Spin control in topological semimetals

Yuriko Baba[1,2], Francisco Domínguez-Adame[1], Rafael A.Molina[2]

[1] Departamento de Física de Materiales - UCM (Madrid, Spain)
[2] Instituto de Estructura de la Materia - CSIC (Madrid, Spain)

PRB **100**, 165105 (2019)

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ESCUELA DE DOCTORADO
UNIVERSIDAD COMPLUTENSE DE MADRID

FACULTAD DE CIENCIAS FÍSICAS

Topology in condensed matter

2005: Kane, Mele connection between Quantum Spin Hall and the Z2 invariant

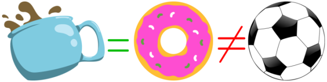
2006: Model by Bernevig, Hughes, Zhang. Topological properties of (Hg,Cd)Te wells

2007: Molenkam experimental work in (Hg,Cd)Te

……

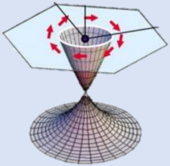
2016: Nobel prize:
Thouless, Haldane, Kosterlitz

TOPOLOGY: Properties preserved under continuous transformation



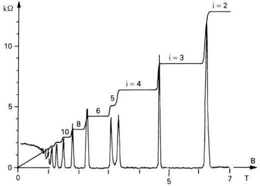
→Robustness of quantized conductivity

BAND THEORY:
The bands with PBC can be described by surfaces with topological properties



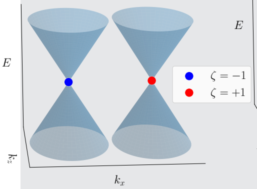
→ Finite systems exhibits topological states

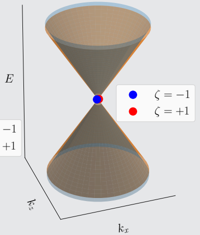
Von Klitzing: 1980 **Quantum Hall Effect**



Introduction: WSMs and DSMs

Weyl (WSM) and Dirac Semimetals (DSM)





- Theory TaAs: S.-M. Huang *et al.*, Nat. Commun. **6**, 7373 (2015)
- Experiments: B. Lv, *et al.*, Phys. Rev. X **5**, 031013 (2015)
- Theory Na_3Bi: Z. Wang *et al.*, PRB **85**, 195320 (2012)
- Experiments Na_3Bi: Z.K. Liu *et al.*, Science **343**, 864 (2014)

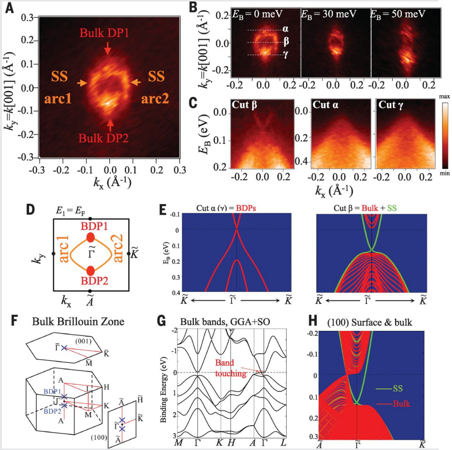


Figure: Fermi surface map of the Na_3Bi sample and energy ARPES spectra as a function of binding energy. S.-Y. Xu *et al.*, Science **347**, 294 (2015)

Models

Model Hamiltonian

- Two-band with two nodes (WSM)

  $\mathcal{H} = \epsilon_0(\mathbf{k})\mathbb{1}_2 + M(\mathbf{k})\sigma_z + v(\zeta k_x\sigma_x - k_y\sigma_y)\,,$

  $\zeta = \pm 1$ is the chirality of the Weyl node

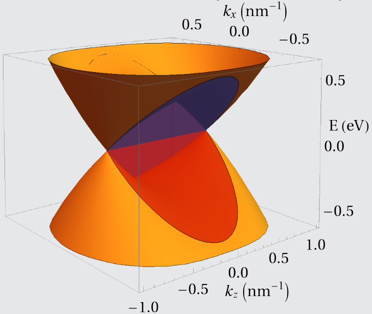
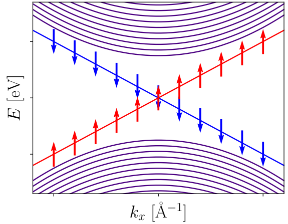


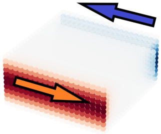
Figure: Bulk (solid colors) and surface (opaque colors) bands in the minimal model.

Z. Wang *et al.*, PRB **85**, 195320 (2012)
J. González, R. A. Molina, PRB**96**, 045437 (2017)

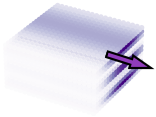
Between the Weyl points there are surface states in the gap:



- Surface states:



- Bulk states:



Electric field: Minimal model

- Electric field perpendicular to the surface: $\mathcal{H}_f = efy\mathbb{1}_2$
- Periodic boundary conditions in x and z

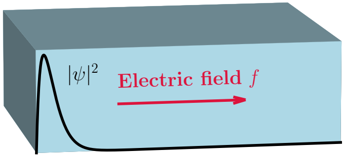


Figure: Set-up

Y. Baba, A. Díaz-Fernández, E. Díaz, F. Domínguez-Adame, and R. A. Molina, PRB **100**, 165105 (2019).

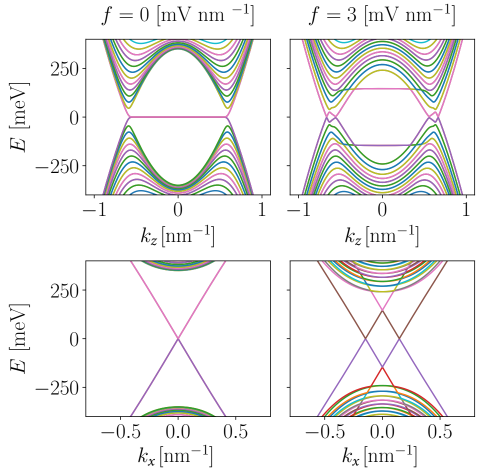


Figure: Dispersion relation of a slab of type A DSM in the plane $k_y = 0$ (upper) and $k_x = 0$ (bottom).

Effects of the electric field on the surface states

- Displacement of the cones in momenta and energy → decay-type changed;
- Renormalization of the velocity: depends on the chirality;
- Non negligible effects for experimentally feasible electric fields.

Coupling between surfaces change!

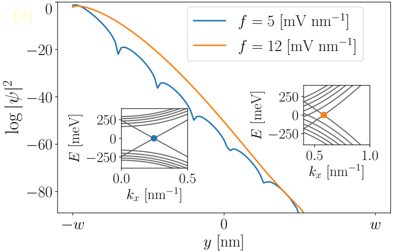


Figure: Decay type changed by the external electric field.

Chiral-dependent velocity renormalization!

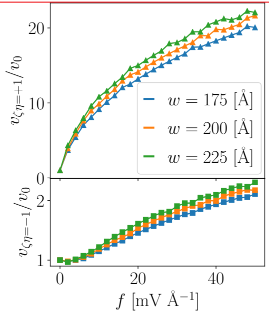
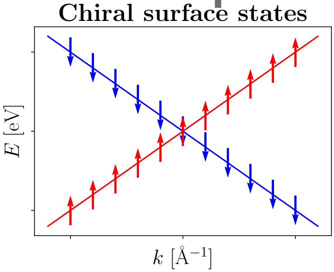


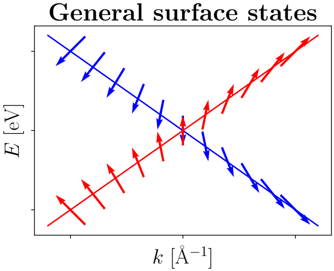
Figure: Effect of $f \sim 10^1$ mVÅ^{-1} on Na_3Bi slabs.

S. Nishihaya *et al.*, Nature Communications **12**, 2572 (2021)

J. L. Collins *et al.*, Nature **564**, 390 (2018).

Rashba Spin Orbit Coupling

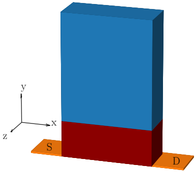




- RSOC interaction in a slab of DSM: local interaction with a substrate

$$\mathcal{H}_R = \begin{pmatrix} 0 & 0 & -iR_0k_- & 0 \\ 0 & 0 & 0 & 0 \\ iR_0k_+ & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix},$$

where $k_\pm \equiv k_z \pm ik_x$.



BHZ model: L. Ortiz, R. A. Molina, G. Platero, and A. M. Lunde, PRB **93**, 205431 (2016)
Na_3Bi ultra-thin: C.M. Acosta and A. Fazzio, PRL **122**, 036401 (2019)

Analytical results

- Effective Hamiltonian:

$$H_{\text{eff}} = \begin{pmatrix} E_{k,\uparrow} & -iR_0 g_{\mathbf{k}} k_- \\ iR_0 g_{\mathbf{k}} k_+ & E_{k,\downarrow} \end{pmatrix} ,$$

  where $g_{\mathbf{k}}$ is an overlap integral.

- Miminal model: anisotropic 2D Dirac

$$E_{\pm}^{\text{RSOC}} = \pm\sqrt{\left(v^2 + \frac{R_0^2}{4}\right) k_x^2 + \frac{R_0^2}{4} k_z^2} ,$$

- Na_3Bi model: spin-mixing

$$E_{\pm}^{\text{RSOC}} = \varepsilon(k_z) \pm v_k |C_3| k_x ,$$

$$v_k \equiv \sqrt{v^2 + \frac{g_{\mathbf{k}}^2 {R_0}^2 \left(k_x^2 + k_z^2\right)}{{C_3}^2 {k_x}^2}} ,$$

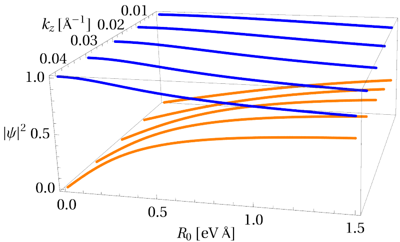


Figure: Absolute value of the upper (blue) and lower (orange) component of ψ_+ for Na_3Bi as a function of R_0 and k_z at fixed $k_x = 0.01\text{Å}^{-1}$.

Y.Baba, F.Domínguez-Adame, G.Platero and R.A. Molina, New J. Phys. **23** 023008 (2021)

Transport results: spin-switcher

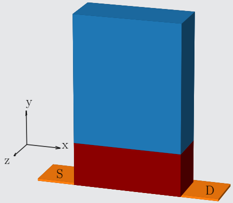


Figure: Schematic view of the device.

- Spin-polarized leads
- Spin-switch conductance induced by RSOC
- Effect resilient to disorder

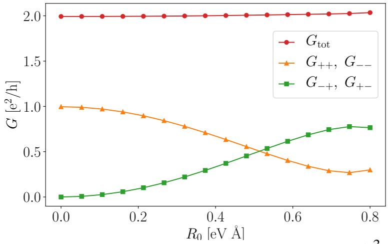


Figure: $\mathbf{Na_3Bi}$ slab 150 × 150 × 100 Å^3.

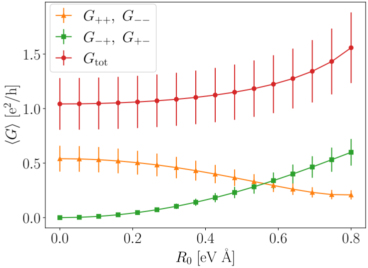


Figure: Average conductance in the presence of point-like impurities ($n_{imp} = 4 \times 10^{19}$ cm^{-3}); error bars from the standard deviation.

Conclusions

- Topological states can be tuned by external fields.
- An electric field changes Fermi velocity and moves the position of the Fermi arcs in momentum space → the velocity is chiral-dependent.
- A RSOC enable chiral-spin flip → spin-switcher devices.

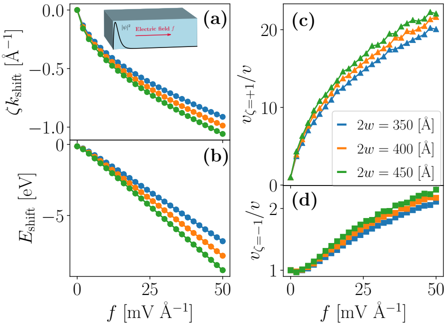


Figure: Effect of $f \sim 10^1$ mVÅ^{-1} on Na_3Bi slabs.

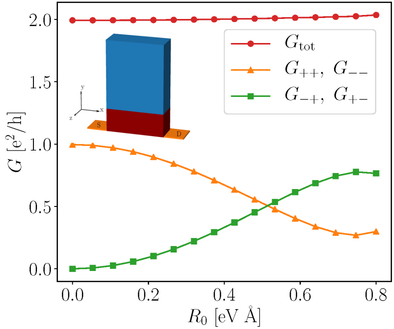
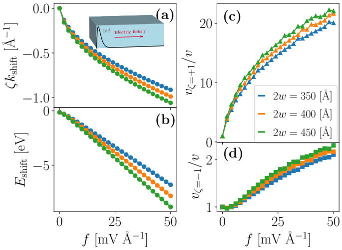
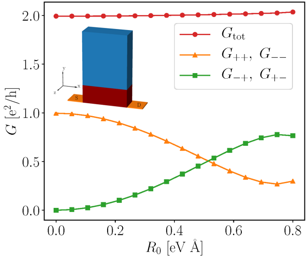
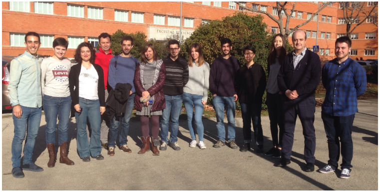


Figure: Full (G_{tot}) and spin-polarized ($G_{\pm}$) conductance as a function of the RSOC on a Na_3Bi slab.

Conclusions







Thank you for your attention!