Correlating the Interface Structure to Spin Injection in Abrupt Fe/GaAs(001) Films

L.R. Fleet[1], K. Yoshida[2,3], H. Kobayashi[4], Y. Kaneko[4], S. Matsuzaka[4], Y. Ohno[4], H. Ohno[4], S. Honda[5], J. Inoue[6] and A. Hirohata[7,8]
Department of [1]Physics / [7]Electronics, The University of York, York, YO10 5DD, UK
[2]Department of Crystalline Materials Science and Ecotopia Science Institute, Nagoya University, Nagoya, 464-8603, Japan
[3]Nanostructures Research Laboratory, Japan Fine Ceramics Center, Nagoya, 456-8587, Japan
[4]Research Institute of Electronic Communication, Tohoku University, Sendai, 980-8577 Japan
[5]Institute of Applied Physics, University of Tsukuba, Tsukuba, 305-8573, Japan
[6]Department of Applied Physics, Nagoya University, Nagoya, 464-8603, Japan
[8]PRESTO, Japan Science and Technology Agency, Kawaguchi, 332-0012, Japan

l.fleet@imperial.ac.uk

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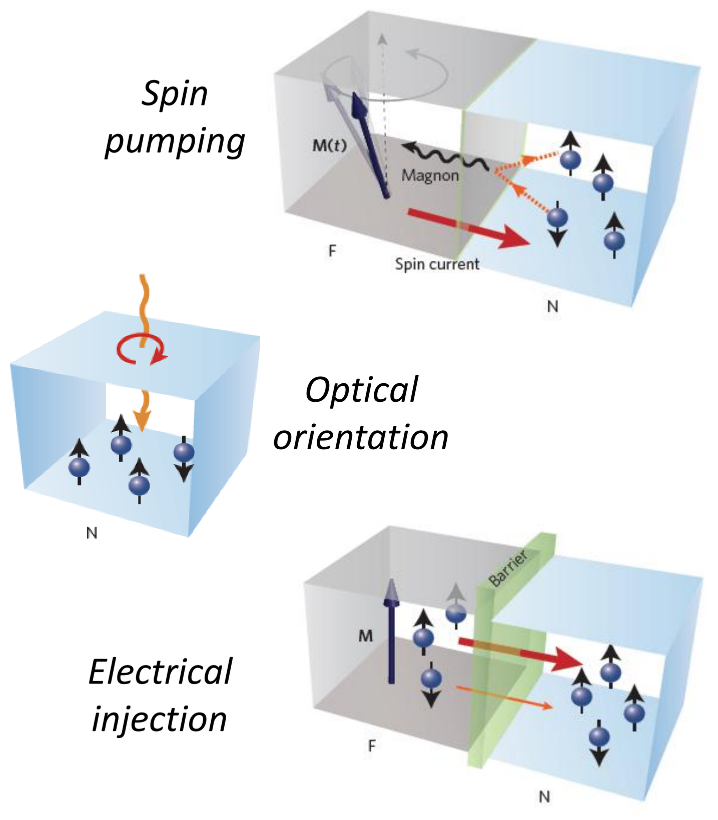
Introduction

Although there are several techniques to create a non-equilibrium spin population in conventional semiconductors, electrical injection/detection is essential for the development of next generation semiconductor spintronic devices [1, 2].

Despite its importance, the effect of the atomic interface structure on electrical spin injection in ferromagnetic/semiconductor heterostructures remains poorly understood.

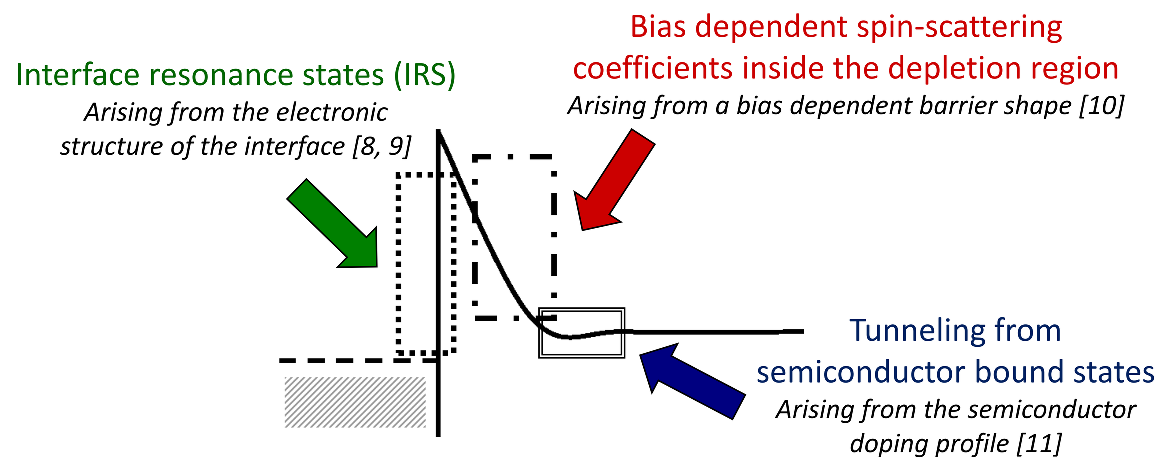
Fe/GaAs(001) is one of the leading candidate systems to explore the effect of the interface structure on spin injection/detection.



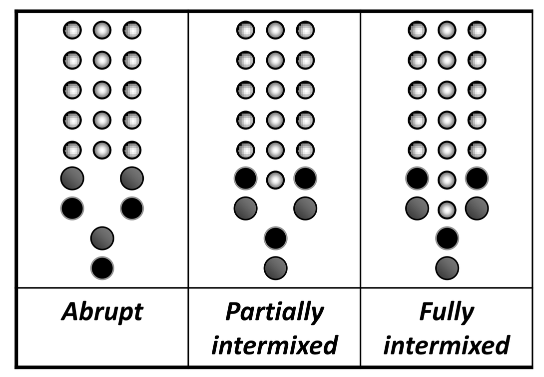
Fe/GaAs(001)

The small lattice mismatch of ~1.4% in Fe/GaAs(001) allows for high quality epitaxial films to be grown [3].
The intrinsic Schottky barrier overcomes the problems arising from the conductivity mismatch [4].

Experiments have shown that electrical injection/detection can be achieved in Fe/GaAs(001) films but a **polarization inversion** [5-7] can occur, most likely due to:



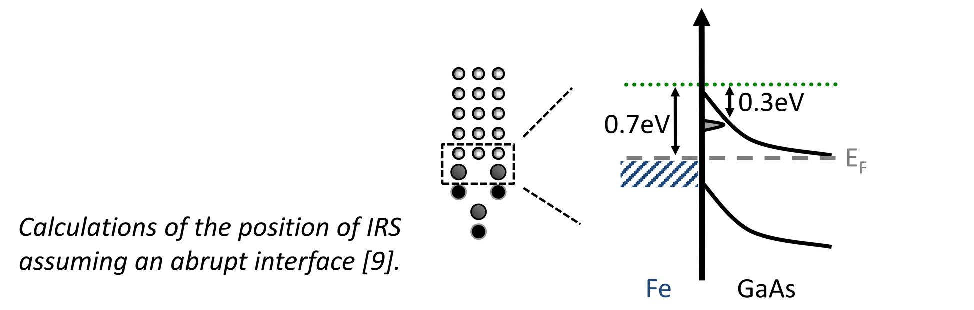
Proposed interface structures [12]



The abrupt interface is predicted to be the most likely interface structure for As-rich terminated surfaces [12].

Despite frequently being used in calculations, the abrupt interface has never previously been reported.

Tunneling from IRS appears to be the most promising mechanism to explain all the observed phenomena.

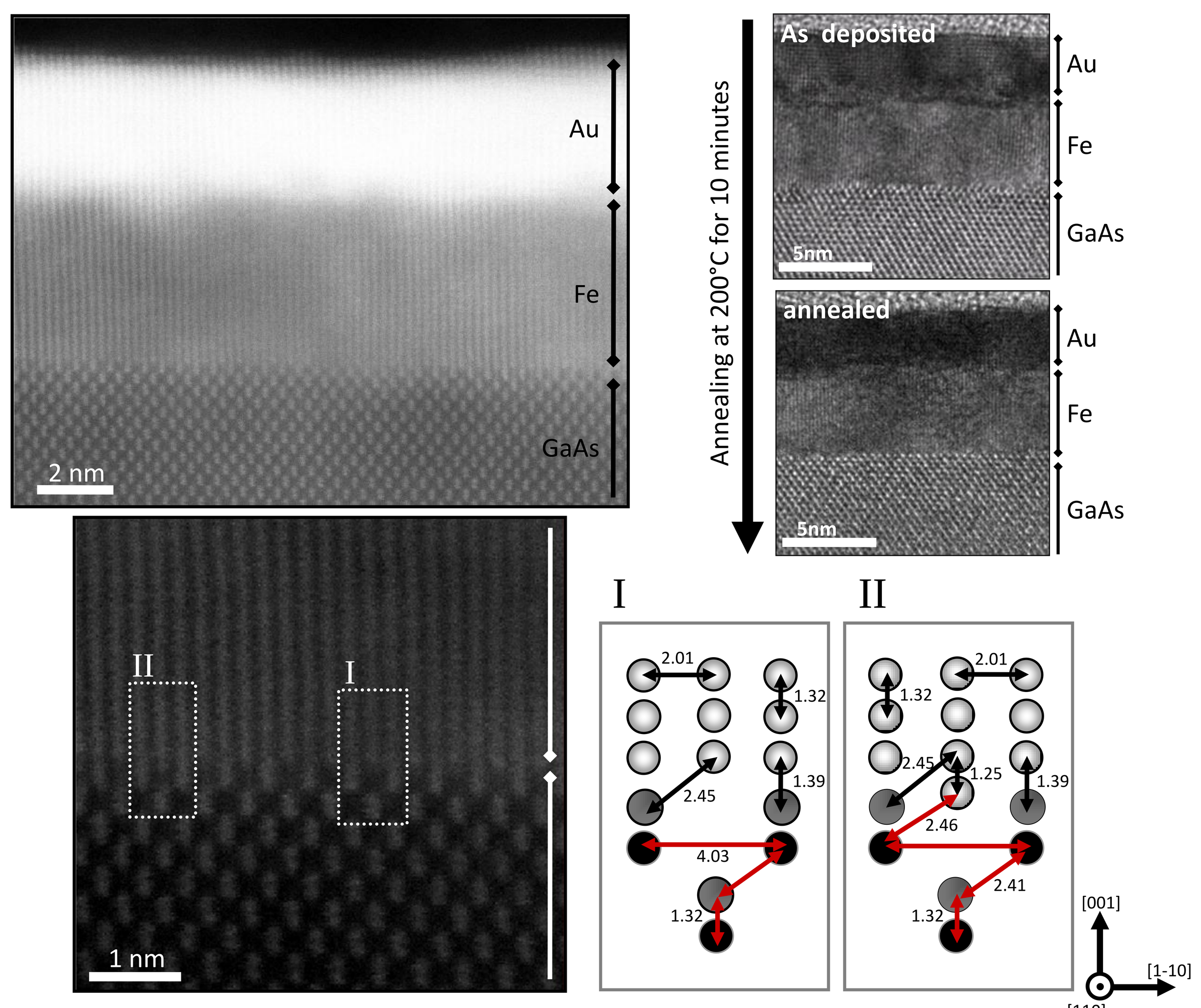


As the strength and position of IRS are extremely sensitive to the atomic interface structure, knowledge of the interface and the effect on the transport is essential.

Interface structure

Images were taken using C_s corrected TEM and STEM showing high quality epitaxial films.

Low temperature annealing reduces the interface roughness.

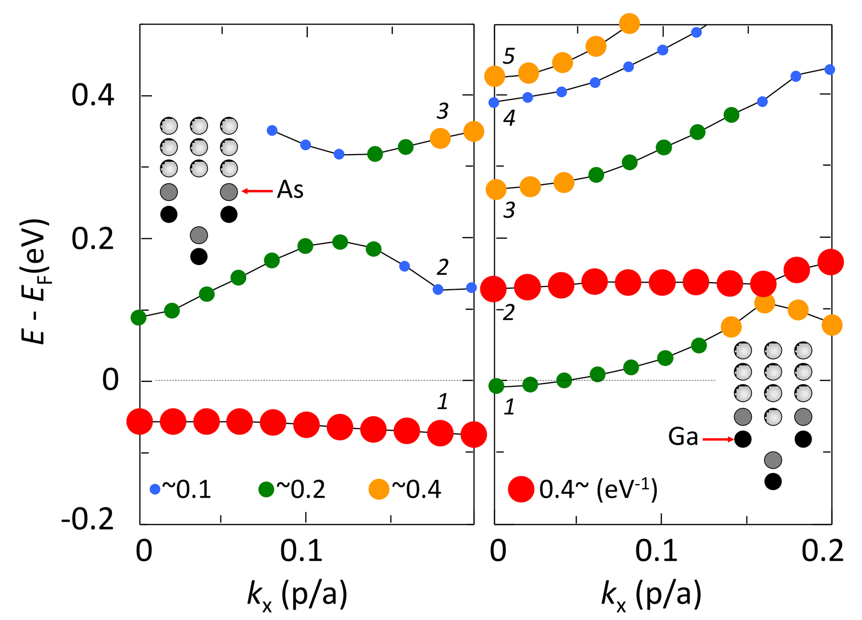


The films consist of a predominantly abrupt interface (~80%) with partial mixing also observed in some regions.

First-principle calculations were used to evaluate the stability of the interfaces, agreeing well with the experimental results.

Energy states and LDOS of the minority spin state were calculated along the k_x line of the 2D Brillouin zone.
- No interface states were found in the majority spin state near the Γ-point at low energy

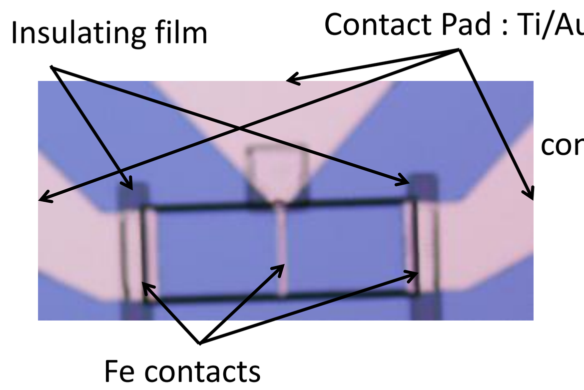
A sum of the LDOS of the s and p_z orbitals are shown by circles.



IRS in the minority spin state are essential for minority carrier injection to occur and could lead to polarization inversions.

Minority carrier injection could be enhanced in regions where partial mixing occurs due to IRS lying close to E_F.

The interface structure was correlated to the magnetotransport properties of 3-terminal devices.



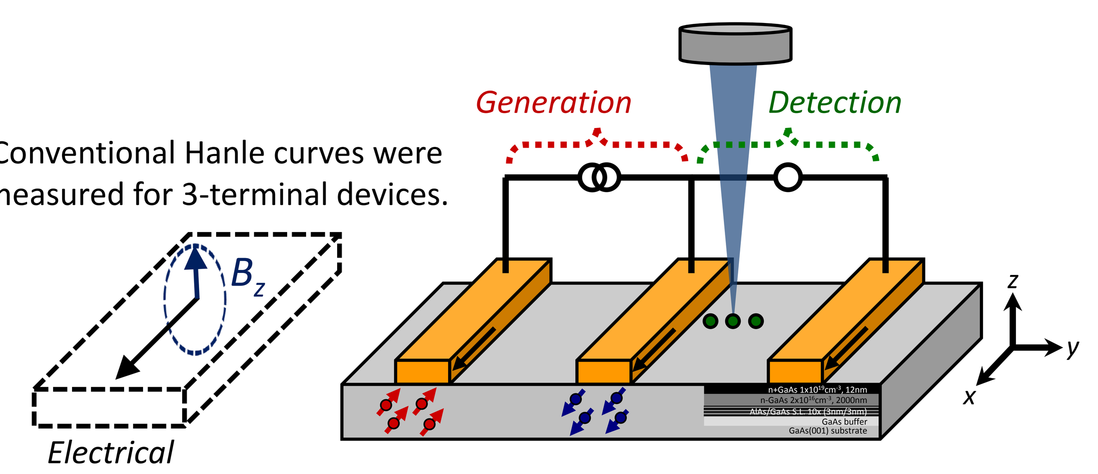
Devices were fabricated using conventional lithography techniques

GaAs mesa 340μm x 110μm

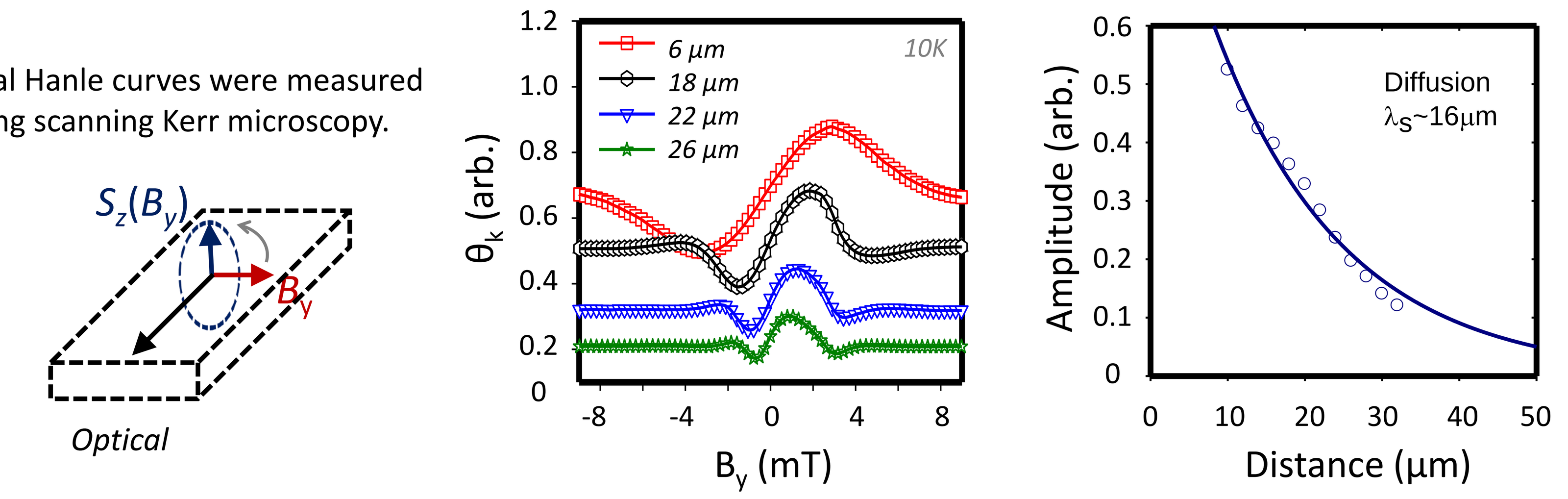
Fe contacts 100μm x 10μm

Transport Properties

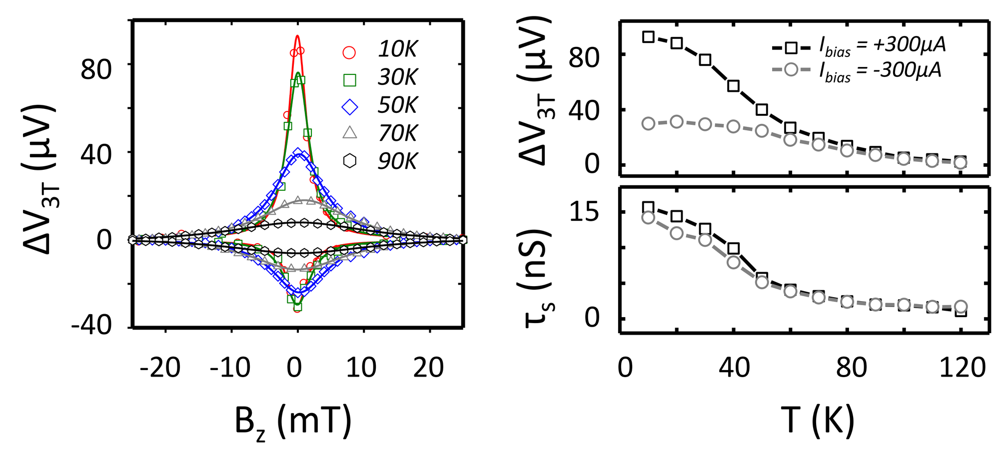
Conventional Hanle curves were measured for 3-terminal devices.



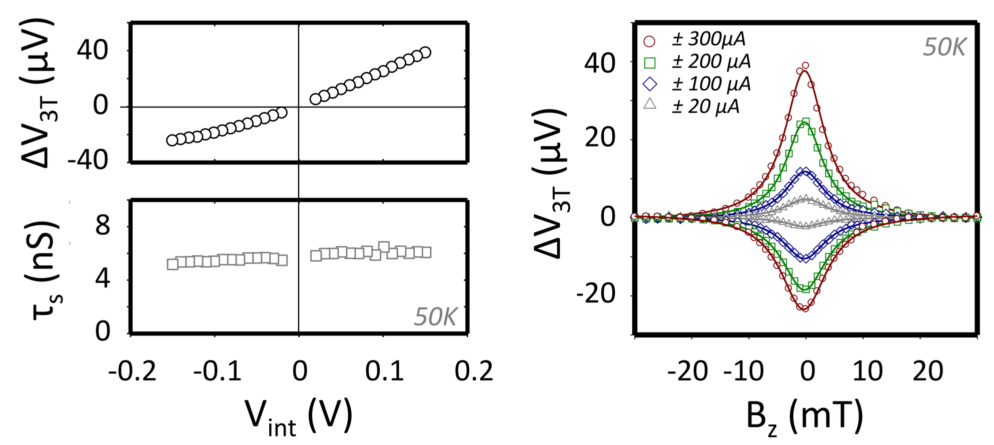
Optical Hanle curves were measured using scanning Kerr microscopy.



Temperature dependence of spin injection



Bias dependence of spin injection



Summary

We present the first report which correlates the experimentally observed Fe/GaAs(001) interface to the spin transport properties.

Using HAADF-STEM we observed an abrupt Fe/GaAs(001) interface as well as regions of partial mixing in the same film.

Using electrical and optical techniques we report reproducible behavior with no bias dependent polarization inversions.
- spin lifetime >15ns and spin diffusion length ~16μm at 10K.

Using ab initio calculations we show that minority carrier injection is strongly dependent on the interface structure.
- minority carrier injection could be enhanced by partial mixing.

References

[1] I. Zutic *et al.*, *Rev. Mod. Phys.* **76**, 323 (2004)
[2] I. Zutic and H. Dery, *Nature Materials* **10**, 647 (2011)
[3] L.R. Fleet *et al.*, *Phys. Rev. B* **87**, 024401 (2013)
[4] E. I. Rashba, *Phys. Rev. B* **62**, R16267 (2000)
[5] C. Adelmann *et al.*, *Phys. Rev. B* **71**, 121301 (2005)
[6] S.A. Crooker *et al.*, *Science* **309** 2191(2005)
[7] X. Lou *et al.*, *Nature Phys.* **3**, 197 (2007)
[8] A. N. Chantis *et al.*, *Phys. Rev. Lett.* **99**, 196603 (2007)
[9] S Honda *et al.*, *J. Phys. D: Appl. Phys.* **43**, 135002 (2010)
[10] D.L. Smith and P.P Ruden, *Phys. Rev. B* **78**, 125202 (2008)
[11] H. Dery and L.J. Sham, *Phys. Rev. Lett.* **98**, 046602 (2007)
[12] D. O. Demchenko and A. Y. Lui, *Phys. Rev. B* **73**, 115332 (2006)

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