European Physical Society
Condensed Matter Division

The European Physics Society (EPS)

2022 EPS Europhysics Prize for Outstanding Achievement in Condensed Matter Physics

Long Citation

The 2022 EPS Condensed Matter Division (CMD) Europhysics Prize is awarded to Prof. Agnès Barthélémy and Dr. Manuel Bibes (CNRS/Thales laboratory of University Paris-Saclay), Prof. Ramamoorthy Ramesh (UC Berkeley) and Prof. Nicola Spaldin (ETH Zurich) for *seminal contributions to the physics and applications of multiferroic and magnetoelectric materials*.

The Prize will be presented on Wednesday August 24th 2022, during the Awards Session of the 29th General Conference of the EPS Condensed Matter Division (CMD29), to be held in Manchester (joint organization with Institute of Physics, UK). This prize has been awarded since 1975 (this is the 39th edition) and is one of Europe's most prestigious prizes in the field of condensed matter physics. It is given in recognition of a prominent and well-identifiable discovery, breakthrough, or contribution to condensed matter physics, by one or more individuals, contribution that, in the opinion of the selection committee, represents scientific excellence. The award recognises research for which a significant portion of the work was carried out in Europe. A summary of all the prize editions can be found here.

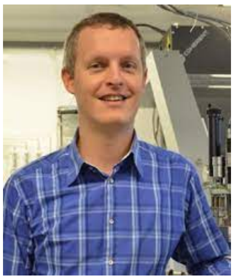
Multiferroics are materials that exhibit simultaneous and coupled magnetism and ferroelectricity. The attraction of combining two such fundamentally interesting and technologically important phenomena –magnetism and ferroelectricity– in a single material had motivated early studies of multiferroics, but progress was hampered by an absence of materials and a lack of understanding of their scarcity. Spaldin's landmark paper in 2000 entitled "Why are there so few magnetic ferroelectrics?" [doi: 10.1021/jp000114x] initiated the renaissance of the field by identifying the basic physics behind the contra-indication between magnetism and ferroelectricity, and proposing new routes to overcome it. Her theoretical ideas would have languished, however, without Ramesh's prior influential work since the 1980's on superconductivity, colossal magnetoresistance, and ferroelectricity, which he leveraged to develop the first model multiferroic, bismuth ferrite, BiFeO3 [doi: 10.1126/science.1080615]. Bismuth ferrite, which is both environmentally benign and consists of earth-abundant elements, is now the most widely studied multiferroic and the focus of major research programs worldwide. Ramesh and Spaldin explained the origin of the multiferroic behavior in $BiFeO_3$ and used it as a model system to demonstrate a range of novel multiferroic phenomena and to develop practical room-temperature technologically relevant functionalities. They were the first to demonstrate electric-field control of magnetism at room temperature in this system [doi: 10.1038/nmat1731], work that Ramesh extended to exchange-coupled ferromagnet-$BiFeO_3$ heterostructures [doi: 10.1038/nature14004]. Together they discovered and explained conducting ferroelectric domain walls in $BiFeO_3$ – these ängstrom-wide conducting channels, which can be manipulated electrically, hold the potential to revolutionize storage or processing technologies. Based on their joint fundamental discoveries, Ramesh continued to independently push technological implementation of multiferroics, demonstrating electric-field control of the magnetic exchange coupling in ferromagnet-multiferroic heterostructures and showing the feasibility of electric-field control of magnetism in a technologically viable, spin-valve structure approaching 100 mV. Meanwhile, Spaldin is using multiferroics to explore fundamental questions in cosmology and high-energy physics and continues to develop new fundamental concepts such as magnetoelectric multipoles, multiferroic quantum criticality, and dynamical multiferroicity [doi: 10.1038/s41563-018-0255-6].

Barthelemy and Bibes independently championed the field of multiferroic and magnetoelectric physics with an application perspective. After pioneering work by Barthelemy on giant magnetoresistance (GMR from 1989) and tunnel magnetoresistance (TMR in the 1990's), they began to introduce functional insulating oxides as tunnel barriers into magnetic tunnel junctions, to expand the functionalities of these devices. They used ferromagnetic oxide barriers able to spin-polarize a tunnelling current from a simple metal electrode such as gold (spin-filtering). Subsequently, they proposed to explore multiferroic barriers with which four-state resistance state memory devices were achieved [doi: 10.1038/nmat1860]. In 2009, Barthélémy and Bibes discovered giant electroresistance in ferroelectric tunnel junctions [doi: 10.1038/nature08128] and patented their use as analogue memory devices called memristors [doi: 10.1038/nmat3415]. Several companies now have programs on such ferroelectric synapses for artificial intelligence. They also explored novel routes for the electrical control of magnetism and spin transport in hybrid oxide-metal architectures at low and room temperature. In particular, they showed that magnetic order can be switched from ferromagnetic to antiferromagnetic just above room temperature in FeRh-based heterostructures, corresponding to record-high magnetoelectric coupling [doi: 10.1038/nmat3870]. They also gave evidence that ferroelectricity could be used to control the spin-polarization of ferromagnets, and thus the spintronic response of devices such as magnetic tunnel junctions [doi: 10.1126/science.1184028]. Most recently, they demonstrated giant spin-charge conversion in oxide two-dimensional electron gases between two nonmagnetic insulating oxides and showed that it can be controlled by ferroelectricity [doi: 10.1038/s41586-020-2197-9], corresponding to an entirely novel approach to magnetoelectric coupling and offering exciting opportunities for ultra-low power spin-based devices.

From a technological standpoint, the field of multiferroics and magnetoelectrics is currently beginning to make marked impact. Considerable efforts are underway to utilize multiferroic materials for a range of logic, memory, and field-sensing applications. For example, the multiferroic of greatest practical importance today is $BiFeO_3$ (the only known material that is multiferroic at room temperature and thermodynamically stable). By coupling $BiFeO_3$ to a ferromagnetic overlayer, it has been demonstrated that energy-efficient control of a non-volatile spin-valve device at room temperature can be accomplished below 1 V. The energy per unit area required for operation is several orders of magnitude lower than that needed for spin-transfer torque switching, making it an extremely promising technology for low-power, high-speed, non-volatile memory and next-generation logic. Based on these observations, companies like Intel are piloting a device they call the magneto-electric spin-orbit (MESO) logic which they envision will enable a new paradigm to continue scaling of logic device performance to near thermodynamic limits for GHz logic (100 kT switching energy at 100 ps delay) [doi: 10.1038/s41586-018-0770-2]. Test MESO devices are currently under development at Intel using $BiFeO_3$ thin films in collaboration with teams at UC Berkeley and CNRS/Thales. Other designs make use of the ferroelectric control of spin-charge conversion co-developed and demonstrated by CNRS/Thales and demonstrated [doi: 10.1038/s41586-020-2197-9]. MESO, and the revolutionary function it would provide, stands poised to change how we do computation, to address challenges of how we expand beyond Moore's law in the coming years, and to dramatically reduce the power per logic operation to assuage concerns about energy consumption as it relates to computational infrastructure.

The appetite of the community of multiferroics and magnetoelectrics has expanded to include new and now regular symposia at the most important international meetings, has created a series of workshops around the world, and is a leading force in the solid-state physics and materials science communities. This influence is also felt in the form of funding for scientific research – governments on every continent have launched focused efforts to impact in the space of multiferroics. Large-scale efforts within the United States (including both basic science efforts at the National Science Foundation and the Department of Energy, applied science efforts within the Department of Defense, and translational efforts with DARPA and others), the European Union (including numerous FET-Open and on-going Pathfinder Open projects, or COST initiatives), Asia (including efforts in Japan, China, and elsewhere). These targeted and sustained research expenditures point to the impact and potential of this field for the greater society.

In conclusion, the research activities of Prof. Agnès Barthélémy and Dr. Manuel Bibes (CNRS/Thales laboratory of University Paris-Saclay), Prof. Ramamoorthy Ramesh (UC Berkeley) and Prof. Nicola Spaldin (ETH Zurich) have initiated an entirely new research field with surprising and unexpected impact on a whole variety of different areas of science and impressive prospects for application, ranging from fundamental physical science to medical diagnostics.



Prof. Agnès Barthélémy

Dr. Manuel Bibes

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