The University of Nottingham

School of Physics & Astronomy

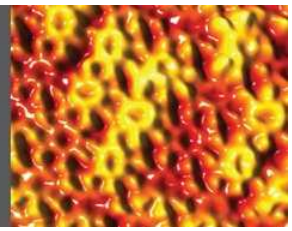
# Surface morphology and magnetic anisotropy in (Ga,Mn)As

*Dr Samanta Piano*

IOP Institute of Physics

Interdisciplinary Surface Science Conference (ISSC-19)

25–28 March 2013, East Midlands Conference Centre, Nottingham, UK



*26-03-2013*

# Spintronics

*A new scheme of electronics using the charge and the spin of the electron*

## Semiconductor devices

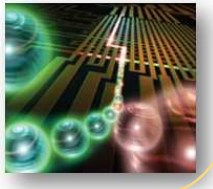
✓Transistor
✓LED
✓CPU,..


## Magnetic devices

✓Non-volatile memory
✓ Storage
✓ Magneto-optical devices,...

## Ferromagnetic semiconductor

✓spin and charge of electrons as information carriers
✓ storing and manipulating data
✓ faster and smaller memories



# Motivations


**Applications**

✓Realisation of devices for **spintronics** industry and quantum information

**Fundamental physics**

✓Study of magnetic properties

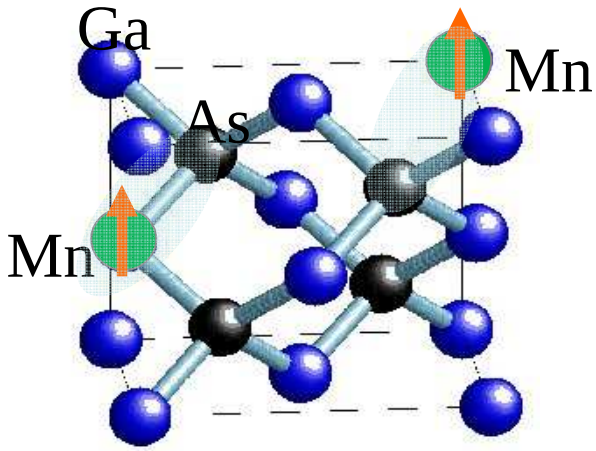
✓Understanding the microscopic origin of the **magnetic anisotropy**

# Contents

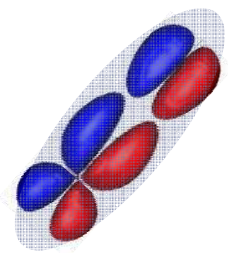
The University of Nottingham

- ✓ Introduction to (Ga,Mn)As
- ✓ AFM images
- ✓ Study of the ripples with Fourier analysis
- ✓ Relation between ripples and magnetic anisotropy
- ✓ GID experiments and analysis
- ✓ Conclusions and future perspectives

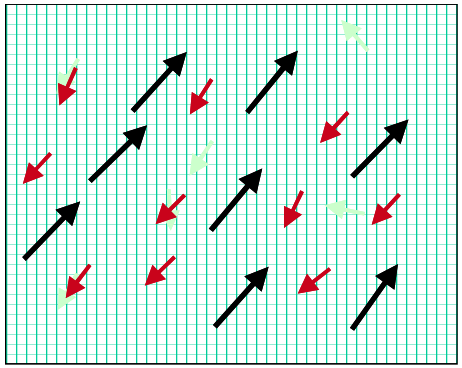
# (Ga,Mn)As



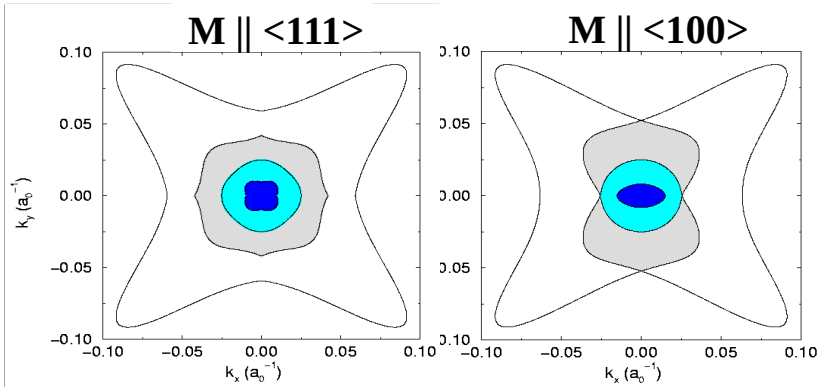

***As-p-like holes***



***Mn-d-like local moments***



Ferromagnetic order is mediated by the itinerant holes for few % Mn
Holes possess **strong SO-coupling**




## Anisotropy

- ✓ Spin-orbit coupling gives rise to large **magnetocrystalline anisotropy**
- ✓ The anisotropy is sensitive to the lattice strain and the carrier density

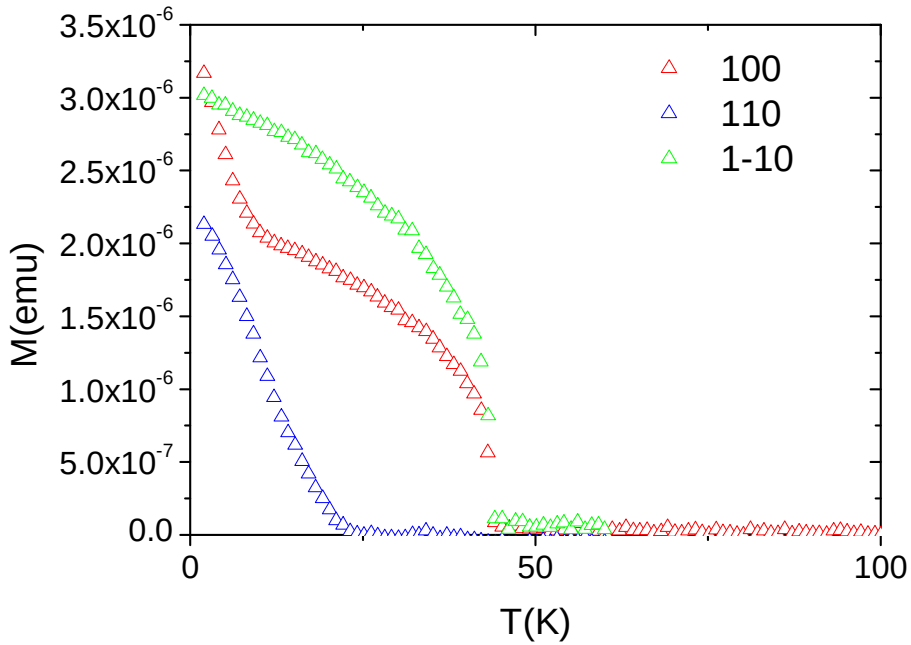


Abolfath et al. Phys. Rev B 63, 054418 (2001)
Dietl et al. Phys. Rev. B 65, 195205 (2001)

# Magnetic properties

**Remanent measurements**

- *dominant in plane [1-10] uniaxial magnetic easy axis at high temperature*
- *competition between in plane [1-10] uniaxial and in-plane [100] bi-axial easy axes at low temperatures.*




**Magnetic anisotropy**

*the relative strength of the uniaxial to cubic anisotropy is phenomelogically described by:*

$$\frac{K_U}{K_C} = \cos 2[\arctan \frac{M1\bar{1}0}{M110}]$$



K.-Y.Wang, et al. , Phys. Rev. Lett 95, 217204 (2005)

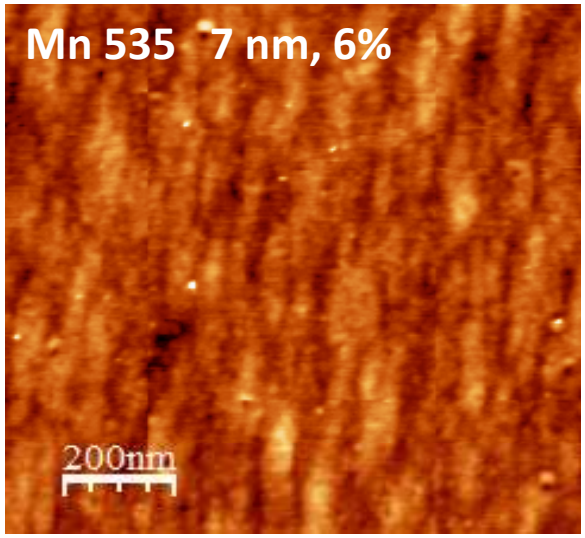
# (Ga,Mn)As growth

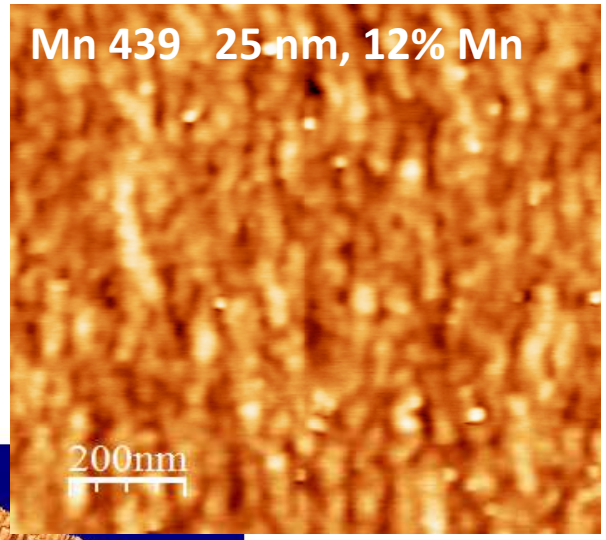
- Molecular Beam Epitaxy growth *(~ 200 °C)*
  - GaAs (100 nm) substrates
  - GaAs or AlGaAs buffer layer
  - 5, 7 and 25 nm thick
  - 6% and 12% Mn concentration

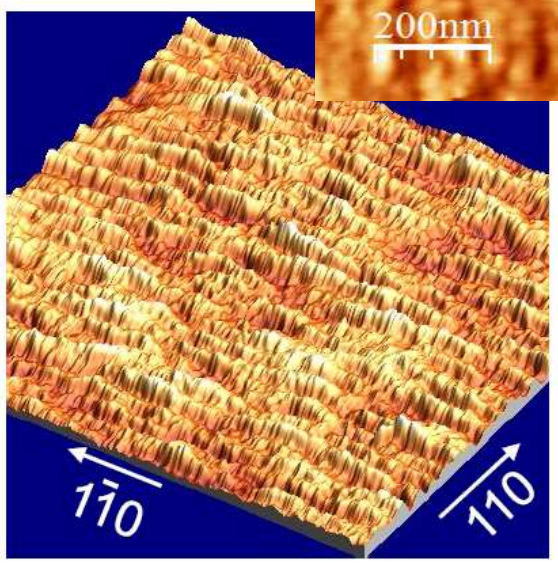


R.P. Campion, *et al., J. Cryst. Growth* ***247, 42 (2003)***

# Atomic Force Microscopy




**Mn 381 7 nm, 6% Mn**

**AFM images:**

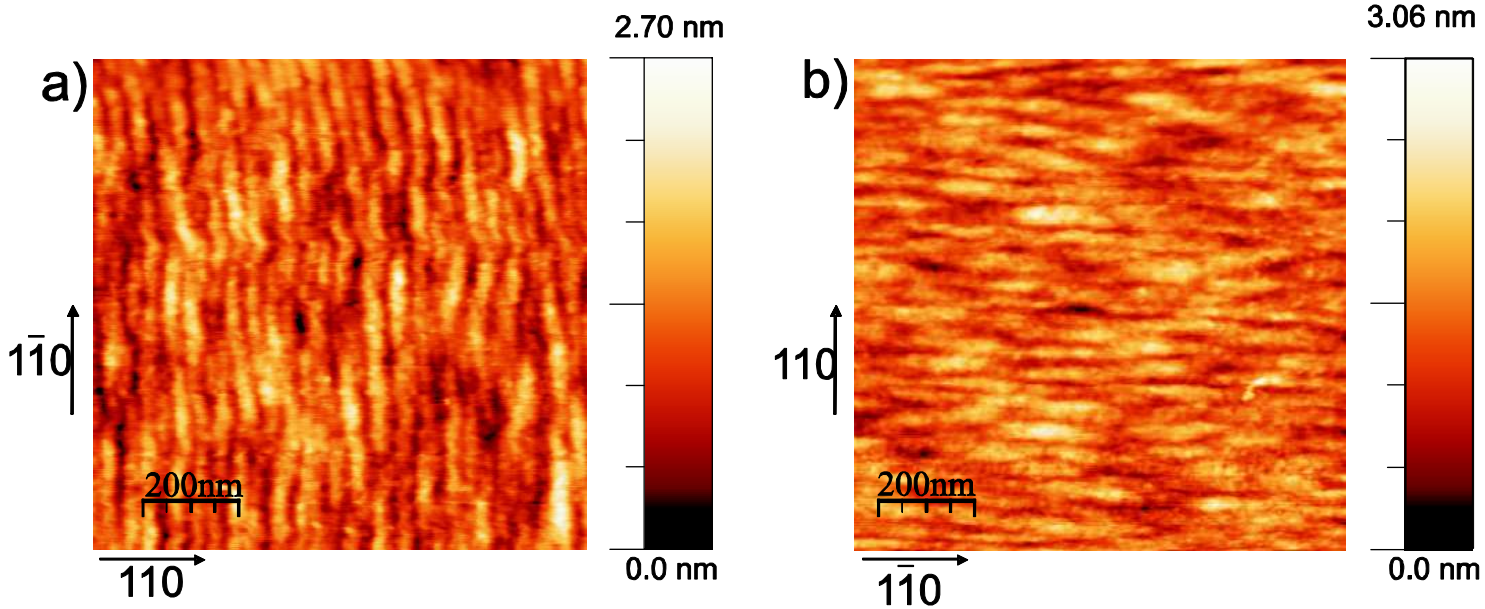
***Asylum Research MFP-3D AFM***

*Presence of ripples along 1-10 direction for all the analysed samples*



**SP,** *et al.* Appl. Phys. Lett. ***98,*** *152503 (2011)*
J. Nanosci. Nanotechnol ***12****, 7545 (2012)*

# Atomic Force Microscopy

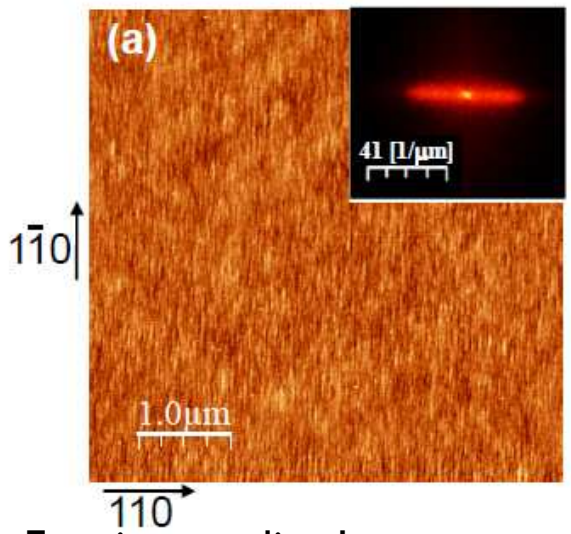



- **Fourier analysis**

  *to extract quantitative information from these images*

  - Effective period of the oscillations
  - Root mean square roughness (RMS)

# 2D Power Spectral Density



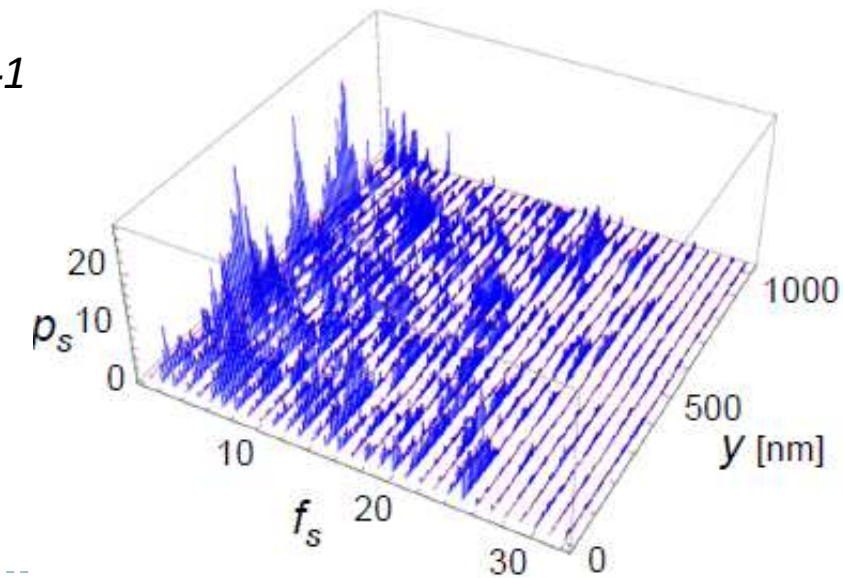

The 2D PSD spectrum shows clearly the **surface anisotropy**, indicating that periodicity across the horizontal direction is strongly enhanced compared to the vertical one

Fourier amplitude corresponding to a frequency *fs=s-1*

$$\phi_s = \frac{1}{\sqrt{n}} \sum_{r=1}^{n} z_r e^{2\pi(r-1)(s-1)/n}$$

The PSD is defined as

$$p_s = |\phi_s|^2$$

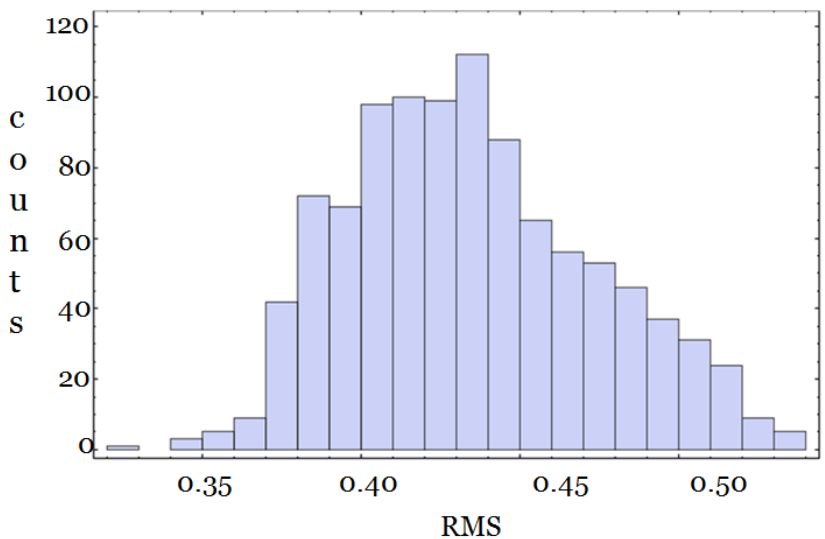


# Amplitude

**RMS roughness** as standard deviation of the *z(y) height data and it is equal* to the amplitude *(A) of the oscillations*

$$A = \sqrt{2}RMS = \frac{\sqrt{2\sum_{s=1}^{n} p_s}}{n-1}$$

***Distribution of the RMS across the horizontal scan lines***



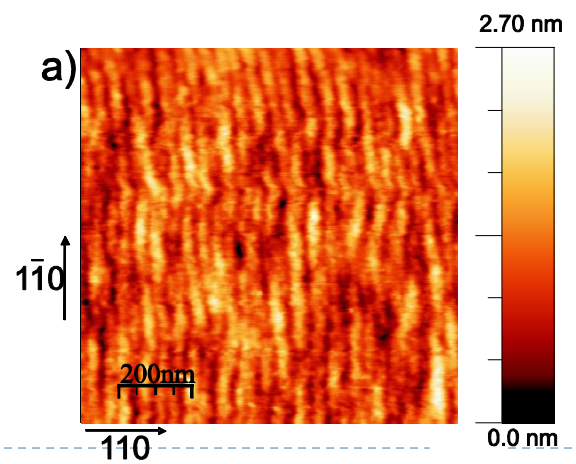
# Period

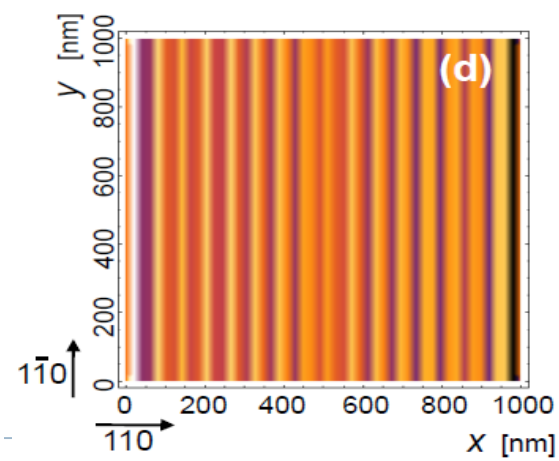
The mean frequency per line is an average of the frequencies of all Fourier harmonics (along a given horizontal scan line) weighted with the corresponding PSDs

$$\overline{f}(y) = \frac{\sum_{s=1}^{n/2} (s-1) p_s}{\sum_{s=1}^{n/2} p_s}$$

the global "effective" mean frequency is given by the mean of the *f(y)'s of each line y along all horizontal* scan lines

**Period of the oscillations:** $\tau = \frac{L}{\overline{f}}$

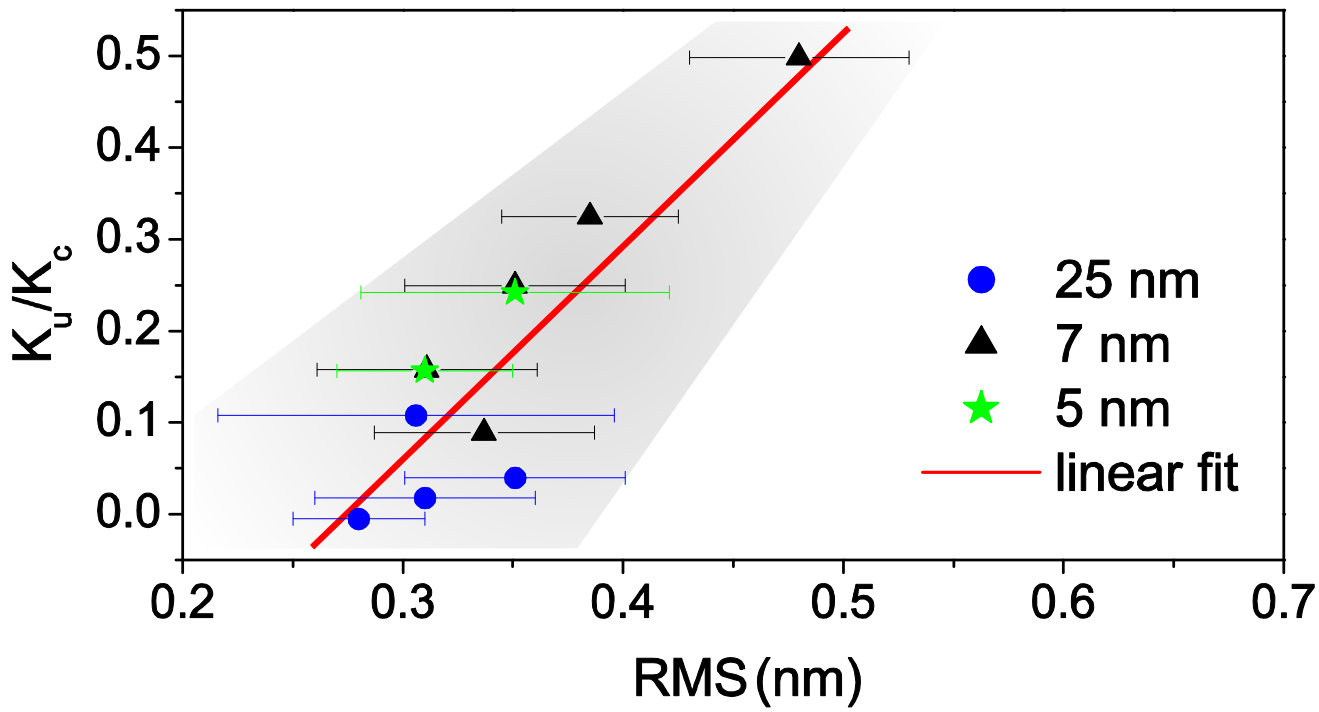


# Data

| sample | t , Mn% | buffer | $\tau$ | RMS | $K_u/K_c$ |
|---|---|---|---|---|---|
| Mn 352 | 5, 6% | A HT | 49.7 ± 12.7 | 0.35±0.07 | 0.241 |
| Mn 536 | 5, 6% | B HT + B LT | 45.5 ± 11.3 | 0.31±0.04 | 0.157 |
| Mn 396 | 7, 6% | B HT | 47.7 ± 8.2 | 0.48±0.06 | 0.498 |
| Mn 381 | 7, 6% | B HT | 41.9 ± 6.4 | 0.38±0.04 | 0.325 |
| Mn 555 | 7, 6% | A HT | 47.7 ± 6.3 | 0.3±0.1 | 0.158 |
| Mn 535 | 7, 6% | B LT | 45.4 ± 10.3 | 0.34±0.04 | 0.089 |
| Mn 394 | 7, 6% | A HT | 59.8 ± 13.5 | 0.35±0.05 | 0.249 |
| Mn 437 | 25, 12% | A LT | 51.5 ± 8.6 | 0.36 ± 0.06 | 0.113 |
| Mn 438 | 25, 12% | A LT | 61.7 ± 11.4 | 0.37 ±0.07 | 0.149 |
| Mn 554 | 25, 6% | B LT | 56.0 ± 16.9 | 0.35 ± 0.04 | 0.039 |
| Mn 499 | 25, 6% | A HT | 47.8 ± 11.8 | 0.31± 0.05 | 0.018 |
| Mn 330 | 25, 6% | A HT | 65.9 ± 11.3 | 0.31 ± 0.09 | 0.107 |
| Mn 490 | 25, 6% | A HT | 52.5 ± 8.3 | 0.28 ± 0.03 | -0.005 |

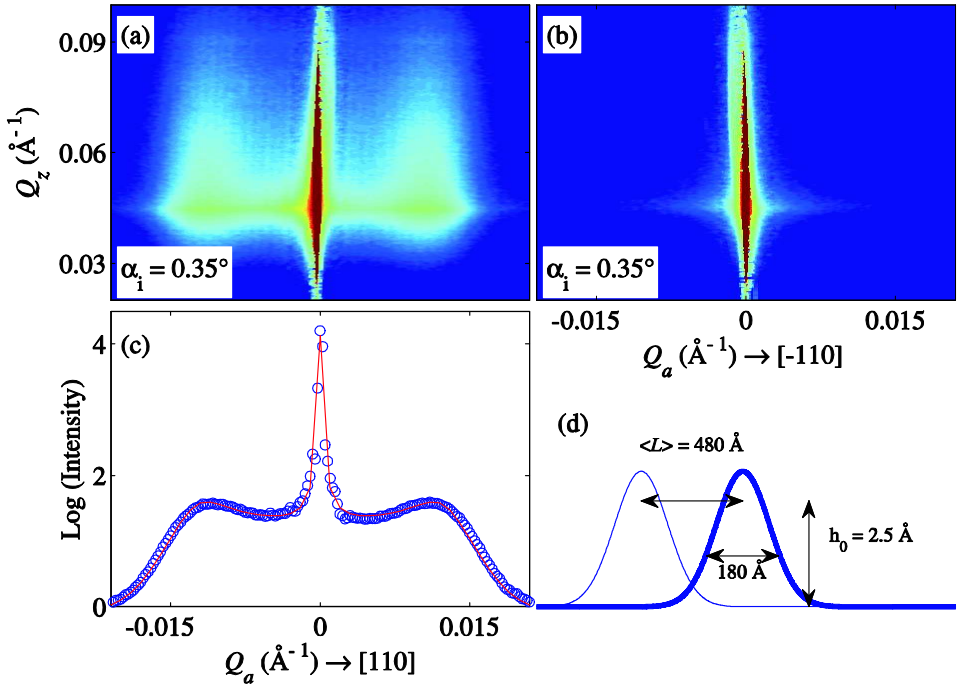
# RMS *vs* magnetic anisotropy




✓ *clear relation between the ratio of the magnetic anisotropy constants* $K_U/K_C$ *and the* ***RMS*** *roughness*

✓ *the uniaxial anisotropy increases as the RMS roughness increases*

# GID experiment




- ✓ Scans with the primary beam directed across the ripples (a) show two symmetric satellites
- ✓ satellites are absent in the scans along the ripples (b)
- ✓ by fitting the profile in (a) by assuming Gaussian-shaped ripples we obtained a periodicity of about 48 nm

# Conclusions

The University of Nottingham

## Our aim was to investigate the magnetic anisotropy in (Ga,Mn)As

- ***AFM*** *and* ***X-ray GID*** *measurements have revealed the presence of* ***ripples*** *aligned along the [1-10] direction on the surface of (Ga,Mn)As layers*
- *We find that the strength of the uniaxial anisotropy of these layers increases with the amplitude of the ripples.*
- *This suggests that* ***the symmetry breaking uniaxial anisotropy*** *observed in (Ga,Mn)As might be related to these symmetry breaking structural features*

- ***...more investigation...***

  *could give us the possibility to relate the formation of the periodic structures with the presence of uniaxial strain, that may lead to a deeper understanding of the origin of the magnetic anisotropy*

# Thank you

University of Nottingham, Physics and Astronomy Department:
***S . Piano***, *A.W. Rushforth, K.W. Edmonds, R.P. Campion, M. Wang, B. L. Gallagher*

University of Nottingham, School of Mathematical Sciences :
*G. Adesso*

Department of Condensed Matter Physics, Charles University:
*X. Marti, V. Holy*

Institute of Condensed Matter Physics, Czech Republic:
*O. Caha*

ESRF, Grenoble
*T. U. Schulli*

Funding from the EU
(Grant No. NAMASTE-214499 and
Grant No. SemiSpinNano-237375).