清華大學物理系 奈米物理特論 2011/0407 上課內容 （III）

半導體奈米結構之成長與光電特性

交通大學電子物理系　周武清 教授

大綱:

Part I:　半導體奈米結構成長---------
分子束磊晶(MBE, molecular beam epitaxy)
半導體奈米結構形貌研究---AFM

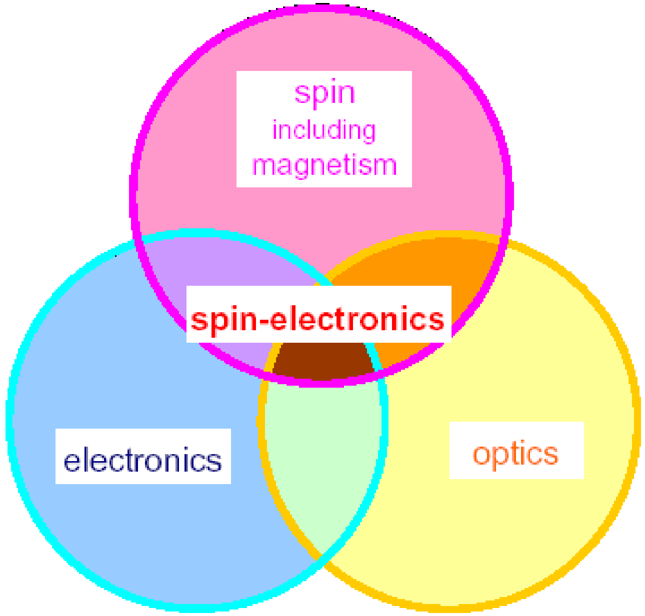
Part II:　半導體奈米結構光電特性---Photoluminescence

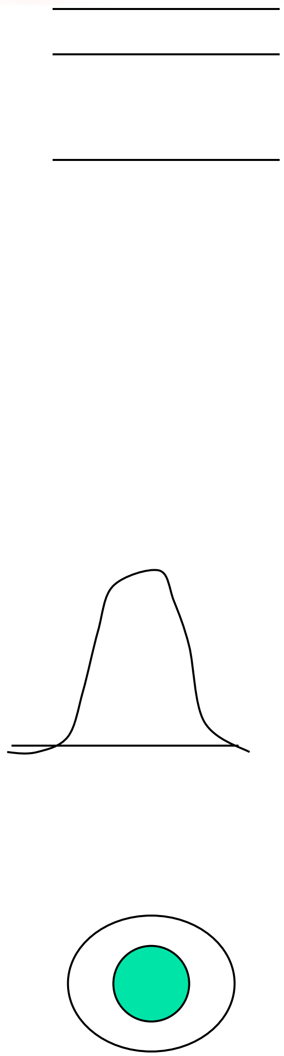
Part III: 半磁性半導體奈米結構之自旋磁光特性

What is "Spin"?
How to manipulate spin?
How can we use "spin" to fabricate useful devices?

Outline

1. Introduction to II-VI diluted magnetic semiconductor (DMS) quantum dots (QDs).
   (比較III-V magnetic semiconductors)
2. Growth, structure and band alignment of ZnMnTe QDs.
3. Circular polarization measurement and spin dynamics.
4. Devices for spintronics
5. Conclusion.

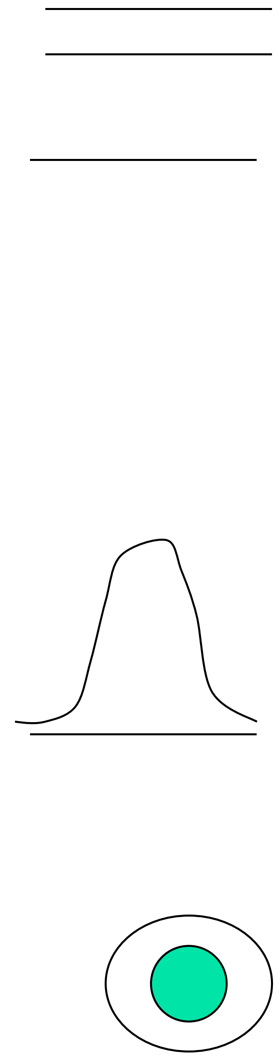




n=2

n=1

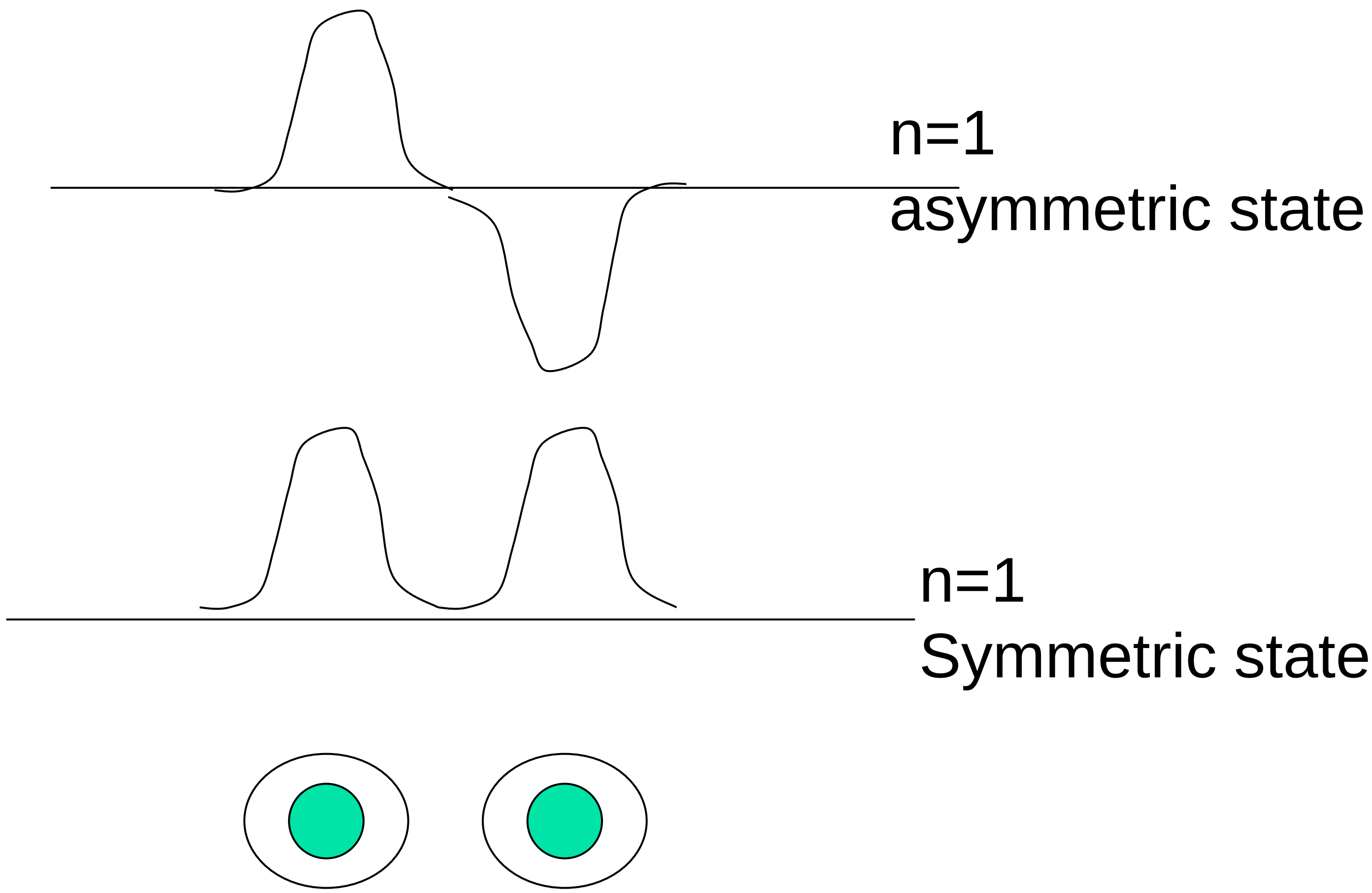
Isolated hydrogen atom

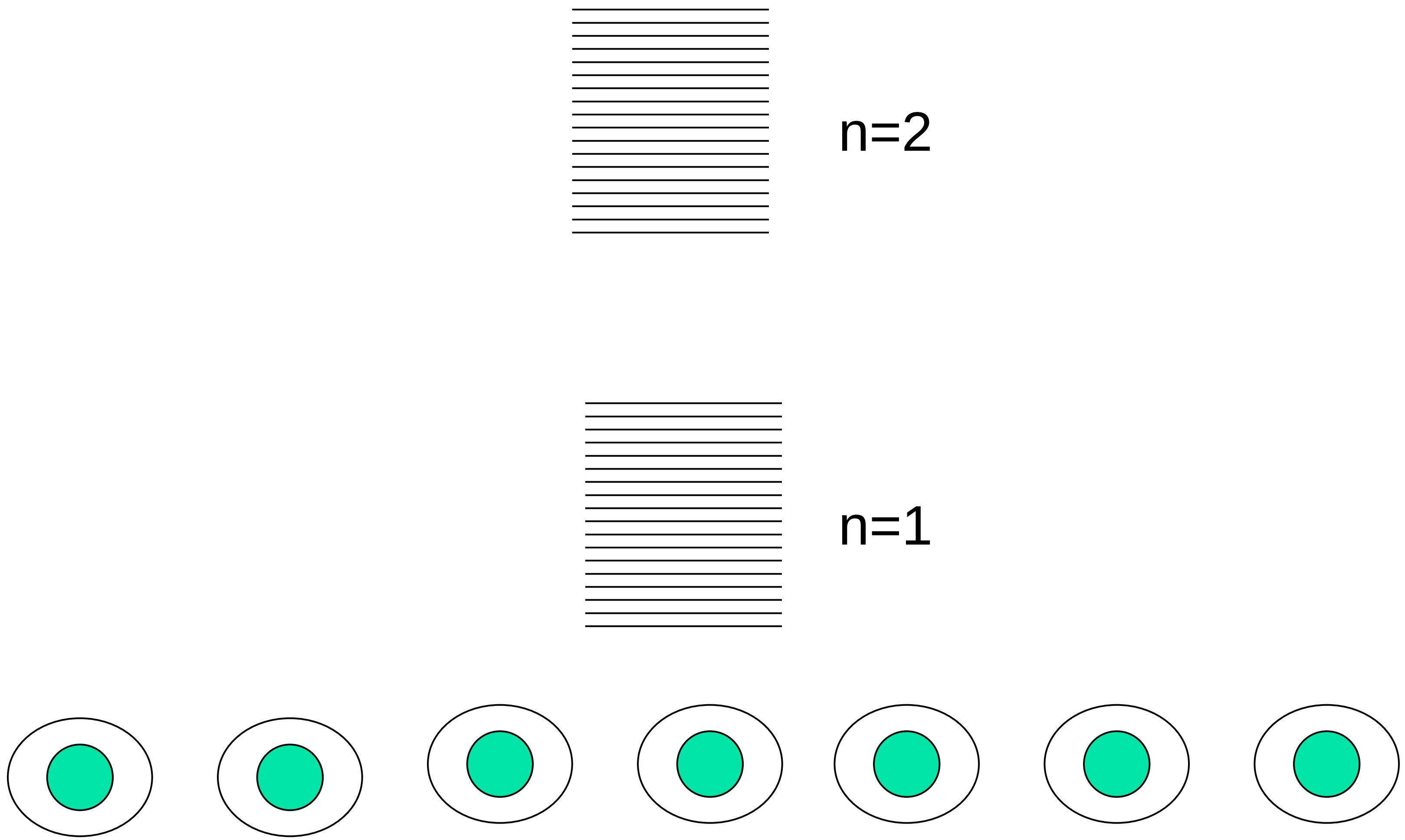


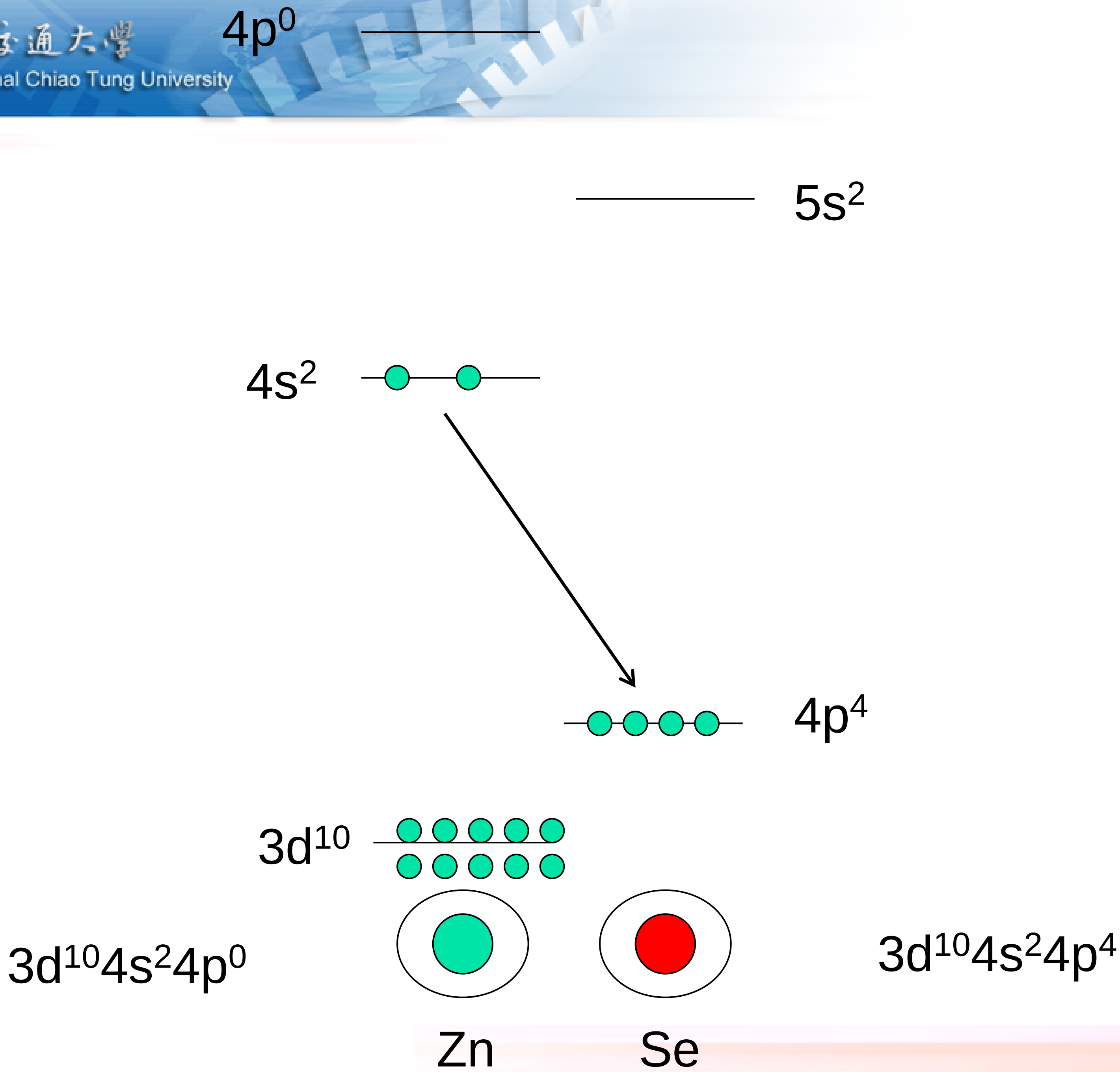
n=2

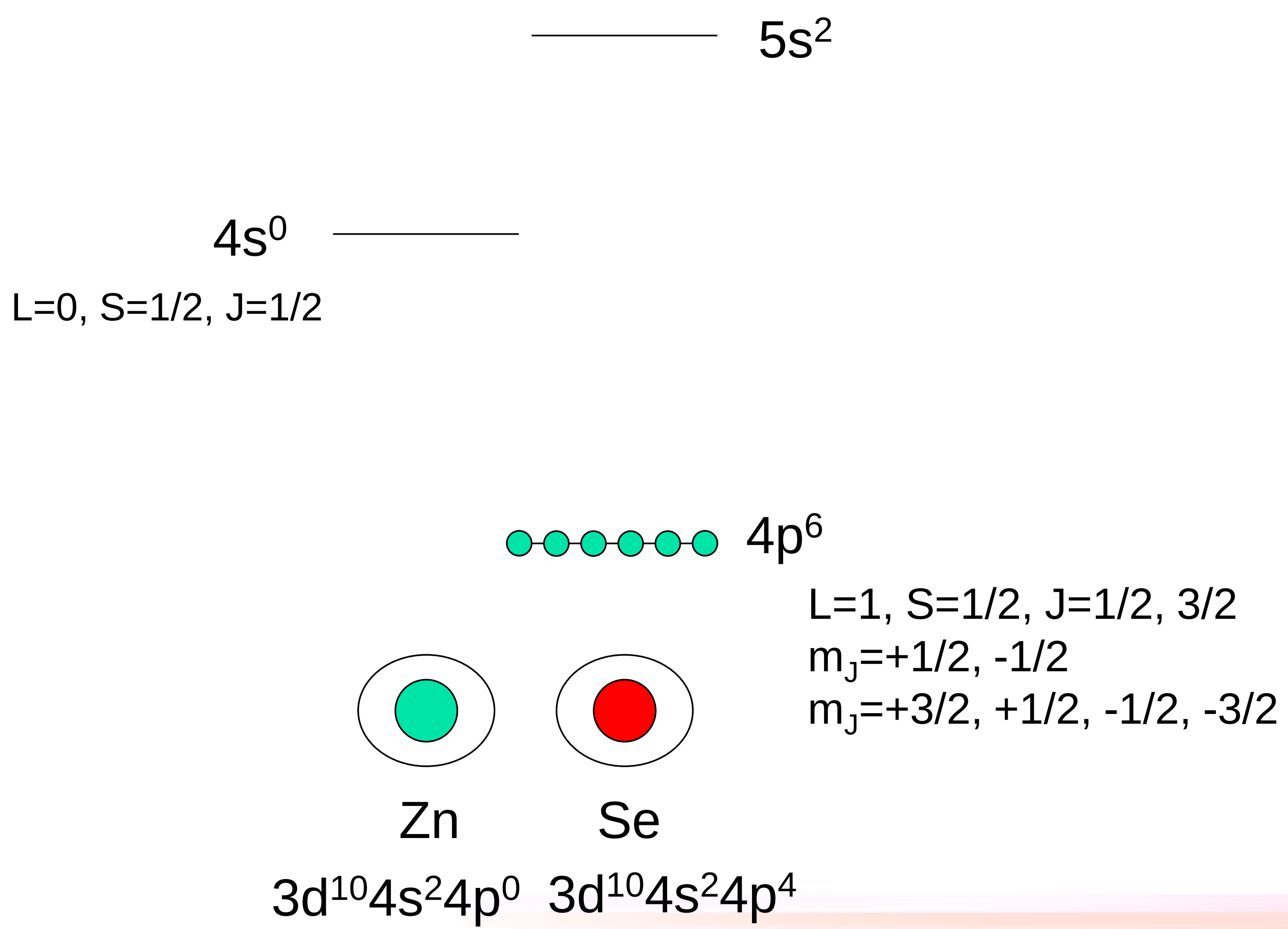
n=1

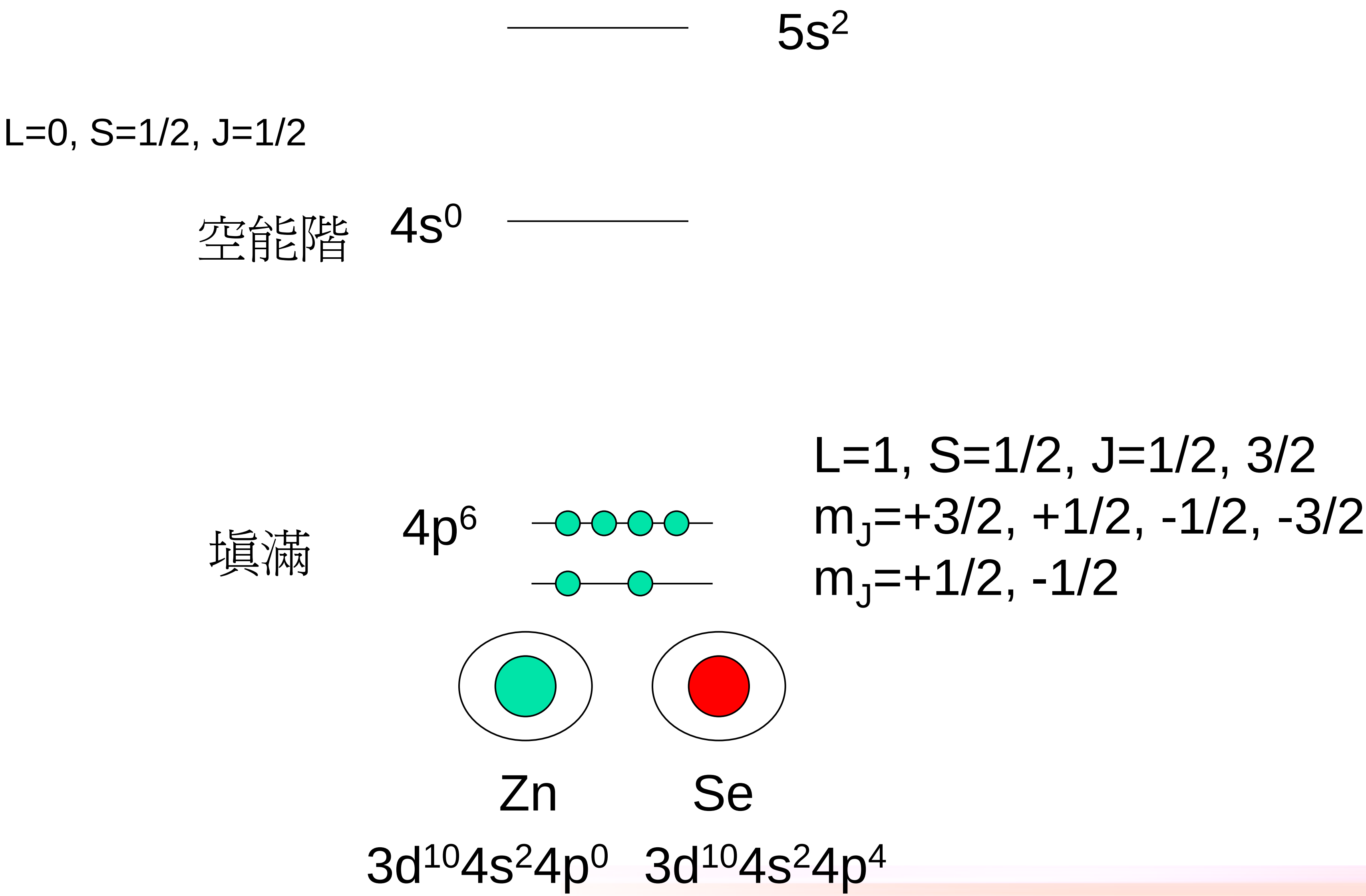
Isolated hydrogen atom

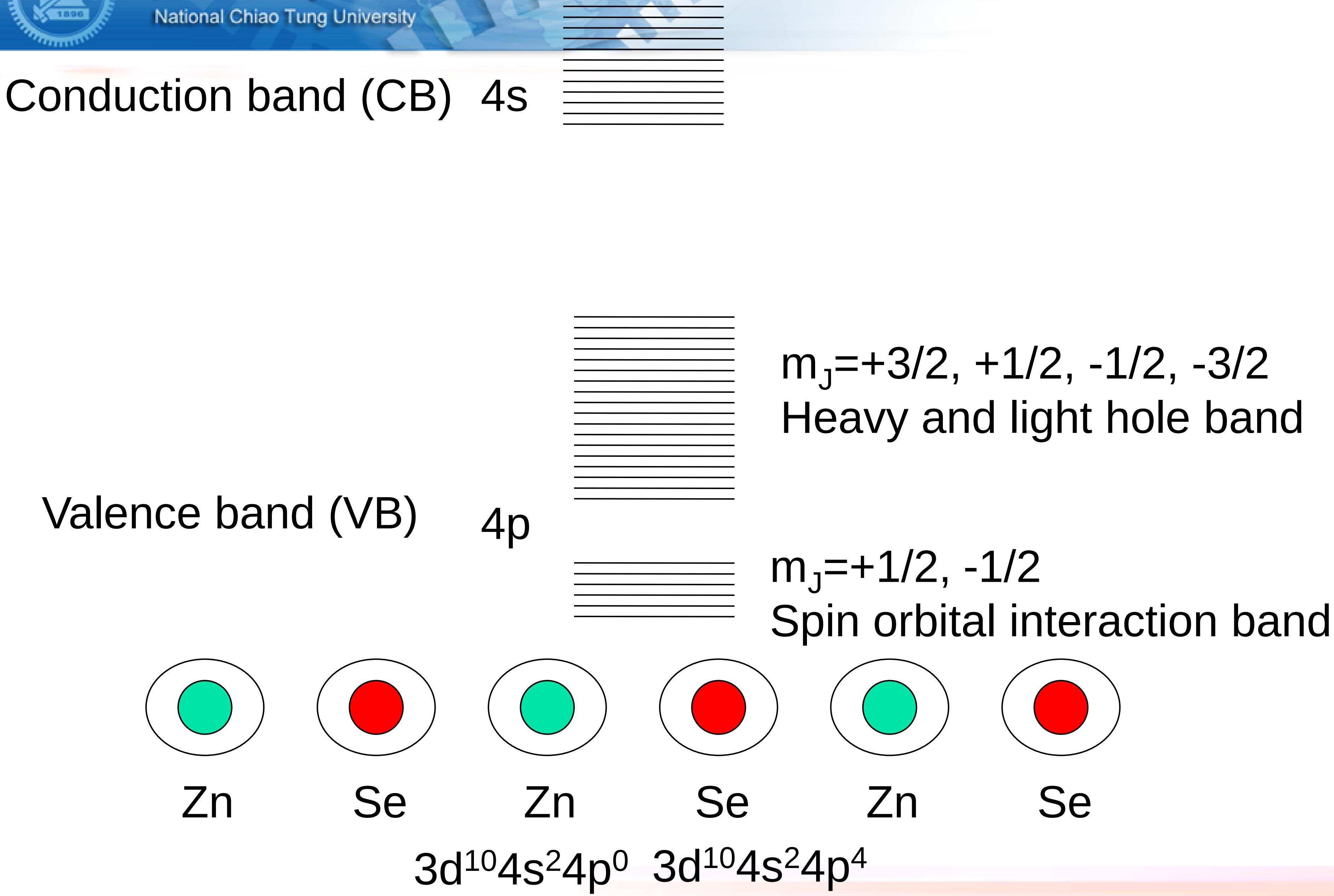

n=1
asymmetric state
n=1
Symmetric state


n=2
n=1

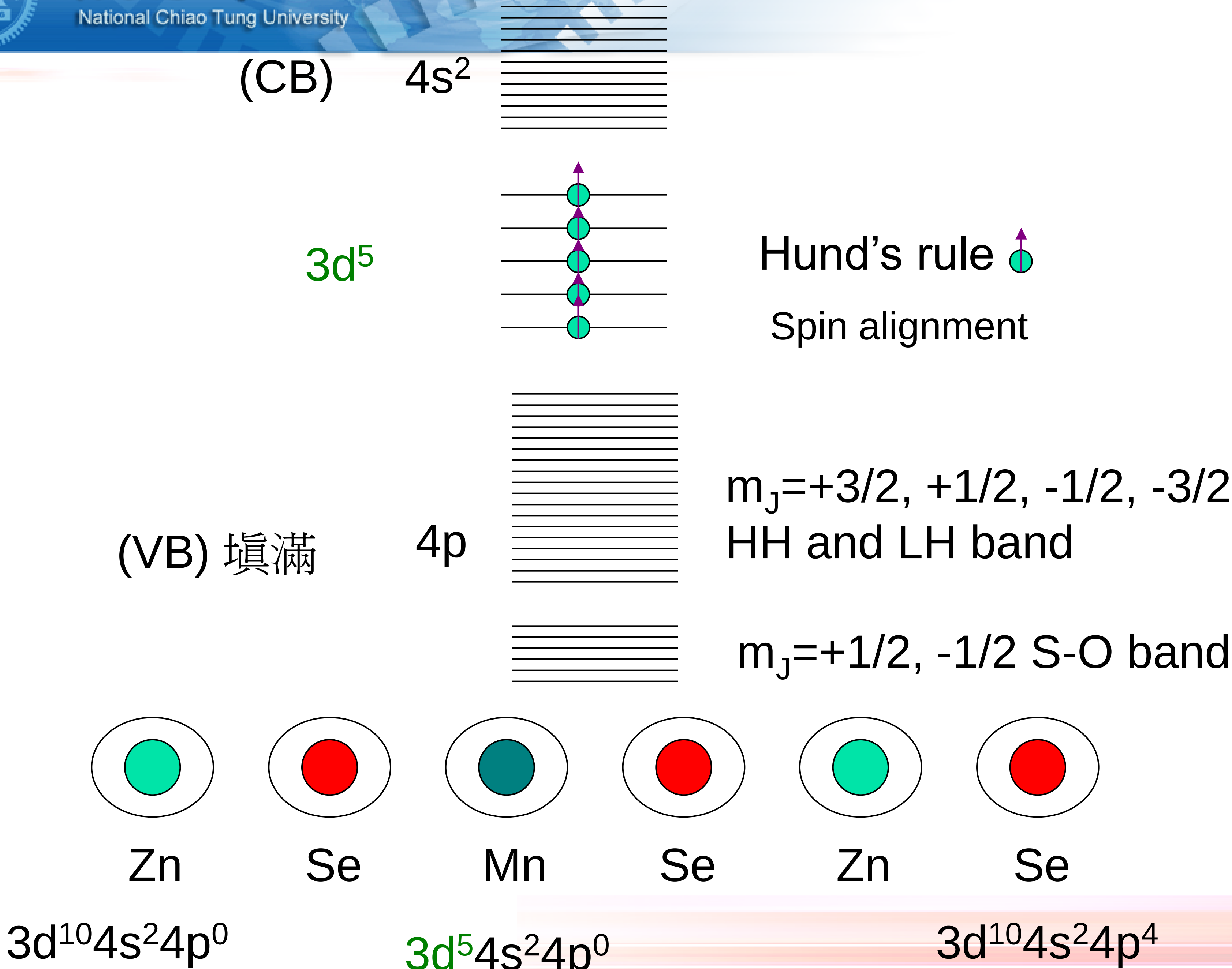

4p0
5s2
4s2
4p4
3d10
3d104s24p0
3d104s24p4
Zn
Se

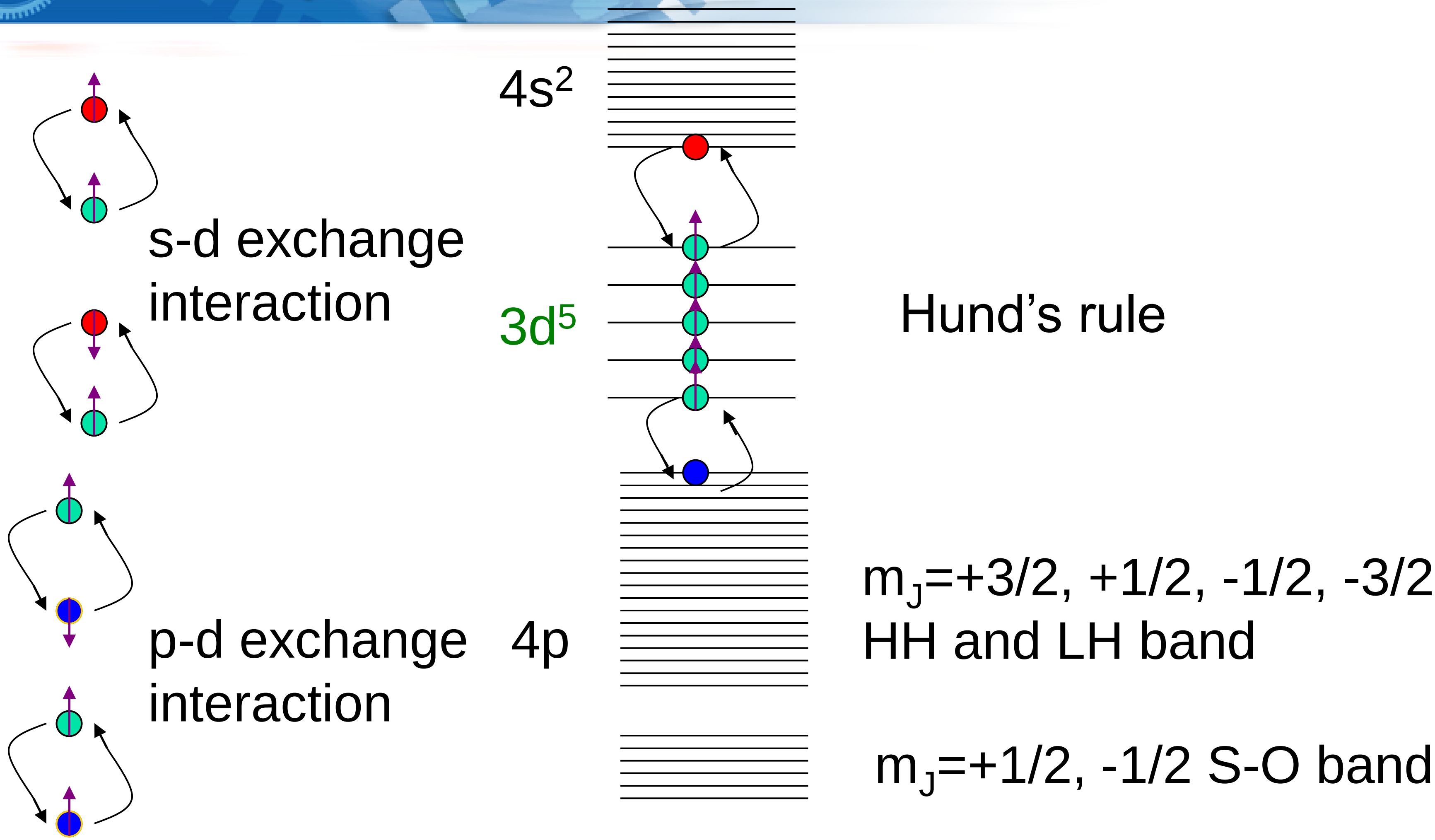

$5s^2$
$4s^0$
L=0, S=1/2, J=1/2
$4p^6$
L=1, S=1/2, J=1/2, 3/2
m_J=+1/2, -1/2
m_J=+3/2, +1/2, -1/2, -3/2
Zn
Se
$3d^{10}4s^24p^0$
$3d^{10}4s^24p^4$


5s²
L=0, S=1/2, J=1/2
空能階
4s⁰
L=1, S=1/2, J=1/2, 3/2
m_J=+3/2, +1/2, -1/2, -3/2
m_J=+1/2, -1/2
填滿
4p⁶
Zn
Se
3d¹⁰4s²4p⁰
3d¹⁰4s²4p⁴


Conduction band (CB)
4s
m_J=+3/2, +1/2, -1/2, -3/2
Heavy and light hole band
Valence band (VB)
4p
m_J=+1/2, -1/2
Spin orbital interaction band
Zn
Se
Zn
Se
Zn
Se
$3d^{10}4s^{2}4p^{0}$
$3d^{10}4s^{2}4p^{4}$

加入錳Mn後能帶的變化
有甚麼特殊的光電特性?


(CB)
4s^2
3d^5
Hund's rule
Spin alignment
m_J=+3/2, +1/2, -1/2, -3/2
HH and LH band
(VB) 填滿
4p
m_J=+1/2, -1/2 S-O band
Zn
Se
Mn
Se
Zn
Se
3d^{10}4s^{2}4p^0
3d^{5}4s^{2}4p^0
3d^{10}4s^{2}4p^4



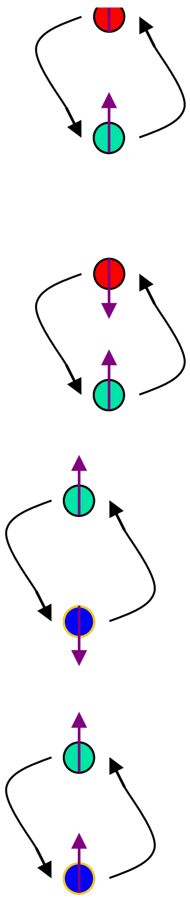
sp-d exchange interaction的結果?

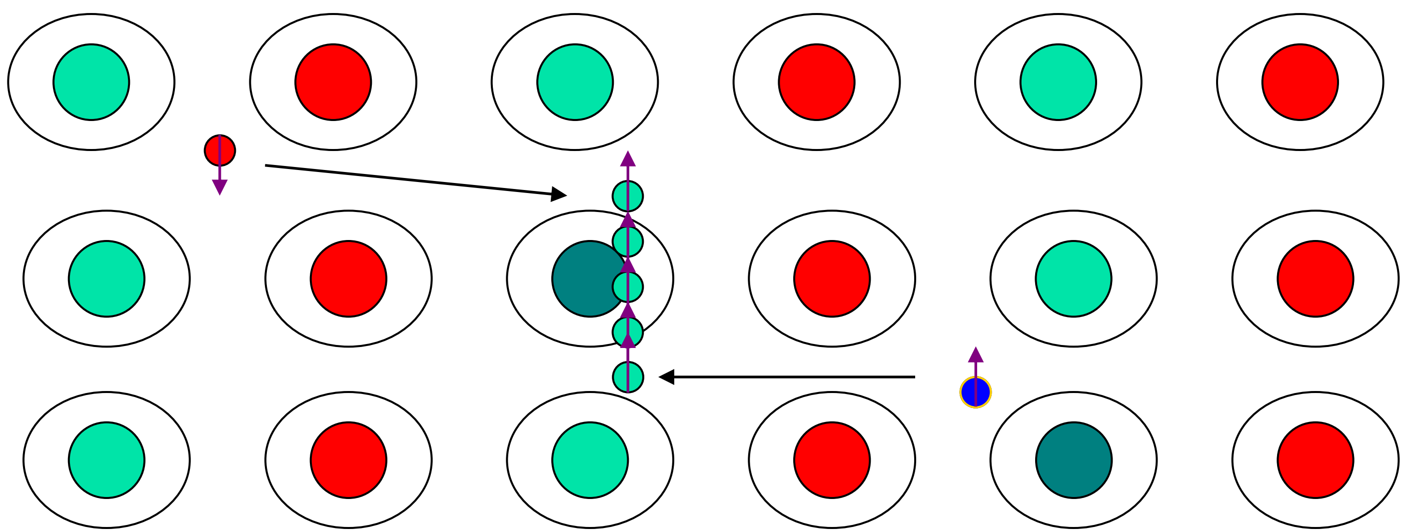
sp-d exchange interaction

$$H_T = H_0 + H_{ex}$$

$$= H_0 + \sum_{\mathbf{R}_l} J^{sp\text{-}d}(\mathbf{r} - \mathbf{R}_l)\mathbf{S}_l \cdot \boldsymbol{\sigma},$$

$$H_{ex} = \sigma_z \langle S_z \rangle x \sum_{\mathbf{R}} J^{sp\text{-}d}(\mathbf{r} - \mathbf{R}),$$



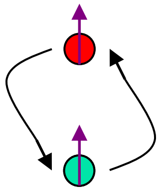


Sp-d exchange interaction

$$H_T = H_0 + H_{ex}$$

$$= H_0 + \sum_{\mathbf{R}_i} J^{sp\text{-}d}(\mathbf{r} - \mathbf{R}_i)\mathbf{S}_i \cdot \boldsymbol{\sigma},$$

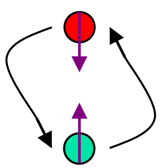
$$H_{ex} = \sigma_z \langle S_z \rangle x \sum_{\mathbf{R}} J^{sp\text{-}d}(\mathbf{r} - \mathbf{R}),$$

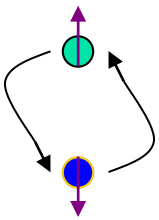


CB Γ_6

$$u_{10} = \left|\tfrac{1}{2},\tfrac{1}{2}\right\rangle_{\Gamma_6} = S\uparrow,$$

$$u_{20} = \left|\tfrac{1}{2},-\tfrac{1}{2}\right\rangle_{\Gamma_6} = S\downarrow;$$





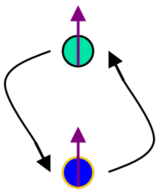
VB Γ_8

$$u_{30} = \left|\tfrac{3}{2},\tfrac{3}{2}\right\rangle = (1/\sqrt{2})(X + iY)\uparrow,$$

$$u_{40} = \left|\tfrac{3}{2},-\tfrac{3}{2}\right\rangle = i(1/\sqrt{2})(X - iY)\downarrow,$$

$$u_{50} = \left|\tfrac{3}{2},\tfrac{1}{2}\right\rangle = (1/\sqrt{6})[(X - iY)\uparrow + 2Z\downarrow],$$

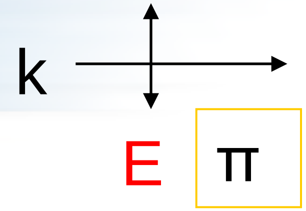
$$u_{60} = \left|\tfrac{3}{2},-\tfrac{1}{2}\right\rangle = i(1/\sqrt{6})[(X + iY)\downarrow - 2Z\uparrow];$$

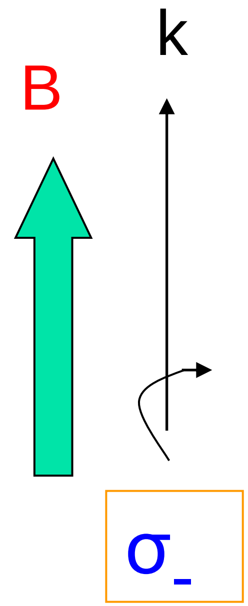


Spin-orbital band Γ_7

$$u_{70} = \left|\tfrac{1}{2},\tfrac{1}{2}\right\rangle = -i(1/\sqrt{3})[(X - iY)\uparrow - Z\downarrow],$$

$$u_{80} = \left|\tfrac{1}{2},-\tfrac{1}{2}\right\rangle = (1/\sqrt{3})[(X + iY)\downarrow + Z\uparrow].$$





$$\langle \Psi_{\Gamma_6} | H_{ex} | \Psi_{\Gamma_6} \rangle = \left\| \begin{matrix} 3A & 0 \\ 0 & -3A \end{matrix} \right\|$$

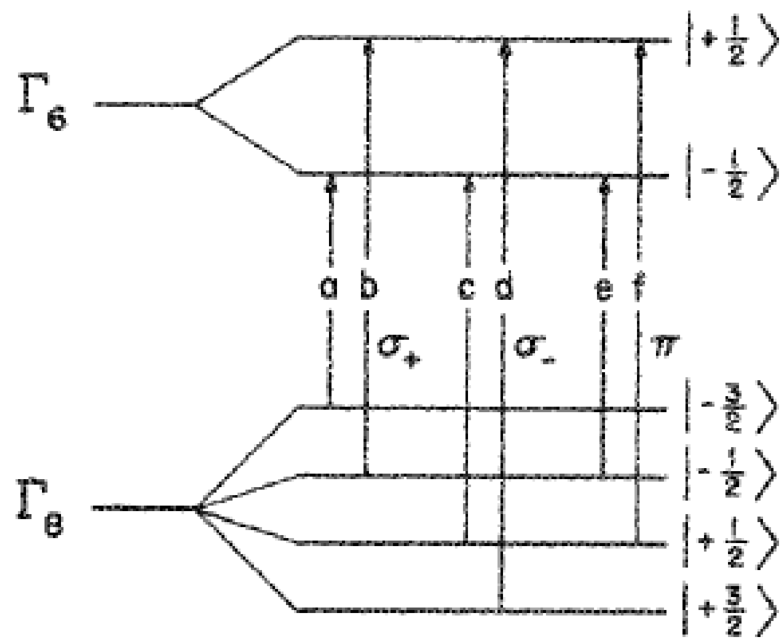
$$\langle \Psi_{\Gamma_8} | H_{ex} | \Psi_{\Gamma_8} \rangle = \left\| \begin{matrix} 3B & 0 & 0 & 0 \\ 0 & B & 0 & 0 \\ 0 & 0 & -B & 0 \\ 0 & 0 & 0 & -3B \end{matrix} \right\|$$

$$A = \frac{1}{6} N_0 \alpha x \langle S_z \rangle = -\frac{1}{6} \frac{\alpha M}{g_{Mn} \mu_B},$$

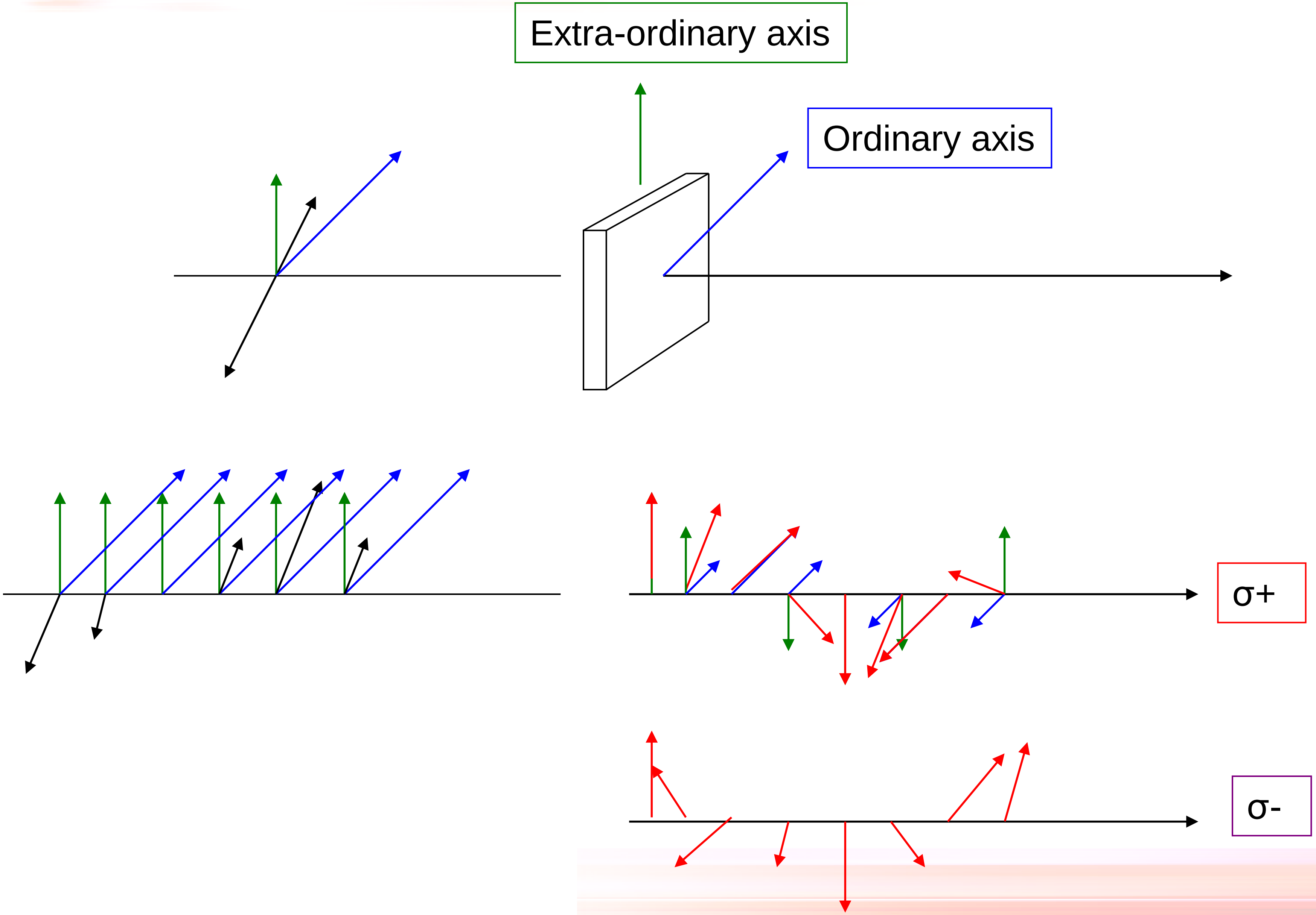
$$B = \frac{1}{6} N_0 \beta x \langle S_z \rangle = -\frac{1}{6} \frac{\beta M}{g_{Mn} \mu_B}$$

$$\alpha = \langle S | J^{sp\text{-}d} | S \rangle / \Omega_0,$$

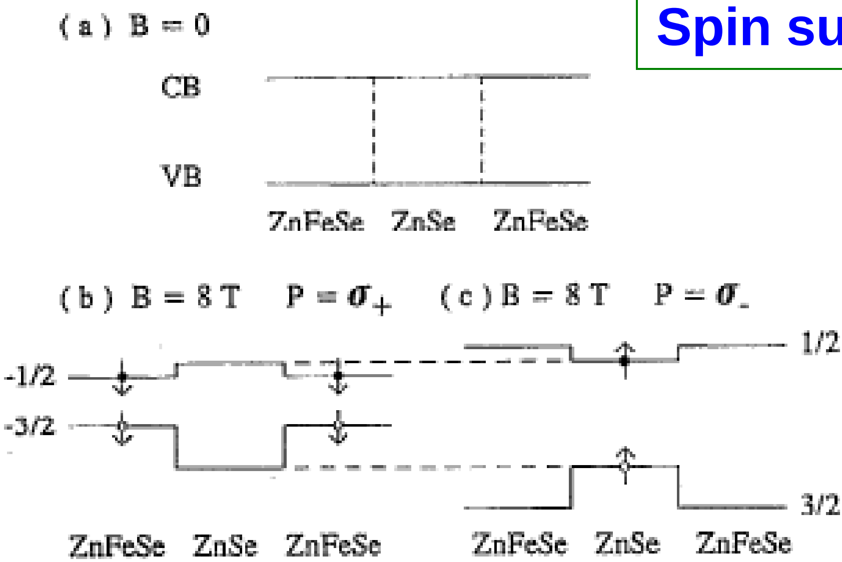
$$\beta = \langle X | J^{sp\text{-}d} | X \rangle / \Omega_0.$$

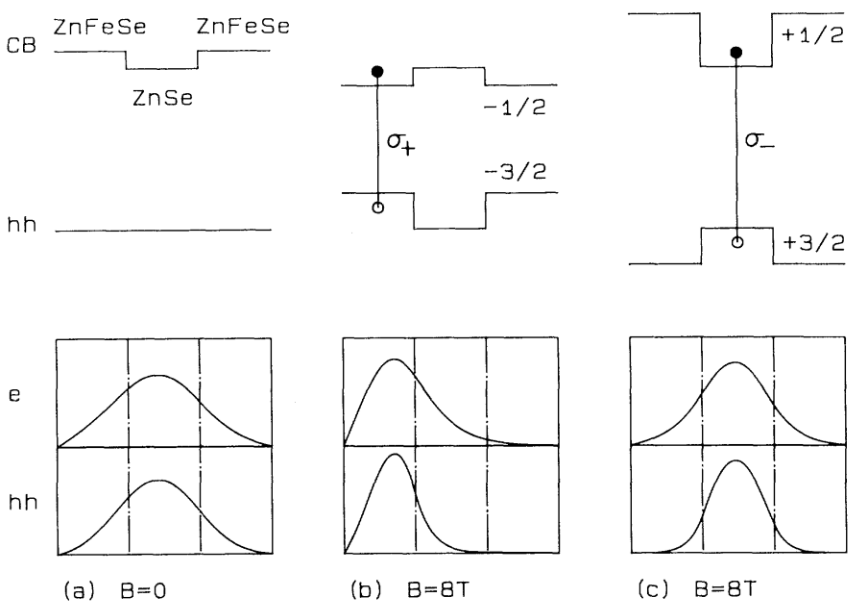


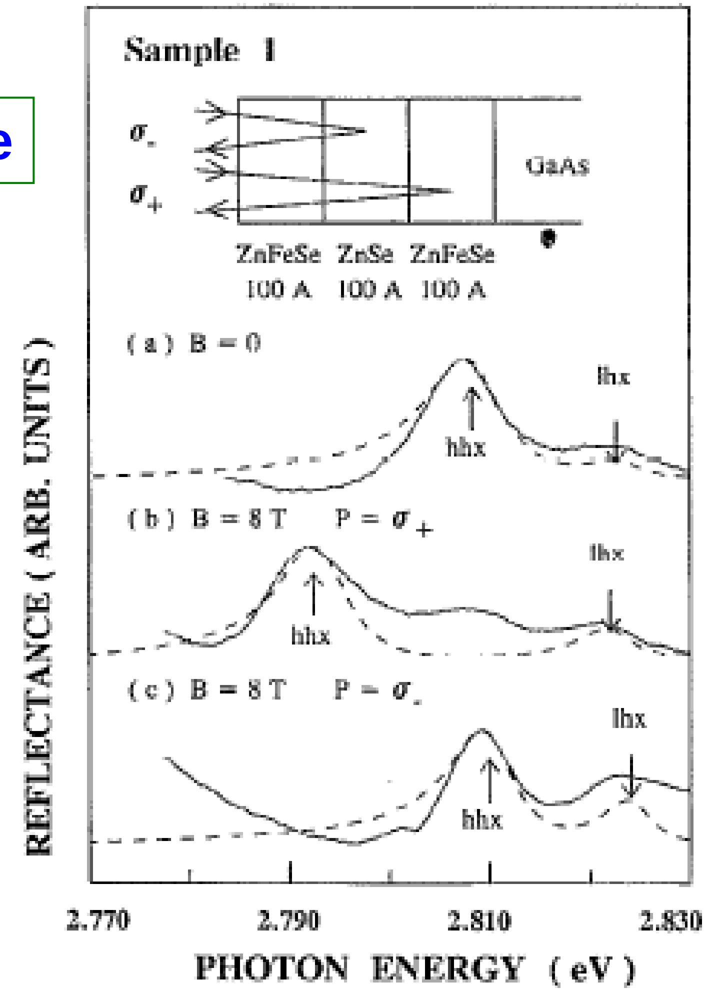
如何產生圓形極化光?



Spin super-lattice





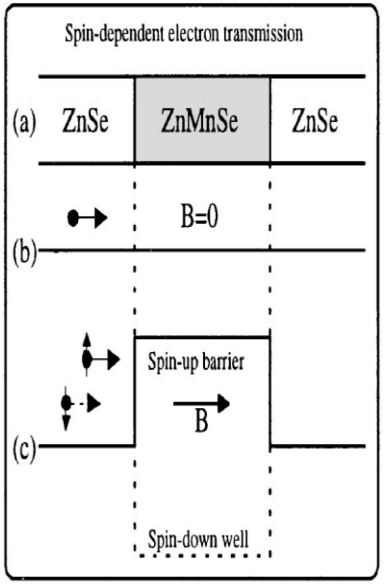


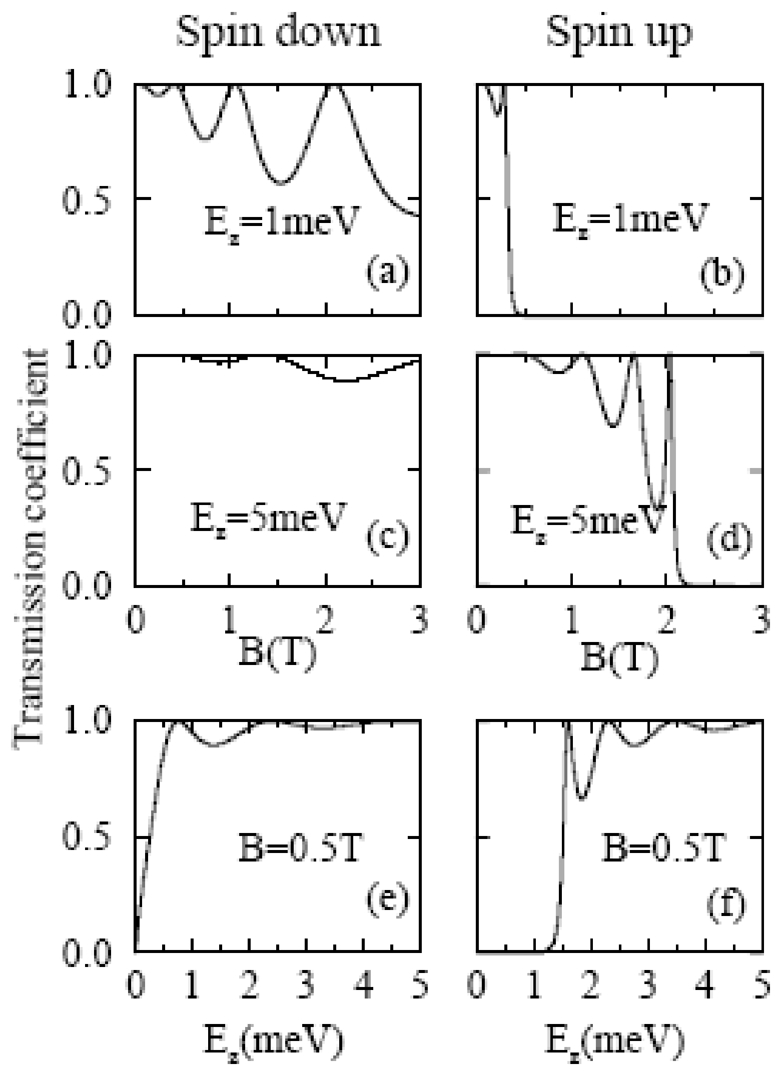
$$R=\left|\frac{E_0'}{E_0}\right|^2 \quad \epsilon=\epsilon_\infty+\sum_\alpha \frac{A_\alpha}{(E_\alpha^2-E^2)-i\Gamma_\alpha E}$$

PRL 67, 3820 (1991),
JAP 75, 2988 (1994)

Spin-Dependent Perpendicular Magnetotransport through a Tunable ZnSe/$Zn_{1-x}Mn_xSe$ Heterostructure: A Possible Spin Filter?

J. Carlos Egues, PRL80, 4578 (1998)





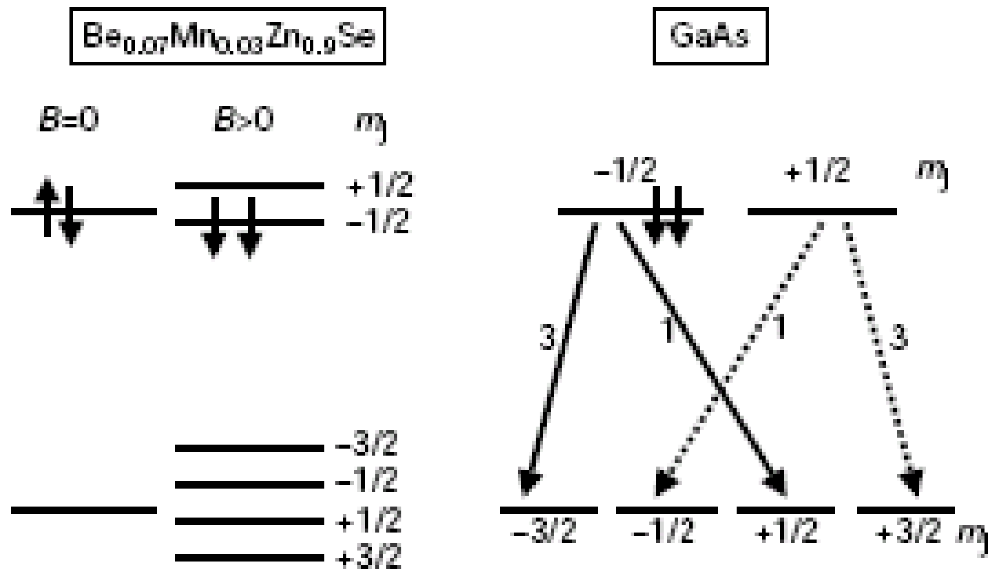
$$T_{\downarrow}(E_z, B) = \left\{ 1 + \frac{\sin^2\left[\sqrt{\frac{2m_z^*(x|\langle S_z\rangle|N_0\alpha/2+E_z)}{\hbar^2}}\,L\right]}{4\left(\frac{E_z}{x|\langle S_z\rangle|N_0\alpha/2}\right)\left(\frac{E_z}{x|\langle S_z\rangle|N_0\alpha/2}+1\right)} \right\}^{-1}. \quad (1)$$

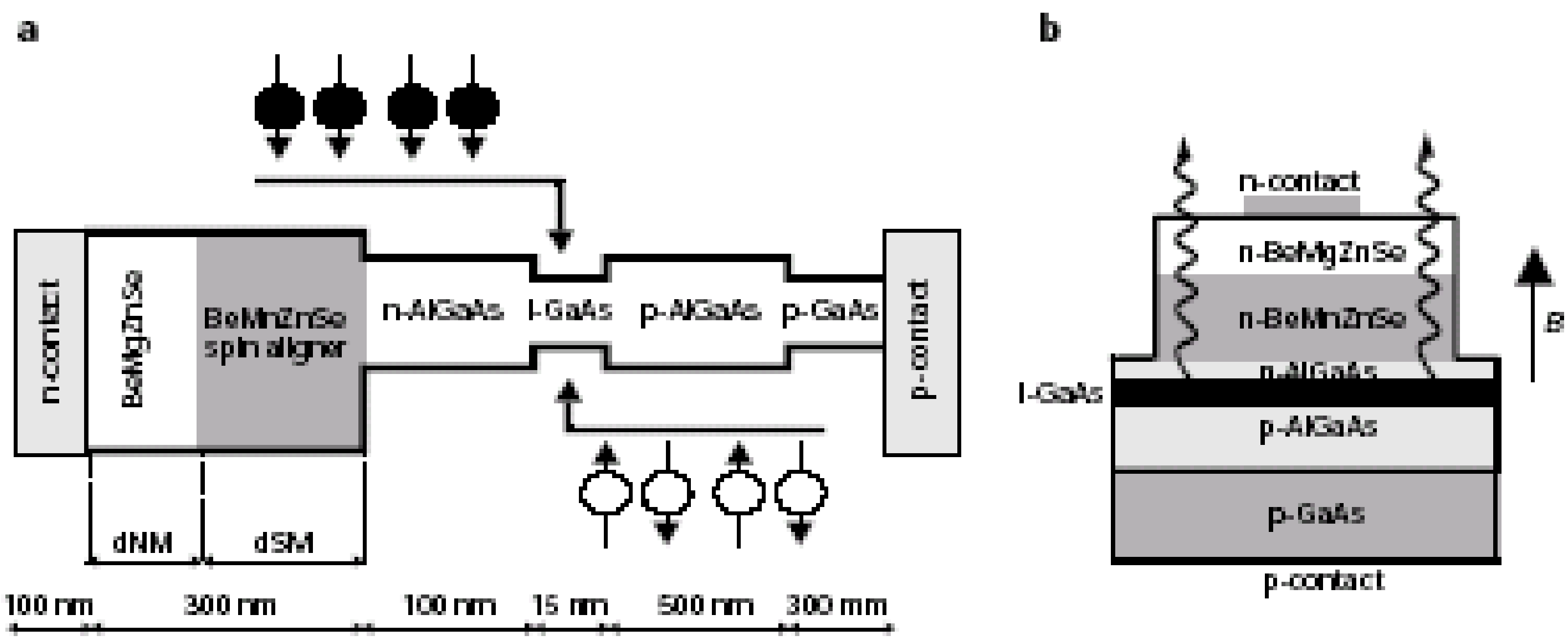
Nature 402, p787 (1999)

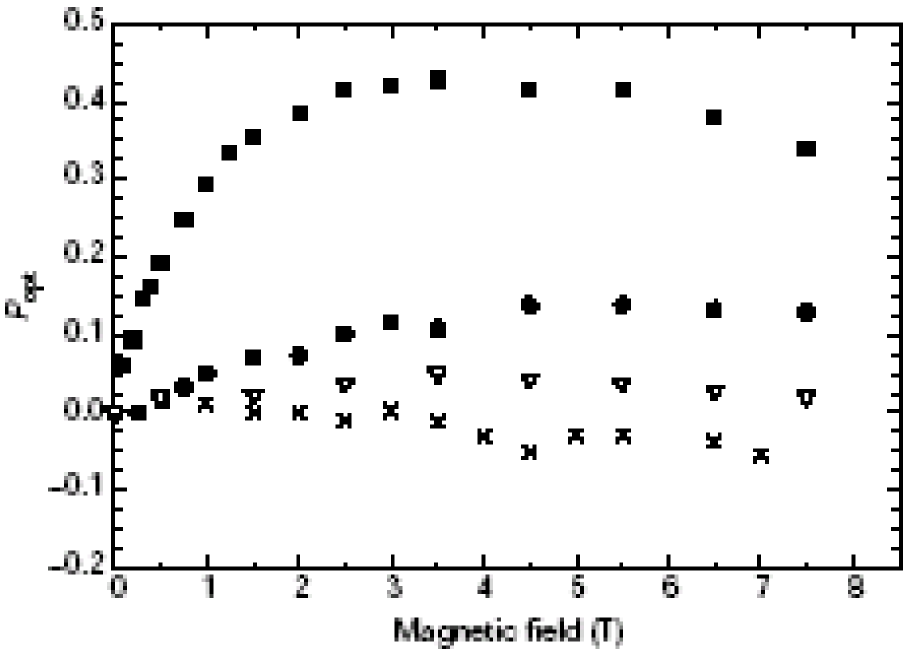
Injection and detection of a spin-polarized current in a light-emitting diode

R. Fiederling, M. Keim, G. Reuscher, W. Ossau, G. Schmidt, A. Waag & L. W. Molenkamp

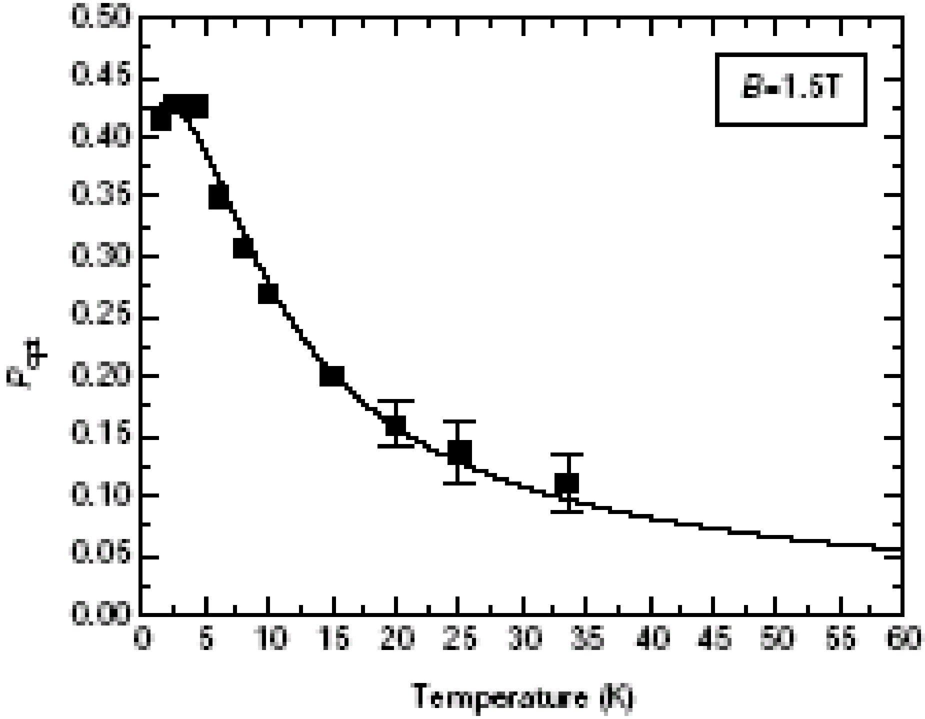
Physikalisches Institut, EP III, Universität Würzburg, 97074 Würzburg, Germany







Nature 402, p787 (1999)

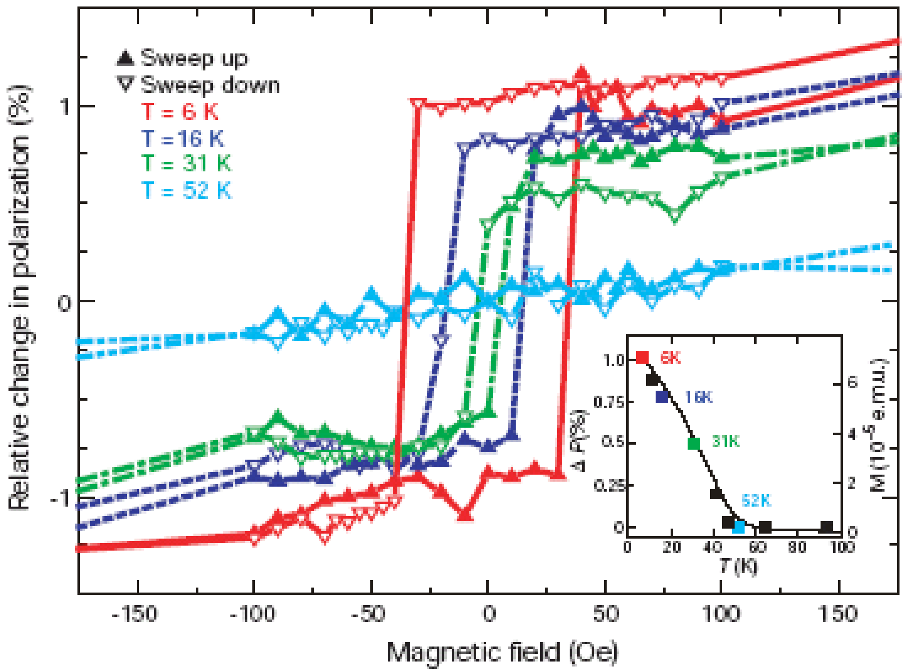


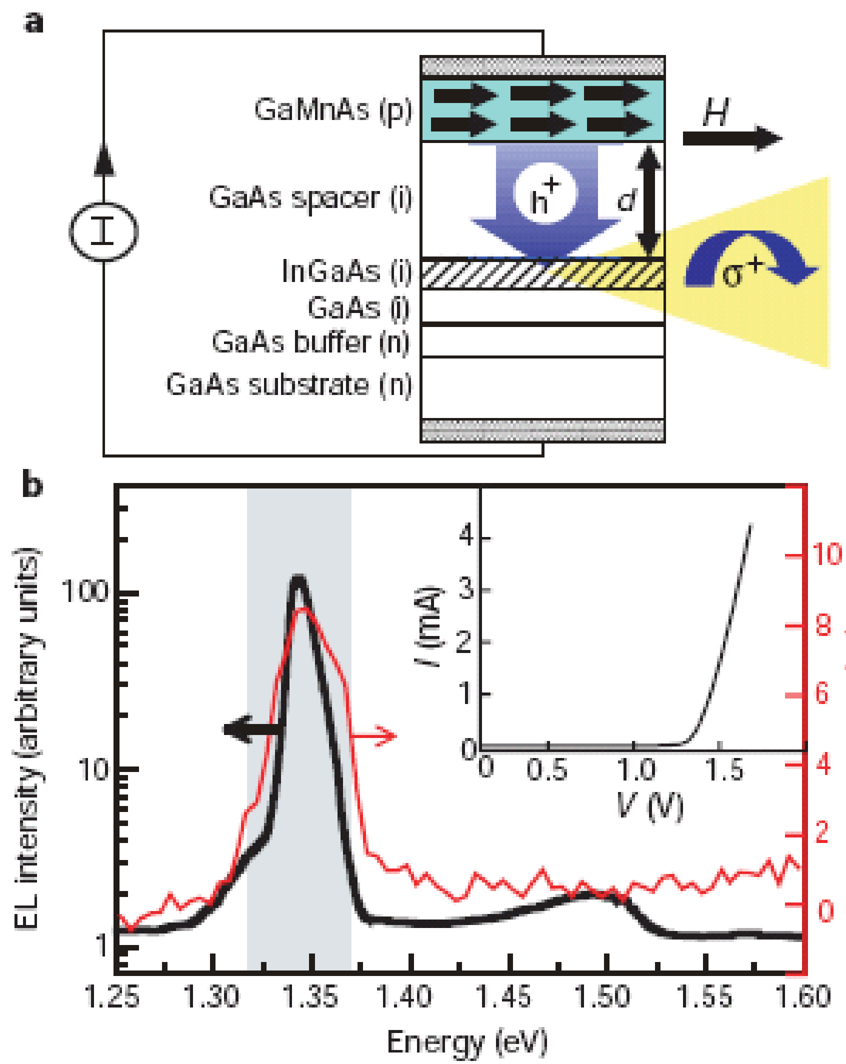
Nature 402, p790 (1999)

Electrical spin injection in a ferromagnetic semiconductor heterostructure

Y. Ohno*, D. K. Young†, B. Beschoten†, F. Matsukura*, H. Ohno* & D. D. Awschalom†

* *Laboratory for Electronic Intelligent Systems, Research Institute of Electrical Communication, Tohoku University, Katahira 2-1-1, Aoba-ku, Sendai 980-8577, Japan*
† *Center for Spintronics and Quantum Computation, Quantum Institute,*





APPLIED PHYSICS LETTERS VOLUME 83, NUMBER 22 1 DECEMBER 2003

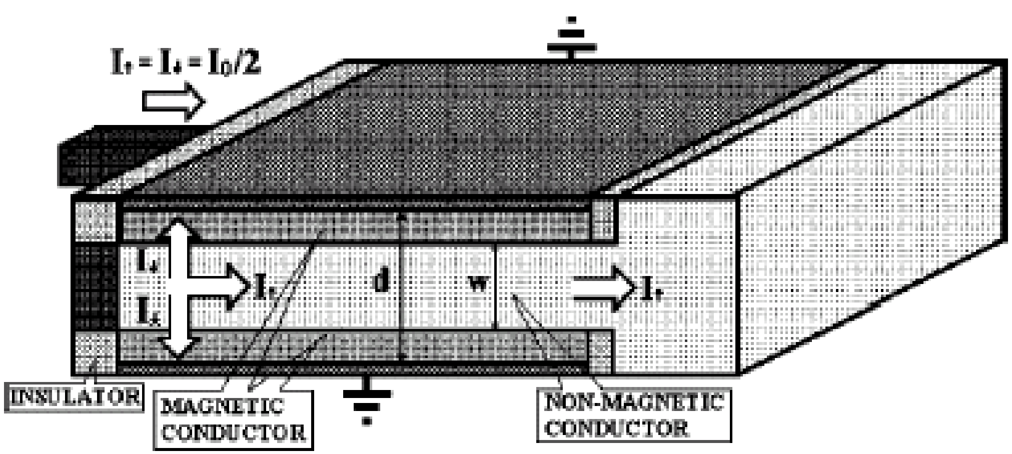
A magnetic-field-effect transistor and spin transport

R. N. Gurzhi, A. N. Kalinenko, A. I. Kopeliovich, and A. V. Yanovsky
B. Verkin Institute for Low Temperature Physics & Engineering of the National Academy of Sciences of the Ukraine, 47 Lenin Ave, Kharkov, 61103, Ukraine

E. N. Bogachek and Uzi Landman[a)]
School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332-0430

(Received 19 May 2003; accepted 7 October 2003)

A magnetic-field-effect transistor is proposed that generates a spin-polarized current and exhibits a giant negative magnetoresistance. The device consists of a nonmagnetic conducting channel (wire or strip) wrapped, or sandwiched, by a grounded magnetic shell. The process underlying the operation of the device is the withdrawal of one of the spin components from the channel, and its dissipation through the grounded boundaries of the magnetic shell, resulting in a spin-polarized current in the nonmagnetic channel. The device may generate an almost fully spin-polarized current, and a giant negative magnetoresistance effect is predicted.
[DOI: 10.1063/1.1630839]



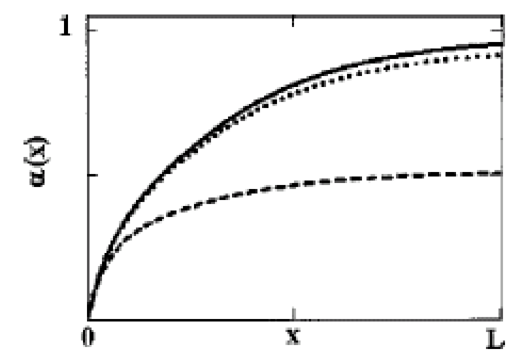
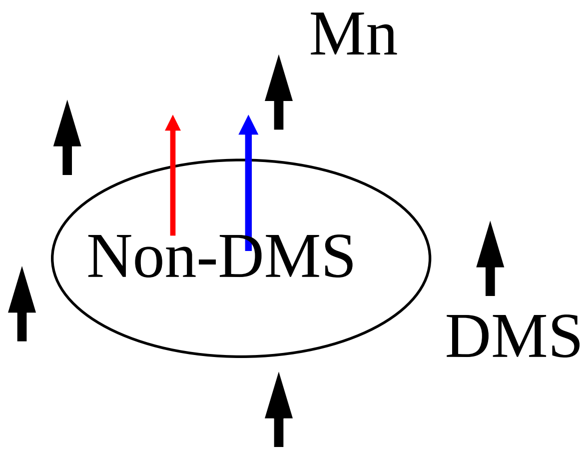
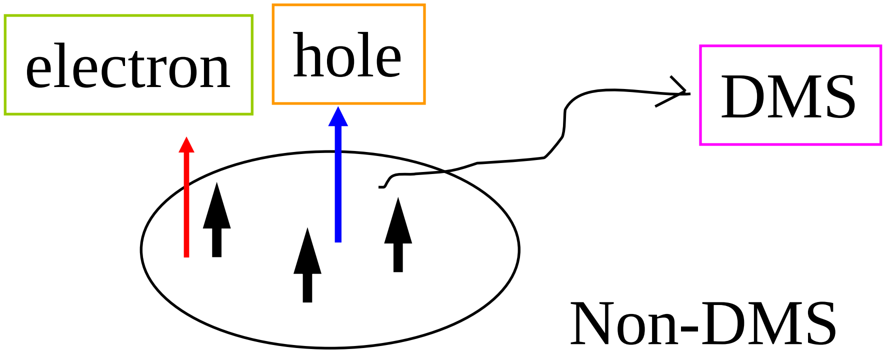


FIG. 2. The degree of SP (α) of the current plotted vs the longitudinal (x) coordinate along the spin guide; the curves were calculated from Eq. (7) with $\sigma_{M\uparrow}/\sigma_{M\downarrow}=0.3$, $\sigma_{M\downarrow}/\sigma_N=1$, $w/d=0.28$, $L=4d$, $w_M/\lambda_M=0.225$, and $w/\lambda_N=0.1$ (solid), $w/\lambda_N=0.5$ (dotted), $w/\lambda_N=0.7$ (dashed).

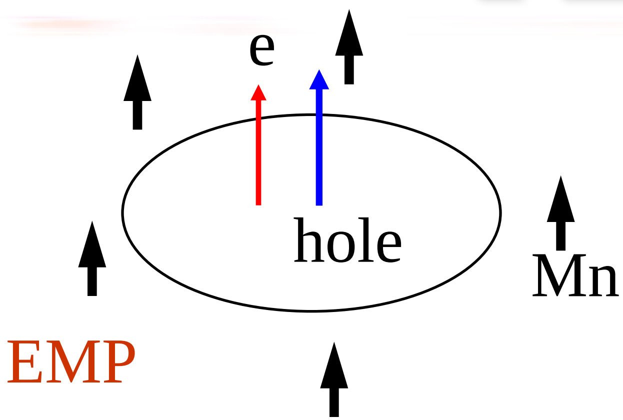
Diluted magnetic semiconductor (DMS) QDs

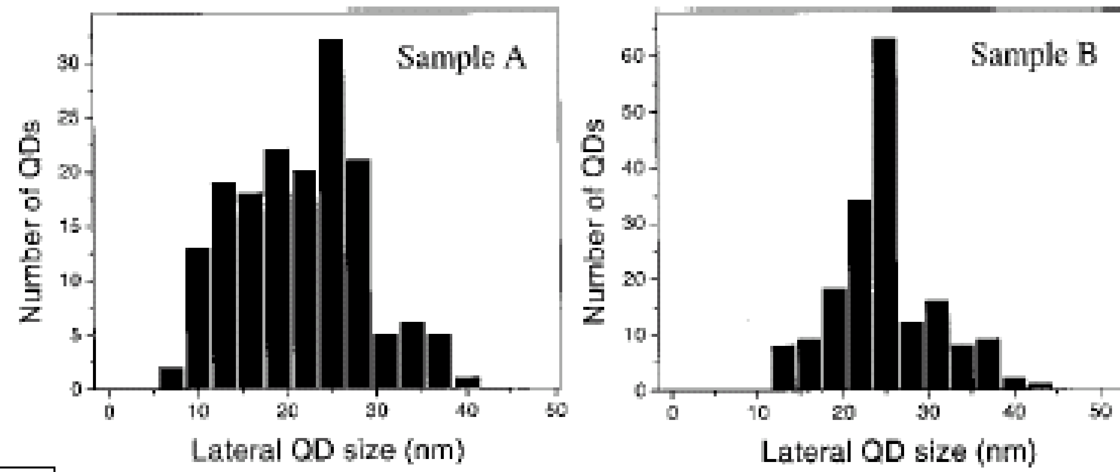
- Give us extra dimensions for the growth of self-assembled QDs passivation, bandgap, lattice constant (strain)
- Offer a QD system for the control and manipulation of spin for the potential application of quantum computing and spintronics





Diluted magnetic semiconductor QDs

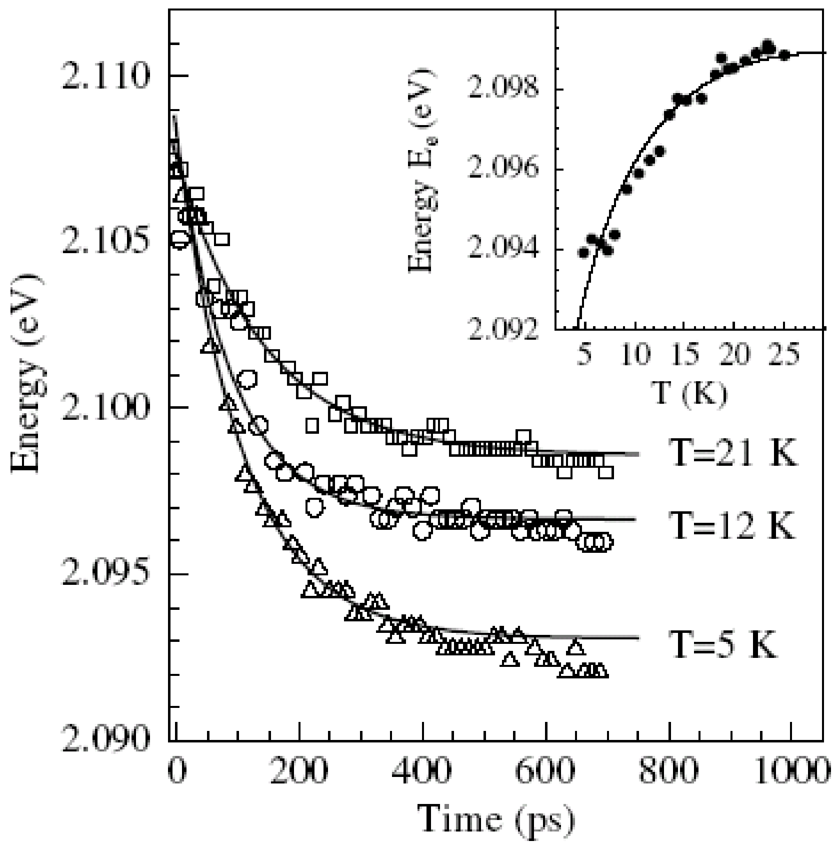




CdSe/ZnSe

CdMnSe/ZnSe,
Mn passivation

L.V. Titova et al., APL 80, 1237 (2002)

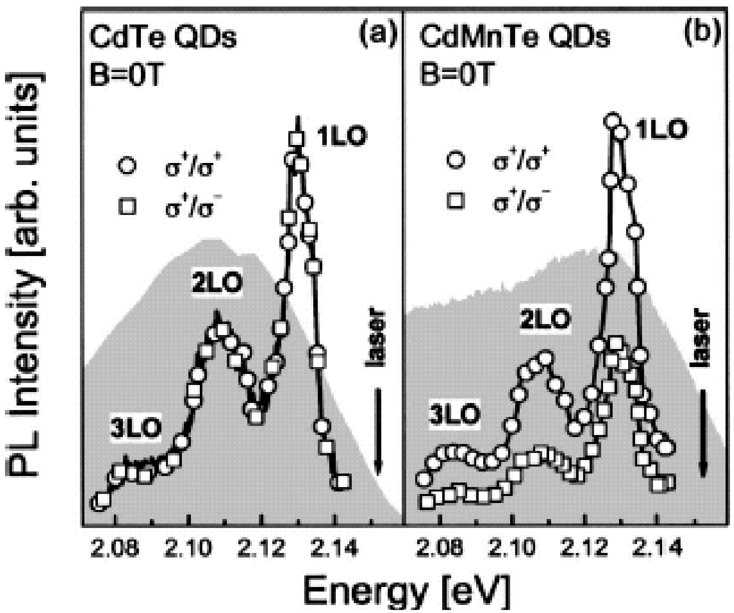


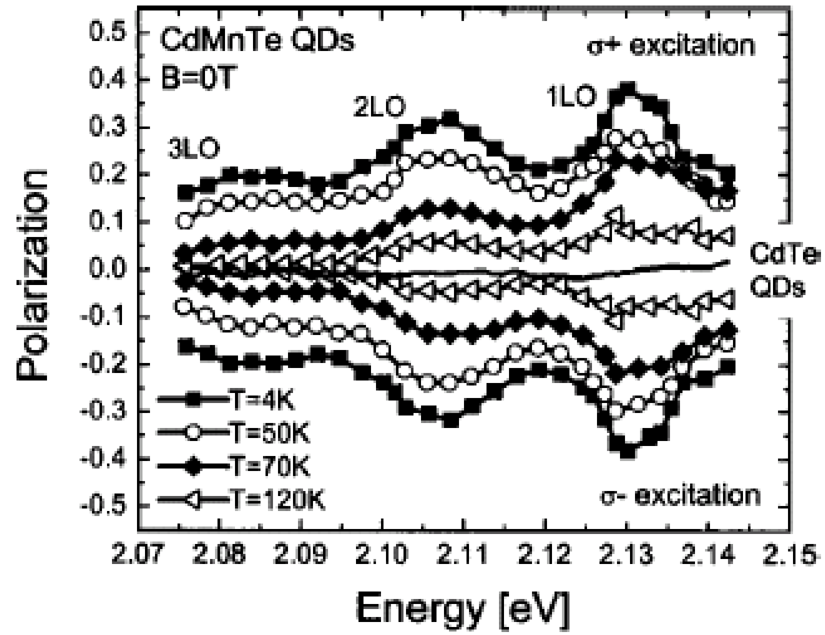
Dynamical spin response in
CdSe (QDs)/ZnMnSe (matrix)
J. Seufert et al.
PRL 88, 027402 (2002)

EMP: Exciton magnetic polaron

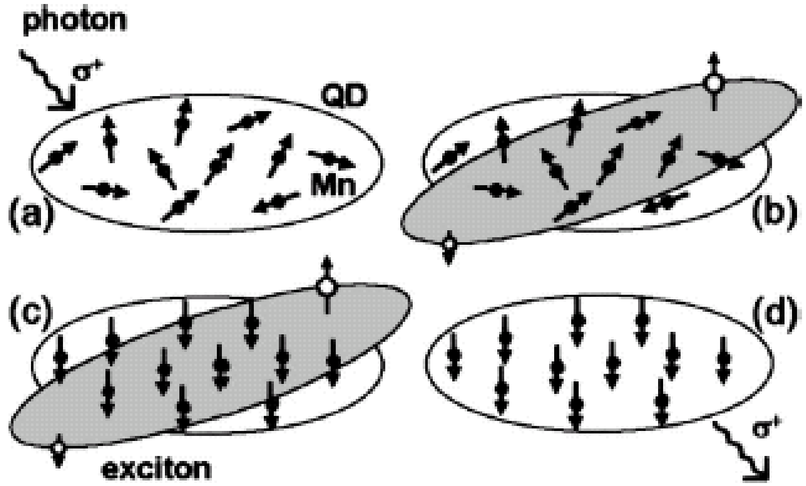
S. Mackowski et al., APL 84, 3337 (2004).

Optically-induced magnetization of CdMnTe self-assembled QDs

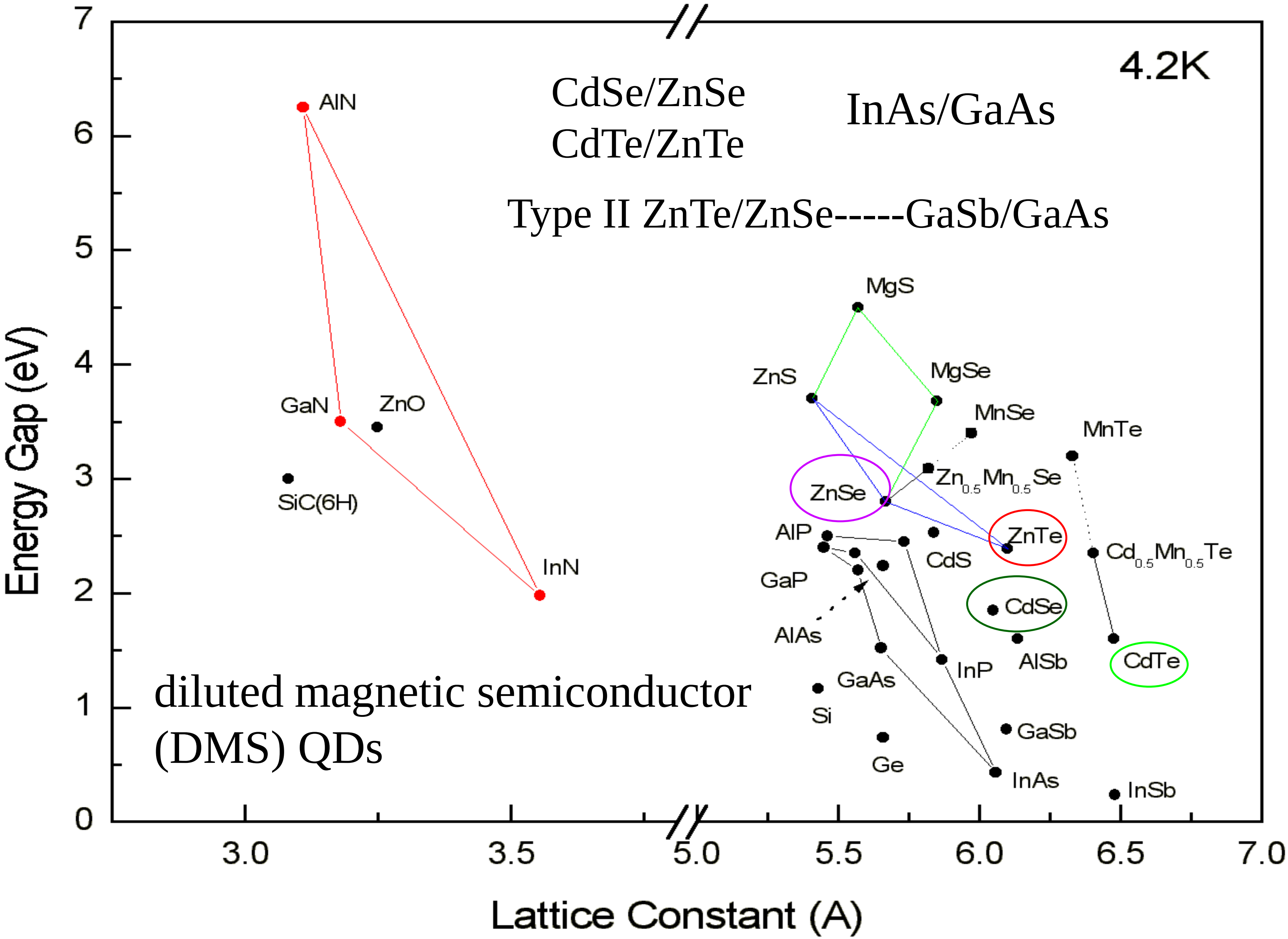




EMP:
Exciton magnetic polaron

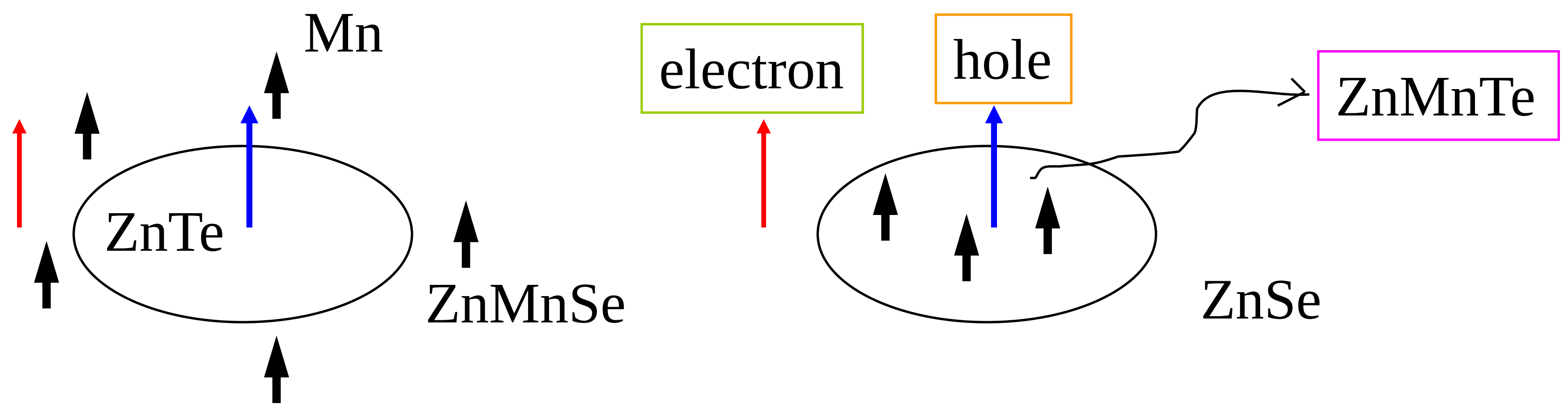


Energy Gap vs Lattice Constant



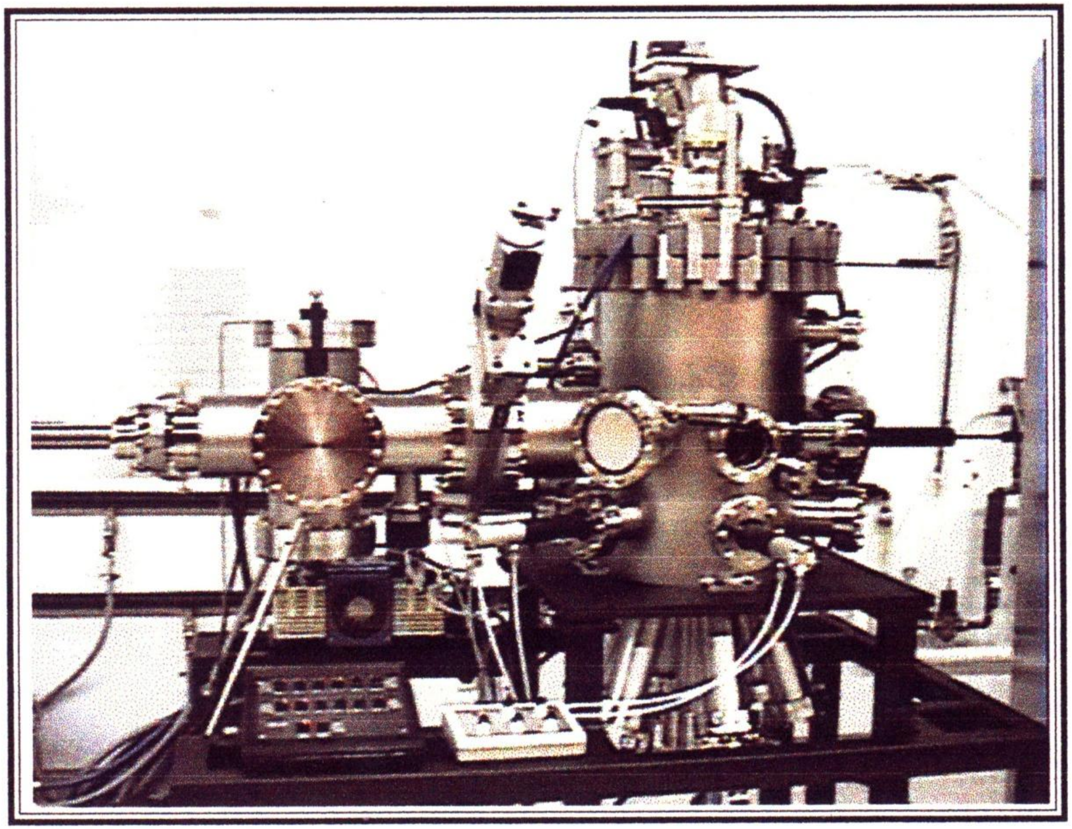
Why ZnMnTe/ZnMnSe QD system? type II band alignment

Electron and hole spatially separated. Novel spin dynamics?



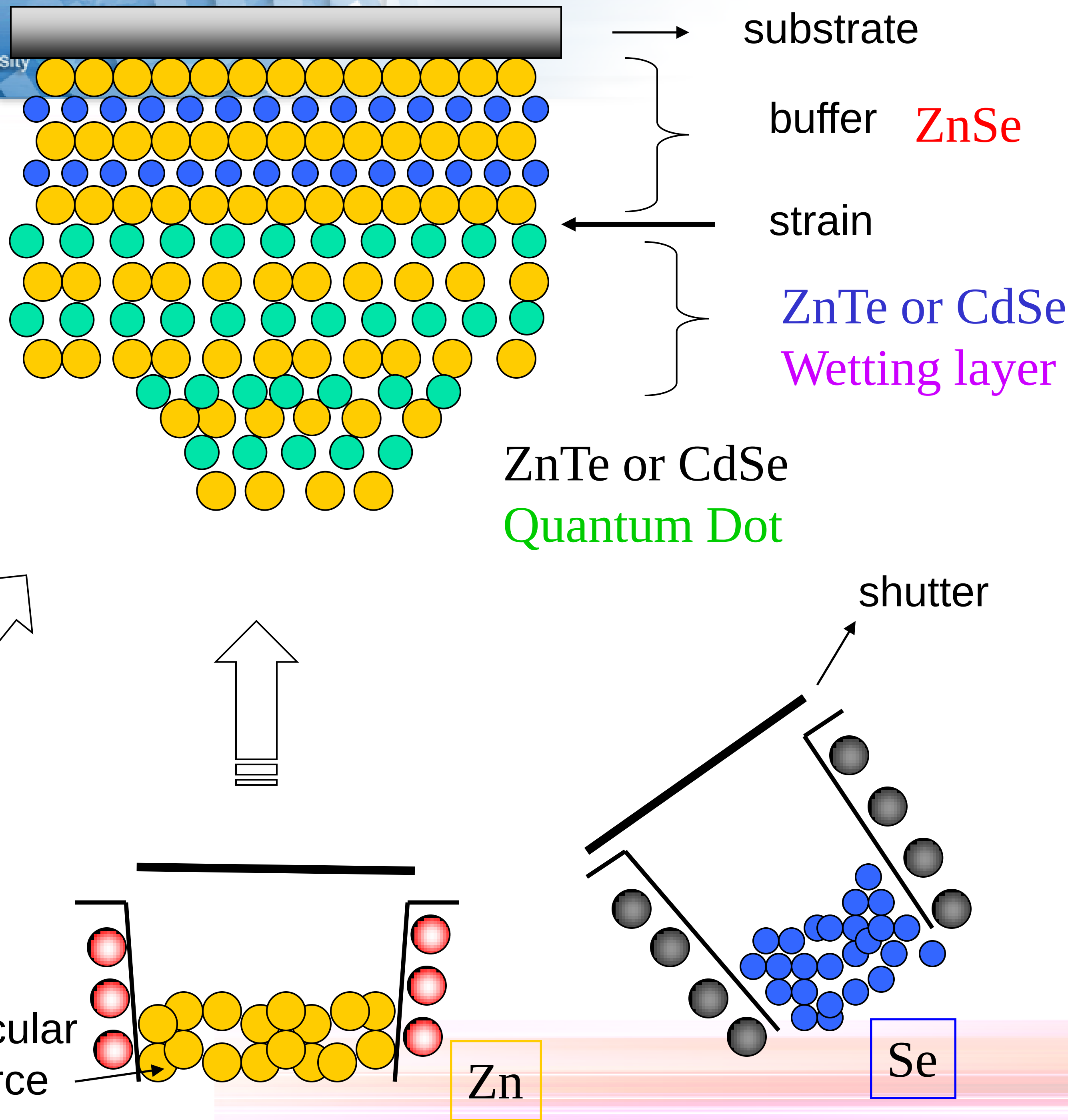
Veeco Applied EPI 620 molecular beam epitaxy (MBE) system

Molecular Beam Epitaxy System

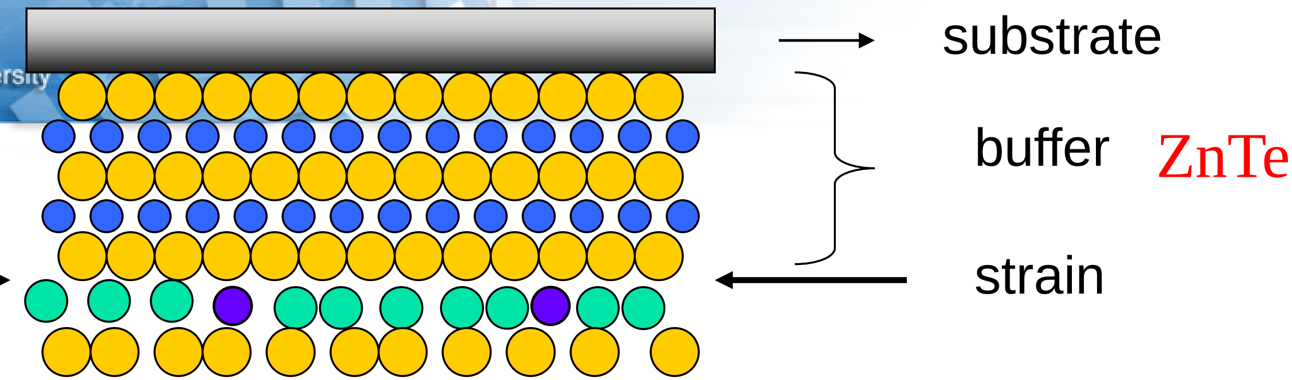


Alternating supply MBE

Atomic Layer Epitaxy (ALE)



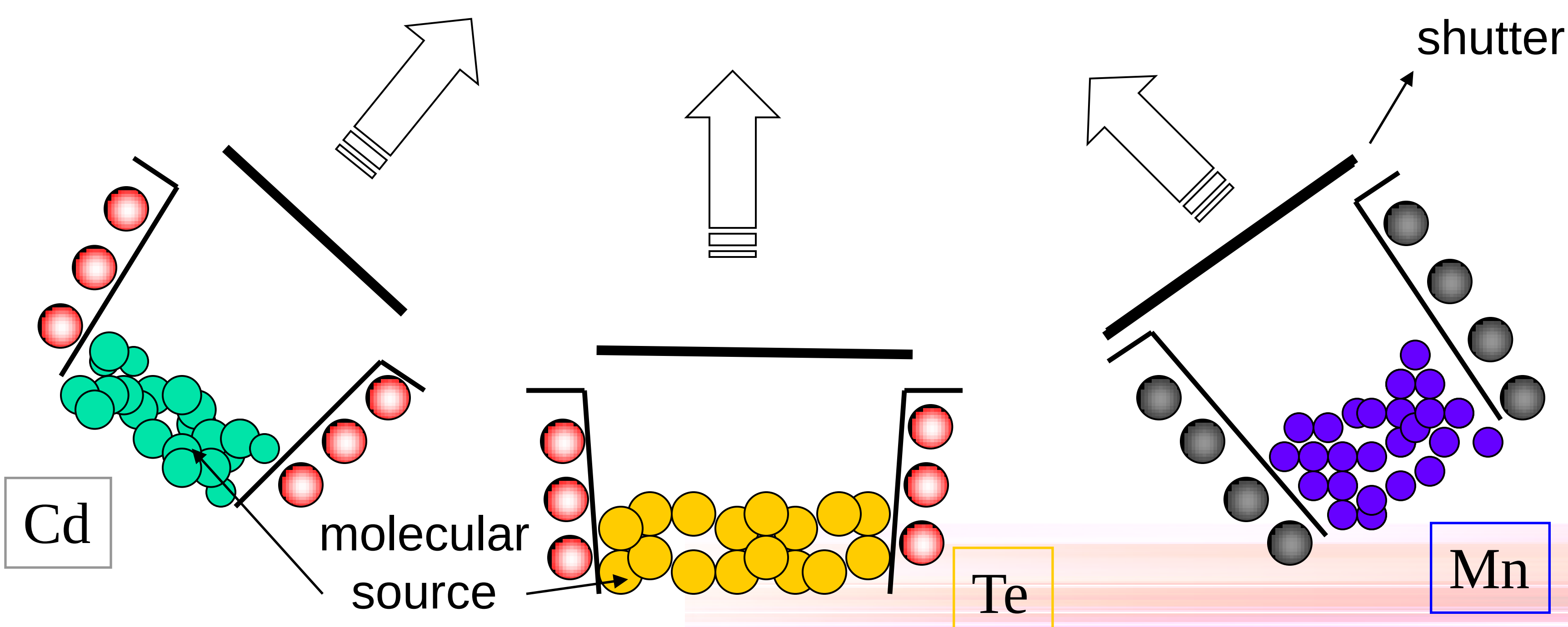
Y. Terai et al.
APL 76, 2400

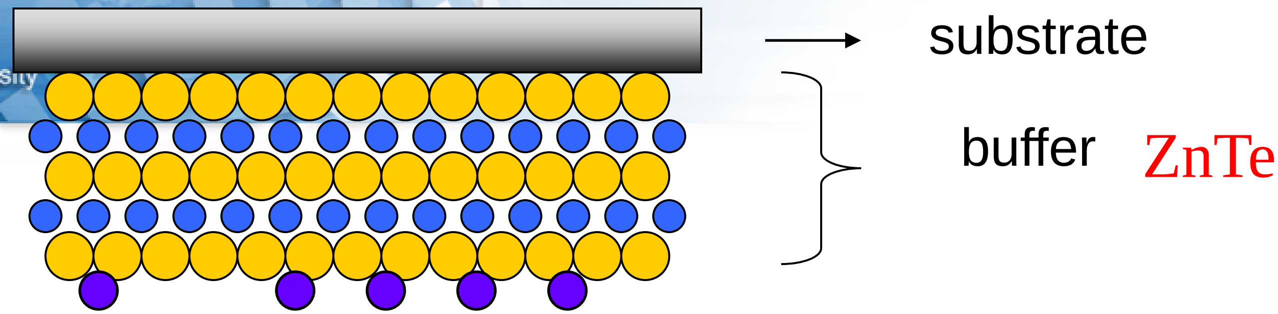


conventional

Alternating supply MBE

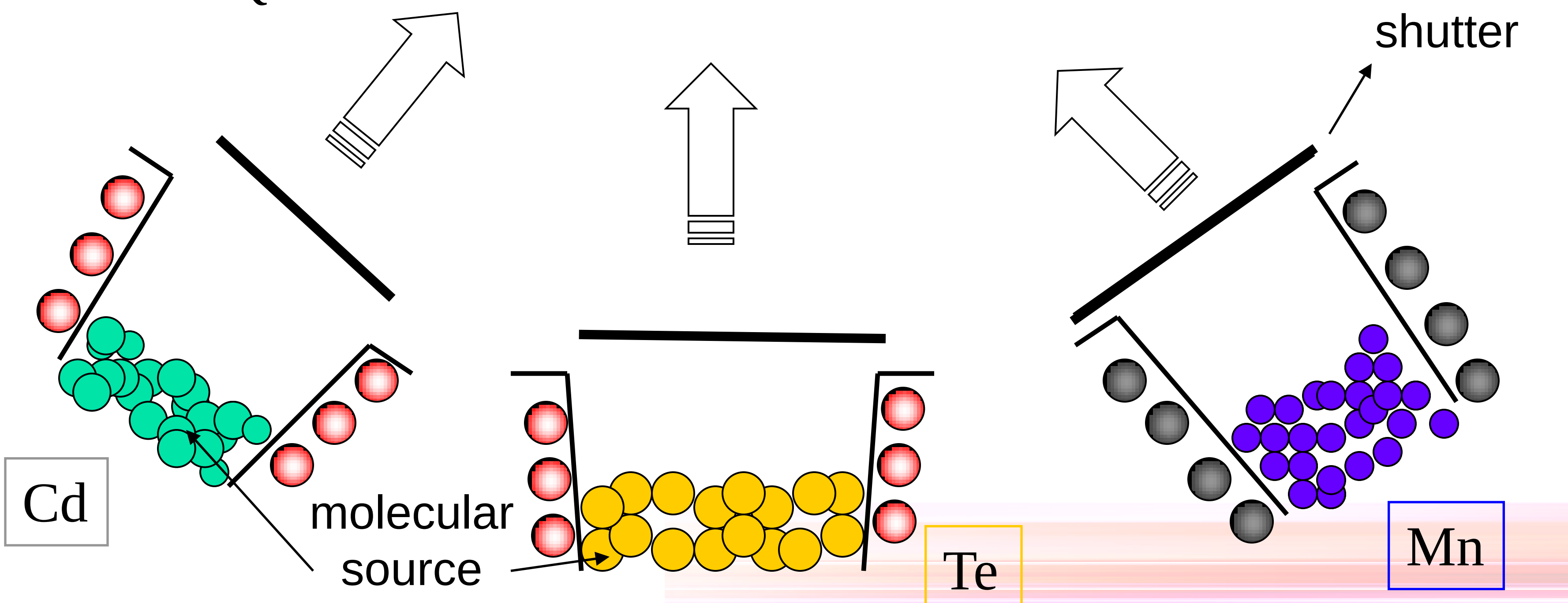
Atomic Layer Epitaxy
(ALE)



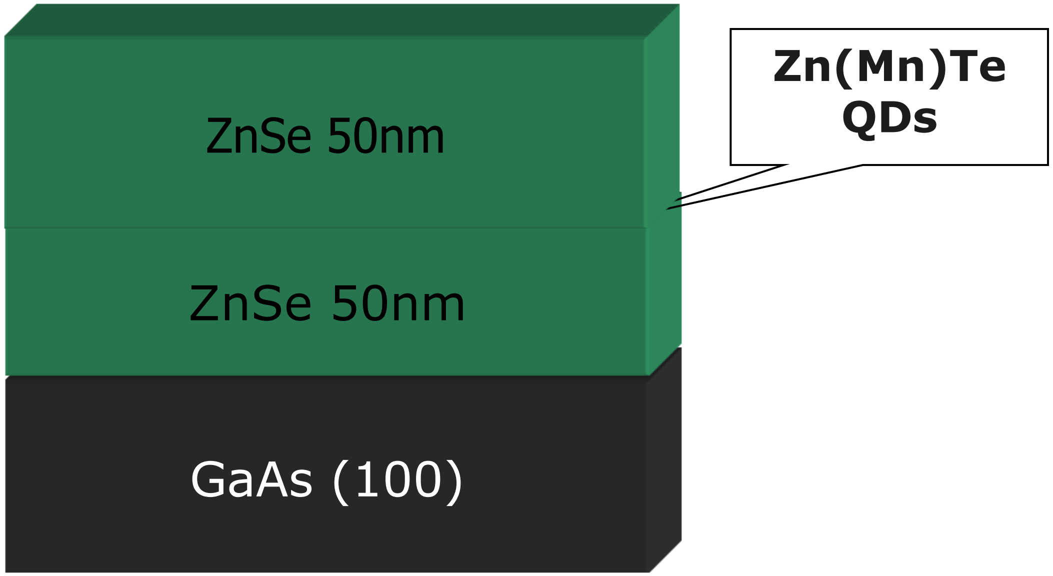


S. Mackowski et al.
APL83, 3575
ZnTe surface
passivation by Mn

L.V. Titova et al.
ZnSe surface
passivation by Mn
For CdMnSe QDs

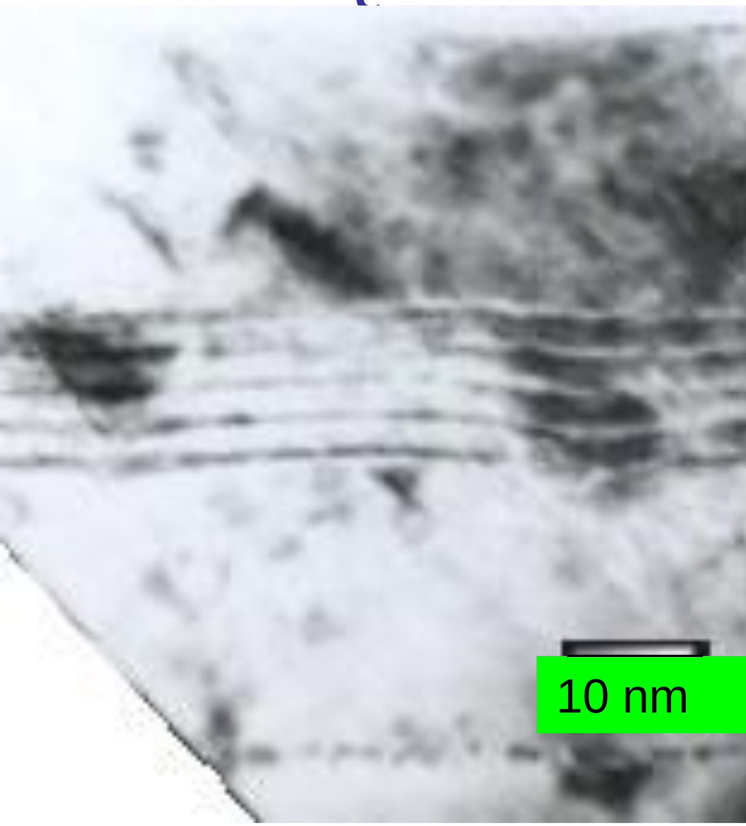


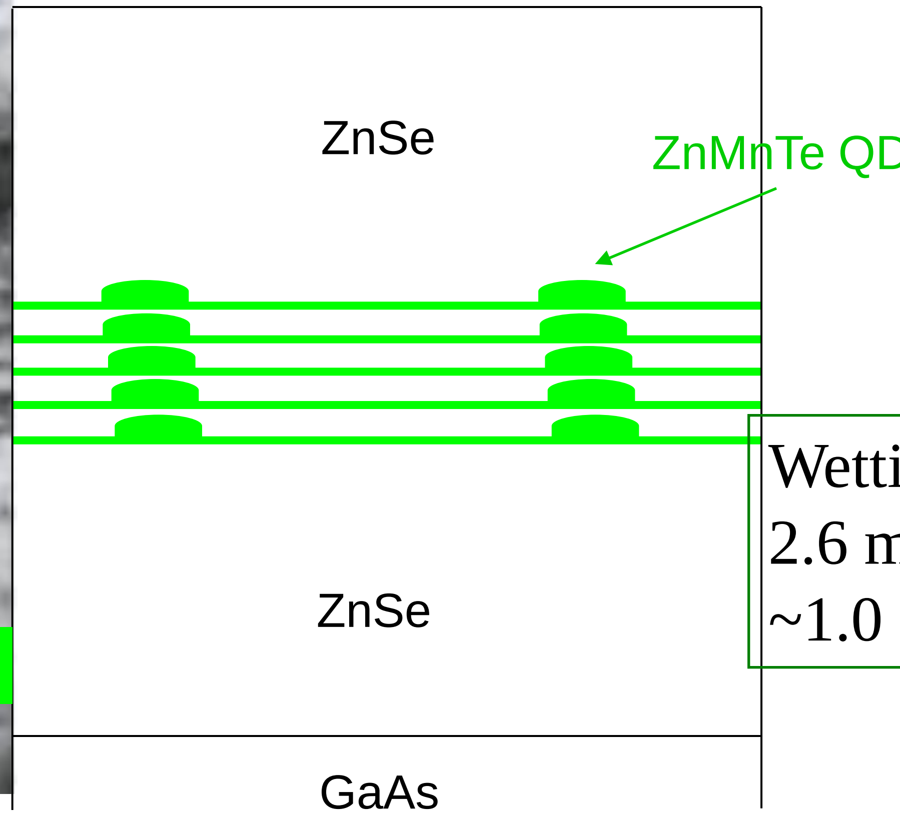
Sample list



ZnMnTe QDs coverage = 1.8, 2.0, 2.2, 2.4, 2.5, 2.6, 2.8, and 3.0 MLs

Cross-section TEM of 2.6 ML ZnMnTe MQDs



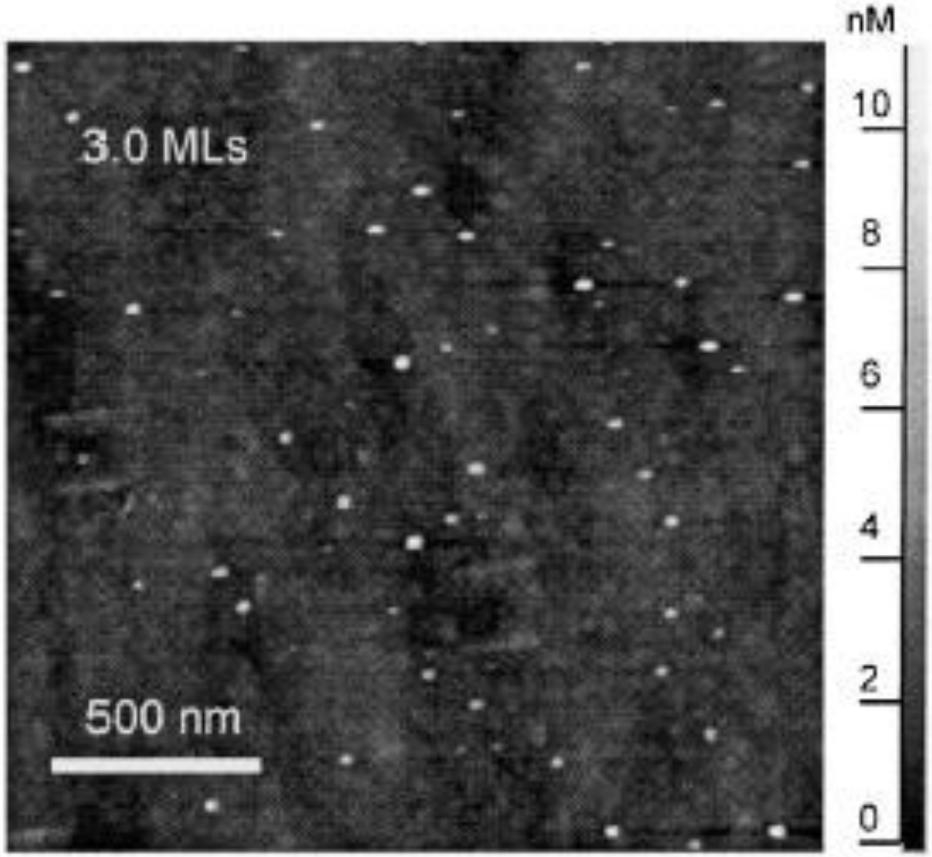


Wetting layer
2.6 monolayers
~1.0 nm

Stranski-Krastanow (SK), 2-D to 3D growth mode

Vertical correlation.

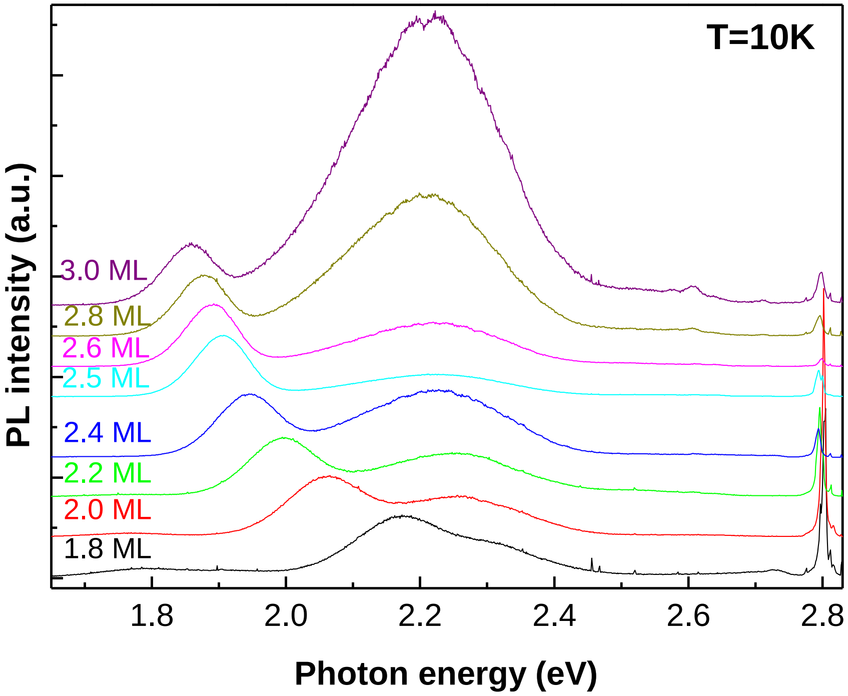
Stranski-Krastanow (SK), 2-D to 3D growth mode

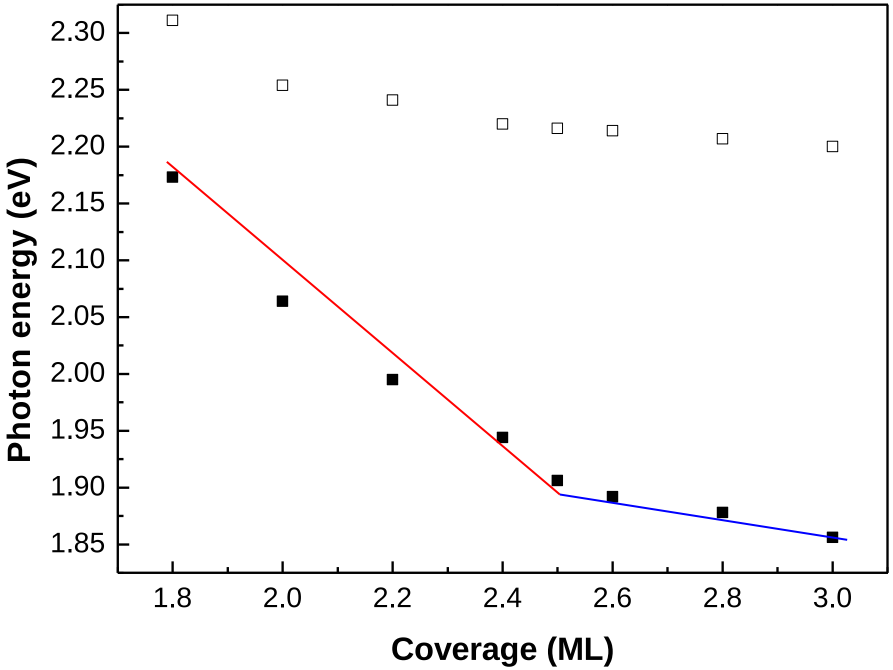


AFM plain view image of ZnTe QDs with 3.0 MLs.

C.S. Yang et al., JAP v94, 033514 (2005) grown by MBE

PL spectra of ZnMnTe QDs at 10K

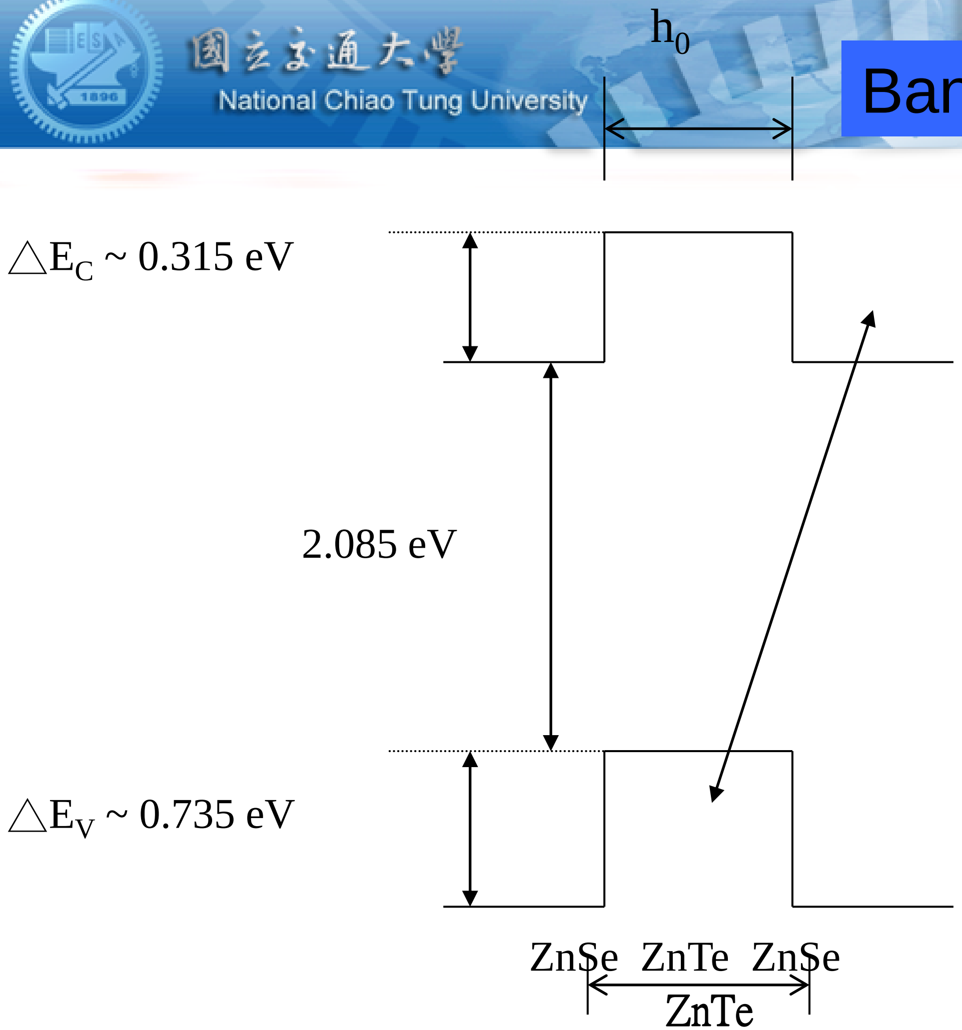


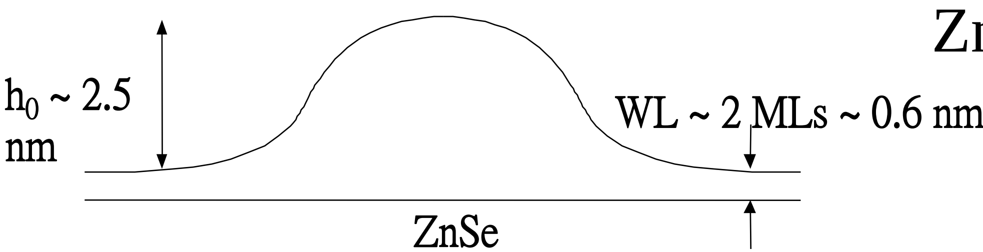


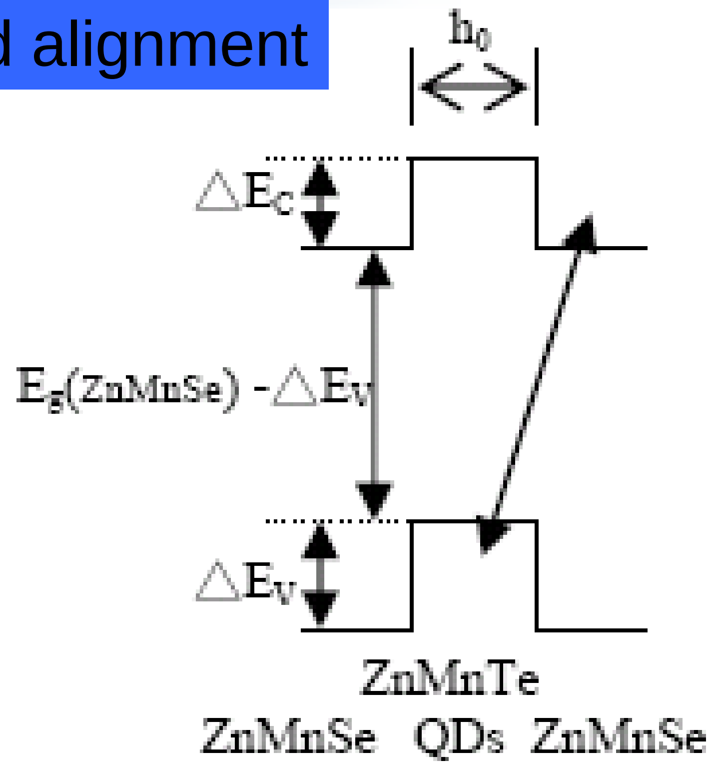
Band diagram of type II: ZnMnTe/ZnSe QDs

Band gaps of ZnTe or ZnMnTe are larger than 2.4 eV.

Band alignment



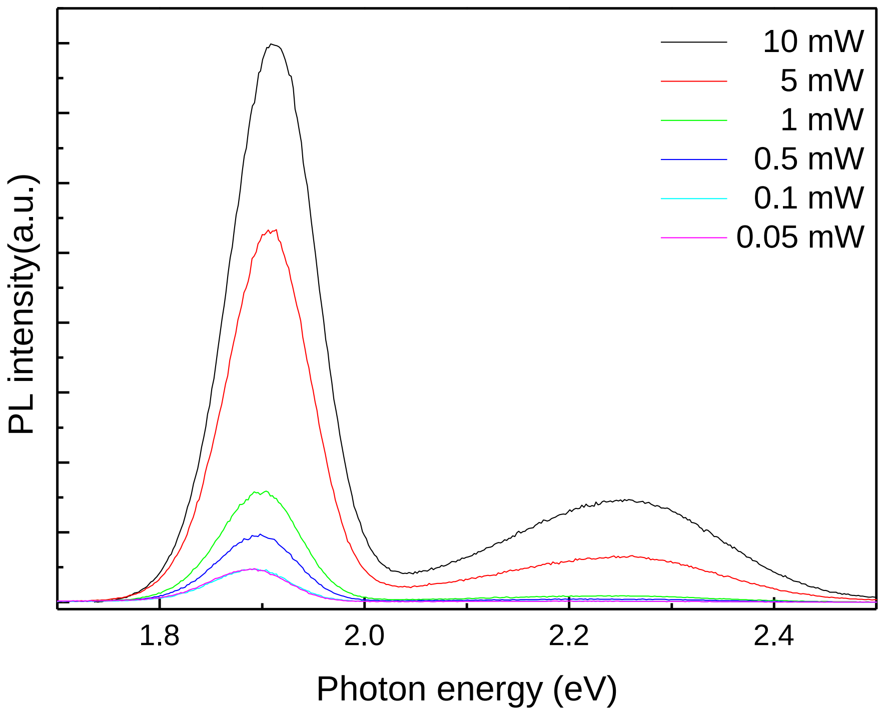


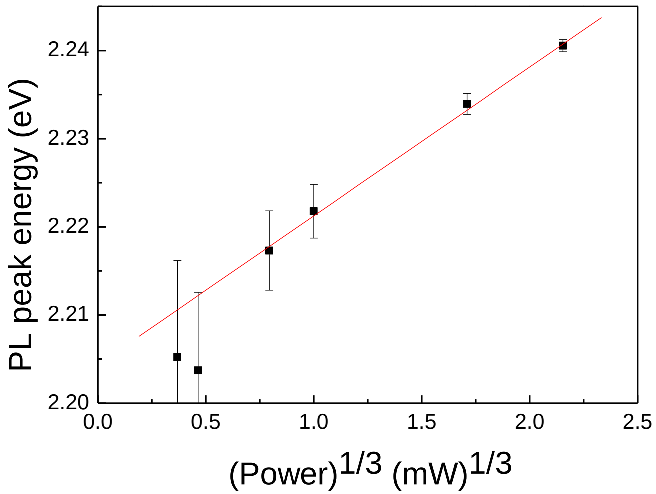


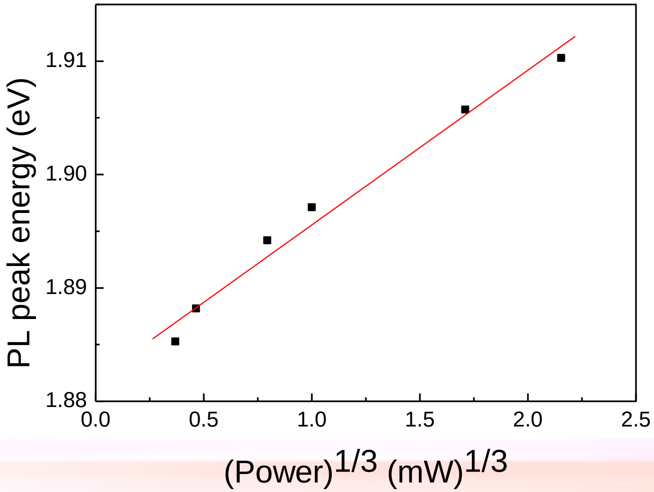
Band diagram of type II
ZnTe/ZnSe QDs
ZnMnTe/ZnMnSe QDs

Johnson Lee et al., *Phys. Stat. Sol. (b)* **241**, 3532-3543 (2004).

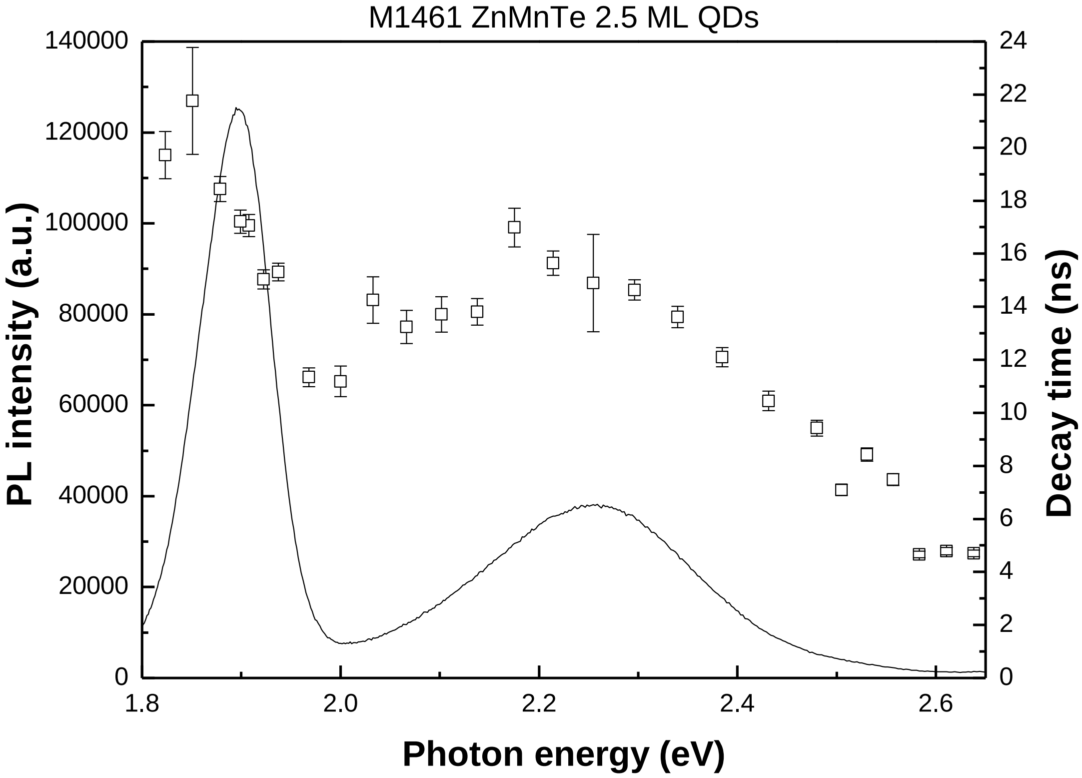
Power dependent PL of ZnMnTe QDs

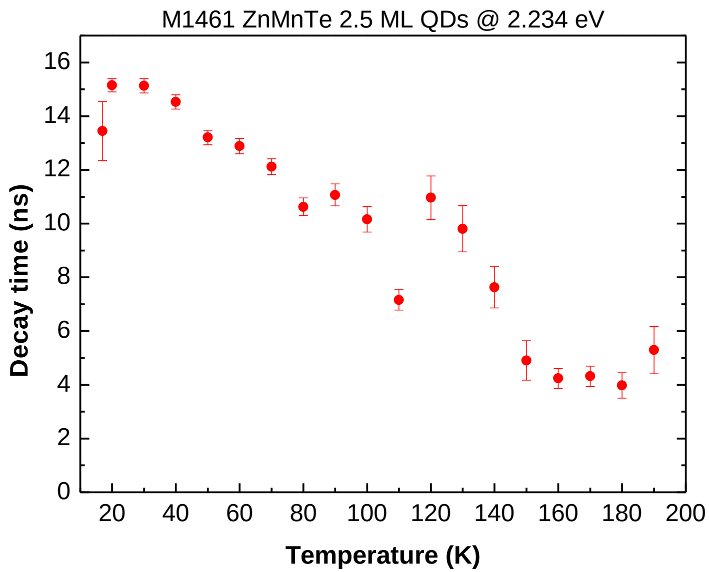


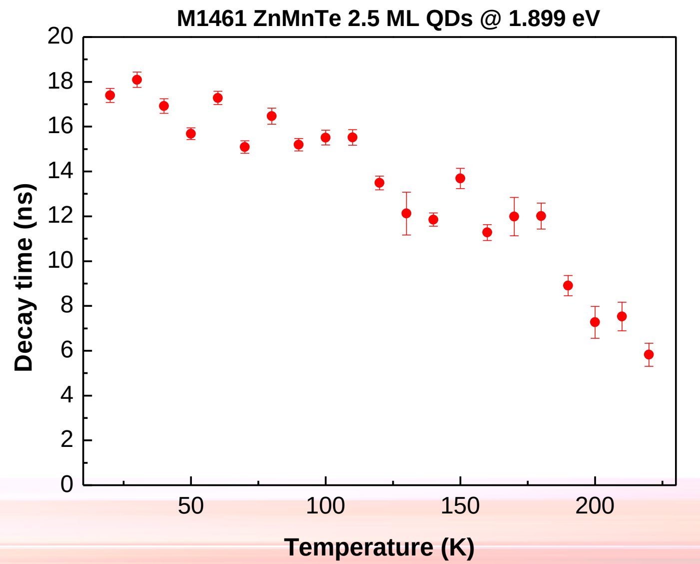




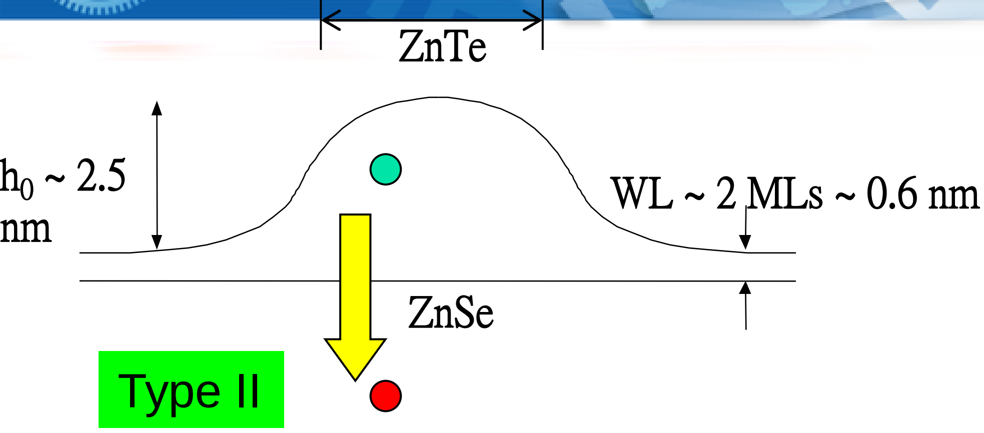
Time resolved photoluminescence of 2.5 ML ZnMnTe QDs



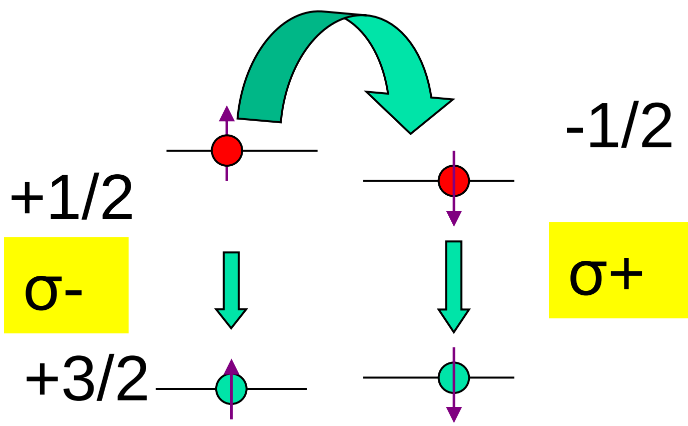


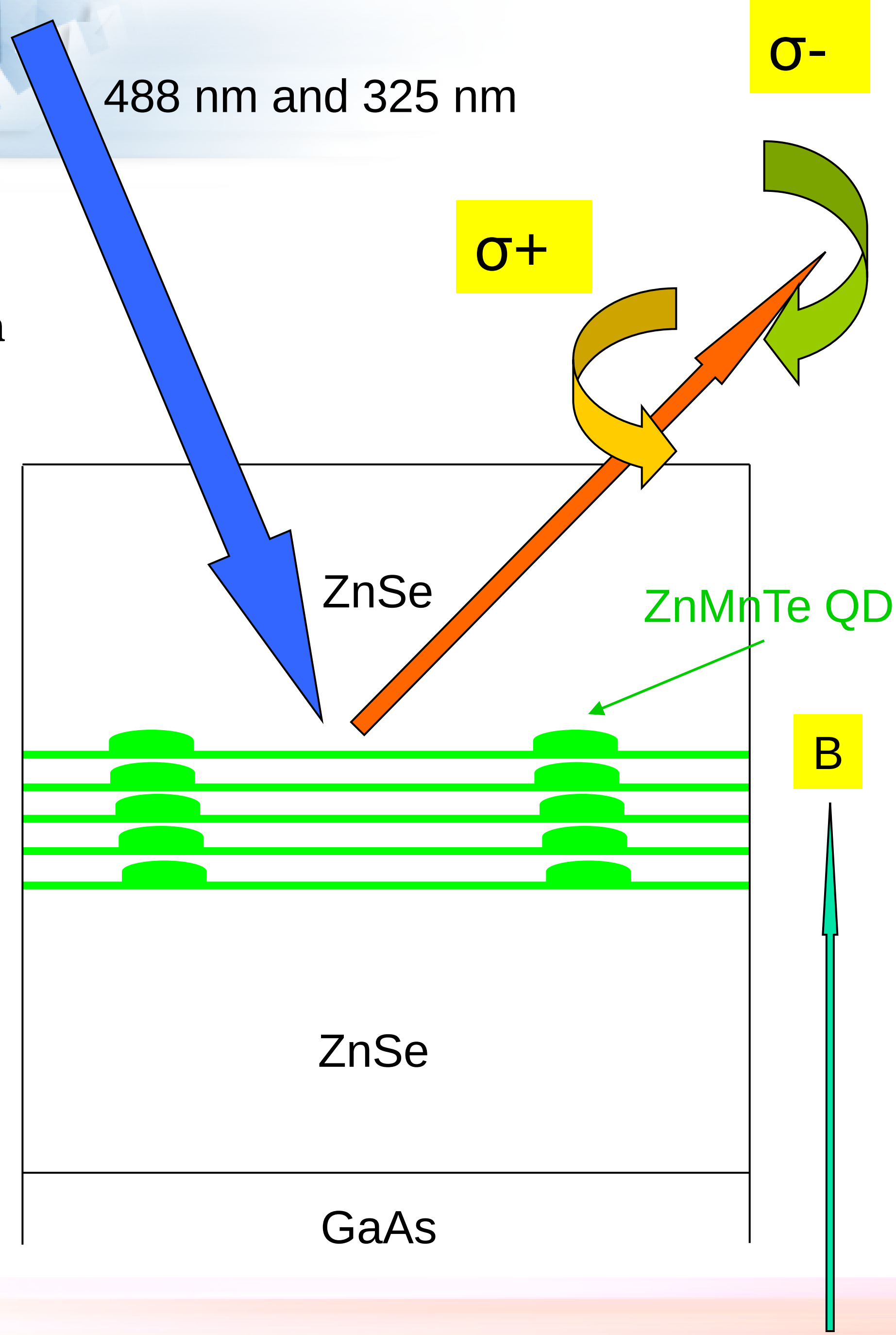


Type II band alignment:
long recombination time

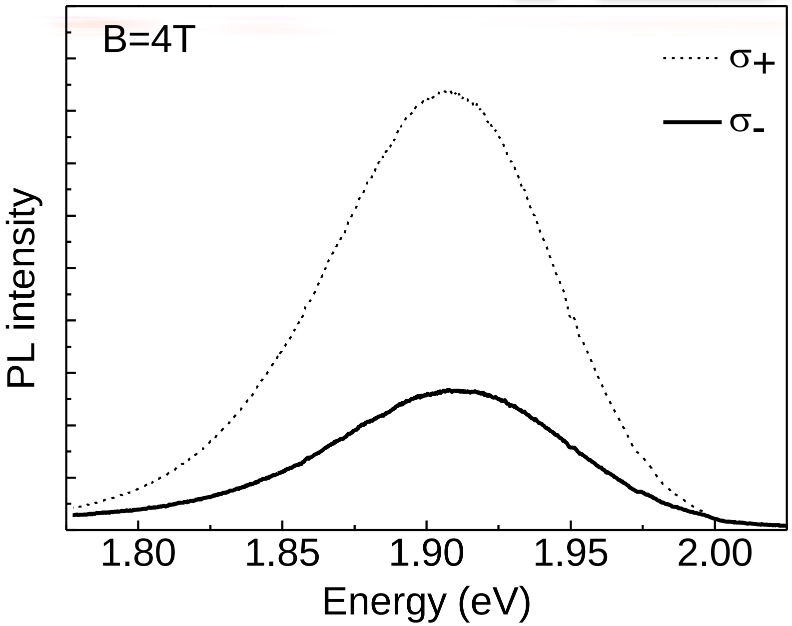


Spin relaxation





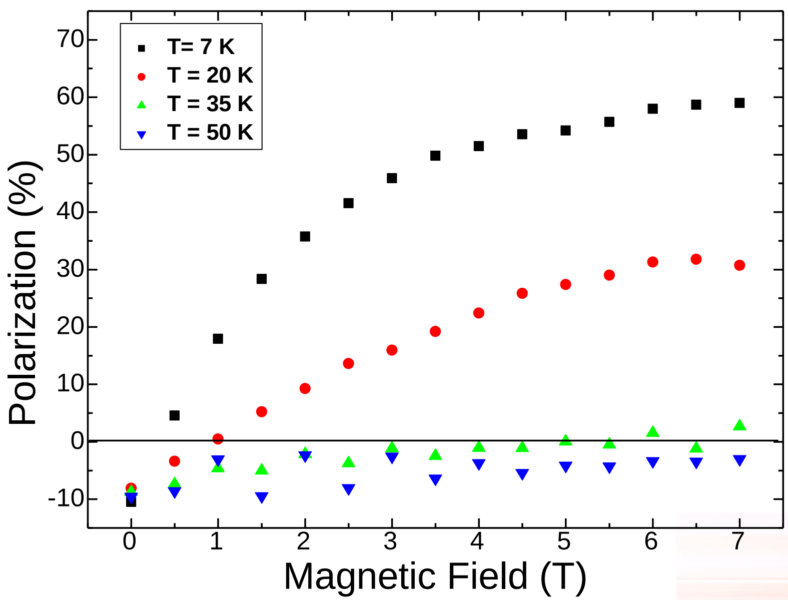
polarization as a function of magnetic field B

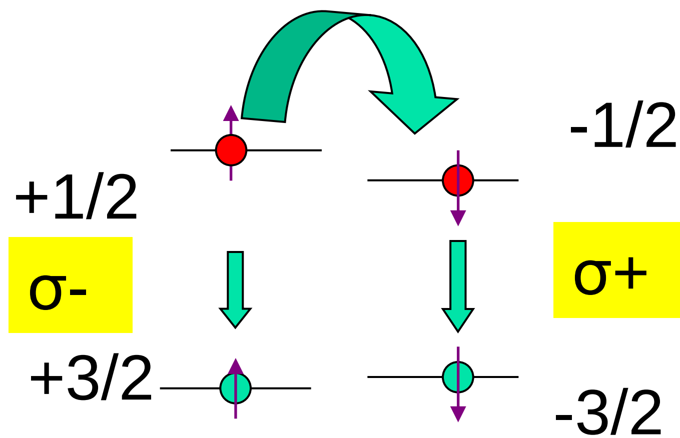


$$dn_-/dt = g_- - n_-/\tau_r - n_-/\tau_s + n_+e^{(-\Delta E/kT)}/\tau_s$$

$$dn_+/dt = g_+ - n_+/\tau_r - n_+e^{(-\Delta E/kT)}/\tau_s + n_-/\tau_s$$

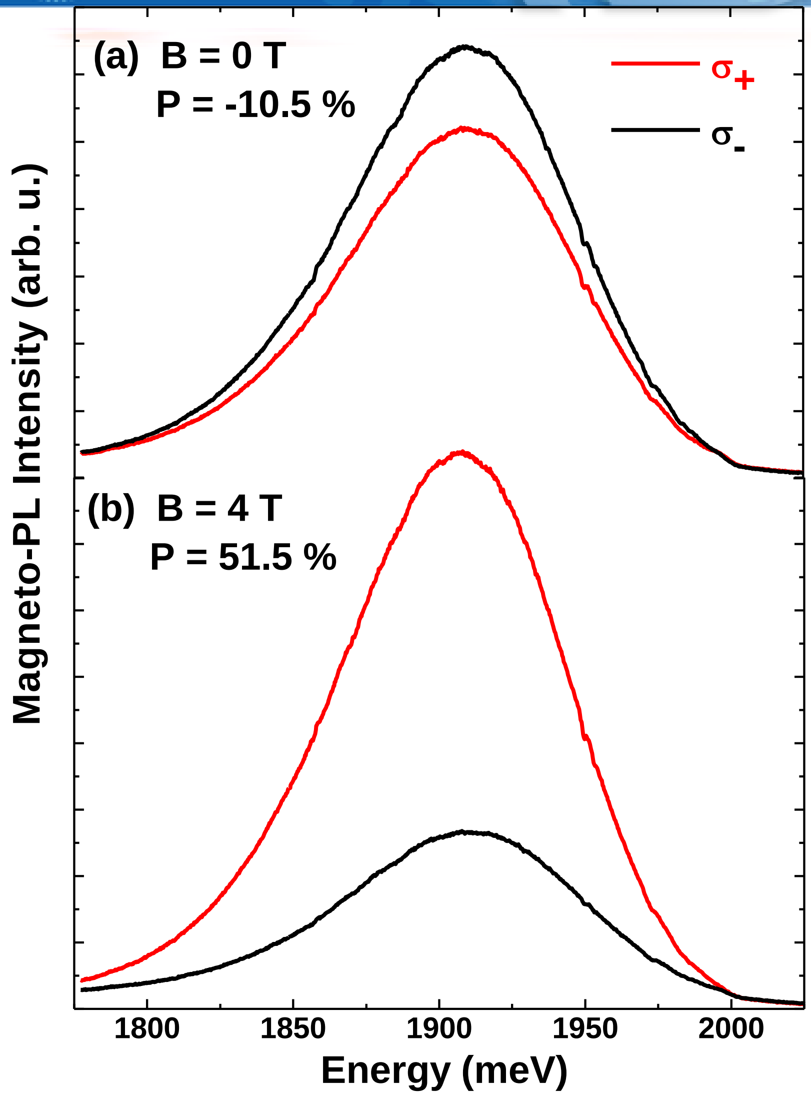
At B=8T,
$P=(I_+-I_-)/(I_++I_-)=60\%$
$\tau_s \sim \tau_r \sim$ ns

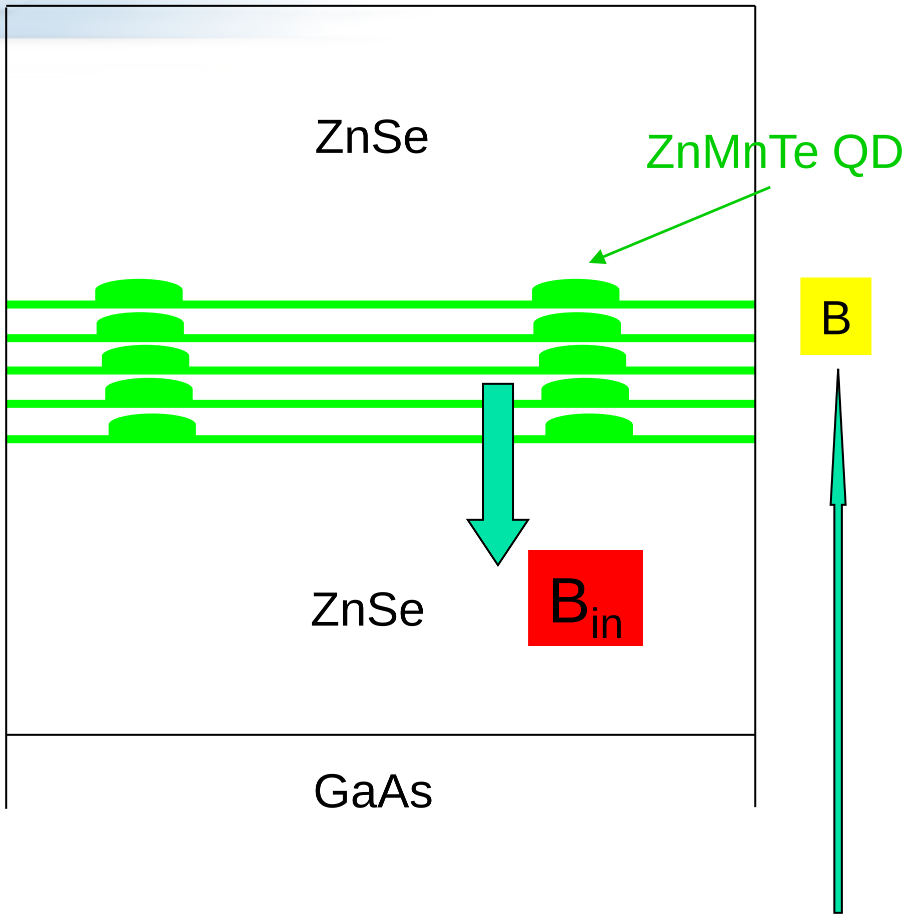




Small thermal energy to randomize spin orientation

non-zero polariation at B=0





Non-zero polarization was also observed in ZnTe/ZnSe QDs

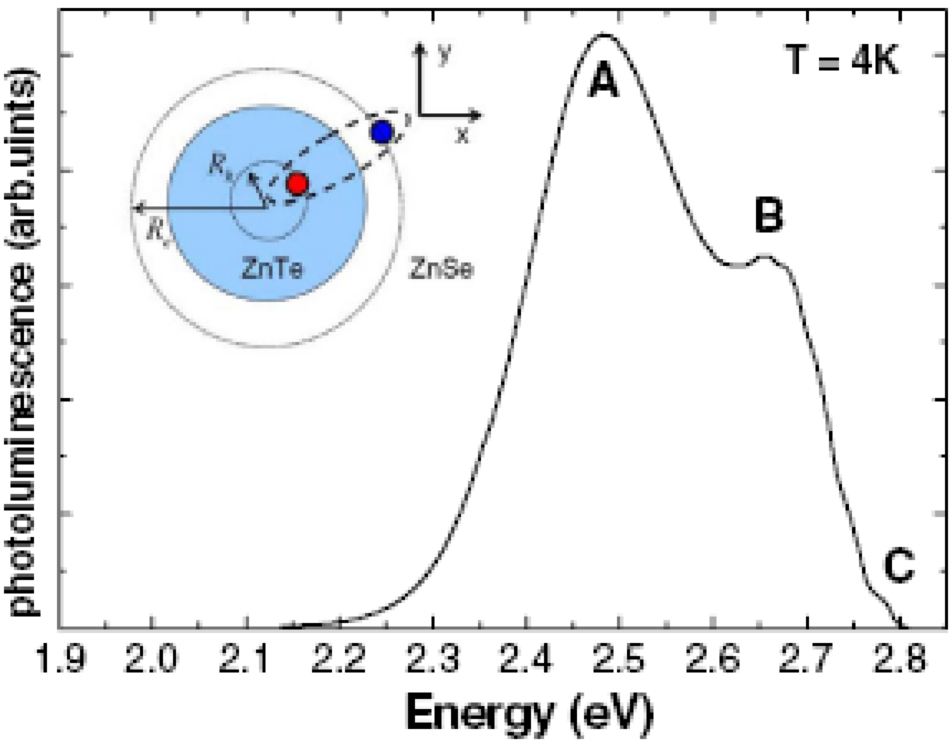
國立交通大學
National Chiao Tung University

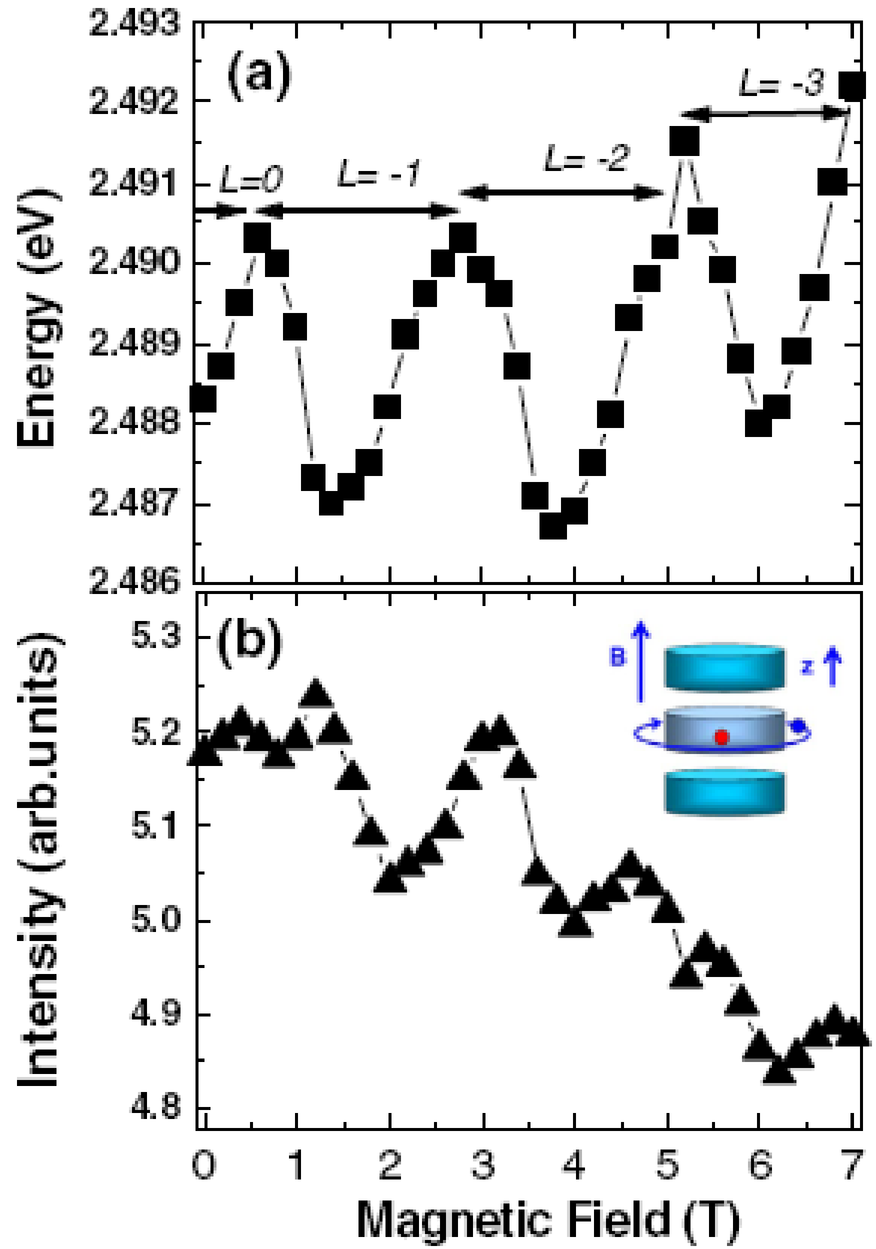
Aharonov-Bohm Excitons at Elevated Temperatures in Type-II ZnTe/ZnSe Quantum Dots

I. R. Sellers, V. R. Whiteside, I. L. Kuskovsky, A. O. Govorov, and B. D. McCombe

Phys. Rev. Lett. **100,** 136405 (2008)

$$E_{exc} = E_g + \frac{\hbar^2}{2MR_0^2}\left(L + \frac{\Delta\Phi}{\Phi_0}\right)^2,$$

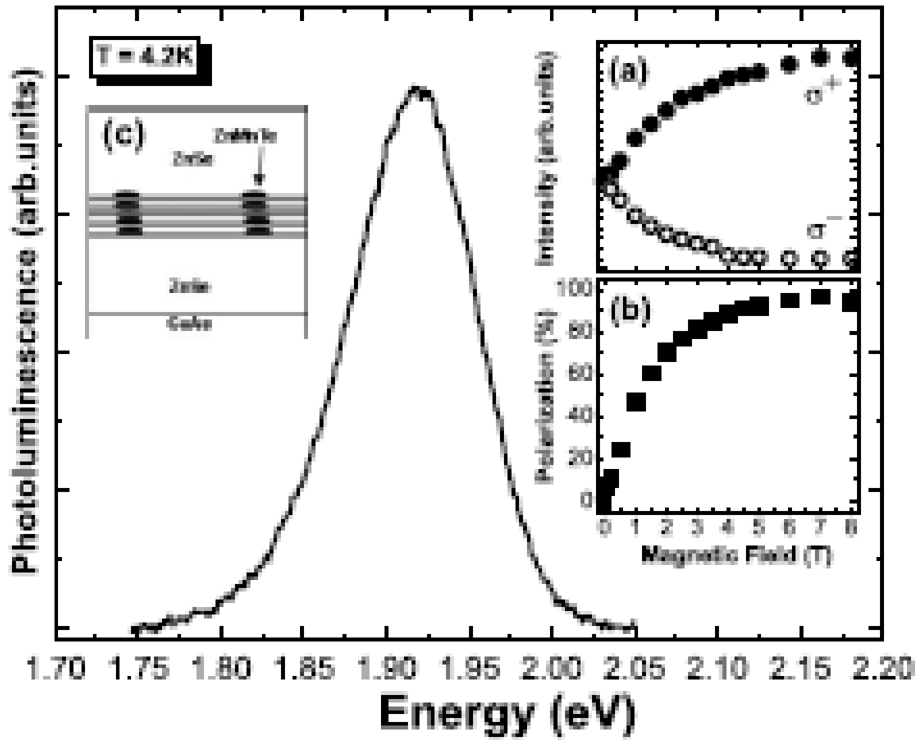




Coherent Aharonov-Bohm oscillations in type-II (Zn,Mn)Te/ZnSe quantum dots

PHYSICAL REVIEW B **77**, 241302R 2008

I. R. Sellers, V. R. Whiteside, A. O. Govorov, W. C. Fan, W-C. Chou, I. Khan, A. Petrou, and B. D. McCombe



$$E_{exc} = E_g + \frac{\hbar^2}{2MR_0^2}\left(L + \frac{\Delta\Phi}{\Phi_0}\right)^2,$$

$$\bar{M}_z = \langle M_z \rangle = S \cdot g_{\mathrm{Mn}} \cdot \mu_B \cdot B_{5/2}(x) \quad \text{and} \quad \sqrt{\Delta M^2} = \sqrt{\langle (M_z - \bar{M}_z)^2 \rangle} = \sqrt{k_B T \frac{\partial \bar{M}_z}{\partial B}},$$