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Recent progress in voltage control of magnetism: Materials, mechanisms, and performance

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ABSTRACT

Voltage control of magnetism (VCM) is attracting increasing interest and exciting significant research activity driven by its profound physics and enormous potential for application. This review article aims to provide a comprehensive review of recent progress in VCM in different thin films. We first present a brief summary of the modulation of magnetism by electric fields and describe its discovery, development, classification, mechanism, and potential applications. In the second part, we focus on the classification of VCM from the viewpoint of materials, where both the magnetic medium and dielectric gating materials, and their influences on magnetic modulation efficiency are systematically described. In the third part, the nature of VCM is discussed in detail, including the conventional mechanisms of charge, strain, and exchange coupling at the interfaces of heterostructures, as well as the emergent models of orbital reconstruction and electrochemical effect. The fourth part mainly illustrates the typical performance characteristics of VCM, and discusses, in particular, its promising application for reducing power consumption and realizing high-density memory in several device configurations. The present review concludes with a discussion of the challenges and future prospects of VCM, which will inspire more in-depth research and advance the practical applications of this field.

Abbreviations: 2-DEG, two dimensional electron gas; AAIM, 1,3-diallylimidazolium; ABIM, 1-allyl-3-butylimidazolium; AEIM, 1-al-lyl-3-ethylimidazolium; AFM, antiferromagnetic; AHE, anomalous Hall effect; ALD, atomic layer deposition; α, magnetoelectric coupling coefficient; BFO, $BiFeO_3$; BTO, $BaTiO_3$; CFO, $CoFe_2O_4$; DEME, N,N-diethyl-N-(2-methoxyethyl)-N-methylammonium; DOS, densities of states; EDL, electric double layer; EELS, electron energy loss spectroscopy; EMIM, 1-ethyl-3-methylimidazolium; FE, ferroelectric; FE-FET, ferroelectric field effect transistor; FET, field-effect transistor; FM, ferromagnetic; GMR, giant magnetoresistance; HAADF, high angle annular dark field; HM, heavy metal; H_C, coercive field; H_{EB}, exchange bias field; IL, ionic liquid; κ, dielectric constant or permittivity; K_U, magnetocrystalline anisotropy; LAO, $LaAlO_3$; LCMO, $La_{1-x}Ca_xMnO_3$; LSMO, $La_{1-x}Sr_xMnO_3$; λ, screening length; MA, magnetic anisotropy; MAE, magnetocrystalline anisotropy; MFM, magnetic force microscopy; MFTJs, multiferroic tunnel junctions; MOKE, magneto-optic Kerr effect; MPPR, N-methyl-N-propylpiperidinium; MR, magnetoresistance; MRAMs, magnetic random access memories; MTJ, magnetic tunnel junction; $\boldsymbol{m}$, magnetic moment; M_S, saturated magnetization; NFO, $NiFe_2O_4$; PCMO, $Pr_{1-x}Ca_xMnO_3$; PEEM, photoemission electron microscopy; PEO, polyethylene oxide; PLD, pulsed laser deposition; PMA, perpendicular magnetic anisotropy; PMN-PT, $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$; PTO, $PbTiO_3$; PZT, $Pb(Zr_{1-x}Ti_x)O_3$; P, polarization; P_{down}, polarization downward; P_{up}, polarization upward; Φ, potential barrier; R_{Hall}, Hall resistance; SHE, spin Hall effect; SOT, spin–orbit torque; SQUID, superconducting quantum interference device; SRO, $SrRuO_3$; STEM, scanning transmission electron microscopy; STO, $SrTiO_3$; STT-MRAM, spin transfer torque magnetic random access memory; $\boldsymbol{\sigma}$, spin polarization direction; TER, tunnel electroresistance; TFSI, bis-(trifluoromethylsulfonyl)imide; TMPA, N,N,N-trimethyl-N-propylammonium; TMR, tunnel magnetoresistance; T, temperature; T_C, Curie temperature; $\boldsymbol{\tau}_{DL}$, damping-like torque; $\boldsymbol{\tau}_{FL}$, field-like torque; VCM, voltage control of magnetism; VCMA, voltage control of magnetic anisotropy; V_G, gate voltage; V_O, oxygen vacancies; XANES, X-ray absorption near edge structure; XAS, X-ray absorption spectroscopy; XLD, X-ray linear dichroism; XMCD, X-ray magnetic circular dichroism; YIG, $Y_3Fe_5O_{12}$; YMO, $YMnO_3$.

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Contents

1. Introduction

The control of magnetism and spin phenomena, which corresponds to switching between the basic "0" and "1" signals in information technology, has been intensely pursued during the past few decades [1–4]. It has generally been accepted that a magnetic field is the only means to switch magnetization and to maintain unchanged the magnetic behaviors of magnetic materials once they have been prepared [4]. The use of cumbersome magnets or coils occupies a large amount of space and entails serious energy consumption, especially when taking the remarkable trend in miniaturization of magneto-electronics into account [4–6]. Thus, there is a pressing need to employ nonmagnetic means to switch and modulate magnetism. Compared with other nonmagnetic routes, such as strain, doping, current, and light, a voltage has been proven to be able to manipulate magnetism with a combination of advantages, including low power dissipation, reversibility, nonvolatility, high speed, and good compatibility with the conventional semiconductor industry [7–13].

In fact, Maxwell's equations first reveal that the two independent phenomena of magnetic interaction and electric charge motion are intrinsically coupled to each other [14]. The thought of utilizing electric fields to control magnetism could date back to the 1960s [15]. In 2000, Ohno et al. [16] demonstrated the tuning of saturated magnetization and Curie temperature by an electric field in a diluted magnetic semiconductor (In,Mn)As. A large number of experimental works and theoretical investigations on the modulation and switching of magnetism have emerged in recent years, driven both by an urge to