Left-handed graphene

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Graphene is a honeycomb lattice of carbon atoms made of two interpenetrating triangular sub lattices.
this particular dispersion mimics the physics of QED for massless Dirac relativistic fermions moving with $v_F = c/300$
\[ \psi = (\psi_A, \psi_B)^T \]

\[ i\hbar \frac{\partial \psi}{\partial t} = (\hat{H}_0 + V)\psi \]

\[ \hat{H}_0 = v_F \vec{\sigma} \vec{p}, \quad \vec{\sigma} = (\sigma_1, \sigma_2), \quad \vec{p} = -i\hbar \vec{\nabla} \]

Dirac equation for massless relativistic particles

Maxwell equations for electromagnetic waves

\[ \frac{\partial \vec{E}}{\partial t} = \frac{c}{\varepsilon} \text{curl}\vec{H} \]

\[ \frac{\partial \vec{H}}{\partial t} = -\frac{c}{\mu} \text{curl}\vec{E} \]
\( V = V(x) \)
\( n(x) = \sqrt{\varepsilon \mu} \)
\( Z(x) = \sqrt{\varepsilon / \mu} \)

\[ E = E_y - iE_x \]
\[ H = ZH_z \]

\[ \psi_{A,B} \sim \exp \left( -i \frac{W}{\hbar} t + ik_y y \right) \]

\[ E, H \sim \exp(-i \omega t + ik_y y) \]

\[ \psi_A = - \frac{iv_F \hbar}{E - V} \left( \frac{d\psi_B}{dx} + k_y \psi_B \right) \]
\[ \psi_B = - \frac{iv_F \hbar}{E - V} \left( \frac{d\psi_A}{dx} - k_y \psi_A \right) \]

\[ H = - \frac{i}{kn} \left( \frac{dE}{dx} + k_y E \right) \]
\[ E = - \frac{i}{kn} \left( \frac{dH}{dx} - k_y H \right) \]
Quasiparticles with the energy \( W \) in the graphene sheet subjected to the electrostatic potential \( V(x) \).

Electromagnetic waves with the frequency \( \omega \) in the dielectric with the refractive index

\[
n(x) = \frac{c(W - V(x))}{\omega \hbar v_F}
\]
$$Z^{(1)} = Z^{(2)}$$

$$H_z^{(1)} = H_z^{(2)}, \quad E_y^{(1)} = E_y^{(2)}$$

$$\psi_A^{(1)} \left/ \psi_A^{(2)} \right. = 1$$
$$\psi_B^{(1)} \left/ \psi_B^{(2)} \right. = 1$$

$$\frac{H^{(1)}}{H^{(2)}} = 1$$
$$\frac{E^{(1)}}{E^{(2)}} = 1$$

$$\frac{E^{(1)}}{E^{(2)}} = \frac{Z^{(2)}}{Z^{(1)}} \left( \frac{n^{(1)}}{n^{(2)}} \frac{1}{H^{(2)}} \frac{dH^{(2)}}{dx} - k_y \right)$$

$$\frac{dH^{(2)}}{dx} = -k_y$$

$$k_y = 0$$
\[ V^{(1)} = V^{(2)} \]

\[ W \]

\[ p-p, n-n, p-n \] junctions

\[ n^{(1)} = \frac{c}{\omega} \frac{W - V^{(1)}}{\hbar v_F} \]

\[ n^{(2)} = \frac{c}{\omega} \frac{W - V^{(2)}}{\hbar v_F} \]

\[ \omega \]

\[ Z^{(1)} = Z^{(2)} \]
V. Cheianov, V. Fal’ko, B. Altshuler,
Science, 2007
Klein paradox

\[ Z^{(1)} = Z^{(2)} = Z^{(3)} \]

\[ R_{12} = R_{23} = 0 \]

matching microwave elements

quantum field theory: ...particle - antiparticle pairs in the potential
Randomly layered graphene

no backscattering in 1-D disordered systems

all states are delocalized, no matter

how strong the disorder is!!!

no localization in 1-d random graphene superlattice?

\[ R_{i,i+1}(\theta = 0) = 0 \]
time-reversal symmetry?
Graphene - metamaterials analogy can be exploited for mutual benefits

\[ V^{(1)} \quad V^{(2)} \]

\[ W \quad A^{(1)} \quad A^{(2)} \]

Crossed magnetic and electric fields applied to a graphene sheet can form a unidirectional conducting channel whose properties are easily tunable by the voltage applied across the strip. The eigenmode of this channel is a one-way propagating wave. This unique property prohibit backscattering and therefore makes the mode resistant to the scattering by impurities.

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