

# Out-of-plane Edelstein effects: Electric field induced magnetization in $p$ -wave magnets

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(Received 3 January 2025; revised 2 March 2025; accepted 24 March 2025; published 14 April 2025)

In-plane magnetization is induced by the Edelstein effect in a Rashba spin-orbit interaction system. However, out-of-plane magnetization is more useful for switching a ferromagnetic memory. We study analytically and numerically electric field induced magnetization in  $p$ -wave magnets with the aid of the Rashba interaction based on a simple two-band model. The out-of-plane magnetization is induced when the Néel vector of the  $p$ -wave magnet is along the  $z$  direction. We also show that no magnetization is induced in the absence of the Rashba interaction. The electric field induced magnetization will be useful for future switching technologies of ferromagnetic memories based on the  $p$ -wave magnet.

DOI: [10.1103/PhysRevB.111.L161301](https://doi.org/10.1103/PhysRevB.111.L161301)

**Introduction.** Multiferroic effects are cross-correlation effects in electromagnetic responses [1–3]. One is the electric polarization induced by a magnetic field [4–6] and the other is the magnetization induced by an electric field [7–10]. Especially, the latter is important for the flip of a magnetic memory under the control of an external electric field. The Edelstein effect [11,12] is a promising way to achieve it. It is based on a spin-momentum-locked Fermi surface induced by the Rashba interaction [13]. In the presence of a Rashba interaction, the spin direction depends on the angle of the momentum as shown in Fig. 1(a), where the Fermi surface forms a perfect circle. By applying an in-plane electric field, the Fermi distribution is shifted, which induces the imbalance in the spin accumulation. It results in a net in-plane magnetization. However, out-of-plane magnetization is desirable for practical applications to ferromagnetic memories because the ferromagnet points to an out-of-plane direction. The Edelstein effect is confirmed in various experiments [14–16]. It is also realized in semiconductors [17,18], Rashba-Dresselhaus systems [19,20], topological insulators [21,22], and Weyl semimetals [23].

Recently, a  $p$ -wave magnet was proposed based on first-principles calculations [24], where the Fermi surface has  $p$ -wave symmetry. A material candidate is CeNiAsO. The system is described by a four-band tight-binding model. Subsequently, the Edelstein effect without the Rashba interaction was proposed in this magnet [25].

In this Letter, we investigate the Edelstein effect in a two-dimensional system made of a  $p$ -wave magnet with the Rashba interaction, which is described by a simple two-band continuum model. By applying an in-plane electric field, we demonstrate the emergence of the out-of-plane magnetization provided the Néel vector of the  $p$ -wave magnet is taken

perpendicular to the plane. Namely, it is possible to switch the out-of-plane magnetization by controlling the external in-plane electric field. It would be useful for the switch of a ferromagnetic memory. Our results will open another method to achieve a magnetic-memory switching device by an electric field.

**Edelstein effect.** The magnetization is induced by the change of the Fermi distribution in the Rashba system, which is called the Edelstein effect. We study such an effect by controlling the external electric field  $\mathbf{E}$ . We expand the Fermi distribution in powers of  $\mathbf{E}$ ,  $f = f^{(0)} + f^{(1)} + \dots$ , where  $f^{(0)} = 1/\{\exp[(\varepsilon - \mu)/k_B T] + 1\}$  is the Fermi distribution function,  $\mu$  is the chemical potential,  $\varepsilon$  is the energy, and  $f^{(1)}$  is the first-order perturbed Fermi distribution function as a function of  $\mathbf{E}$ . By solving the Boltzmann equation, it is explicitly given by

$$f^{(1)} = \frac{e\tau}{\hbar} \mathbf{E} \cdot \nabla_{\mathbf{k}} f^{(0)}, \quad (1)$$

where  $\tau$  is the relaxation time. We focus on the linear response.

The magnetization is given by the formula [25–36]

$$\mathbf{M} = g\mu_B \int \frac{d^3k}{(2\pi/a)^3} \mathbf{S}(\mathbf{k}) f^{(1)}, \quad (2)$$

where  $\mathbf{S}(\mathbf{k}) \equiv \langle \psi_{\mathbf{k}} | \boldsymbol{\sigma} | \psi_{\mathbf{k}} \rangle$  is the expectation value of the spin operator  $\boldsymbol{\sigma}$ ,  $g$  is the  $g$  factor,  $\mu_B$  is the Bohr magneton, and  $a$  is the lattice constant. The magnetization formula is rewritten as

$$\mathbf{M} = \frac{e\tau}{\hbar} g\mu_B \int \frac{d^3k}{(2\pi/a)^3} \mathbf{S}(\mathbf{k}) (\mathbf{E} \cdot \nabla_{\mathbf{k}} \varepsilon) \frac{\partial}{\partial \varepsilon} f^{(0)}. \quad (3)$$

At zero temperature, it is given by

$$\mathbf{M} = e\tau g\mu_B \int \frac{d^3k}{(2\pi/a)^3} \mathbf{S}(\mathbf{k}) (\mathbf{E} \cdot \mathbf{v}) \delta(\varepsilon_{\mathbf{k}} - \mu), \quad (4)$$

where we have defined the velocity operator  $\hbar \mathbf{v} = \nabla_{\mathbf{k}} \varepsilon$ .

We apply the electric field along the  $x$  axis in the two-dimensional system. When there are two Fermi surfaces  $k_{\pm}(\phi)$

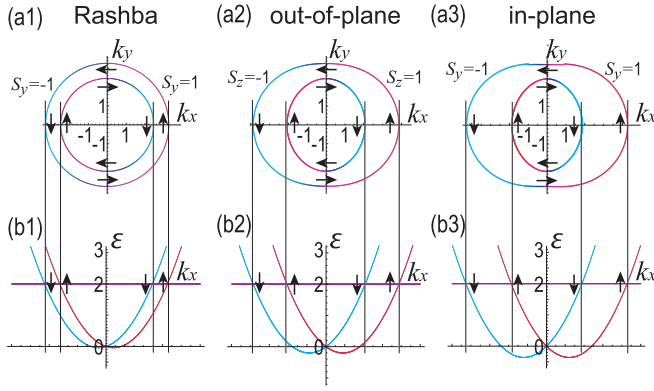


FIG. 1. (a1), (a2), and (a3) Fermi surfaces at  $\mu = 2\varepsilon_0$  in the  $(k_x, k_y)$  plane. The momentum axis is in units of  $k_0$ . (b1), (b2), and (b3) Energy spectrum along the  $x$  axis. The vertical axis is the energy  $\varepsilon$  in units of  $\varepsilon_0$ , while the horizontal axis is  $k_x$  in units of  $k_0$ . Purple lines represent  $\mu = 2\varepsilon_0$ . (a1) and (b1) Rashba model. (a2) and (b2) Out-of-plane  $p$ -wave magnet. (a3) and (b3) In-plane  $p$ -wave magnet. The red color represents  $S_y = 1$ , while the cyan color represents  $S_y = -1$  in (a1), (b1), (a3), and (b3). On the other hand, the red color represents  $S_z = 1$ , while the cyan color represents  $S_z = -1$  in (a2) and (b2). Arrows represent the spin direction. We have set  $m = 4\hbar^2 k_0^2 / \varepsilon_0$ ,  $J = 0.4\varepsilon_0 / k_0$ , and  $\lambda = 0.2\varepsilon_0 / k_0$ .

around the origin as illustrated in Fig. 1, it is rewritten as

$$\mathbf{M} = \frac{e\tau g\mu_B a^3 E_x}{(2\pi)^2 W} \sum_{\pm} \int k dk d\phi \mathbf{S}(\mathbf{k}) v_x \frac{\delta(k_{\pm}(\phi) - k)}{\left| \frac{\partial \varepsilon}{\partial k} \right|}, \quad (5)$$

or

$$M_i = g\mu_B \chi_{ij}^{\text{ME}} E_j, \quad (6)$$

in terms of the magnetoelectric susceptibility  $\chi_{ij}^{\text{ME}}$  given by

$$\chi_{ix}^{\text{ME}} = \frac{e\tau a^3}{(2\pi)^2 W} \sum_{\pm} \int d\phi \frac{k v_x S_i(\mathbf{k})}{\left| \frac{\partial \varepsilon}{\partial k} \right|} \bigg|_{k=k_{\pm}(\phi)}, \quad (7)$$

where  $k_{\pm}(\phi)$  is obtained by solving  $\varepsilon[k_{\pm}(\phi)] = \mu$ ,  $v_x = \frac{\partial \varepsilon}{\hbar \partial k_x}$  is the velocity along the  $x$  axis,  $W^{-1} \equiv \int dk / (2\pi)$  is the width of the sample, and we have introduced the polar coordinate  $k_x = k \cos \phi$ ,  $k_y = k \sin \phi$ .

**Out-of-plane  $p$ -wave Edelstein effects.** We consider a two-dimensional system made of a  $p$ -wave magnet with the Rashba interaction. The simplest model is a two-band model consisting of the free-electron term, the Rashba term [37–45], and the  $p$ -wave term [24,37,46–49], which is realized as a heterostructure of a magnet on a substrate. The Hamiltonian is given by [37]

$$H(\mathbf{k}) = \frac{\hbar^2 (k_x^2 + k_y^2)}{2m} \sigma_0 + \lambda (k_x \sigma_y - k_y \sigma_x) + J k_x \mathbf{n} \cdot \boldsymbol{\sigma}, \quad (8)$$

where  $m$  is the effective mass of free electrons,  $\lambda$  is the magnitude of the Rashba interaction, and  $\mathbf{n}$  is the  $p$ -wave Néel vector with  $J$  its magnitude. The Rashba interaction is introduced by placing a sample on the substrate. We study the case where the Néel vector is along the  $z$  direction,  $\mathbf{n} = (0, 0, 1)$ .

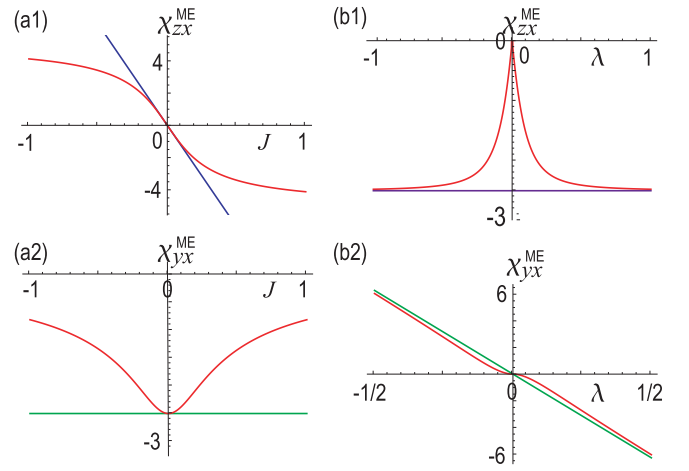


FIG. 2. Out-of-plane Edelstein effect. (a1)  $\chi_{zx}^{\text{ME}}$  and (a2)  $\chi_{yx}^{\text{ME}}$  as a function of  $J$ . We have set  $\lambda = 0.2\varepsilon_0 / k_0$ . (b1)  $\chi_{zx}^{\text{ME}}$  and (b2)  $\chi_{yx}^{\text{ME}}$  as a function of  $\lambda$ . We have set  $J = 0.2\varepsilon_0 / k_0$ . Red curves represent the numerical results without using the perturbation theory. Blue and green lines represent the analytic results for  $\chi_{zx}^{\text{ME}}$  and  $\chi_{yx}^{\text{ME}}$  in Eq. (13), respectively.  $\chi_{zx}^{\text{ME}}$ ,  $\chi_{yx}^{\text{ME}}$ , and  $\chi_{xx}^{\text{ME}}$  are in units of  $\frac{e\tau k_0}{\hbar W}$ , while  $J$  and  $\lambda$  are in units of  $\varepsilon_0 / k_0$ . We have set  $\mu = 2\varepsilon_0$  and  $m = 4\hbar^2 k_0^2 / \varepsilon_0$ .

The energy spectrum is given by

$$\varepsilon_{\pm} = \frac{\hbar^2 k^2}{2m} \pm k \sqrt{F_z(\phi)}, \quad (9)$$

with

$$F_z(\phi) \equiv \lambda^2 + J^2 \cos^2 \phi. \quad (10)$$

The expectation value of the spin operator  $\mathbf{S}(\mathbf{k})$  is determined as

$$S_x^{\pm} = \mp \frac{\lambda \sin \phi}{\sqrt{F_z(\phi)}}, \quad S_y^{\pm} = \pm \frac{\lambda \cos \phi}{\sqrt{F_z(\phi)}}, \quad S_z^{\pm} = \pm \frac{J \cos \phi}{\sqrt{F_z(\phi)}}, \quad (11)$$

which does not depend on  $k$  and shown in Fig. 1(a3).

The integrand of Eq. (5) is given analytically. By integrating it over  $\phi$  numerically, we obtain the susceptibility  $\chi_{ix}^{\text{ME}}$ . We show the components  $\chi_{zx}^{\text{ME}}$  and  $\chi_{yx}^{\text{ME}}$  in Fig. 2, while  $\chi_{xx}^{\text{ME}} = 0$ .

We derive an analytic formula for the susceptibility up to the first order in  $J$  and  $\lambda$ . There are two Fermi surfaces  $k_{\pm}(\phi)$  as shown in Fig. 1(a). The outer Fermi surface  $k_-(\phi)$  and the inner Fermi surface  $k_+(\phi)$  are given by

$$\hbar k_{\pm}(\phi) = \sqrt{2\mu m} \mp m J \cos \phi, \quad (12)$$

which are shown in color in Fig. 1(a). The  $y$  spin polarization is maximized along the  $x$  axis ( $\phi = 0, \pi$ ).

The susceptibility (7) is calculated as

$$\chi_{xx}^{\text{ME}} = 0, \quad \chi_{yx}^{\text{ME}} = -\frac{e\tau a^3 m}{2\pi \hbar^3 W} \lambda, \quad \chi_{zx}^{\text{ME}} = -\frac{e\tau a^3 m}{2\pi \hbar^3 W} J, \quad (13)$$

for  $\mu > 0$  up to the first order in  $J$  and  $\lambda$ , which are shown as the blue and green lines in Fig. 2, respectively.

We show the numerically obtained susceptibility in the  $J - \lambda$  plane in Fig. 3. Equation (13) agrees well with the numerical result for small  $J/\lambda$ . We find that  $\chi_{zx}^{\text{ME}} = 0$  along

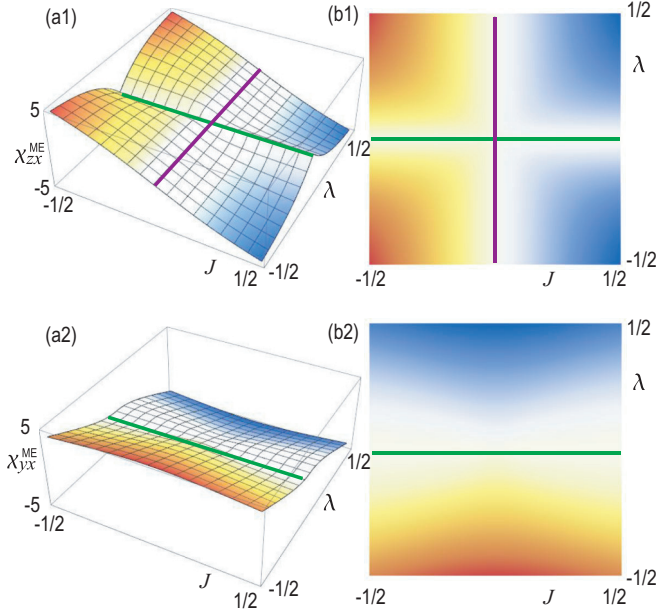


FIG. 3. Out-of-plane Edelstein effect. (a1) Bird's-eye view of  $\chi_{zx}^{\text{ME}}$  in the  $J - \lambda$  plane, and (b1) its color plot. (a2) Bird's-eye view of  $\chi_{yx}^{\text{ME}}$  in the  $J - \lambda$  plane, and (b2) its color plot. The green line represents the condition  $\lambda = 0$  and the purple line represents the condition  $J = 0$ . See the caption of Fig. 2 for the units of various variables. We have set  $\mu = 2\varepsilon_0$  and  $m = 4\hbar^2 k_0^2 / \varepsilon_0$ .

the lines  $J = 0$  and  $\lambda = 0$  as in Fig. 3(b1), while  $\chi_{yx}^{\text{ME}} = 0$  along the line  $\lambda = 0$ . The susceptibility  $\chi_{zx}^{\text{ME}}$  is positive for  $J < 0$  and negative for  $J > 0$ , where the sign of  $\chi_{zx}^{\text{ME}}$  does not depend on  $\lambda$ . On the other hand,  $\chi_{yx}^{\text{ME}}$  is positive for  $\lambda < 0$  and negative for  $\lambda > 0$ , where the sign of  $\chi_{yx}^{\text{ME}}$  does not depend on  $J$ .

*In-plane p-wave magnet along the y direction.* We next study the case where the Néel vector is along the y direction. The energy spectrum is given by

$$\varepsilon_{\pm} = \frac{\hbar^2 k^2}{2m} \pm k\sqrt{F_y(\phi)}, \quad (14)$$

with

$$F_y(\phi) \equiv \lambda^2 \sin^2 \phi + (J + \lambda)^2 \cos^2 \phi. \quad (15)$$

The Fermi surface is shown in Fig. 1(a3). There are two Fermi surfaces  $k_{\pm}(\phi)$ . The outer Fermi surface  $k_{-}(\phi)$  and the inner Fermi surface  $k_{+}(\phi)$  are analytically given by

$$\hbar k_{\pm}(\phi) = \sqrt{2\mu m} \mp m\lambda + J \left( m \mp \frac{m\sqrt{m\lambda}}{\sqrt{2\mu}} \right) \cos^2 \phi \quad (16)$$

up to the first order in  $J$  and  $\lambda$ . The spin direction is

$$S_{\pm}^x = \pm \frac{\lambda y}{\sqrt{F_x(\phi)}}, \quad S_{\pm}^y = \pm \frac{(J + \lambda)x}{\sqrt{F_y(\phi)}}, \quad S_{\pm}^z = 0. \quad (17)$$

The susceptibility (7) is calculated as

$$\chi_{yx}^{\text{ME}} = -\frac{e\tau a^3 \mu_B}{4\pi \hbar^3 W} (J + 2\lambda), \quad \chi_{xx}^{\text{ME}} = \chi_{zx}^{\text{ME}} = 0 \quad (18)$$

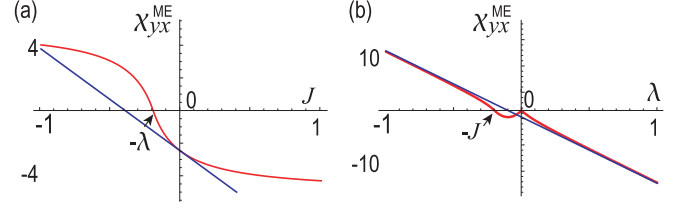


FIG. 4. In-plane Edelstein effect. (a)  $\chi_{yx}^{\text{ME}}$  as a function of  $J$ . We have set  $\lambda = 0.2\varepsilon_0/k_0$ . (b)  $\chi_{yx}^{\text{ME}}$  as a function of  $\lambda$ . We have set  $J = 0.2\varepsilon_0/k_0$ . Red curves represent the numerical results without using the perturbation theory. Blue lines represent the analytic results Eq. (18) based on the perturbation theory. See the caption of Fig. 2 for the units of various variables. We have set  $\mu = 2\varepsilon_0$  and  $m = 4\hbar^2 k_0^2 / \varepsilon_0$ .

for  $\mu > 0$  up to the first order in  $J$  and  $\lambda$ , which is shown as the blue lines in Fig. 4.

We show the numerically obtained susceptibility in Fig. 4. Equation (18) agrees well with the numerical result for small  $J/\lambda$ . The susceptibility is zero  $\chi_{ix}^{\text{ME}} = 0$  for  $\lambda = 0$  or  $J + \lambda = 0$  as shown in Figs. 4(a) and 4(b), where the Hamiltonian (8) is diagonal. The susceptibility  $\chi_{yx}^{\text{ME}}$  is positive for  $J + \lambda < 0$  and negative for  $J + \lambda > 0$  as shown in Figs. 5(a) and 5(b). It is because the spin direction along the x axis matters for the electric field induced magnetization. On the other hand, the sign of the susceptibility  $\chi_{yx}^{\text{ME}}$  does not change at  $\lambda = 0$  because  $f^{(1)}(0, k_y) = 0$ .

*In-plane p-wave magnet along the x direction.* Finally, we study the case where the Néel vector is along the x direction. The energy spectrum is given by

$$\varepsilon_{\pm} = \frac{\hbar^2 k^2}{2m} \pm k\sqrt{F_x(\phi)}, \quad (19)$$

with

$$F_x(\phi) \equiv \lambda^2 \cos^2 \phi + (J \cos \phi - \lambda \sin \phi)^2. \quad (20)$$

The outer Fermi surface  $k_{-}(\phi)$  and the inner Fermi surface  $k_{+}(\phi)$  are analytically given by

$$\hbar k_{\pm}(\phi) = \sqrt{2\mu m} \mp m\lambda + \frac{Jm}{2} \left( \frac{\sqrt{m\lambda}}{\sqrt{2\mu}} \pm 1 \right) \sin 2\phi \quad (21)$$

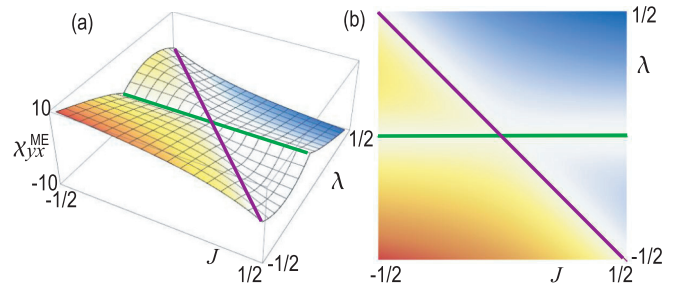


FIG. 5. In-plane Edelstein effect. Bird's-eye view of  $\chi_{yx}^{\text{ME}}$  in the  $J - \lambda$  plane, and (b) its color plot. The green line represents the condition  $\lambda = 0$  and the purple line represents the condition  $\lambda + J = 0$ . See the caption of Fig. 2 for the units of various variables. We have set  $\mu = 2\varepsilon_0$  and  $m = 4\hbar^2 k_0^2 / \varepsilon_0$ .

up to the first order in  $J$  and  $\lambda$ . The spin direction is

$$S_{\pm}^x = \pm \frac{Jx - \lambda y}{\sqrt{F_x(\phi)}}, \quad S_{\pm}^y = \pm \frac{\lambda x}{\sqrt{F_x(\phi)}}, \quad S_{\pm}^z = 0. \quad (22)$$

The susceptibility (7) is calculated as

$$\chi_{xx}^{\text{ME}} = -\frac{e\tau a^3 m}{4\pi \hbar^3 W} J, \quad \chi_{yx}^{\text{ME}} = -\frac{e\tau a^3 m}{2\pi \hbar^3 W} \lambda, \quad \chi_{zx}^{\text{ME}} = 0 \quad (23)$$

for  $\mu > 0$  up to the first order in  $J$  and  $\lambda$ .

*Discussion.* We investigated the electric field induced magnetization in a simple two-band  $p$ -wave magnet model, where the Rashba interaction is essential. On the other hand, the electric field induced magnetization was shown to occur without the Rashba interaction in the  $p$ -wave magnet system described by the four-band model [24,25]

$$H = 2t \left( \tau_x \cos \frac{ak_x}{2} + \cos ak_y \right) + 2t_J \left( \sigma_x \tau_y \sin \frac{ak_x}{2} + \sigma_y \tau_z \cos ak_y \right), \quad (24)$$

where  $\sigma$  and  $\tau$  correspond to the spin and site degrees of freedom,  $t$  is the hopping amplitude with  $t = 0.8$  eV,  $t_J$  is the magnitude of the  $p$ -wave magnet with  $t_J = 0.2$  eV, and  $a$  is the lattice constant  $a = 8.1$  Å.

The above four-band model is derived for a specific material candidate CeNiAsO [24], which is a metal. The dependence of the pseudospin  $\tau$  enters in a specific way, and hence this four-band Hamiltonian is applicable to a specific case. The band structure of CeNiAsO indicates that the Néel vector is along the  $z$  direction [24,25].

The two-band Hamiltonian (8) is quite universal. Furthermore, various analytic formulas are obtained. On the other hand, it is impossible to analytically diagonalize the Hamiltonian (24). There are two possibilities to realize the Hamiltonian (8). One is the metallic  $p$ -wave magnet without the pseudospin degrees of freedom on a substrate producing the Rashba interaction. The other is the insulating  $p$ -wave magnet, where free electrons exist away from the  $p$ -wave magnet, while the interface produces the Rashba interaction. Our results will open another way to multiferroics based on the  $p$ -wave magnet.

We estimate the magnitude of the magnetoelectric susceptibility. First, the relations between the tight-binding model

(24) and the continuum model (8) are given by

$$2t \cos \frac{ak_x}{2} \simeq 2t - \frac{ta^2 k_x^2}{2} = 2t - \frac{\hbar^2 k_x^2}{2m},$$

$$2t_J \sin \frac{ak_x}{2} \simeq t_J ak_x = Jk_x, \quad (25)$$

which lead to the relations  $m = \hbar^2/(ta^2)$  and  $J = t_J a$ . The relaxation time  $\tau$  is related to the strength of the disorder [32] as  $\tau = \hbar/2\Gamma$ , where  $\Gamma = 0.1$  eV. Thus, the magnetoelectric susceptibility is estimated as

$$\chi_{xx}^{\text{ME}} \sim \frac{e\tau a^3 m}{2\pi \hbar^3 W} J = \frac{ea}{4\pi \Gamma} \frac{t_J}{t} \frac{a}{W} \sim 3 \text{ Å/V}. \quad (26)$$

Next, we compare the magnetoelectric susceptibility between the out-of-plane Edelstein effect and the conventional Rashba-Edelstein effect. The ratio between the out-of-plane Edelstein effect and the conventional Rashba-Edelstein effect is estimated to be  $J/\lambda$ . On one hand, the  $p$ -wave magnetization is estimated as  $J = at_J = 8.1 \text{ Å} \times 0.2 \text{ eV} = 1.6 \text{ eV Å}$ . On the other hand, the strength of the Rashba interaction is  $\lambda = 0.03 \text{ eV Å}$  at the Ag(111) surface [50],  $\lambda = 0.07 \text{ eV Å}$  at the InGaAs/InAlAs surface [51], and  $\lambda = 0.33 \text{ eV Å}$  at the Au(111) surface [52]. Hence, the ratio is  $J/\lambda \sim 53$  at the Ag(111) surface,  $J/\lambda \sim 23$  at the Ag(111) surface at the InGaAs/InAlAs surface, and  $J/\lambda \sim 4.8$  at the Au(111) surface. Namely, the out-of-plane Edelstein effect is considerably larger than the conventional Rashba-Edelstein effect.

*Note added.* Recently, we became aware of Ref. [53], in which an experiment on a  $p$ -wave magnet in  $\text{Gd}_3\text{Ru}_4\text{Al}_{12}$  was reported, where the Néel vector is along the  $x$  direction and a similar two-band Hamiltonian is given.

*Acknowledgment.* This work is supported by CREST, JST (Grants No. JPMJCR20T2) and Grants-in-Aid for Scientific Research from MEXT KAKENHI (Grant No. 23H00171).

*Data Availability.* The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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