**INTERVIEW**

Special Topic: Multiferroic Physics and Materials

*Pas de deux of electricity and magnetism: an interview with Sang-Wook Cheong*

By Weijie Zhao

Materials can be ferroelectric, having a spontaneous electric polarization that can be reversed by an external electric field, or they can be ferromagnetic, exhibiting spontaneous magnetization that is switchable by an applied magnetic field. However, until the 1960s, scientists did not expect that these two ferroic properties could co-exist in a single material. Today, materials exhibiting more than one of the primary ferroic properties are called multiferroics. Here, the primary ferroic properties can be ferroelectricity, ferromagnetism, antiferromagnetism, ferroelasticity, ferrotoroidicity or others. Basically, the multiferroic effect originates from the simultaneous breaking of space inversion and time-reversal symmetries. Multiferroics can be imagined as a pas de deux of electricity and magnetism. Recently, National Science Review interviewed Professor Sang-Wook Cheong from Rutgers University, who is one of the pioneering scientists in this field. Cheong talked about the multiferroics field, which has been fast developing since the early 2000s. His introductions and opinions on diverse multiferroic materials and potential multiferroic devices, as well as future research directions, may provide a useful resource for researchers both inside and outside the multiferroic research field.

**MULTIPLE FERROIC MATERIALS**

*NSR:* What are the major discoveries in the history of multiferroics research?

*Cheong:* Research on both magnetism and ferroelectric has a long history. The first manmade perovskite ferroelectric, barium titanate (BaTiO₃), was synthesized in the 1940s. After that, many perovskite ferroelectrics were discovered. Then, in the 1960s, researchers found that some of the ferroelectric oxides are also magnets at low temperature. Several groups in Europe and Russia were interested in this magneto-electric coupling and researched these materials. Bismuth ferrite (BiFeO₃), which is a very popular multiferroic material with perovskite structure, was also discovered around the 1960s. Then the multiferroic field became quiet until the early 2000s, when two important discoveries came out.

The first one is the discovery of the so-called CME effect, the colossal magnetoelectric effect. The CME effect is somewhat similar to the CMR effect, the colossal magnetoresistance effect. The CMR effect describes a huge change of the resistance of materials, which is achieved by controlling the metal–insulator phase transition by an external magnetic field. Similarly, certain multiferroic phase transitions controlled by electric or magnetic fields can give rise to a huge magnetoelectric response, which is called the CME effect. For example, we are able to manipulate reversibly electric polarization by applying an external magnetic field. The CME effect can be observed in materials like TbMnO₃ and TbMn₂O₅.

The second important thing is about BiFeO₃. In 2003, scientists found that the residual polarization of BiFeO₃ is large. By developing advanced fabrication techniques, we are able to synthesize high-quality single crystals and films of BiFeO₃. That was an important step for the fabrication of multiferroic devices.

I think these two things, the discovery of the CME effect and being able to fabricate BiFeO₃, which both happened in the early 2000s, are important steps towards the modern era of multiferroics.

*NSR:* Perovskite structure is a superstar for materials science. Why is it so special? Why do so many multiferroics have this structure?

*Cheong:* Compared with other common structures, such as the spinel structure, there are actually more perovskite multiferroics. Spinels such as magnetite (Fe₃O₄) can have properties of magnetism. But few of them are ferroelectrics, and even fewer are multiferroics.

Perovskite has several unique characteristics. First, it is very flexible for element substitution. Many different elements and ions can get into the structure to form different compounds.
Second, it is a cubic-like structure with high symmetry. In the perovskite structures, B-site metallic ions are connected by anions with bonding of more or less 180°, so they can be good at electric transport and electromagnetic coupling. Also, the lattice symmetries of a cubic-like structure can be readily broken with internal or external perturbations. When certain symmetries are broken, it can give rise to polarization and multiferroicity. I think these points come together to raise the special properties of perovskite.

In terms of physics, it [Type-II multiferroics] is beautiful and wonderful, but in terms of making room-temperature devices, there may be certain limitations.

—Sang-Wook Cheong

NSR: Multiferroics are often classified into Type-I multiferroics and Type-II multiferroics. What are the definitions of Type-I and Type-II? And why is Type-II multiferroics important for new physics?

Cheong: Type-I means that the ferroelectric phase transition happens at a relative high temperature, but its magnetic coupling is usually small and comes in at low temperature. Type-I can be further classified into Type-Ia and Type-Ib. Type-Ia is polar and ferroelectric, which means that we are able to flip its polarization direction by an applied electric field. Type-Ib is polar but not ferroelectric. Its polarization direction cannot be flipped by an external electric field.

Type-II multiferroics usually have very complicated magnetic orders. With a certain symmetry of this magnetic order broken, the symmetry of the crystal lattice would also be broken, which can induce electric polarization. Then it becomes ferroelectric and multiferroic. Type-II multiferroics are driven by magnetic ordering, and there is very strong coupling between magnetic order and ferroelectric polarization, so this kind of material often shows the CME effect. External electric or magnetic fields can control its phase transition. However, this coupling usually happens at low temperatures, so it is not easy to have room-temperature Type-II multiferroics. In terms of physics, it is beautiful and wonderful, but in terms of making room-temperature devices, there may be certain limitations.

NSR: What are the major applications of multiferroics?

Cheong: Multiferroics can be used in devices when magnetoelectric coupling is required. One example is low-energy-consuming memory devices. Memory devices such as hard disks record information by magnetism. In certain multiferroics, we can flip its magnetization by flipping the external electric field at room temperature. Since flipping ferroelectric polarization requires only voltage, the energy consumption can be rather low.

Another example is high-frequency devices, such as high-frequency filters and high-frequency inductors. When lattice fluctuations couple with spin fluctuations, the coupling can produce so-called electromagnons. These fluctuations can be high frequency and can be controlled by electric fields or magnetic fields. So this kind of dynamic property of multiferroics is also very practical.

MAGIC OF DOMAIN WALLS

NSR: Some of your works are about domain walls. What are the definitions of domain and domain wall?

Cheong: In multiferroics, spins and dipoles are aligned along certain directions. There is more than one possible direction of ordering orientation. So in a given sample, different parts can have different orientation directions. Each region with a particular type of orientation is called a domain. The boundary between domains is called a domain wall.

NSR: What is the size of a domain?

Cheong: Domain size can vary. Roughly speaking, the size of a ferroelectric domain is of the order of one micrometer. The width of a ferroelectric domain wall is less than one
nанометр, около нескольких ангстромов. Ширина магнитной доменной стены может быть такой же, как у микрометра. Поэтому ширина доменов и доменных стен, которые обеспечивают контролируемый переход фазы, может быть значительной, и между этими двумя размерами может быть существенное различие.

Многие интересные эффекты могут происходить в доменных стенах. Также, в типе II мултиферроик, где мы можем контролировать область, в которой происходит переход фазы, и область доменов, которые контролируют этот процесс. Понимание и контроль доменных стен и доменных областей является значительной частью всех исследований.

CHEONG: Домены имеют свои уникальные характеристики, которые отличаются от простых доменов. Есть много различных исследований, которые идут в различных областях, но все они включают в себя домены и доменные стены. Мы должны понимать их свойства, чтобы изучать весь образец. Я верю, что доменные стены являются одной из главных областей будущих исследований.

NSR: Что вы считаете основными проблемами, которые нужно решить относительно мултиферроик?

CHEONG: Во-первых, это тяжело предсказать новую мултиферроику. Мы можем прогнозировать электроферроику, но предсказание магнетизма более сложное. Второе, мултиферроики сложны, поэтому трудно сказать, является ли что-то новым мултиферроиком, или нет. Третье, статические магнетоэлектрические характеристики доменной стены требуют дальнейших исследований. Исследования доменных областей теоретически и экспериментально являются сложными. Кроме того, доменные стены могут быть изучены с помощью и других типов исследований. Эти виды исследований очень важны.

NSR: Как вы оцениваете искусственный интеллект (AI) в качестве инструмента для прогнозирования мултиферроиков?

CHEONG: Магнетоэлектрический эффект — это взаимодействие магнетизма и электричества, и при этом магнетоэлектрический материал не обязательно должен быть строго мултиферроидным. Можно говорить о не-тривиальных магнетоэлектрических эффектах в не-тривиальных мултиферроиках, которые могут быть суперпроводниками, полупроводниками или топологическими материалами.

NSR: Какие ваши основные интересы в настоящий момент?

CHEONG: Наше основное направление исследования — синтез высококачественных материалов. Мы используем различные методы, такие как атомно-силовая микроскопия (AFM), сканирующая туннельная микроскопия (STM) и многие другие методы. Мы используем процедуры, которые позволяют нам получать высококачественные образцы и исследовать их свойства.

NSR: В каком направлении вы видите развитие мултиферроиков в будущем?

CHEONG: Прогресс на пути к созданию мултиферроиковых устройств будет постепенным, но он будет иметь большое значение для развития новых материалов. Мы продолжаем исследовать различные методы и техники, которые могут помочь нам в этом.

NSR: Как вы думаете, что может быть сделано с помощью AI?

CHEONG: AI может быть очень полезным при исследовании сложных систем. Он может помочь нам получать более точные результаты и улучшить качество наших исследований. Мы продолжаем исследовать возможности AI и стараемся использовать его для нашего исследования.

NSR: В каких направлениях вы планируете проводить исследования в будущем?

CHEONG: Мы планируем продолжать исследовательские работы в области мултиферроиковых материалов. Мы также планируем работать с другими группами, чтобы совместно решать сложные проблемы и достигать общих целей.

NSR: Какие ваши текущие интересы в области исследований мултиферроиковых материалов?

CHEONG: Наши основные интересы в данной области — это синтез высококачественных материалов. Мы используем различные методы и техники, которые позволяют нам получать высококачественные образцы и исследовать их свойства. Мы также планируем работать с другими группами, чтобы совместно решать сложные проблемы и достигать общих целей.
ADVICE AND MORE

NSR: How are Chinese scientists performing in this field?

Cheong: In the last 5 or 10 years, China has made significant contributions in the fields of topological materials and Fe-based superconductors. Compared with those, the Chinese contribution to multiferroics is somewhat weaker.

There are two major factors in China’s success with topological materials and superconductors: one is people, the other is scientific focusing and official strategic investment. A whole set of experimental facilities for topological materials and superconductors can be very costly. For example, in situ characterization tools (STM, ARPES, etc.) combined with fabrication equipment (molecular-beam epitaxy chambers etc.) are expensive, but have been successfully set up in China, and have been essential tools enabling new discoveries to be made in China.

I suppose that multiferroics encounters the same issue. If China focuses on this field, and makes strategic investment into, for example, high-spatial/temporal-resolution imaging and spectroscopic tools, Chinese researchers will be able to create something really new and important.

NSR: What is your advice for the young generation?

Cheong: I believe that, in the next 10 years, numerous achievements can be made in the field of multiferroics. There are many significant problems to be solved, many complex materials to be studied, and many sophisticated experimental and fabrication tools, as well as powerful computational tools such as AI, to be used. Combining these factors together, it is a good direction for young people, and I am really eager to see what they can do.

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