Institution: University of York

Unit of Assessment: 9, Physics

Title of case study: A New Paradigm for Exchange Bias in Polycrystalline Films

1. Summary of the impact (indicative maximum 100 words)

A new procedure for the measurement and characterisation of polycrystalline exchange bias systems has been developed which has impacted significantly the manufacture of computer hard drive read-heads by companies such as Seagate Inc and Western Digital Corp. The new measurement procedure has enabled a typical 40% increase in the thermal stability of the antiferromagnetic materials used in computer hard drive read heads. The procedure has also improved the manufacturing process of the read-heads giving increased material performance and has resulted in a ~25% improvement in the resolution of detecting a bit.

2. Underpinning research (indicative maximum 500 words)

Since 1996 read heads based on the Giant Magneto Resistive effect have used exchange bias technology. Exchange bias systems are a ferromagnetic (F) film grown on an antiferromagnetic (AF) film pinning the magnetic orientation of the ferromagnet. Control of the behaviour of an antiferromagnetic material used in exchange bias systems is vital. Thin film antiferromagnetic materials do not give a measureable signal related to their degree of order and thermal stability by any direct technique making the study of these properties difficult.

Prof O'Grady and Dr Vallejo-Fernandez who at the time was a PhD student funded by an EU Training Network known as NEXBIAS, have developed a new measurement protocol which allows the thermal stability within AF layers to be determined. These layers consist of polycrystalline grains with sizes 5-15 nm produced by sputtering. To initiate the exchange bias effect the sample is heated and field cooled with the F layer saturated in one direction. Reversing the direction of the F layer then reverses the direction of the exchange field on the AF and allows for thermal activation to be used progressively to alter the orientation of the AF grains. The measurement protocols developed at York based on this concept enables the so-called distribution of blocking temperatures of the AF grains to be determined. Such exchange bias characterisation takes 15 hours per sample for a statistically significant measurement.

Using the developed exchange bias characterisation procedure, it was found that the thermal stability of the AF materials is a grain volume dependent effect. The measurement of a grain volume distribution is challenging. Typically 800 grains are required to characterise the median volume and the standard deviation. It was shown that the initial alignment process used by manufacturers was incomplete and a significant fraction of the grains were not stable at room temperature. The exchange bias effect is proportional to the integral over the volume distribution. The developed analysis procedure produced a remarkable fit to experimental data for the film thickness and the grain size within a series of films. It was possible to predict the rate of alignment of AF grains during the setting process. This has an impact on the design of the setting procedures used in manufacturing. The grain size work, whilst not undertaken in collaboration with industry, was rapidly adopted first by Western Digital Corporation and subsequently by Seagate Technology. These two companies manufacture 90% of the world's read heads with a value of ~$10Billion. Dr A Johnson (Vice President, Transducer Development, Seagate Technology, Northern Ireland in a letter of support states: "(this work)…constituted the only known mechanism for assessing the degree of order and thermal stability of antiferromagnetic grains."

The exchange bias work has shown that the interfaces between the layers consist of spin clusters whose alignment can occur spontaneously at low temperatures, be increased by high setting fields and behave independently of the AF grains. Subsequently O'Grady reported on factors which control the anisotropy of the AF grains including texture, composition and impurities. The model has been extended to explain exchange bias in single crystal and large grain systems based on a strong domain wall pinning concept. A patent for a new design for advanced solid state magnetic

memory has been filed and is being developed in collaboration with Hitachi Europe Ltd.

3. References to the research (indicative maximum of six references)

[1] Measurement of the Anisotropy Constant of Antiferromagnets in Metallic Polycrystalline exchange biased systems (**37 citations**)
G Vallejo-Fernandez, L E Fernandez-Outon and K O'Grady
Appl. Phys. Lett. 91, (2007) p. 212503

[2] Interfacial Spin Order in Exchange Biased Systems (**10 citations**)
L E Fernandez-Outon, G Vallejo-Fernandez, Sadia Manzoor, B Hillebrands and K O'Grady
J. Appl. Phys. 104, (2008) 093907

[3] Antiferromagnetic Grain Volume Effects in Metallic Polycrystalline Exchange Bias Systems (**28 citations**)
G Vallejo-Fernandez, L E Fernandez-Outon and K O'Grady
J. Phys. D: Appl. Phys. 41, (2008) 112001 (5pp)

[4] Tuning of Anisotropy in IrMn/CoFe Exchange Bias Systems (**7 citations**)
N.P. Aley, R. Kroeger, B. Lafferty, J. Agnew, Y. Lu and K. O'Grady
IEEE TransMag, 45 (10) (2009), p.3869 – 3872

[5] A New Paradigm for Exchange Bias in Polycrystalline Thin Films (invited) **97 citations**)
K. O'Grady, L.E.Fernandez-Outon and G.Vallejo-Fernandez
J. Magn. Magn. Mater. 322 (2010) p883 – 899

All citations taken from Scopus, 14/11/2013

4. Details of the impact (indicative maximum 750 words)

The impact of the York Model of Exchange Bias has been significant in that every magnetic recording read head in the world is now designed based on the underpinning physical insight that was developed. In 2011 alone this involved about one billion components, 400 million of which were manufactured by Seagate Technology in Northern Ireland. The total revenue from these products is approximately $6 billion based on an output of 2.5 million heads/day each with a unit value of circa $6. Following a series of mergers Seagate and Western Digital now command over 90% of the world-wide hard drive industry with a turnover of $34 billion per annum. . In a letter of support from Dr Mahendra Pakela (former Director Western Digital Fremont) to Professor O'Grady, the commercial value of this impact is confirmed: "I am happy to confirm that your work, which is now broadly accepted as the correct interpretation of exchange bias in granular antiferromagnetic layers, has enabled my company to design and develop improved layers which we incorporate in all the read heads we currently manufacture. This amounts to hundreds of millions of components each year." Using the work it was possible to design an antiferromagnetic layer in terms of its crystal orientation, grain size, size distribution and layer thickness, tailored to the equipment/process used to achieve exchange bias. This in turn allowed for the development of layers with up to two times greater alignment and thermal stability. In consequence thinner layers could be used for increasing resolution.

The close relationship between O'Grady's group and the major magnetic recording companies ensured that the work was disseminated, not only via publications, but via regular visits to the three major hard drive manufacturers, i.e. Seagate, Western Digital and Hitachi GST. Hitachi GST and Western Digital are in the process of merging which means that all hard drive manufacturers are involved in utilising this work. Additionally Seagate Northern Ireland, have sponsored students in O'Grady's group continuously for the last six years and Seagate Media Research in Fremont sponsored students prior to that. Subsequently Western Digital provided financial support for contract measurements which supported post docs in York and Seagate Technology, Northern Ireland, are now doing the same. Further support for another PhD student for 3 years has been

secured from Seagate from January 2012. A further contract with Seagate with a value of $400K has been secured which includes 50% support for a new lectureship (taken up Vallejo-Fernandez).

All the major manufacturers of read heads in the world have modified both the growth processes for antiferromagnetic layers and their setting processes based on the new physical insights into exchange bias that we developed.

All work associated with the development of the York Model of Exchange Bias was undertaken here in York. The York Model has now displaced all other models of exchange bias based on computer simulations of complex AF domain structures. Working in collaboration with Western Digital in 2009, an increase in the maximum reported value of exchange bias of more than a factor 2 to 3.6 kOe was reported. This system was designed using the York Model and remains the world record value [4].

The new insight into exchange bias materials that has been established has improved the thermal stability of the AF layers in certain designs of read heads by up to a factor 2. The new understanding has also enabled AF materials to be designed for purpose. For example, for perpendicular recording the overall thickness of the read head stack determines the linear data density along the track. In collaboration with Seagate in Northern Ireland, studies have been undertaken that allowed for the stack thickness to be reduced from 12nm to 6nm for certain applications. This allows for a potential doubling of the linear density along track although in practice the increased resolution was used to improve signal to noise.

5. Sources to corroborate the impact (indicative maximum of 10 references)

Relevant references have been cited but in particular reference to the article from 2010, 'A New Paradigm for Exchange Bias in Polycrystalline Thin Films' [4], describes the bulk of the original work. A more recent major invited work 'Exchange Bias in Polycrystalline Metallic Thin Films' shows subsequent results obtained using the York Model.

There are confidential reports to both Seagate and Western Digital but these cannot be made available for commercial reasons.

The University's financial records show that 8 short contracts were undertaken between 2007 and 2013 with a total value of $100k.

Letters are available confirming the use of the York Model of Exchange Bias from a former Director from Western Digital in Fremont, and the VP R&D of Seagate Technology in Northern Ireland/Minneapolis MN.