Anjan Barman

Professor
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Professor Barman obtained Ph.D. from IACS (Jadavpur University) in 1999. He worked as Postdoctoral Fellow in Europe and USA between 1999 and 2006, and as Assistant Professor at University of South Carolina, USA and IIT Delhi between 2006 and 2009. He joined SNBNCBS in 2009. He works in Magnonics and Spintronics, including ultrafast magnetization dynamics, nanomagnetism, spin Hall effect and interface magnetism.

Supervision of Research / Students

Ph.D. Students

1. Arnab Ganguly: Investigation and Control of Magnetization Dynamics in Ferromagnetic/ Nonmagnetic Bi-Layer Systems (completed)
2. Debanjan Polley: Manipulating THz Radiation Using nanostructures (completed)
3. Kallol Mukherjee: Interactions and Dynamics in Complex Systems (completed)
4. Chandrima Banerjee: Experimental Study of Spin Waves in Magnetic Thin Films and Nanostructures (ongoing)
5. Santanu Pan: Ultrafast Spin Dynamics in Ferromagnetic Thin Films (ongoing)
6. Samiran Choudhury: Spin Waves in Two-Dimensional Magnonic Crystals (ongoing)
7. Sucheta Mondal: Spin Dynamics and Spin Hall Effect in Metallic Thin Films and Nanostructures (ongoing)
8. Anulekha De: Spectroscopic Studies of Metallic Nano and Microstructures (ongoing)
9. Avinash Kumar Chaurasiya: Brillouin Light Scattering Studies of Interfacial Dzyaloshinskii-Moriya Interaction (ongoing)
10. Kartik Adhikari: Ferromagnetic Resonance of Patterned Magnetic Nanostructures (ongoing)
11. Sourav Sahoo: Spin Dynamics in 3D Magnonic crystal and 2D Spin Ice Systems (ongoing)

Projects of M.Sc./ M.Tech./ B.Tech./ Post B.Sc. students

1. Suryanarayan Panda (IPhD student, SNBNCBS); Project 1: Investigation of Magnetic Anisotropy in W/CoFeB/SiO2 Thin Films; completed; Project 2: Investigation of Spin Pumping Effect in Heavy Metal/ Ferromagnetic Bilayer System Using Time Resolved Magneto-optical Kerr Effect Technique; completed; Project 3: All Optical Detection of Spin Diffusion Length of a Heavy Metal; completed.
2. Sudip Majumdar (IPhD student, SNBNCBS); Project 1: Investigation of Spin Wave Dynamics in Ferromagnetic Nanostructures - I; completed; Project 2: Investigation of Spin Wave Dynamics in Ferromagnetic Nanostructures - II; completed.
3. Tanwistha Chakrabarti (Presidency University, Kolkata); Project 1: The Effect of Variation in the Diameter of Antidots on the Spin Wave Spectra using VNA-FMR Technique; completed.
4. Neha Jha (IPhD Student, SNBNCBS); Project 1: Time-Domain Study of Spin Hall Effect in Nonmagnet/Ferromagnet Bilayer Thin Films; completed.
5. Sourav Sahoo (IPhD Student, SNBNCBS); Project 1: Spin Waves in Nonmagnet/Ferromagnet/Oxide Heterostructures; completed.

Post Doctoral Research Scientists

1. Jaivardhan Sinha
2. Sumona Sinha
3. Rakhi Acharya

Teaching activities at the Centre

1. PHY301: Atomic and Molecular Physics, IPhD, No. of students: 07, Co-Teacher: Dr. Rajib Kumar Mitra.
2. CB527: Molecular Physics and Spectroscopy, Post MSc, No. of students: 07, Co-Teacher: Dr. Rajib Kumar Mitra.
3. PHY292: Summer Project Research, IPhD, No. of Students: 01.
4. PHY304: Project Research, IPhD, No. of students: 02.
5. PHY401: Project Research III, IPhD, No. of students: 04; Independent: 02, Shared with Dr. Rajib K. Mitra: 02.

Publications in Journals

1. K. Neeraj, S. Choudhury, D. Polley, R. Acharya, J. Sinha, **A. Barman,** and R. K. Mitra; *Efficient Terahertz Anti-Reflection Properties of Metallic Anti-Dot Structures;* Optics Letters; 2017; **42;** 1764.

2. N. Samanta, D. Das Mahanta, S. Choudhury, **A. Barman** and R. K. Mitra; *Collective Hydration Dynamics in Some Amino Acid Solutions: A Combined GHz-THz Spectroscopic Study;* J. Chem. Phys.; 2017; **146;** 125101.

3. D. Polley, A. Patra, **A. Barman** and R. K. Mitra; *Terahertz Conductivity Engineering in Surface Decorated Carbon Nanotube Films by Gold Nanoparticles;* Applied Optics; 2017; **56;** 1107.

4. K. Adhikari, S. Choudhury, R. Mandal, S. Barman, Y. Otani and **A. Barman;** *Bias Field Tunable Magnetic Configuration and Magnetization Dynamics in $Ni_{80}Fe_{20}$ Nano-cross Structures with Varying Arm Length;* J. Appl. Phys.; 2017; **121;** 043909.

5. S. Bhardwaj, A. Pal, K. Chatterjee, P. Chowdhury, S. Saha, **A. Barman,** T. Rana, G. D. Sharma and S. Biswas; *Electrophoretic deposition of plasmonic nanocomposite for the fabrication of dye-sensitized solar cells;* Indian Journal of Pure & Applied Physics; 2017; **55;** 73.

6. D. Polley, **A. Barman** and R. K. Mitra; *Diameter-Dependent Shielding Effectiveness and Terahertz Conductivity of Multiwalled Carbon Nanotubes;* Journal of the Optical Society of America B; 2016; **33,** 2430.

7. S. Mondal, S. Choudhury, S. Barman, Y. Otani and **A. Barman;** *Transition from Strongly Collective to Completely Isolated Ultrafast Magnetization Dynamics in Two-Dimensional Hexagonal Arrays of Nanodots with Varying Inter-dot Separation;* RSC Advances; 2016; **6;** 110393.

8. S. Pan, S. Mondal, T. Seki, K. Takanashi, and **A. Barman;** *Influence of thickness-dependent structural evolution on ultrafast magnetization dynamics in $Co_2Fe_{0.4}Mn_{0.6}Si$ Heusler alloy thin films;* Phys. Rev. B; 2016; **94;** 184417.

9. S. Barman, S. Saha, S. Mondal, D. Kumar and **A. Barman;** *Enhanced Amplification and Fan-Out Operation in an All-Magnetic Transistor;* Scientific Reports; 2016; **6;** 33360.

10. A. K. Chaurasiya, C. Banerjee, S. Pan, S. Sahoo, S. Choudhury, J. Sinha and **A. Barman;** *Direct Observation of Interfacial Dzyaloshinskii-Moriya Interaction from Asymmetric Spin-wave Propagation in W/CoFeB/SiO_2 Heterostructures Down to Sub-nanometer CoFeB Thickness;* Scientific Reports; 2016; **6;** 32592.

11. C. Banerjee, S. Pal, M. Ahlberg, T. N. Anh Nguyen, J. Åkerman, and **A. Barman;** *All-optical Study of Tunable Ultrafast Spin Dynamics in [Co/Pd]/NiFe Systems: The Role of Spin-Twist Structure on Gilbert Damping;* RSC Advances; 2016; **6;** 80168.

12. C. Banerjee, L. Ming Loong, S. Pal, X. Qiu, Y. Hyunsoo, and **A. Barman;** *Improvement of Chemical Ordering and Magnetization Dynamics of Co-Fe-Al-Si Heusler Alloy Thin Films by Changing Adjacent Layers;* RSC Advances; 2016; **6;** 77811.

13. K. Mukherjee, **A. Barman** and R. Biswas; *Impact of the Aggregation Behaviour of Sodium Cholate and Sodium Deoxycholate on Aqueous Solution Structure and Dynamics: A Combined Time Resolved Fluorescence and Dielectric Relaxation Spectroscopic Study;* J. Mol. Liq.; 2016; **222;** 495.

14. S. Choudhury, S. Saha, R. Mandal, S. Barman, Y. Otani, and **A. Barman;** *Shape- and Interface-Induced Control of Spin Dynamics of Two-dimensional Bicomponent Magnonic Crystals;* ACS Appl. Mater. Interfaces; 2016; **8;** 18339.

15. N. Hasegawa, S. Sugimoto, D. Kumar, S. Barman, **A. Barman,** K. Kondou, and Y. Otani; *Observation of anisotropic energy transfer in magnetically coupled magnetic vortex pair;* Appl. Phys. Lett.; 2016; **108;** 242402.

16. R. K. Upadhyay, S. Pan, **A. Barman,** J. A. Mclaughlin, and S. S. Roy; *Oil swollen surfactant gel based synthesis of metal oxides nanoparticles: An attractive alternative for the conventional Sol gel synthesis;* Ceramics International; 2016; **42;** 12119.

17. B. Samantaray, A. K. Singh, C. Banerjee, **A. Barman,** A. Perumal, and P. Mandal; *Perpendicular standing spin wave and magnetic anisotropic study on amorphous FeTaC films;* IEEE Trans. Magn.; 2016; **52;** 2003104.

Lectures Delivered

1. Ultrafast Magnetization Dynamics in Artificially Structured Ferromagnetic Nanomaterials for Applications in Spintronics and Magnonics, **A. Barman,** MRSI Medal Lecture, IIT Bombay, 13-15 Feb, 2017.

2. Magnetization Dynamics: From Theory to Experiment, **A. Barman,** Science Academies' Lecture Workshop "Recent Trends in Physics", St. Xaviers College, Kolkata, 10-11 Feb, 2017.

3. Interface Controlled magnetization Dynamics in ferromagnetic/Nonmagnetic Bilayer Thin Films, **A. Barman,** 61st DAE Solid State Physics Symposium, Bhubaneswar, 26-30 Dec, 2016.

4. Seeing and Tailoring Spin Dynamics on Ultrafast Time Scale, **A. Barman,** Institute Seminar, NISER, Bhubaneswar, 8 Dec, 2016.

5. Interface Controlled Magnetization Dynamics in Ferromagnet/Nonmagnet Bilayer Thin Films, **A. Barman,** Indo-Japan Workshop on Magnetism at the Nanoscale, Sendai, Japan, 1-2 Dec, 2016.

6. Femto- and Picosecond Spin Dynamics in Ferromagnetic Thin Films, Multilayers and Nanostructures, **A. Barman,**

Ultrafast Science 2016 (UFS-2016), BARC, Mumbai, 24-26 Nov, 2016.

7. Optical, Thermal and Spin Torque Induced Magnetization Dynamics in Ferromagnetic Nanostructures and FM/NM Bilayers, **A. Barman,** IUMRS-ICEM 2016 Conference, Suntec City, Singapore, 4-8 July, 2016.
8. Optical, Thermal and Spin Torque Induced Magnetization Dynamics in Ferromagnetic Nanostructures and Multilayers, **A. Barman,** Inhouse Meeting, Physics Department, University of Calcutta, 20-21 Jun, 2016.

Membership of Committees

External Committee

Member of Faculty Selection Committee of Jadavpur University; Member of Executive Committee of MRSI- Kolkata Chapter; Expert for PhD Thesis Examination Committee at NISER Bhubaneswar and LNMIIT Jaipur.

Internal Committee

Member of Admission Committee; Member of Works Committee; Member of Faculty Search Committee; Member of Technical Cell Advisory Committee; Convener of the Thematic Unit of Excellence on Nanodevice Technology at the S. N. Bose Centre; Convener of the Advanced Spectro-Microscopy Unit at the S. N. Bose Centre.

Awards / Recognitions

1. MRSI Medal, 2017

Fellow / Member of Professional Body

1. Life Member of MRSI.
2. Member of IEEE.

Sponsored Projects

1. Project Title: 3D Nanomagnetic Crystal Fabrication for Advanced Microwave Devices and Water Treatment

   Funding Agency: EPSRC Global Challenges Research Fund jointly with Cardiff University, UK.

   Principal Investigator: Sam Ladak and Anjan Barman 2016
2. Project Title: Nanoscale Modifications and Active Control of Magnonic Crystals for On-Chip Microwave Communication

   Funding agency: DST under India-Poland Collaborative Research Project

   Principal Investigator: Anjan Barman. 2015-18.
3. Project Title: Advanced Spectro-Microscopy for Novel Materials

   Funding agency: S. N. Bose National Centre for Basic Sciences

   Principal Investigator: Anjan Barman, Co-PI, Ranjit Biswas, Rajib K. Mitra, Manik Pradhan. 2012-17
4. Project Title: Thematic Unit of Excellence on Nanodevice Technology

   Funding Agency: Nano Mission, DST

   Convener: Anjan Barman, Members: A. K. Raychaudhuri, Rajib K. Mitra, Manik Pradhan 2011-17

Conference / Symposia / Workshops / Seminars etc. organized

1. Indo-Japan Workshop on Magnetism at the Nanoscale under DST-JSPS S&T Programme at Tohoku University, Sendai, Japan 1-2 Dec, 2016

Collaborations including publications (Sl. No. of paper/s listed in 'Publications in Journals' jointly published with collaborators)

National

1. Prof. Prabhat Mandal (Sl. No. 17)
2. Dr. Susanta SinhaRoy (Sl. No. 16)
3. Dr. Subhayan Biswas (Sl. No. 5)

International

1. Prof. Yoshichika Otani (Sl. No. 4, 7, 14, 15)
2. Prof. Johan Akerman (Sl. No. 11)
3. Prof. Koki Takanashi (Sl. No. 8)
4. Prof. Takeshi Seki (Sl. No. 8)
5. Prof. Hyunsoo Yang (Sl. No. 12)

Member of Editorial Board

1. Editorial Board member of Scientific Reports

Significant research output / development during last one year

General research areas and problems worked on

Ultrafast Spin Dynamics; Ultrafast Demagnetization, Magnetization Precession; Spin Waves; Gilbert Damping; Lithographically Patterned Magnetic Nanostructures; Magnonic Crystal; GHz Frequency Magnonic Filter; Magnetic Vortex Transistor; Magnetic Thin Films, Multilayers and Heterostructures; Spin Hall Effect; Interfacial Dzyaloshinskii-Moriya Interaction; Skyrmions; Heusler Alloy Thin Films; Nanomaterials for THz Applications; Dielectric Relaxation Spectroscopy.

Interesting results obtained

a. **Shape and Interface Induced Control of Spin Dynamics of Two-dimensional Bi-component Magnonic Crystals:** We have fabricated two-dimensional bi-component magnonic crystals (BMCs) in form of embedded $Ni_{80}Fe_{20}$ nanostructures in $Co_{50}Fe_{50}$ thin films by nanolithography.

The spin-wave spectra showed significant variation as the shape of the embedded nanostructure changes from circular to square. Significantly, in both shapes, a minimum in frequency is obtained at a negative value of bias field during the field hysteresis **(Fig. 1)** confirming the presence of a strong exchange coupling at the interface between the two materials, which increases the spin-wave propagation velocity in such structures leading to faster GHz frequency magnetic communication and logic devices. The spin-wave frequencies and bandgaps show bias-field tunability, which is important for above device applications.

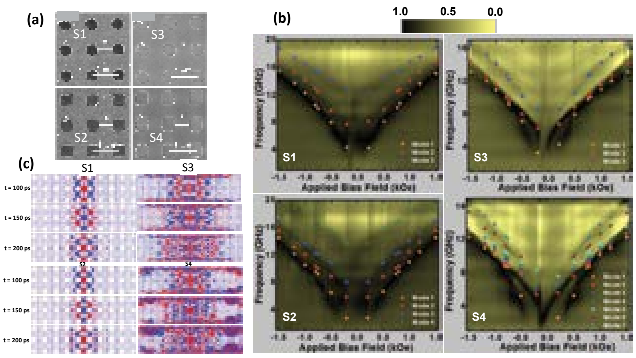

Fig. 1. (a) Scanning Electron Micrographs of antidot lattices (S1, S2) and bicomponent magnonic crystals (S3, S4) of two different shapes. Dispersion of spin-wave frequency with applied bias-field for all four lattices. (c) Simulation results of spin-wave propagation in S1 and S3.

b. Ultrafast Magnetization Dynamics of Heusler Alloy Thin Films: We experimentally investigated thickness (t) dependent evolution of structural and magnetic properties in $Co_2Fe_{0.4}Mn_{0.6}Si$ (CFMS) thin films and correlate them with ultrafast demagnetization time, relaxation time and Gilbert damping coefficient (α). Structural ordering and magnetic parameters, including α, exhibit a non-monotonic variation with increasing *t*. A remarkably low value of α of 0.009 is obtained for the CFMS film with *t* = 20 nm without any buffer layers, which helps to avoid possible diffusion of buffer layer into CFMS. Highest saturation magnetization, lowest coercivity and α value imply CFMS film with *t* = 20 nm is most suitable for integrated spintronics devices. Finally, unique band structure controlled demagnetization and fast relaxation in half-metallic CFMS is correlated to α.

We also demonstrated an improvement of chemical ordering and magnetic properties of $Co_2FeAl_{0.5}Si_{0.5}$ (CFAS) Heusler alloy thin films, and investigated the correlation between these two, to elucidate the influence of different capping-layers and under-layers. The structural characterization reveals a variation in the surface roughness, grain size and the chemical ordering. The Gilbert damping constants show a broad tunability with the chemical order. A Gilbert damping constant as low as about 0.002 has been found. The observed effects can be attributed to the different melting points of the under-layers and thermal expansion stress between the adjacent layers and CFAS thin films.

c. Direct Observation of Interfacial Dzyaloshinskii-Moriya Interaction Using Brillouin Light Scattering: Interfacial Dzyaloshinskii-Moriya interaction (IDMI) is important for its roles in stabilizing the skyrmionic lattice as well as soliton-like domain-wall motion leading towards new generation spintronic devices. However, achievement and detection of IDMI is often hindered by various spurious effects. We have demonstrated pure IDMI originating from W/CoFeB interface in W/CoFeB/SiO_2 heterostructures using Brillouin light scattering technique **(Fig. 2)**. The DMI constant is found to scale as the inverse of CoFeB thickness, over the whole studied thickness range, confirming the presence of pure IDMI in our system without any extrinsic effects. The W/CoFeB interface shows no degradation down to sub-nanometer CoFeB thickness, which would be useful for devices.

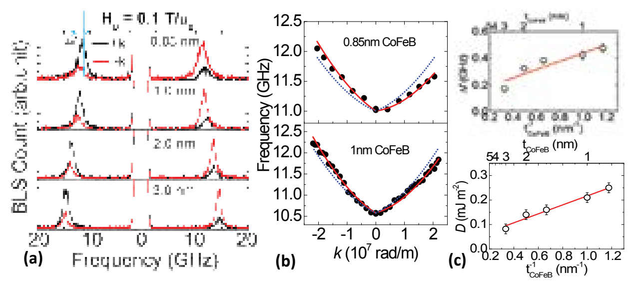

Fig. 2. (a): Asymmetric spin-wave propagation in the Damon-Eshbach geometry for W(2 nm)/CoFeB(*t*) /SiO2 heterostructures with varying CoFeB thickness. Asymmetric spin-wave dispersion for two values of CoFeB thickness (symbols: experimental data; solid red line: theoretical fit with DMI term; dotted line: theoretical fit without the DMI term in the effective field. (c) Frequency difference between two counter-propagating spin wave (top panel) and the extracted DMI constant *D* as a function of CoFeB thickness.

d. Experimental and Numerical Studies of Magnetic Vortex Transistor: Development of all-magnetic transistor with favorable properties is an important step towards a new paradigm of all-magnetic computation. Recently, we showed such possibility in a Magnetic Vortex Transistor (MVT). We further demonstrated enhanced amplification in MVT achieved by introducing geometrical asymmetry in a three vortex sequence. The resulting asymmetry in core-to-core distance in the three vortex sequence led to enhanced amplification of the MVT output. A cascade of antivortices travelling in different trajectories including a nearly elliptical trajectory through the dynamic stray field is found to be responsible for this amplification. This is further used for a successful fan-out operation.

Further, we have experimentally investigated the energy transfer and storage in the magnetostatically coupled vortices in a pair of disks. We observed a specific gyrating motion due to anomalous energy storage at the off-resonance frequency. Micromagnetic simulations revealed that the behavior arises from the modulation of effective damping constant of the pair disks, originating from the phase difference between coupled vortex cores. The above observations promote the magnetic vortex transistors to be used in complex circuits and logic operations.

Proposed research activities for the coming year

a. Investigation of Magnonic Band Structure in Co/Pd Stripe Domain System for Energy Efficient Spin Wave Propagation:

By combining Brillouin Light Scattering and numerical simulations we will investigate the spin-wave dynamics of a Co/Pd thin film multilayer, featuring stripe domain structure at remanence. The domain walls can cause scattering of bulk and surface spin-wave modes similar to one dimensional magnonic crystal towards development of energy efficient magnonic crystal.

b. Development of Pseudo One-Dimensional Magnonic Crystal for High Frequency Nanoscale Devices:

We will develop array of asymmetric sawtooth shaped width modulated nanoscale ferromagnetic waveguides forming a pseudo one-dimensional magnonic crystal. Control over the internal field distribution as well as the dispersion properties would find potential applications in dynamic spin wave filters and magnonic waveguides.

c. All-optical Detection of Spin Hall Angle in W/CoFeB/SiO2 Heterostructures by Varying Tungsten Layer Thickness:

We will employ a novel all-optical time-resolved magneto-optical Kerr microscope for unambiguous determination of SHA in W/CoFeB/SiO_2 heterostructures using the principle of modulation of Gilbert damping of the adjacent ferromagnetic layer by the spin-orbit torque from the W layer. The effects of structural phase transition of W with varying thickness and spin diffusion length in W will be thoroughly studied.

d. Spin Waves in Two-Dimensional Quasi-Periodic Magnonic Crystal:

We will develop two-dimensional ferromagnetic antidot lattices arranged in the octagonal lattice which can be considered as quasi-periodic magnonic crystals. A rich variation in the spin wave spectra is expected with the variation of lattice constant as well as the strength and orientation of the bias magnetic field. In addition to this, possibility of observation of eight-fold anisotropy will be investigated.

e. Observation of Skyrmions at Room Temperature in Heusler Alloy Ultrathin Films:

Magnetic skyrmions are topological spin structure having immense potential for energy efficient spintronic devices. However, observation of skyrmions at room temperature is limited to patterned nanostructures. We will investigate stable skyrmions at room temperature and zero external magnetic field in unpatterned Heusler alloy based thin film heterostructures with strong interfacial Dzyaloshinskii-Moriya interaction employing the magnetic force microscopy.