Spin photocurrents in semiconductors

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Main outline:

*The ordinary spin photocurrents in semiconductors

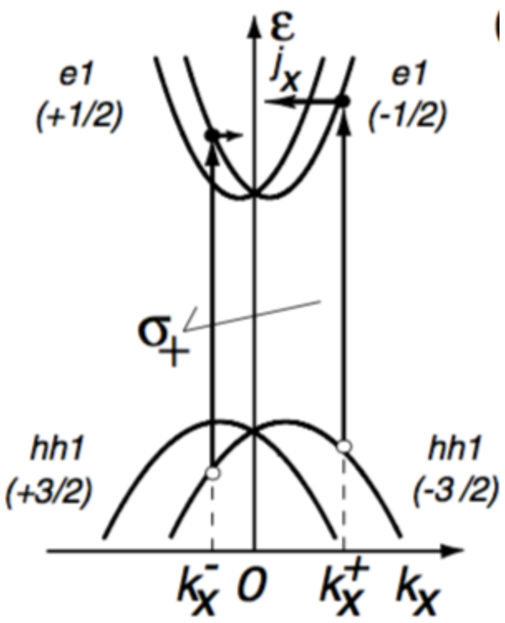
*Symmetry analysis of CPGE

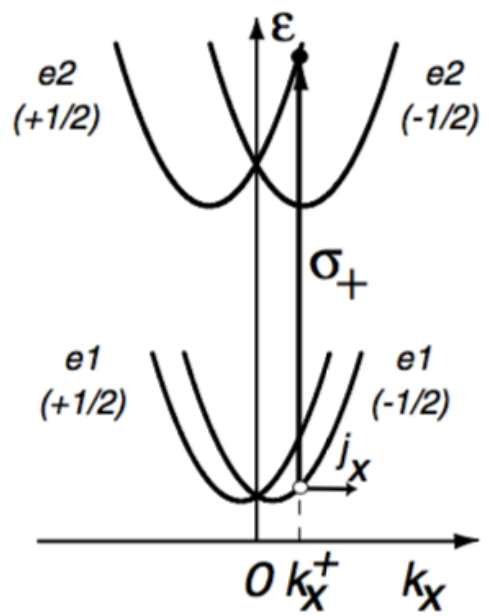
*Some special CPGE in semiconductors

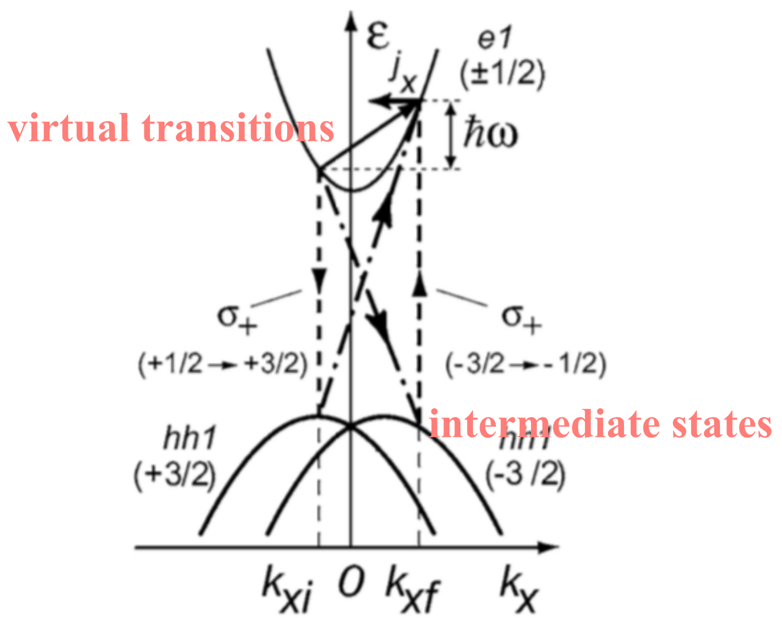
*Some personal thoughts

The origination of CPGE in semiconductors

*The microscopic model for CPGE







1.Inter-band transitions: between conduct band and valence band

2.Inter-subband transitions(infrared and far infrared):between size-quantized subbands in the conduction band

3.Intra-subband transitions(far-infrared range):phonon needed

S D Ganichev and W Prettl 2003 *J. Phys.: Condens. Matter*

Phenomenology theory of CPGE

*The macroscopic model for CPGE

$$j_\lambda = \sum_\mu \gamma_{\lambda\mu} \mathrm{i}(\boldsymbol{E} \times \boldsymbol{E}^*)_\mu,$$

$$\mathrm{i}(\boldsymbol{E} \times \boldsymbol{E}^*)_\mu = \hat{e}_\mu E_0^2 P_{circ}$$

γ is a second-rank pseudo-tensor;P_{cric} is the radiation helicity

Sub problem (solved)

$$p_{circ} = \frac{I_{\sigma+} - I_{\sigma-}}{I_{\sigma+} + I_{\sigma-}}$$

$$i(\vec{E} \times \vec{E}^*) = E_0^2 \, p_{circ} \, \vec{e}_K$$

$\vec{E}$ 为电磁波的复电矢量. $\vec{e}_K$ 为电磁波传播方向

$$\vec{E}_{\sigma+} = a_1 e^{i(\delta_1 + \frac{\pi}{2})} \vec{x}_0 + a_1 e^{i\delta_1} \vec{y}_0$$

$$\vec{E}_{\sigma-} = a_2 e^{i(\delta_2 - \frac{\pi}{2})} \vec{x}_0 + a_2 e^{i\delta_2} \vec{y}_0$$

$$\vec{E} = \vec{E}_{\sigma+} + \vec{E}_{\sigma-}$$

$$E_0^2 = I_{\sigma+} + I_{\sigma-}$$

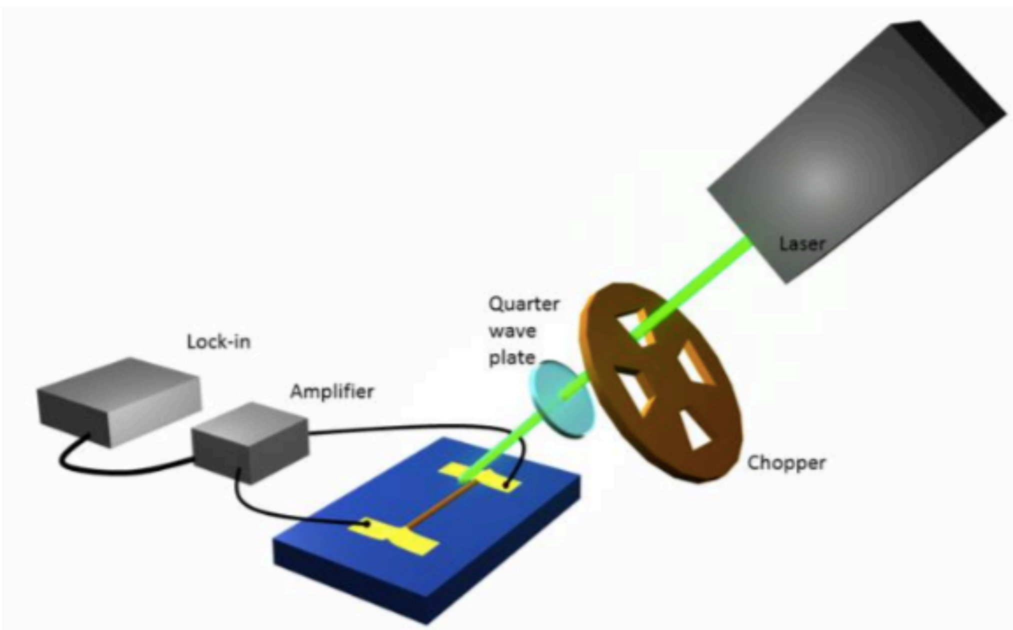
$$\vec{E} \times \vec{E}^* = 2i(a_1^2 - a_2^2) = 2i(I_{\sigma+} - I_{\sigma-})$$

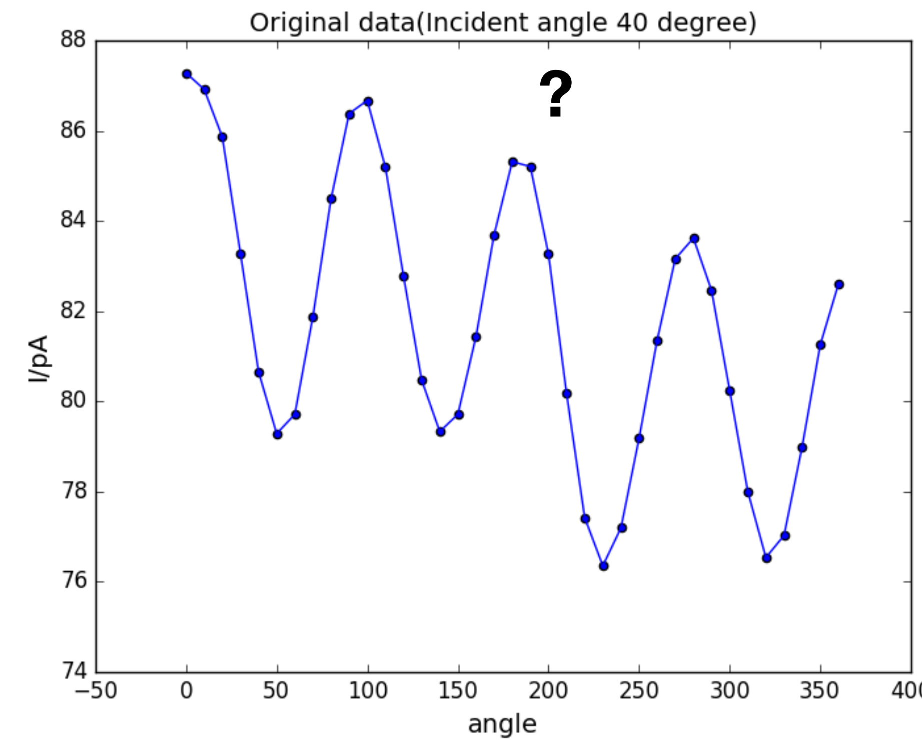
$$P_{circ} = \frac{I_{\sigma_+} - I_{\sigma_-}}{I_{\sigma_+} + I_{\sigma_-}} = \sin 2\varphi$$

The definition of P_{circ}

The Experiment of measuring CPGE

*The measuring system

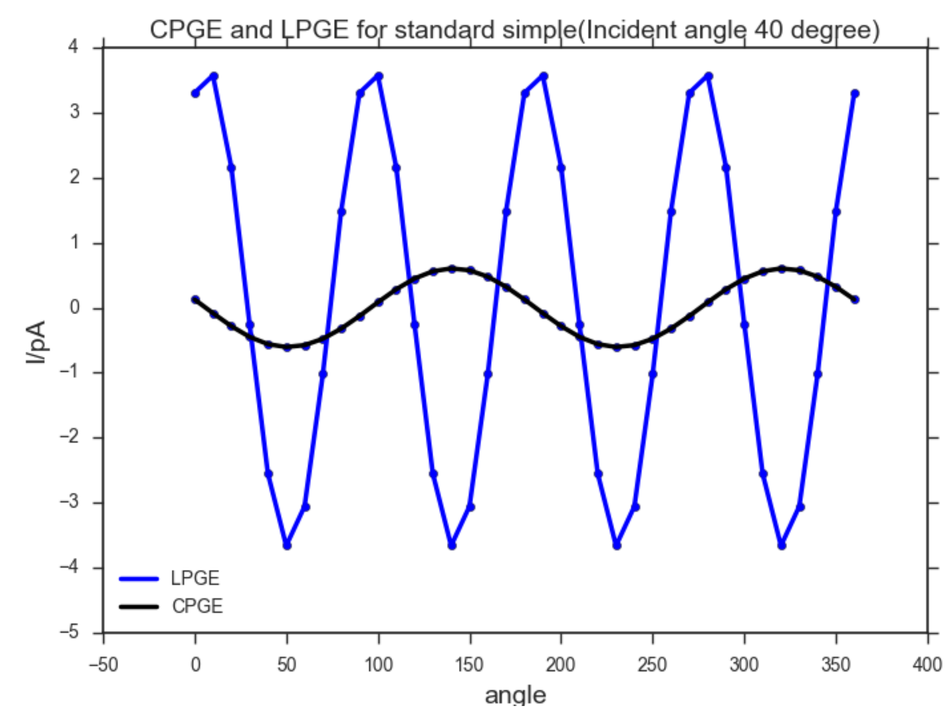




The equation used to fit the experimental datas:

$$j = j_c \sin 2\varphi + j_L \sin 2\varphi \cos 2\varphi + j_0$$

J_L is the Linear photogalvanic originating from the spin selective scattering by phonons, defects, etc



Multi-layer MoS2/**should be zero theoretically**

张姗(2015),博士毕业论文

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*Some personal thoughts

The symmetry analysis of CPGE in semiconductors

*The properties of matter tensor in Crystals

1.The First-Rank matter Tensor(vector)

$$V_j^{'} = R_{ji} V_i$$

2.The second-Rank matter Tensor

$$T_{ij}^{'} = R_{ik} R_{jl} T_{kl}$$

For pseudo-tensor the $det(R)$ should be added

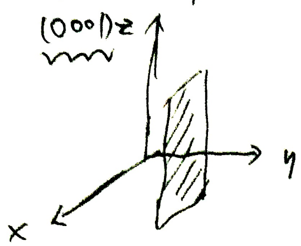
*The symmetry analysis of CPGE

$$j_\lambda = \sum_\mu \gamma_{\lambda\mu} \mathrm{i} (\boldsymbol{E} \times \boldsymbol{E}^*)_\mu ,$$

Considering the symmetry of semiconductors ,many component of the second-rank pseudo-tensor will be zero

The symmetry analysis of CPGE in semiconductors

C_s point group (仅含个镜像反演操作)



$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\chi = \begin{pmatrix} \chi_{xx} & \chi_{xy} & \chi_{xz} \\ \chi_{yx} & \chi_{yy} & \chi_{yz} \\ \chi_{zx} & \chi_{zy} & \chi_{zz} \end{pmatrix}$$

$$\chi \xrightarrow{R} \chi' = R\chi R^T \det R$$

$$= \begin{pmatrix} -\chi_{xx} & \chi_{xy} & -\chi_{xz} \\ \chi_{yx} & -\chi_{yy} & \chi_{yz} \\ -\chi_{zx} & \chi_{zy} & -\chi_{zz} \end{pmatrix}$$

$\chi' = \chi \Rightarrow \chi_{xy}, \chi_{yx}, \chi_{yz}, \chi_{zy}$ 非零

其它均为零

$$j_\lambda = \sum_\mu \chi_{\lambda\mu} E_0^2 P_{circ} \hat{e}_\mu$$

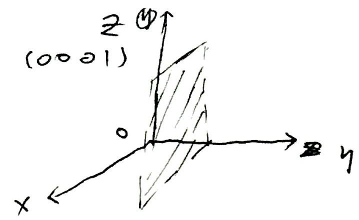
$$j_x = \chi_{xy} |\hat{e}_y'| E_0^2 P_{circ}$$

$$j_y = (\chi_{yx} \hat{e}_x' + \chi_{yz} \hat{e}_z') E_0^2 P_{circ}$$

$$j_z = \chi_{zy} |\hat{e}_y'| E_0^2 P_{circ}$$

($\hat{e}'$ 光的坐标系)

C_{2v} point group



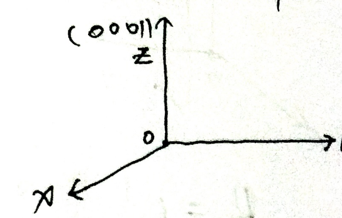
二阶轴 + σ_v

$$R(C_2) = \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad R(\sigma_v) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

$$\chi \xrightarrow{R(C_2)} \chi' = \chi$$
$$\chi \xrightarrow{R(\sigma_v)} \chi' = \chi \Rightarrow \chi = \begin{pmatrix} 0 & \chi_{xy} & 0 \\ \chi_{yx} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

C_{6v}/C_{3v} GaN、ZnO.

AlGaN/GaN 异质结



$$R(C_3) = \begin{pmatrix} -\frac{1}{2} & -\frac{\sqrt{3}}{2} & 0 \\ \frac{\sqrt{3}}{2} & -\frac{1}{2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$R(C_6') = \begin{pmatrix} \frac{1}{2} & -\frac{\sqrt{3}}{2} & 0 \\ \frac{\sqrt{3}}{2} & \frac{1}{2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\vdots$

$$R(\sigma_v) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\chi \xrightarrow{R(C_3), R(C_6) R(\sigma_v)} \chi'$$

$$\chi = \begin{pmatrix} 0 & \chi_{xy} & 0 \\ -\chi_{xy} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

*The information we can get from the symmetry analysis

1.For C_{3v} or higher symmetry:The CPGE is perpendicular to the direction of light propagation.

2.For C_{2v} or higher symmetry:The CPGE only exist in the X-Y plane

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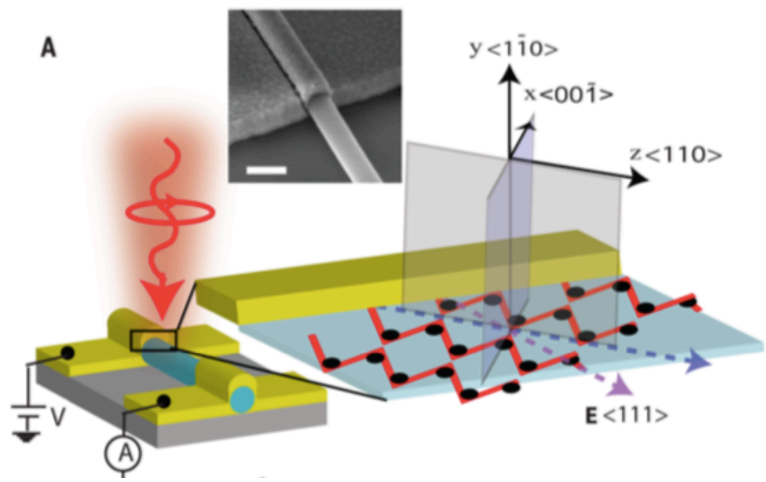
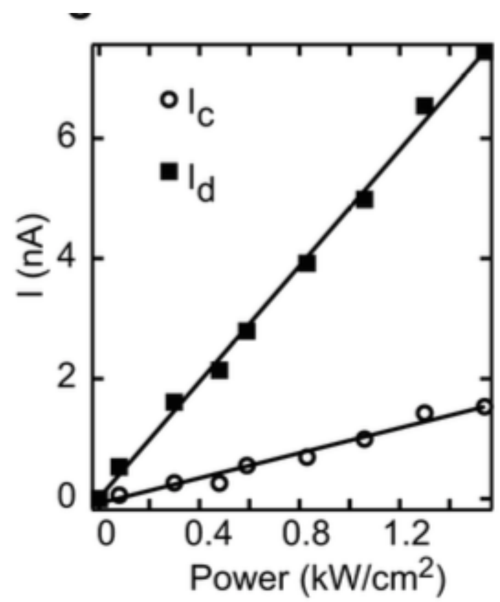
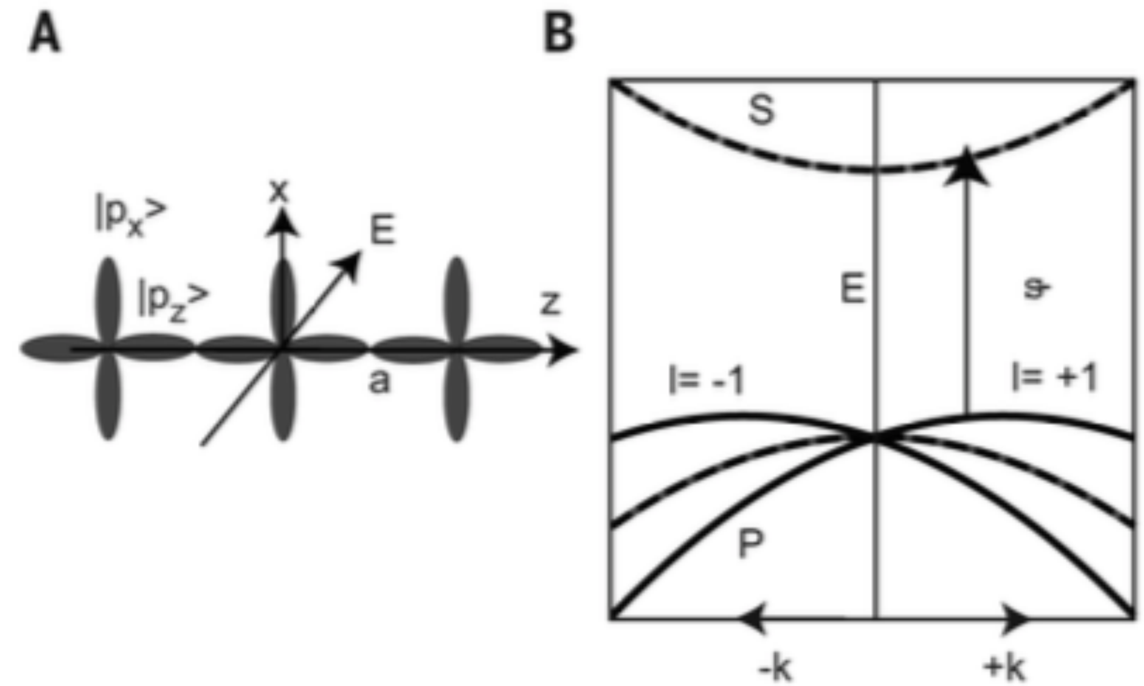
The CPGE of orbital mechanism

*Si nanowires without breaking spin degeneracies





1.Special direction which contain zigzag atomic chains can generate CPGE



2.sensitive to circular polarization of light, tunable with an external bias.

一维原子链 简并微扰论计算能带非自旋分裂

$V_s = r E_x \sin\theta \cos\phi$ (微扰势)

微扰前态矢量的构成

$|\psi_s(\vec{k},\vec{r})\rangle = \frac{1}{\sqrt{N}}\sum_j e^{ik_z z_j} S(\vec{r}-z_j)$

$|\psi_{p_x}(\vec{k},\vec{r})\rangle = \frac{1}{\sqrt{N}}\sum_j e^{ik_z z_j} p_x(\vec{r}-z_j)$

类似地还有 $|\psi_{p_y}\rangle$ $|\psi_{p_z}\rangle$

由E的取向(E处于x,z平面)可知

仅有 $\langle\psi_{p_y}|V_x|\psi_{p_z}\rangle = \langle\psi_{p_z}|V_x|\psi_{p_y}\rangle \neq 0$

$\langle\ |\hat{V}|\ \rangle = \begin{pmatrix} 0 & 0 & irk_z a \\ 0 & 0 & 0 \\ irk_z a & 0 & 0 \end{pmatrix}$

$\Rightarrow \psi_\pm = \frac{1}{\sqrt{2}}(|\psi_{p_x}(\vec{k},\vec{r})\rangle \pm i|\psi_{p_z}(\vec{k},\vec{r})\rangle)$ (波函数一级近似)

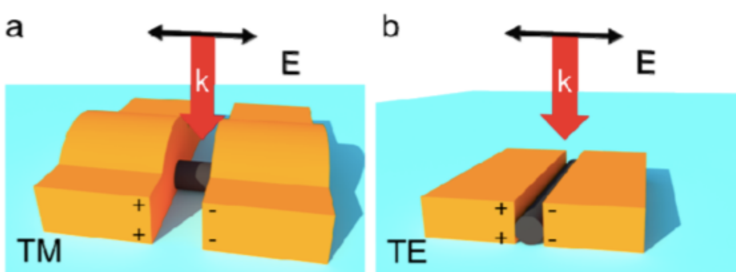
$\Delta E_{\psi_+,\psi_-} = 2|k_z r a|$

电偶极跃迁几率 $P \propto \langle\psi_s|\vec{\varepsilon}\cdot\vec{d}|\psi_+\rangle \propto i\vec{\varepsilon}\times\vec{\varepsilon}^*$

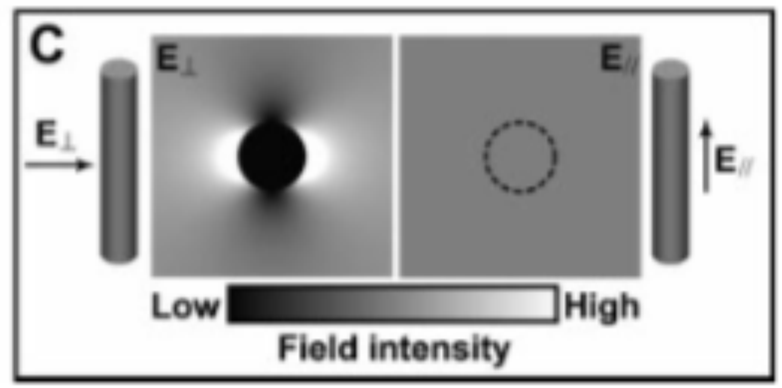
Dhara, S(2015). *Science*

The CPGE of orbital mechanism

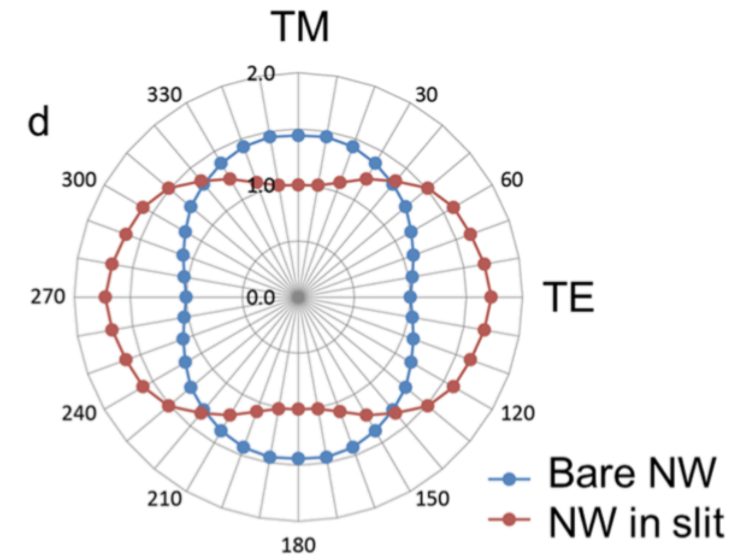
*The mechanism for LPGE



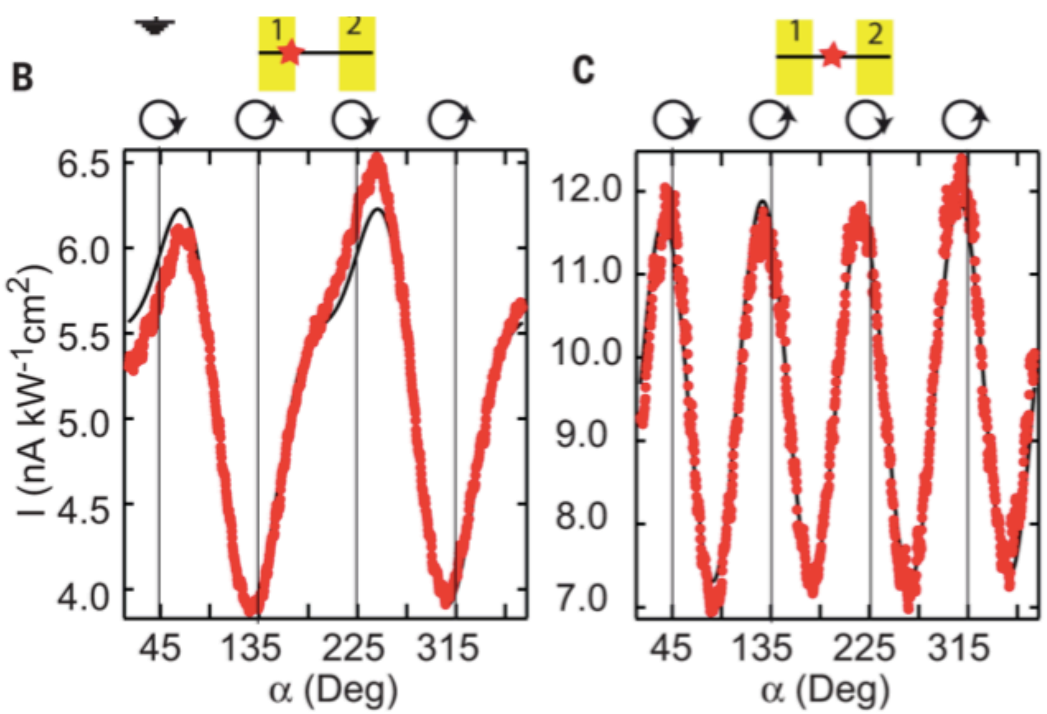
preferential absorption: metal-NW region(TE) ;bare NW(TM)

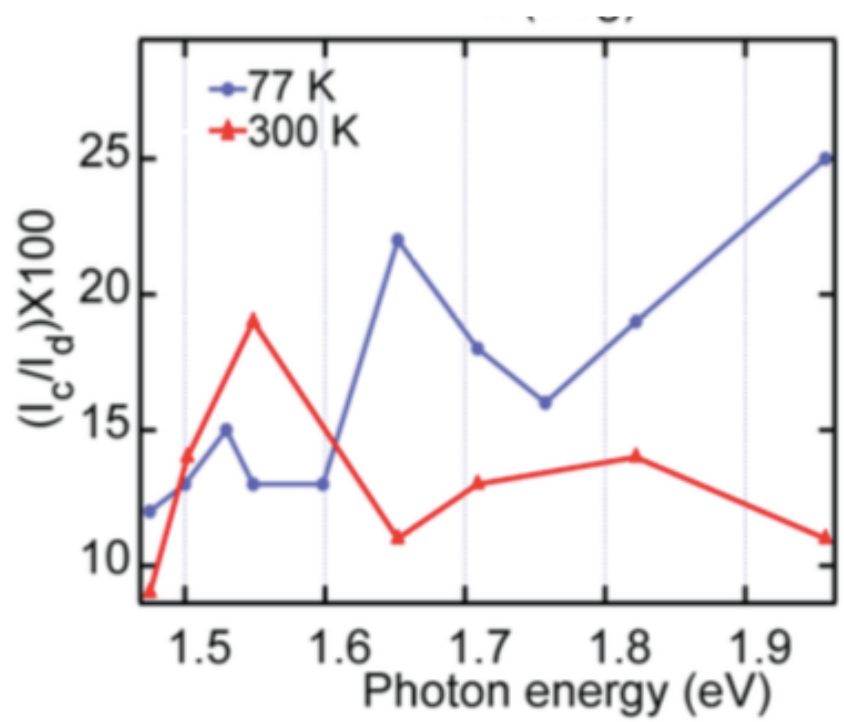


bare NW



*The difference between metal-NW contact region and the bare NW





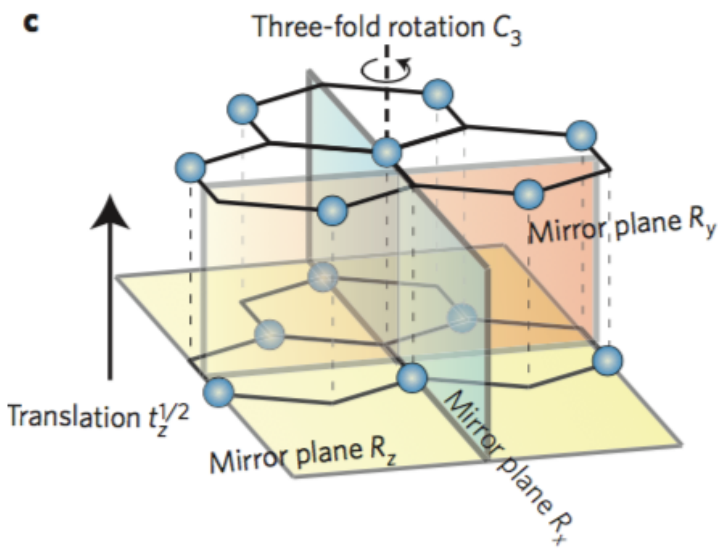
The reason is unknown

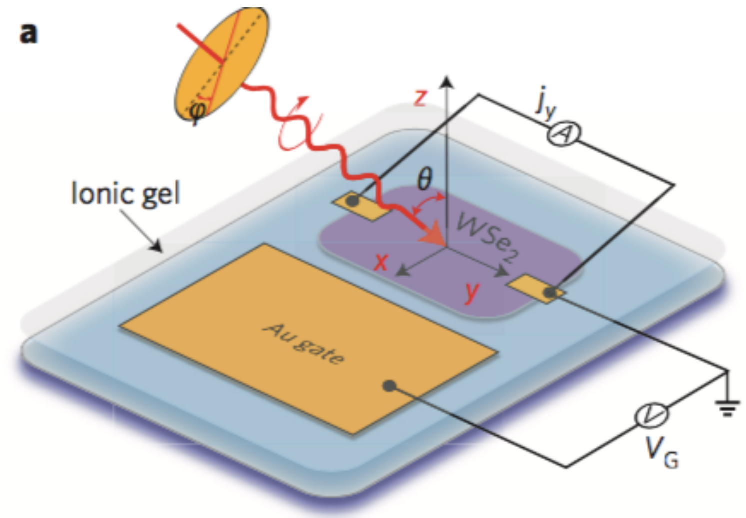
Dhara, S(2015). Science
Pengyu Fan(2013),nanoletter
Jianfang Wang (2001).Science

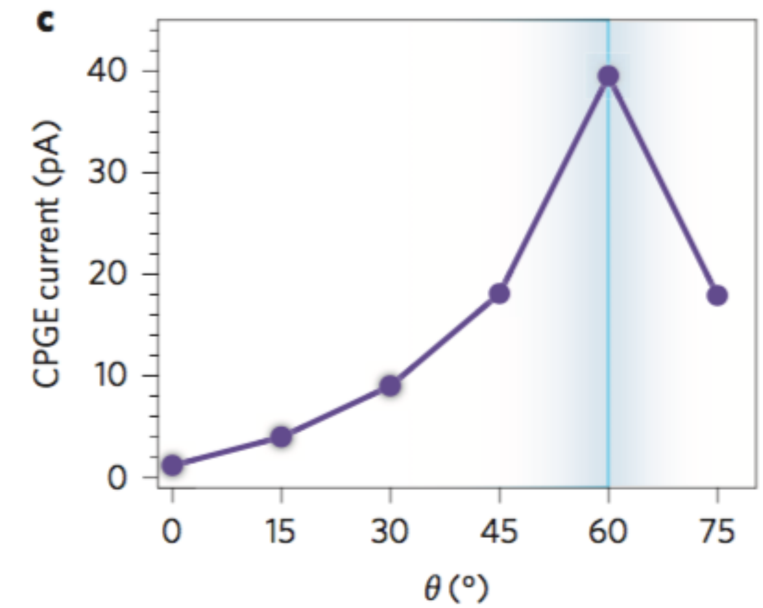
The spin–valley coupled CPGE

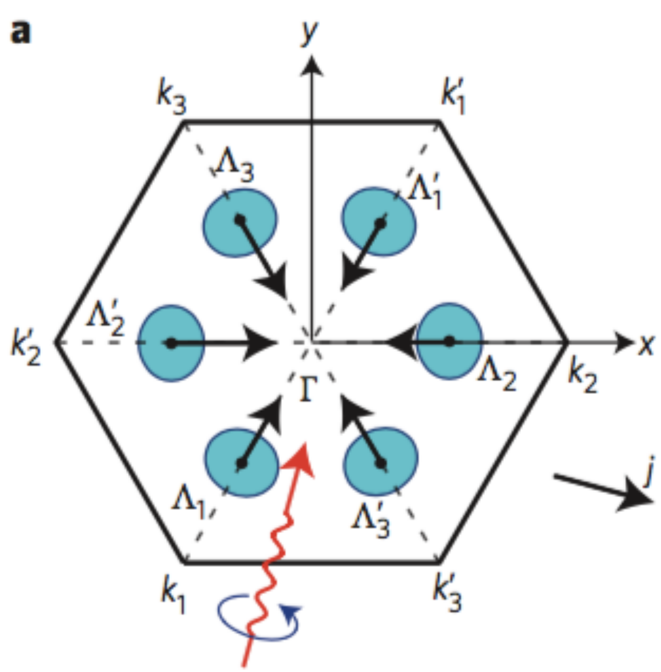
***The CPGE in WSe2(SOC is not necessary)**

The external electronic field don't break the symmetry C_{3v}









$$\boldsymbol{A}(\theta,\phi) = A\Big[(\mathbf{e}_x \sin\phi - \mathbf{e}_y \cos\phi)(1 + i\cos 2\varphi) + i(\mathbf{e}_z \sin\theta - \mathbf{e}_x \cos\theta\cos\phi - \mathbf{e}_y \cos\theta \sin\phi)\sin 2\varphi\Big]$$

The origination of Helicity dependence

$$H' = \int d\mathbf{r}^3 (ie\hbar/mc)\mathbf{A}(\mathbf{r})\cdot\nabla$$

$$\mathcal{M}_2(\mathbf{A}) = \mathcal{M}_{2,x}A_x + \mathcal{M}_{2,y}A_y + \mathcal{M}_{2,z}A_z = \boldsymbol{\mathcal{M}}_2\cdot\mathbf{A}$$

$$\mathcal{M}_{2,u} = (e\hbar/mc)\langle F, \mathbf{k}_{\Lambda_2}|i\partial_u|I, \mathbf{k}_{\Lambda_2}\rangle$$

$$\boldsymbol{j} = \frac{\xi I}{A^2}\sum_{i=1}^{3}\boldsymbol{e}_i\left(\left|\boldsymbol{\mathcal{M}}_2\cdot\boldsymbol{A}\left(\theta,\phi-\frac{2(i-2)\pi}{3}\right)\right|^2 - \left|\boldsymbol{\mathcal{M}}_2^*\cdot\boldsymbol{A}\left(\theta,\phi-\frac{2(i-2)\pi}{3}\right)\right|^2\right)$$

contain C_3 and time-reversal symmetry

$$\begin{aligned}|\boldsymbol{\mathcal{M}}_2\cdot\boldsymbol{A}(\theta,\phi)|^2 - |\boldsymbol{\mathcal{M}}_2^*\cdot\boldsymbol{A}(\theta,\phi)|^2 &= (\boldsymbol{\mathcal{M}}_2\cdot\boldsymbol{A}(\theta,\phi))(\boldsymbol{\mathcal{M}}_2^*\cdot\boldsymbol{A}^*(\theta,\phi)) - (\boldsymbol{\mathcal{M}}_2^*\cdot\boldsymbol{A}(\theta,\phi))(\boldsymbol{\mathcal{M}}_2\cdot\boldsymbol{A}^*(\theta,\phi))\\ &= (\boldsymbol{A}(\theta,\phi)\times\boldsymbol{A}^*(\theta,\phi))\cdot(\boldsymbol{\mathcal{M}}_2\times\boldsymbol{\mathcal{M}}_2^*).\end{aligned}$$

Non-vanishing current equivient to $M_2^* \neq C_{phase}M_2$

Hongtao Yuan(2014),Nanotechnology

The spin–valley coupled CPGE

Key point:breaking R_z symmetry

***The symmetry analysis of CPGE in WSe2**

$Y^2 = t_z = \bar{1}$ "+" indicate the value of Y

originate from fist principle calculation

$|I, \boldsymbol{k}_{\Lambda_2}\rangle = ia_0|d_{xy}^{+}\rangle + b_0|d_{x^2-y^2}^{+}\rangle + c_0|d_{z^2}^{+}\rangle$

$|F_1, \mathbf{k}_{\Lambda_2}\rangle = ia_1|d_{xy}^{+}\rangle + b_1|d_{x^2-y^2}^{+}\rangle + c_1|d_{3z^2-r^2}^{+}\rangle$

$|F_2, \mathbf{k}_{\Lambda_2}\rangle = |d_{yz}^{+}\rangle$

$|F_3, \mathbf{k}_{\Lambda_2}\rangle = ia_3|d_{xy}^{-}\rangle + b_3|d_{x^2-y^2}^{-}\rangle + c_3|d_{3z^2-r^2}^{-}\rangle$

time-reversal symmetry T,

R_x $(x \to -x)$

R_z $(z \to -z)$

$Y = t_z^{1/2} \otimes R_y(y \to -y)$

***Without External field**

$Y|I, \boldsymbol{k}_{\Lambda_2}\rangle = |I, \boldsymbol{k}_{\Lambda_2}\rangle$

$Y|F_1, \boldsymbol{k}_{\Lambda_2}\rangle = |F_1, \boldsymbol{k}_{\Lambda_2}\rangle$

$Y M_2^{I\to F_1} = M_2^{I\to F_1}$

$R_z|I, \boldsymbol{k}_{\Lambda_2}\rangle = |I, \boldsymbol{k}_{\Lambda_2}\rangle$

$R_z|F_1, \boldsymbol{k}_{\Lambda_2}\rangle = |F_1, \boldsymbol{k}_{\Lambda_2}\rangle$

$R_z M_2^{I\to F_1} = M_2^{I\to F_1}$

M is a fist-rank tensor,only $M_x \neq 0$

$\boldsymbol{\mathcal{M}}_2^{(I\to F_1)} = \mathcal{M}_{2,x}^{(I\to F_1)}\boldsymbol{e}_x = e^{2i\delta}\mathcal{M}_{2,x}^{(I\to F_1)^*}\boldsymbol{e}_x = e^{2i\delta}\boldsymbol{\mathcal{M}}_2^{(I\to F_1)^*}$

Hongtao Yuan(2014),Nanotechnology

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time-reversal symmetry T,

R_x $(x \to -x)$

R_z $(z \to -z)$

$Y = t_z^{1/2} \otimes R_y(y \to -y)$

***With External field**

$$|F_1{}',\mathbf{k}_{\Lambda_2}\rangle = |F_1,\mathbf{k}_{\Lambda_2}\rangle + gE_{ex}|F_2,\mathbf{k}_{\Lambda_2}\rangle$$

$$|F_2{}',\mathbf{k}_{\Lambda_2}\rangle = |F_2,\mathbf{k}_{\Lambda_2}\rangle - gE_{ex}|F_1,\mathbf{k}_{\Lambda_2}\rangle$$

$Y|F_1{}',\mathbf{k}_{\Lambda_2}\rangle = |F_1{}',\mathbf{k}_{\Lambda_2}\rangle$ $\mathcal{M}_{2,y}^{(I\to F_1{}')} = 0$

$$\mathcal{M}_{2,x}^{(I\to F_1{}')} = \mathcal{M}_{2,x}^{(I\to F_1)} \neq 0$$

$$\mathcal{M}_{2,z}^{(I\to F_1{}')} = gE\mathcal{M}_{2,z}^{(I\to F_2)} = m_{2,z}^{(I\to F_1{}')}E_{ex} \neq 0$$

$TR_x|I,\mathbf{k}_{\Lambda_2}\rangle = |I,\mathbf{k}_{\Lambda_2}\rangle$

$TR_x|F_1,\mathbf{k}_{\Lambda_2}\rangle = |F_1,\mathbf{k}_{\Lambda_2}\rangle$ $\mathcal{M}_{2,x}^{(I\to F_1{}')} = \mathcal{M}_{2,x}^{(I\to F_1{}')*}$

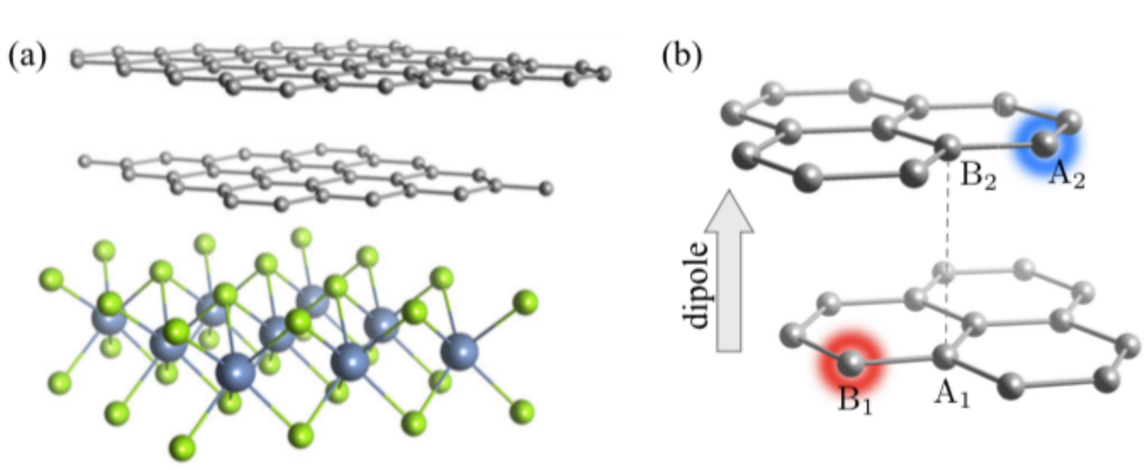
$TR_x|F_2,\mathbf{k}_{\Lambda_2}\rangle = -|F_2,\mathbf{k}_{\Lambda_2}\rangle$ $\mathcal{M}_{2,z}^{(I\to F_1{}')} = -\mathcal{M}_{2,z}^{(I\to F_1{}')*}$

$$\boldsymbol{\mathcal{M}}_2 \times \boldsymbol{\mathcal{M}}_2^* = 2\mathcal{M}_{2,x}^{(I\to F_1{}')}\mathcal{M}_{2,z}^{(I\to F_1{}')}\boldsymbol{e}_y \neq 0$$

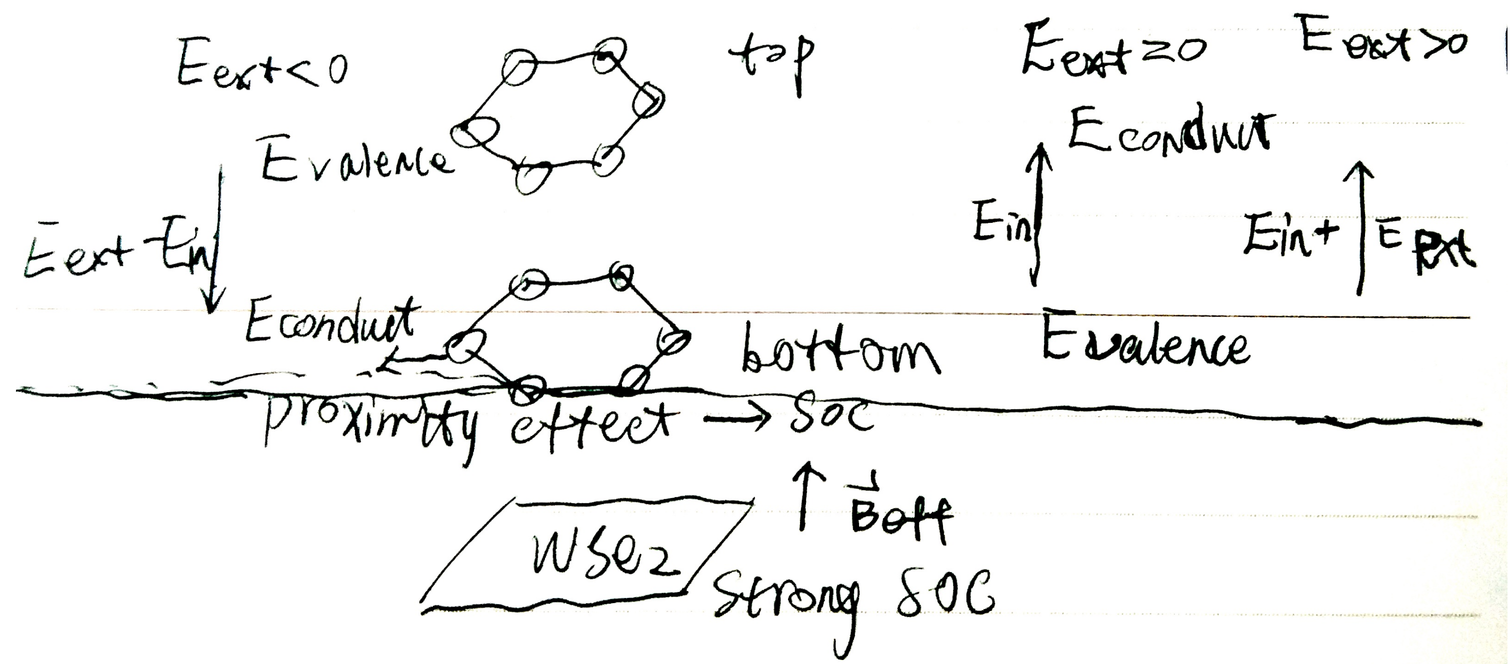
Hongtao Yuan(2014),Nanotechnology

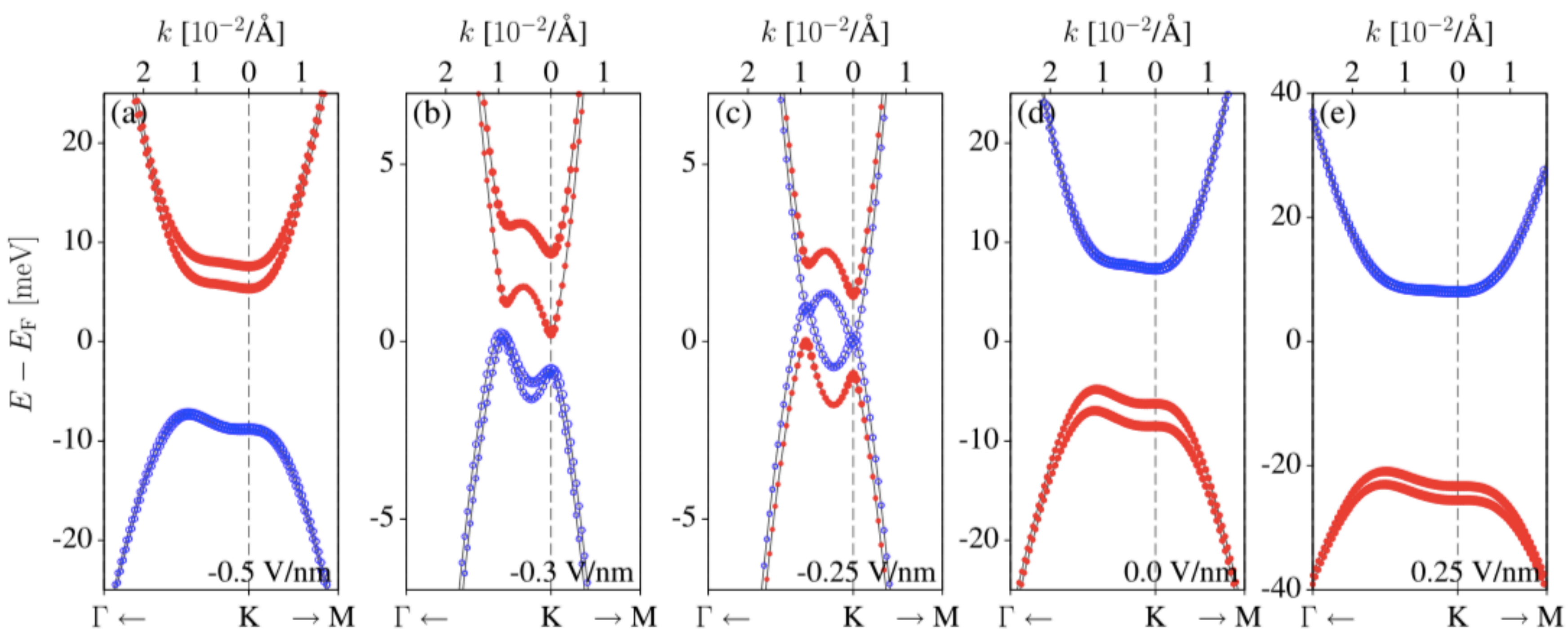
Spin orbit valve

***Bilayer Graphene on Monolayer WSe_2**



Spontaneous polarization create built-in transverse electric



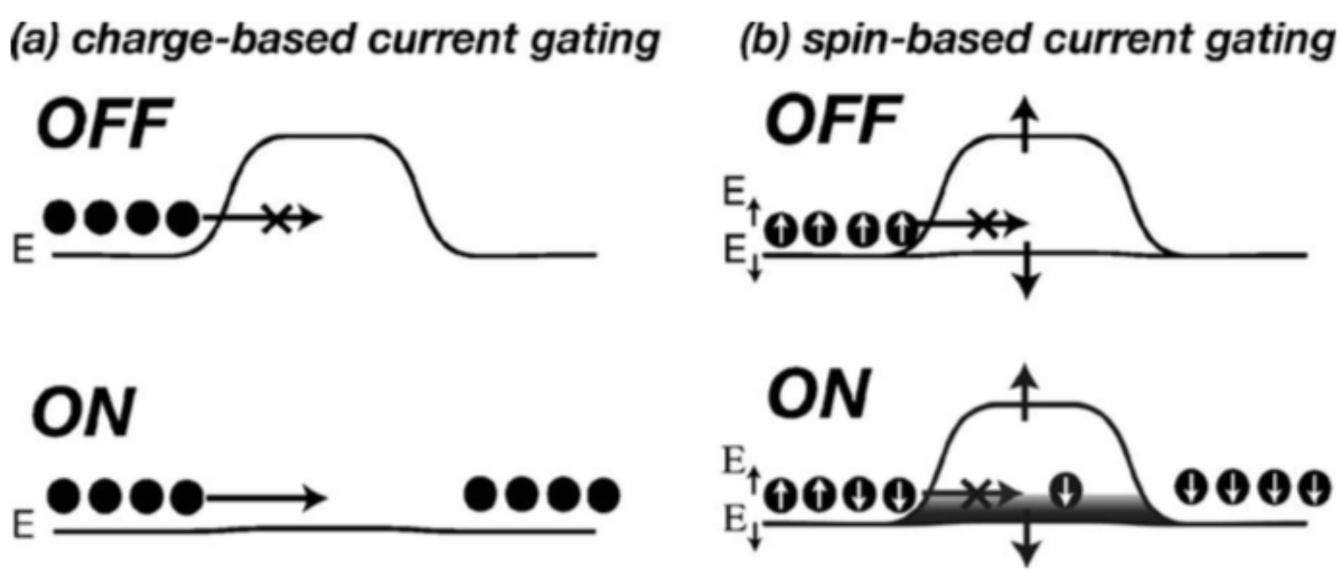


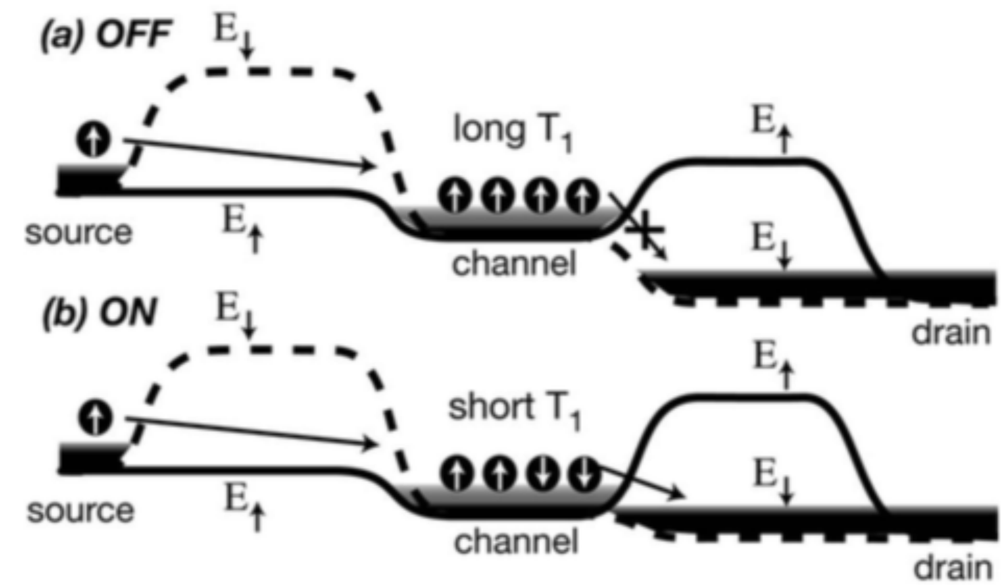
$$E^{on}_{soc}/E^{off}_{soc} = 100$$

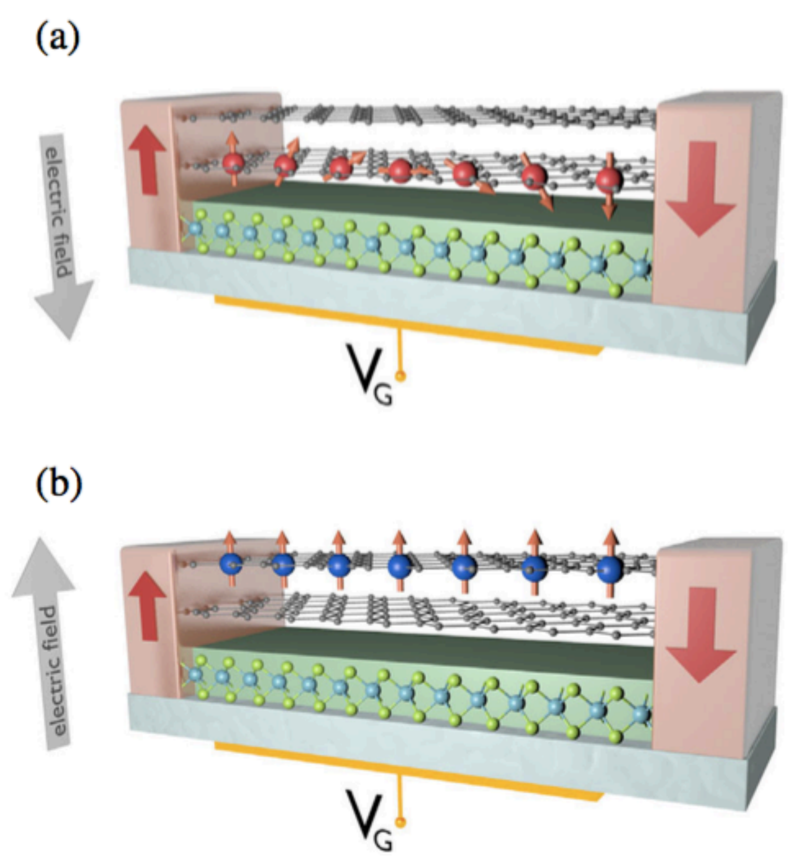
Martin Gmitra and Jaroslav Fabian(2017).PRL

Spin orbit valve

***Bilayer Graphene on Monolayer WSe2 construct spin FET**







For D-P spin relaxation mechanism:

$$\frac{1}{\tau_s} = \Omega^2\tau_p, \tau^{on}/\tau^{off} = 1/10000$$

Martin Gmitra and Jaroslav Fabian(2017).PRL
Kimberley C. Hall(2006),APL

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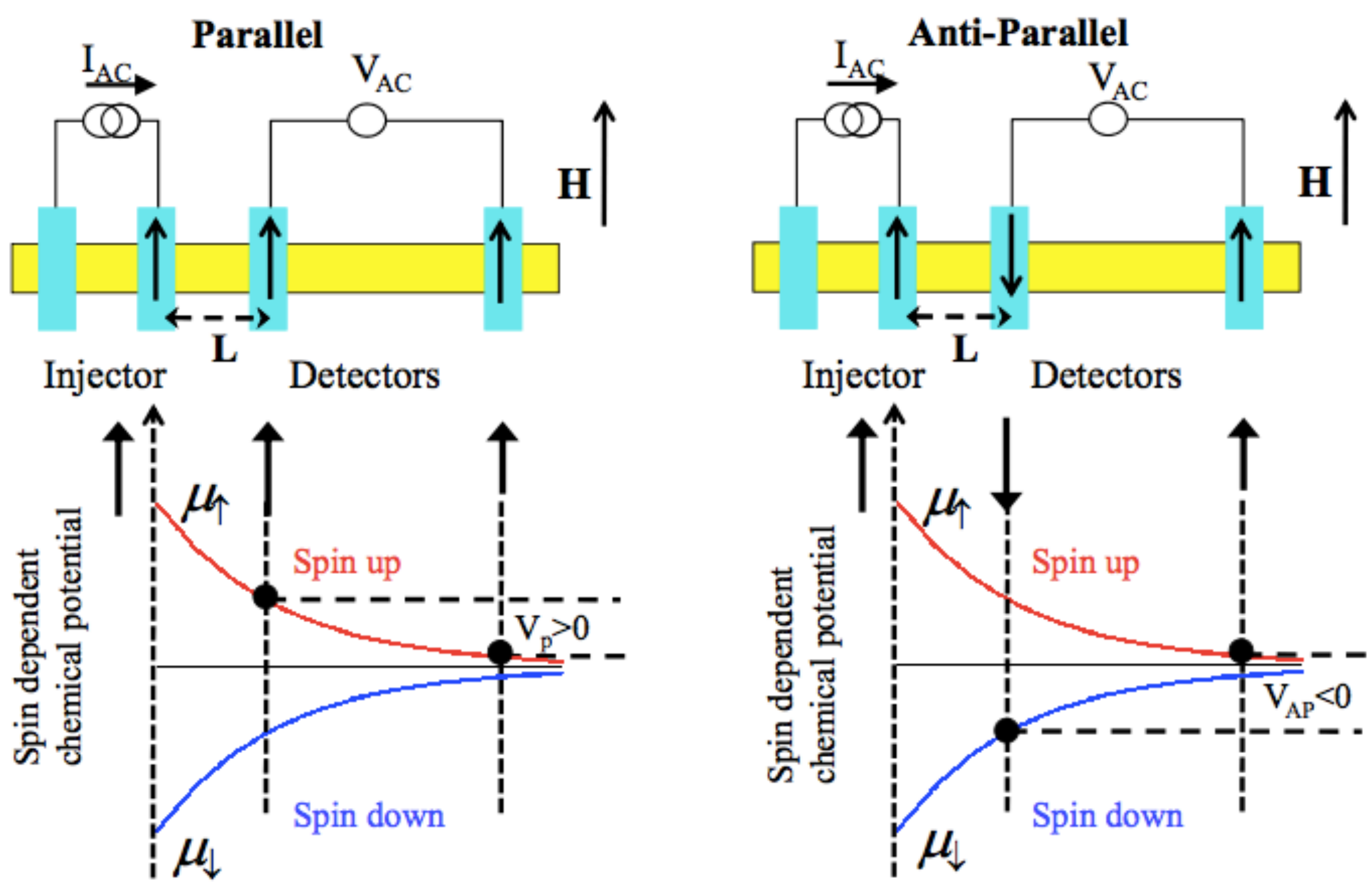
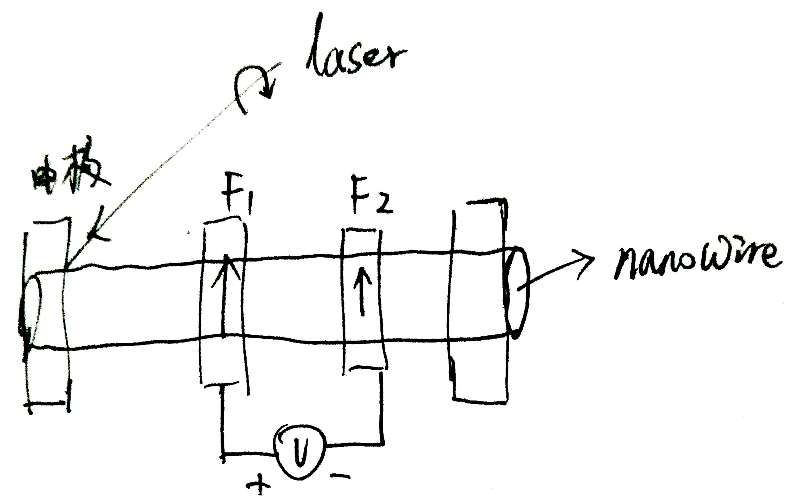
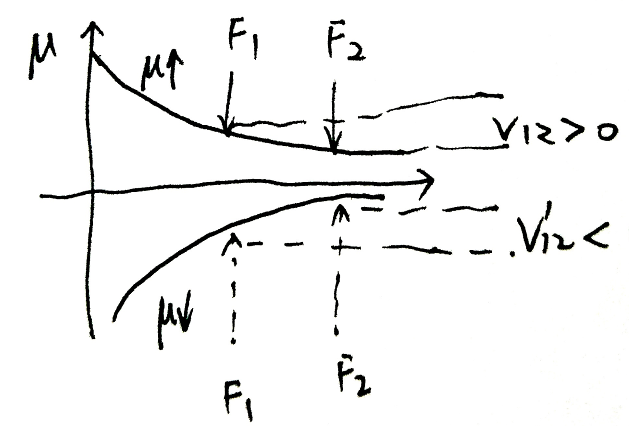
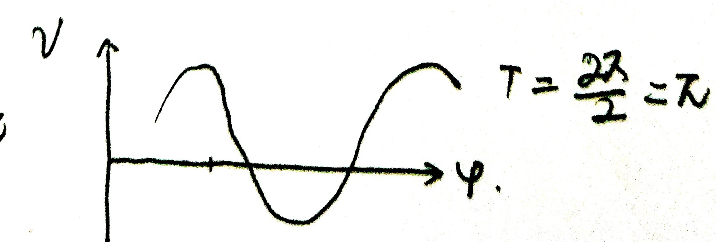
Identify whether the "CPGE" is spin polarized



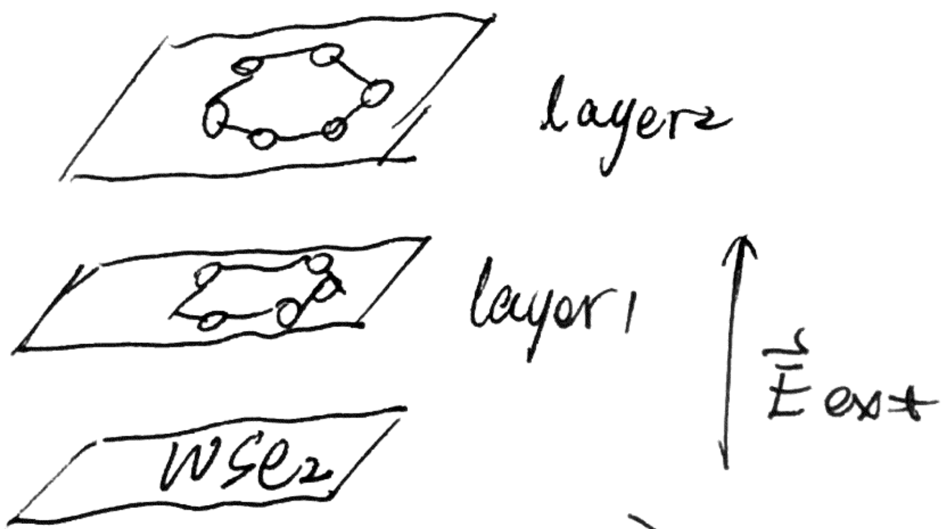




如果自
旋极化



Bilayer Graphene on Monolayer WSe2



Energy band or surface state [ARPES]

Kerr rotation. directly measuring I_s

CPGE measuring

① p-type . n-type

② gate voltage dependence

③ Saturation phenomenon (p-type)

Thanks for your listening!