

Manchester, UK and ³Chongqing 2D Materials Institute, China
E-mail: kostya@nus.edu.sg

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PHYSICS

Towards two-dimensional room temperature multiferroics

Hongjun Xiang ^{1,2,3}

Multiferroic materials with coupled ferroelectricity (FE) and magnetism have long been sought for novel memory devices [1–3]. The co-existence of FE and magnetism is rare in nature, which can be attributed to their mutual exclusive origins (empty d shell for conventional ferroelectric order and partially filled d shell for magnetic order). Moreover, magnetoelectric (ME) coupling is weak in type-I multiferroics with FE and magnetism arising respectively from different mechanisms, while for type-II multiferroics with FE induced by magnetic ordering, their low spin-driven ferroelec-

tric polarizations (mostly <0.01 C/m²) and Curie temperature (mostly <150 K) hinder their practical applications [4,5]. To date, almost all synthesized magnetoelectric multiferroics have been three-dimensional.

In a recent work, Zhong *et al.* [6] instead focused on 2D ferroelectrics [7] and predicted a room temperature multiferroic with a desirable co-existence of ferromagnetism (FM) and FE and strong magnetoelectric coupling. To be more specific, they investigated 2D thin-layer CuCrX₂ (X = S or Se). The Curie temperatures of FM and FE were

both above room temperature, where the FM is stabilized by enhanced carrier density and polarization-driven orbital shifting. Moreover, the gradient of interlayer coupling parameter between adjacent layers gave rise to diversified types of magnetoelectric layers of different thicknesses. For example, tri-layer Cu-intercalated CrS₂, denoted as Cu₂(CrS₂)₃, is ferroelectric in-plane while ferrimagnetic vertically as shown in Fig. 1(a), with a net magnetization of $2.62 \mu_B/\text{f.u.}$ For the ground state with polarization downwards, the middle layer is antiferromagnetically coupled

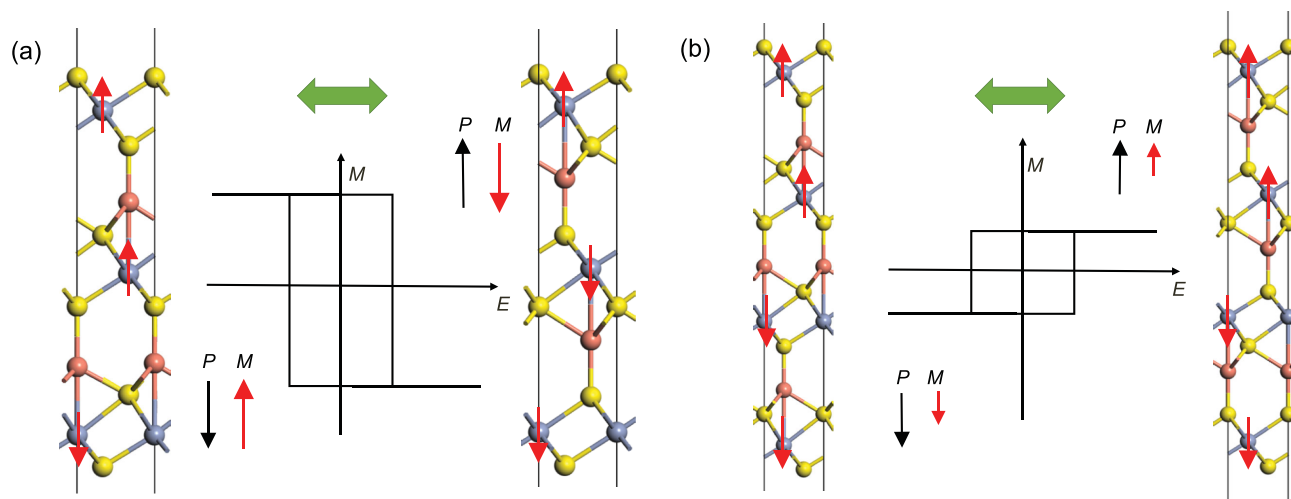


Figure 1. Spin configurations and multiferroic switching for (a) Cu₂(CrS₂)₃ and (b) Cu₃(CrS₂)₄ thin films. Black and red arrows denote the directions of polarization and magnetization, respectively. Adapted from Fig. 4 of Ref. [6].

with the down layer while ferromagnetically coupled with the top layer; when the polarization is upwards, the magnetization of the middle layer will be reversed, ferromagnetically coupled with the down layer while antiferromagnetically coupled with the top layer. Hence FE switching should enable a 180-degree reversal of a considerable magnetization of $2.62 \mu_B/\text{f.u.}$ The ground state for four-layer Cu-intercalated CrS_2 denoted as $\text{Cu}_3(\text{CrS}_2)_4$ is shown in Fig. 1(b), where the upper two layers are ferromagnetically coupled while antiferromagnetically coupled with the two layers downwards. The net magnetization of $0.35 \mu_B/\text{f.u.}$, which is much reduced, can also be reversed via polarization switching. The swapping of spin-up and spin-down channel in band structures during FE switching may result in a new type of 'electrical writing + magnetic reading' memory architecture.

The work by Zhong *et al.* [6] not only paves a new way to realize a room temperature ferromagnetic-ferroelectric multiferroic with strong magnetoelectric coupling [5,8,9], but may also stimulate

more studies on multiferroicity in 2D systems. It remains to be seen whether the 2D multiferroic material or concept conveyed in this study can be experimentally confirmed or whether the predicted ME coupling can be confirmed in a more direct simulation of the FE switching process.

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Hongjun Xiang ^{1,2,3}

¹Key Laboratory of Computational Physical Sciences (Ministry of Education), State Key Laboratory of Surface Physics, and Department of Physics, Fudan University, China; ²Collaborative Innovation Center of Advanced Microstructures, China and ³Shanghai Qi Zhi Institute, China
E-mail: hxiang@fudan.edu.cn

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INFORMATION SCIENCE

Exploring the electromagnetic information of metasurfaces

Din-Ping Tsai 

Metasurfaces, a 2D counterpart of metamaterials, are made of planar subwavelength-scale meta-atoms with designed distributions. The meta-atoms of a metasurface can be used to couple incident waves to free space with controllable amplitudes, phases and polarizations, yielding many novel photonic devices such as optical meta-lenses [1–4]. In recent years, with the bloom of information technologies, efforts have been made to braid metasurfaces with digital and information science, rendering the emergence of a digital-coding metasurface, field-programmable metasurface, information metasurface and intelligent metasurface [5–7].

In 2020, Prof. Tie Jun Cui and team members Haotian Wu, Guo Dong Bai, Shuo Liu, Xiang Wan and Qiang Cheng from Southeast University and Prof. Lianlin Li from Peking University brought new physical insights into metasurfaces from an information perspective [8]. In this work, the researchers built on the concept of observation information from the information optics [9] and developed a generalized theory to characterize the information of the digital-coding pattern (I_1) and the far-field pattern (I_2) of metasurfaces. Here, the far-field information (I_2) of a metasurface is defined as the entropy difference between the normalized

radiation function and the uniformly distributed pattern. Subsequently, by leveraging the generalized uncertainty relation between two non-commuting observables [10], it is revealed that the upper bound of the far-field information is determined by the size of the meta-surface and the working frequency (Fig. 1).

As an important application, the researchers adopted the established far-field information to predict the upper limit of the number of orthogonal radiation states generated by the digital-coding metasurface, thus providing guidance for metasurface-based computational imaging, for which orthogonal

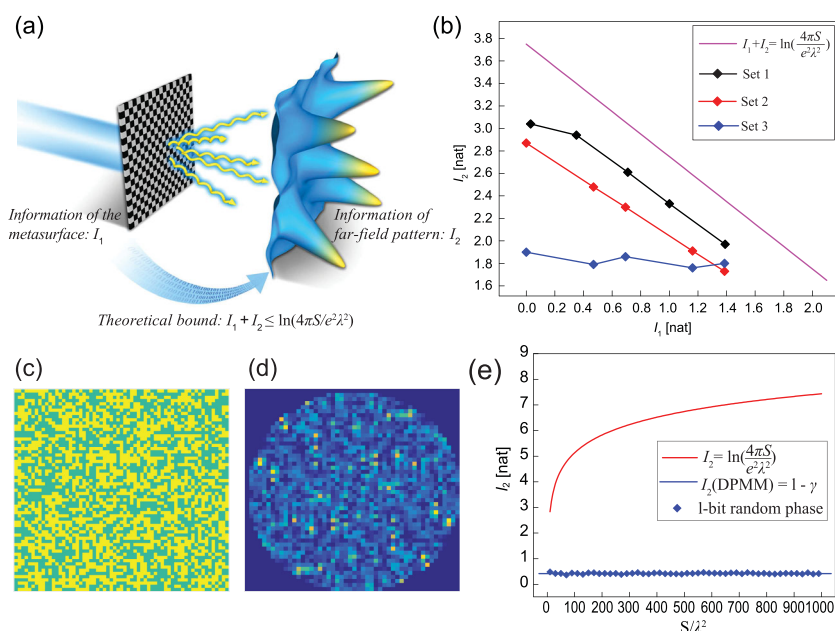


Figure 1. (a) Schematic of the information relationship between the digital-coding metasurface and its far-field pattern. (b) Calculated results of the information relationship between the metasurface samples and their far-field patterns with respect to different modulation schemes and the information upper bound. (c) and (d) A sample of a 1-bit disordered-phase pattern of the metasurface and the generated far-field intensity distribution. (e) Theoretical and calculated results of the far-field information (I_2) with respect to different sizes and phase patterns of metasurfaces. Adapted from Ref. [8].

radiation patterns are preferred for compressive-sensing imaging. They explored the information relation between the metasurface and the generated radiation pattern to determine the lower bound of metasurface size as well. Specifically, they demonstrated that, once the required radiation patterns are specified, the size of the metasurface must be larger than the value predicted by the proposed theory; otherwise, it would be impossible to realize the required radiation patterns no matter which design strategies are adopted.

More intriguingly, through investigating the information of a disordered-phase

modulated metasurface (DPMM), the researchers found the information-invariance property of chaotic far-field patterns. That is to say, the far-field information of a DPMM is always equal to $1 - \gamma$ (γ is the Euler's constant, $\gamma \approx 0.5772$), which is independent of the size of the metasurface, the number of meta-atoms and the phase patterns. The obtained far-field information of a DPMM is close to zero and might be the theoretical lower bound, which indicates that DPMMs are preferred for stealth applications.


The proposed electromagnetic-information theory has considered both

the digital world (digital-coding pattern) and the physical world (far-field pattern) and hence will have novel applications on new information theory for 5G and 6G wireless communications.

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Din-Ping Tsai 
Department of Electronic and Information
Engineering, The Hong Kong Polytechnic University,
China
E-mail: dinping.tsai@polyu.edu.hk

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