Comparison of Spin and Polarization Caloritronics

Collaborative Research Center on Energy Materials

The spontaneous order of electric and magnetic dipoles in ferroelectrics and ferromagnets, even at high temperatures, is both fascinating and useful. Spintronics studies the transport of magnetic order in the form of spin currents, but the polarization current of the ferroelectric order has escaped attention. We present a time-dependent diffusion theory for heat and polarization transport in a planar ferroelectric capacitor with parameters derived from a one-dimensional phonon model. We predicted the steady-state Seebeck and transient Peltier effects.

Ferromagnetism and ferroelectricity describe the order of magnetic and electric dipoles that spontaneously form, often far above room temperature and have much in common [1]. The robustness of the order and the associated stray magnetic and electric fields give rise to numerous technological applications that affect our daily lives. However, the physics appears to be very different. The Amperian electric (Gilbertian magnetic) dipoles break the (conserve) inversion symmetry but conserve the (break) time-reversal symmetry. Nevertheless, the phenomenology of these material classes displays similar analogies. The dipolar order is staggered in antiferromagnets and antiferroelectrics. The electrocaloric (magnetocaloric) effect is based on the dependence of the entropy of electric (magnetic) dipolar ensembles as a function of the applied electric (magnetic) field and temperature [2]. Both the magneto- and electrocaloric heat pumps appear to be close to the market. However, an equivalent for spin caloritronics [3] in ferroelectric materials does not exist.

Motivated by the need to find new uses for ferroelectric materials in energy applications and supported by the co-appointment scheme between NIMS and Tohoku University, we studied the caloritronics of ferroelectric capacitors [4], i.e., ferroelectric insulators sandwiched between two metal contacts.

The linear response relation in a ferro*magnetic* insulator (Ohm's law) is as follows [3]:

$$\begin{pmatrix} J_s \\ J_q \end{pmatrix} = G \begin{pmatrix} 1 & ST \\ \Pi & K/G \end{pmatrix} \begin{pmatrix} \Delta H \\ \Delta T \end{pmatrix}, \qquad (1)$$

where J_s is the spin current, J_q is the heat current, G is the spin conductance, T is the temperature, S is the Seebeck coefficient, Π is the Peltier coefficient, K the heat conductance ΔH is the magnetic field difference, and ΔT is the temperature difference between the devices. For a ferro*electric* insulator, the equation is almost the same [4].

$$\begin{pmatrix} J_p \\ J_q \end{pmatrix} = G \begin{pmatrix} 1 & ST \\ \Pi & K/G \end{pmatrix} \begin{pmatrix} \Delta E \\ \Delta T \end{pmatrix}, \qquad (2)$$

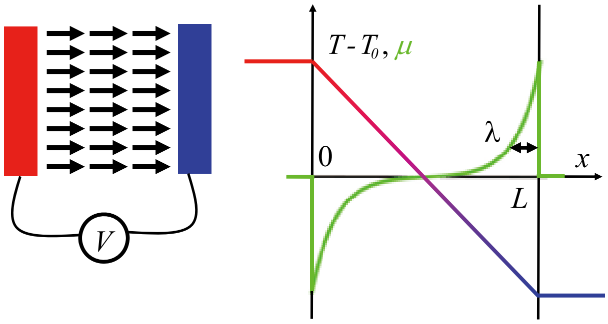

Fig. 1 A temperature gradient over a ferroelectric capacitor (left) drives a polarization current. For opaque interfaces, this leads to polarization accumulation μ on the scale of the diffusion length λ. The latter may generate an observable thermovoltage V.

However, the spin current is replaced by a polarization current, the drive is an electric instead of a magnetic field difference, and the material constants have other units.

Excited magnetic or electric polarizations are not conserved but characterized by material-dependent lifetimes. In diffusion approximation, this leads to spin (or magnon) accumulation in magnets and polarization accumulation in ferroelectrics, parameterized by non-equilibrium chemical potentials. The solution of the diffusion equation shows that the accumulations exist near interfaces on the scale of the diffusion length λ, as shown in Fig. 1. The spin diffusion length can be tens of micrometers in yttrium iron garnets, but there is no data on ferroelectrics. In the absence of experiments, we estimated the model parameters using a simple one-dimensional phonon model of elastically coupled electric dipoles [4].

References

[1] N. A. Spaldin, Topics Appl. Phys. **105**, 175 (2007).
[2] S. Crossley et al., AIP Advances **5**, 067153 (2015).
[3] G.E.W. Bauer, E. Saitoh, and B.J. van Wees, Nature Mat. **11**, 391 (2011).
[4] G.E.W. Bauer, R. Iguchi, and K. Uchida, Phys. Rev. Lett., (2021) in press.

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Gerrit Bauer (Corresponding Author, Theory of Solid State Physics Research Laboratory)
E-mail: g.e.w.bauer@imr.tohoku.ac.jp
Tetsu Ichitsubo (Head of Collaborative Research Center on Energy Materials)
E-mail: tichi@imr.tohoku.ac.jp
URL: http://www.imr.tohoku.ac.jp/en/about/divisions-and-centers/facilities/05.html