Superconducting Proximity Effect in Silicene: Spin-Valley Polarized Andreev Reflection, Non-Local Transport, and Supercurrent

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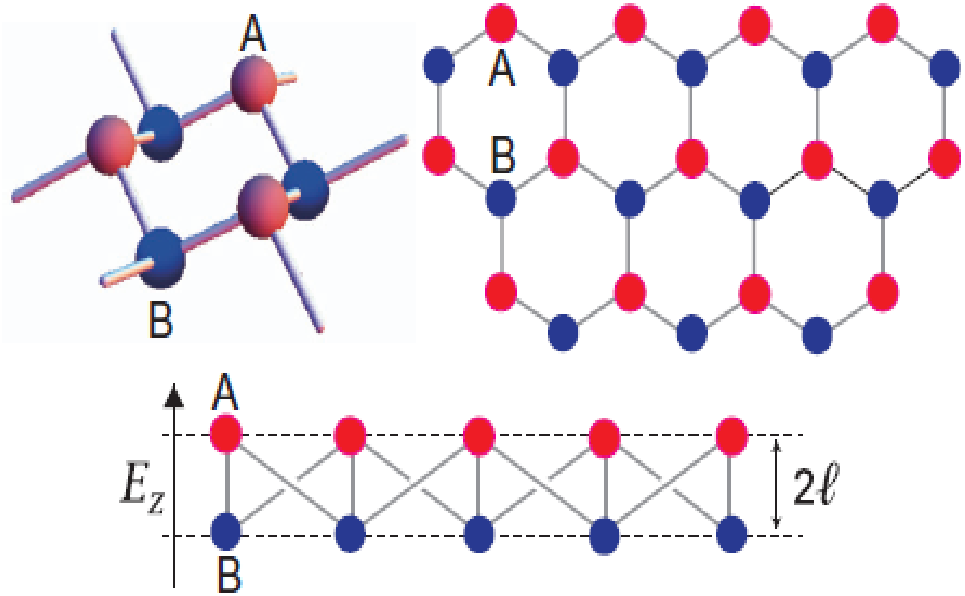
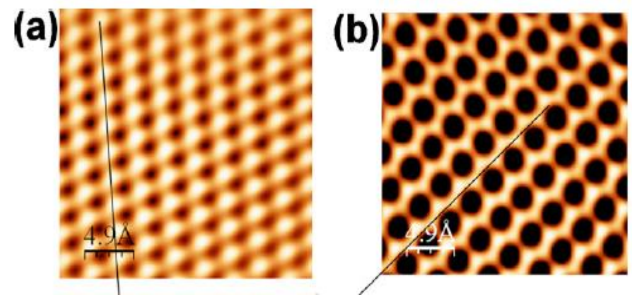
UNI BASEL

Outline of the talk

- Introduction to Silicene
- Proximity effect in Silicene
- Conclusion

Introduction to Silicene





Appl. Phys. Lett. 97, 223109 (2010)

l=0.02nm

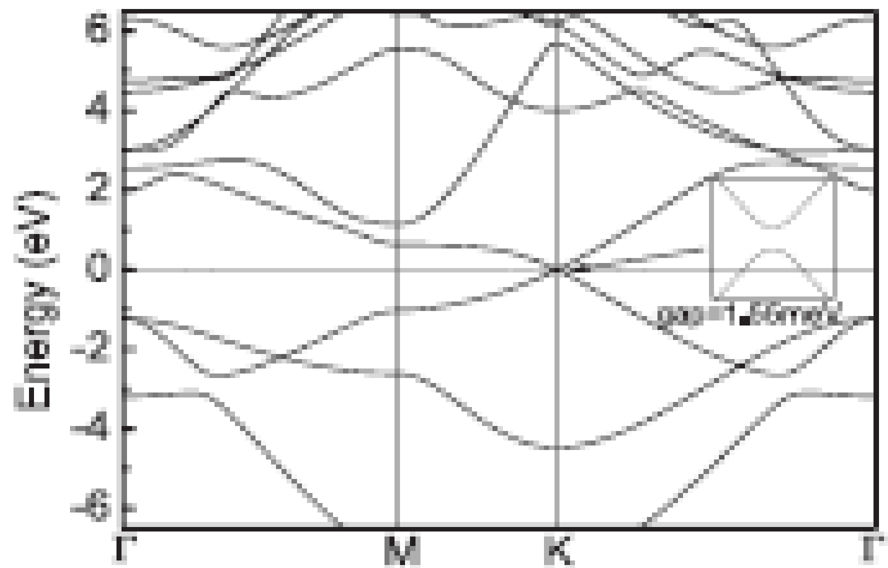
Figure 1. Illustration of the buckled honycomb lattice of silicene. A honeycomb lattice is distorted due to a large ionic radius of a silicon atom and forms a buckled structure. The A and B sites form two sublattices separated by a perpendicular distance 2ℓ. The structure generates a staggered sublattice potential in the electric field E_z, which leads to various intriguing pheneomena.

Model Hamiltonian

$$H = -t \sum_{\langle i,j\rangle\alpha} c^{\dagger}_{i\alpha} c_{j\alpha} + \mathrm{i}\frac{\lambda_{\mathrm{SO}}}{3\sqrt{3}} \sum_{\langle\langle i,j\rangle\rangle\alpha\beta} \nu_{ij} c^{\dagger}_{i\alpha} \sigma^{z}_{\alpha\beta} c_{j\beta} - \mathrm{i}\frac{2}{3}\lambda_{\mathrm{R}} \sum_{\langle\langle i,j\rangle\rangle\alpha\beta} \mu_{ij} c^{\dagger}_{i\alpha} (\vec{\sigma} \times \vec{d}^{0}_{ij})^{z}_{\alpha\beta} c_{j\beta}$$

$$+ \ell \sum_{i\alpha} \zeta_i E^{i}_{z} c^{\dagger}_{i\alpha} c_{i\alpha}.$$

$$t = 1.6eV$$
$$\lambda_{SO} = 3.9meV$$
$$\lambda_R = 0.7meV$$
$$l = 0.23\mathring{A}$$



Phys. Rev. B 84, 195430 (2011)

Low energy Dirac theory

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

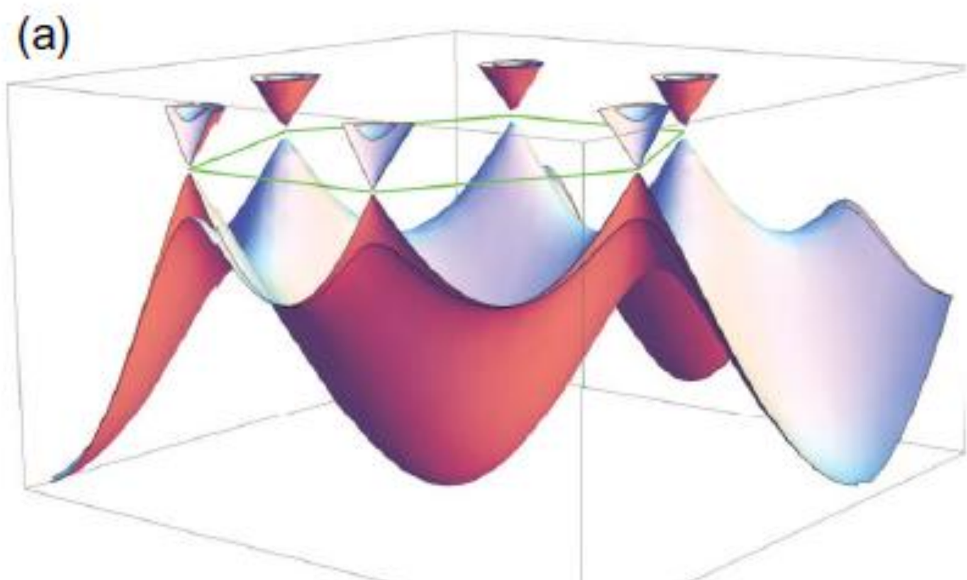
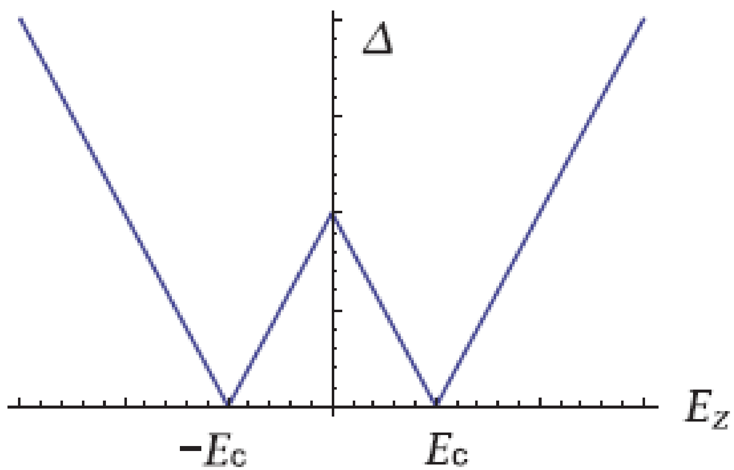


Figure 3. Band structure of silicene at the critical electric field E_c. (a) A bird's-eye view. Dirac cones are found at six corners of the hexagonal Brillouin zone.

For k=0

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

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



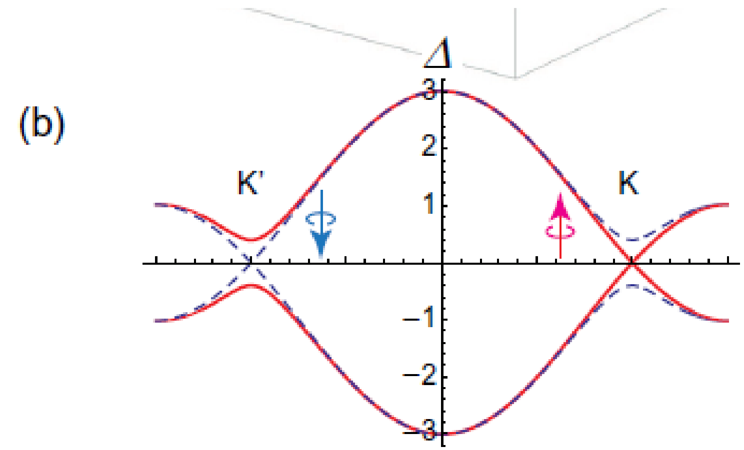


Figure 2. The band gap Δ as a function of the electric field E_z. The gap is open for $E_z \neq \pm E_c$, where silicene is an insulator. It can be shown that it is a topological insulator for $|E_z| < E_c$ and a band insulator for $|E_z| > E_c$.

New J. Phys. 14, 033003 (2012)

Silicene nanoribbon

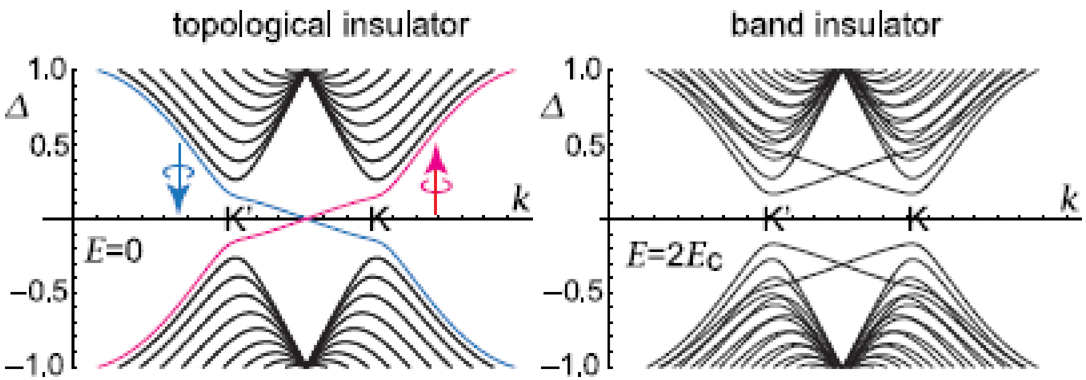
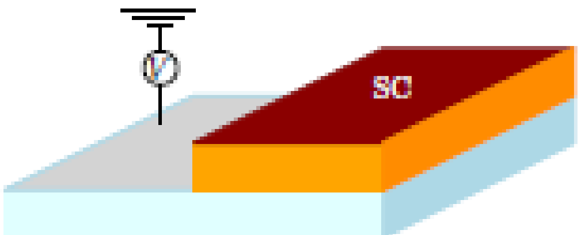


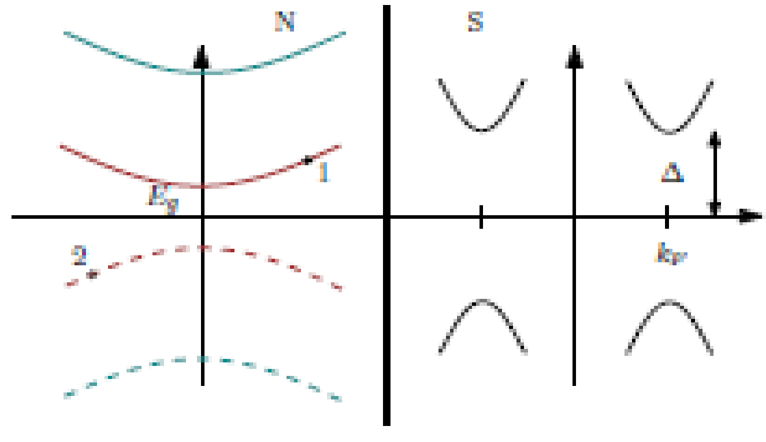
Figure 4. 1D energy bands for a silicene nanoribbon. (a) The bands crossing the gap are edge states, demonstrating that it is a topological insulator. There are two edge states since a nanoribbon has two edges (red and blue lines for the left and right edges). (b) All states are gapped, demonstrating that it is a band insulator.

New J. Phys. 14, 033003 (2012)

Proximity effect in Silicene

NS Junction





Andreev Reflection

Hamiltonian

$$H = -t \sum_{\langle i,j \rangle, \alpha} c^{\dagger}_{i\alpha} c_{j\alpha} + \frac{i\lambda}{3\sqrt{3}} \sum_{\langle\langle i,j \rangle\rangle, \alpha, \beta} \nu_{ij} c^{\dagger}_{i\alpha} \sigma^{z}_{\alpha\beta} c_{j\beta}$$

$$+ l \sum_{i\alpha} \zeta_i E^{i}_{z} c^{\dagger}_{i\alpha} c_{i\alpha} - \mu \sum_{i\sigma} c^{\dagger}_{i\sigma} c_{i\sigma} + \sum_{i\sigma} (\sigma \Delta_0 c^{\dagger}_{i\sigma} c^{\dagger}_{i,-\sigma} + \text{h.c.})$$

Low energy Spectrum

$$E_{\eta,\sigma}(\mathbf{k}) = \pm\sqrt{\left(\sqrt{k^2+(lE_z-\eta\sigma\lambda_{SO})^2}\pm\mu_S\right)^2+|\Delta_0|^2}.$$

At Interface x=0

$$\begin{aligned}\psi_N &= \frac{1}{\sqrt{2E\tau_+}}[\eta k_F e^{i\eta\theta},\tau_+,0,0] + \frac{r_e}{\sqrt{2E\tau_+}}[-\eta k_F e^{-i\eta\theta},\tau_+,0,0] \\ &+ \frac{r_h}{\sqrt{2E\tau_-}}[0,0,\eta k_F e^{-i\eta\theta},\tau_-], \\ \psi_S &= \frac{t_e}{\sqrt{2}}[\eta e^{i\eta\theta_S}u_+,u_+,\eta e^{i\eta\theta_S}u_- e^{-i\phi},u_- e^{-i\phi}] \\ &+ \frac{t_h}{\sqrt{2}}[-\eta e^{-i\eta\theta_S}u_- e^{i\phi},u_- e^{i\phi},-\eta e^{-i\eta\theta_S}u_+,u_+].\end{aligned} \qquad (3)$$

Conductance

$$G/G_N = \frac{1}{4}\Sigma_{\eta,\sigma}\int_{-\pi/2}^{\pi/2} d\theta\cos\theta(1+|r^h_{\eta,\sigma}|^2-|r^e_{\eta,\sigma}|^2)$$

Normal incidence $\theta = 0$

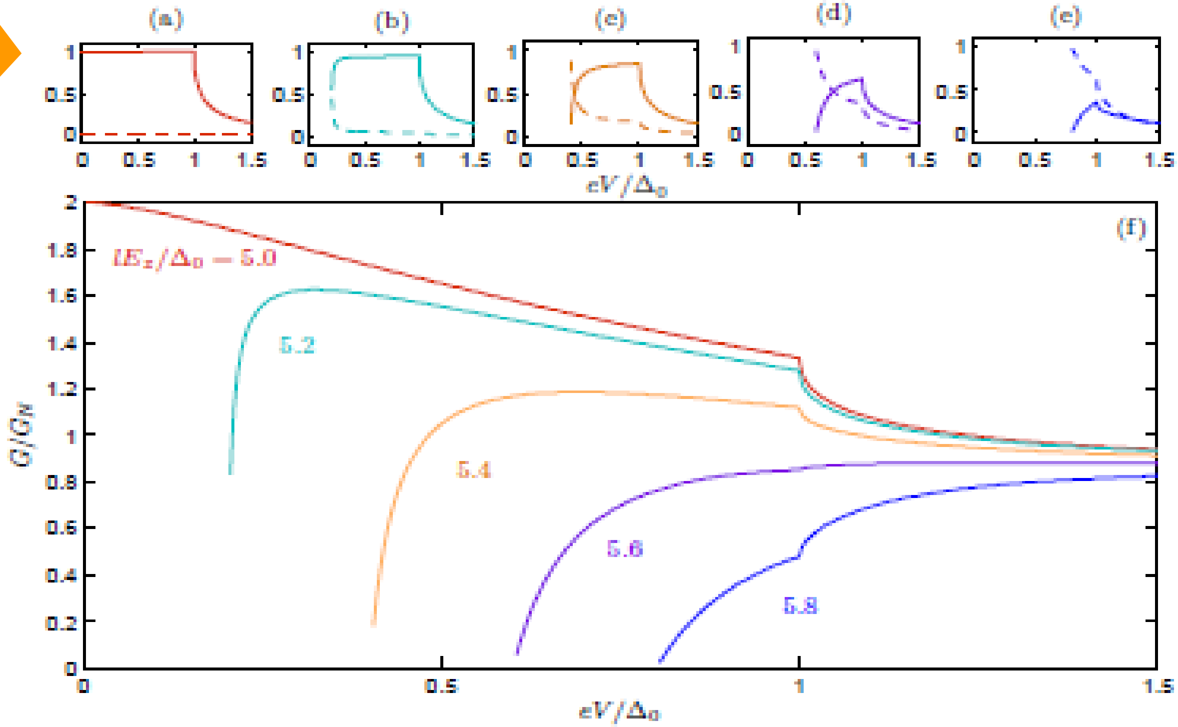
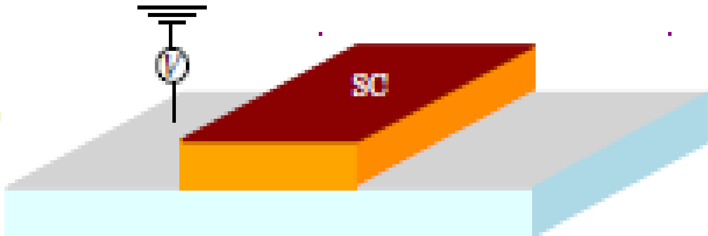


FIG. 2: (Color online) (a)-(e): Normal (dashed lines) and Andreev reflection (full lines) probabilities for an N|S junction with $\eta = \sigma = +1$, $\lambda_{SO}/\Delta_0 = 5.0$, and lE_z/Δ_0 ranging from 5.0 to 5.8 from (a) to (e). In (f), the conductance G/G_N (averaged over spin and valleys) is plotted vs. bias voltage for the same choices of lE_z/Δ_0.

NSN Junction



Normal incidence $\theta = 0$

$$(a) m_L = 0; m_R \neq 0$$

$$(b) m_L \neq 0; m_R \neq 0$$

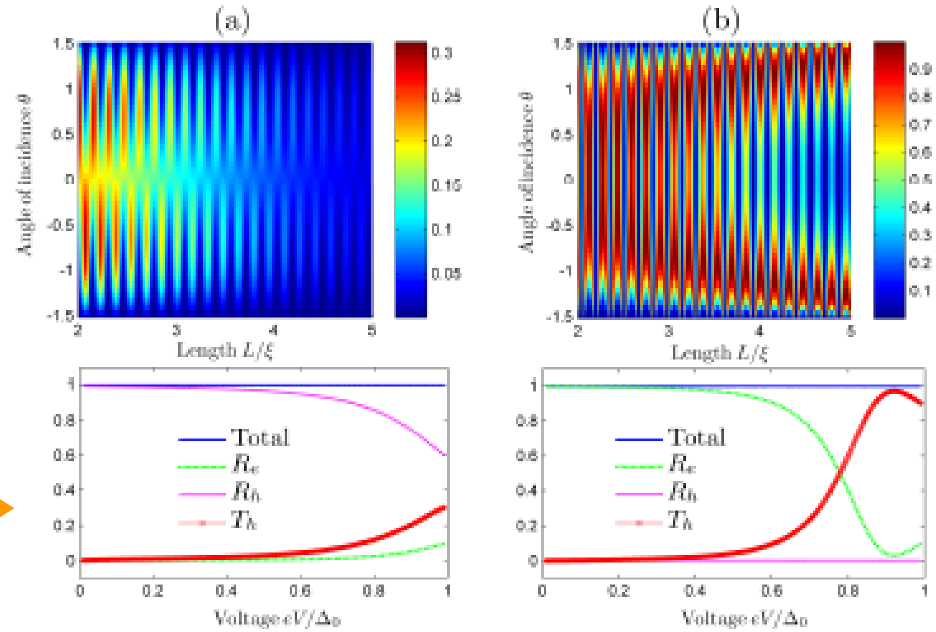


FIG. 3: (Color online) *Top row:* Contour-plot of the CAR probability for a bias voltage $eV/\Delta_0 = 0.9$ vs. angle of incidence θ and junction length L. *Bottom row*: Probabilities for the different scattering events for a fixed junction length $L/\xi = 2.1$ for normal incidence. In column (a), we consider scenario (i) as described in the main text (non-gapped/superconductor/gapped) whereas in (b) we consider scenario (ii) as described in the main text (gapped/superconductor/gapped). We have considered in all cases a strongly doped superconducting region with $\mu_S/\Delta_0 = 20$ and set $m_L/\Delta_0 = 0$ and $m_R/\Delta_0 = 5$ in (a) whereas $m_L/\Delta_0 = m_R/\Delta_0 = 5$ in (b). The coefficients (R_e, R_h, T_h) are the probabilities for normal, Andreev, and crossed Andreev reflection, respectively.

Conductance

$$\frac{G_{nl}}{G_0} = \frac{1}{4}\sum_{\eta,\sigma}\int_{-\pi/2}^{\pi/2} d\theta\, \mathcal{P}_h |t_h|^2 \sqrt{q_F^{h\,2} - k_y^2},$$

$$\mathcal{P}_h = 1/(E-\mu_R),\quad q_F^h = \sqrt{(\mu_R - E)^2 - m_R^2} \qquad k_y = k_L \sin\theta$$

Non local current is spin valley polarized

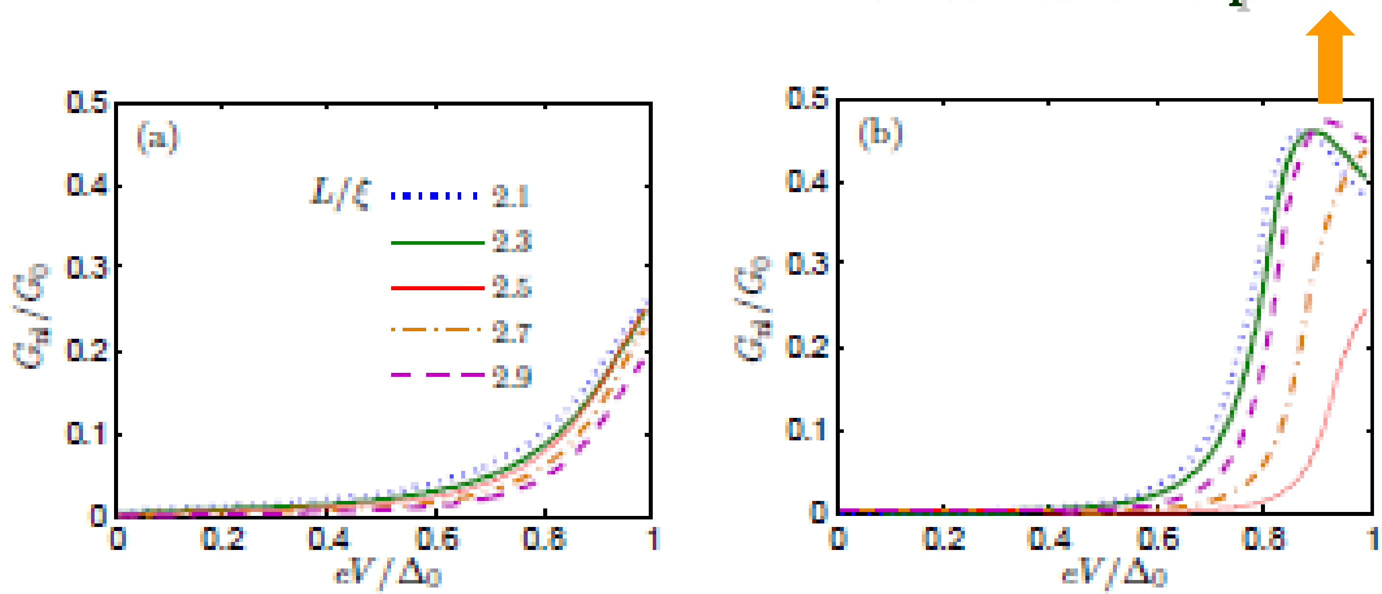


FIG. 4: (Color online) Non-local conductance for (a) gapless and (b) gapped silicene on the left side [corresponding to scenarios (i) and

SNS Junction

$$\frac{\varepsilon(\Delta\phi)}{\Delta_0} = \pm\sqrt{\frac{4\mathcal{M}^2\cos^2(\Delta\phi/2) + L^2(\mathcal{M}^2 - k^2)^2}{4\mathcal{M}^2 + L^2(\mathcal{M}^2 - k^2)^2}} \qquad L \ll \xi$$

$$\mathcal{M} = \mu_N + (\eta\sigma\lambda_{SO} - lE_z)$$

Josephson Current T~0

$$\frac{I(\Delta\phi)}{I_0} = \sum_{\eta\sigma} \frac{\mathcal{M}^2 \sin\Delta\phi}{[4\mathcal{M}^2 + L^2(\mathcal{M}^2 - k^2)^2]\varepsilon(\Delta\phi)}.$$

(a) Tunable supercurrent by Ez
(b) Supercurrent also spin valley polarized

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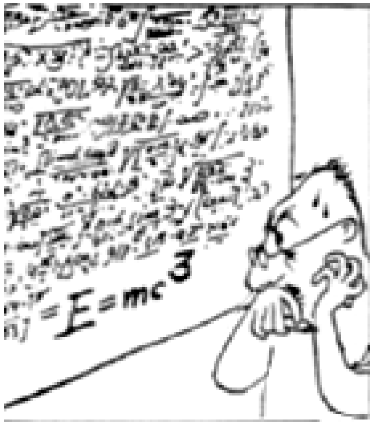
Conclusions



- Tunable nonlocal current and supercurrent by electric field unlike graphene
- Interesting to study transport through other junctions with silicene like NIS, NMS etc


THANKS