Electromagnetically controlled Multiferroic thermal diode

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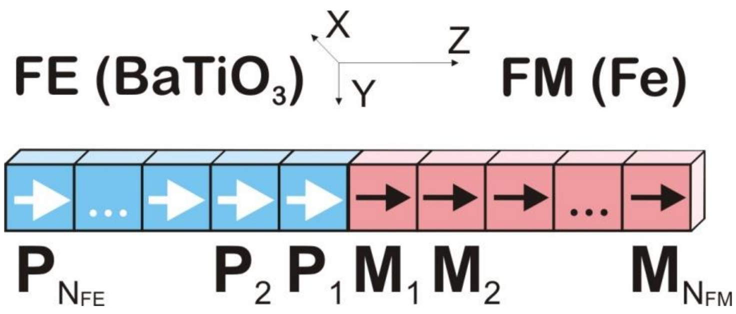
- Composite two phase multiferroics
- Zero temperature Ferroelectric/Ferromagnetic solitons
- Multiferroic thermal diode

Magnetoelectric coupling two phase multiferroics



$$F_{\Sigma} \sim a_{\mathrm{FE}}^{3} F_{\mathrm{FE}} + a_{\mathrm{FM}}^{3} F_{\mathrm{FM}} + E_{\mathrm{C}}$$

Landau-Khalatnikov equation

$$\gamma_{v} \frac{d\mathbf{P}_{i}}{dt} = -\frac{\delta F_{\Sigma}}{\delta \mathbf{P}_{i}}$$

Landau-Lifshitz-Gilbert equation

$$\frac{d\mathbf{M}_{j}}{dt} = -\frac{\gamma}{1+\alpha_{\mathrm{FM}}^{2}}\left[\mathbf{M}_{j} \times \mathbf{H}_{j}^{\mathrm{eff}}(t)\right] - \frac{\alpha_{\mathrm{FM}}\gamma}{1+\alpha_{\mathrm{FM}}^{2}} \frac{1}{M_{\mathrm{S}}}\left[\mathbf{M}_{j} \times \left[\mathbf{M}_{j} \times \mathbf{H}_{j}^{\mathrm{eff}}(t)\right]\right]$$

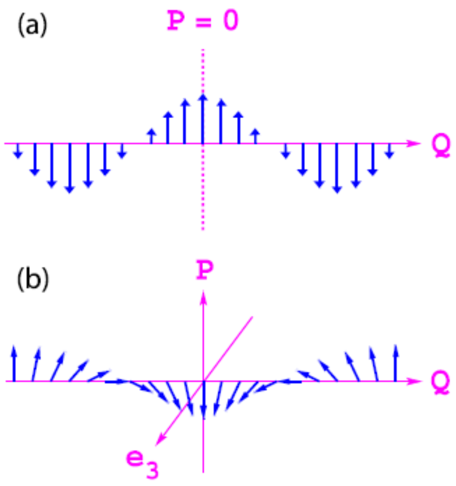
$$\mathbf{H}_{j}^{\mathrm{eff}}(t) = -\delta F_{\Sigma} / \delta \mathbf{M}_{j}$$

Screening effect and magnetoelectric coupling

$$V_{ME} = -g_{1}\left(P_{N} M_{N+1}^{z}\right) - g_{2}\left(P_{N} M_{N+1}^{z}\right)^{2}$$

C.-L. Jia, T.-L. Wei, C.-J. Jiang, D.-S. Xue, A. Sukhov, and J. Berakdar Phys. Rev. B **90**, 054423 (2014);
L. Chotorlishvili, S. R. Etesami, and J. Berakdar R. Khomeriki, Jie Ren, Phys. Rev. B **92**, 134424 (2015)

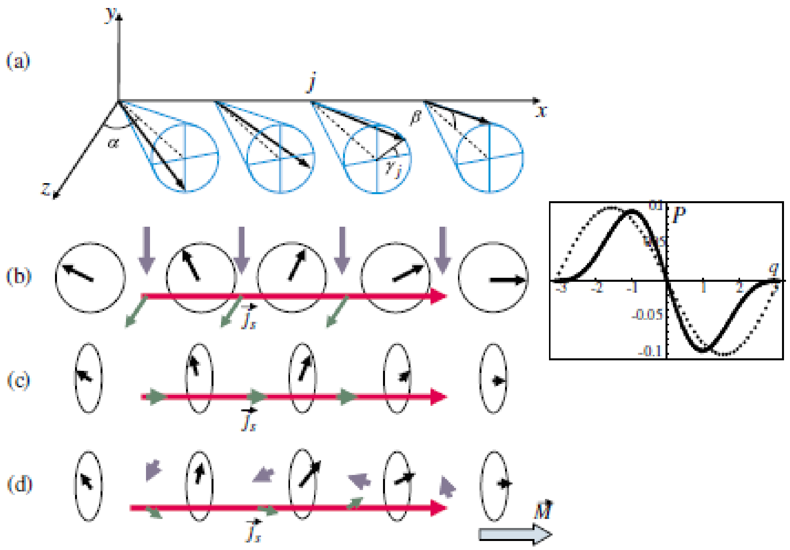
Magnetoelectric coupling single phase multiferroics



S. W. Cheong and M. Mostovoy, Nat. Mater. **6**, 13 (2007); M. Mostovoy, Phys. Rev. Lett. **96**, 067601 (2006).

The sinusoidal spin wave does not induce a electric polarization but Helicoidal does

$$\vec{P} = \gamma\chi_e\left[\left(\vec{M}\cdot\vec{\nabla}\right)\vec{M} - \vec{M}\left(\vec{\nabla}\cdot\vec{M}\right)\right]$$

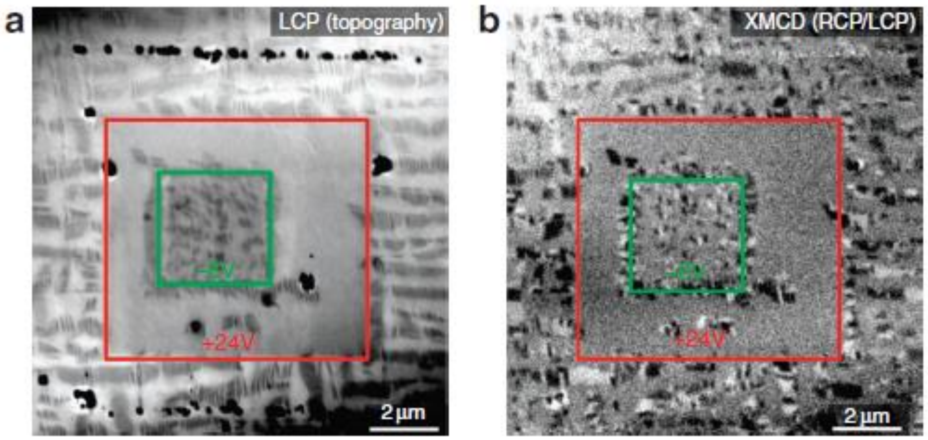


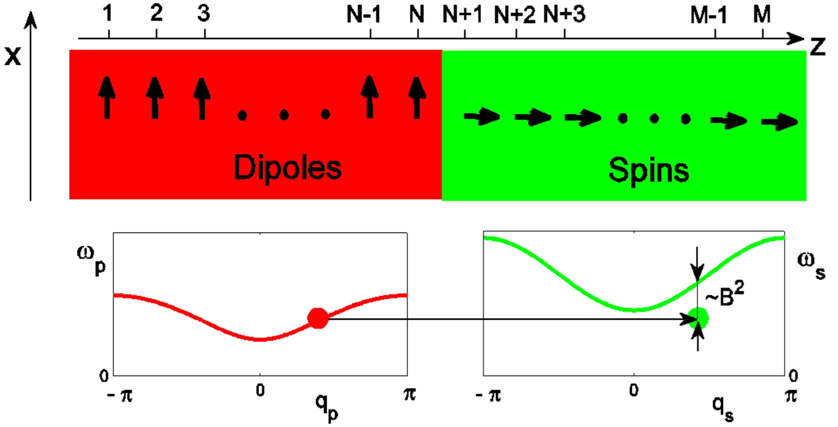
H. Katsura, N. Nagaosa, and Alexander V. Balatsky Phys. Rev. Lett. **95**, 057205 (2005);

$$V_{ME} = -\vec{E}\vec{P}$$

$$\vec{P} \sim \vec{e}_{i,i+1}\times\left(\vec{S}_i\times\vec{S}_{i+1}\right)$$

Electrical control of magnetism two phase multiferroics $BaTiO_3Fe$





Hamiltonian of model: *Coarse-grained approach for system Ginzburg-Landau-Devonshire* (GLD) *potential*

$$H = H_P + H_S + V_{ME},$$

$$H_P = \sum_{n=1}^{N}\left(\frac{1}{2}\frac{dP_n^2}{dt^2} + \frac{\alpha^{FE}}{2}P_n^2 + \frac{\beta^{FE}}{4}P_n^4 + \frac{1}{2}\left(P_{n+1} - P_n\right)^2 - Ep_n\right)$$

$$H_S = \sum_{k=N+1}^{M}\left(-J\vec{M}_k\vec{M}_{k+1} - D\left(M_k^z\right)^2 - BM_k^z\right)$$

$$V_{ME} = -g_1\left(P_N M_{N+1}^z\right) - g_2\left(P_N M_{N+1}^z\right)^2,$$

R. Ramesh and N. Spaldin Nature **6**, 21 (2007); M. Fiebig J. Phys. D: Appl. Phys. **38** R123 (2005)

Soliton solutions

$$p_n = \sum_{\alpha=1}^{\infty} \varepsilon^{\alpha} \sum_{m=-\infty}^{\infty} \Psi_m^{(\alpha)}(\xi,\tau) e^{im(\omega t - pn)}; \qquad \xi = \varepsilon(n - \mathrm{v}t); \qquad \tau = \varepsilon^2 t,$$

$$\frac{\partial}{\partial t}\Psi_m^{(\alpha)} = -\varepsilon \mathrm{v} \frac{\partial}{\partial \xi}\Psi_m^{(\alpha)} + \varepsilon^2 \frac{\partial}{\partial \tau}\Psi_m^{(\alpha)}; \qquad \frac{\partial}{\partial n}\Psi_m^{(\alpha)} = \varepsilon \frac{\partial}{\partial \xi}\Psi_m^{(\alpha)},$$

$$p_n = \frac{A\cos\left[\omega_p t - q_p n + \delta\omega_p t\right]}{\cosh\left[\left(n - V_p t\right)/\Lambda_P\right]}, \quad s_k^{\pm} = \frac{Be^{\pm i\left(\omega_s t - q_s k + \delta\omega_s t\right)}}{\cosh\left[\left(k - V_s t\right)/\Lambda_S\right]},$$

$$\omega_P = \sqrt{\alpha + 2\left(1 - \cos q_P\right)}, \qquad \omega_S = 2\left[D + J\left(1 - \cos q_s\right)\right],$$

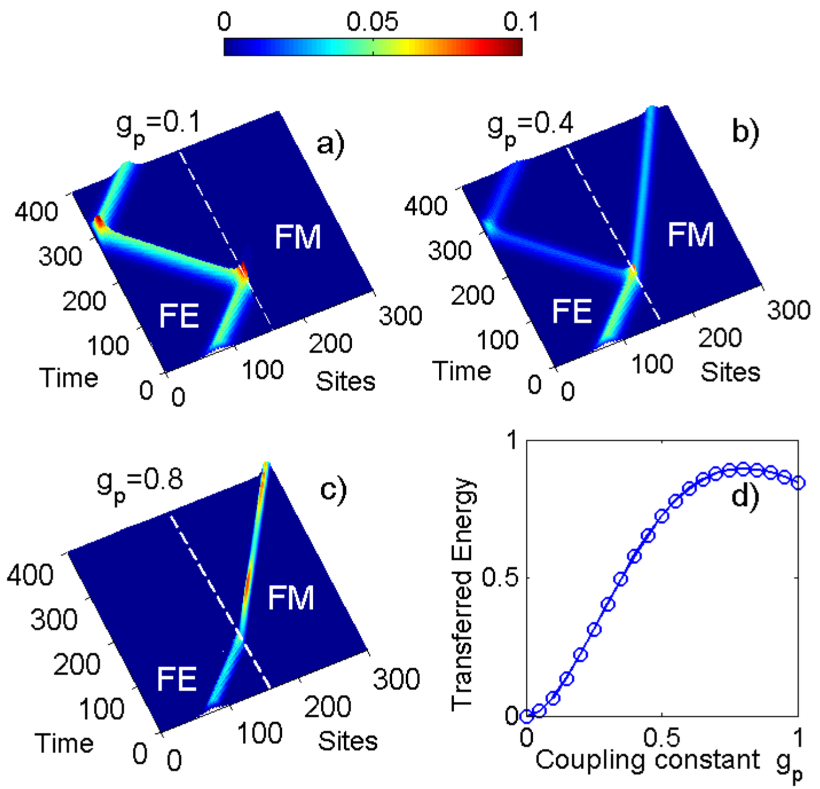
$$\Lambda_P = \frac{1}{A}\sqrt{\frac{2\left(\omega_P^4 - \alpha^2 - 4\alpha\right)}{3\omega_P^2\beta}}, \qquad \Lambda_S = \frac{1}{B}\sqrt{\frac{4J\cos q_S}{\omega_S}},$$

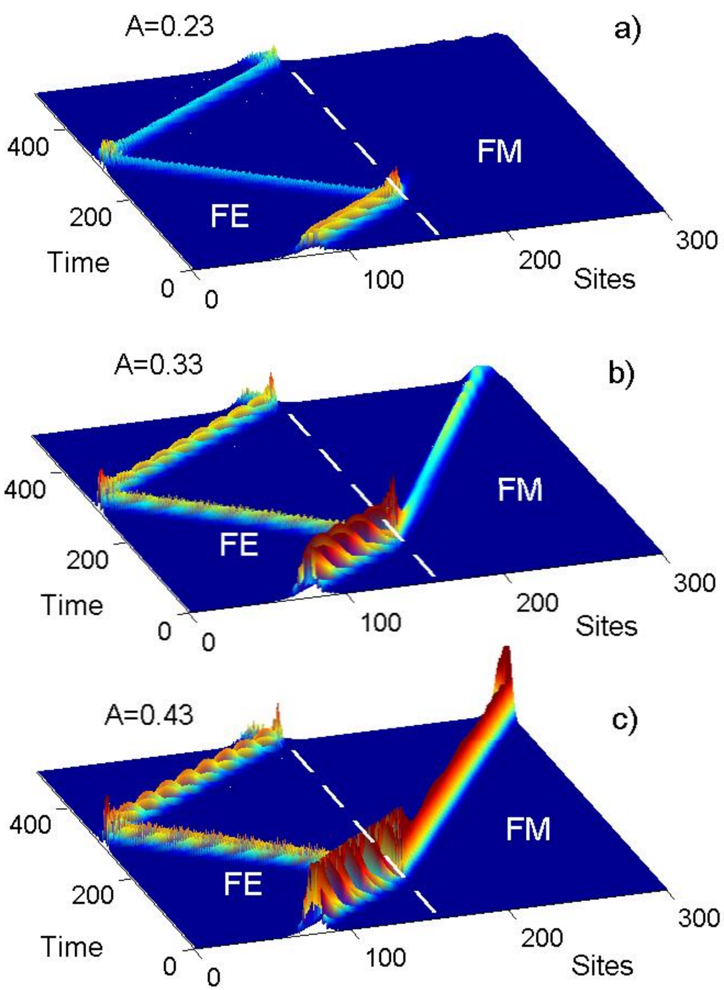
$$\delta\omega_P = A^2\frac{3\beta}{16\omega_P}, \quad \delta\omega_S = -B^2\frac{\omega_S}{4}, \quad \omega_P + \delta\omega_P = \omega_S + \delta\omega_S,$$

$$\omega_S - \omega = \left(\frac{g_P^2\omega}{4} + \frac{3\beta}{16\omega}\right)A_{cr}^2.$$

L. Chotorlishvili, R. Khomeriki, A. Sukhov, S. Ruffo, and J. Berakdar Phys. Rev. Lett. **111**, 117202 (2013)

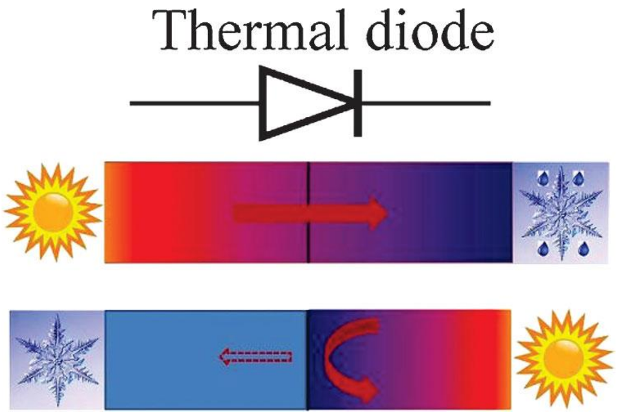
Transfer of the soliton through the interface





L. Chotorlishvili, R. Khomeriki, A. Sukhov, S. Ruffo, and J. Berakdar Phys. Rev. Lett. **111**, 117202 (2013)

Thermal diode

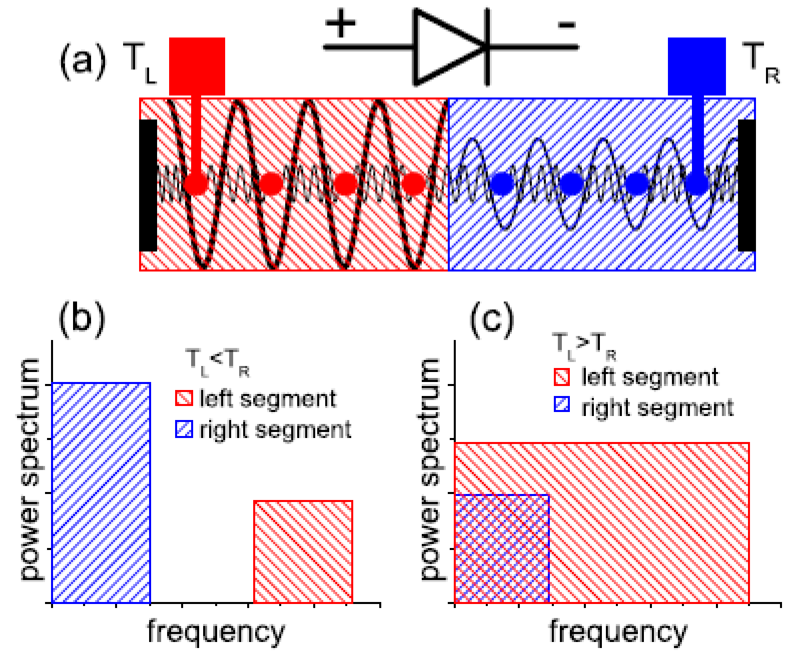


The interface thermal resistance (Kapitza resistance)

$$R_+ = \frac{\Delta T}{J_+}, \qquad \Delta T = \left|T_L - T_R\right|, \qquad T_L - T_R > 0$$

$$R_- = \frac{\Delta T}{J_-}, \qquad \Delta T = \left|T_L - T_R\right|, \qquad T_L - T_R < 0$$

$$\frac{R_+}{R_-} = \text{measures the rectification effect}$$



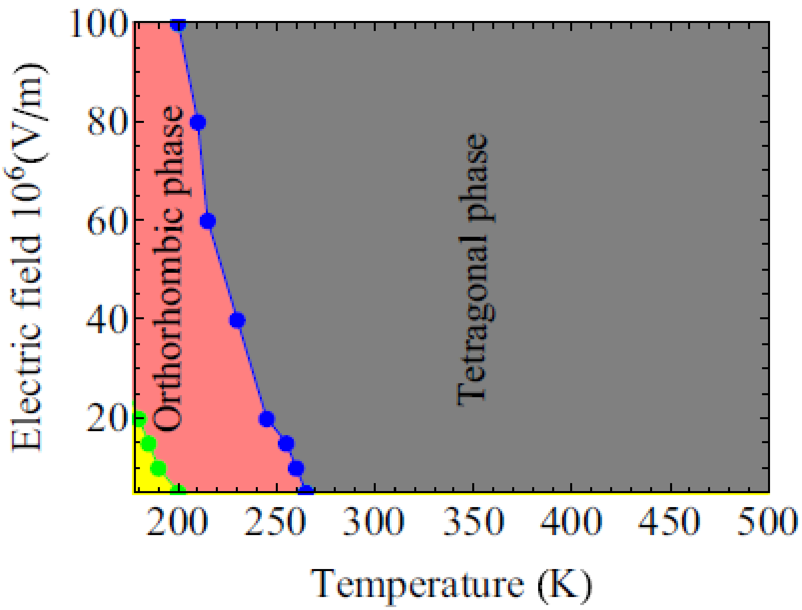
Power spectra between left (L) and right (R) parts

$$S = \frac{\int_0^\infty P_L(\omega) P_R(\omega) d\omega}{\int_0^\infty P_L(\omega) d\omega \int_0^\infty P_R(\omega) d\omega}$$

N. Li, J. Ren, L. Wang, G. Zhang, P. Hänggi, and B. Li, Rev. Mod. Phys. **84**, 1045 (2012).

Advantage of the electric field

a) Tetragonal phase can be enlarged



b) Ferroelectric frequency spectrum can be controlled

$$\omega_{FE}(E) = \left\{ 4\alpha^{FE} \cos^2 \left[\cos^{-1} \left(\frac{3|E|}{2\alpha^{FE}} \sqrt{\frac{3\beta^{FE}}{\alpha^{FE}}} \right) / 3 \right] - \alpha^{FE} \right\}^{1/2}$$

Optimal electric field

$$E = \left| \frac{2\alpha^{FE}}{3} \sqrt{\frac{\alpha^{FE}}{3\beta^{FE}}} \cos\left[\frac{3}{2} \arccos\left(\frac{4D^2 - \alpha^{FE}}{2\alpha^{FE}} \right) \right] \right|$$

$$E = 3.4 \times 10^4 \,(\mathrm{V/sm})$$

$$H = H_P + H_S + V_{ME},$$

$$H_P = \sum_{n=1}^{N} \left(\frac{1}{2} \frac{dP_n^2}{dt^2} + \frac{\alpha^{EF}}{2} P_n^2 + \frac{\beta^{EF}}{4} P_n^4 + \frac{1}{2} (P_{n+1} - P_n)^2 - EP_n \right)$$

$$H_S = \sum_{k=N+1}^{M} \left(-J_1 \vec{M}_k \vec{M}_{k+1} - D (M_k^z)^2 - BM_k^z \right)$$

$$V_{ME,m} = -g_m (P_N M_{N+1}^z), \qquad g < J_2 < J_1$$

Equations of motion

Ferroelectric, part in tetragonal phase

$$\frac{dp_n}{dt} = q_n,$$
$$\frac{dq_n}{dt} = \alpha^{FE} p_n - \beta^{FE} p_n^3 - \left(2p_n - p_{n+1} - p_{n-1}\right) + E +$$
$$g_1 M_1^z \delta_{nN} + 2g_2 p_n \left(M_1^z\right)^2 \delta_{nN} - \gamma_n q_n \delta_{1n} + \xi_n \delta_{1n},$$
$$\left\langle \xi_n(t), \xi_m(t') \right\rangle = 2\gamma_m T_m \delta(t-t'), \qquad m = 1,\dots,N$$

Ferromagnetic part

$$\frac{d\vec{M}_k}{dt} = -\frac{1}{1+\alpha_k^2} \vec{M}_k \times \left(\vec{B}_k^{eff} + \alpha_k \vec{M}_k \times \vec{B}_k^{eff}\right),$$
$$\alpha_k = \alpha \delta_{kM}, \quad \vec{B}_k^{eff} = \frac{\partial H}{\partial \vec{M}_k} + \delta_{kM} \vec{\eta}_k,$$
$$\left\langle \eta_k^i(t), \eta_k^j(t') \right\rangle = 2\alpha_k T_k \delta_{ij} \delta(t-t'),$$
$$k = N+1,\dots M$$

Ferroelectric, part **heat current**

$$\frac{\partial h_{k,k+1}}{\partial t} = i\left[H_s, h_{k,k+1}\right],$$
$$J_k^H = i\left[h_{k+1,k}, h_{k,k-1}\right],$$
$$H_S = \sum_{k=N+1}^{M} \left(-J\vec{M}_k \vec{M}_{k+1} - D\left(M_k^z\right)^2 - BM_k^z\right).$$

Ferromagnetic part **heat current**

$$J_k^H = -\left\langle \dot{p}_k \left(p_{k+1} - p_k\right) \right\rangle$$
$$T_k = \left(\frac{dp_k}{dt}\right)^2$$

L. Chotorlishvili, S. R. Etesami, and J. Berakdar R. Khomeriki, Jie Ren, Phys. Rev. B **92**, 134424 (2015)

Inverting the thermal bias

$$\Delta \rightarrow -\Delta$$

$$T_1 = T_0(1+\Delta), \quad T_M = T_0(1-\Delta)$$

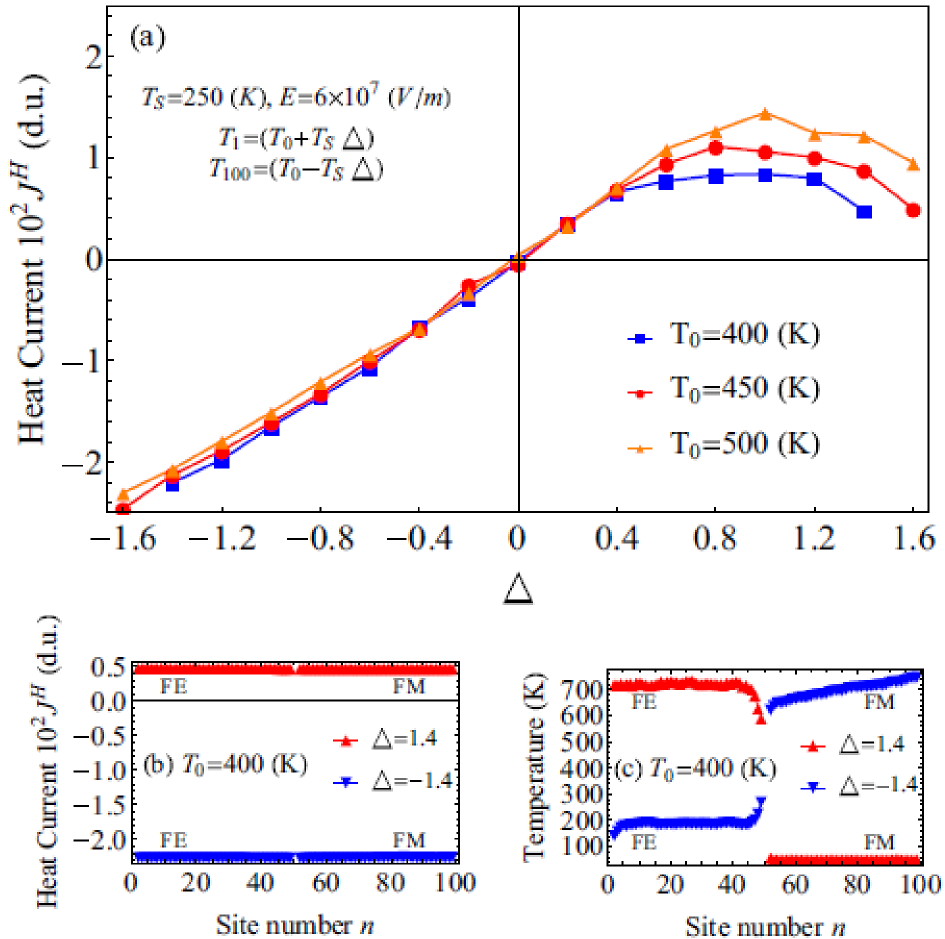
$$T_1 - T_M = 2T_0\Delta$$

We observe asymmetry $\Delta \rightarrow -\Delta$

Temperature profiles are calculated **self-consistently**

$$M_k^z = L\left(\frac{M_k^z B_k^{eff}}{T_k}\right)$$

$$T_k = \left(\frac{dp_k}{dt}\right)^2$$



Heat currents **Temperature profiles**

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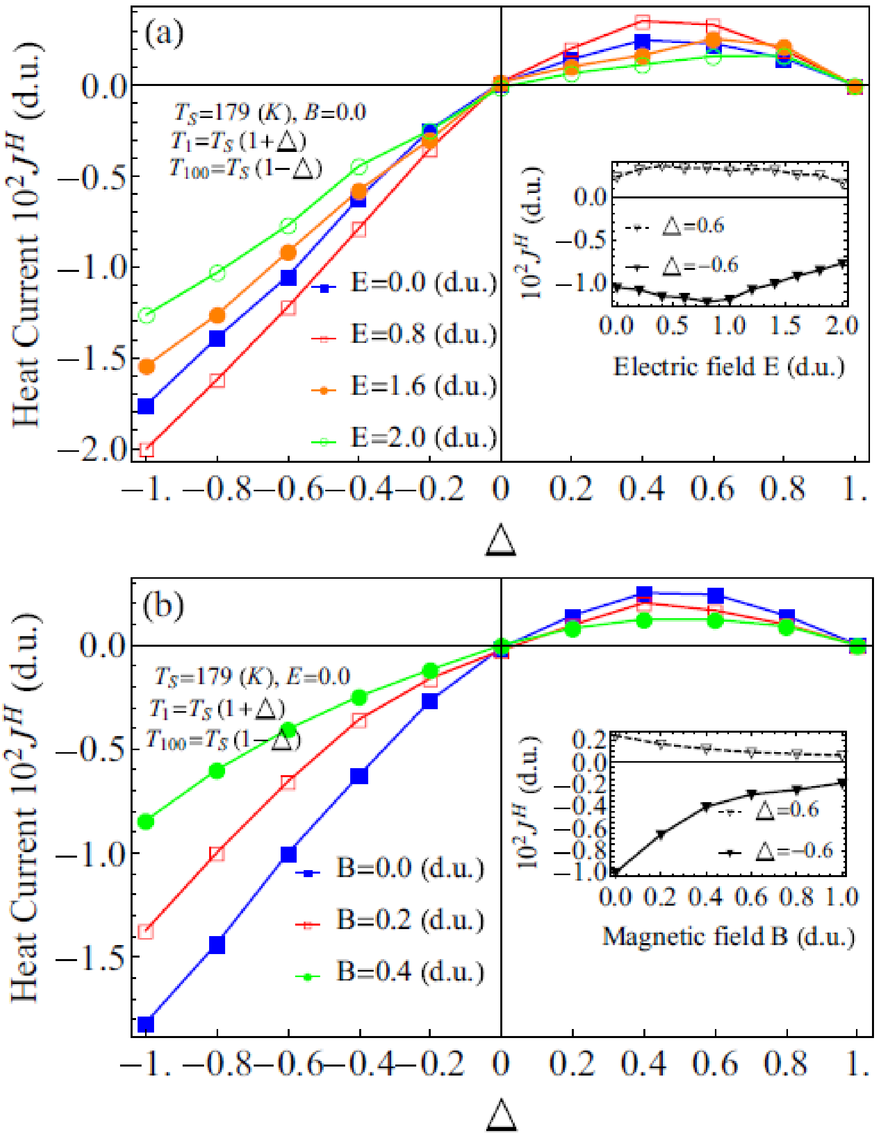

Heat current for different electric fields:
Optimal electric field

$$E=3.4\times10^4\,(\mathrm{V/sm})$$

Rectification

$$R_+ = \frac{\Delta T}{J_+}, \quad \Delta T = |T_L - T_R|, \quad T_L - T_R > 0$$

$$R_- = \frac{\Delta T}{J_-}, \quad \Delta T = |T_L - T_R|, \quad T_L - T_R < 0$$

$$\frac{R_+}{R_-} \approx 4$$

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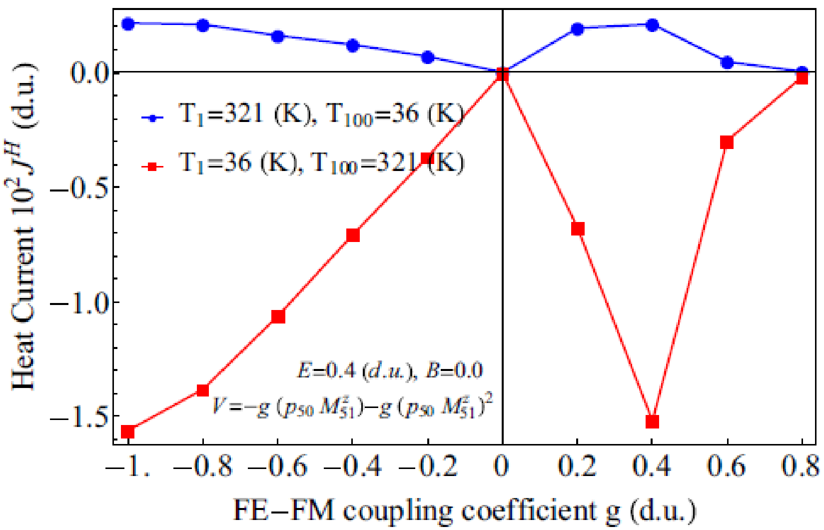
Heat current as a function of magnetoelectric coupling



We observe asymmetry $g \to -g$

$$V_{ME} = -g\left(P_N M_{N+1}^z\right), \qquad g > 0, \quad \Rightarrow \quad M_{N+1}^z \to 1$$

For large M_{N+1}^z **current is suppressed**

L. Chotorlishvili, S. R. Etesami, and J. Berakdar R. Khomeriki, Jie Ren, Phys. Rev. B **92**, 134424 (2015)

Parameters

Parameter	SI units	Dimensional unit (d.u.)
	Bulk $BaTiO_3$ single crystal	
P_0	$0.265\,C/m^2$	$p_n = P_n/P_0$
α_1	2.770×10^7 V m/C	$\alpha^{FE} = \frac{\alpha_1}{\kappa} \approx 0.213$
α_2	$1.7 \times 10^8\ Vm^5/C^3$	$\beta^{FE} = \frac{\alpha_2 P_0^2}{\kappa} \approx 0.0918$
γ_ν	2.5×10^{-5} V m s/C	$\gamma_m = \frac{\gamma_\nu \omega_0}{\kappa} \approx 0.192$
a_{FE}	1.02×10^{-9} m	
κ	1.3×10^8 V m/C	1
E	parameter (V/m)	$E \to \frac{1}{\kappa P_0} E \approx 3.4 \times 10^7 E$
T	parameter (K)	$T \to \frac{k_B}{\kappa P_0^2 a_{FE}^3} T \approx 1.4 \times 10^{-3} T$
J	joules/s	$J \to \frac{1}{\kappa P_0^2 \omega_0 a_{FE}^3} J \approx 10^8 J$
	Bulk bcc Fe	
M_S	1.71×10^6 A/m	$\vec{s}_k = \vec{M}_k/M_S = (\vec{S}_k/S)$
γ	$1.76 \times 10^{11}\ (T\ s)^{-1}$	
a_{FM}	1.0×10^{-9} m	
$\mu_S = M_S a_{FM}^3$	1.71×10^{-21} J/T	
α_{FM}	1.0	
K_1	$2.0 \times 10^6\ J/m^3$	$D = \frac{\gamma a_{FM}^3 K_1}{\omega_0 \mu_S} = 0.206$
A	2.1×10^{-11} J/m	$J = \frac{\gamma a_{FM} A}{\omega_0 \mu_S} = 2.16$
B	parameter (T)	$B \to \frac{\gamma}{\omega_0} B \approx 0.17 B$
T	parameter (K)	$T \to \frac{k_B \gamma}{\omega_0 \mu_S} T \approx 1.4 \times 10^{-3} T$
J	joules/s	$J \to \frac{\gamma}{\omega_0^2 \mu_S} J \approx 10^8 J$

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