Strain-induced Ettingshausen effect in spin-orbit coupled noncentrosymmetric metals

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ABSTRACT

Recent studies have revealed that CA is not necessarily only a Weyl-node property, but is rather a Fermi surface property, and is also present in a more general class of materials, for example, in spin-orbit-coupled noncentrosymmetric metals (SOC-NCMs). Using a tight-binding model for SOC-NCMs, we first demonstrate that strain in SOC-NCMs induces anisotropy in the spin-orbit coupling and generates an axial electric field. Then, using the quasi-classical Boltzmann transport formalism with momentum-dependent intraband and interband scattering processes, we show that strain in the presence of external magnetic field can generate temperature gradients via the Nernst-Ettingshausen effect, whose direction and behavior depends the on interplay of multiple factors: the angle between the applied strain and magnetic field, the presence of the chiral anomaly, the Lorentz force, and the strength of interband scattering.

INTRODUCTION

- Chiral anomaly have been observed in SOC-NCMs, which renders it to be a Fermi surface property rather than a Weyl-node property.
- SOC-NCMs have an additional k^2 dependence in the hamiltonian. As a result, there will be two fermi surfaces associated with a single node.
- Strain induces anisotropy in the spin-orbit coupling and generates an axial electric field.
- Strain in the presence of external magnetic field can generate temperature gradients via the Nernst-Ettingshausen effect whose direction and behavior depends on the angle between the applied strain and magnetic field, and the strength of interband scattering.

MATHEMATICAL MODELLING

- For SOC-NCMs under strain, we consider the Hamiltonian:

$$\frac{\hbar^2 k^2}{2m} + \alpha k\cdot\sigma + b_z k_z \sigma_z$$

We have taken into account the effect of Berry curvature on the semi-classical dynamics of Bloch electrons as per the equations:

$$\dot{\mathbf{r}}^\lambda = D^\lambda\left(\frac{e}{\hbar}(\mathbf{E}\times\mathbf{\Omega}^\lambda + \frac{e}{\hbar}(\mathbf{v}^\lambda\cdot\mathbf{\Omega}^\lambda)\mathbf{B} + \mathbf{v}_k^\lambda)\right)$$

$$\dot{\mathbf{p}}^\lambda = -eD^\lambda(\mathbf{E} + \mathbf{v_k}^\lambda\times\mathbf{B} + \frac{e}{\hbar}(\mathbf{E}\cdot\mathbf{B})\mathbf{\Omega}^\lambda)$$

- We solved the Maxwell-Boltzmann Equation for a given distribution function without loss of generality.

$$\frac{\partial f^\lambda}{\partial t} + \dot{\mathbf{r}}^\lambda\cdot\nabla_{\mathbf{r}} f^\lambda + \dot{\mathbf{k}}^\lambda\cdot\nabla_{\mathbf{k}} f^\lambda = I_{coll}[f^\lambda]$$

and in accordance with Fermi-Golden rule we have,

$$I_{\text{coll}}[f_{\mathbf{k}}^m] = \sum_p\sum_{\mathbf{k}'} W_{\mathbf{k},\mathbf{k}'}^{mp}(f_{\mathbf{k}'}^p - f_{\mathbf{k}}^m)$$

Where,

$$W_{\mathbf{k},\mathbf{k}'}^{mp} = \frac{2\pi}{\hbar}\frac{n}{\mathcal{V}}|\langle\psi_{\mathbf{k}'}^p|U_{\mathbf{k}\mathbf{k}'}^{mp}|\psi_{\mathbf{k}}^m\rangle|^2\delta(\epsilon_{\mathbf{k}'}^p - \epsilon_F)$$

- In the presence of finite temperature, the Maxwell Boltzmann equation is modified as:

$$\left[\left(\frac{\partial f_{\mathbf{k}}^\lambda}{\partial \epsilon_{\mathbf{k}}^\lambda}\right)\left(e\mathbf{E} + \frac{\epsilon_{\mathbf{k}}^\lambda - \mu}{T}\nabla T\right)\cdot\left(\mathbf{v}_{\mathbf{k}}^\lambda + \frac{e\mathbf{B}}{\hbar}(\mathbf{\Omega}^\lambda\cdot\mathbf{v}_{\mathbf{k}}^\lambda)\right)\right] = -\frac{1}{\mathcal{D}^\lambda}\sum_{\lambda'}\sum_{\mathbf{k}'} W_{\mathbf{k}\mathbf{k}'}^{\lambda\lambda'}(g_{\mathbf{k}'}^{\lambda'} - g_{\mathbf{k}}^{\lambda})$$

- The distribution function is obtained by solving the above equation, and is substituted in the current density equation:

$$\mathbf{J} = -\frac{e}{\mathcal{V}}\sum_{\lambda,k}\dot{\mathbf{r}} f_{\mathbf{k}}^\lambda.$$

- From the above equation we get the Hall and Peltier coefficients driven by electric and temperature gradient responses.
- At the steady state, the current density vanishes and we get the following equation:

$$\frac{\nabla T}{E_5} = \hat{\alpha}^{-1}\hat{\sigma}$$

RESULTS

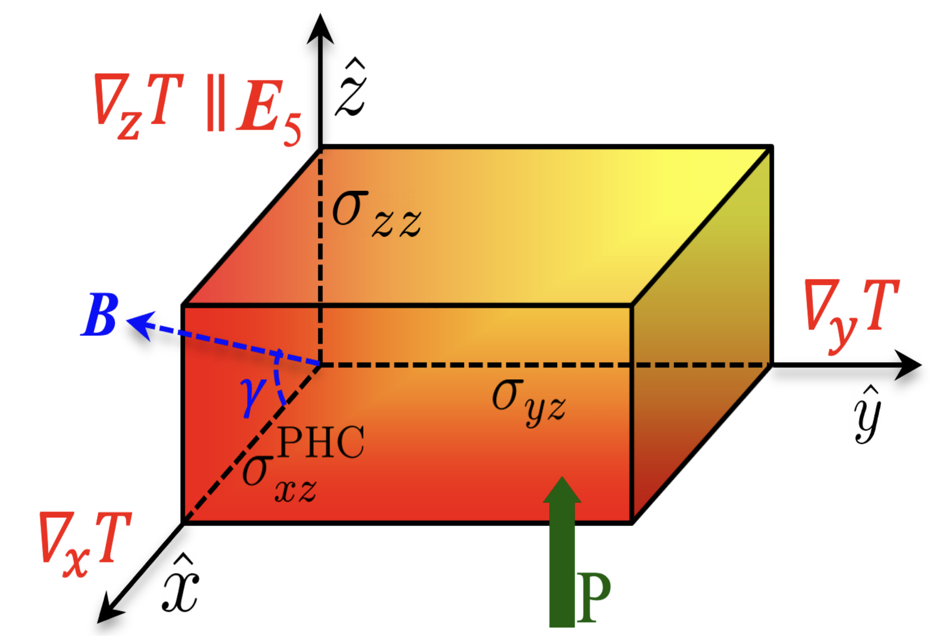

Fig1: Schematic that shows the strain-induced Ettingshausen effect

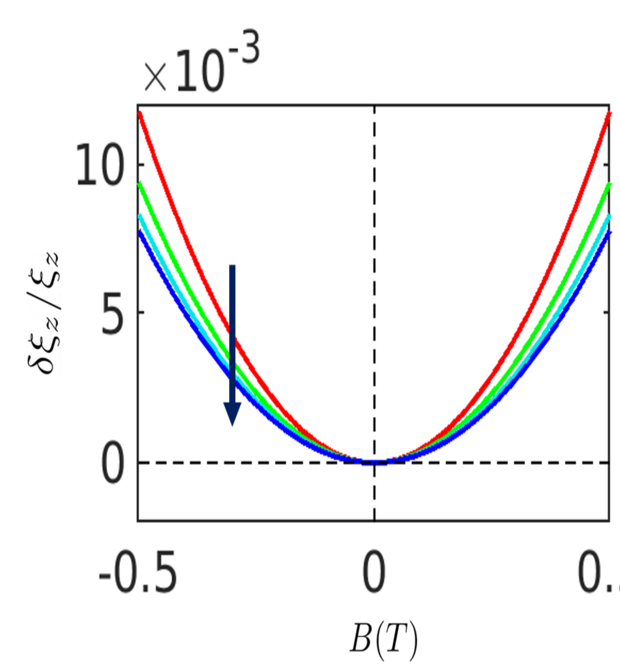

Fig 2: Temperature gradient for the case when direction of strain and magnetic field are parallel.

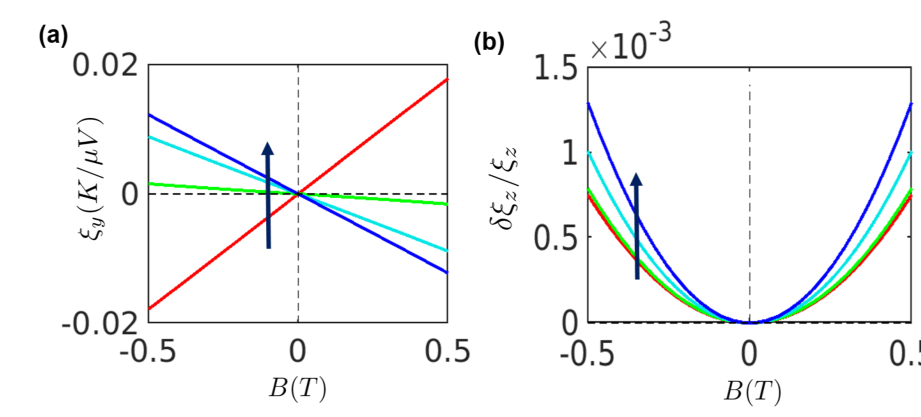

Fig 3:Temperature gradients for the case when strain and magnetic field are perpendicular.

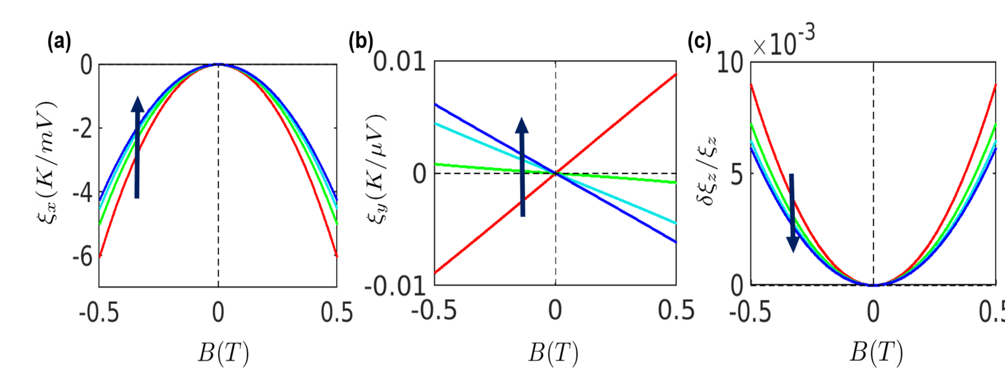

Fig 4: temperature gradient for an arbitrary angle.

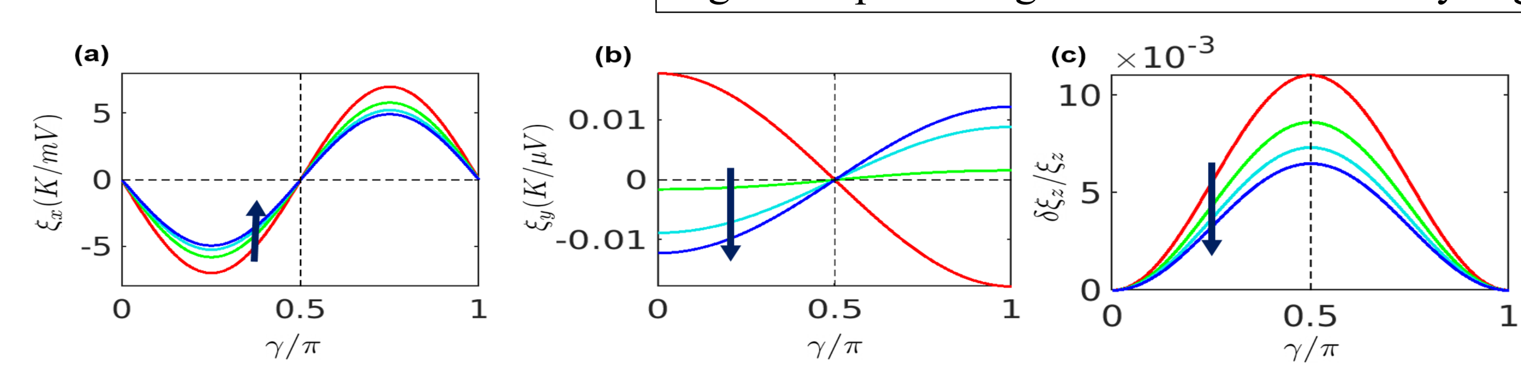

Fig 5: Dependence of temperature gradients on the angle between strain direction and magnetic field.

CONCLUSIONS

- SOC-NCMs will have anisotropy in the spin-orbit coupling due to strain.
- Strain generates an axial electric field in SOC-NCMs along the direction of application.
- At the steady state, strain generates temperature gradients whose direction depends on the angle between the strain direction and magnetic field and the strength of interband scattering.
- Temperature gradient along x-direction is purely induced by chiral anomaly via PHC, while that along the y- and z-directions are generated by Lorentz Hall and LMC(chiral anomaly induced) respectively.

REFERENCES

1. S. Cheon, G. Y. Cho, K.-S. Kim, and H.-W. Lee, Chiral anomaly in noncentrosymmetric systems induced by spin-orbit coupling, Physical Review B 105, L180303(2022).
2. S. Das, K. Das, and A. Agarwal, Chiral anomalies in three-dimensional spin-orbit coupled metals: Electrical, thermal, and gravitational anomalies, Physical Review B 108, 045405 (2023).
3. G. Varma K, A. Ahmad, S. Tewari, and G. Sharma, Magnetotransport in spin-orbit coupled noncentrosymmetric and weyl metals, Physical Review B 109, 165114 (2024).

ACKNOWLEGEMENTS

I wish to extend my gratitude to my supervisor Dr. Gargee Sharma for her valuable insights and discussions. I wish to thank IIT Mandi for providing me with HTRA funding for my work. I also thank my group members for their valuable discussions.