Graphene-based valleytronics:

Applications in

Quantum Computing / Communications / FETs

G.-Y. Wu

National Tsing-Hua University

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Coworkers: N.-Y. Lue, M.-K. Lee, L. Chang

References

Phys. Rev. B 84, 195463 (2011)

Phys. Rev. B 86, 045456 (2012)

arXiv 1208.0064 (2012)

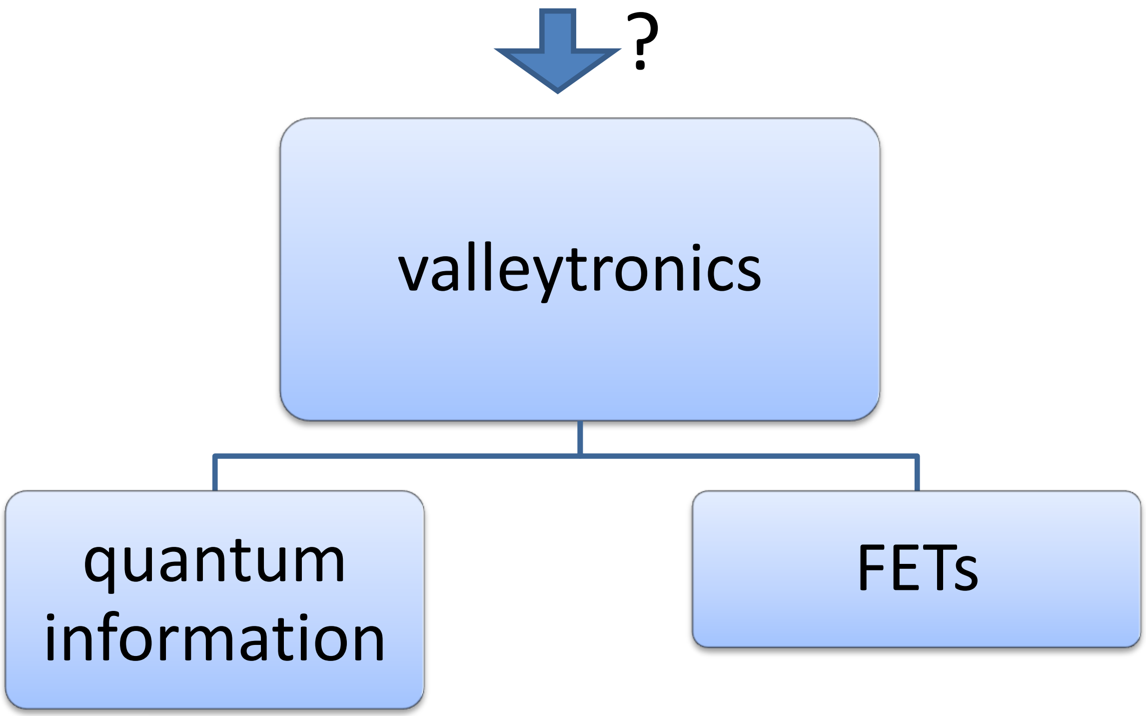
Outline

- **introduction**
  - motivation
  - quantum information
  - FETs
- **graphene-based valleytronics**
  - **graphene basics**
  - **quantum networks**
  - **FETs**
- **summary**

Motivation

- **Si** / **III-V** ------> graphene ?
- spintronics in graphene ?

high spin coherence vs. weak SOI



Quantum Information

- **Benioff, Bennett, Feynman (1980s)**
  . quantum simulations, **Feymann (1982)**
  . factorization of large numbers, **Shor (1994)**
  . quantum search, **Grover (1995)**

- **qubit** - information unit

$|\psi\rangle = \alpha\, |\uparrow\rangle + \beta\, |\downarrow\rangle$ (spin)

$|\psi\rangle = \alpha\, (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) + \beta\, (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$ (decoherence free)

$|\psi\rangle = \alpha\, |\sigma+\rangle + \beta\, |\sigma-\rangle$ (photon)

others ……

QD spin approach

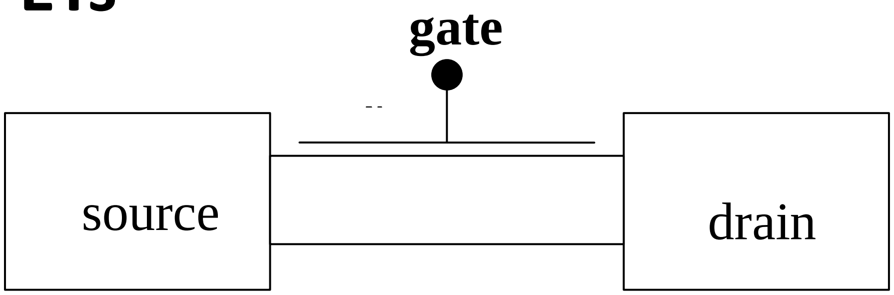
- **Loss, DiVincenzo, Burkard** (1998, 1999)
  spin qubit + qugate ----> universal quantum computing

- **all electrical manipulation**
  Rashba SOI ~ **p** x (**∂**V)·**σ**

- **challenges**
  - g-factor engineering:
    $\Delta g \neq 0$ (computing)
    $g_e = 0$ (communication)
  - spin flip scattering ----> decoherence

FETs

- **standard FETs**



- **post-Si FETs**

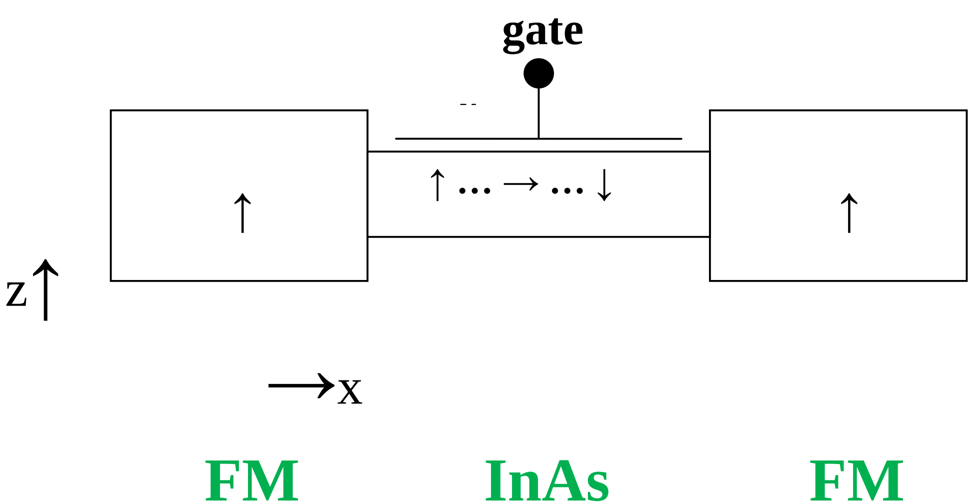
  - graphene-based FETs (Novoselov et al., 2004)
  easier to scale (F. Schwierz, Nature Nanotech. **5**, 487 (2010))

  - spin FETs (Datta & Das, 1990)
  low power consumption

Spin FETs

- **structure**

Rashba SOI ~ $\mathbf{p_x} \times (\partial V)_z \cdot \boldsymbol{\sigma_y}$



- **challenges**

- FM / semiconductor mismatch → tunnel FETs
- spin-flip scattering (σ_x) → stray electric fields

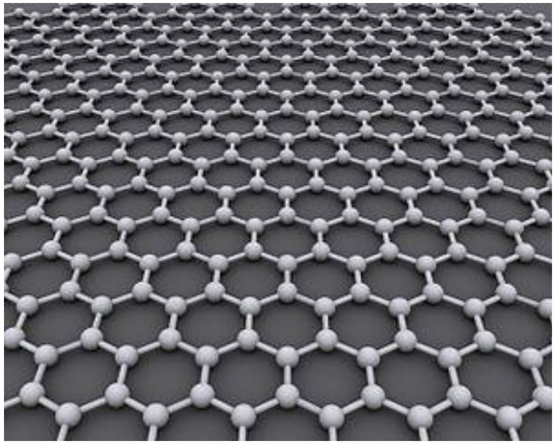
Graphene-Based Valleytronics

- **graphene basics**
- **quantum networks**
  - qubit structure
  - qubit state
  - all-electric manipulation
  - qubit coherence ……
- **FETs**
  - structure
  - lead state / injection / detection
  - all-electric manipulation

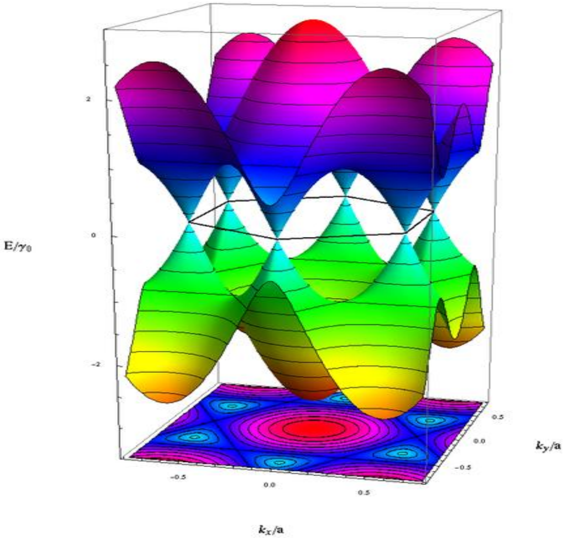
Graphene Basics-1

- **Novoslov, Geim (2004)**

a) crystal → π-bond



b) bands → **K, K' valleys (τ_v = ±)**



Graphene Basics-2

- **graphene on BN or SiC**

$E = \pm(\Delta^2 + v_F{}^2 p^2) \rightarrow$ **massive Dirac particle**

[cp. $E = \pm(m^2c^4 + c^2p^2)$]

$c \rightarrow v_F$

$mc^2 \rightarrow \Delta$

2Δ (energy gap) → QD confinement

Graphene Basics-3

. Schrodinger type description (for E ~ Δ) in ε / B fields (Wu et al., 2011)

nonrelativistic part

$$H^{(0)} = \frac{\vec{\pi}^2}{2m^*} + V + \boldsymbol{\tau}_{\mathrm{v}} \boldsymbol{\mu}_{\mathrm{v0}} \mathbf{B}_{\mathrm{normal}}$$

→ **valley magnetic moment**

$$\mu_{v0} \equiv \frac{e\hbar}{2m^*}$$

Graphene Basics-4

relativistic part (1st order)

$$H^{(1)} = -\frac{1}{2\Delta}\left(\frac{\vec{\pi}^2}{2m^*} + \boldsymbol{\tau}_v \boldsymbol{\mu}_{v0} \mathbf{B}_{\mathrm{normal}}\right)^2 + \boldsymbol{\tau}_v \frac{\hbar}{\mathbf{4m^*\Delta}} (\nabla \mathbf{V}) \times \vec{\pi}$$

$$-\frac{1}{8m^*\Delta}(\vec{p}^2 V).$$

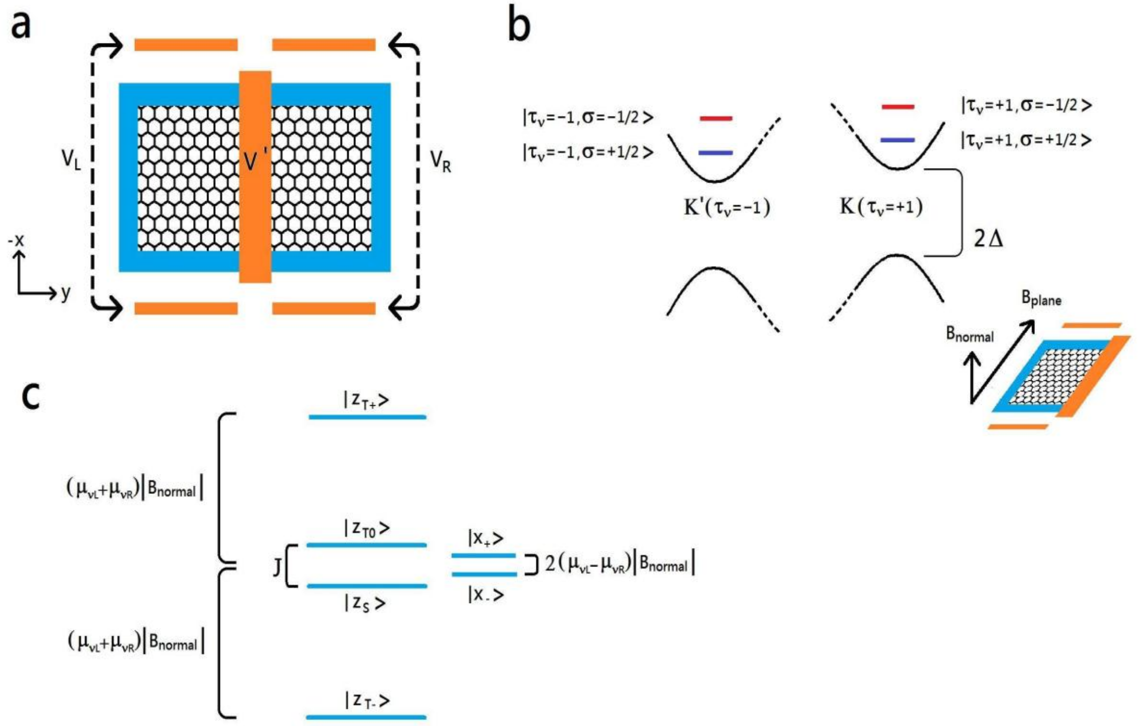
→ valley-orbit interaction ~ $\tau_v(\mathbf{p} \times \partial V)\cdot\mathbf{z}$

cp. spin-orbit interaction ~ $(\mathbf{p} \times \partial V)\cdot\boldsymbol{\sigma}$

Valley-based Quantum Networks

- qubit structure / state
- all-electric single-qubit manipulation
- coherence / initialization / readout / qugate

Qubit Structure / State



two-electron states: $\mathbf{Z_S}$ (isospin = 0) → **logic 0**

$\mathbf{Z_{T0}}$ (isospin = 1) → **logic 1**

Z_{T+}, Z_{T-} (isospin = 1)

Qubit State

- **isomorphism**

valley pair $\leftrightarrow$ spin 1/2

$Z_S \leftrightarrow |\downarrow>$

$Z_{T0} \leftrightarrow |\uparrow>$

$X_- \leftrightarrow |\leftarrow>$

$X_+ \leftrightarrow |\rightarrow>$

$$|Z_S>=\frac{1}{\sqrt{2}}(|K_L K_R'>-|K_L' K_R>),\quad |Z_{T0}>=\frac{1}{\sqrt{2}}(|K_L K_R'>+|K_L' K_R>)$$

$$|X_+>=|K_L K_R'>,\quad |X_->=|K_L' K_R>$$

Effective Interaction

$$H_J = \frac{1}{4} J \vec{\tau}_L \cdot \vec{\tau}_R \qquad \tau_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \tau_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \tau_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$

$$H_Z = -g^* \sigma \mu_B |\mathbf{B}_{total}| + \tau_v \mu_v |\mathbf{B}_{normal}|$$

spin valley

-------->

$$H_{eff} = (\mu_{vL} - \mu_{vR}) B_{normal} \tau_x + \frac{J}{2} \tau_z$$

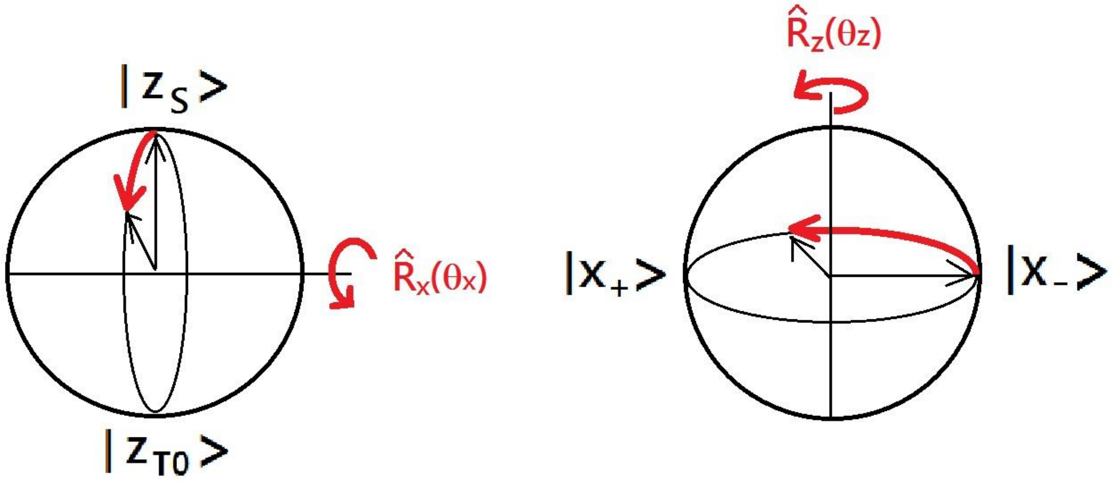
in {0,1} space

Single Qubit Manipulation

- **DC mode (**$B_{normal} \neq 0$**)**

  $\mu_v = \mu_{v0}\,[\,1 - \boldsymbol{O(E-\Delta)/\Delta}\,]$

  → **electric tuning of μ_v in QDs**



$\Omega_x = 2(\mu_{vL} - \mu_{vR})B_{normal}/\hbar$

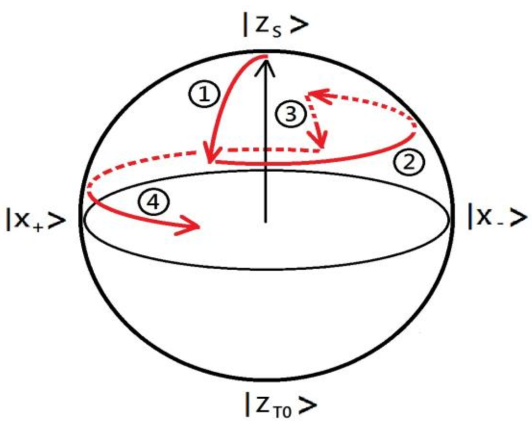
$\Omega_z = J/\hbar$

→ manipulation time ~ O(ns)

Single Qubit Manipulation

- **AC mode**

  ($B_{normal} = 0$**)**



$$|Z_S\rangle \xrightarrow{①} \hat{R}(\theta_x^{(AC)})|Z_S\rangle \xrightarrow{②} \hat{R}(\theta_z=\pi)\hat{R}(\theta_x^{(AC)})|Z_S\rangle$$

$$\xrightarrow{③} \hat{R}(-\theta_x^{(AC)})\hat{R}(\theta_z=\pi)\hat{R}(\theta_x^{(AC)})|Z_S\rangle$$

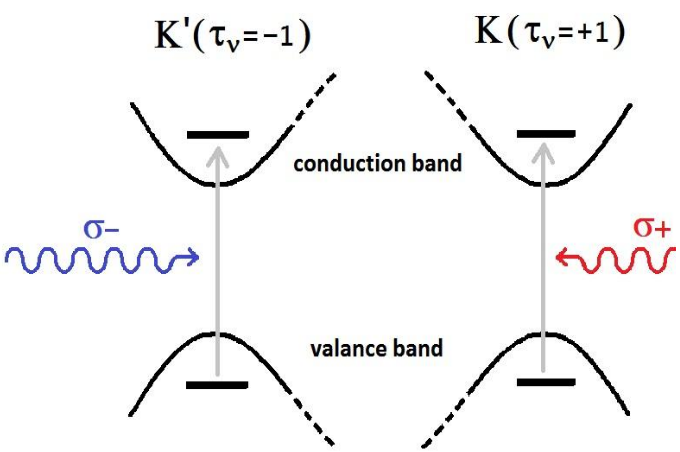
$$\xrightarrow{④} \hat{R}(\theta_z=\pi)\hat{R}(-\theta_x^{(AC)})\hat{R}(\theta_z=\pi)\hat{R}(\theta_x^{(AC)})|Z_S\rangle$$

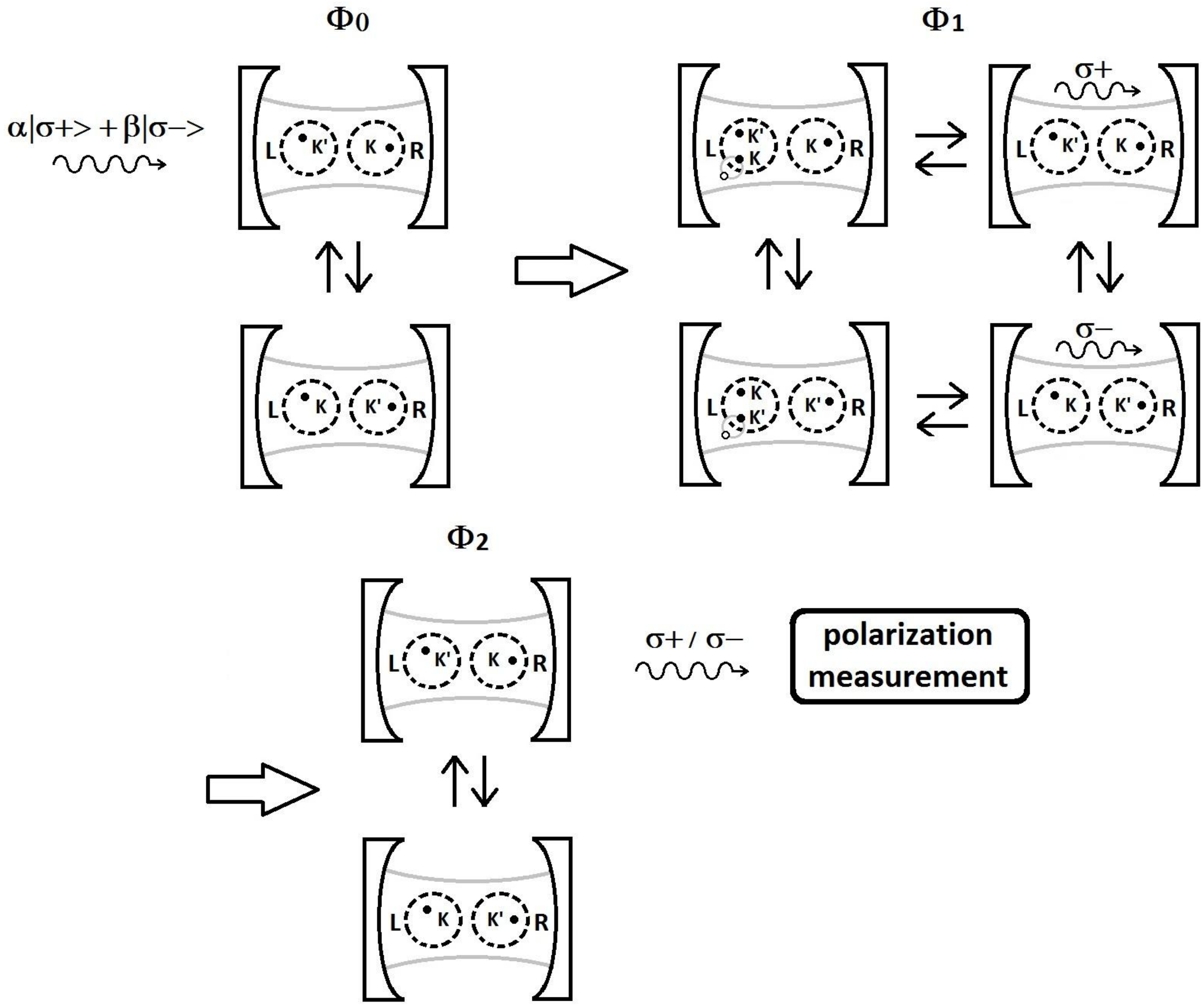
$$\cdots \xrightarrow{\hat{R}(\theta_z^{(target)}+\pi/2)} |\text{target state}\rangle$$

AC Mode

- B_{normal} = 0 **---->** faithful quantum state transfer

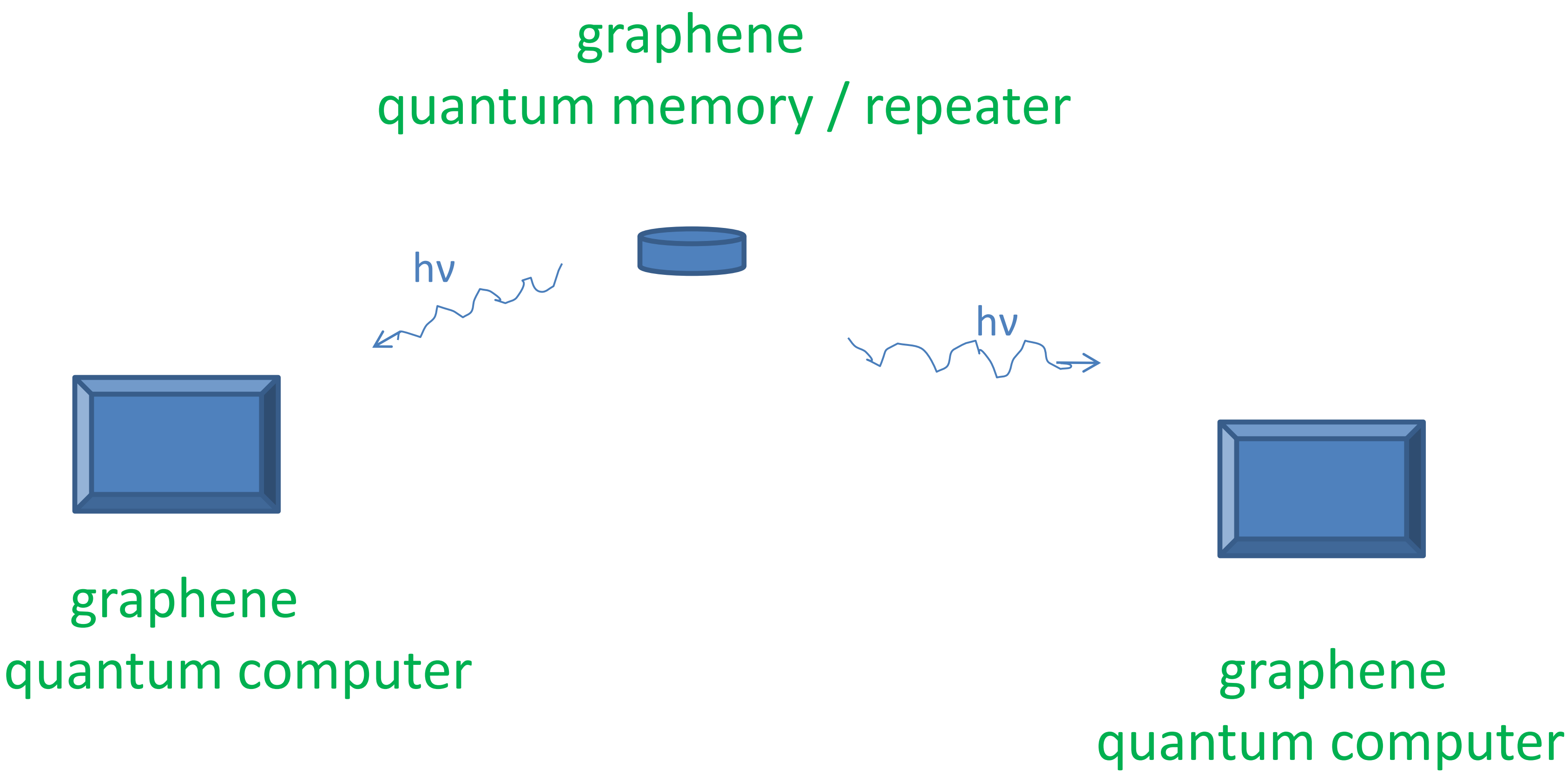
$$\alpha|\sigma+\rangle + \beta|\sigma-\rangle \rightarrow \alpha|K\rangle + \beta|K'\rangle$$





photon → valley pair

Graphene + Photon Quantum Network



Qubit Coherence and Etc.

- **coherence**

  phonon-mediated relaxation:

  L = *dot size* ~ 350A,

  V_0 = *QD potential depth* ~ 70meV,

  B_{normal} = 100mT, T = 10K

  valley relaxation time ~ O(ms)

- **initialization / readout / qugate operation**

  J. M. Taylor et al, *Fault-tolerant architecture for quantum computation using electrically controlled semiconductor spins*, Nature Phys. **1**, 177 (2005)

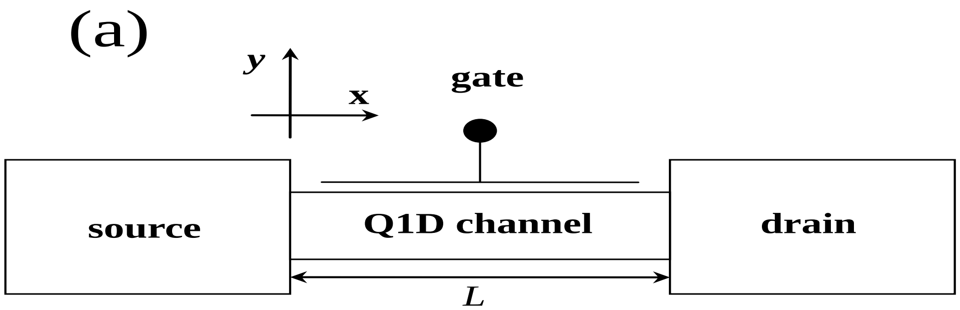
Valley FETs

- structure

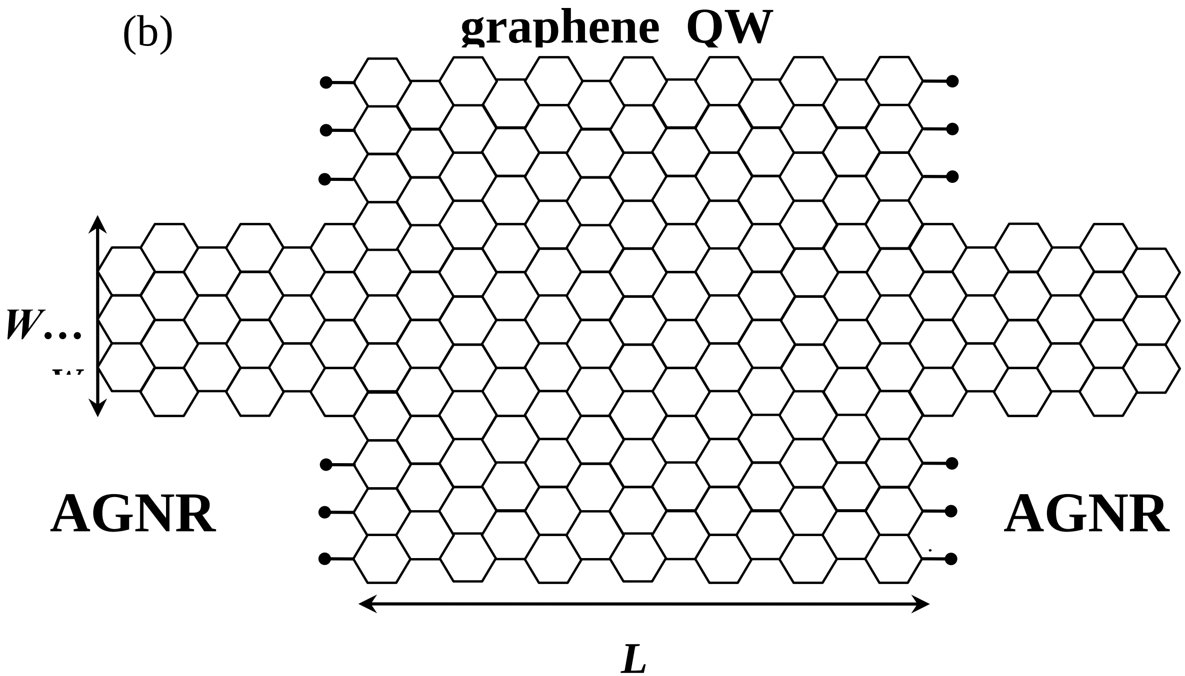
- lead state / injection / detection

- all-electric manipulation

Structure



(a)
y
x
gate
source
Q1D channel
drain
L



(b)
graphene QW
W...
AGNR
AGNR
L

Lead State / Injection / Detection

AGNR solution:

$$\begin{pmatrix} \Psi_A \\ \Psi_B \end{pmatrix} = e^{i\vec{K}\cdot\vec{r}} \psi_{D,+} + e^{i\vec{K}'\cdot\vec{r}} \psi_{D,-}$$

$$\propto \begin{pmatrix} e^{ikx} e^{i\vec{K}\cdot\vec{r}} & S_{K'/K} e^{ikx} e^{i\vec{K}'\cdot\vec{r}} \end{pmatrix} \begin{pmatrix} e^{ik_y y} \\ e^{-ik_y y} \end{pmatrix} \begin{pmatrix} 1 \\ \dfrac{\hbar v_F (k_y - ik)}{2\Delta + E} \end{pmatrix}$$

K' component : K component = $S_{K'/K} = (-1)^{n+1}$

$E = E_n$, $k_y = k_n$,

$(E_n+\Delta)^2 = \Delta^2 + \hbar^2 (k^2 + k_n^2) / 2m^*$,

$k_n = n\pi / W - 4\pi / 3a_0$,

$n = 1$.

All-electric Manipulation

channel state

$$\Phi_0 \approx \begin{pmatrix} e^{ik_+ x} e^{i\vec{K}\cdot\vec{r}} & S_{K'/K} e^{ik_- x} e^{i\vec{K}'\cdot\vec{r}} \end{pmatrix} \begin{pmatrix} \exp(-\beta y^2) \\ \exp(-\beta y^2) \end{pmatrix}$$

K' component : K component

$$= S_{K'/K} e^{i(k_- - k_+)x}$$

“Rashba” Effect

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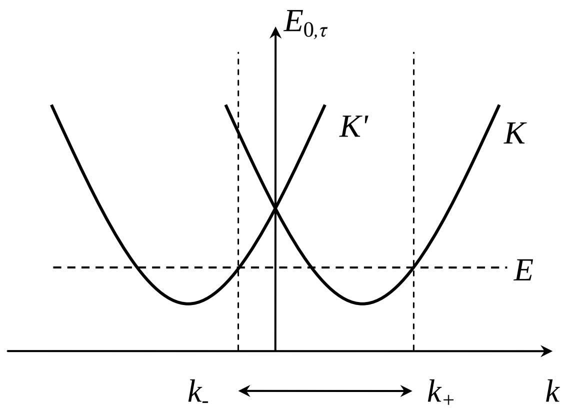
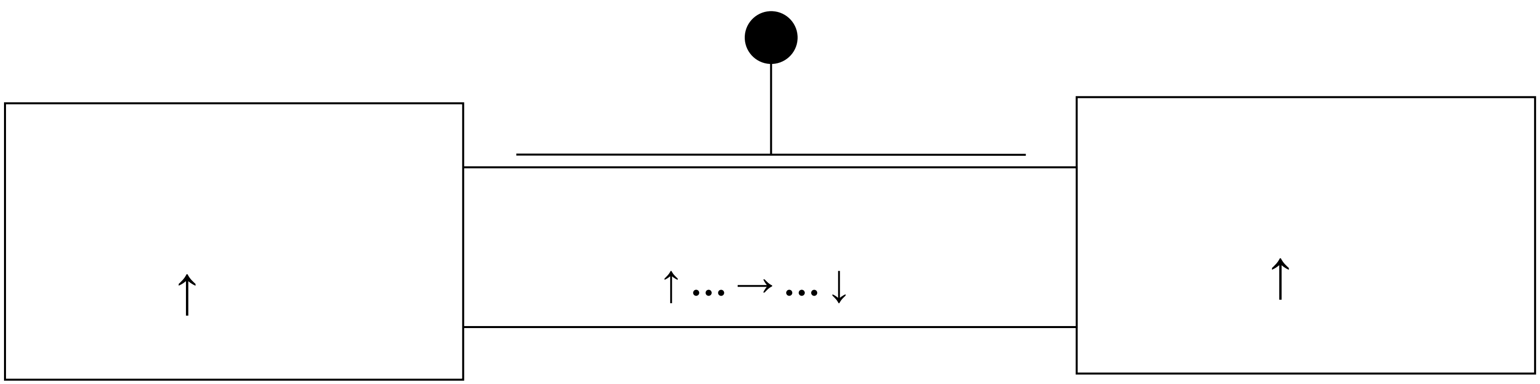
$$k_+ - k_- = \frac{2m^*\alpha_{vo}}{\hbar^2}$$



$$\alpha_{vo} \approx \frac{3e\hbar^3}{2m^{*3}w_0^3\Delta} D\varepsilon_y \approx 6.4\times10^{-12}\, eV\cdot m$$



Valley FET vs. Spin FET

FET	d.o.f.	lead	channel	physical mechanism
valley FET (all graphene)	valley K,K'	AGNR	graphene	VOI
spin FET (hybrid)	spin ↑,↓	FM	semiconductor	Rashba SOI

Summary

- **gated device**

  ---> scalable, all-electric manipulation

- **VOI mechanism** ~ $\tau_v(\mathbf{p} \times \partial V)\cdot \mathbf{z}$

  ---> state coherence / fault tolerant

↓↓

graphene + photon quantum networks

all-graphene valley FETs

↓↓

EXPERIMENTAL REALIZATION ?

☺ Thank You ☺