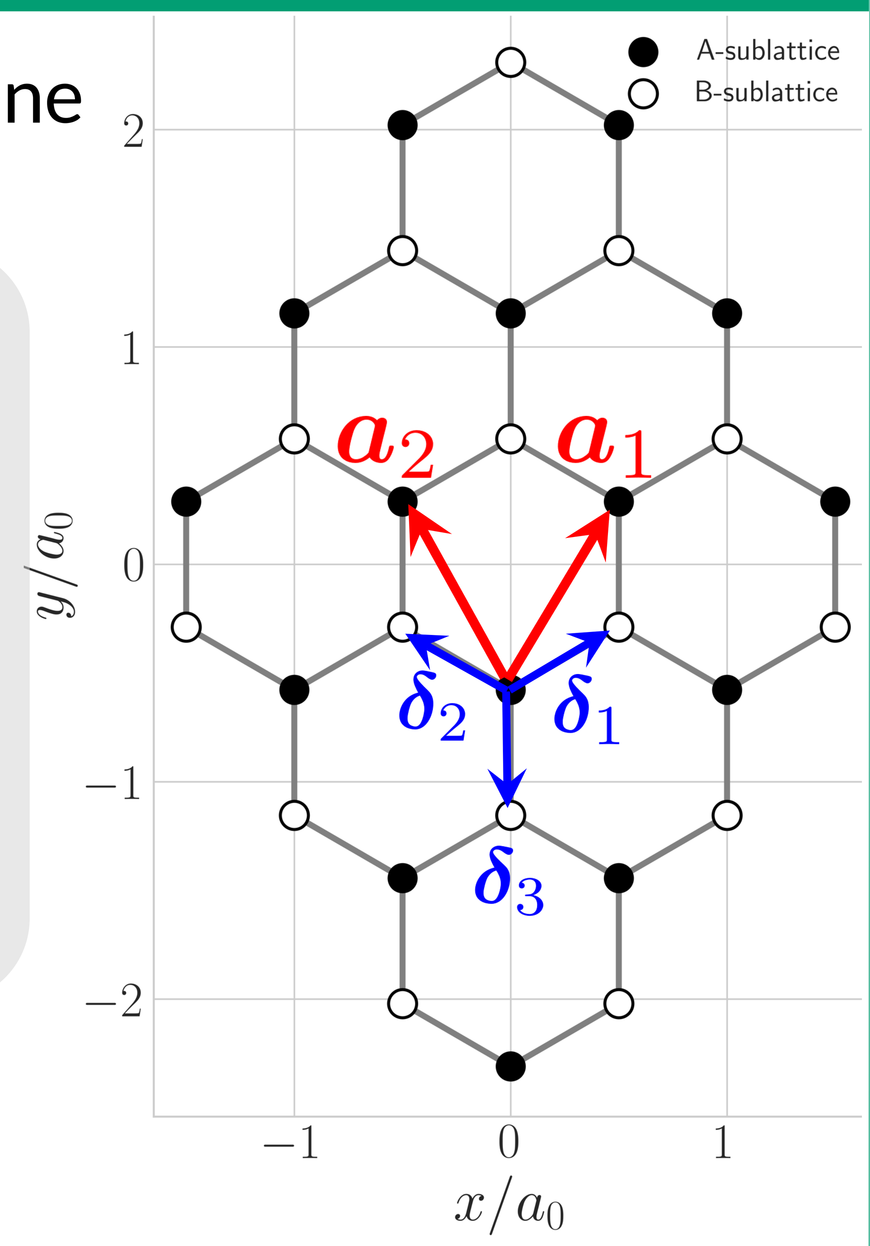
Graphene Under Surface Acoustic Waves

Naoki Itsui
The Institute for Solid State Physics, the University of Tokyo

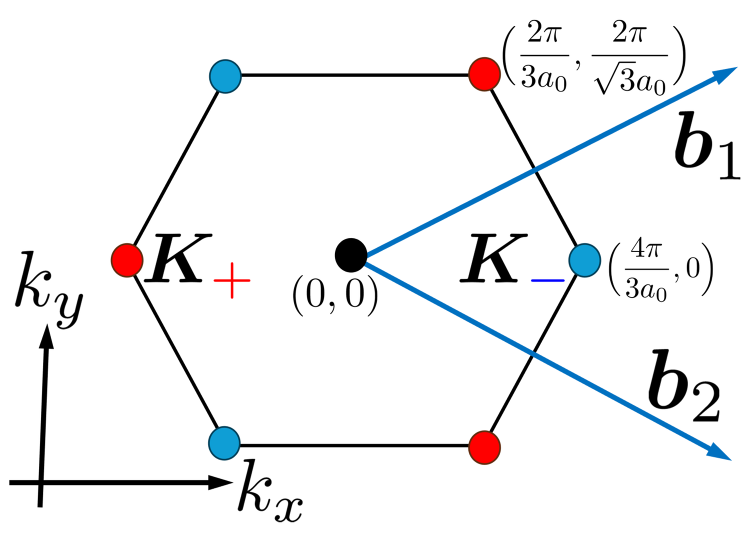
1. Model of Graphene

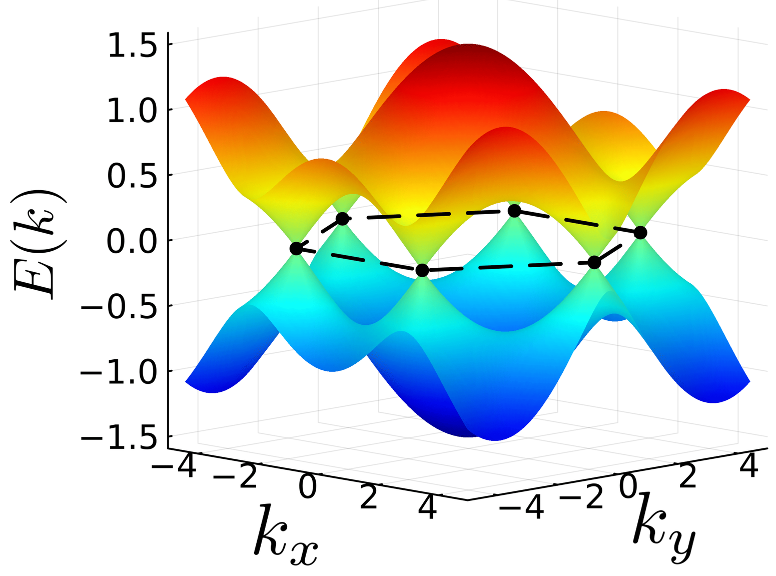
◆The Hamiltonian of graphene is given by

$$\hat{H} = t\sum_{\langle i,j\rangle} c_i^\dagger c_j = \sum_{\boldsymbol{k}} c_{\boldsymbol{k}}^\dagger H(\boldsymbol{k}) c_{\boldsymbol{k}},$$
$$H(\boldsymbol{k}) = R_1(\boldsymbol{k})\sigma^1 + R_2(\boldsymbol{k})\sigma^2,$$
$$R_1(\boldsymbol{k}) = t\sum_{a=1,2,3} \cos \boldsymbol{k}\cdot\boldsymbol{\delta}_a,$$
$$R_2(\boldsymbol{k}) = -t\sum_{a=1,2,3} \sin \boldsymbol{k}\cdot\boldsymbol{\delta}_a$$



◆The Brillouin zone and the band structure are





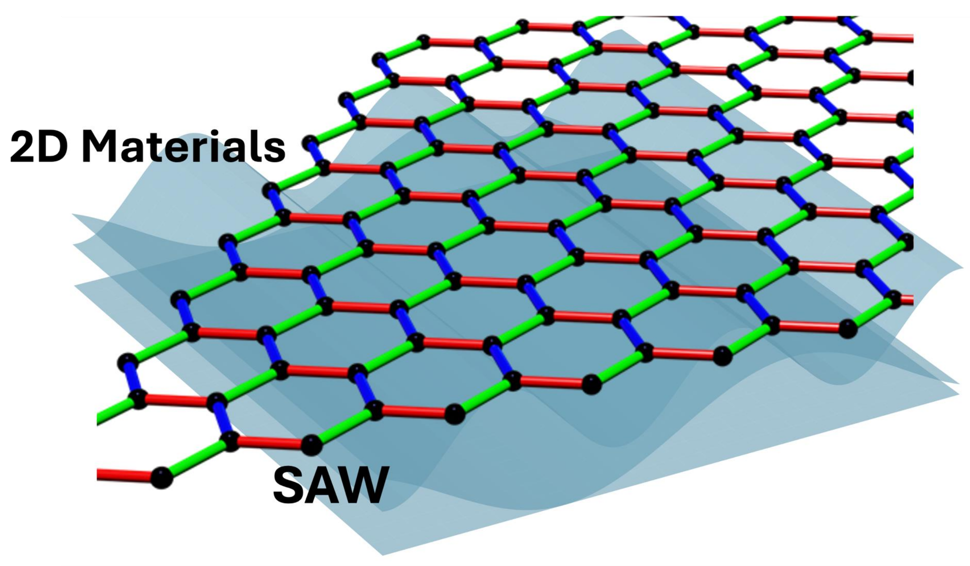
◆Expanding the Hamiltonian around valley points $\boldsymbol{K}_\pm$ the continuum model is

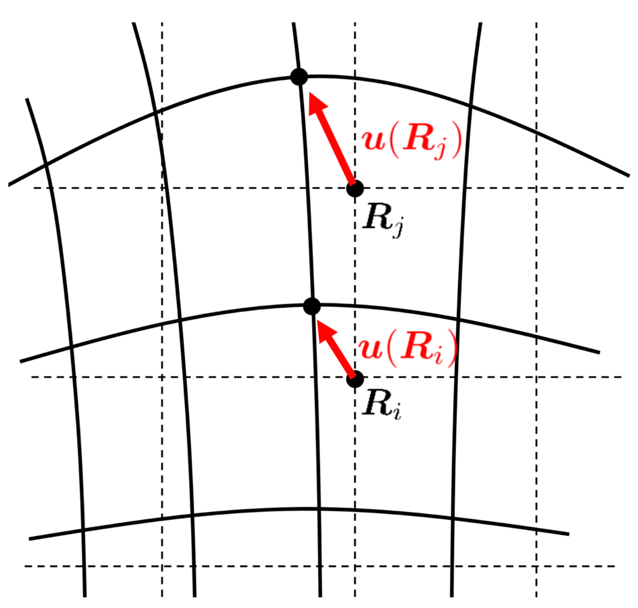
$$H_\tau(\boldsymbol{q}) = v_F(\tau q_x\sigma^x + q_y\sigma^y),$$

where $\tau = \pm 1$ is the valley degree of freedom.

2. Surface Acoustic Waves

◆**Surface acoustic waves** (**SAWs**) [1] are mechanical waves that propagate on the surface of a piezoelectric substrate, generating lattice structure deformations.





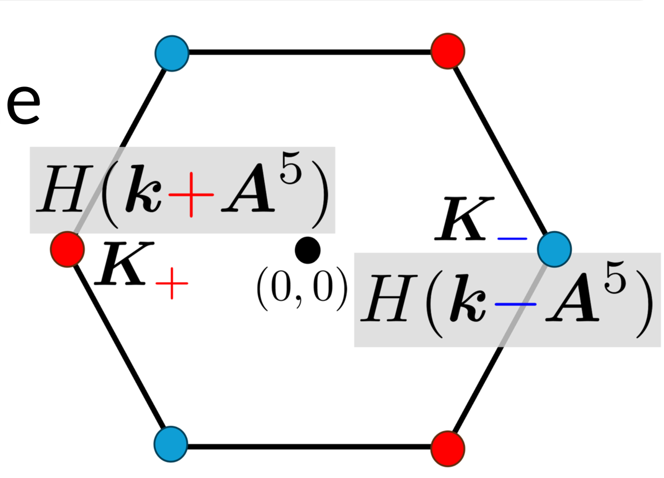
- Position change:
$$\boldsymbol{r} \to \boldsymbol{r}' = \boldsymbol{r} + \boldsymbol{u}(\boldsymbol{r}, t),$$
$$\boldsymbol{r} + \boldsymbol{\delta}_i \to \boldsymbol{r}' + \boldsymbol{\delta}_i' = \boldsymbol{r} + \boldsymbol{u}(\boldsymbol{r}, t) + \boldsymbol{\delta}_i + \boldsymbol{u}(\boldsymbol{r} + \boldsymbol{\delta}_i, t).$$

◆For materials with a honeycomb lattice structure, the effect of the SAW works as a **pseudo-gauge field** that has opposite signs at the two valley points.

$$\boldsymbol{A}^5 = \begin{pmatrix} A_x^5 \\ A_y^5 \end{pmatrix} = \frac{\sqrt{3}\beta}{2a_0}\begin{pmatrix} \epsilon_{xx} - \epsilon_{yy} \\ -2\epsilon_{xy} \end{pmatrix}, \quad \epsilon_{\alpha\beta} \equiv \frac{1}{2}(\partial_\alpha u_\beta + \partial_\beta u_\alpha).$$

◆The continuum model of graphene under a SAW is

$$H_\tau(\boldsymbol{q} + \tau\boldsymbol{A}^5).$$



3. Symmetries of Physical Quantities

Physical quantity	Name	P	T	PT
$\boldsymbol{A}$	gauge field	−	−	+
$\boldsymbol{E} = -\frac{\partial \boldsymbol{A}}{\partial t}$	electric field	−	+	−
$\boldsymbol{B} = \nabla\times\boldsymbol{A}$	magnetic field	+	−	−
$\boldsymbol{A}^5$	pseudo-gauge field	+	+	+
$\boldsymbol{E}^5 = -\frac{\partial \boldsymbol{A}^5}{\partial t}$	pseudo-electric field	+	−	−
$\boldsymbol{B}^5 = \nabla\times\boldsymbol{A}^5$	pseudo-magnetic field	−	+	−
$\boldsymbol{J}_{\mathrm{C}}$	charge current	−	−	+
$\boldsymbol{J}_{\mathrm{S}}$	spin current	−	+	−
$\boldsymbol{J}_{\mathrm{V}}$	valley current	+	+	+
$\boldsymbol{J}_{\mathrm{Q}}$	heat current	−	−	+
$\boldsymbol{P}$	electric polarization	−	+	−
$\boldsymbol{M}$	magnetization	+	−	−

4. Nonlinear Responses against SAWs

◆We consider the Graphene under a SAW [2]. The Hamiltonian and the strain field are given by

$$H_\tau = v_F\left[\tau\left(q_x + \tau A_x^5\right)\sigma^x + \left(q_y + \tau A_y^5\right)\sigma^y\right] + V,$$
$$\boldsymbol{u} = \mathrm{Re}\left[\left(u_L\hat{\boldsymbol{Q}} - iu_z\hat{\boldsymbol{z}}\right)e^{i(\boldsymbol{Q}\cdot\boldsymbol{r} - \Omega t)}\right].$$

- The net charge current from the linear response to SAWs is **zero**, so we consider nonlinear responses against SAWs.

◆**Acoustoelectric Effect**:

The acoustoelectric (AE) effect [3] is a second-order response to the piezoelectric potential associated with a propagating SAW.

$$j_a^{\mathrm{AE}} = \chi_{ann}^{(2)}(\boldsymbol{Q}, \Omega, -\boldsymbol{Q}, -\Omega)V(\boldsymbol{Q}, \Omega)V(-\boldsymbol{Q}, -\Omega)$$

◆**Acoustogalvanic Effect**:

The acoustogalvanic (AG) effect [4] is a second – order response to the pseudo-electromagnetic field.

$$j_a^{\mathrm{AG}} = \chi_{abc}^{(2)}(\boldsymbol{Q}, \Omega, -\boldsymbol{Q}, -\Omega)A_b^5(\boldsymbol{Q}, \Omega)A_c^{5*}(\boldsymbol{Q}, \Omega).$$

◆These two nonlinear response currents have been observed in graphene [5].

Conclusion and Outlook

- We review recent progress on 2D Dirac materials under SAWs, with a primary focus on graphene.
- Other materials, such as TMDs and Kitaev Quantum Spin Liquids, are also promising candidates for study.

[1] X. Nie et al., Nanoscale Horiz. **8**, 158-175 (2023).
[2] P. Bhalla et al, Phys. Rev. B **105**, 125407 (2022).
[3] R. H. Parmenter, Phys. Rev. **89**, 990–998 (1953).
[4] P. O. Sukhachov et al, Phys. Rev. Lett. **124**, 126602 (2020).
[5] P. Zhao et al., Phys. Rev. Lett. **128**, 256601 (2022).