清華大學物理系 奈米物理特論 2013/0328 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

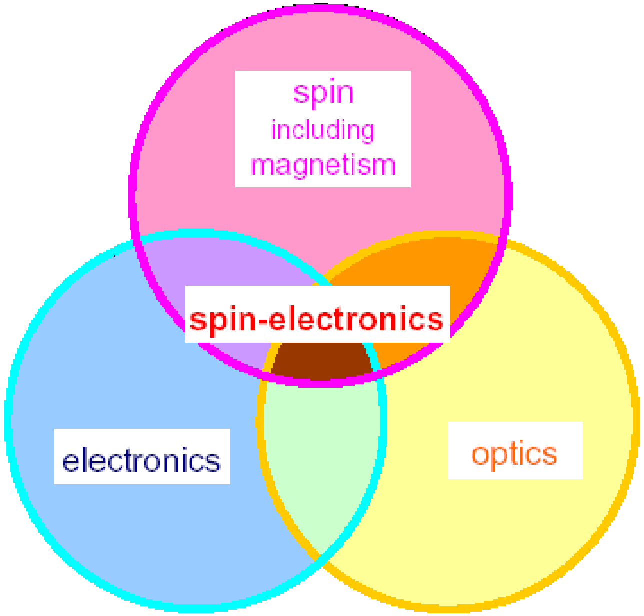
Part II: 半導體奈米結構光電特性---Photoluminescence

Part III: 半磁性半導體奈米結構之自旋磁光特性

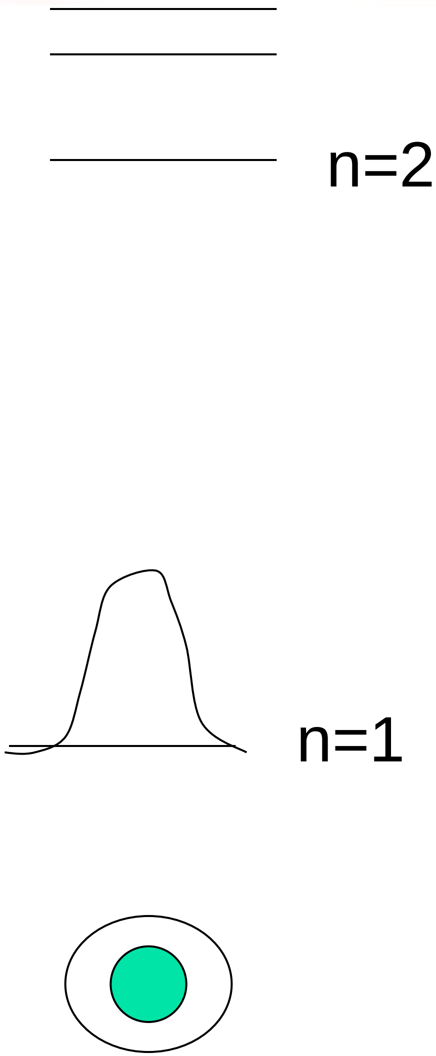
What is "Spin"?
How to manipulate spin?
How can we use "spin" to fabricate useful devices?

Outline

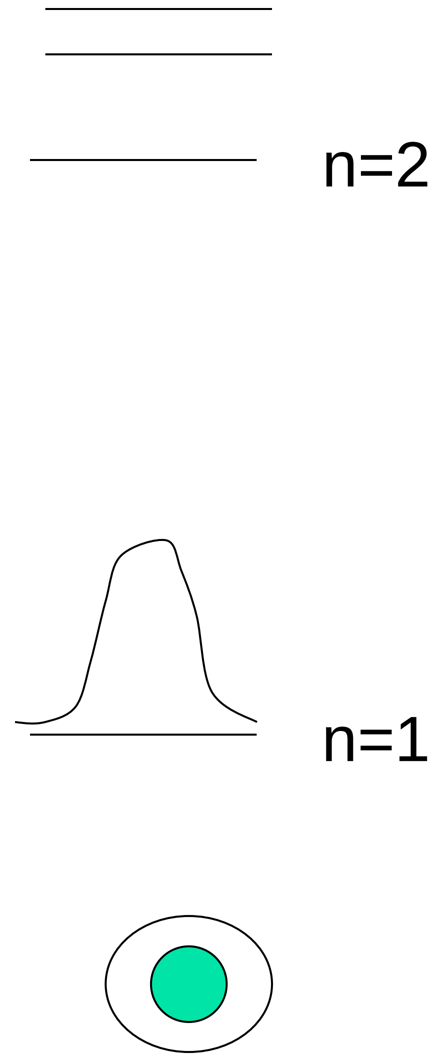
1. Introduction to II-VI diluted magnetic semiconductor (DMS) quantum dots (QDs).
   (比較III-V magnetic semiconductors)
2. Growth, structure and band alignment of ZnMnTe QDs.
3. Circular polarization measurement and spin dynamics.
4. Devices for spintronics
5. Conclusion.



加入錳Mn後能帶的變化
有甚麼特殊的光電特性?



Isolated hydrogen atom



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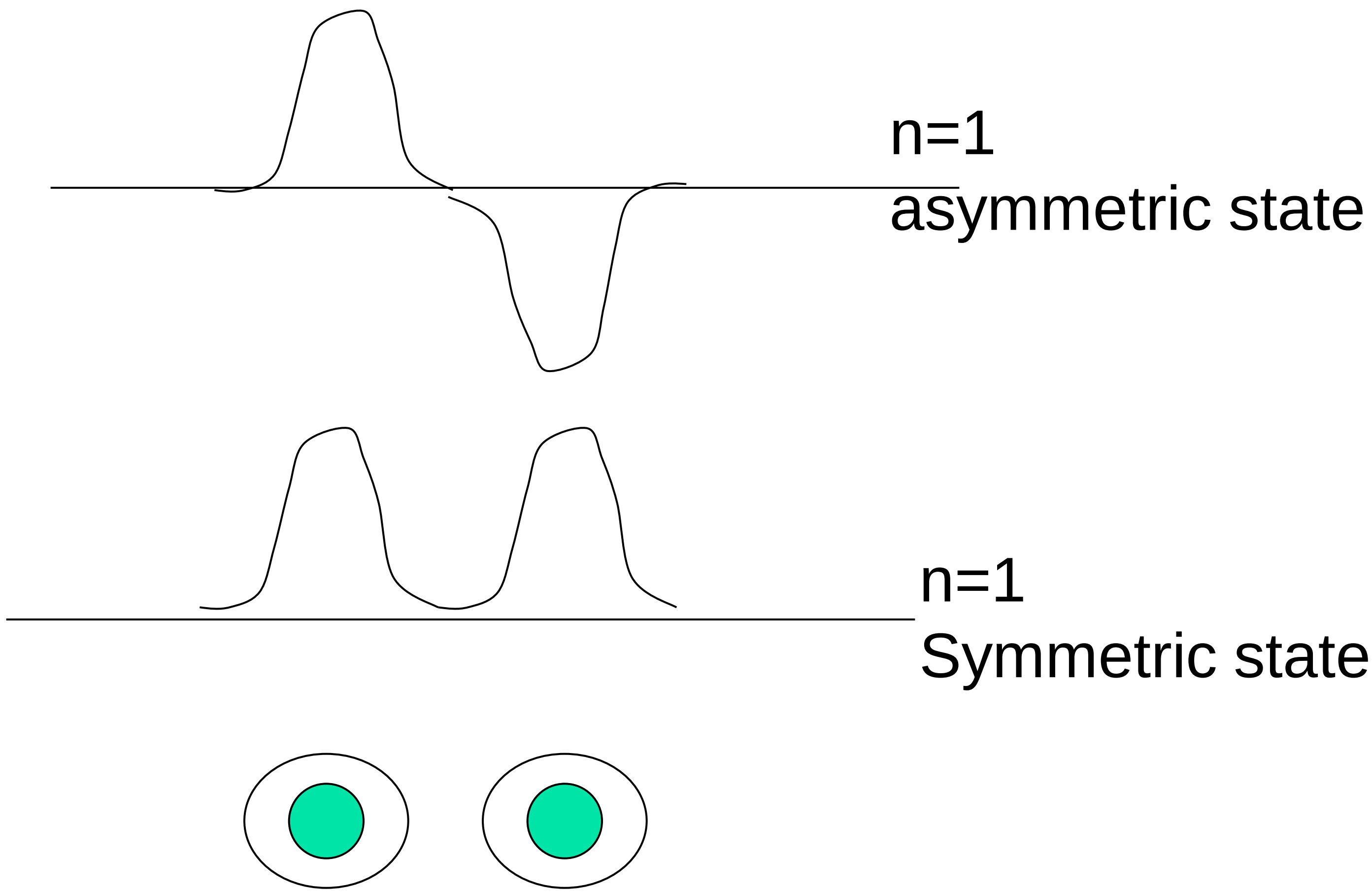

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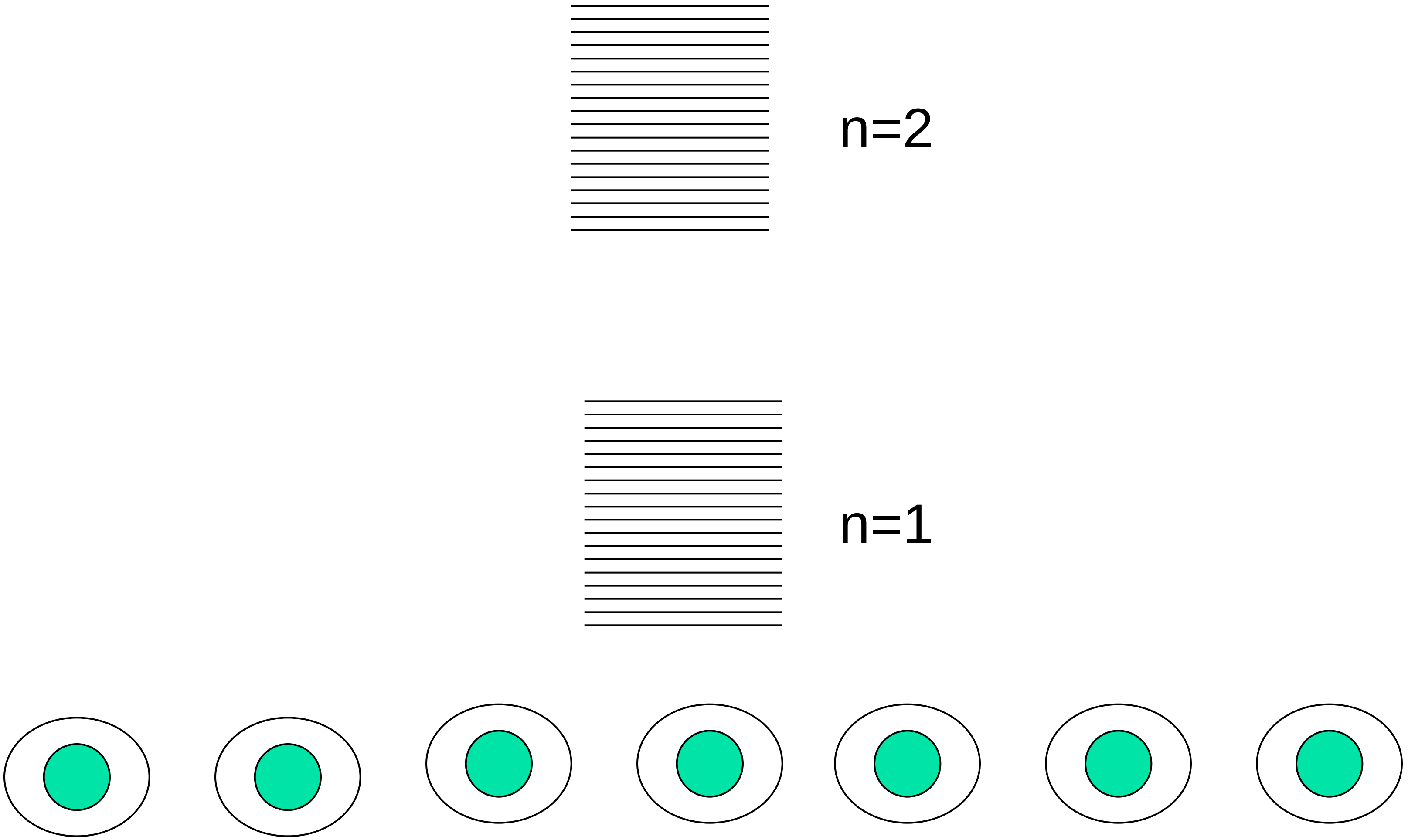

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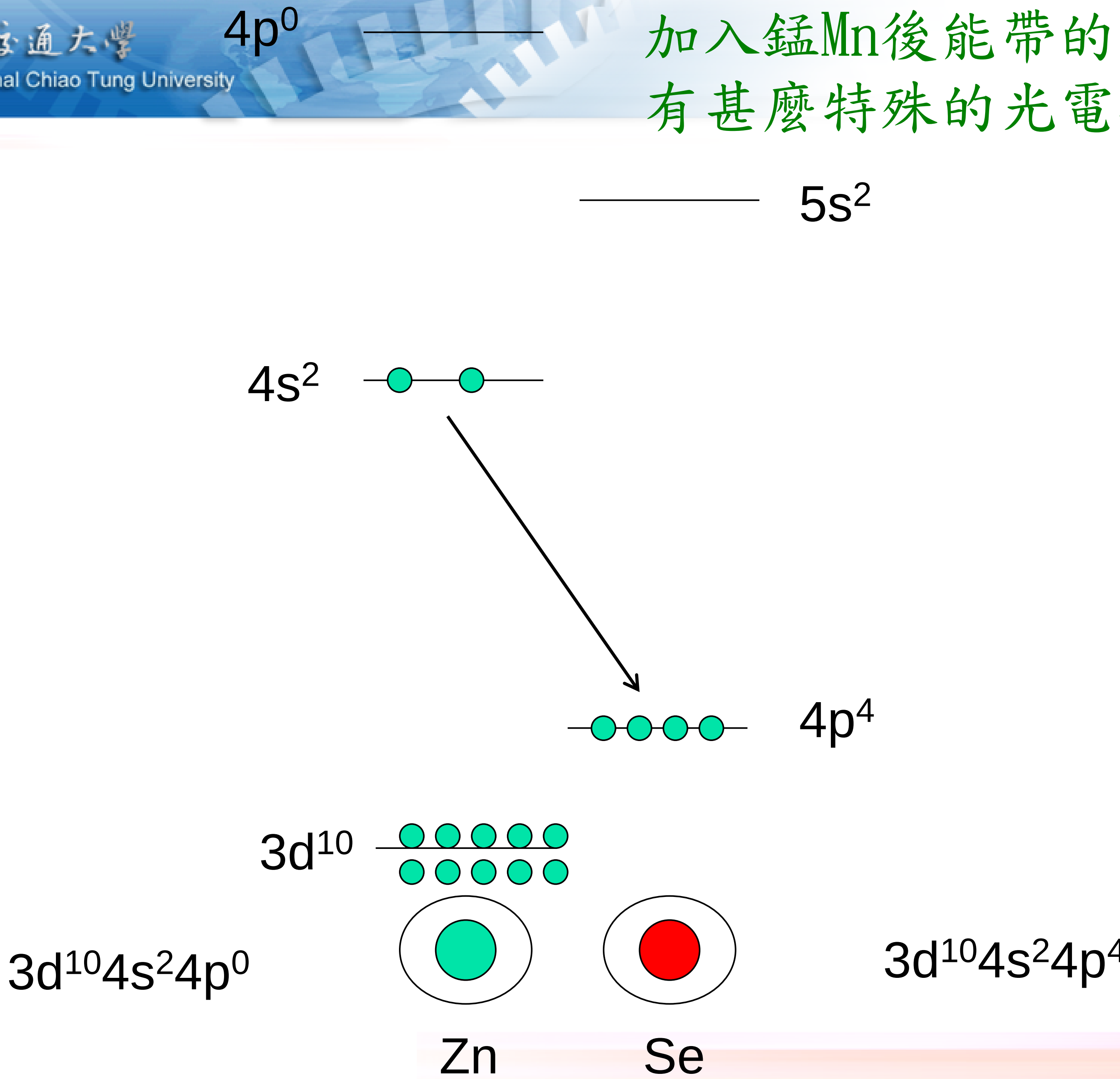

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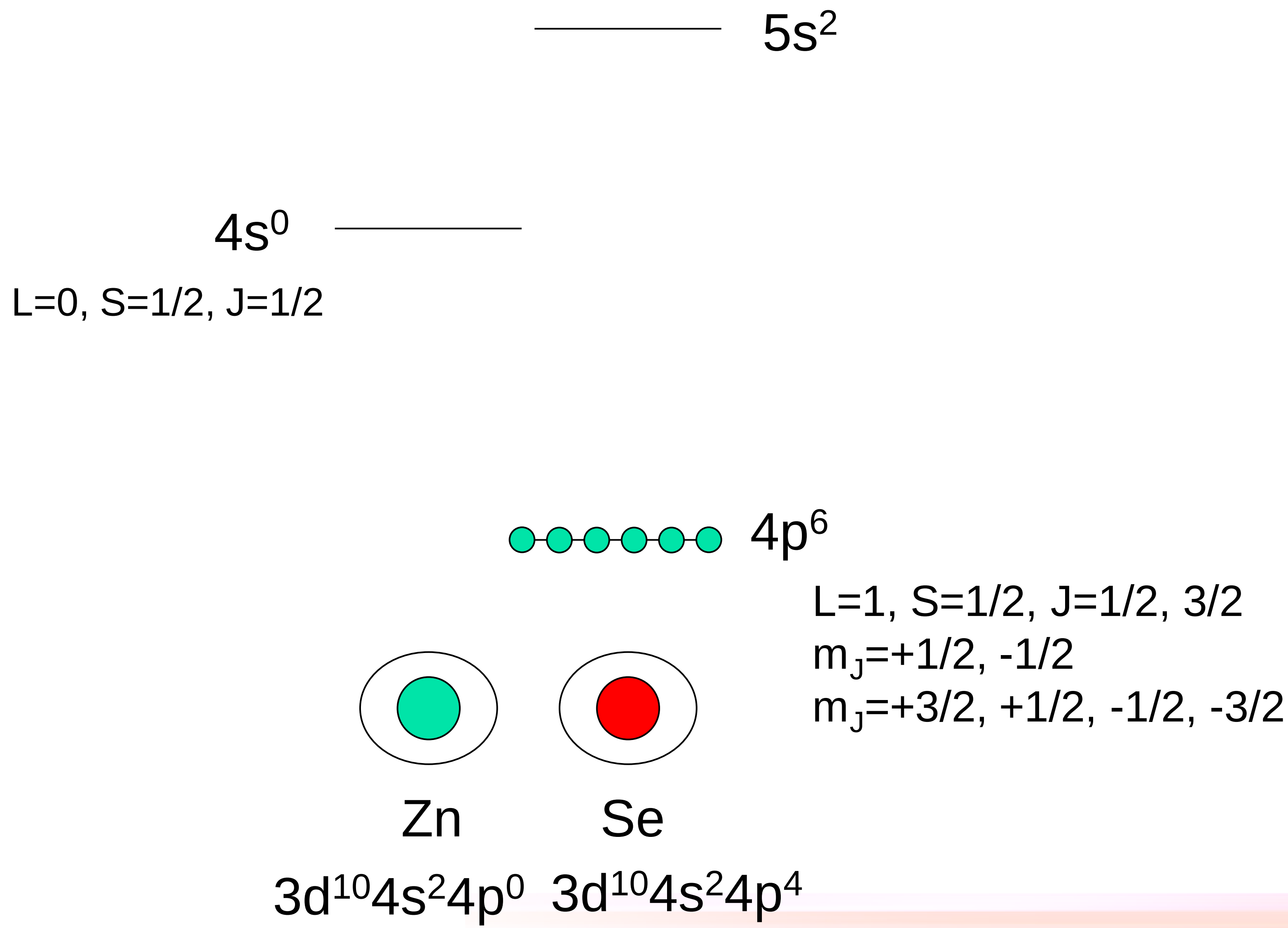

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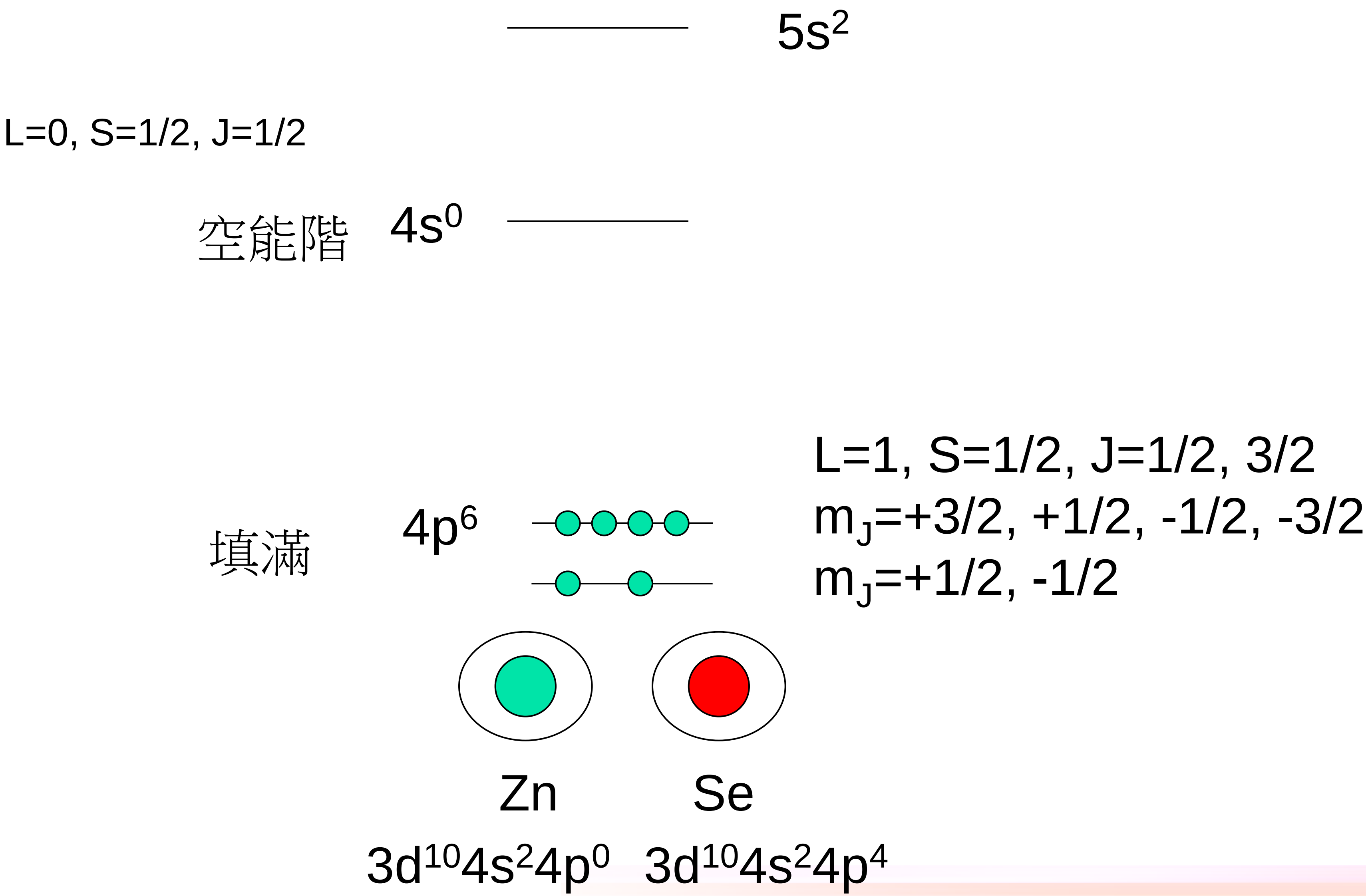

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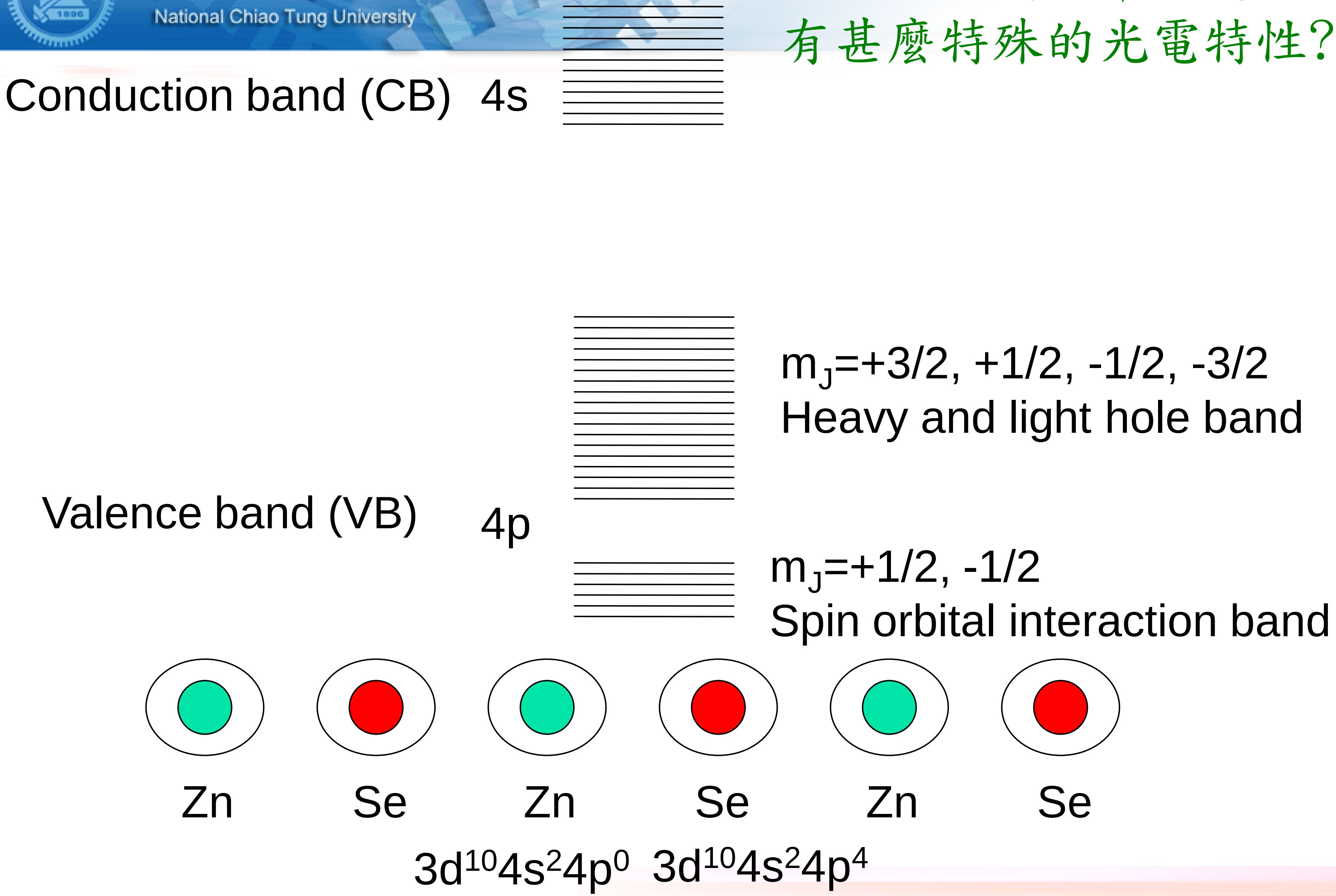

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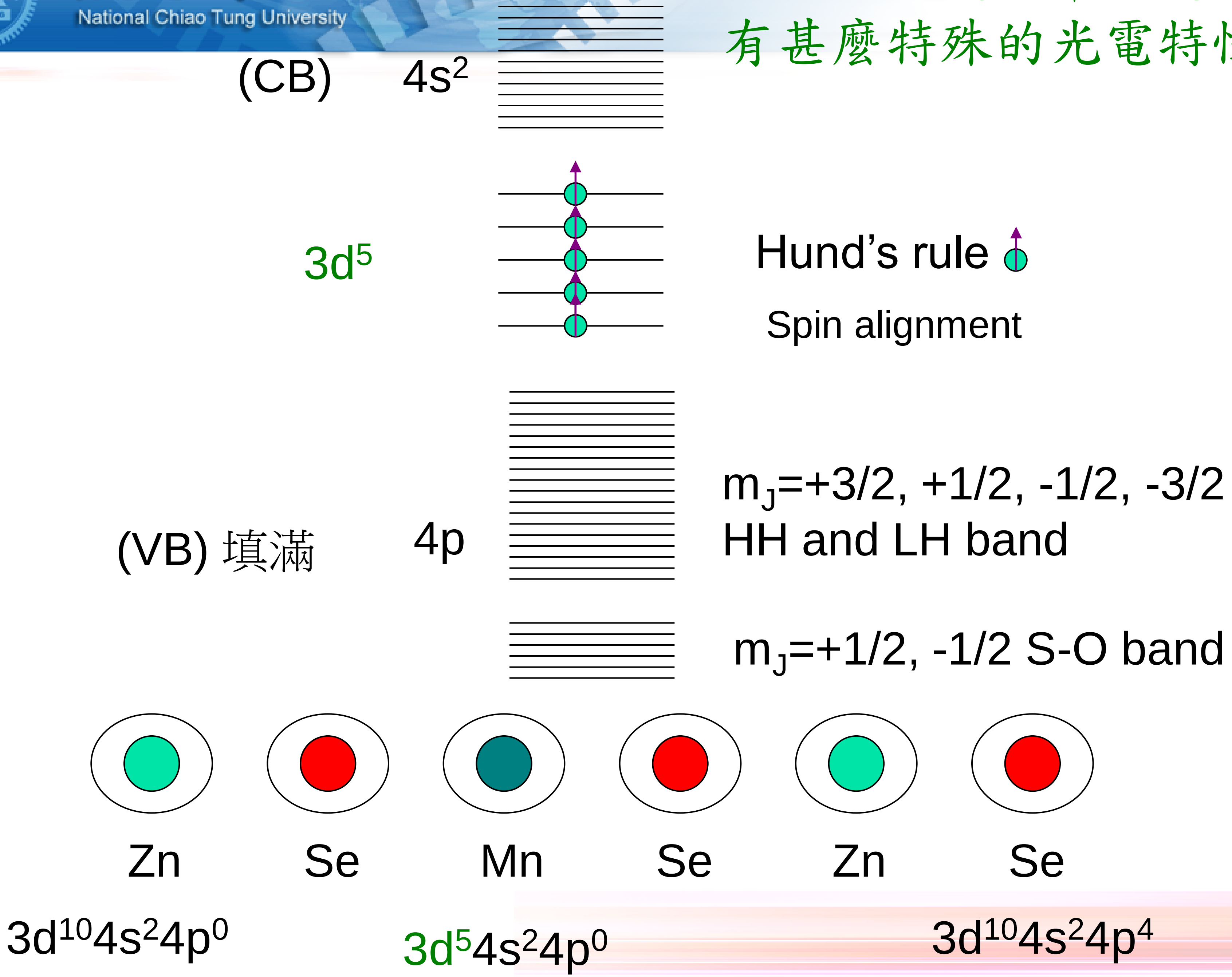

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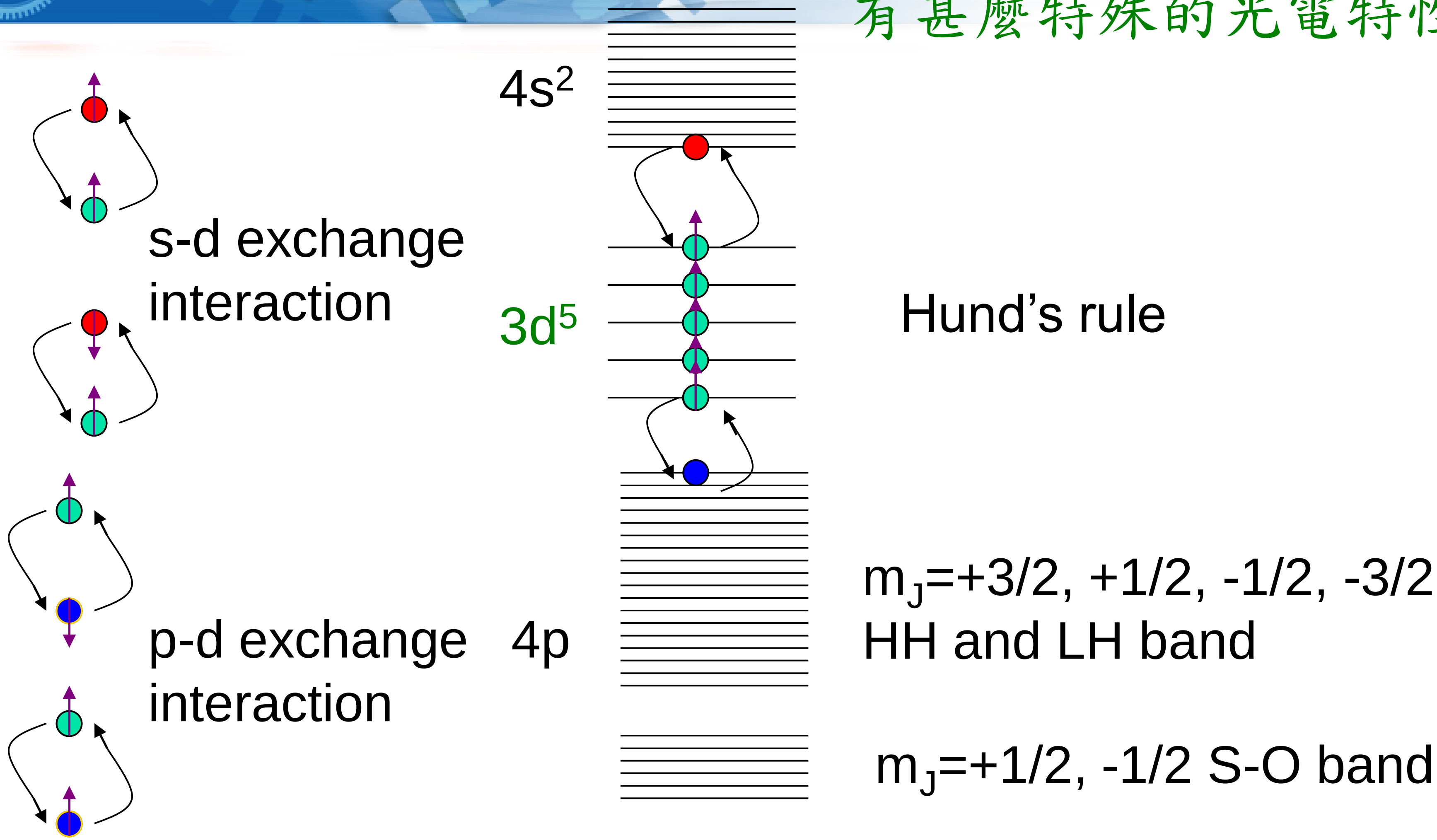
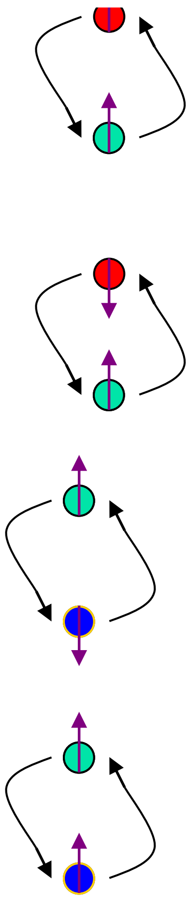


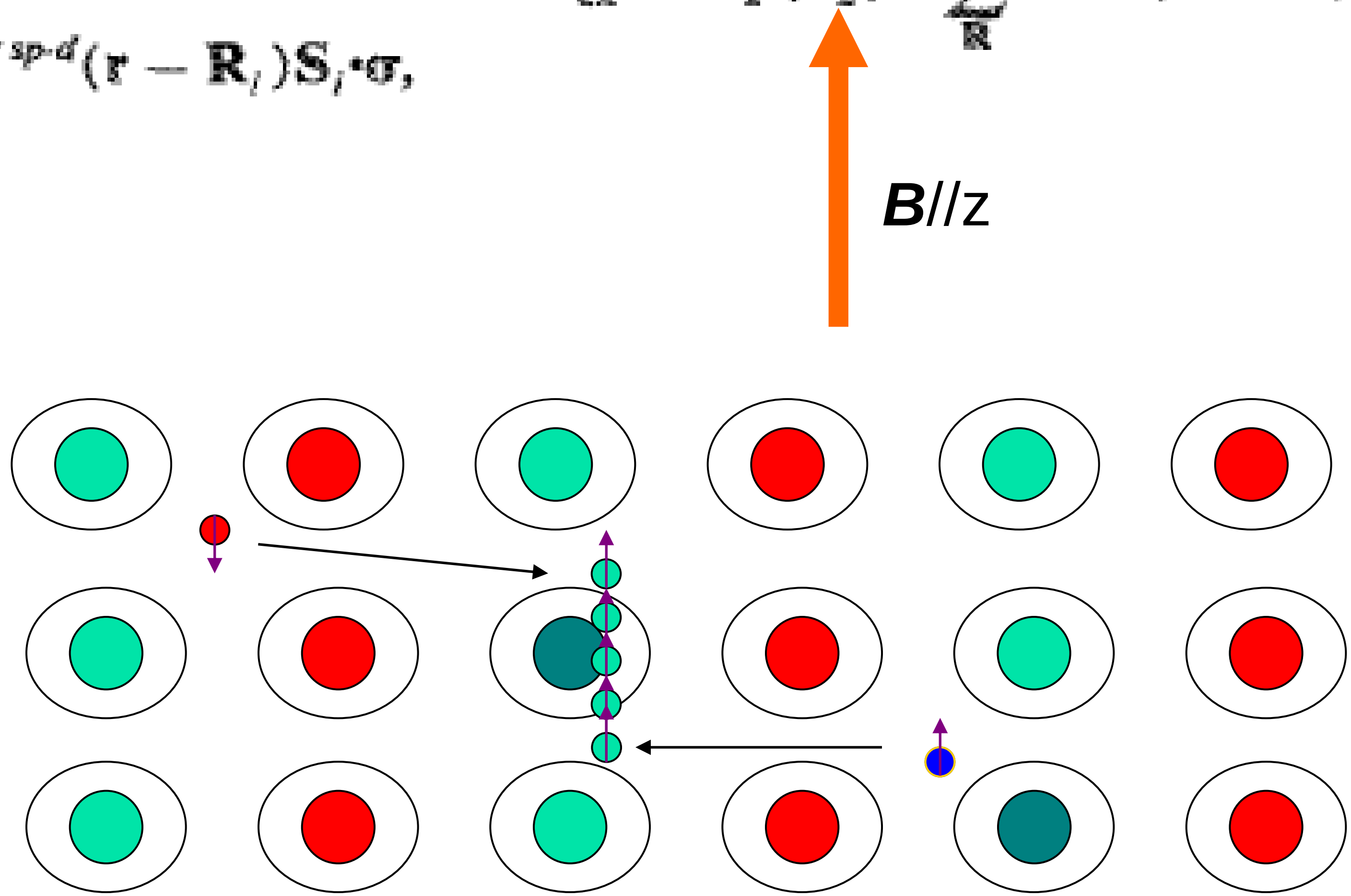
sp-d exchange interaction的結果?

sp-d exchange interaction

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

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



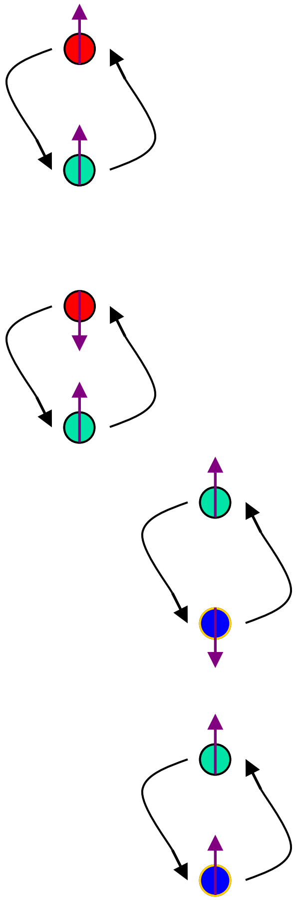


Sp-d exchange interaction

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

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

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



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

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

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

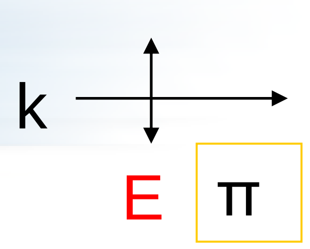
$$u_{50} = \left|\tfrac{3}{2},\tfrac{1}{2}\right\rangle = (1/\sqrt{6})[(X - iY)\uparrow + 2Z\downarrow],$$

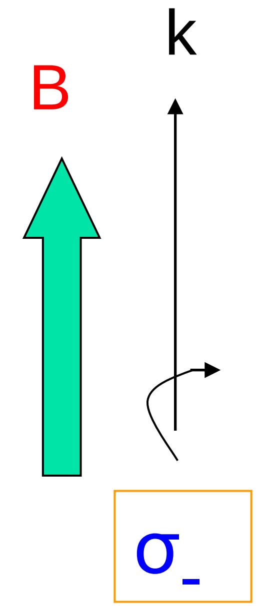
$$u_{60} = \left|\tfrac{3}{2},-\tfrac{1}{2}\right\rangle = i(1/\sqrt{6})[(X + iY)\downarrow - 2Z\uparrow];$$

Spin-orbital band Γ_7

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

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





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

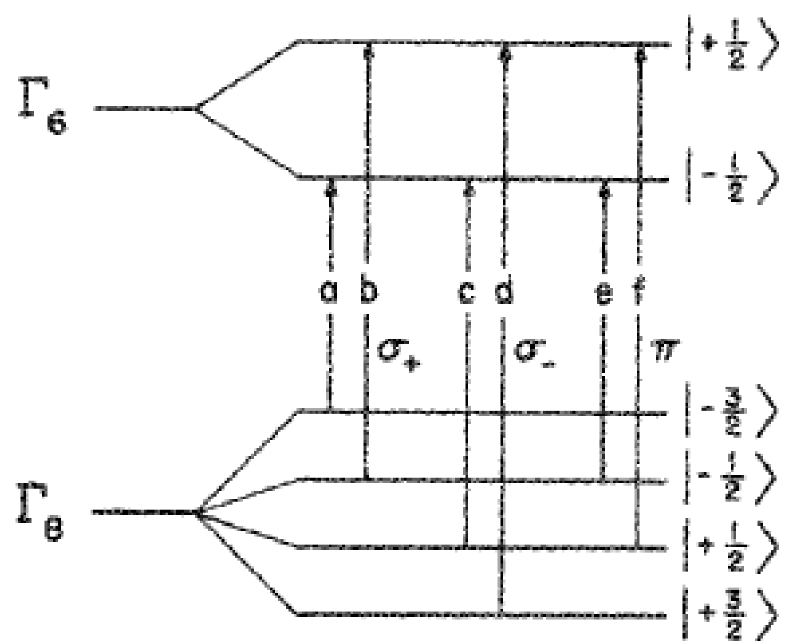
$$\langle \Psi_{\Gamma_8} | H_{ex} | \Psi_{\Gamma_8} \rangle = \left\| \begin{matrix} 3B & 0 & 0 & 0 \\ 0 & B & 0 & 0 \\ 0 & 0 & -B & 0 \\ 0 & 0 & 0 & -3B \end{matrix} \right\|$$

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

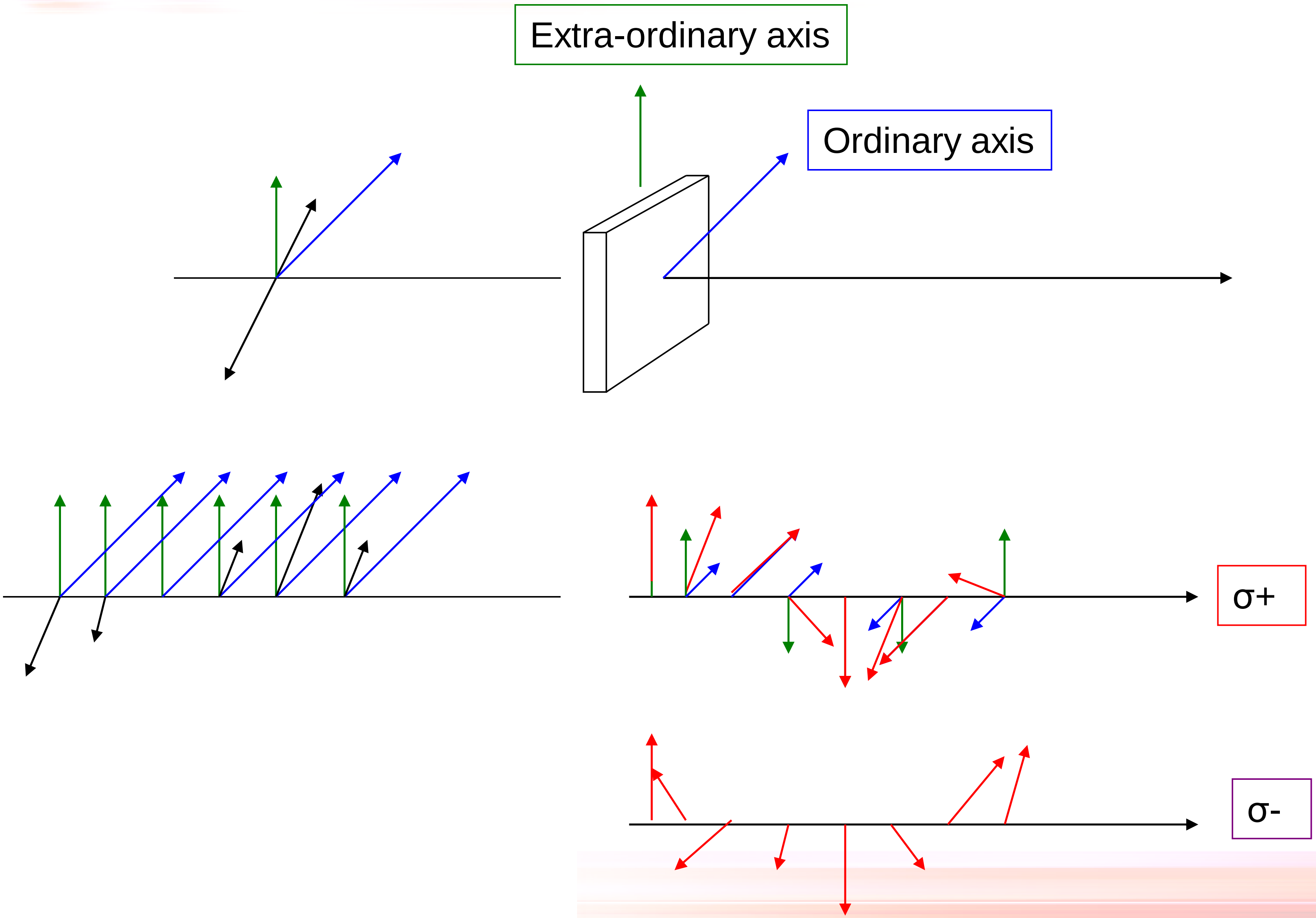
$$B = \frac{1}{6} N_0 \beta x \langle S_z \rangle = -\frac{1}{6} \frac{\beta M}{g_{Mn} \mu_B}$$

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

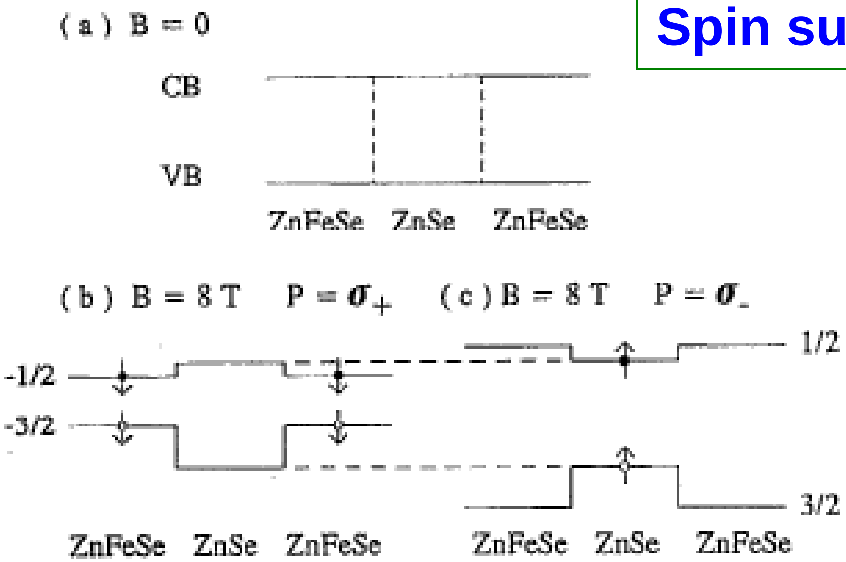
$$\beta = \langle X | J^{sp\text{-}d} | X \rangle / \Omega_0.$$

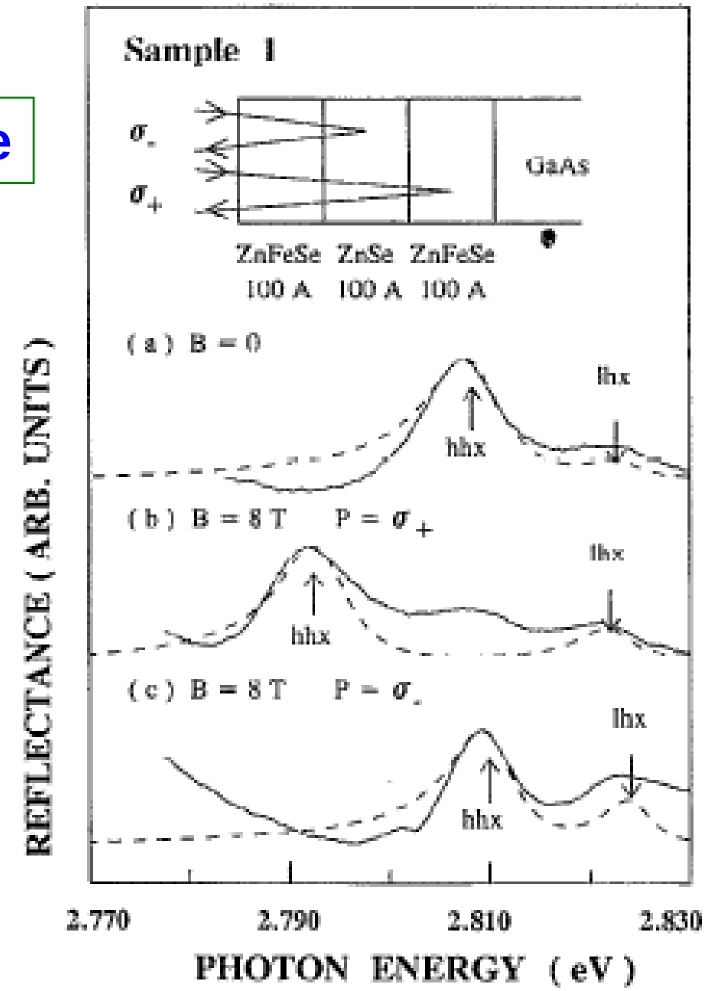


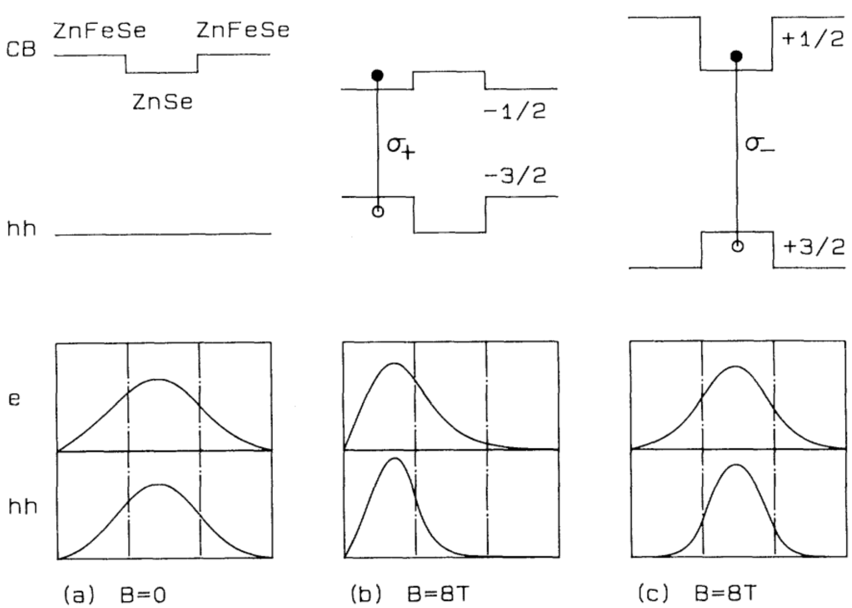
如何產生圓形極化光?



Spin super-lattice





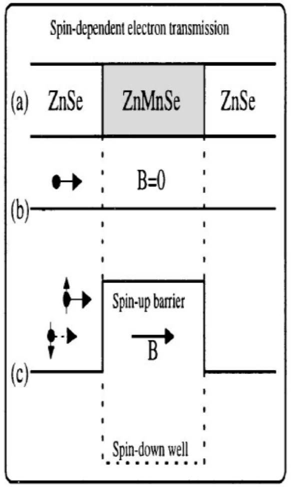


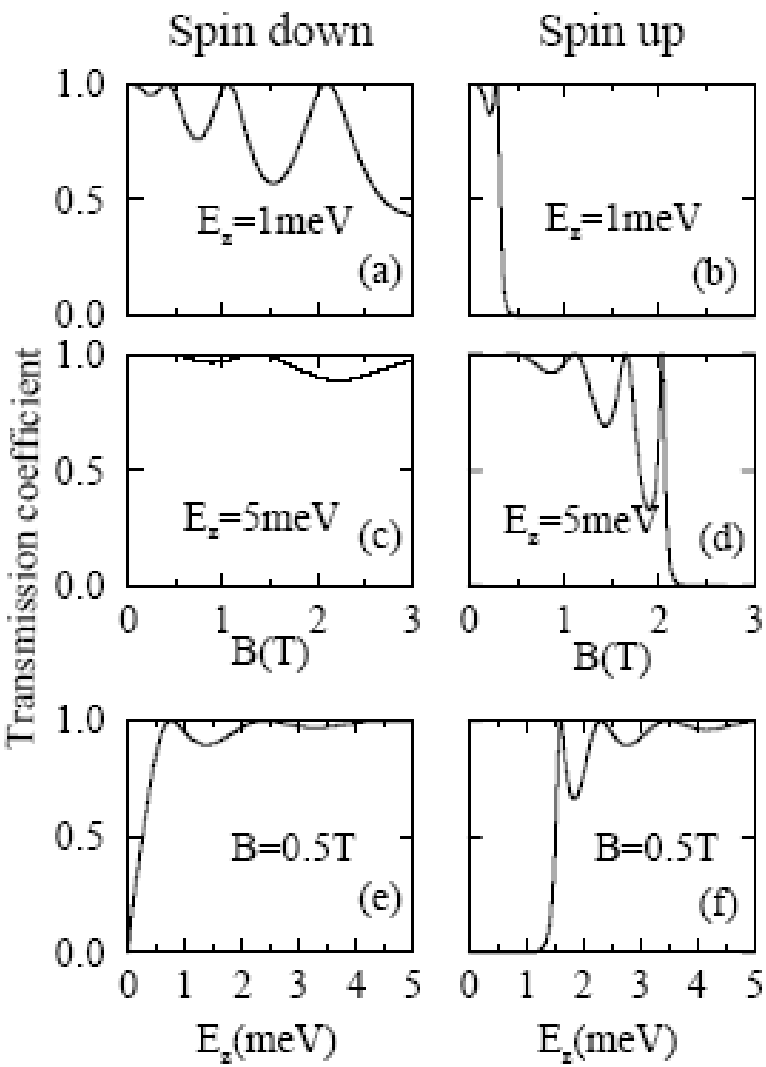
$$R=\left|\frac{E_0'}{E_0}\right|^2 \quad \epsilon=\epsilon_\infty+\sum_\alpha \frac{A_\alpha}{(E_\alpha^2-E^2)-i\Gamma_\alpha E}$$

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)





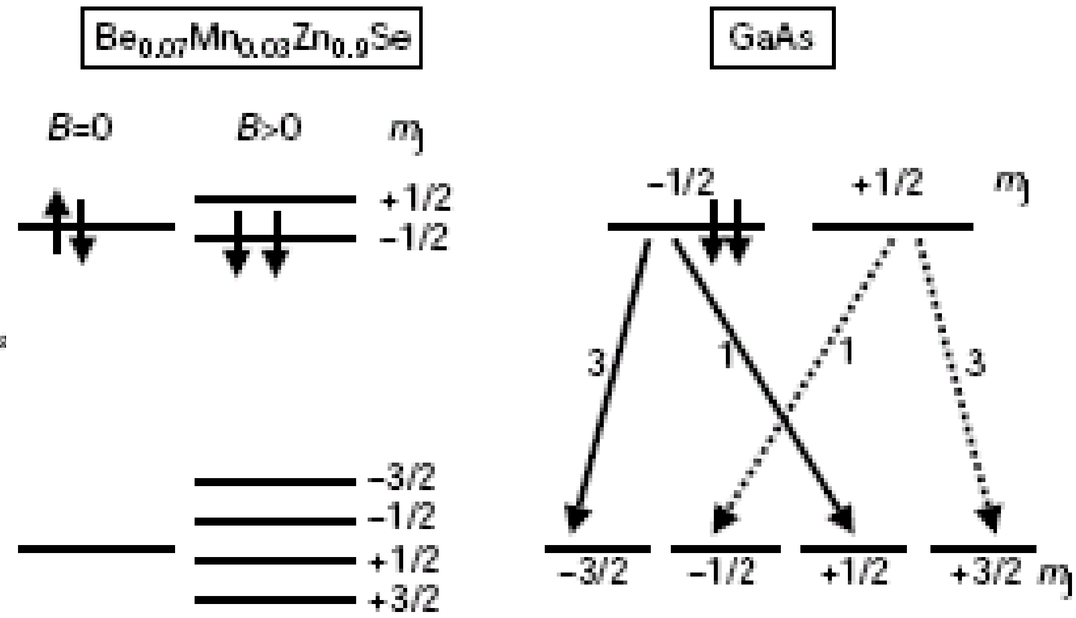
$$T_{\downarrow}(E_z, B) = \left\{ 1 + \frac{\sin^2\left[\sqrt{\frac{2m_z^*(x|\langle S_z\rangle|N_0\alpha/2+E_z)}{\hbar^2}}L\right]}{4\left(\frac{E_z}{x|\langle S_z\rangle|N_0\alpha/2}\right)\left(\frac{E_z}{x|\langle S_z\rangle|N_0\alpha/2}+1\right)} \right\}^{-1}. \quad (1)$$

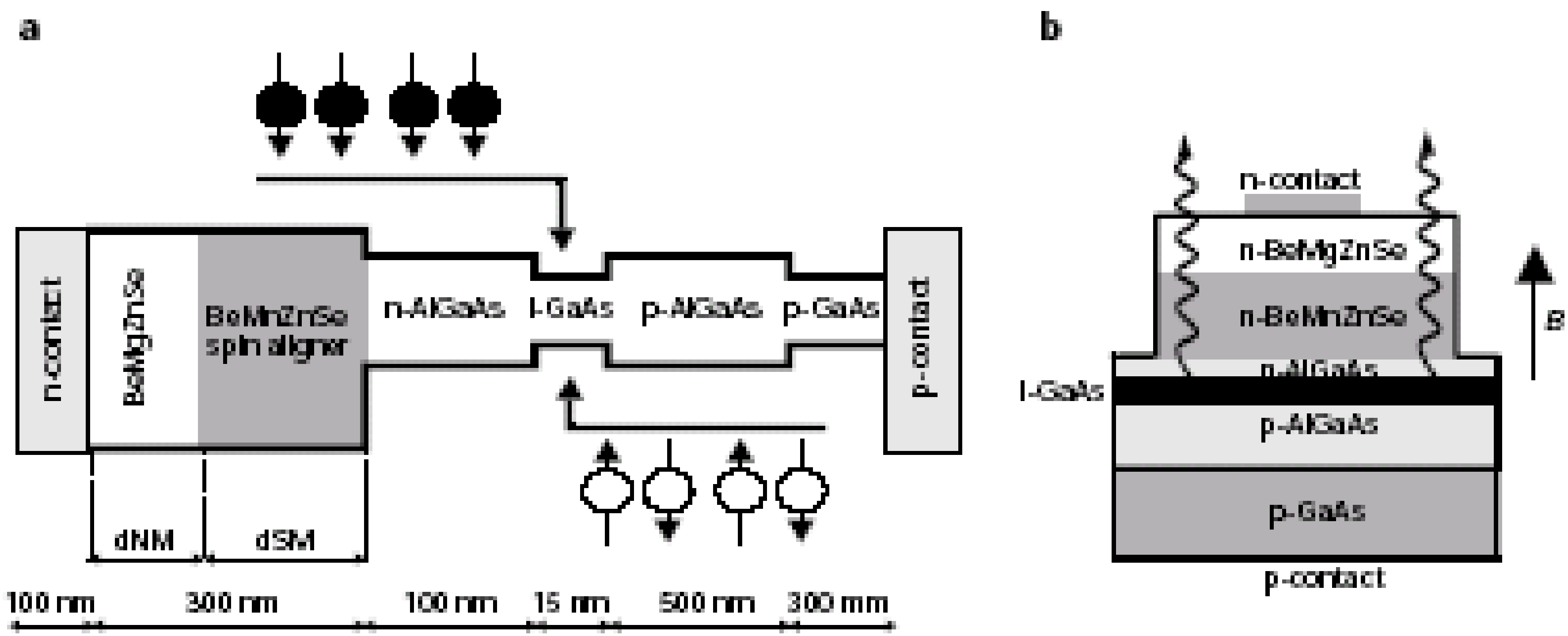
Injection and detection of a spin-polarized current in a light-emitting diode

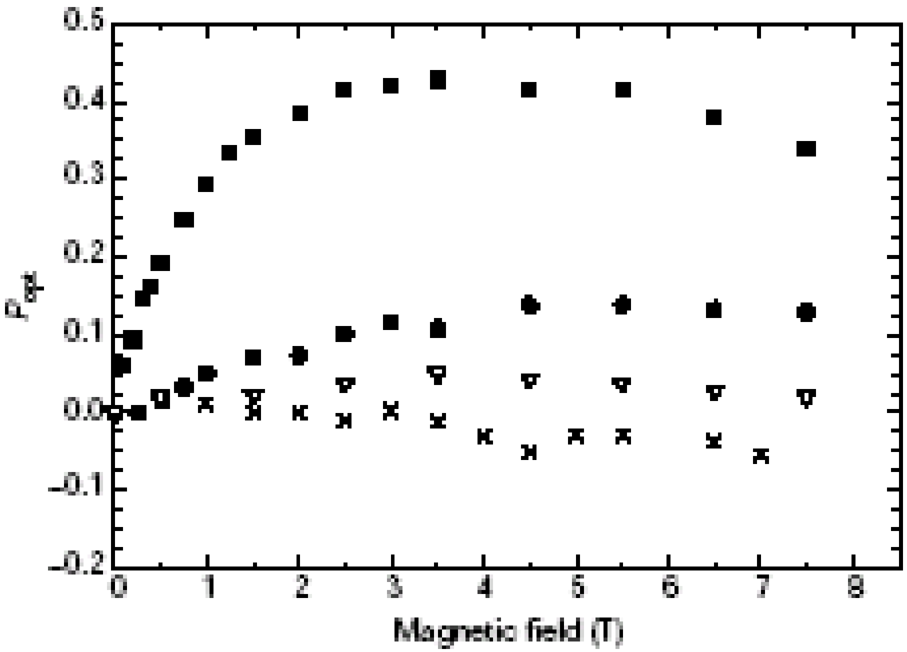
R. Fiederling, M. Keim, G. Reuscher, W. Ossau, G. Schmidt, A. Waag & L. W. Molenkamp

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

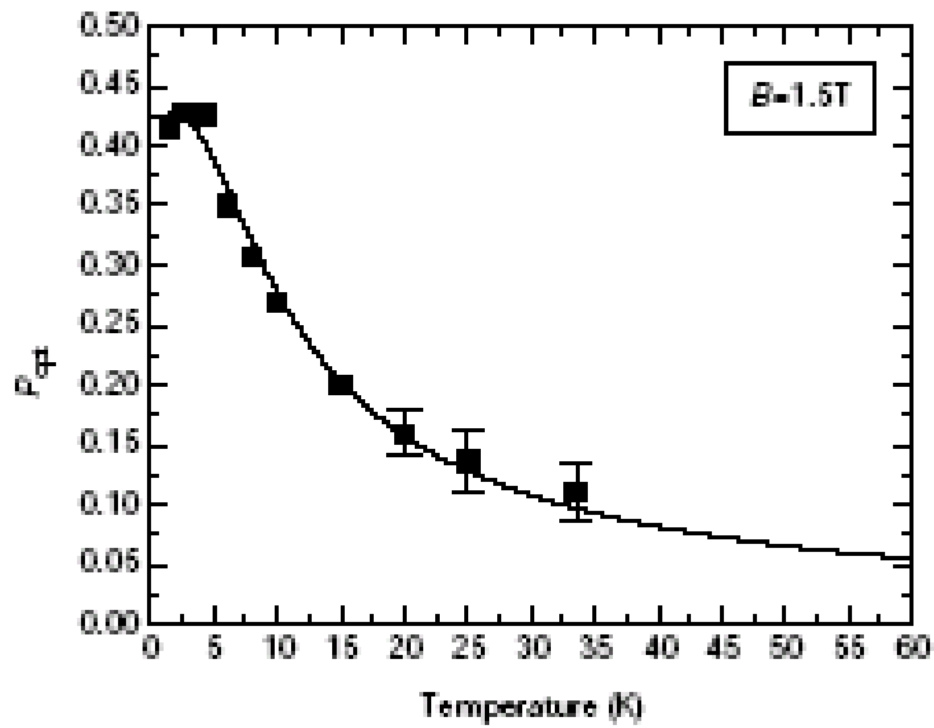
Nature 402, p787 (1999)







Nature 402, p787 (1999)



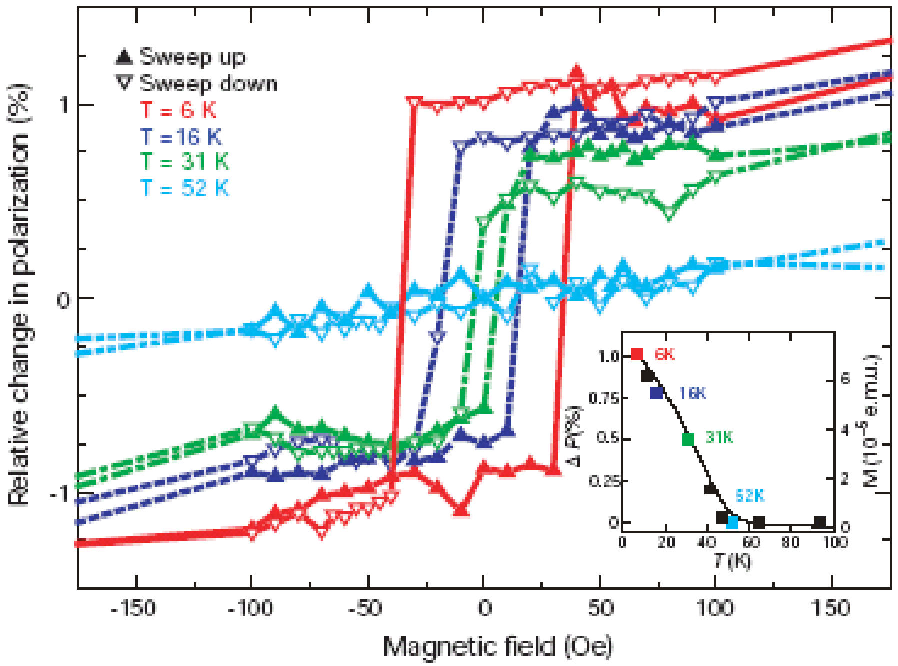
Electrical spin injection in a ferromagnetic semiconductor heterostructure

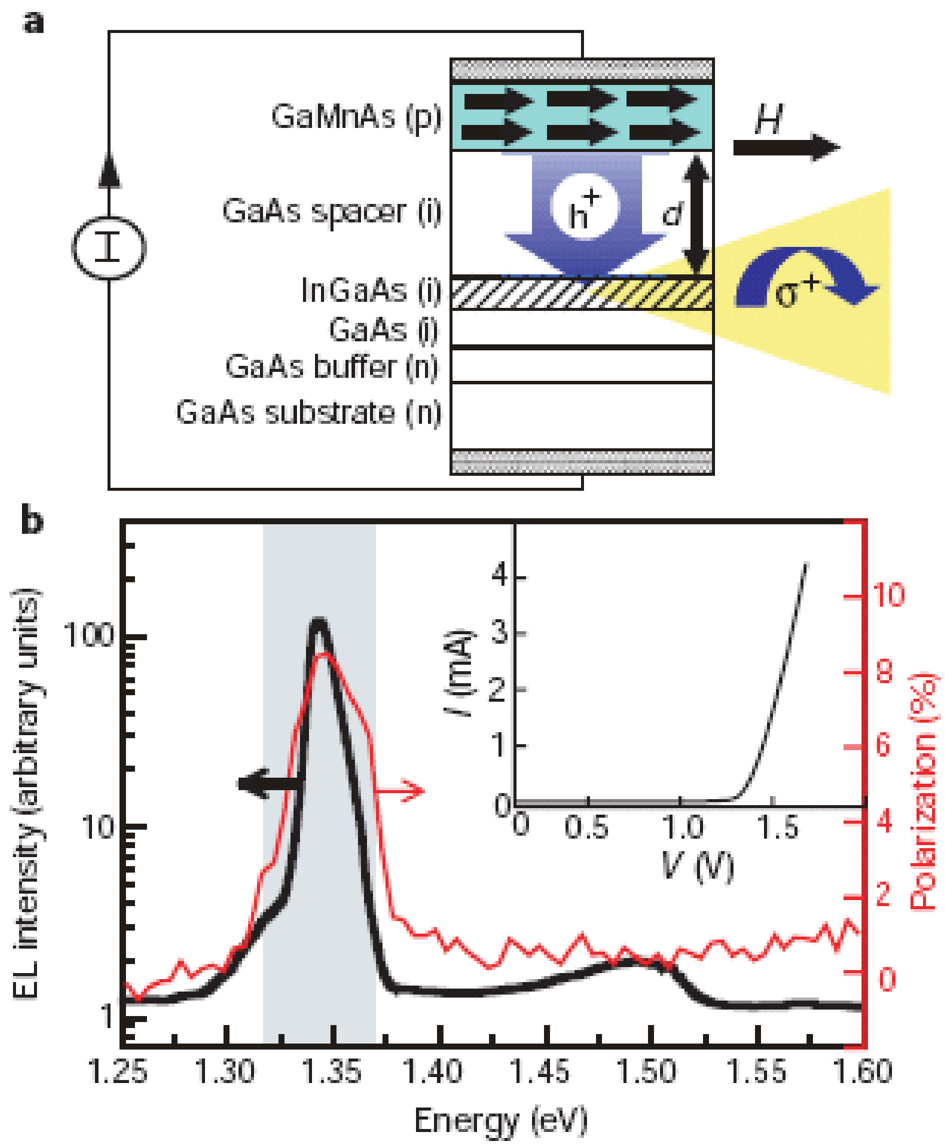
Y. Ohno*, D. K. Young†, B. Beschoten†, F. Matsukura*, H. Ohno* & D. D. Awschalom†

* *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, University of California, Santa Barbara, California 93106, USA*

Nature 402, p790 (1999)





APPLIED PHYSICS LETTERS VOLUME 83, NUMBER 22 1 DECEMBER 2003

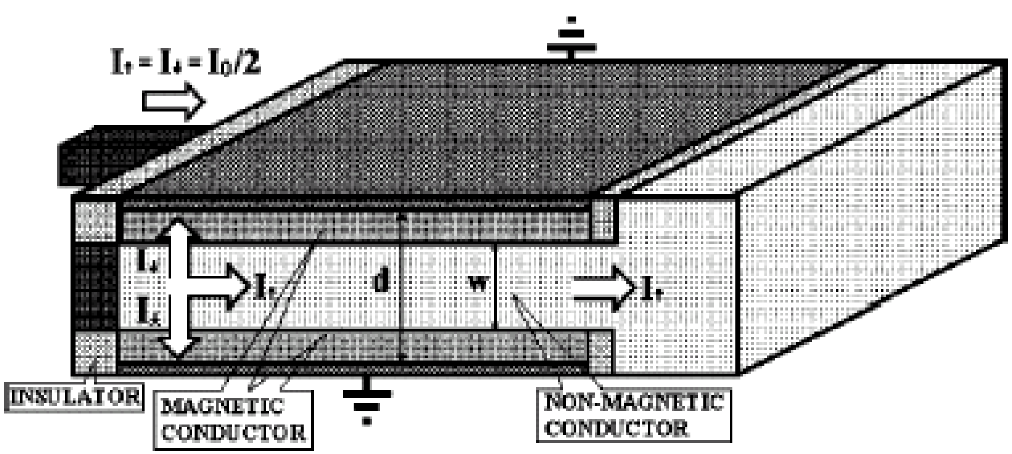
A magnetic-field-effect transistor and spin transport

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]



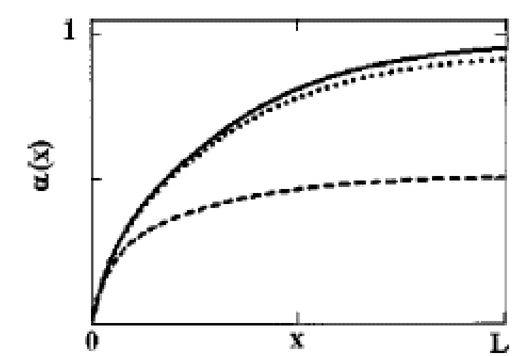
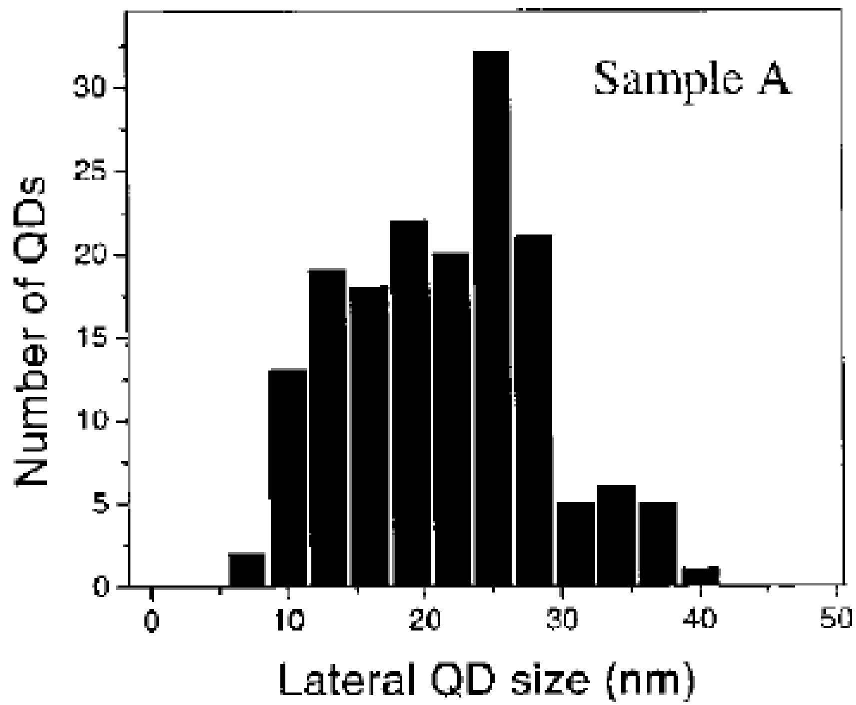


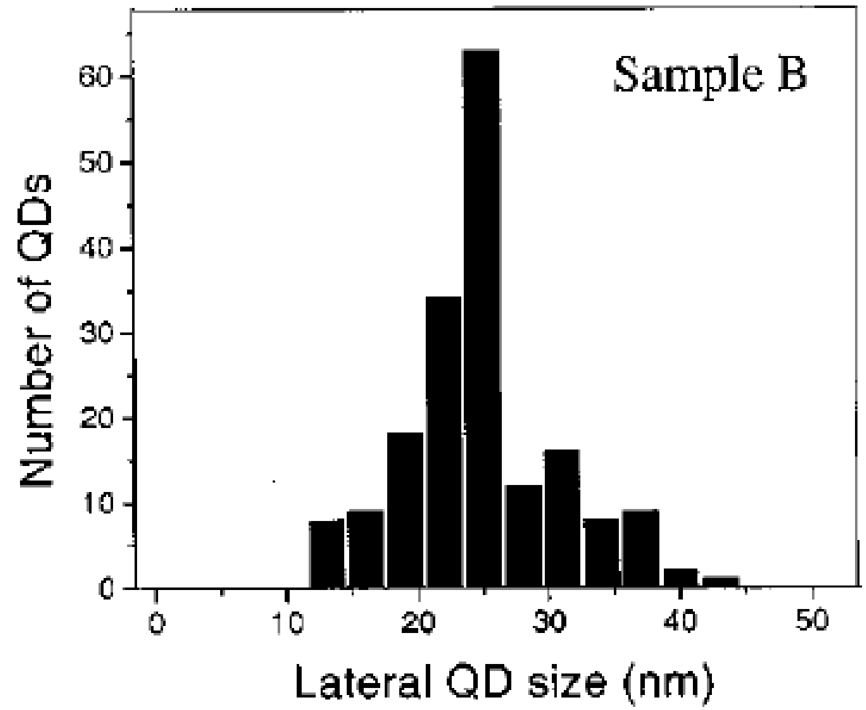
FIG. 2. The degree of SP (α) of the current plotted vs the longitudinal (x) coordinate along the spin guide; the curves were calculated from Eq. (7) with $\sigma_{M\uparrow}/\sigma_{M\downarrow}=0.3$, $\sigma_{M\downarrow}/\sigma_N=1$, $w/d=0.28$, $L=4d$, $w_M/\lambda_M=0.225$, and $w/\lambda_N=0.1$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

Epitaxially grown magnetic semiconductor nanostructures

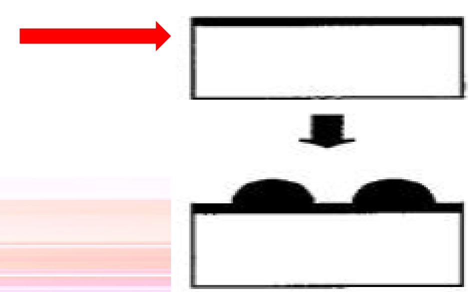
CdSe/ZnSe QDs



CdSe/ZnSe QDs

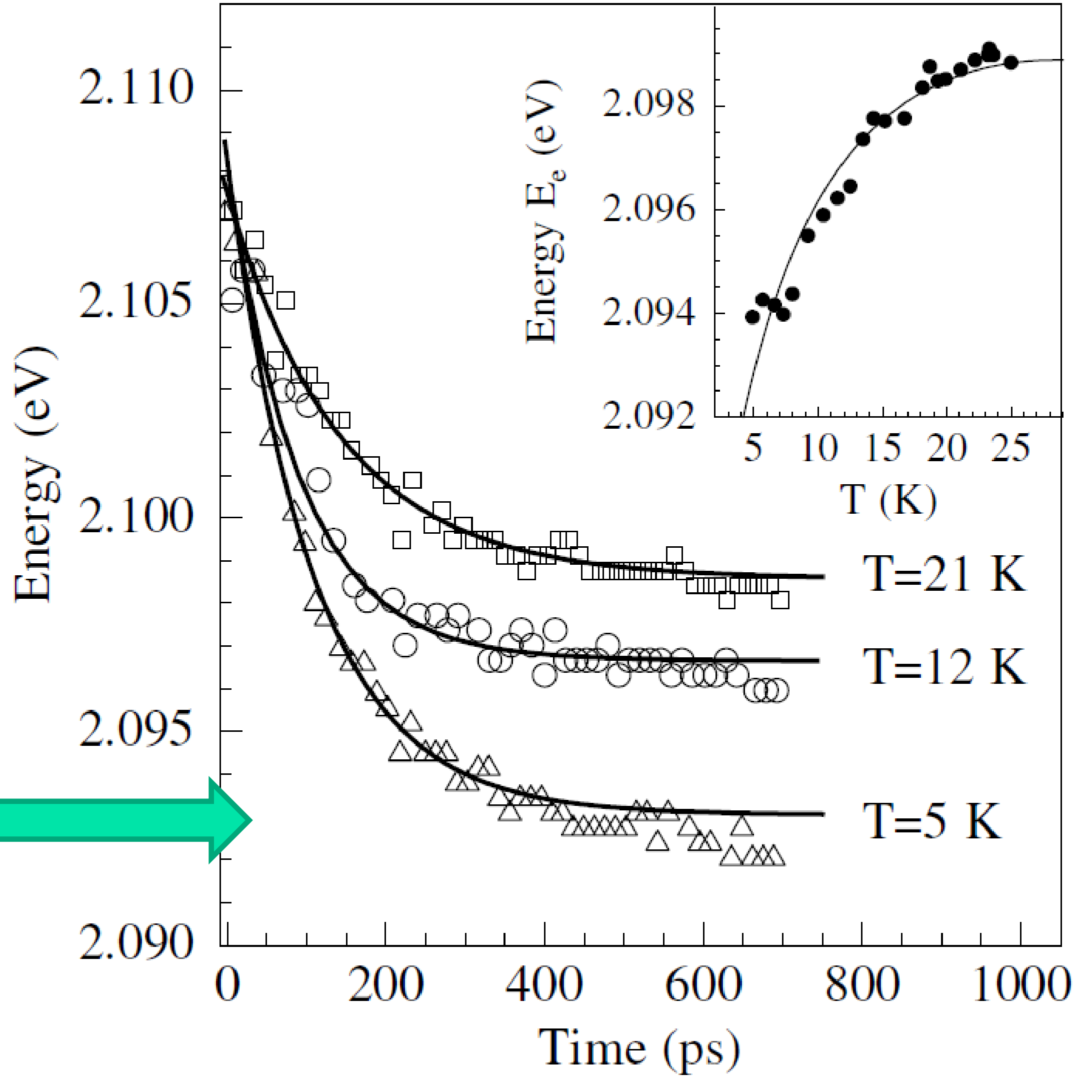


Magnetic CdSe-based quantum dots grown on Mn-passivated ZnSe



Prof. JK Furdyna's group APL 80, 1237 (2002)

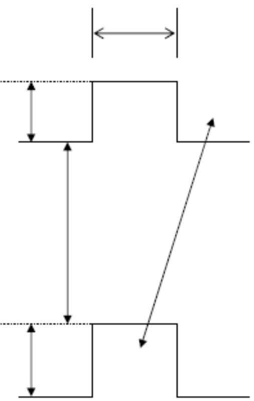
Dynamical Spin Response in Semimagnetic Quantum Dots
Prof. JK Furdyana's group

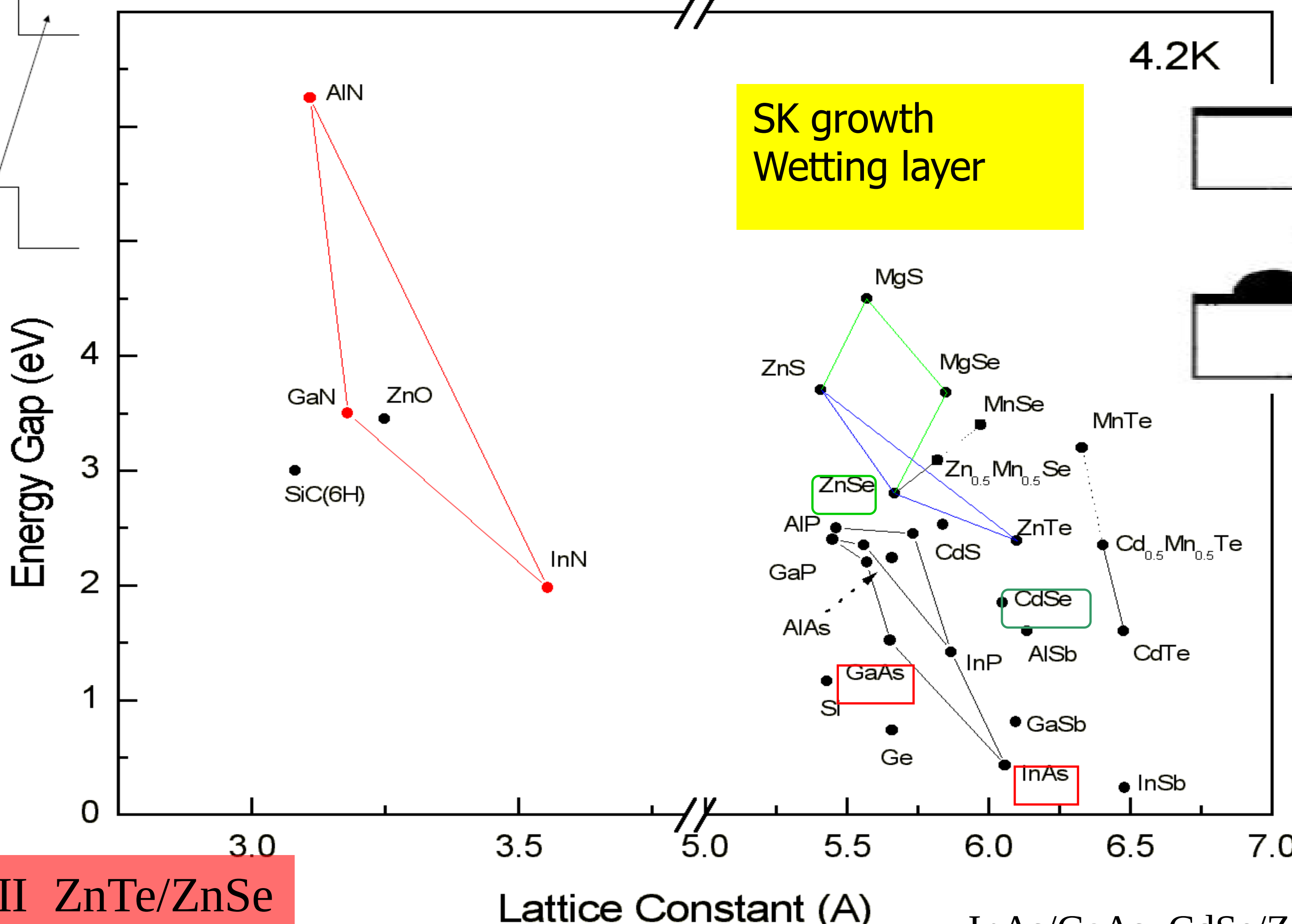


Formation of magnetic polaron in CdSe/ZnMnSe QDs

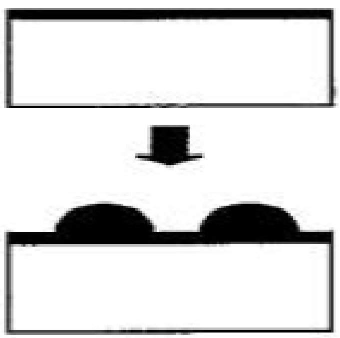
Their results from the magnetic semiconductor nanostructures are very fruitful.

Energy Gap vs Lattice Constant





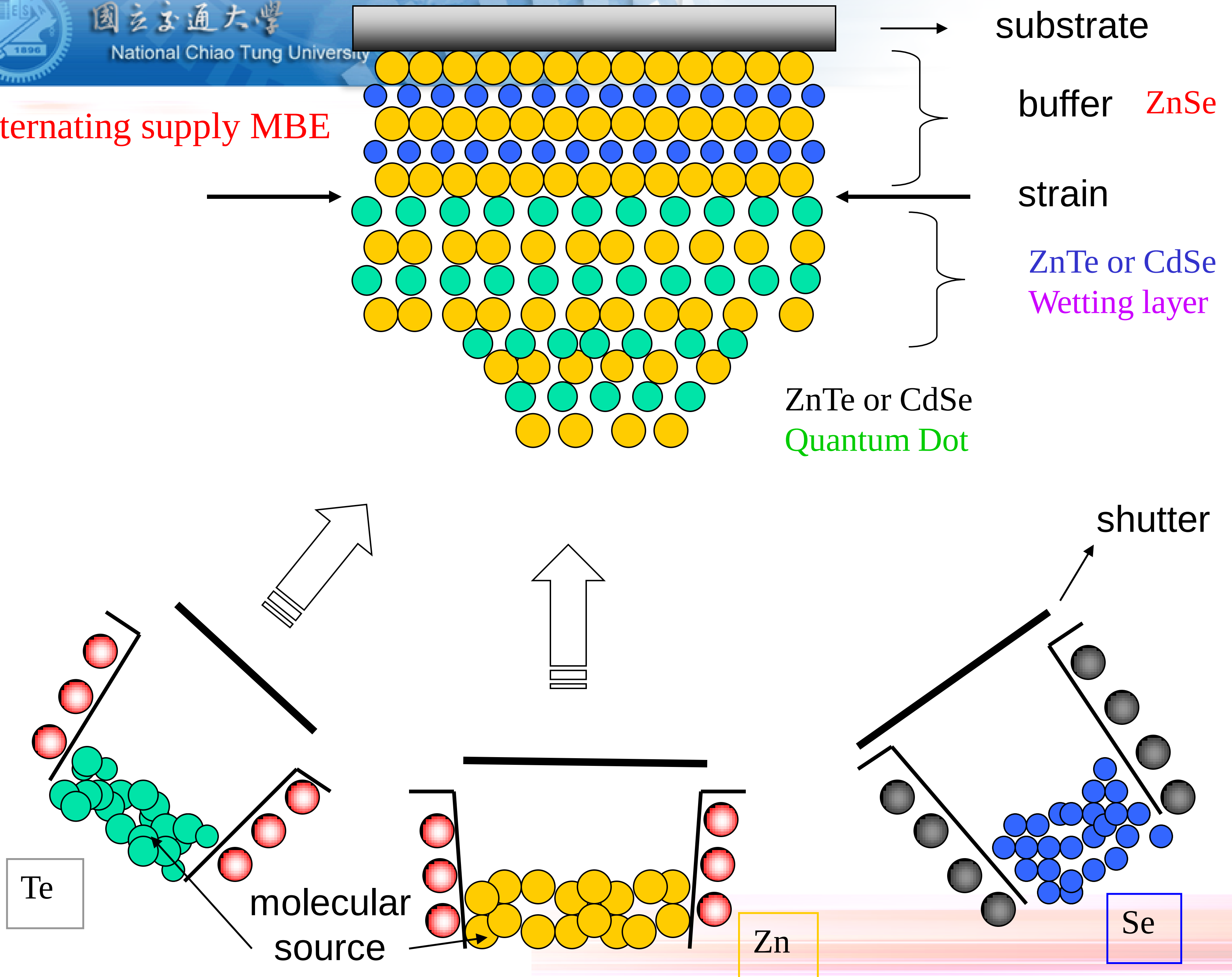
SK growth
Wetting layer



Type II ZnTe/ZnSe
GaSb/GaAs

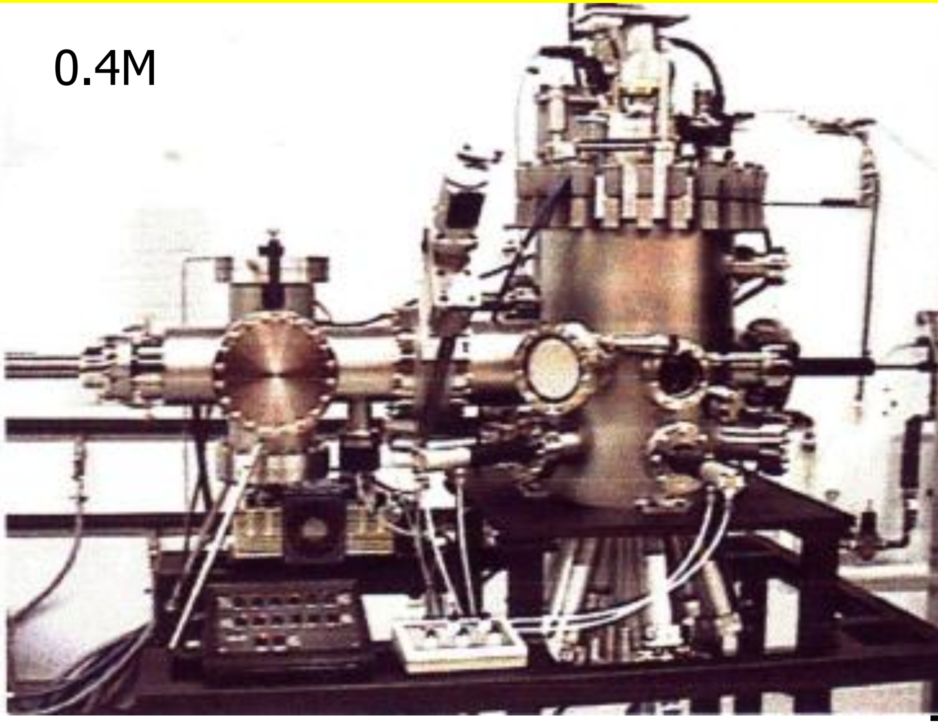
InAs/GaAs, CdSe/ZnSe

Alternating supply MBE

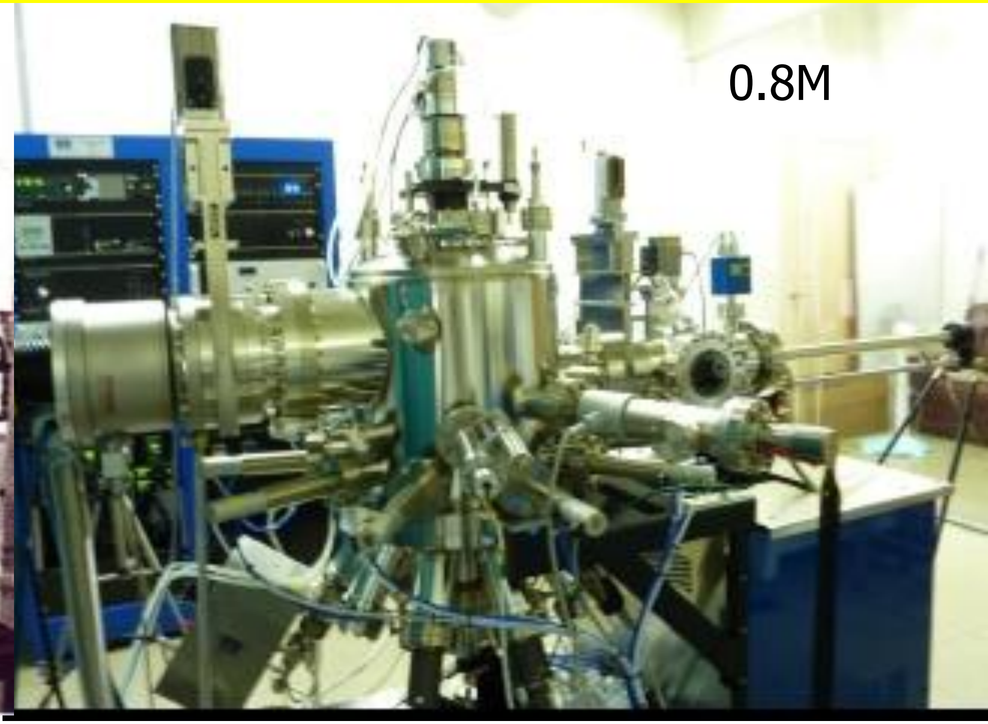


How to realize the growth of ZnMnTe QDs on ZnSe?

What kind of type-II quantum dots (QDs)? How to grow them?

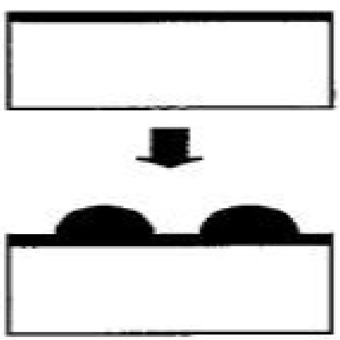


Veeco EPI 620
molecular beam epitaxy
(MBE) system



SVT (MBE) system

Self-assembled
Quantum dots (QDs)



O

Mg Cr Mn Zn Se

Cd Te

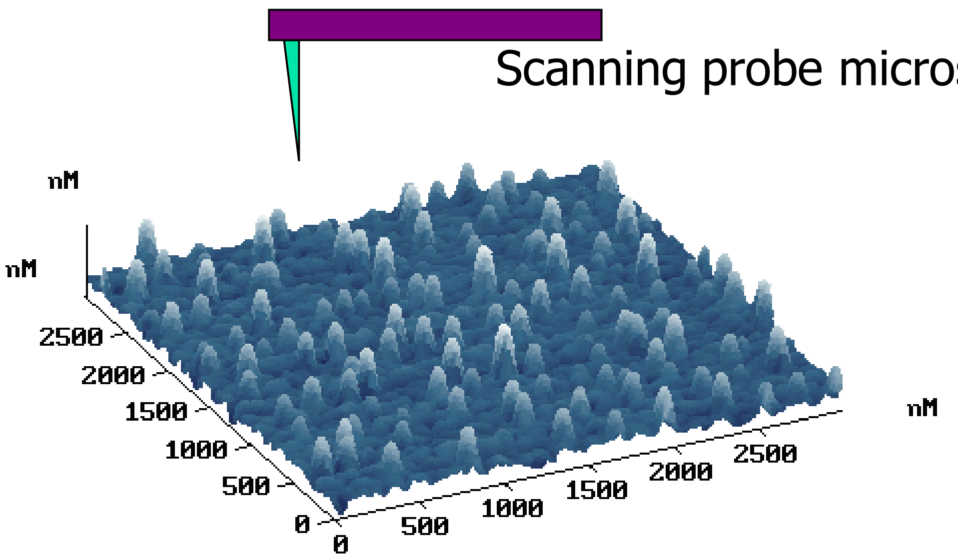
Cl^- n-type doping

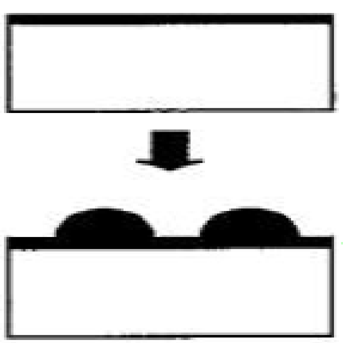
N^+ p-type doping

It's very important to have a smooth buffer layer.

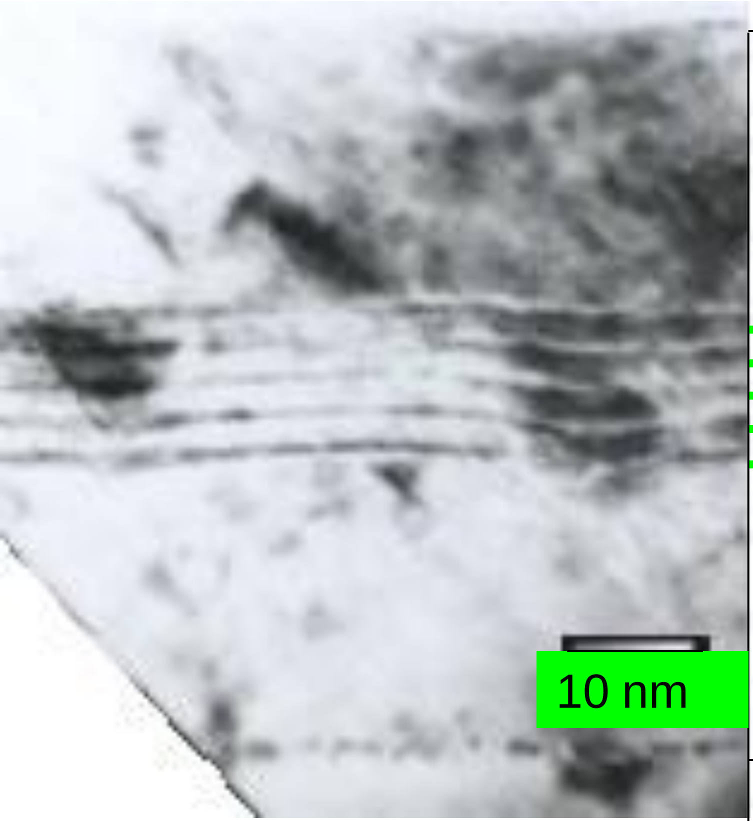
Atomic force microscopy, AFM

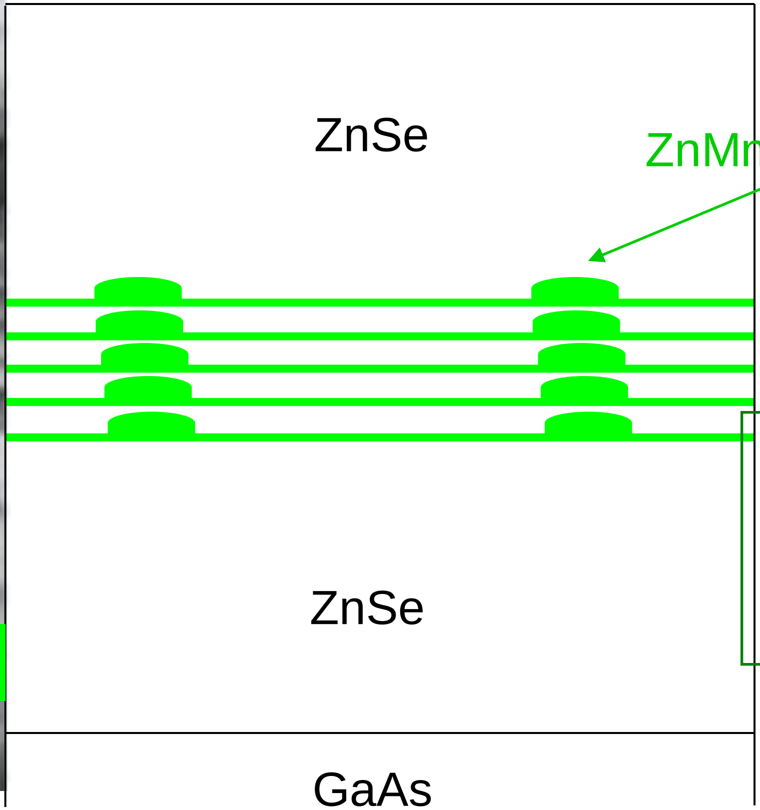
Scanning probe microscopy





Cross-section TEM of 2.6 ML ZnMnTe MQDs



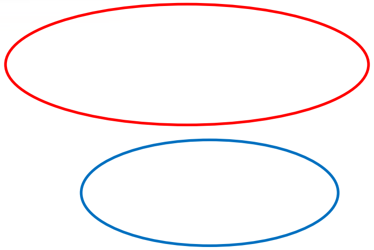


Wetting layer
2.6 monolayers
~1.0 nm

Stranski-Krastanow (SK), 2-D to 3D (0D) growth mode

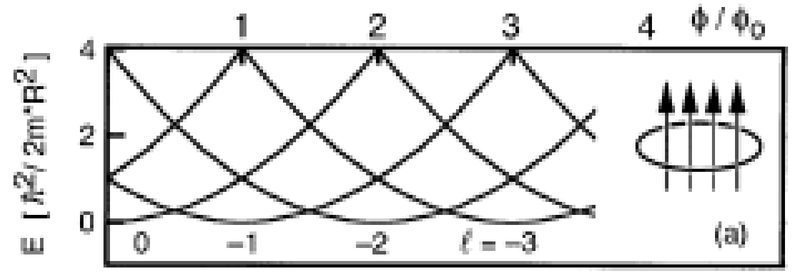
Vertical correlation.

Magnetic semiconductor
QD (type-II QD)



Electron orbit

Hole orbit



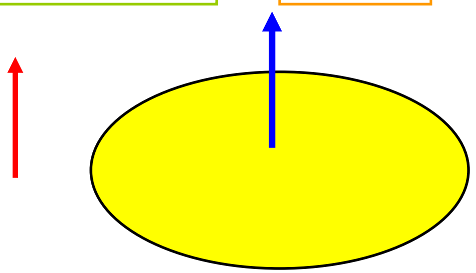
Magnetic flux $\Delta\varphi$

φ_0 =flux quanta

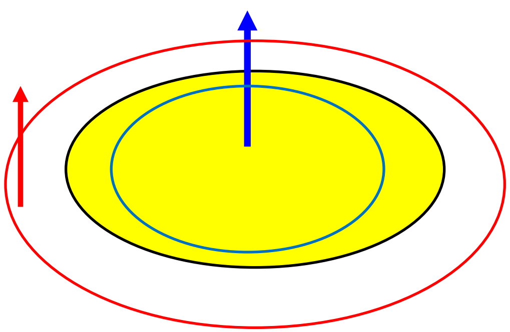
$$E_{exc} = E_g + \frac{\hbar^2}{2MR_0^2}\left(L + \frac{\Delta\Phi}{\Phi_0}\right)^2,$$

electron

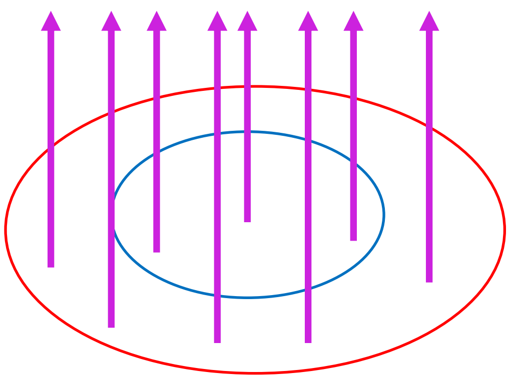
hole



Magnetic field B=0



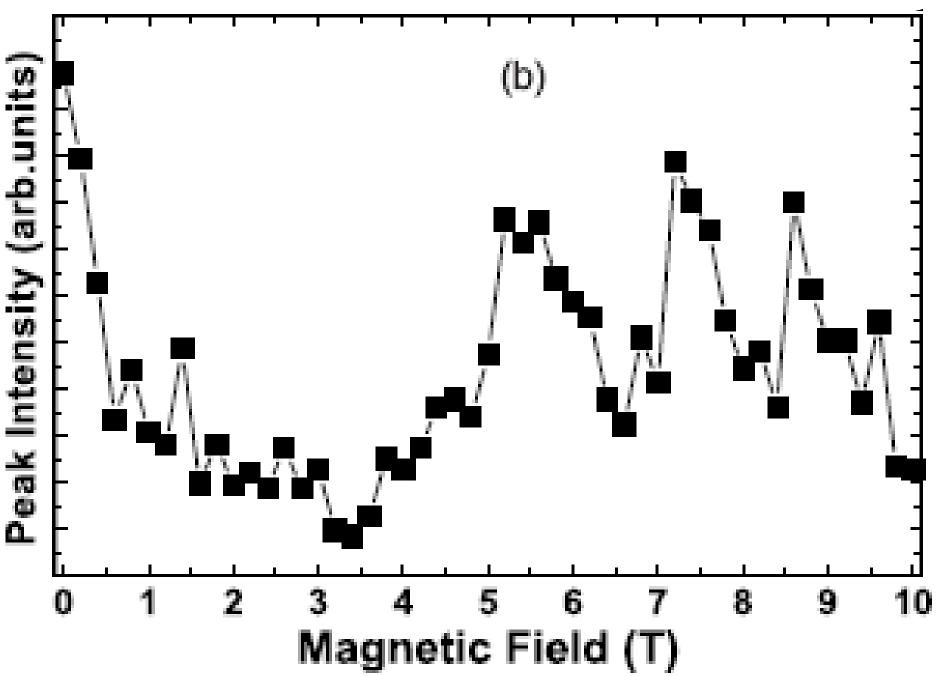
Magnetic field B>0

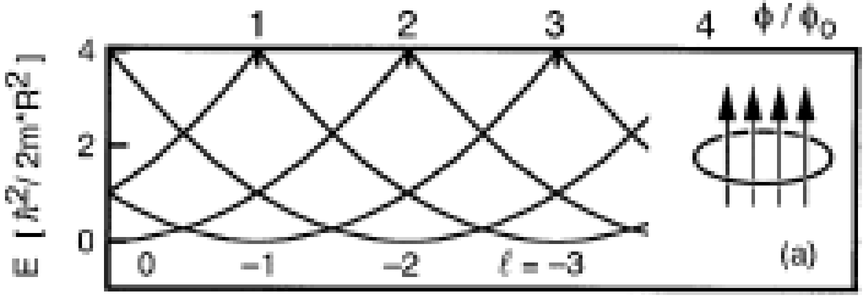


Magnetic field B>0

Observation of optical Aharonov-Bohm oscillation

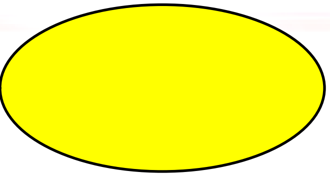
Coherent Aharonov-Bohm oscillation in ZnMnTe/ZnSe quantum dots PRB77, 241302(2008)





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

Observation of optical Aharonov-Bohm oscillation



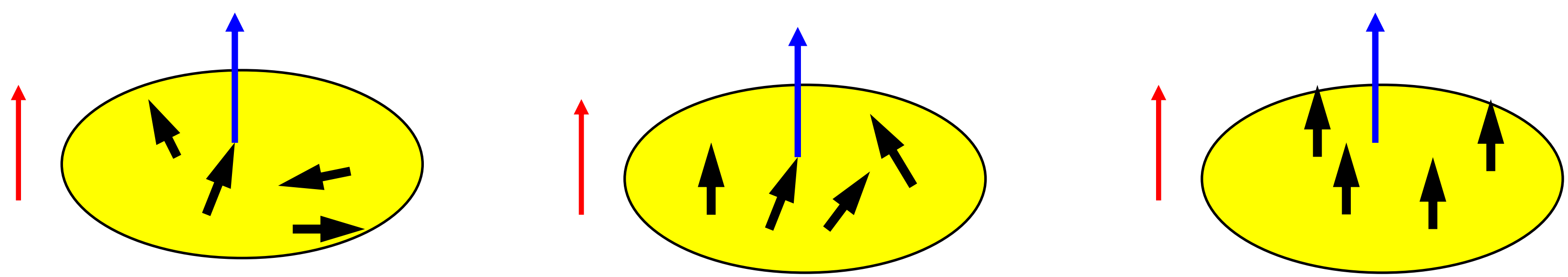
Magnetic semiconductor QD

Mn^{2+} spin

electron

hole

Time resolved photoluminescence is sensitive to probe MP.



initially t=0

t>0

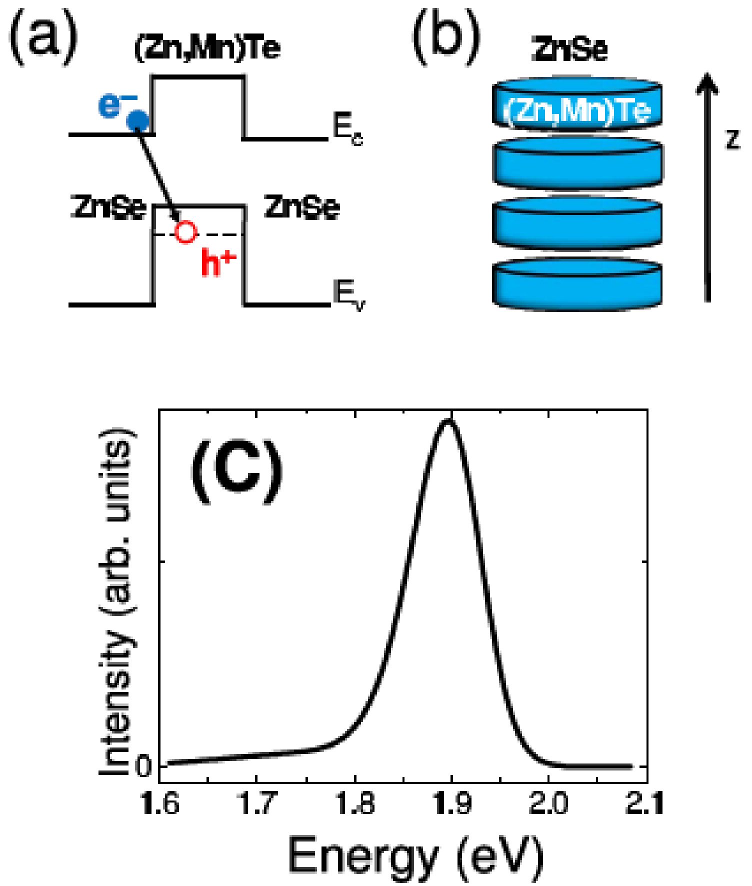
Right after pulse laser excitation

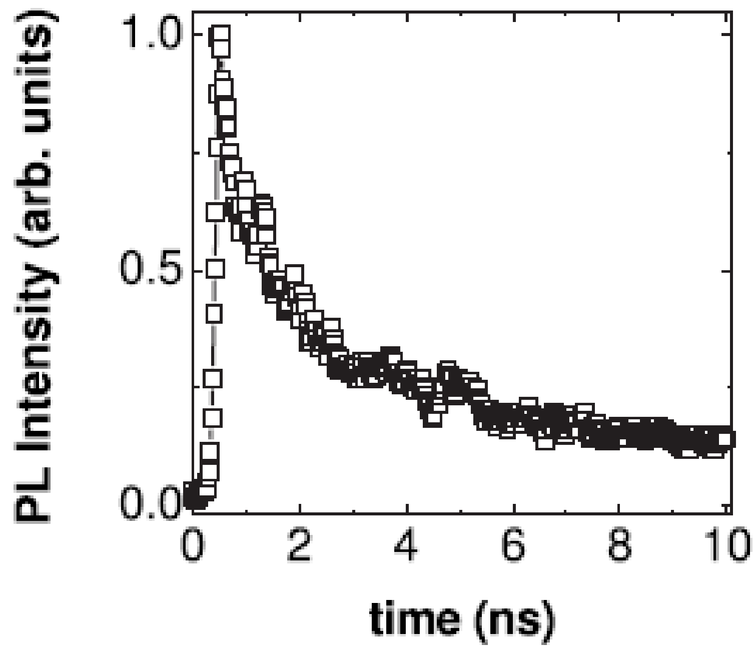
Exchange interaction between hole spin and manganese ion spin

Exciton emission energy decreases with time.

Formation of magnetic polaron (MP).

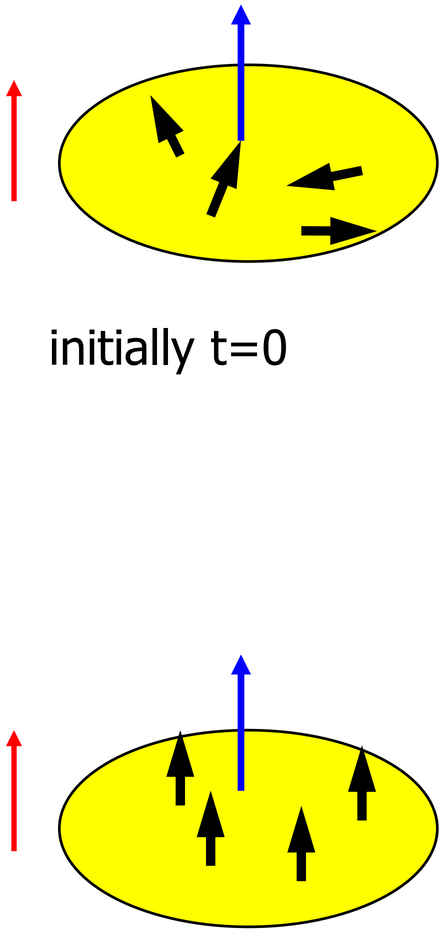
Robust magnetic polarons in ZnMnTe/ZnSe quantum dots
PRB82, 195320(2010)

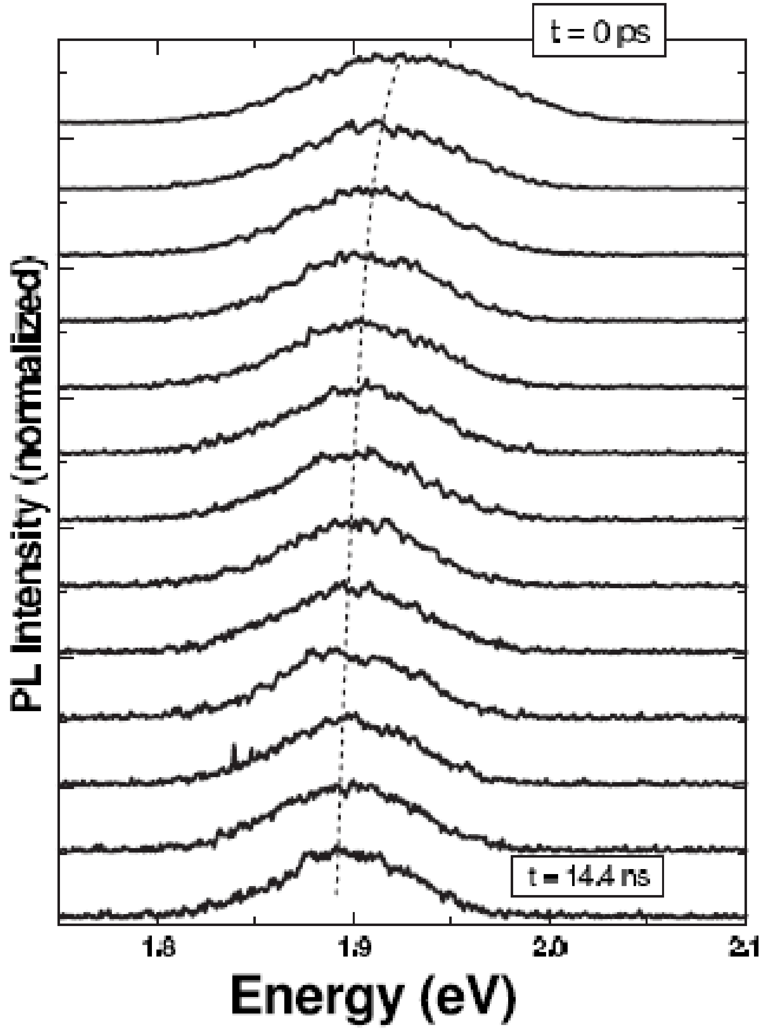




Photoluminescence (PL) spectrum of ZnMnTe/ZnSe QDs.

Robust magnetic polarons in ZnMnTe/ZnSe quantum dots PRB82, 195320(2010)

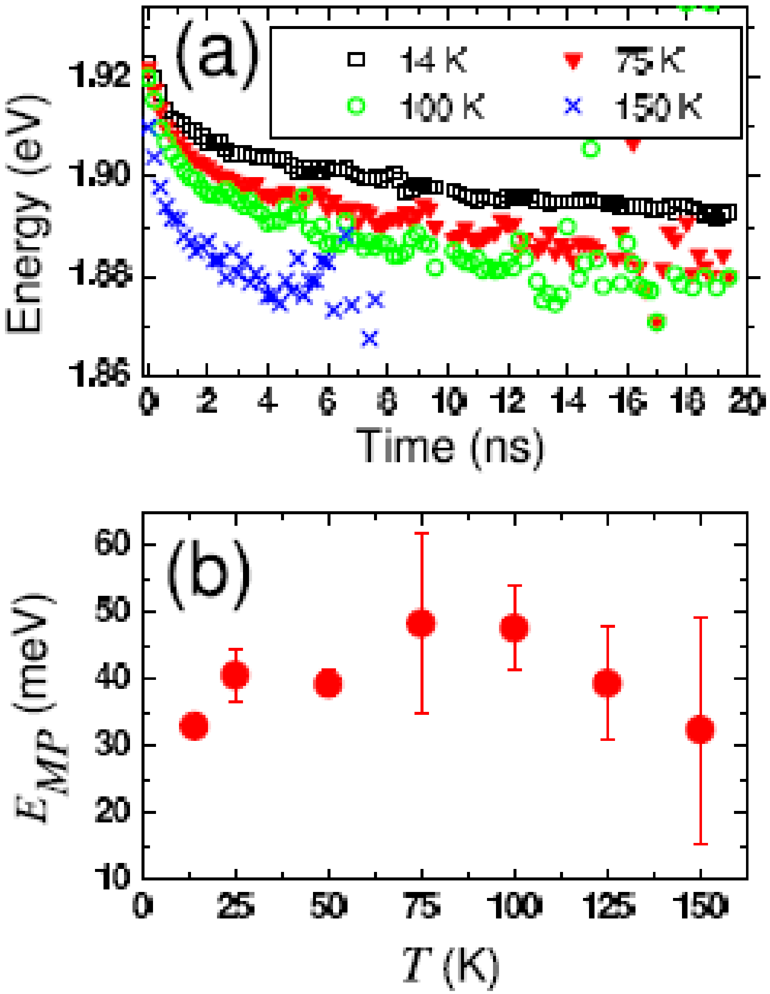




PL spectra as a function of time.

Formation of magnetic polaron (MP).

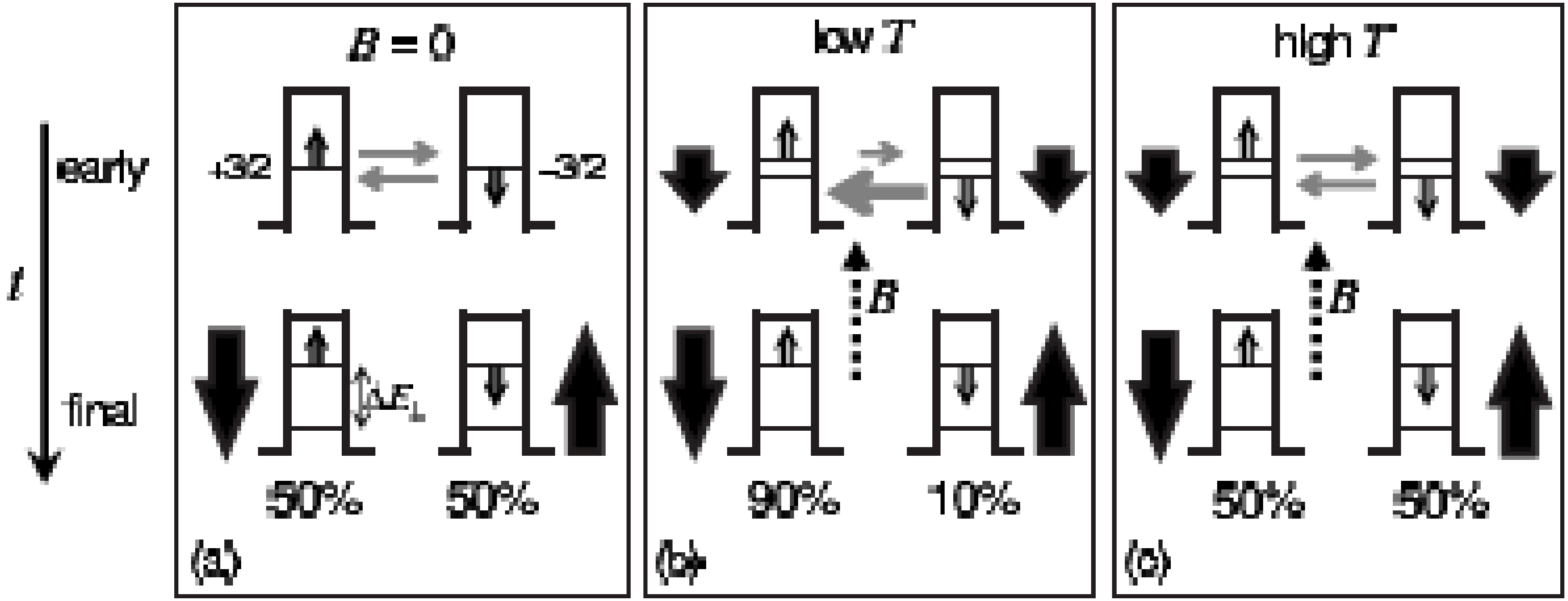
Robust magnetic polarons in ZnMnTe/ZnSe quantum dots
PRB82, 195320(2010)



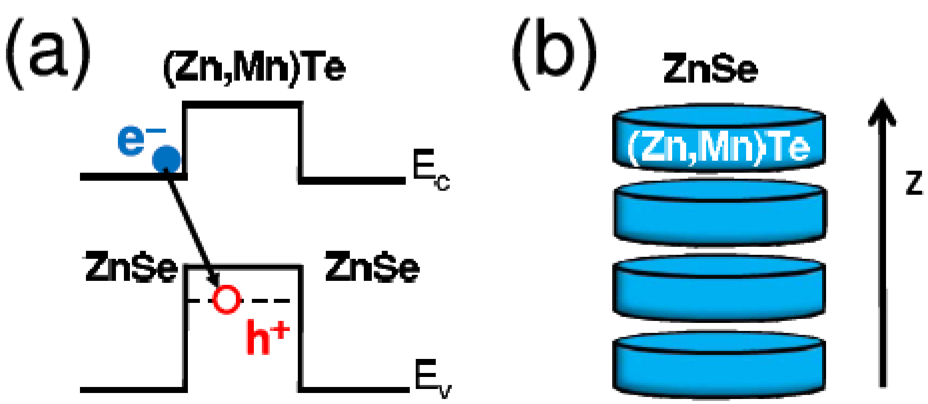
$$E_{\mathrm{MP}} = \mu_0^{-1}(J_{ex}/2g\mu_B N_0)^2\,\eta(E_{\mathrm{MP}}/k_B T)\,\Omega_{eff}^{-1}\chi(T)$$

(a) Time dependence of peak PL energy for T=14 to 150K.
(b) Temperature dependence of the magnetic-polaron formation energy.

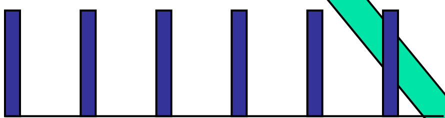
Robust magnetic polarons in ZnMnTe/ZnSe quantum dots PRB82, 195320(2010)



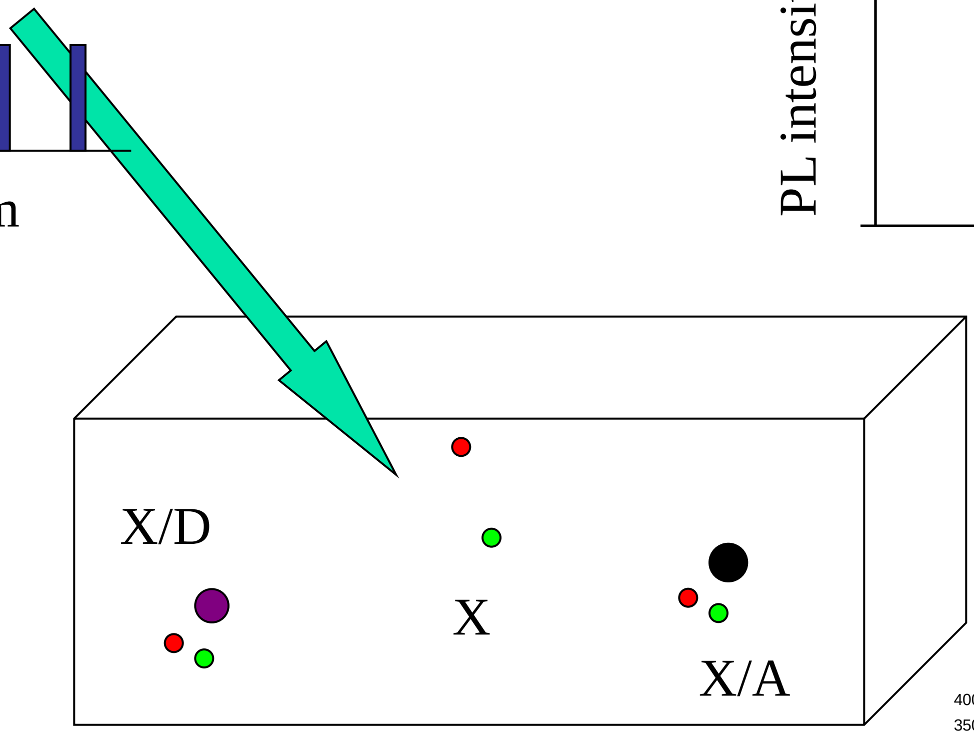
Schematic illustration of the magnetic-polaron formation.

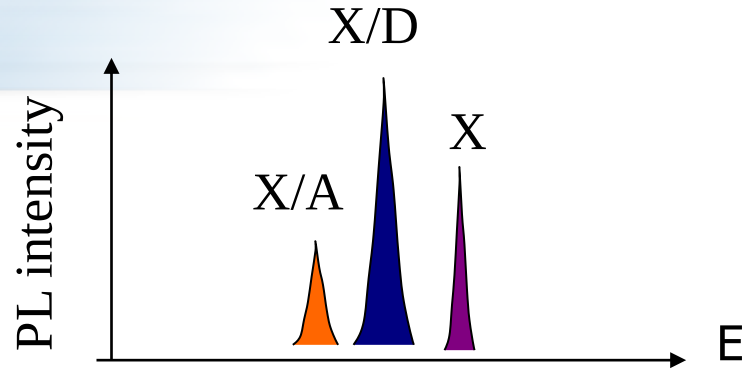


Time integrated and time resolved photoluminescence



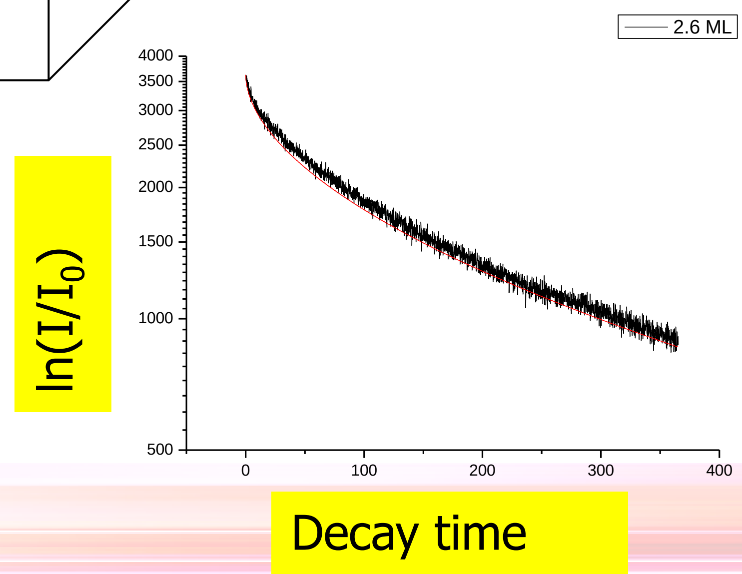
300 ps, 405 nm
2.5 MHz

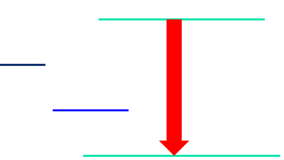




Phonon replica
DA pairs ….

Decay rate $dn/dt = - n/\tau$
$n = n_0 \exp(- t/\tau)$
$\ln(I/I_0) = - t/\tau$ to find lifetime





Unfortunately, it's not linear.

Stretched exponential relaxation (SER)
-the problem that is 150 years old-

In 1847, R. Kohlrausch found that the decay of the residual charge on a glass Leyden jar was described by a stretched exponential function $\exp[-(t/\tau)^{\beta}]$, and he showed that this function could be derived by assuming that the decay rate was not constant, but decreased with time as $t^{\beta-1}$.

Reference:

1847 *Ann. Phys., Lpz.* **12** 393

Decay rate

$dn/dt = - n/\tau$

$n = n_0 \exp(- t/\tau)$

$\ln(I/I_0) = - t/\tau$

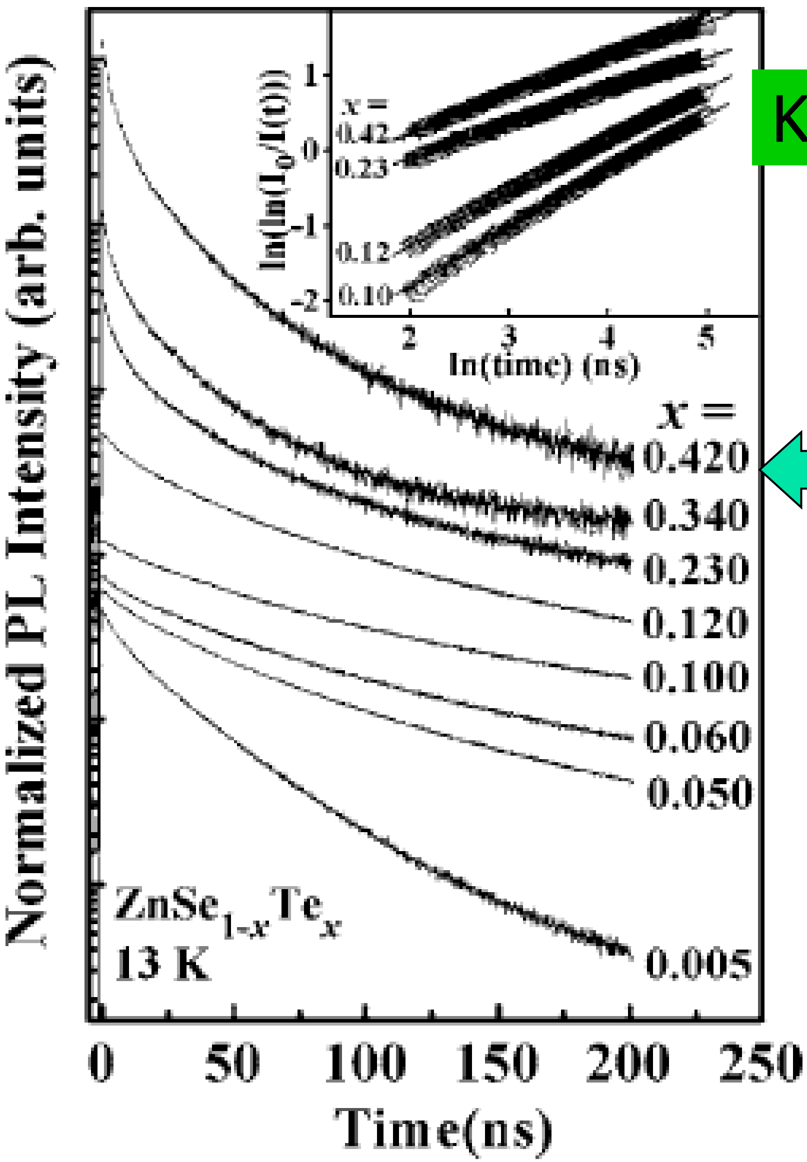
What is the origin SER?

What is the physics behind the Kohlrausch’s stretched exponential law ?

Although the Kohlrausch law closely fits donor-acceptor pair luminescence decay, Kuskovsky *et al.* concluded that it has no fundamental significance. (PRL 80, 2412)

However, Phillips, who reviewed the decay dynamics of numerous material systems, summarized a few microscopic models based on the Kohlrausch law and concluded that this law is nature’s best kept secret. (Rep. Prog. Phys. **59**, 1133)

Lin et al., APL93, 241909 (2008)



Kohlrausch's stretched exponential law

Non-mono-exponential

$$I(t) = I_0 \cdot e^{-(t/\tau)^{\beta}}$$

τ: decay time

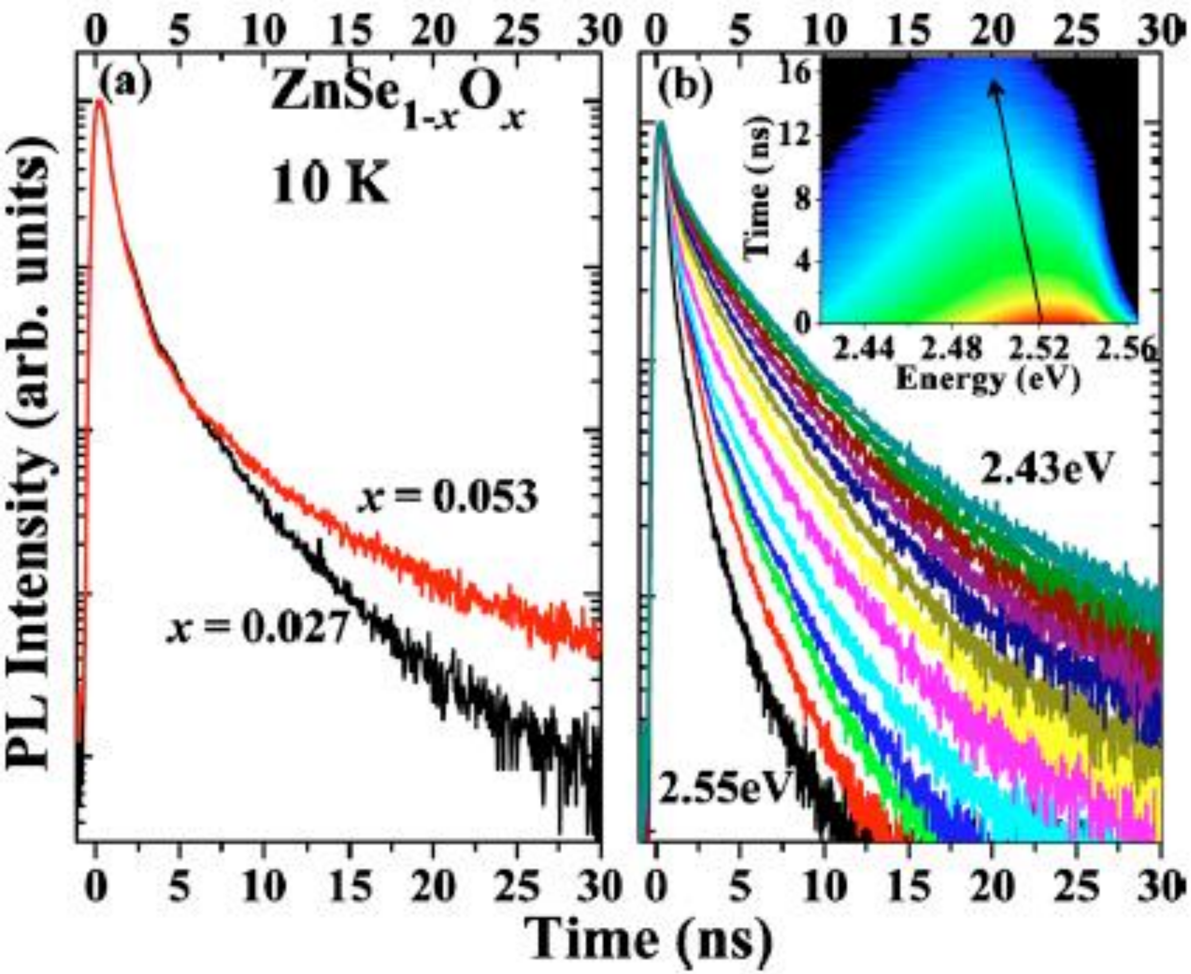
β: stretched exponent

What is the origin of non-mono-exponential photoluminescence decay?

Kohlrausch's stretched exponential law

Lin et al., APL97, 041909 (2010)

Carrier dynamics in isoelectronic $ZnSe_{1-x}O_x$ *semiconductors*



Non-mono-exponential

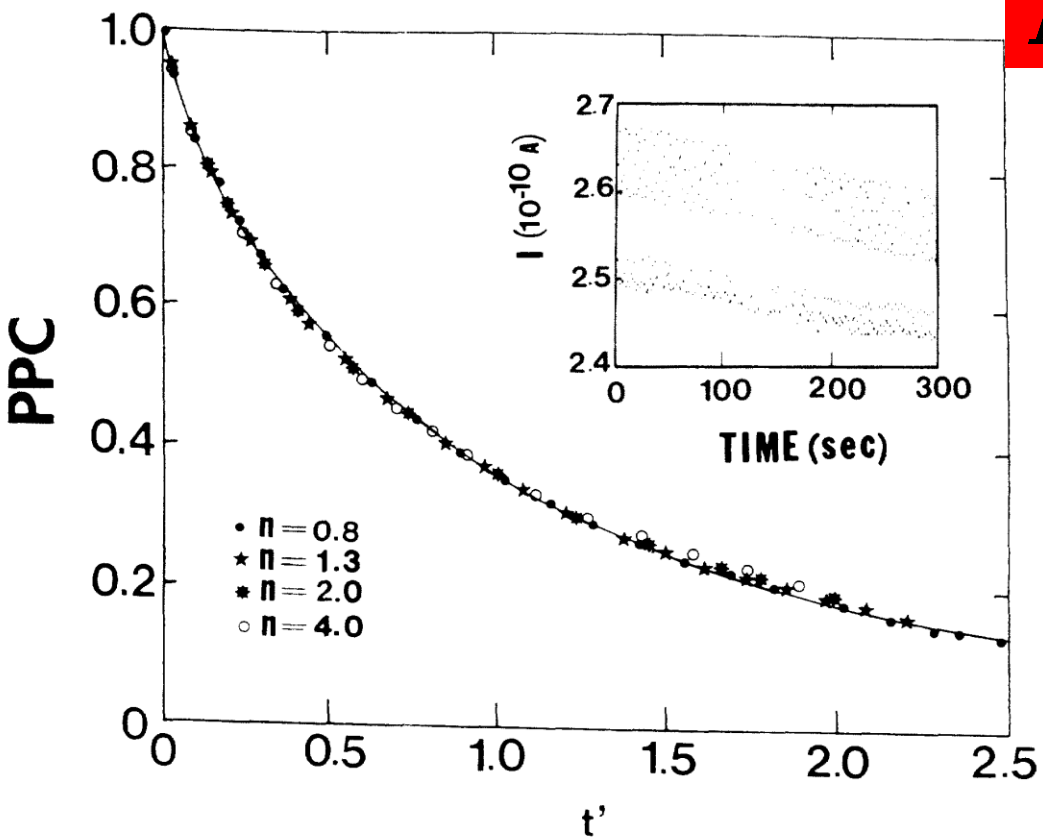
$$I(t) = I_0 \cdot e^{-(t/\tau)^\beta}$$

τ: decay time
β: stretched exponent

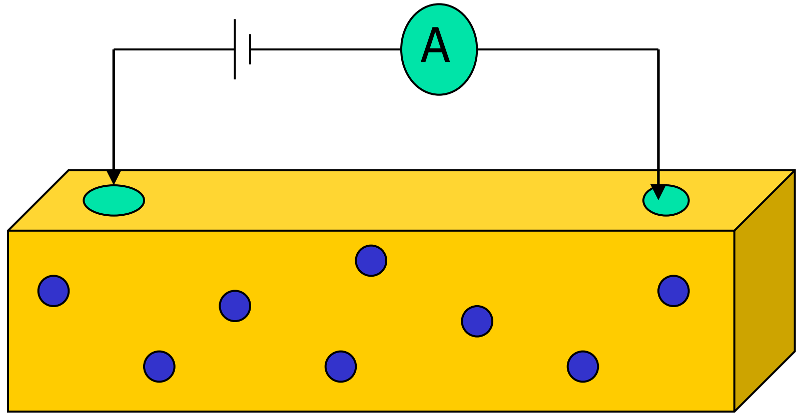
What is the origin of non-mono-exponential photoluminescence decay?

Percolation transition of persistent photoconductivity in II-VI mixed crystals, H.X. Jiang and J.Y. Lin, PRL 64, 2547 (1990)

$$I_{ppc}(t)=I_{ppc}(0)\ \exp\ [(-\ t/\tau)^{\beta}]$$



$\tau' = t/\tau$, $\beta = 0.77$

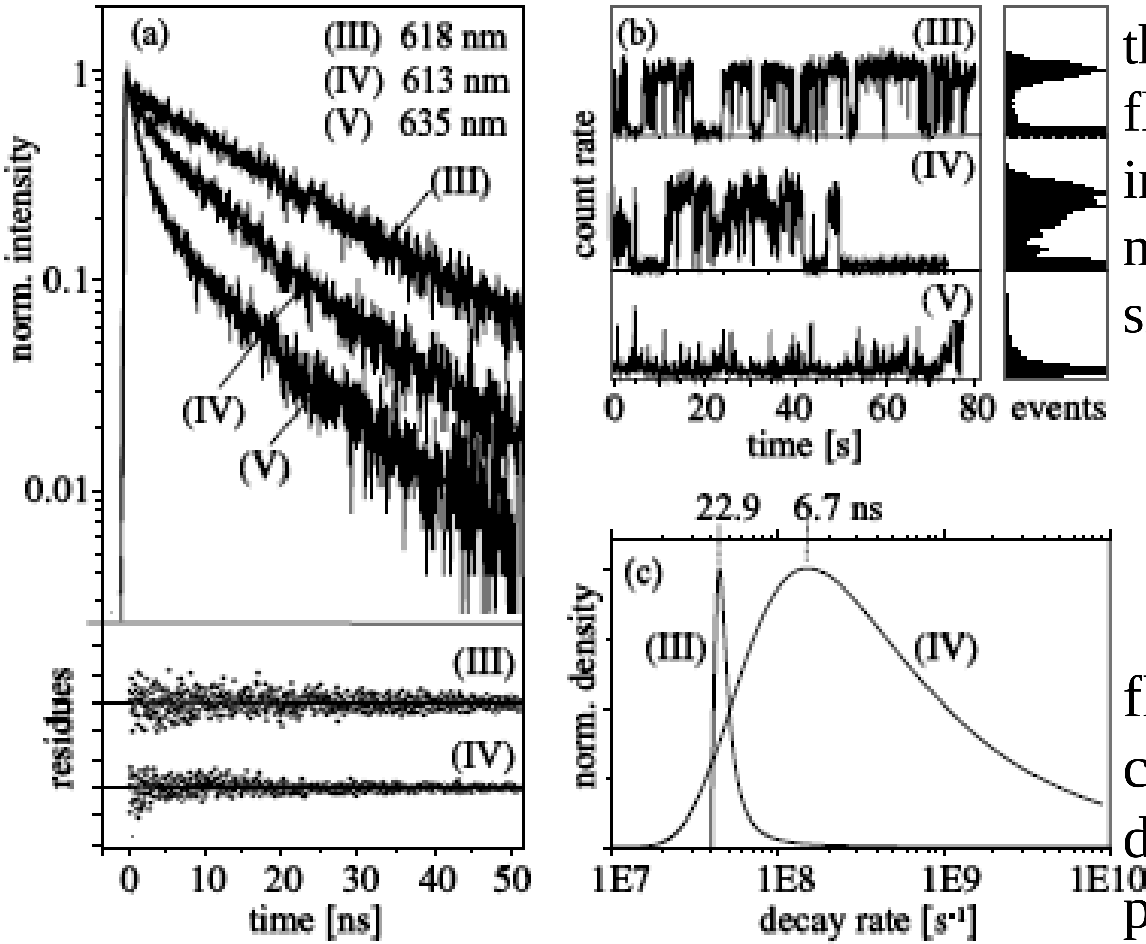


$Zn_{0.3}Cd_{0.7}Se$

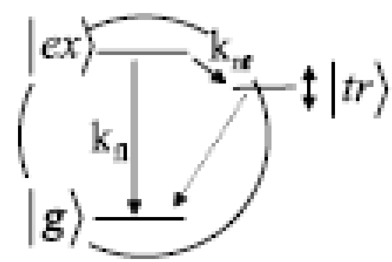
Random local potential fluctuation

Fluorescence Decay Time of Single Semiconductor Nanocrystals, G. Schlegel et al., PRL 88, 137401 (2002)

CdSe/ZnS core shell quantum dots



the fluorescence decay time is fluctuating during the investigation leading to a multiexponential decay even for a single nanocrystal

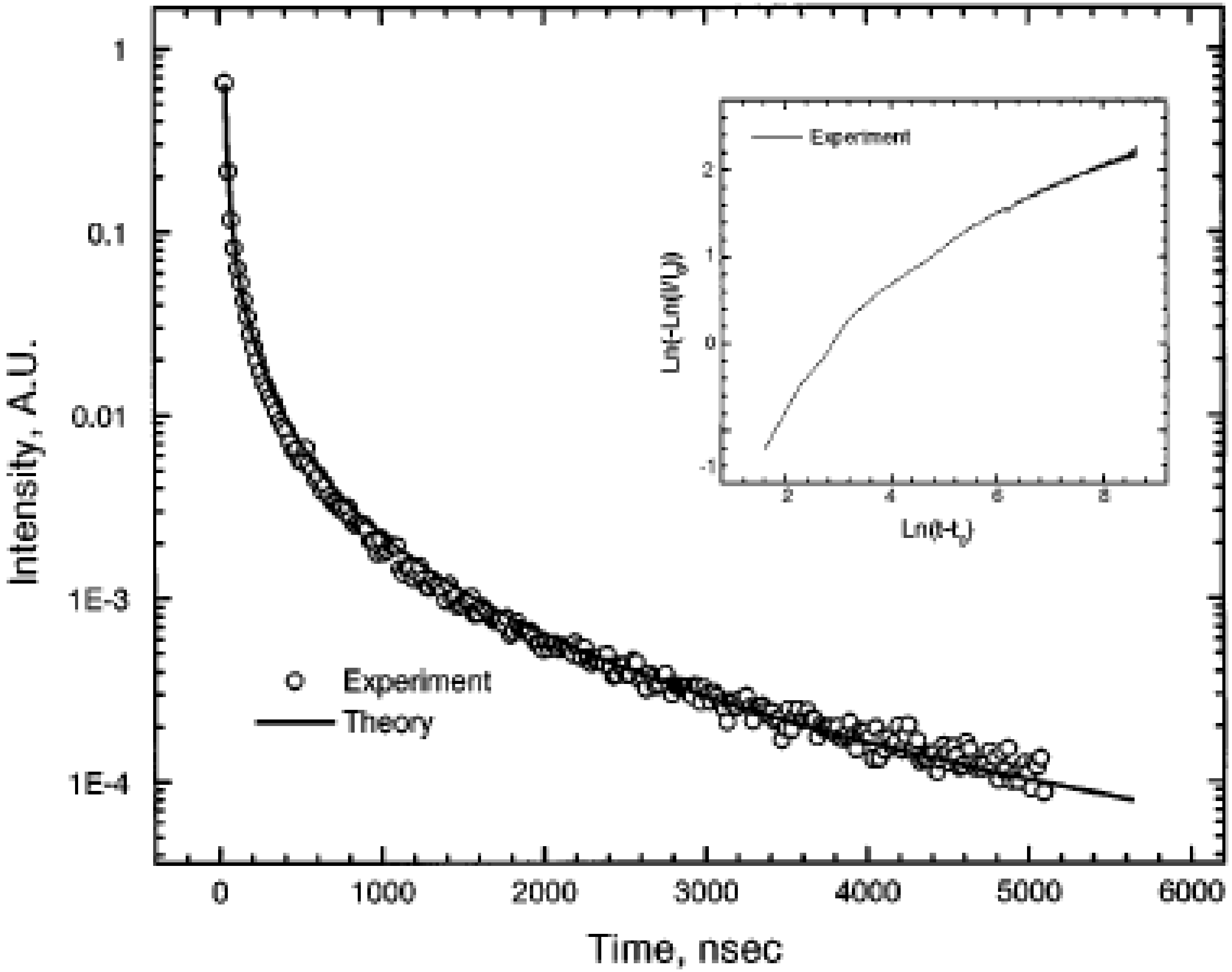


fluctuating nonradiative decay channels leading to variable dynamic quenching processes of the excited state

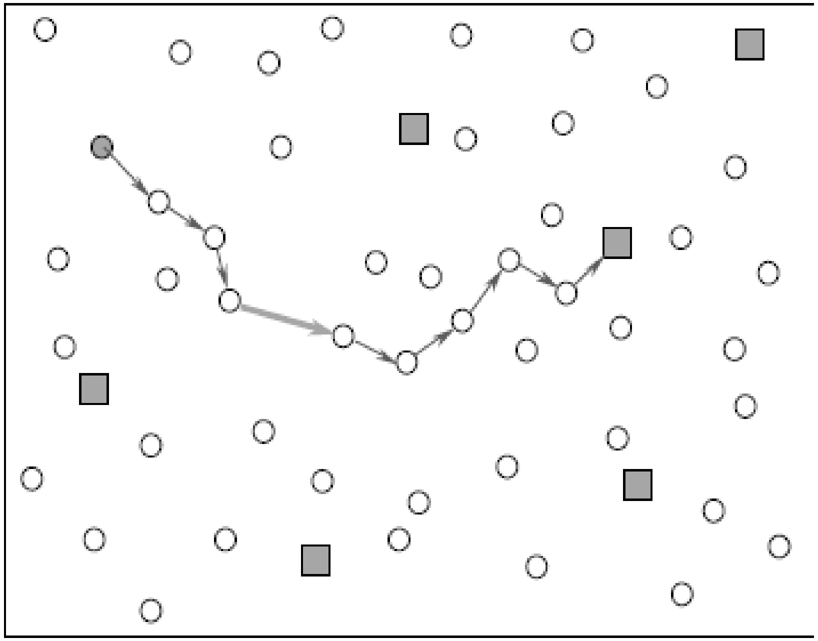
$\beta_{III}=0.97$, $\beta_{IV}=0.66$

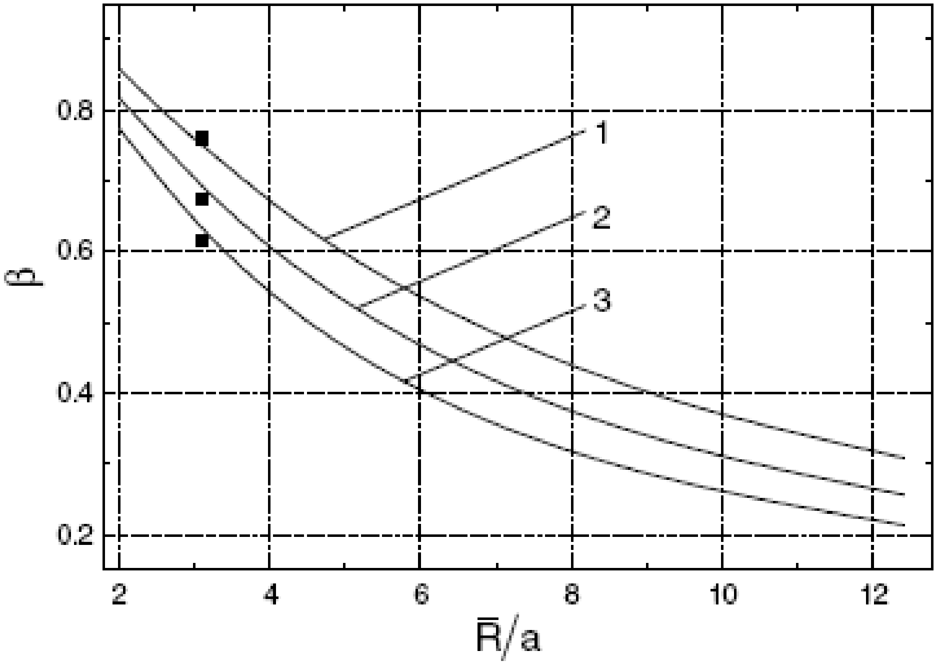
$$I(t)=I_0\cdot e^{-(t/\tau)^\beta}$$

Decay Dynamics in Disordered Systems: Application to Heavily Doped Semiconductors (**ZnSe:N**), PRL 80, 2413, (1998)



Origin of Stretched Exponential Relaxation for Hopping-Transport Models



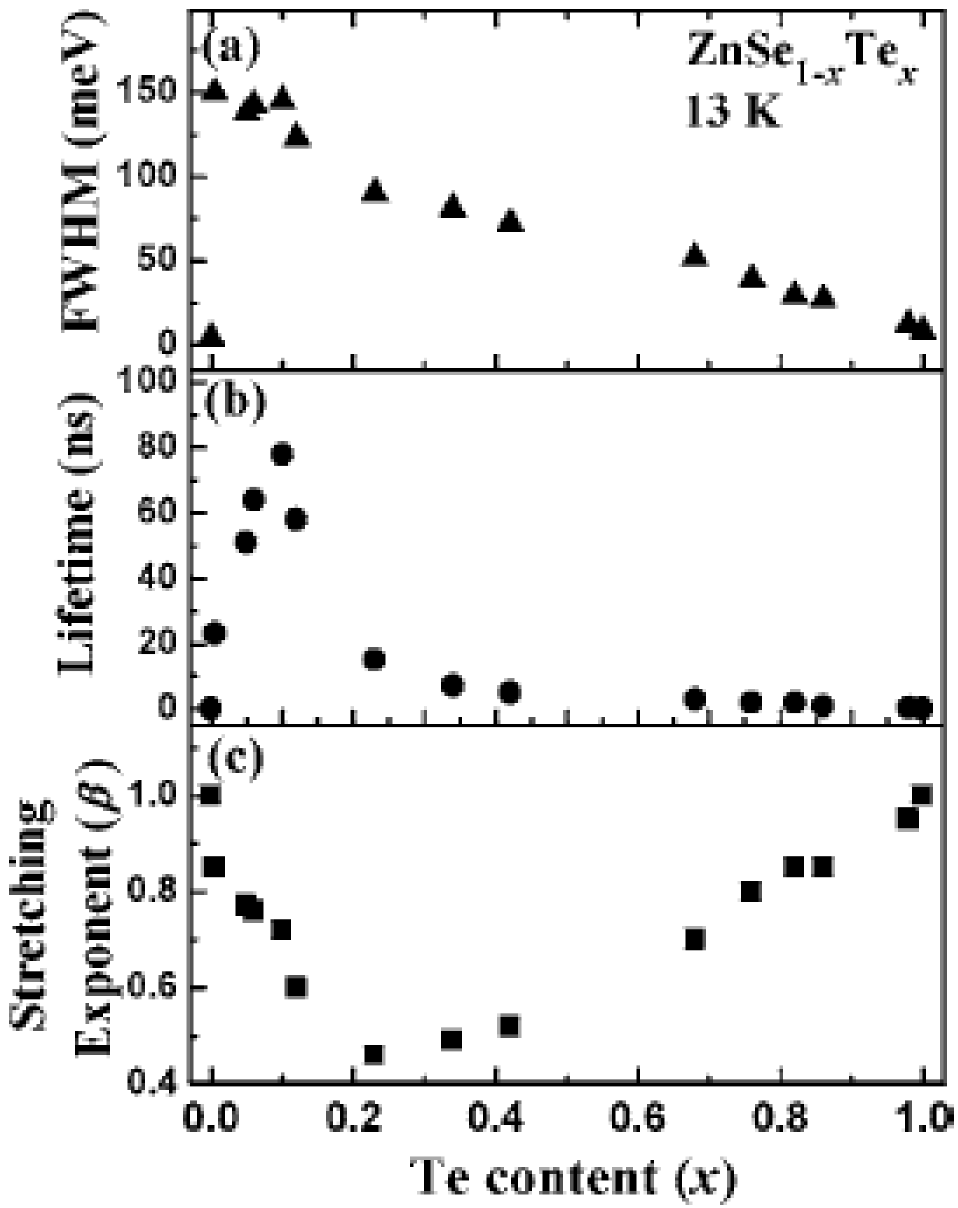


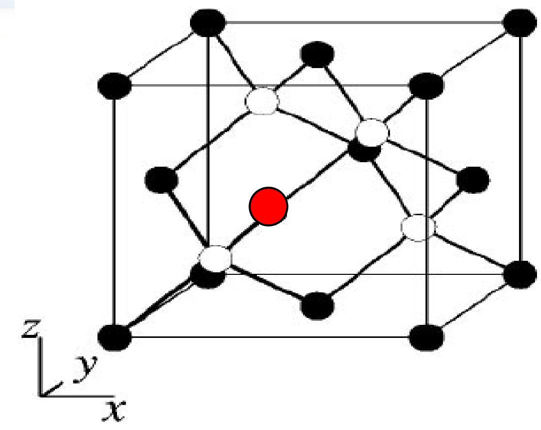
$$I(t) = I_0 \cdot e^{-(t/\tau)^{\beta}}$$

Dependence of the stretching index on $R = a$; the curves 1, 2, and 3 are plotted for N_0/N_T = 40, 20, and 10.

B. Sturman et al., PRL 91, 176602

Lin et al., APL93, 241909 (2008)

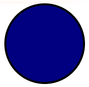


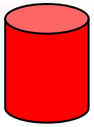


Magic number for long-range Coulomb force

(Rep. Prog. Phys. **59**, 1133)

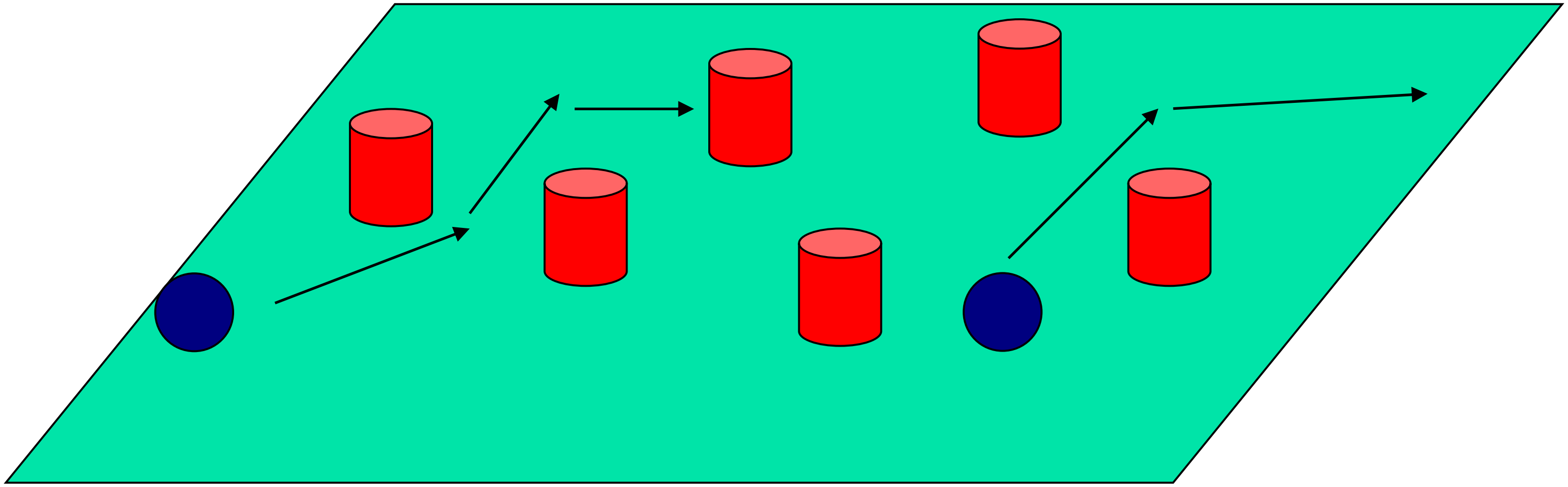
β=3/7 ?


electron


ZnMnTe quantum dot (hole)


ZnSe buffer layer

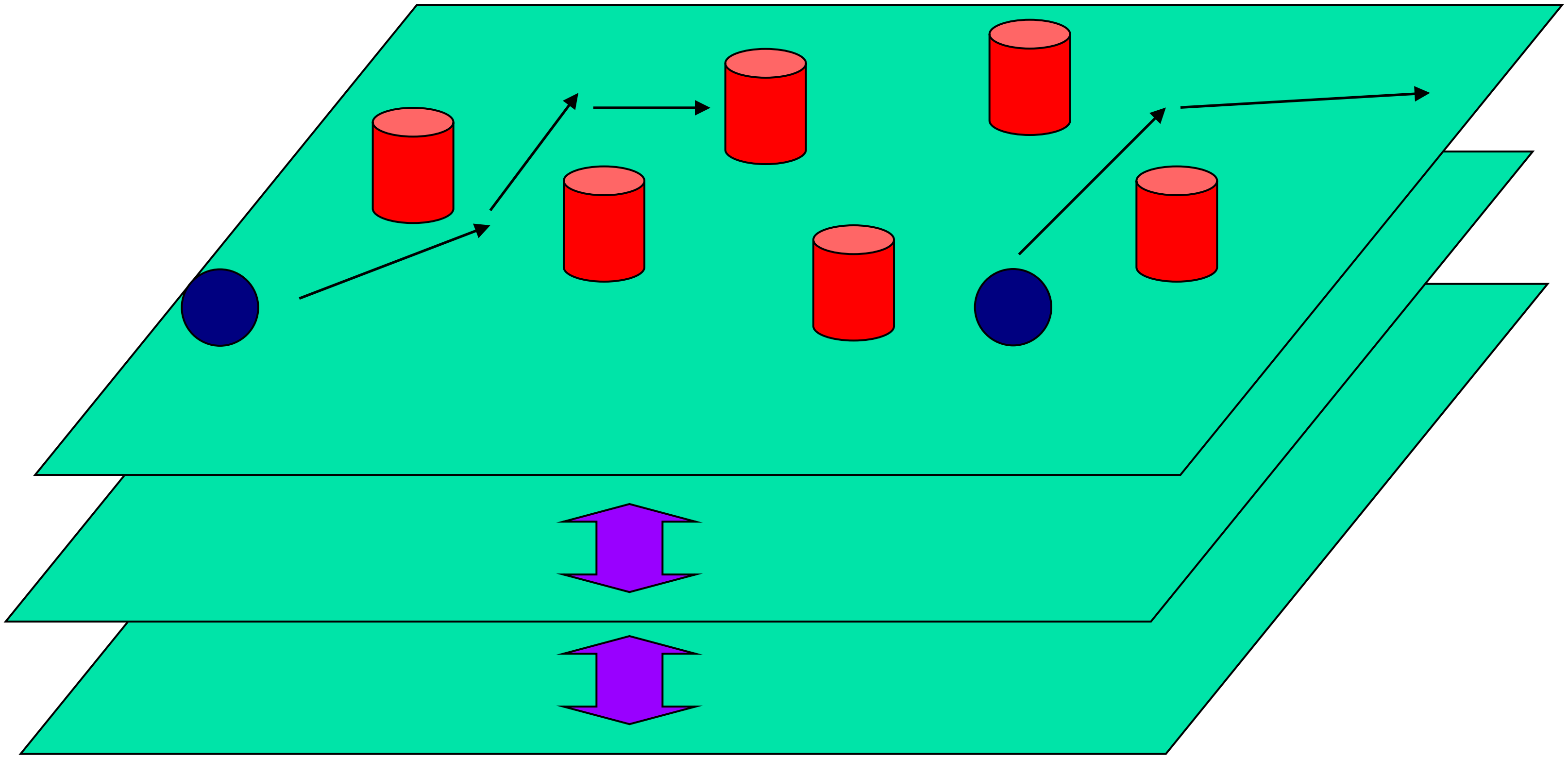
Two dimensional transport.



Does the Kohlrausch's stretched exponential law apply?

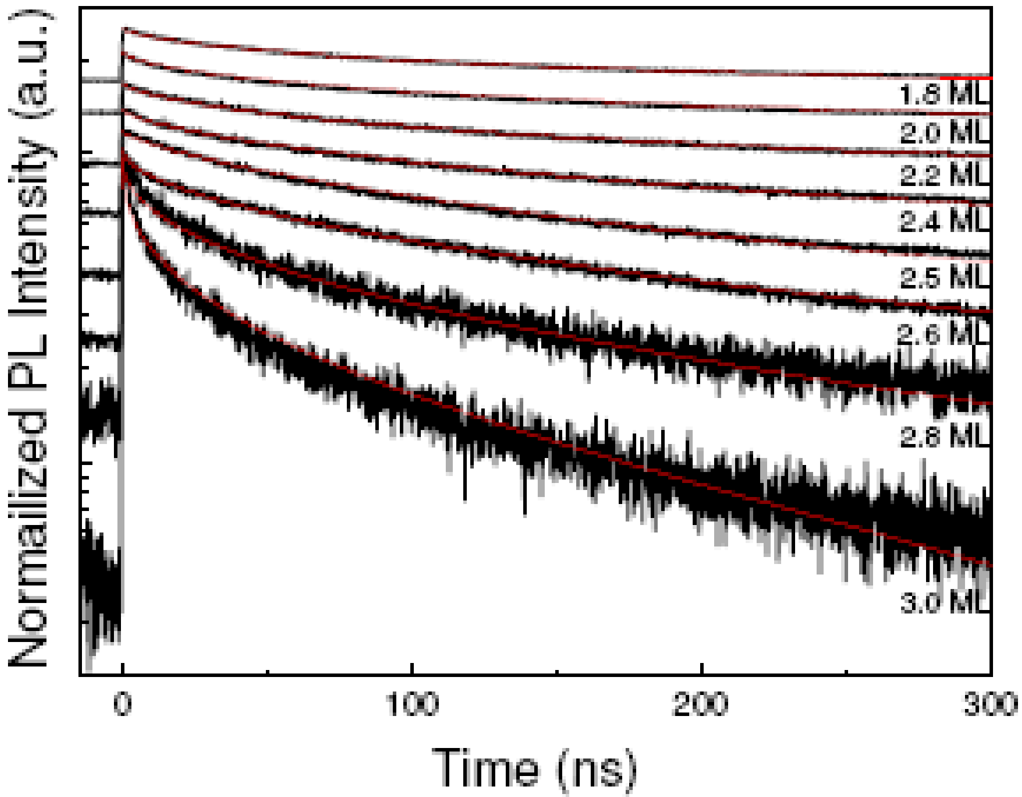
$$I(t) = I_0 \cdot e^{-(t/\tau)^{\beta}}$$

Multi-layered QDs:Two-three dimensional transport?



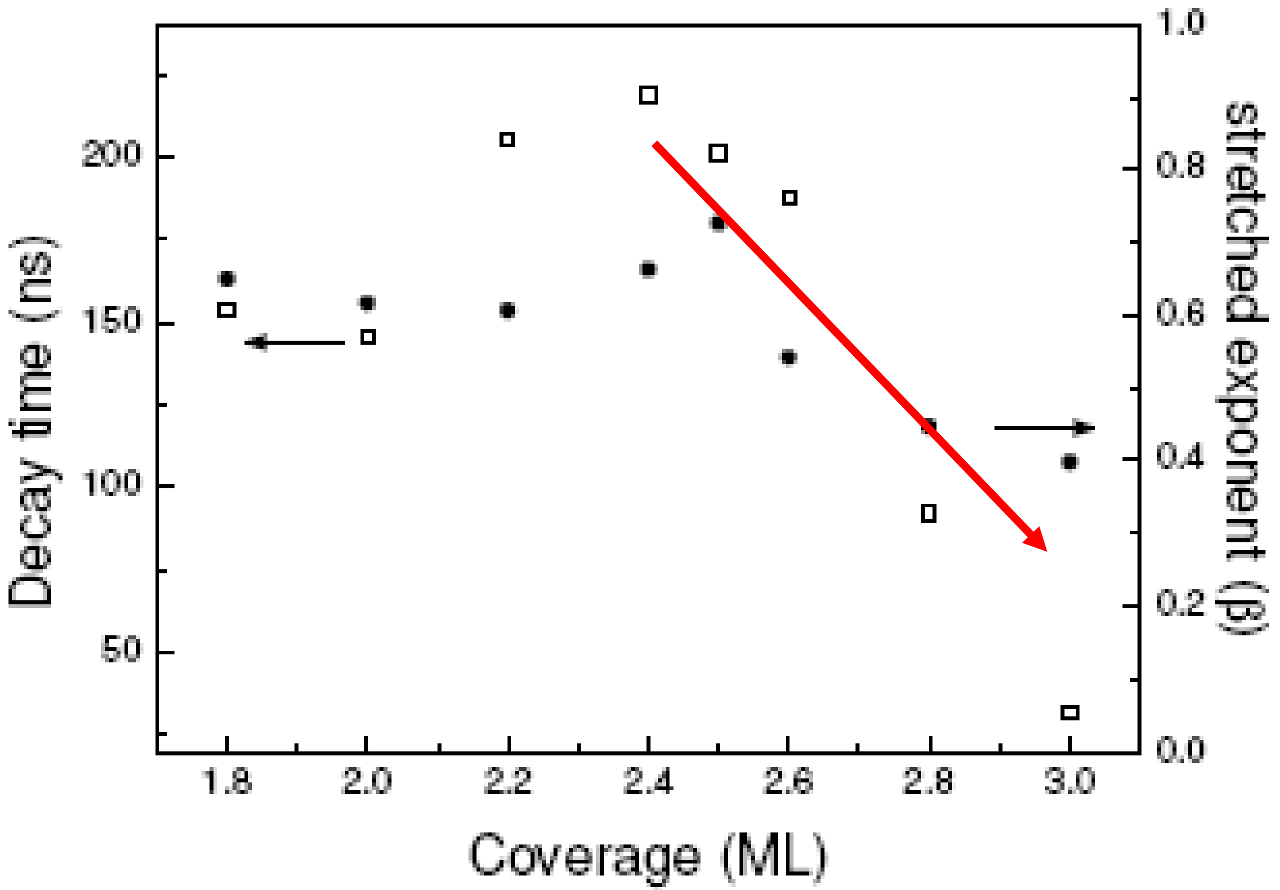
Does the Kohlrausch's stretched exponential law apply?

$$I(t) = I_0 \cdot e^{-(t/\tau)^{\beta}}$$

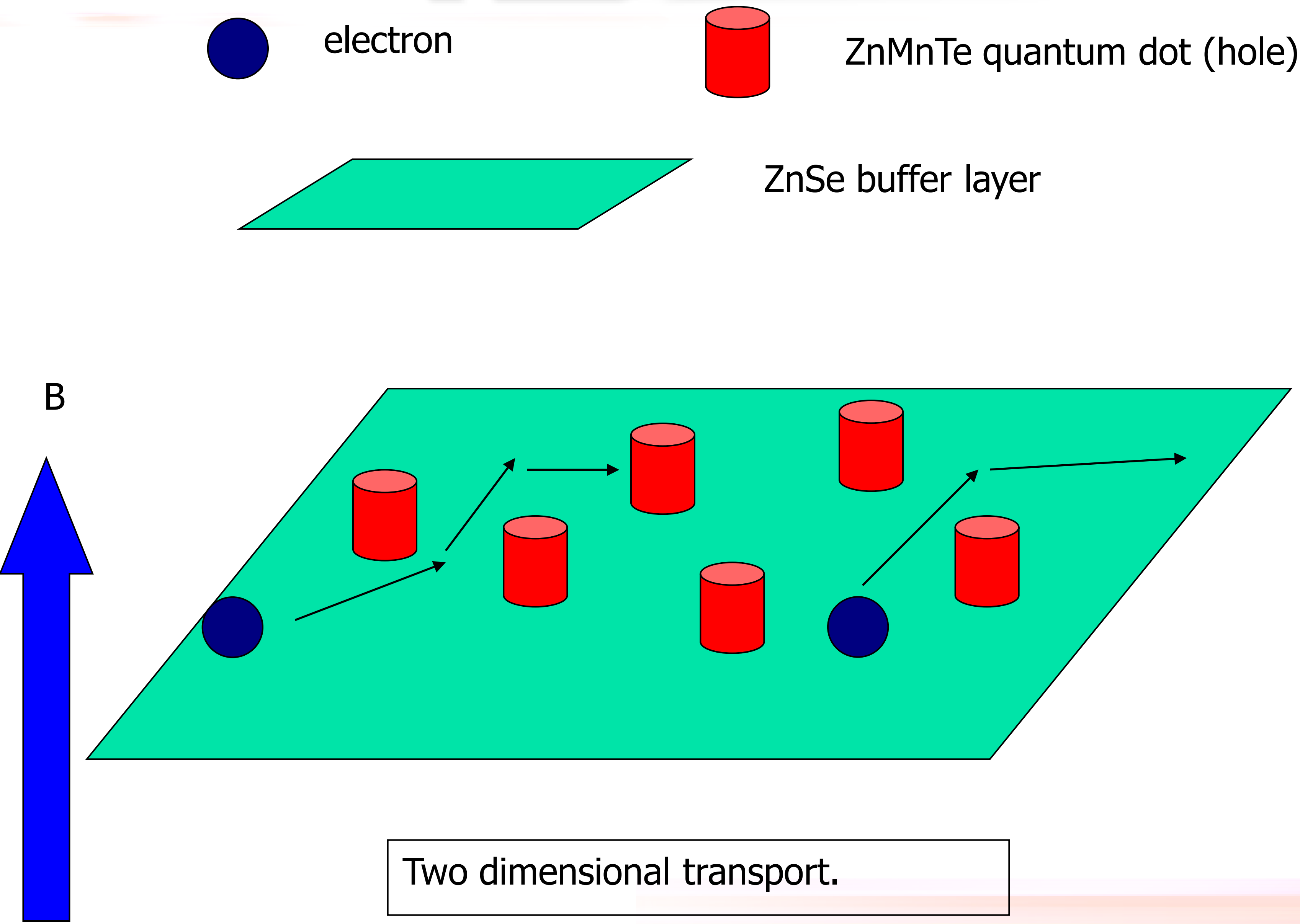


Kohlrausch's stretched exponential law

$$I(t) = I_0 \cdot e^{-(t/\tau)^{\beta}}$$


Decay time (ns)
200
150
100
50
1.8
2.0
2.2
2.4
2.6
2.8
3.0
Coverage (ML)
stretched exponent (β)
1.0
0.8
0.6
0.4
0.2
0.0

$\beta=3/7$?



Two dimensional transport.

ZnMnTe/ZnSe MQDs 2.6 MLs