Topologically protected spin and valley currents via mass inversion in Dirac materials

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Journal Club

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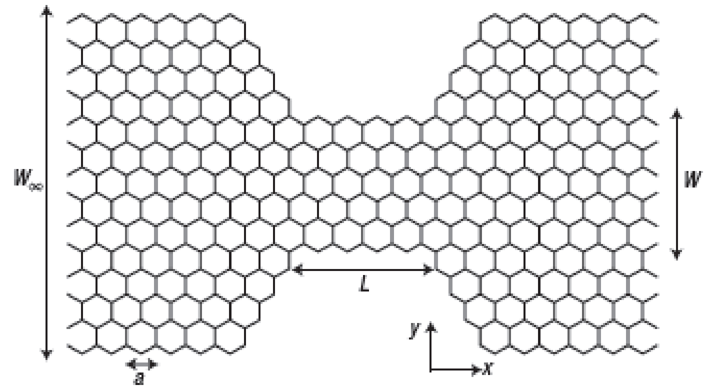
Outline of the talk

- Introduction
- General idea: Dirac materials with mass gap
- Examples: Silicene and MoS2
- Conclusion

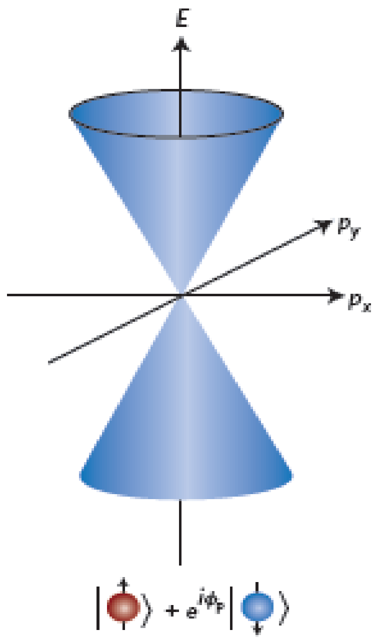
Introduction

Valleytronics: A key ingredient for 'valleytronics' would be a controllable way of occupying a single valley in graphene, thereby producing a valley polarization.



Nat. Phys. 3, 172 (2007)

Spintronics:



Topological insulator surface states
are described by 2D Dirac equation
with strong coupling between electron
spin and momentum due to spin-orbit coupling

Nat. Mat. 11, 409 (2012)

General idea

Dirac Hamiltonian with a mass gap

$$H = \hbar v(\hat{k}_x \tau_x + \hat{k}_y \tau_y) + \Delta \tau_z$$

Chern number (integral of the Berry curvature over the Brillouin zone)

$$C(\Delta) = \frac{1}{4\pi}\left(\int_0^\Lambda d^2\vec{k} + \int_{|k|>\Lambda} d^2\vec{k}\right)\epsilon^{\mu\nu\lambda}\bar{d}_\mu \partial_{k_x}\bar{d}_\nu \partial_{k_y}\bar{d}_\lambda$$

$$= C^{(1)}(\Delta,\Lambda) + C^{(2)}(\Delta,\Lambda) \ .$$

contributions from wave vectors near to the gapless point

contributions from the rest of the Brillouin zone where we assume there are no further gap closings

Change in Chern number

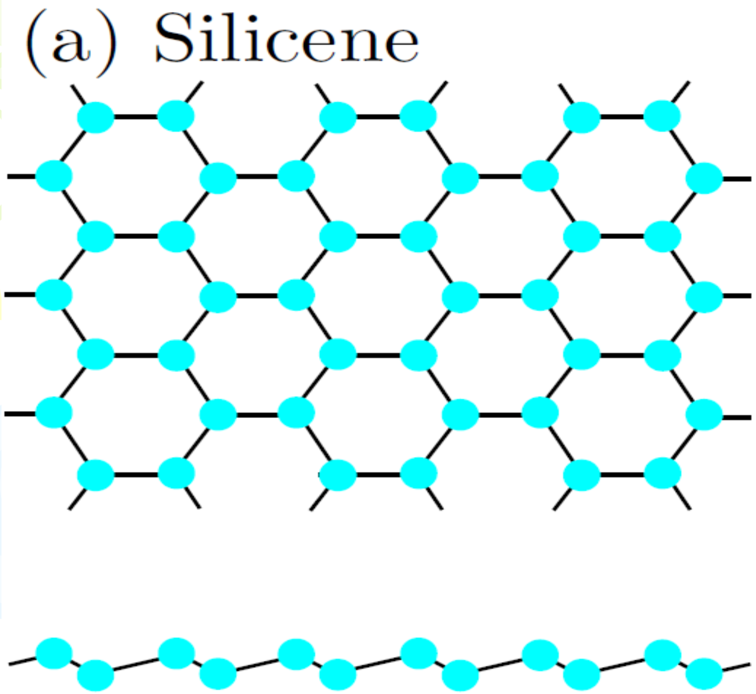
$$\delta C = C^{(1)}(\Delta) - C^{(1)}(-\Delta)$$

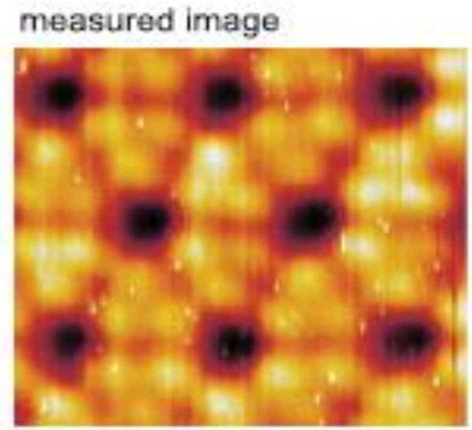
In the limit $\Delta \to 0$ **and** $\Lambda \gg \Delta/(\hbar v)$

$$\delta C = \frac{1}{4\pi}\int_0^{\Lambda} \frac{2\hbar^2 v^2 \Delta}{(\hbar^2 v^2 |\vec{k}|^2 + \Delta^2)^{3/2}} d^2k = 1$$

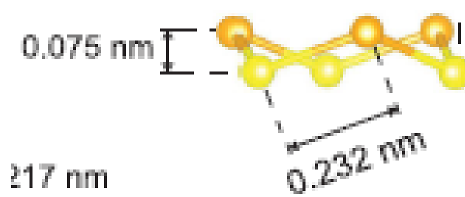
Therefore, since there is a change in the Chern number when the sign of Δ is reversed, the boundary between regions of a system with $\Delta > 0$ and $\Delta < 0$ hosts a topologically protected interface state.

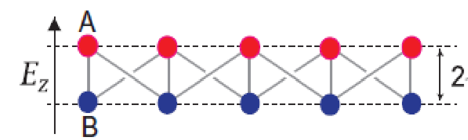
Silicene





PRL 108, 155501 (2012)





$$H_{\xi s}^{\mathrm{Sil}} = \hbar v(\hat{k}_x \tau_x - \xi \hat{k}_y \tau_y) + \xi s \lambda_{SO} \tau_z + \frac{l E_z}{2} \tau_z$$

Spin $s = \pm 1$ **Valley** $\xi = \pm 1$

Low energy Dirac theory

$$\mathcal{E}_\eta = \pm\sqrt{\hbar^2 v_F^2 k^2 + \left(\ell E_z - s\sqrt{\lambda_{SO}^2 + a^2\lambda_R^2 k^2}\right)^2} \qquad s = \eta s_z$$

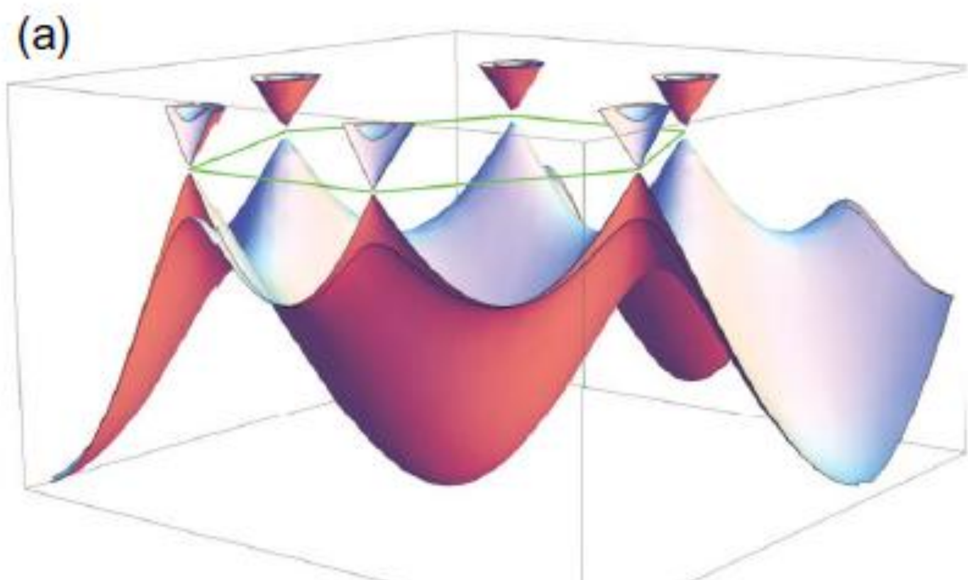


Figure 3. Band structure of silicene at the critical electric field E_c. (a) A bird's-eye view. Dirac cones are found at six corners of the hexagonal Brillouin zone.

New J. Phys. 14, 033003 (2012)

For k=0

$$\Delta\,(E_z) = 2\,|\ell E_z - \eta s_z \lambda_{SO}|$$

$$E_c = \lambda_{SO}/\ell = 17\,\mathrm{meV}\,\mathrm{\AA}^{-1}.$$

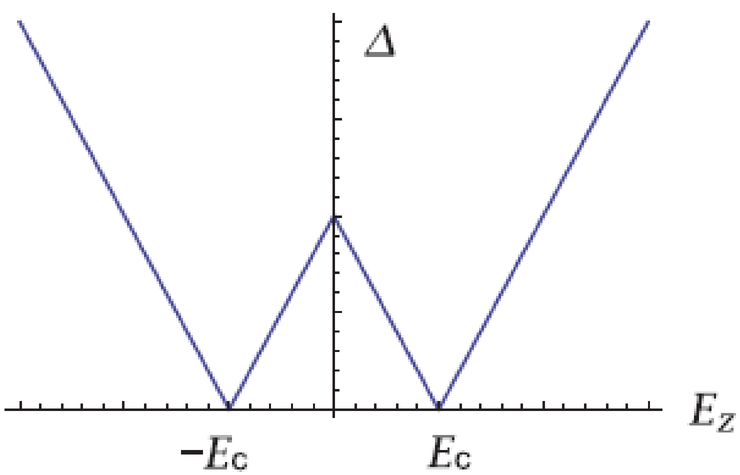


Figure 2. The band gap Δ as a function of the electric field E_z. The gap is open for $E_z \neq \pm E_c$, where silicene is an insulator. It can be shown that it is a topological insulator for $|E_z| < E_c$ and a band insulator for $|E_z| > E_c$.

New J. Phys. 14, 033003 (2012)

Inhomogeneous electric field → $E_z = x\mathcal{E}/R$

$\Delta < 0$ when $lE_z(x) < -\xi s\lambda,$ otherwise $\Delta > 0$

For $\xi s = 1,$ two interface modes near $x = -\lambda R/(\mathcal{E}l)$

For $\xi s = -1,$ two interface modes near $x = \lambda R/(\mathcal{E}l)$

Spectral asymmetry

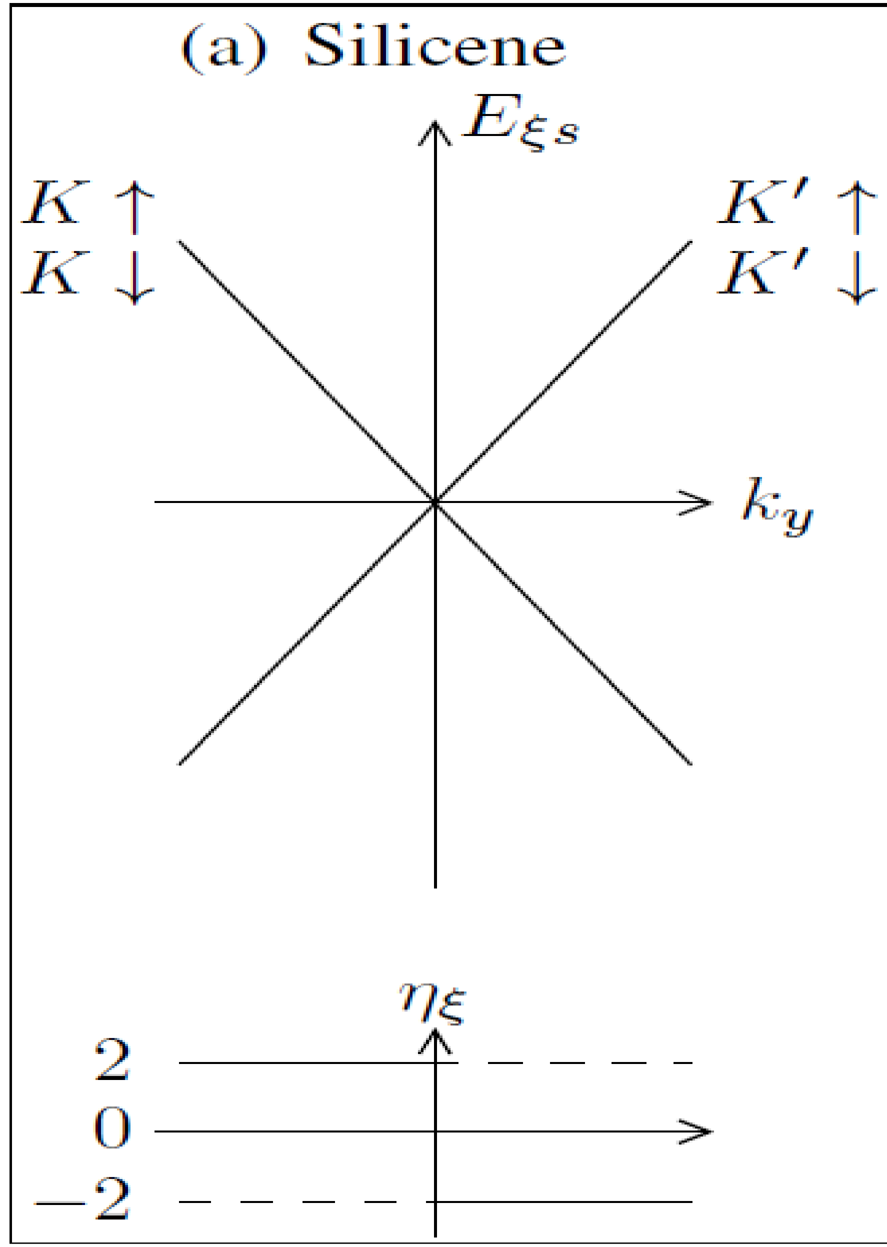
$$\eta_s = \frac{2}{\sqrt{\pi}} \mathrm{Tr} \int_0^\infty \mathrm{H} e^{-y^2 H^2} P_s dy \ ,$$

$$\eta_\xi = \frac{2}{\sqrt{\pi}} \mathrm{Tr} \int_0^\infty \mathrm{H} e^{-y^2 H^2} P_\xi dy$$

$$\eta_K = 2\mathrm{sgn}(k_y)$$

$$\eta_{K'} = -2\mathrm{sgn}(k_y)$$

This index indicates that there is a fundamental asymmetry in the valley distribution of the interface modes in silicene.



Dispersion of the interface modes

$$\varepsilon_{\xi s}^{\mathrm{Sil}} = -\xi\hbar v k_y$$

Spin and Valley current

$$v_{K\uparrow} = v_{K\downarrow} = -\hbar v$$ → Left moving

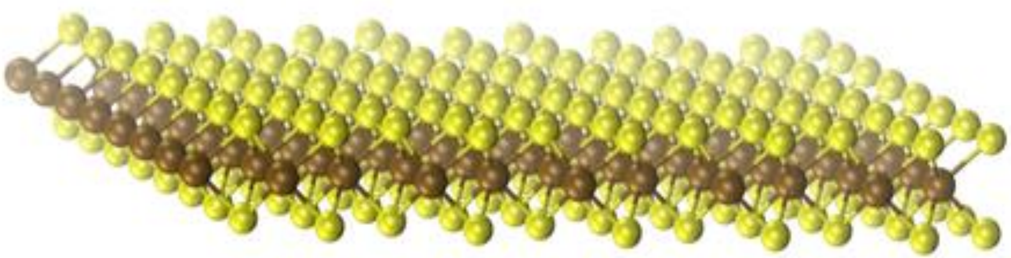
$$v_{K'\uparrow} = v_{K'\downarrow} = \hbar v$$ → Right moving

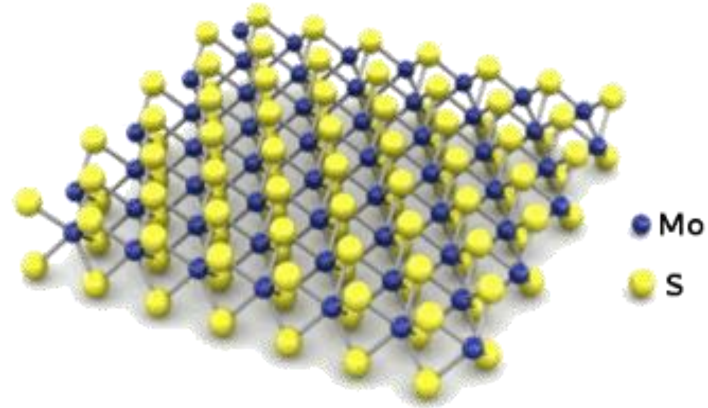
$$j_{\xi s} = \frac{1}{2\hbar k_c}\int_{-k_c}^{k_c} dk_y v_{\xi s} n_{\xi s} \qquad v_{\xi s} = d\varepsilon_{\xi s}^{\mathrm{Sil}}/dk_y$$

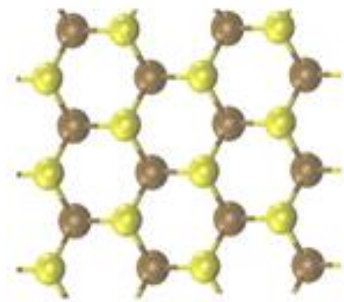
$$j_s = j_{K\uparrow} + j_{K'\uparrow} - j_{K\downarrow} - j_{K'\downarrow}, \qquad j_s = 0$$

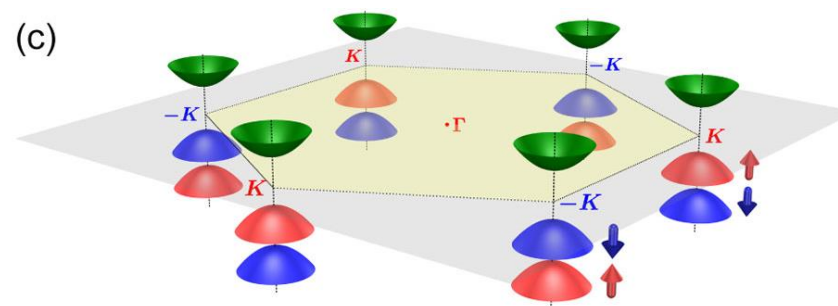
$$j_\xi = j_{K\uparrow} + j_{K\downarrow} - j_{K'\uparrow} - j_{K'\downarrow}. \qquad j_\xi = -2\hbar v$$

MoS_2







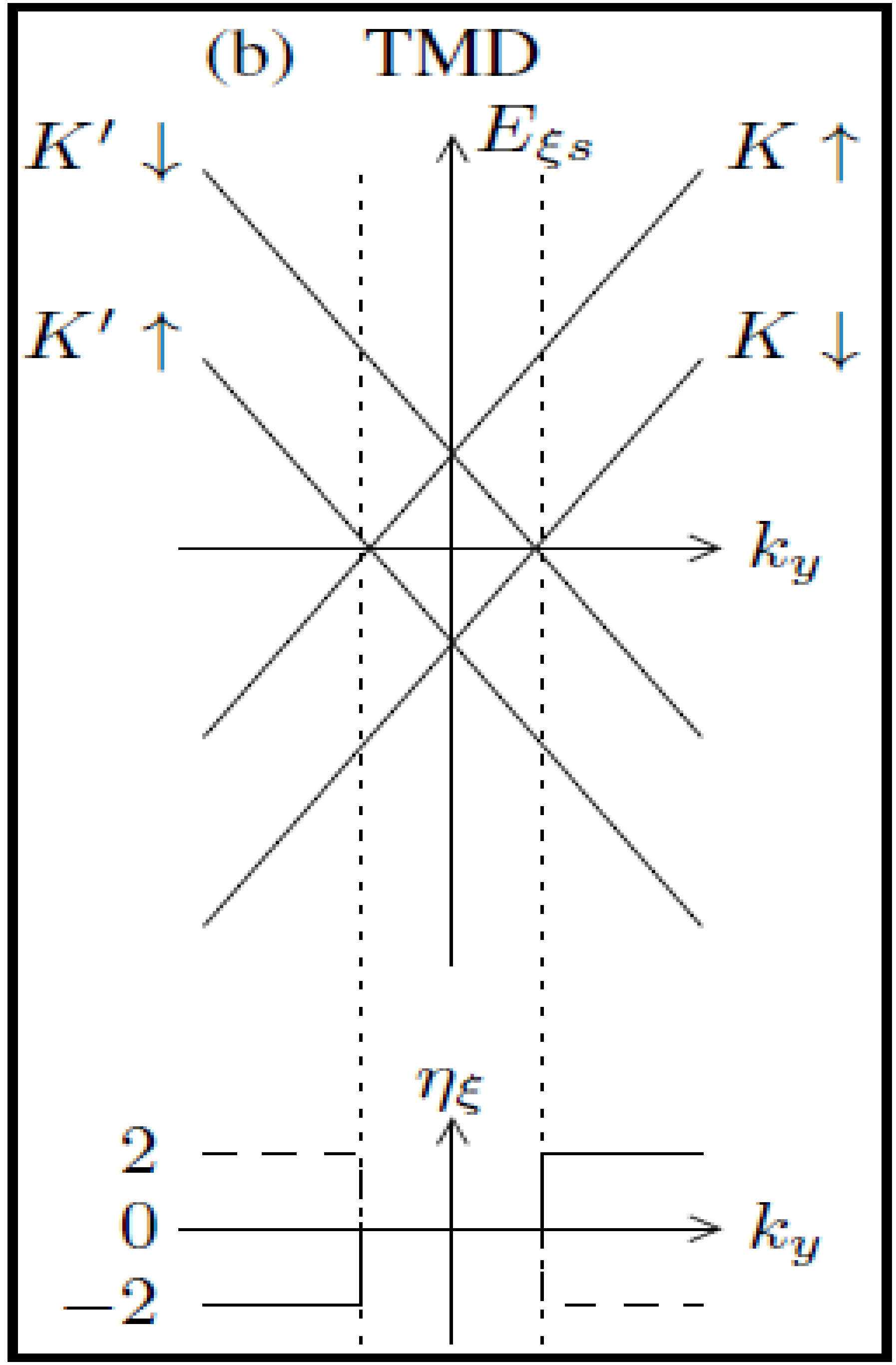


$$H_{\xi s}^{\mathrm{TMD}} = \hbar v(\xi k_x \tau_x + k_y \tau_y) + \frac{\Delta}{2}\tau_z - \frac{\xi s \lambda}{2}(\tau_z - \tau_0)$$

Inhomogeneous mass term → $\Delta(x) = \Delta_0 x/R$

Dispersion of the interface modes

$$\varepsilon_{\xi s}^{\mathrm{MoS2}} = \xi \hbar v k_y + \xi s \lambda / 2$$



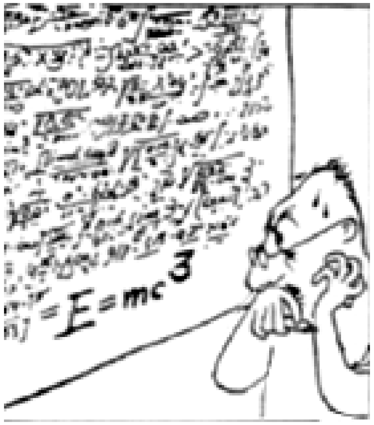
Valley current

$$j_\xi \approx 2v$$

Spin current

$$j_s \approx -\lambda$$

Conclusions



- Pseudo-spin polarized currents by topologically protected modes created by mass inversion
- Silicene: interface modes carry valley current
- MoS2: exhibit both spin and valley currents at interfaces
- Short range scatterers can introduce inter valley scattering which can destroy such interface modes


THANKS!