

QUANTUM DEVICE PHYSICS LABORATORY

(量子元件物理實驗室)

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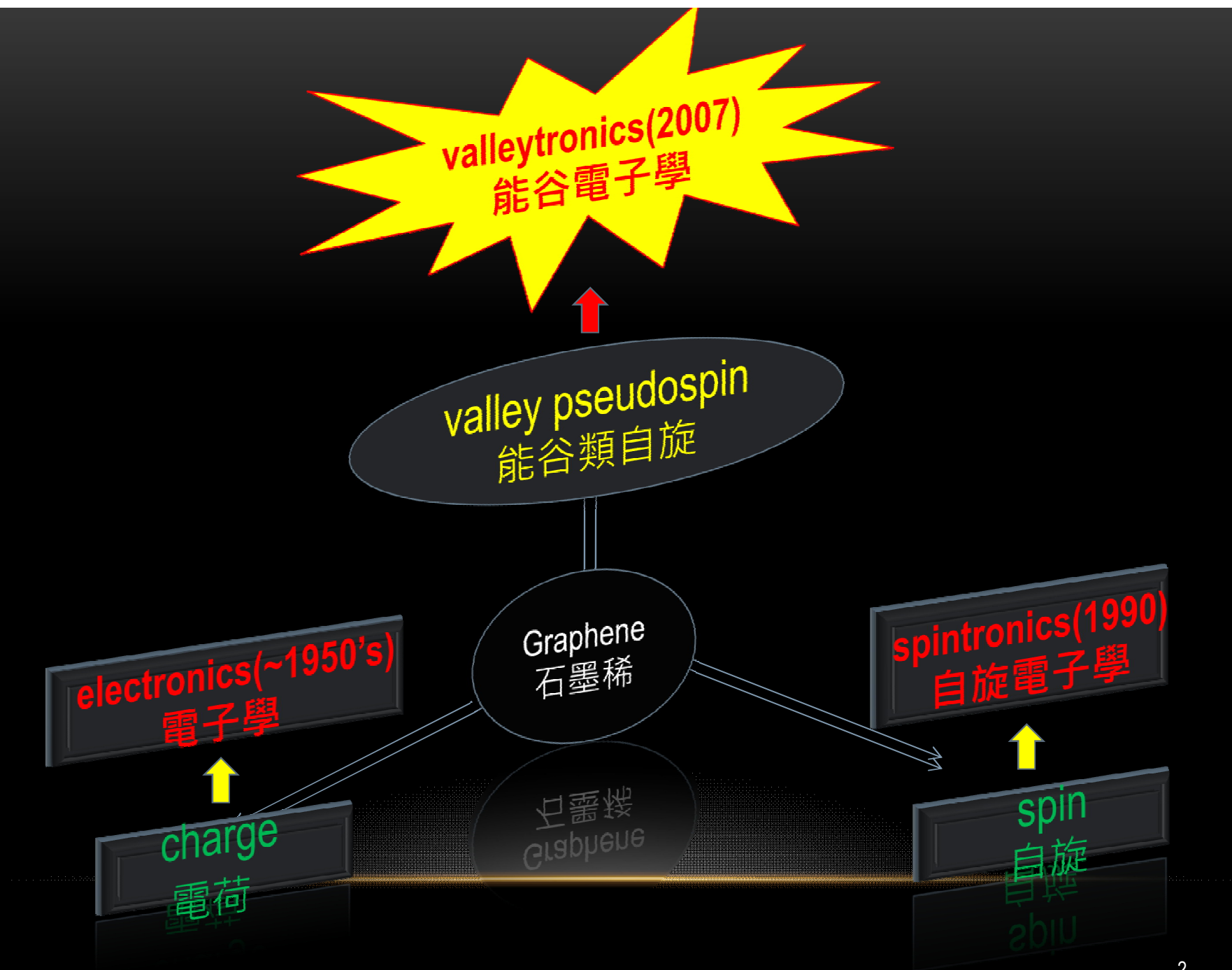
黃輝博(後右二) (H. P. Huang) 彭翰穎 (H. Y. Pang)

實驗室: 量子元件物理實驗室(Quantum Device Physics Laboratory)

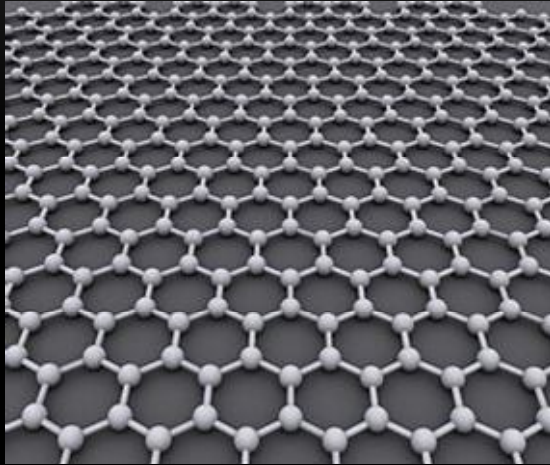
資電館 520A & 520B - 03- 571-5131 轉34019

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GRAPHENE



六角晶格結構

2004年 由英國Manchester大學 Geim & Novoselov 成功從”石墨”中分離出石墨稀(Graphene), 並且證實可以獨立存在。

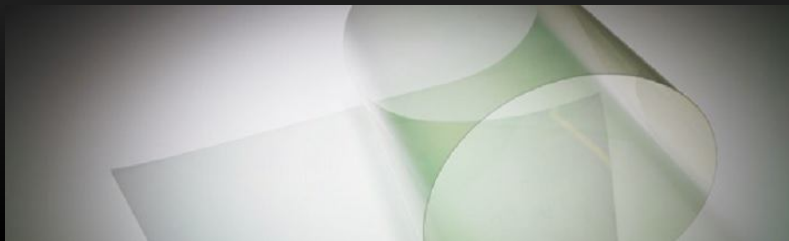


1. 熱傳導係數極高
2. 透光率達 97.7%
3. 電子遷移率 $2 \times 10^5 \text{ cm}^2/\text{V} \cdot \text{s}$
4. 電阻率僅 $10^{-6} \Omega \cdot \text{cm}$
5. 厚度 0.335 nm → 一個碳原子

2010年 榮獲諾貝爾物理獎



GRAPHENE



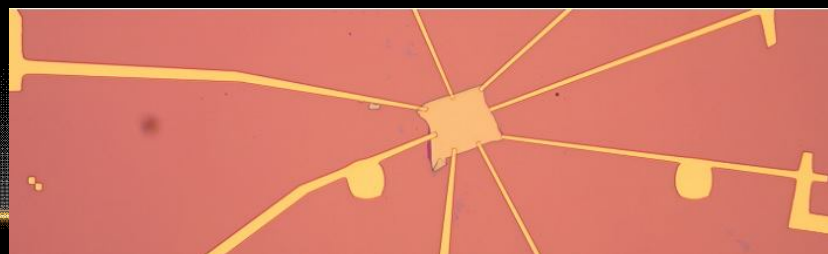
→透明導電薄膜可廣泛應用於光電產業

有望成為下一世代積體電路的材料→

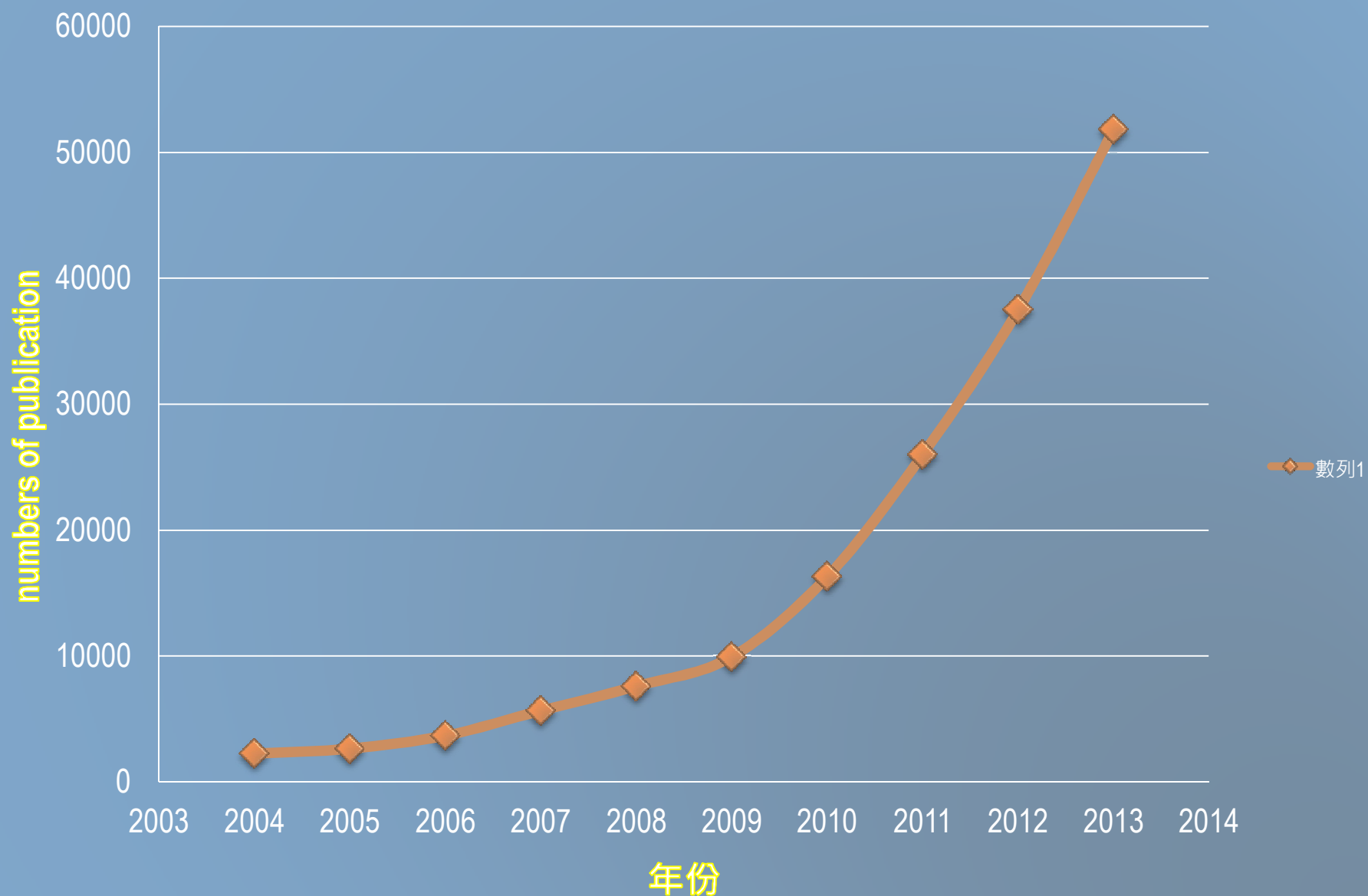


→在太陽能電池領域扮演重要角色

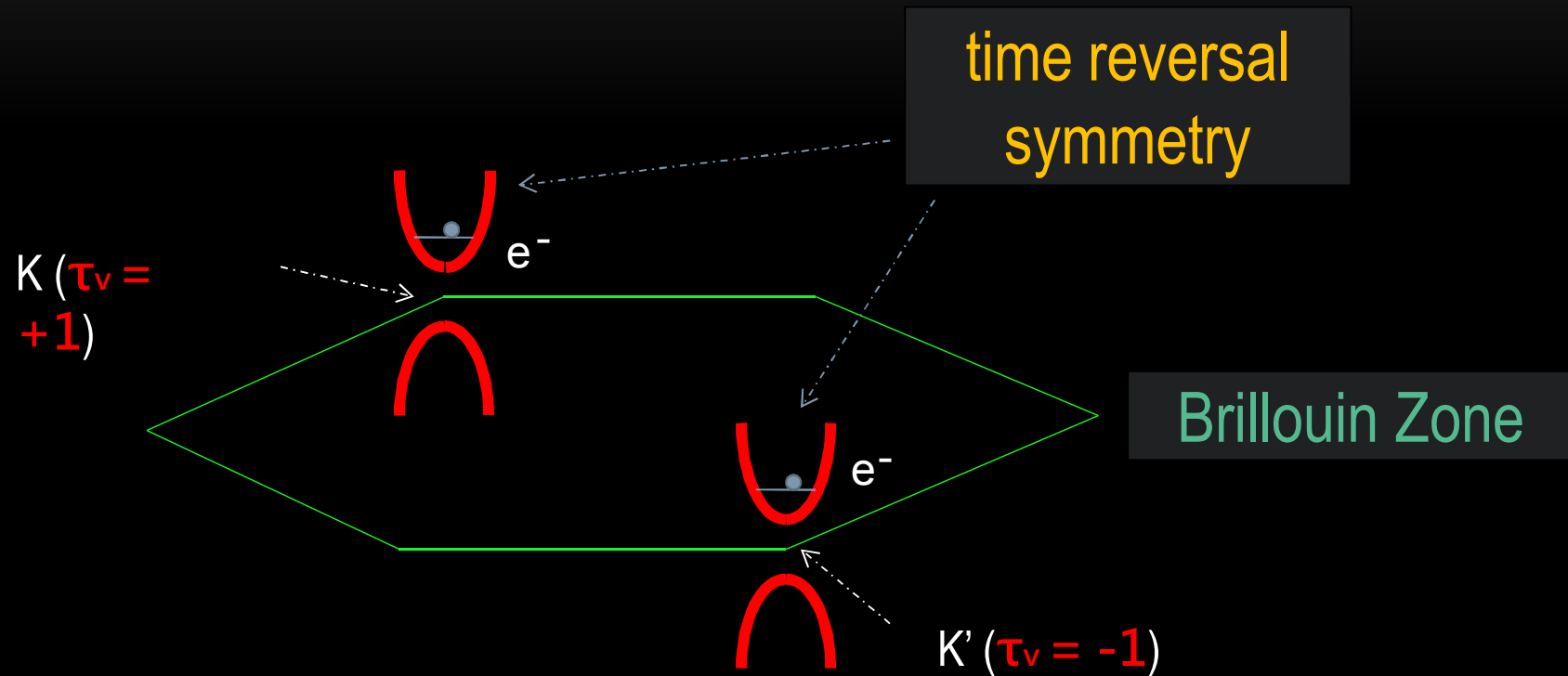
其應用將有助於電子領域發展上的重大突破→



Graphene 相關期刊統計表

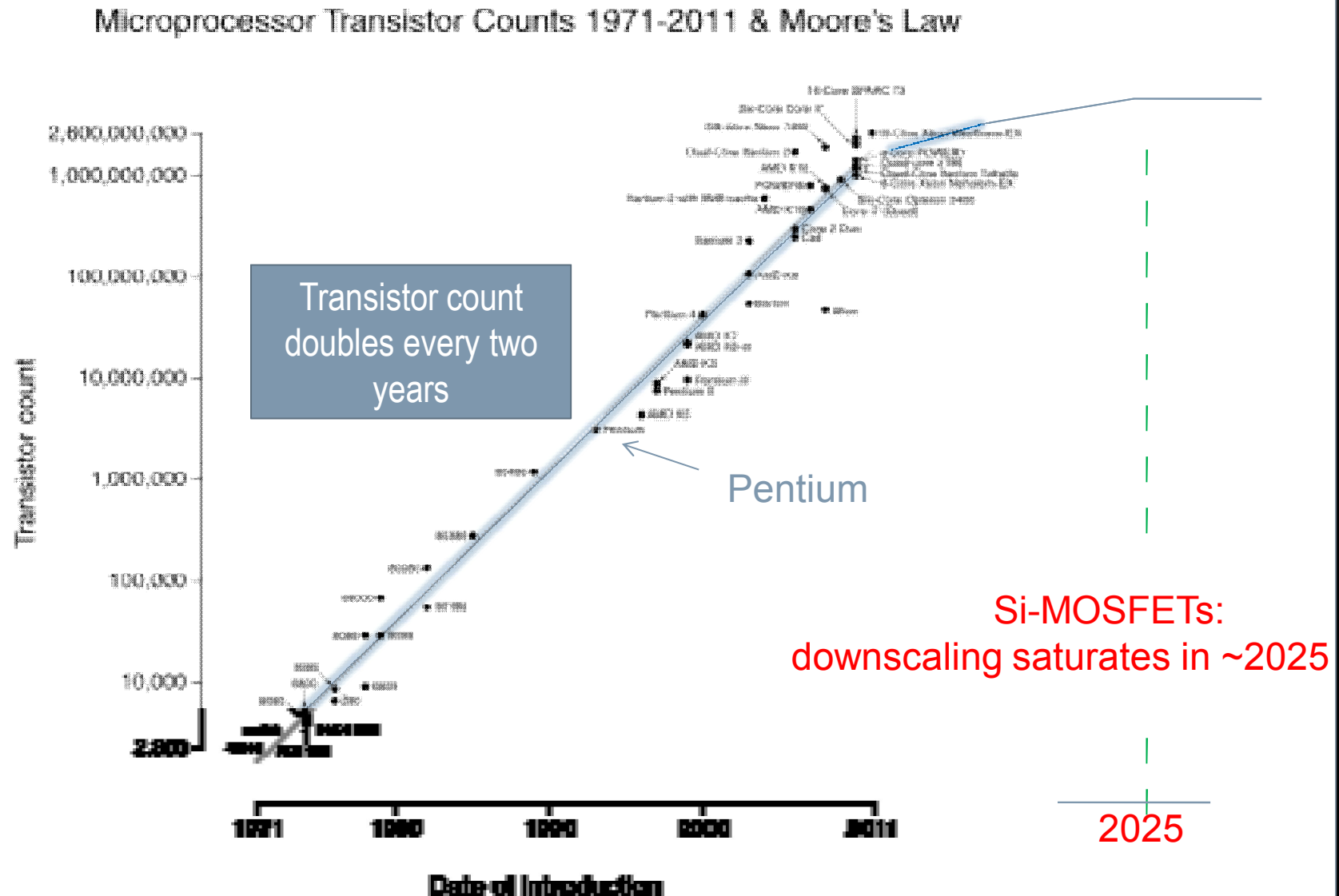


能谷電子學 / 能谷類自旋 (VALLEYTRONICS / VALLEY PSEUDOSPIN)

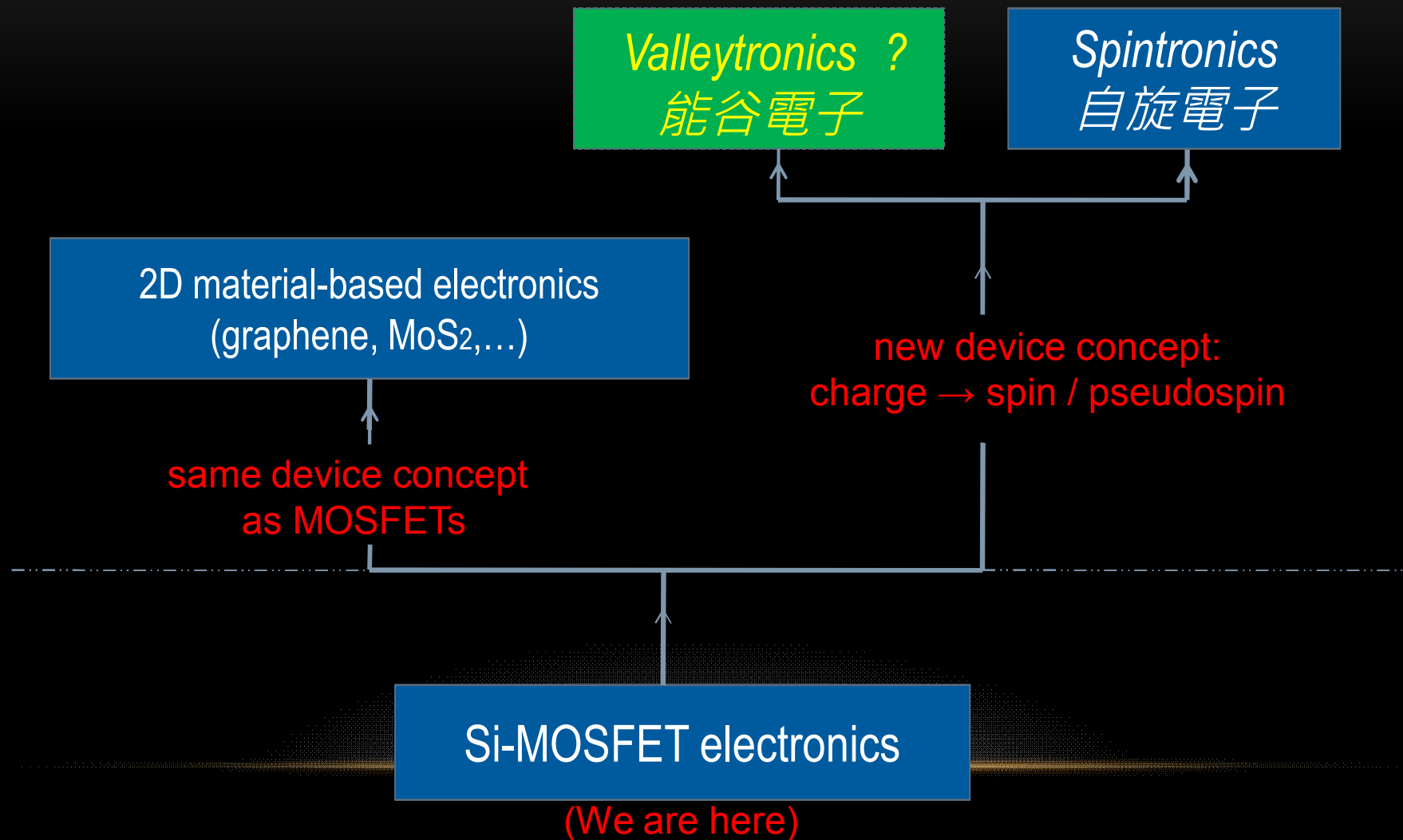


將一顆電子放入Graphene時，只會坐落於 K 或 K' 點
→ 類自旋 (pseudospin)
→ pseudospin-based electronics (能谷電子 - valleytronics)

矽金氧半電晶體 集成趨勢：摩爾定律



POST-SILICON ELECTRONICS ROADMAP



POST-SILICON ELECTRONICS ROADMAP

Survey: Carbon-based Valleytronics

Rycerz et al., Nature Phys. (2007) [**valley filtering**]

(The 1st work in graphene-based valleytronics)

Xiao et al., PRL (2007) [**valley Hall effect**]

Yao et al., PRB (2007) [**valley dependent optoelectronics**]

Palyi et al., PRL (2011) [**valley manipulation in CNTs**]

Gunlycke et al., PRL (2011); Nano. Lett. (2013) [**valley filtering**]

A YOUNG FIELD!

OUR WORKS

- Our works can be separated to two part (Theory and Experiment)

(I) Theory Part

- (1) 元件模擬 (Device Simulation)
- (2) 開發新的能谷電子元件

(II) Experiment Part

- (1) Valley Based FETs
- (2) Valley Based Qubit

(I) Theory Part

等效薛丁格理論 (EFFECTIVE SCHRODINGER THEORY)

- Phys. Rev. B 84, 195463 (2011)

$$\hat{H} = \begin{pmatrix} \Delta + V(\vec{r}) & v_F (\hat{p}_- + eA_-(\vec{r})) \\ v_F (\hat{p}_+ + eA_+(\vec{r})) & -\Delta + V(\vec{r}) \end{pmatrix} \dots \begin{cases} \hat{p}_- = \hat{p}_x - i\tau_v \hat{p}_y \\ \hat{p}_+ = \hat{p}_x + i\tau_v \hat{p}_y \end{cases}, \begin{cases} A_-(\vec{r}) = A_x - i\tau_v A_y \\ A_+(\vec{r}) = A_x + i\tau_v A_y \end{cases}$$



non-relativistic:

$$\hat{H}_0 = \frac{\hat{\pi}^2}{2m^*} + V + \tau_v \mu_{vo} B_{normal}$$

(Zeeman interaction)

$$\mu_{vo} = \frac{e\hbar}{2m^*} (\text{valley magnetic moment})$$

$V = \text{potential potential}$
(due to in-plane $\vec{\epsilon}$)

relativistic (1st order):

$$\hat{H}^{(1)} = -\frac{1}{2\Delta} \left(\frac{\vec{\pi}^2}{2m^*} + \tau_{vo} \mu_{vo} B_{normal} \right)^2$$

$$+ \tau_v \frac{\hbar}{4m^* \Delta} \vec{\epsilon} \times \vec{\pi} \cdot \hat{z} \quad (VOI)$$

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

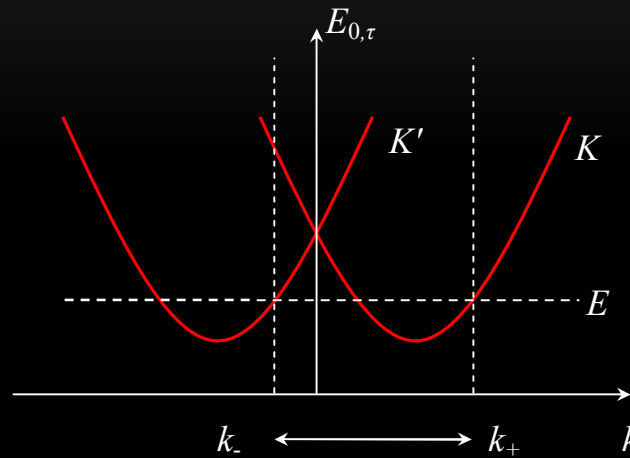
能谷電晶體 (VALLEY FETS)

- Phys. Rev. B 86, 165411 (2012), Phys. Rev. B 87, 039904 (2013)

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

→

$$\delta\phi = (k_+ - k_-)L = \frac{2m^* \alpha_{vo}}{\hbar^2} L$$



$$\alpha_{vo} \approx \frac{6e\hbar^3}{m^{*4}w_0^5\Delta} D\delta\epsilon \approx 5.4 \times 10^{-12} \text{ eV} \cdot \text{m}$$

Lateral electric field

$|K\rangle + |K'\rangle$
(Brey et al.)

$\exp(i\phi/2) |K\rangle + \exp(-i\phi/2) |K'\rangle$

$|K\rangle + |K'\rangle$

$\phi = \begin{matrix} 2n\pi & (2n+1)\pi \\ \text{ON} & \text{OFF} \end{matrix}$

不同種類的量子位元 (TYPES OF QUBIT)

1.
$$|\psi\rangle = \overset{0}{\alpha} |\uparrow\rangle + \overset{1}{\beta} |\downarrow\rangle \quad (\text{one spin})$$
2.
$$|\psi\rangle = \alpha \overset{0 \text{ (S)}}{(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)} + \beta \overset{1 \text{ (T}_0\text{)}}{(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)}$$

(decoherence free)
3.
$$|\psi\rangle = \overset{0}{\alpha} |\sigma+\rangle + \overset{1}{\beta} |\sigma-\rangle \quad (\text{photon})$$

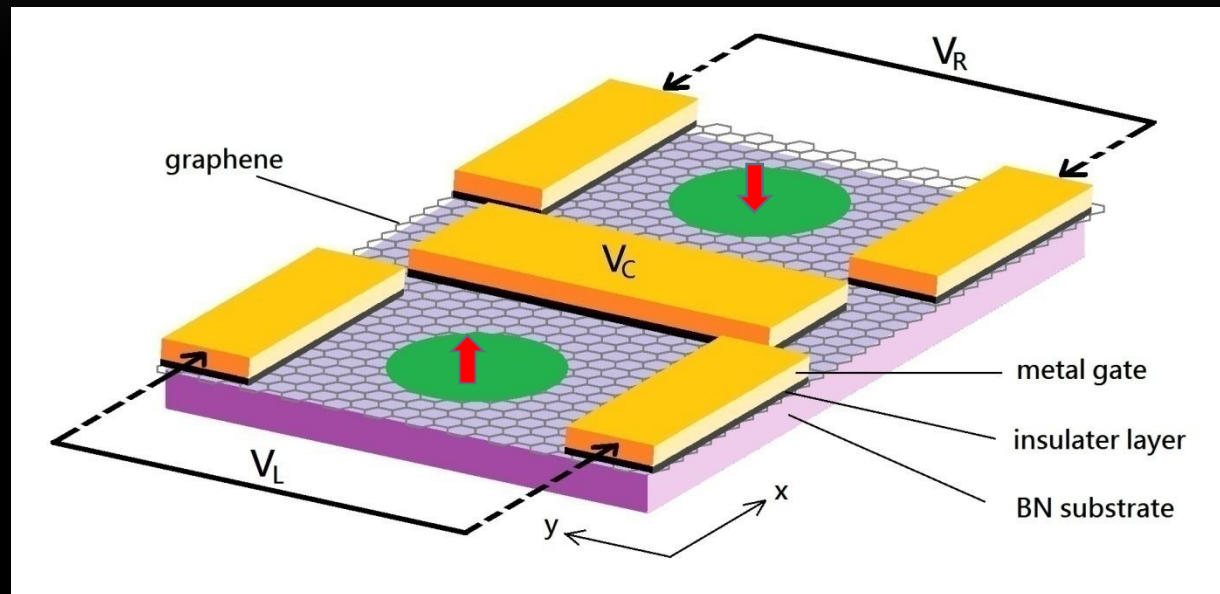
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能谷量子位元 (VALLEY QUBIT)

- Phys. Rev. B 84, 195463 (2011), Phys. Rev. B 86, 045456 (2012)



two pseudospins

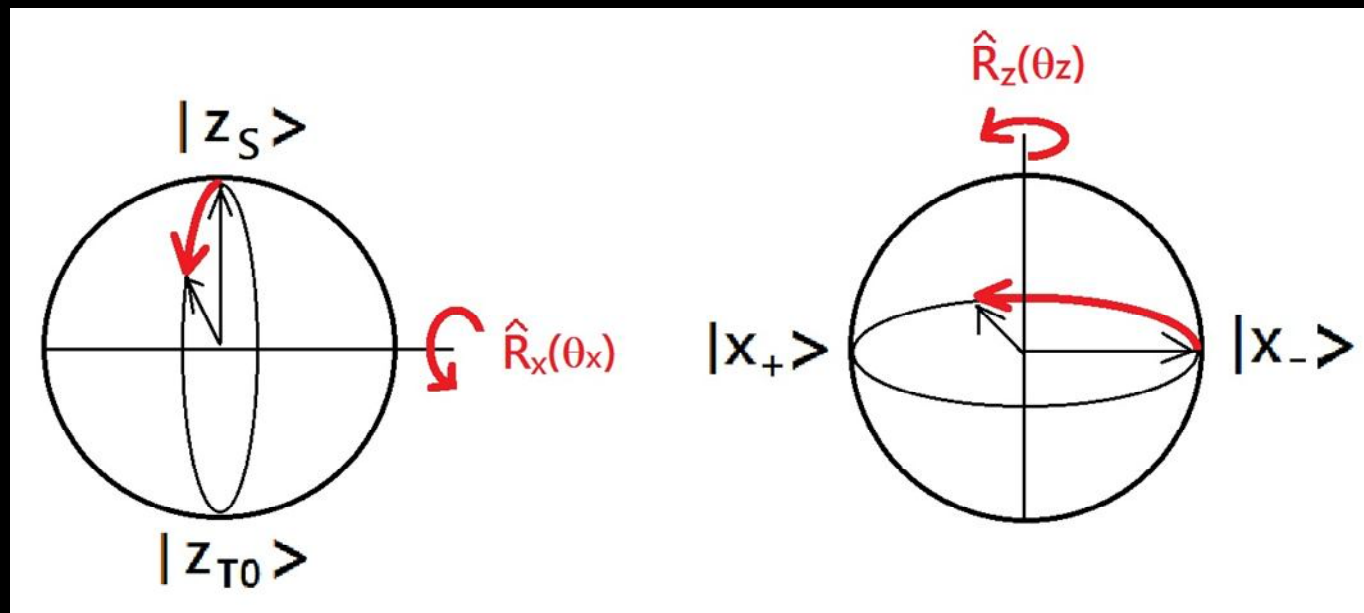
pseudospin singlet (S)/ triplet states (T₀):

$$|\uparrow_L \downarrow_R\rangle \pm |\downarrow_L \uparrow_R\rangle \rightarrow 0, 1$$

能谷量子位元 (VALLEY QUBIT)

- Phys. Rev. B 84, 195463 (2011), Phys. Rev. B 86, 045456 (2012)

Two-pseudospin manipulation



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

$$\Omega_z = J / \hbar$$

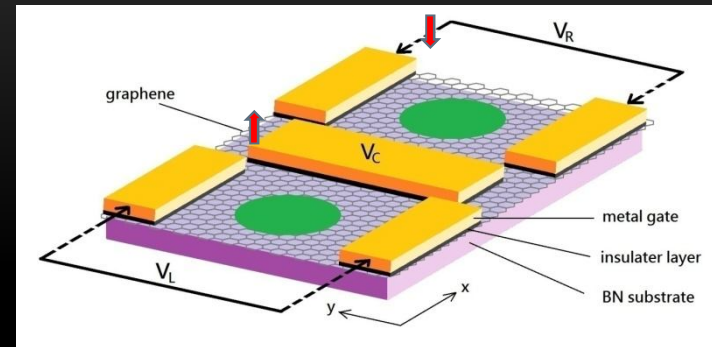
→ manipulation time $\sim O(\text{ns})$

能谷量子位元 (VALLEY QUBIT)

ELECTRICAL QUBIT MANIPULATION

(PRB 84, 195463 (2011); B 86, 045456 (2012))

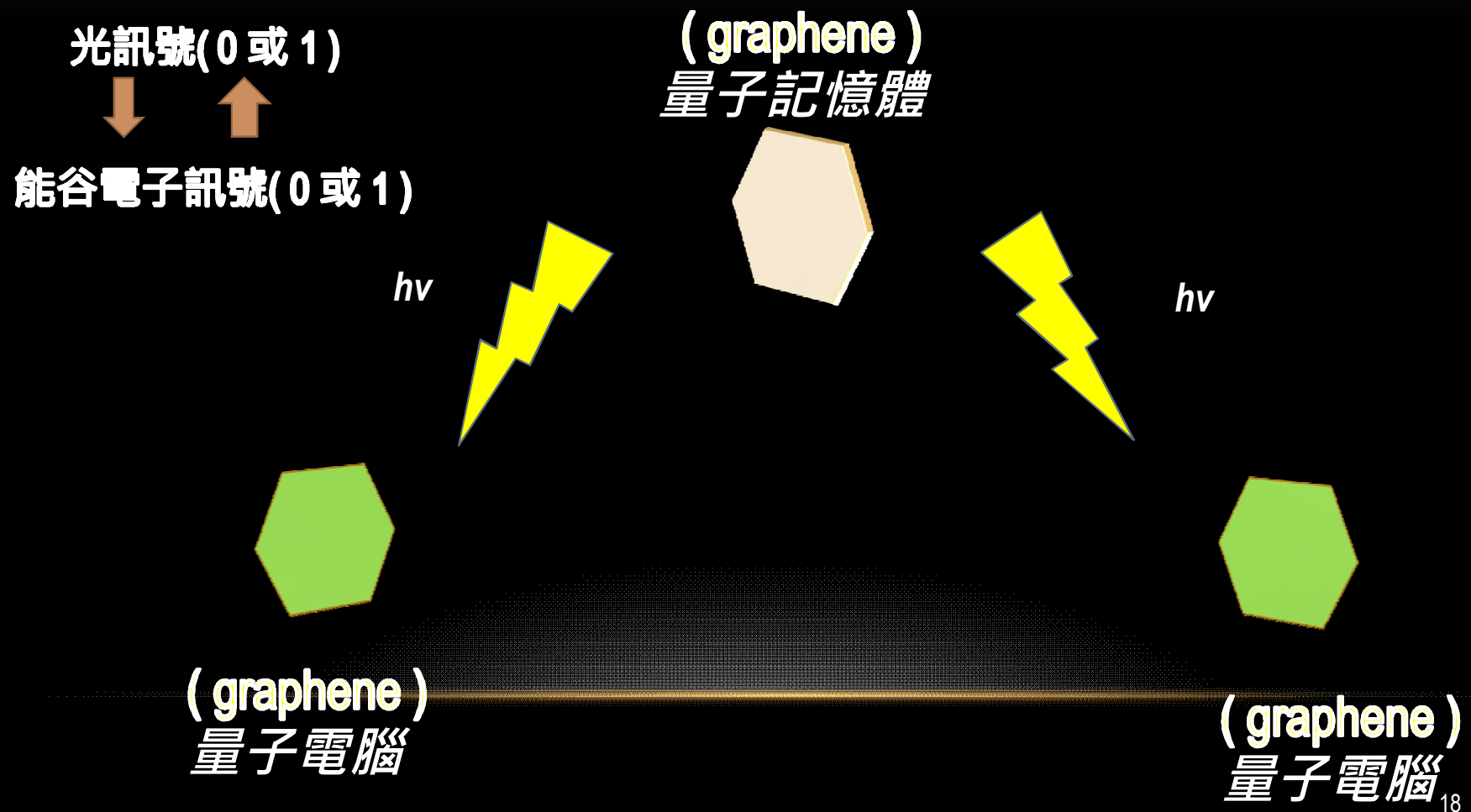
- Two effects for electrical control
exchange: $J \tau_{vL} \tau_{vR}$ ($J \sim t/U \rightarrow$ control: V_C)
contrasting phases in QDL, QDR (control: V_L, V_R)
- Two modes of manipulation
 $B_{\text{normal}} \neq 0$ (for computing)
 $B_{\text{normal}} = 0$ (for communications)



B_{normal}

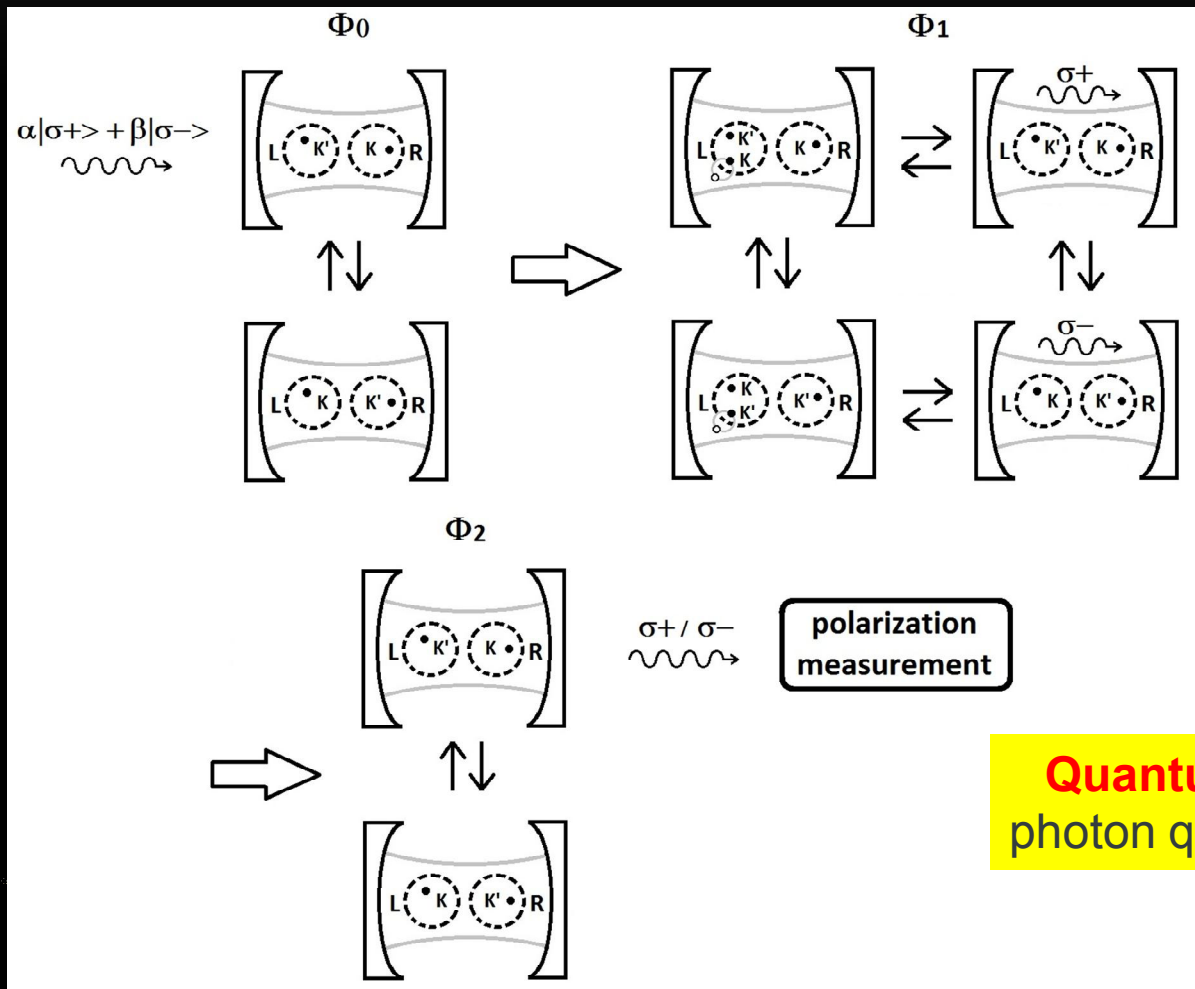
量子網路 (QUANTUM COMMUNICATION)

- Phys. Rev. B 86, 045456 (2012)



量子網路 (QUANTUM COMMUNICATION)

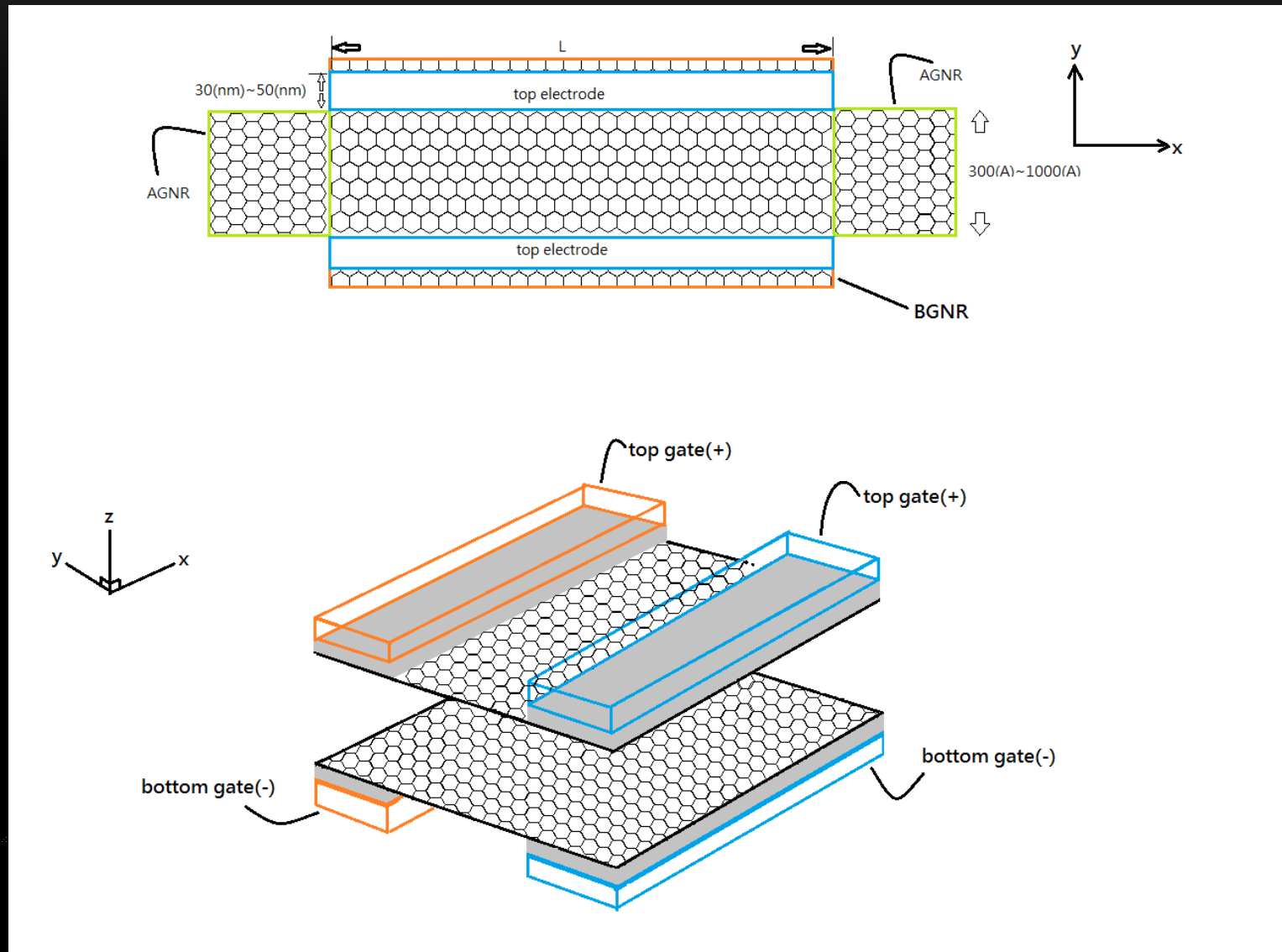
- Phys. Rev. B 86, 045456 (2012)



Quantum State Transfer:
photon qubit $\rightarrow$ valley qubit

(II) Experiment Part

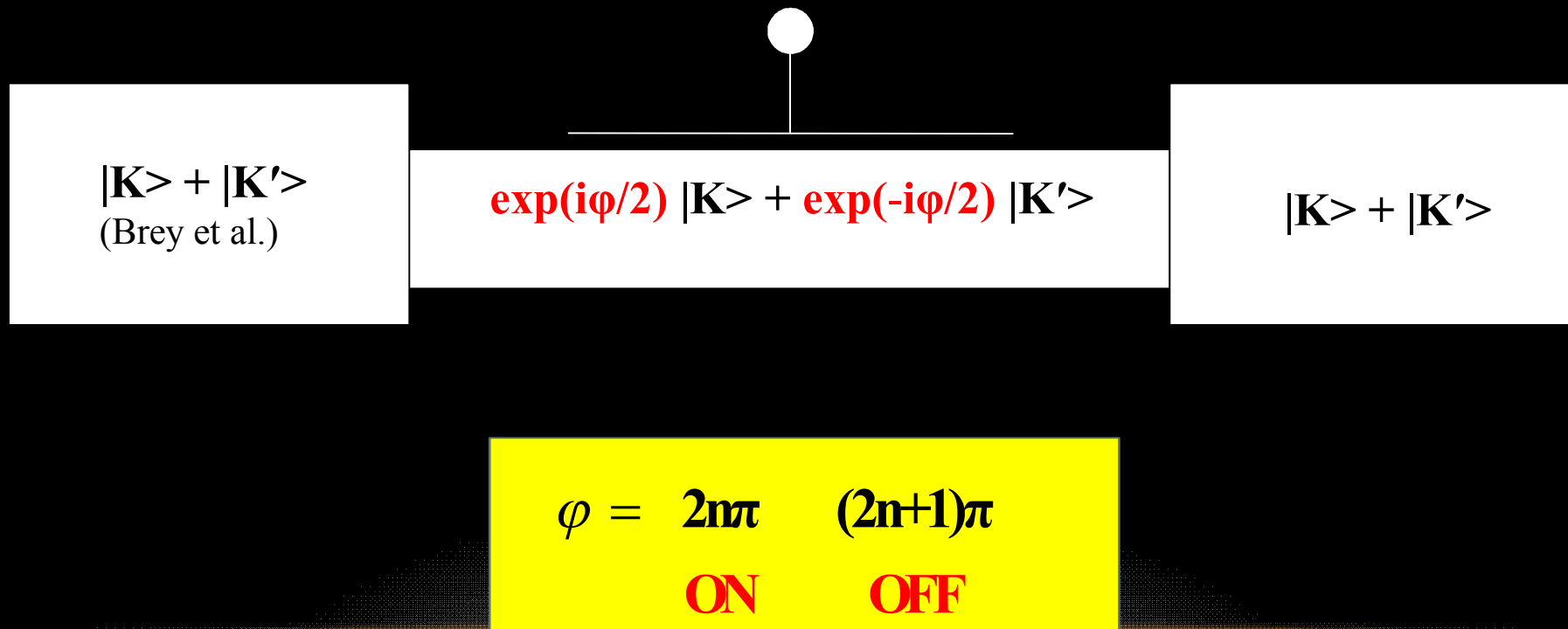
能谷電晶體 (VALLEY FETS) – 現在實行中



能谷電晶體 (VALLEY FETS)

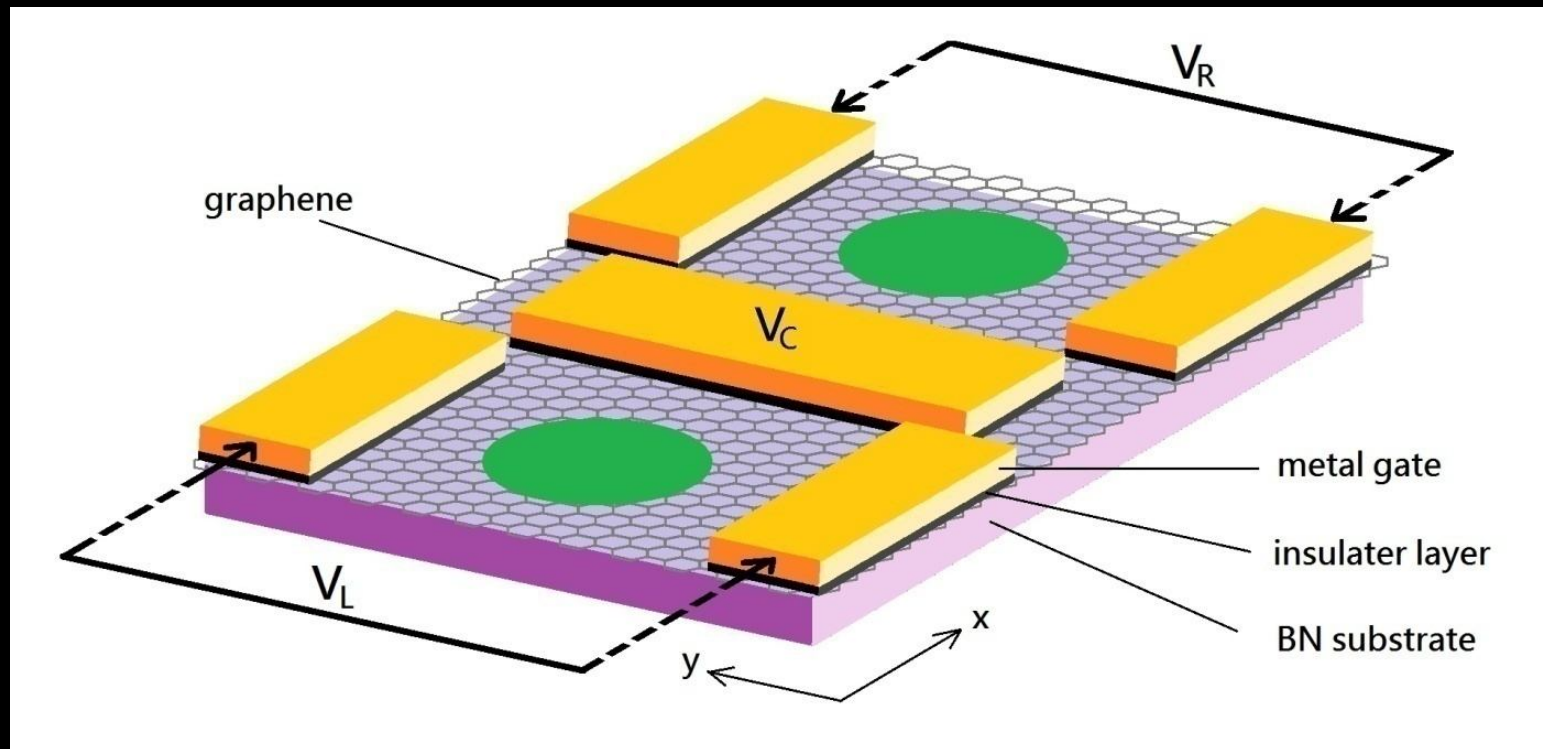
- Phys. Rev. B 86, 165411 (2012), Phys. Rev. B 87, 039904 (2013)

加入側向電場作為開關使用



能谷量子位元 (VALLEY QUBIT) – 未來即將實現

- Phys. Rev. B 84, 195463 (2011), Phys. Rev. B 86, 045456 (2012)



能谷電晶體 (VALLEY FETS) – 現在實行中

優點：

- (1) 耗電量低，並且可以集成使用
- (2) 有望成為下一世代的電晶體

能谷量子位元 (VALLEY QUBIT) – 未來即將實現

優點：

- (1) 適合集成
- (2) 操作時間快

實驗合作關係

量子元件物理實驗室
清華大學電子工程所
吳玉書 老師

提供理論模型、實驗
裝置構想，並派遣人
力至兩大實驗室合作

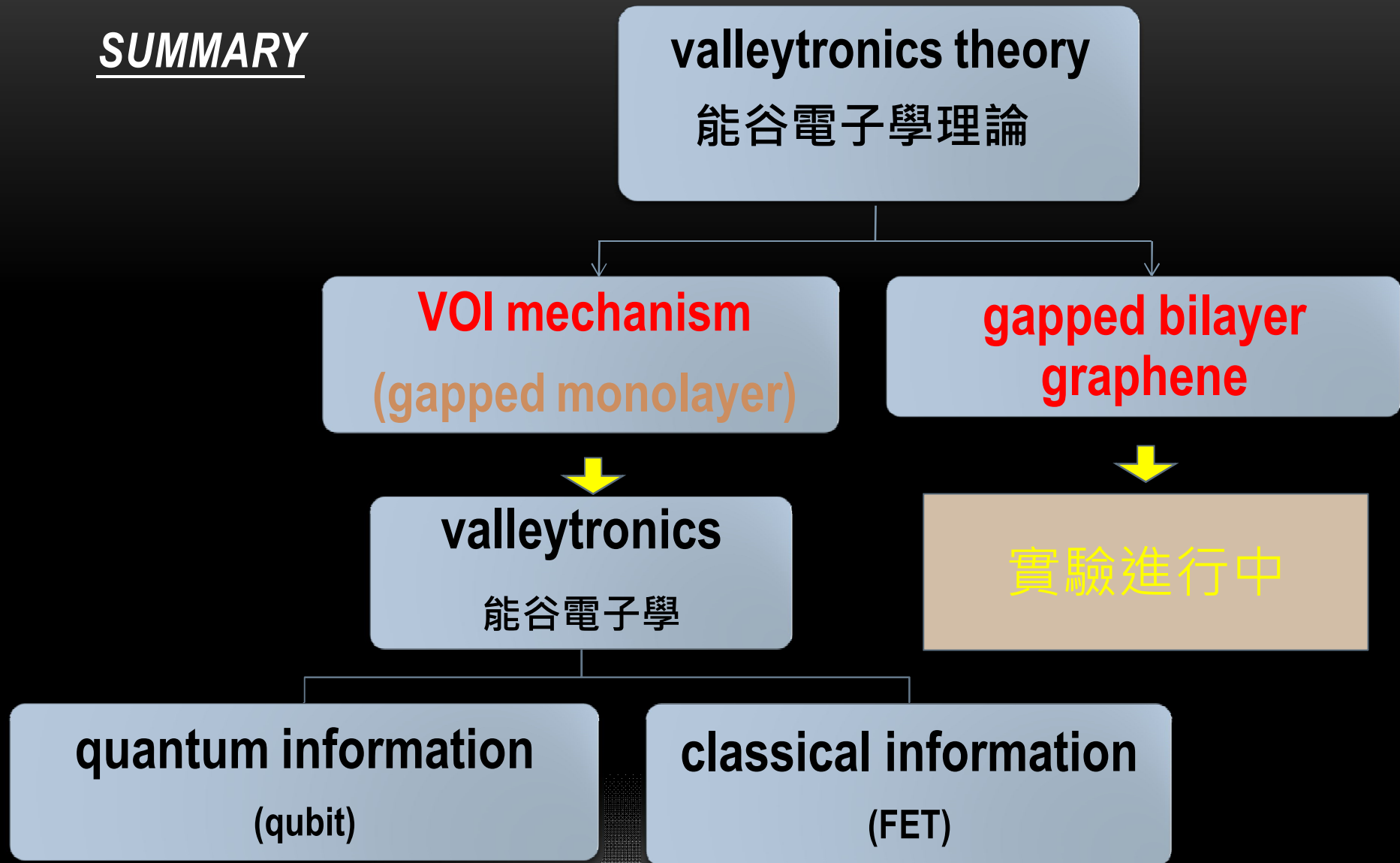
奈米電子實驗室
清華大學電子工程所
邱博文 老師

量子電子元件實驗室
中央研究院物理所
陳啟東 老師

Graphene樣品成長、元件裝置製作

低溫量測能谷軌道交互
作用(VOI)之效應

SUMMARY



PUBLICATION:

近三年(2011~2013)來，Graphene相關期刊的發表如下

1. Phys. Rev. B 84, 195463 (2011) – Quantum Computing/Manipulation
2. Phys. Rev. B 86, 045456 (2012) – Quantum Communication
3. Phys. Rev. B 86, 165411 (2012) – Valley FETs
4. Phys. Rev. B 87, 039904 (2013) – Valley FETs (variation gap)
5. Phys. Rev. B 88, 125422 (2013) – Bilayer Gapped Graphene

Thanks for your attention