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Exchange Bias: from basic physics towards applications

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This is the nal performance report on Grant-FA9550-16-1-0122, whose Principal Investigators are Miguel Kiwi and Ivan K. Schuller. It covers from March 2017 to August 2020, including a no cost extension period that was granted. Exchange Bias continued at the forefront of our interest, and was explored both experimentally and theoretically; several publications of novel results were published. Moreover, another novel problem became an important and significant challenge: the fabrication and theoretical understanding of a different, but related subject: one-dimensional magnetic systems. Additional related research problems were also actively pursued, and results published in high impact journals. All in all the proposal objectives were achieved, and a good number of significant publications were generated.

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Exchange Bias: from basic physics towards applications

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Abstract

This is the final performance report on Grant-FA9550-16-1-0122, whose Principal Investigators are Miguel Kiwi and Ivan K. Schuller. It covers from March 2016 to August 2020, including a no cost extension period that was granted. Exchange Bias continued at the forefront of our interest, and was explored both experimentally and theoretically; several publications of novel results were published. Moreover, another novel problem became an important and significant challenge: the fabrication and theoretical understanding of a different, but related subject: one-dimensional magnetic systems. Additional related research problems were also actively pursued, and results published in high impact journals. All in all the proposal objectives were achieved, and a good number of significant publications were generated.

ACCOMPLISHMENTS

Exchange Bias (EB) is a phenomenon that has attracted much attention because of its basic science interest and relevant technological applications as spin valves magnetic sensors, and spintronic devices These interesting effects, with potential technological applications, such as tunable EB-based devices constitute a step forward in the field of EB, as well as the understanding of the physical mechanism of the long-range interaction.

Our main interest relates to the observation of long range switching, from negative to positive EB in FeF_2/Au/Ni trilayers, and our intent to provide a theoretical model that qualitatively and quantitatively describes the results. In fact, the researchers that participated in this endeavor are Dr. Ivan Schuller (UCSD, CA, USA), Dr. Rafael Morales (University of the Basque Country, Spain), Dr. Rafael Torres and Miguel Kiwi (Universidad de Chile). The experiments were conceived jointly, the data was extensively debated and the paper was written by multiple iteration between all the coauthors. Samples were fabricated and characterized at UCSD. Kerr effect measurements were carried out at UPV/EHU. The theoretical calculations were performed at U. de Chile.

It was established that positive (PEB) and negative exchange bias (NEB) can be tuned as a function of both the field cooling strength H_{FC}, and the PM thickness. In order to investigate this long-range FM-AFM coupling an FeF_2/PM(t_{Au})/Ni wedge-shaped trilayer, was fabricated by electron beam evaporation, at a base pressure of 5×10^{-7} Torr. FeF_2 was deposited onto a MgF_2 (110) single crystal at 300°C. The long range interaction that was found requires a completely novel approach to be described properly. This is precisely what we did, by means of our highly collaborative research effort.

In order to explain the experimental results we put forward a model whose main features are: i) the breaking of the AFM magnetic symmetry in the vicinity of the AFM-PM interface, by quantum fluctuations; ii) a long range dipolar coupling between the FM and the AFM magnetization; and iii) a competition of the strength of the Zeeman and dipolar fields that controls the magnitude and sign of the exchange bias, by varying the size of the magnetic domains induced at the FM-PM and the AFM-PM interfaces. This differs from the conventional approach that attributes EB to interface exchange, between two differently ordered magnetic materials in close atomic contact, and whose main ingredient is the exchange coupling between the FM and the AFM. Moreover, no FM-PM nor AFM-PM exchange interactions are included here. Therefore the exchange bias field does depend on spacer thickness, and consequently the presence of a spacer is a *sine qua non* requirement for our model.

The publication of this work can be found as
"Dipole-Induced Exchange Bias"
Felipe Torres, Rafael Morales, Ivan K. Schuller and Miguel Kiwi
Nanoscale 9, 17074-17079 (2017).
DOI: 10.1039/C7NR05491B

An enhanced exchange bias was found in FeF_2/Ni interfaces by inserting dusting of Pd and Cu atoms. We have used an ultrathin wedge to investigate systematically the effect of a discontinuous nonmagnetic spacer between the antiferromagnetic and ferromagnetic layers. Negative and positive exchange biases are symmetric and maximized for less than two angstroms of the nonmagnetic layer. Moreover, the dusting reduces the field cooling threshold to switch between the negative and the positive exchange bias. This finding demonstrates that nonmagnetic dusted layers can improve the interfacial exchange energy density in antiferromagnetic/ferromagnetic heterostructures and modify the bulk antiferromagnetic domain structure. Other dusting materials such as Ag, Ti, V, and SiO_2 showed no enhancement in FeF_2/Ni bilayers, which indicates the atomic sensitivity of this effect.

The exchange coupling is a short-range interaction; therefore, this effect is mainly produced at the AFM/FM interface. Many theoretical models and experimental evidence have corroborated this origin. Pinned spins at the AFM interface determine the magnitude of the exchange bias field (HEB). However, in certain systems, the bulk AFM structure may determine the interfacial configuration and, therefore, define the exchange bias properties of the system. The role of the AFM bulk was confirmed in experimental thin film measurements and theoretical calculations. Despite the short-range nature of the exchange interaction, exchange bias effects were also observed in AFM and FM films separated by non-magnetic (NM) spacers. The exchange bias field monotonously decreases with the thickness of the NM spacer and vanishes beyond a few nanometers. The spacer layer prevents the interlayer exchange coupling in these systems. Recently, a model based on dipolar interac- tions between induced AFM domains and FM moments was proposed to account for the experimental results. The model also explains the twofold sign of exchange bias experimentally observed in AFM/NM/FM trilayers, where the hysteresis loop exhibits both positive and negative shifts tuned by magnitude of the cooling field.

Consequently, our findings demonstrate that ultrathin spacer layers can generate a twofold effect in compensated AFM-FM interfaces: (i) enhancement of the exchange bias by the generation of new pinning centers in the vicinity of NM atoms and (ii) threshold reduction of the cooling field necessary for positive exchange bias by rear rangement of AFM domains with higher net magnetic moments. Moreover, the exchange bias enhancement is symmetric in interfaces that exhibit both positive and negative exchange bias. The intrinsic improvement of the interfacial exchange coupling energy due to new pinning centers can be used to increase and tune the sign of the exchange bias field without disrupting the FM/AFM coupling, even at a compensated AFM surface.

The publication of this work can be found as
"Enhanced positive and negative exchange bias in FeF_2/Ni with dusted interfaces"
I. Montoya, F. Torres, C. Redondo, M. Kiwi, Ivan K. Schuller, and R. Morales
Appl. Phys. Letters,**117,** XXX (2020). Published online.
doi: 10.1063/5.0021267

In addition to the exchange bias work several closely related research efforts, which acknowledge support form the AFOSR, have been published.

1. "Mechanical properties of iron filled carbon nanotubes: numerical simulations",
   Vicente Munizaga, Ricardo Ramírez, Miguel Kiwi and Griselda García.
   J. Appl. Phys. **121,** 234303 (2017).

2. "Inducing Porosity on Hollow Nanoparticles by Hypervelocity Impacts",
   Felipe Valencia, Rafael González, Juan Alejandro Valdivia, Miguel Kiwi, Eduardo Bringa and José Rogan.
   J. Phys. Chem. C **121,** 17856-17861 (2017).
   DOI 10.1021/acs.jpcc.7b03126

3. "Hillock formation on nanocrystalline diamond"
   Felipe Valencia, Rafael Gonzalez, Eduardo Bringa, Rafael Gonzalez, Diego Tramontina, José Rogan, Juan Alejandro Valdivia, **Miguel Kiwi,** and Eduardo Bringa
   Carbon **119,** 219 (2017).
   DOI: 10.1016/j.carbon.2017.04.020

4. "Advances on the synthesis of building block materials: Experimental evidence and model

interpretations of the effect of Na and K on imogolite synthesis"
Nicolás Arancibia-Miranda, Mauricio Escudey, Ricardo Ramírez, Rafael I. González, Adri C.T. van Duin, and **Miguel Kiwi**
J. Phys. Chem. C **121,** 12658 (2017).
DOI 10.1021/acs.jpcc.6b12155

5. "Nucleation of superfluid-light domains in a quenched dynamics"
   Joaquín Figueroa, José Rogan, Juan Alejandro Valdivia, **Miguel Kiwi,** Guillermo Romero and Felipe Torres
   Scientific Reports-Nature Publishing Group, **8,** 12766 (2018).
   DOI:10.1038/s41598-018-32564-2

6. "Inducing Porosity on Hollow Nanoparticles by Hypervelocity Impacts"
   Felipe Valencia, Rafael González, Juan Alejandro Valdivia, Miguel Kiwi, Eduardo Bringa and José Rogan
   J. Phys. Chem. **121,** 17856-17861 (2017).
   DOI 10.1021/acs.jpcc.7b03126

7. "Ion implantation in nanodiamonds: size effect and energy dependence"
   A.A. Shiryaev, J.A. Hinks, N.A. Marks, G. Greaves, F.J. Valencia, S.E. Donnelly, R.I. González, Miguel Kiwi, A.L. Trigub, E.M. Bringa, J. Fogg, I.I. Vlasov
   Scientific Reports-Nature Publishing Group, **8,** 5099 (2018).
   DOI:10.1038/s41598-018-23434-y

8. "Nucleation of superfluid-light domains in a quenched dynamics"
   Joaquín Figueroa, José Rogan, Juan Alejandro Valdivia, Miguel Kiwi, Guillermo Romero and Felipe Torres.
   Scientific Reports-Nature Publishing Group, **8,** 12766 (2018).
   DOI:10.1038/s41598-018-30789-9.

9. "The stability of hollow nanoparticles and the simulation temperature ramp"
   Paula N. Reyes, Felipe J. Valencia, Héctor Vega, Carlos Ruestes, José Rogan, J. A. Valdivia and Miguel Kiwi
   Inorganic Chemistry Frontiers, **5,** 1139-1144 (2018).
   DOI: 10.1039/C7QI00822H

10. “The Stochastic Transport Dynamics of a Conserved Quantity on a Complex Network” Pablo Medina, Jaime Clark, Miguel Kiwi, Felipe Torres, Jose Rogan, and Juan Alejandro Valdivia
Scientific Reports-Nature Publishing Group, 8, 14288 (2018).
DOI:10.1038/s41598-018-32677-8

11. “Mechanical properties obtained by indentation of hollow Pd nanoparticles” Felipe Valencia, Rafael I. Gonzalez, Héctor Vega, Carlos Ruestes, José Rogan, Juan Alejandro, Valdivia, Eduardo Bringa, and Miguel Kiwi
Journal of Physical Chemistry C, **122,** 25035–25042, 2018.
DOI: 10.1021/acs.jpcc.8b07242

For some time now we have been working on a problem closely related to exchange bias: the creation of long range magnetic order in one dimension. In fact, in Prof. Schuller's lab at UCSD unconventional chiral magnetic ordering in ultra-short one-dimensional (1D) ferromagnetic chains, achieved by means of a novel manufacturing method to build superlattice arrays, was obtained. It allows precisely controlled fabrication, composition, and manipulation through the boundary conditions. We were able to develop a theoretical model that quantitatively describes the results and the underlying physics.

As the size of a magnetic system shrinks, magnetic ordering is quenched by thermal and quantum fluctuations. Therefore, the observation of one-dimensional magnetic order, a goal that has been pursued for a long time, as well as a theoretical understanding of the phenomenon, is a topic of significant interest. As is well known, the Mermin-Wagner theorem proved that it is not possible to establish magnetic ordering in one- and two-dimensions, due to thermal fluctuations. However, later it was shown that the inclusion of the Dzyaloshinski-Moriya interaction is able to overcome these thermal fluctuations.

To the best of our knowledge, this is the first time experimental evidence that magnetic chiral states, due to electronic interactions, can overcome the atomic-scale randomness. Electronic changes at the end of the ultra-short iron chains produce a strong effect, which allows for magnetic ordering. We anticipate that this discovery, and the physical realization of 1D systems with magnetic interactions, will become essential to address other pressing problems such as quantum criticality, many-body physics, and spin transport. Moreover, the possibility of fabricating 1D

chains, where the length and composition can be strictly controlled, provides scientists an essential tool to explore solid-state physics problems like the emergence of new (topological) magnetic phases, such as the ones predicted in 2016 by F. D. M. Haldane.These results are contained in the manuscripts "Chiral symmetry and scale invariance breaking in spin chains",
Felipe Torres, Miguel Kiwi, Nicolas M. Vargas, Carlos Monton, and Ivan K. Schuller.
AIP Advances, **10,** 025215, (2020).
DOI: 10.1063/1.5130190

In addition, very recently "Helical Spin Structure in Iron Chains with Hybridized Boundaries" by Nicolas M. Vargas, F. Torres, A. Baker, J. R. I. Lee, M. Kiwi, T. Willey, Ivan K. Schuller, and C. Monton, was submitted for publication in Applied Physics Letters.

SUMMARY AND CONCLUSION

This research project has achieved all the objectives that were initially put forward; they generated publications in high impact journals. In addition, several related problems were also investigated by our team and also led to a good number of relevant publications.

The focus of our interest was put on the exchange bias phenomenon, an effect that has found wide use in applications, such as sensors and spin valves, showing giant or tunnel magnetoresistance. Moreover, exchange bias plays an important role in novel spin-orbit torque functionalities, as current-induced switching of nano-oscillators or spin logic devices that are at the forefront of modern electronics and spintronics. In addition, several intimately related subject matters were also studied, and as well gave origin to high impact publications.