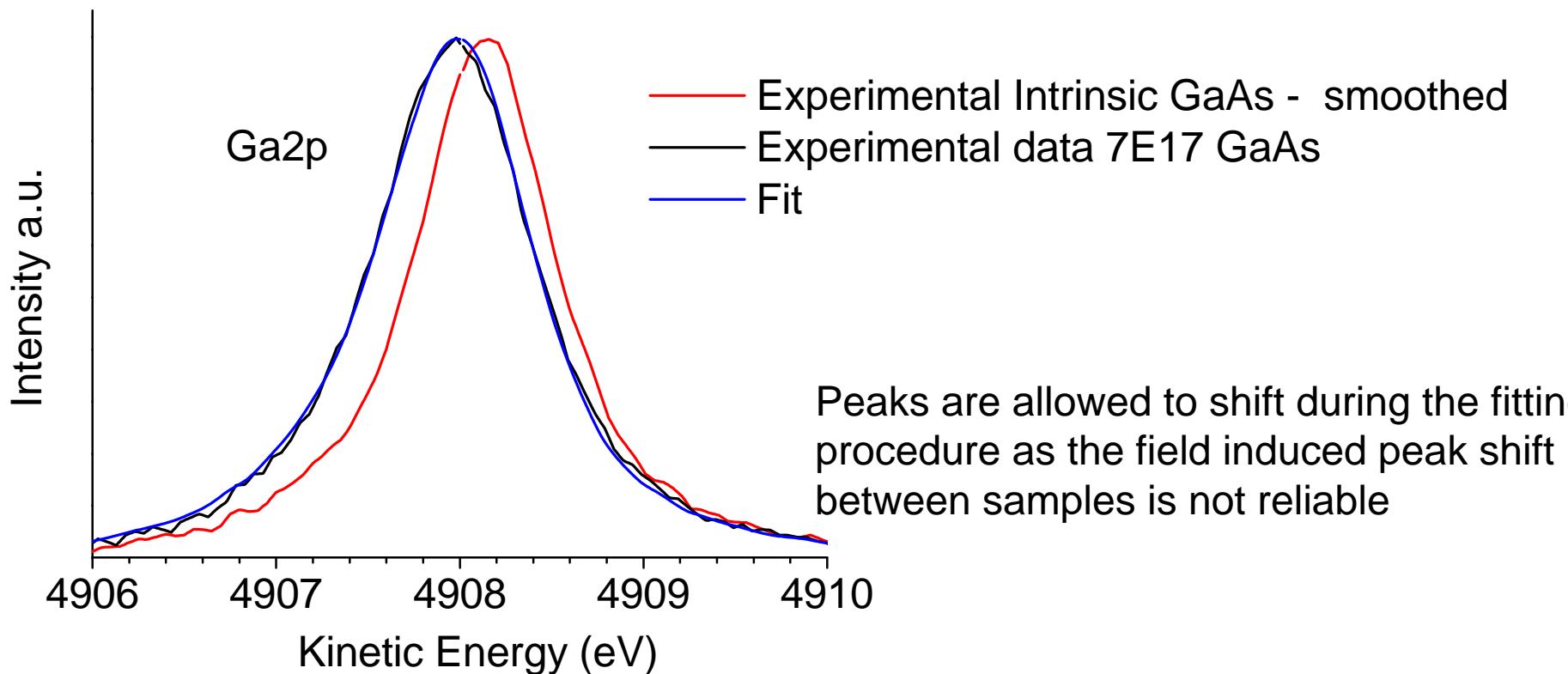


Both peak **shift** AND peak **broadening** can be monitored when the field in the same sample is varied using an applied bias

## Peak fitting



Fits performed by taking the experimental curve of i-GaAs and convoluting with an exponential function to represent the effect of an electric field.

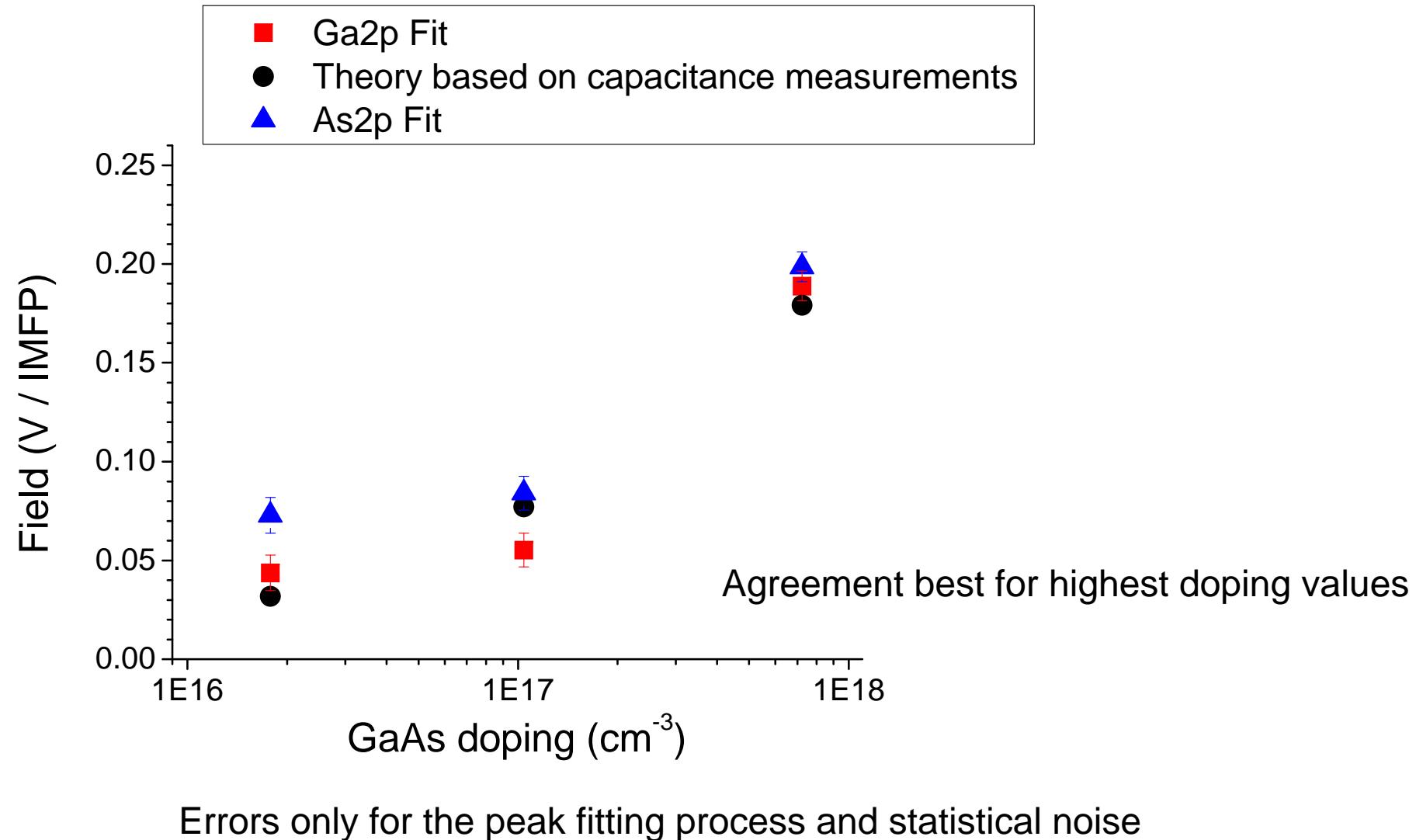


Monte Carlo type error analysis.

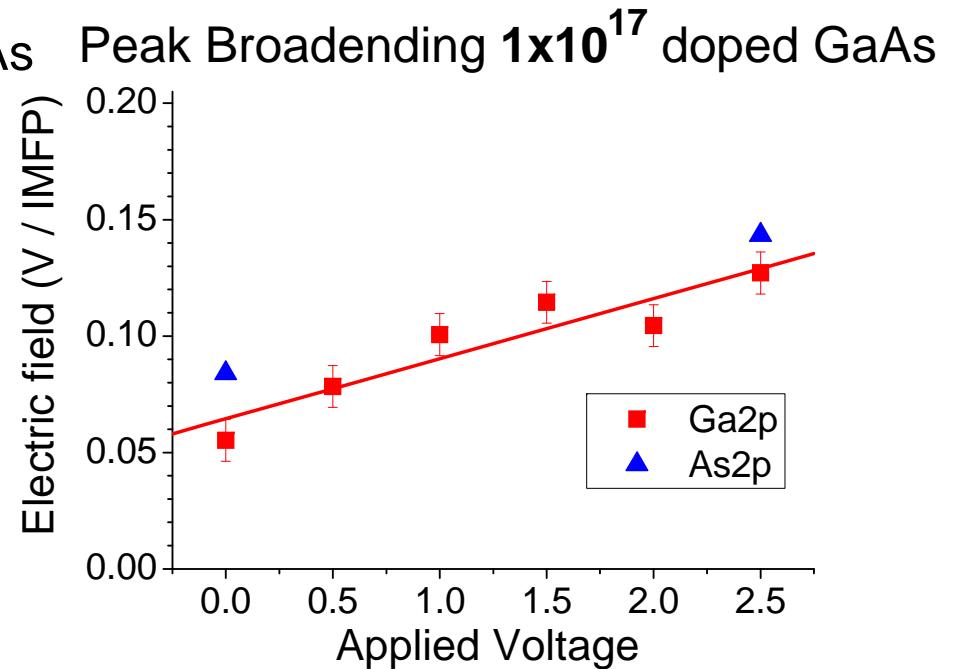
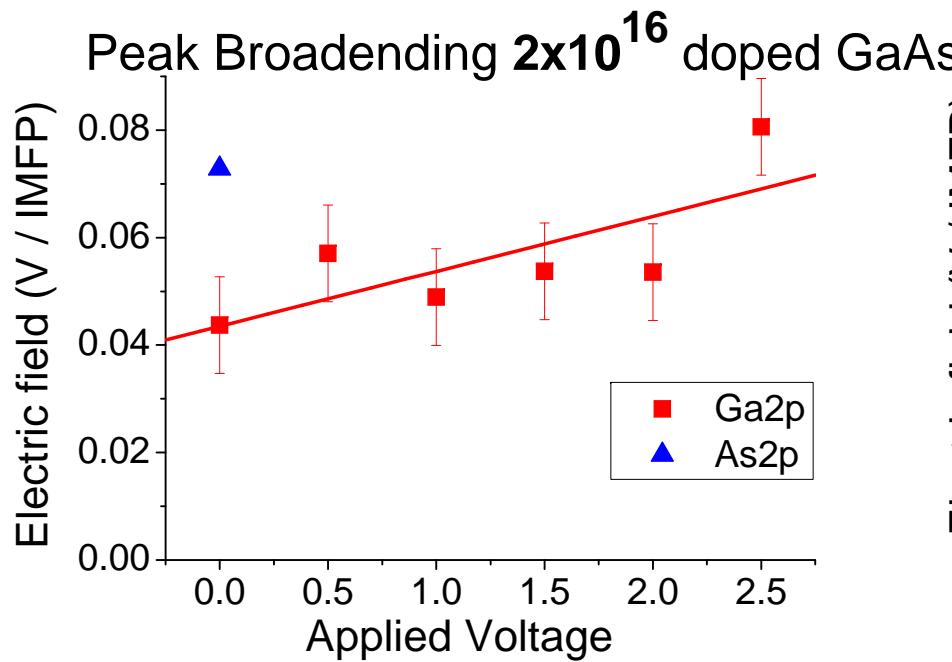
- Intrinsic GaAs fitted using 2 Voigt peaks.
- New doped/biased peaks generated using convolution with given electric field
- Poisson noise estimated from experimental curves and added to peaks. (x50)
- Fits performed
- Standard deviation calculated

Reference doping levels measured using capacitance methods (Mott-Schottky type)

## Results: Different doping levels



# Peak broadening with applied bias



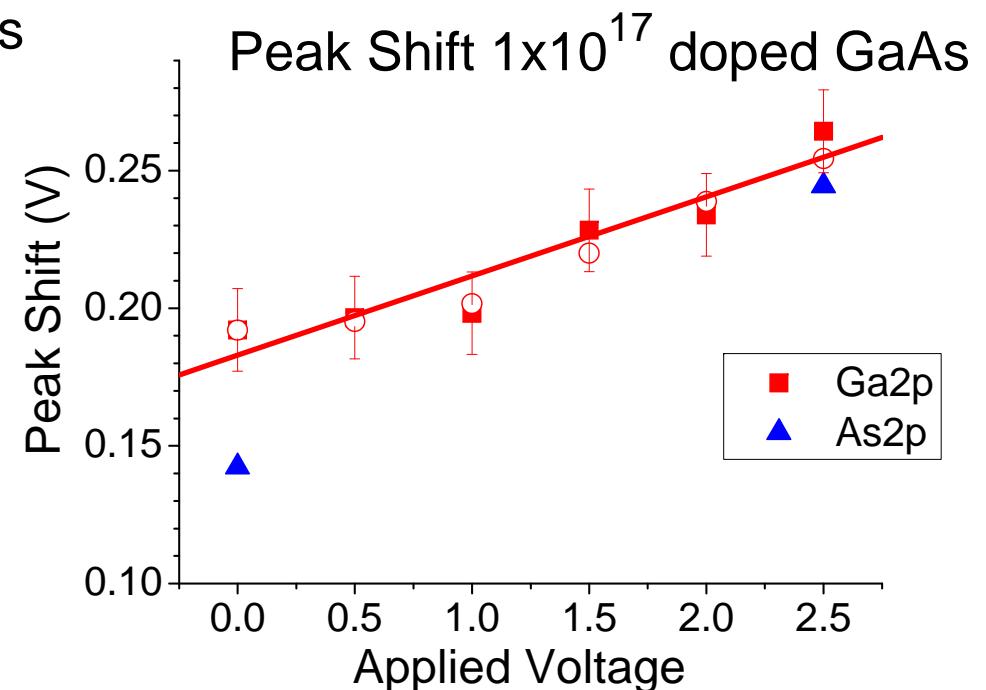
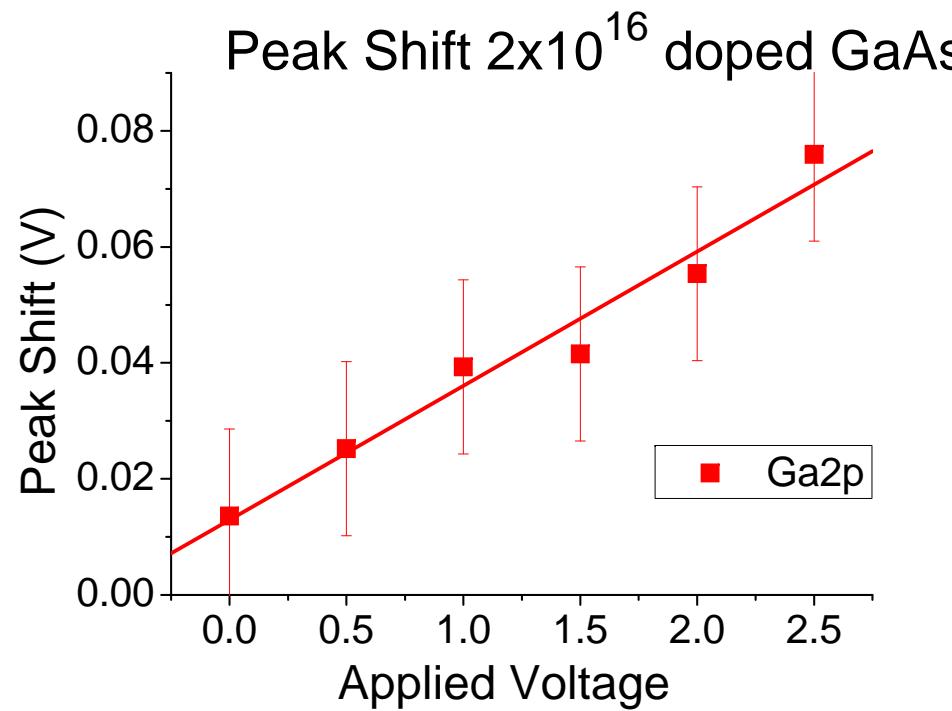
Estimated doping

min	$3.5 \times 10^{15}$
	$1.1 \times 10^{16}$
max	$2.1 \times 10^{16}$

Estimated doping

min	$1.5 \times 10^{17}$
	$4.2 \times 10^{17}$
max	$8.3 \times 10^{17}$

## Peak shift with applied bias



Estimated doping

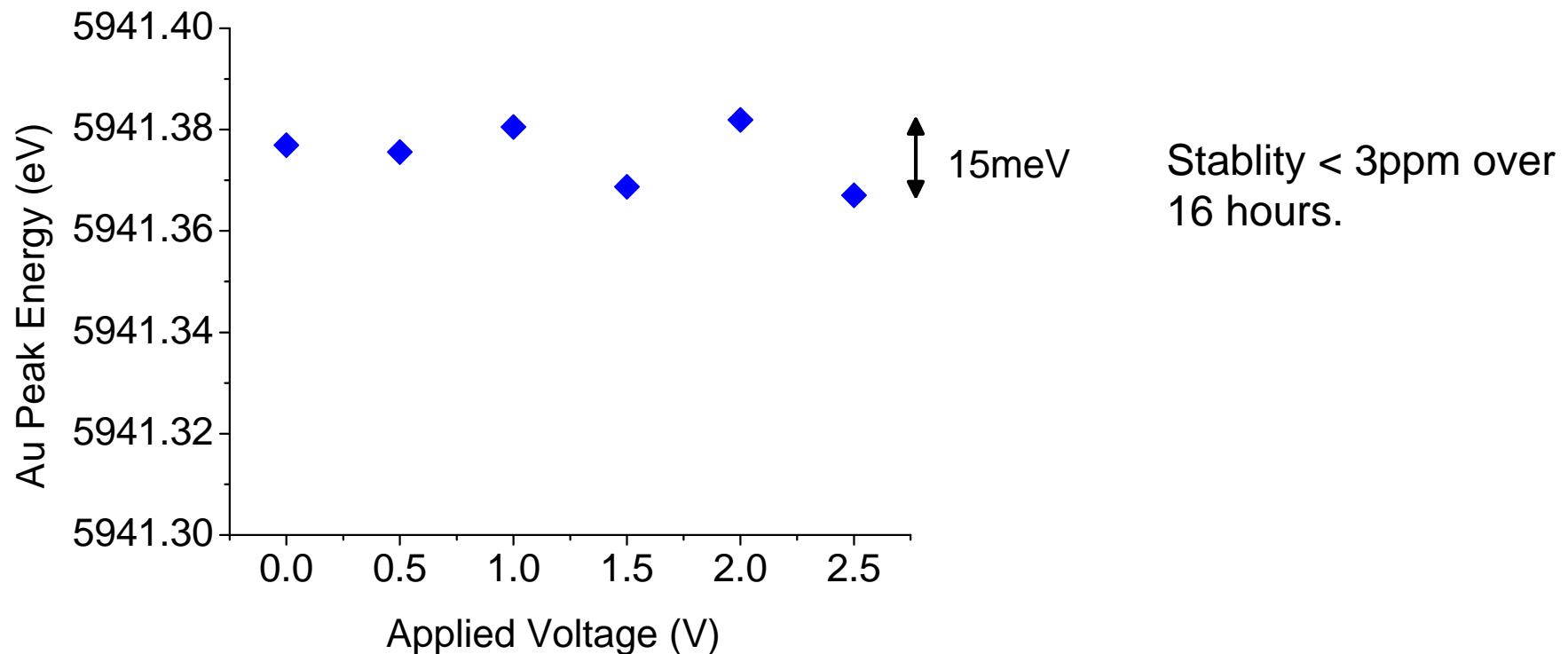
min	$3.6 \times 10^{16}$
max	$6.4 \times 10^{16}$
	$1.0 \times 10^{17}$

Estimated doping

min	$5.5 \times 10^{16}$
max	$9.8 \times 10^{16}$
	$1.5 \times 10^{17}$

## Stability

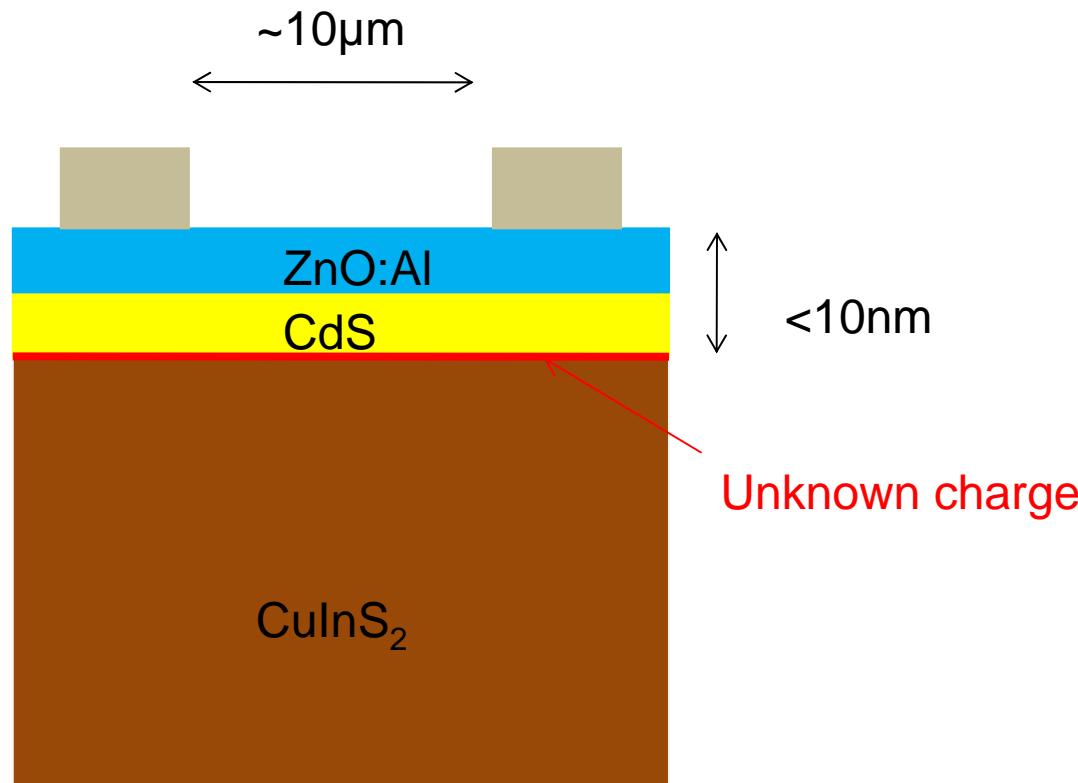
One of the key requirements for the experiment is a very high stability of the beam energy. Bias measurements for one sample needs ~16h



Only possible because:

1. Beryllium filter is used – reduced thermal load on crystal
2. Automatic beam optimisation disabled (some intensity loss)

## Possible thin film test structures



Additional problems:

- Low cross sections of the peaks at 6keV excitation
- Large intrinsic widths of the strongest peaks



## Conclusions

- The effect of the electric field on peak widths and peak shifts can be seen in high energy PES measurements through 5 nm of gold.
- Controlled variation of the electric field using an in-situ applied bias was used to confirm the effects.
- Peak shifts are more sensitive when the field is changed in-situ.
- May provide an additional tool to characterise complex devices.
- Beam stability is of critical importance.



## Acknowledgements

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**Thank you for your attention!**