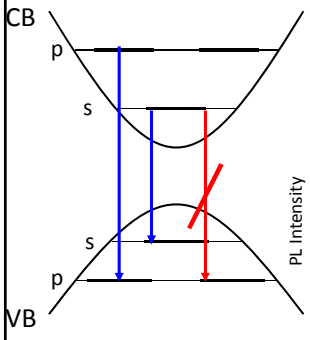
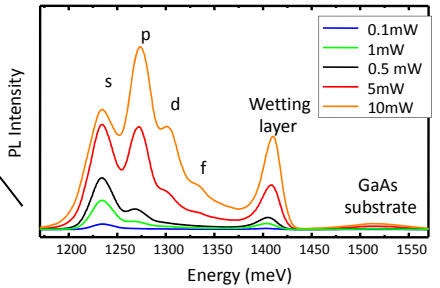
Nanostructures

Harmonic potential 2D



Harmonic oscillator model:

- s-, p-, d-,… shells
- Allowed interband transition



Fermi golden rule

Transition rate (probability of transition per unit time) :

$$W(t) = W \quad 0 \le t \le \tau$$

$$P_{mn} = \frac{w_{mn}}{\tau} = \frac{2\pi}{\hbar}|\langle m|W|n\rangle|^2 \delta(E_m - E_n)$$

Transitions possible only when $E_m = E_n$

$$W(t) = w^{\pm} e^{\pm i\omega t} \quad 0 \le t \le \tau$$

$$P_{nm} = \frac{w_{nm}}{\tau} = \frac{2\pi}{\hbar}\left|\langle n|w^{\pm}|m\rangle\right|^2 \delta(E_n - E_m \pm \hbar\omega)$$

Transitions possible only when $E_m = E_n \pm \hbar\omega$

Electromagnetic disturbance in the form of waves

$$A_{nm} = \frac{{\omega_{nm}}^3 e^2}{3\pi\varepsilon_0 \hbar c^3}|\langle m|\vec{r}|n\rangle|^2 = \frac{4\alpha}{3}\frac{{\omega_{nm}}^3}{c^2}|\langle m|\vec{r}|n\rangle|^2$$

$$P_{nm} = A_{nm}\delta(E_n - E_m \pm \hbar\omega)$$

Fermi golden rule

Transition rate (probability of transition per unit time) – from the initial state $|i\rangle$ to final $|f\rangle$

$$P_{mn} = \frac{2\pi}{\hbar}|\langle f|W|i\rangle|^2 \rho(E_f)$$

W - interaction

$\rho(E_f)$ - density of final states

Disturbance W is not necessery in the form of electromagnetic wave.

We will be back soon

Interband transitions

Proof:
Carrier's Bloch function

$$\Psi(\vec{r}) = \sum_{n,k} c_{n,k} u_{n,k}(\vec{r}) e^{i\vec{k}\vec{r}}$$

For an electron:

$$\Psi_c(\vec{r}) \approx \sum_{k} c_{1,k} u_{\Gamma_6,0}(\vec{r}) e^{i\vec{k}\vec{r}} = u_{\Gamma_6,0}(\vec{r}) F_e(\vec{r})$$

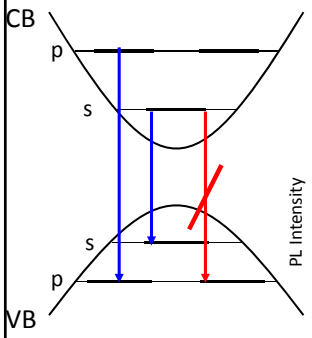
For a hole:

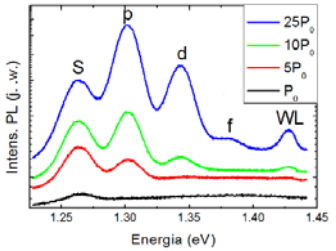
$$\Psi_v(\vec{r}) \approx \sum_{J_z=\pm 3/2,\pm 1/2,k} c_{J_z,k} u_{\Gamma_8,J_z}(\vec{r}) e^{i\vec{k}\vec{r}} = \sum_{J_z=\pm 3/2,\pm 1/2,k} u_{\Gamma_8,J_z}(\vec{r}) F_{J_z}(\vec{r})$$

Dipole optical transitions:

$$\langle \Psi_c(\vec{r})|\vec{p}|\Psi_{v,J_z}(\vec{r})\rangle = \underbrace{\langle u_{\Gamma_6,0}(\vec{r})|u_{\Gamma_8,J_z}(\vec{r})\rangle}_{=0}\langle F_e(\vec{r})|\vec{p}|F_{J_z}(\vec{r})\rangle + \langle u_{\Gamma_6,0}(\vec{r})|\vec{p}|u_{\Gamma_8,J_z}(\vec{r})\rangle\langle F_e(\vec{r})|F_{J_z}(\vec{r})\rangle$$

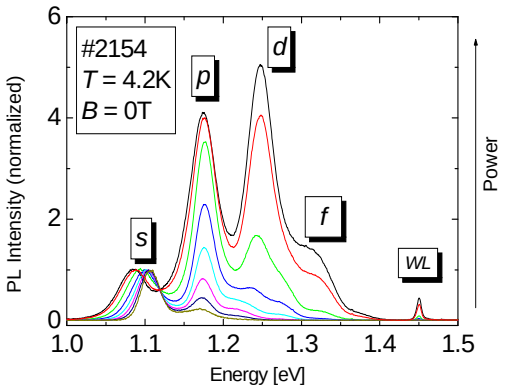
Potencjał harmoniczny 2D





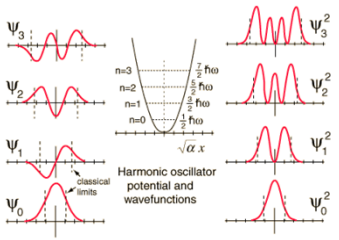
Zależność od mocy pobudzania widm fotoluminescencji otrzymanych w temperaturze bliskiej temperatury ciekłego helu (ok. 5 K) dla licznego (wielomilionowego) zbioru kropek kwantowych InAs/GaAs.

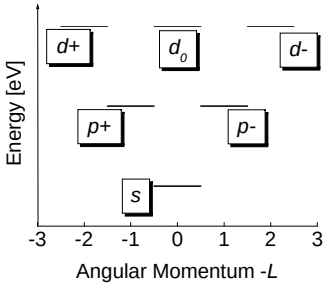
Potencjał harmoniczny 2D



Adam Babiński

Potencjał harmoniczny 2D





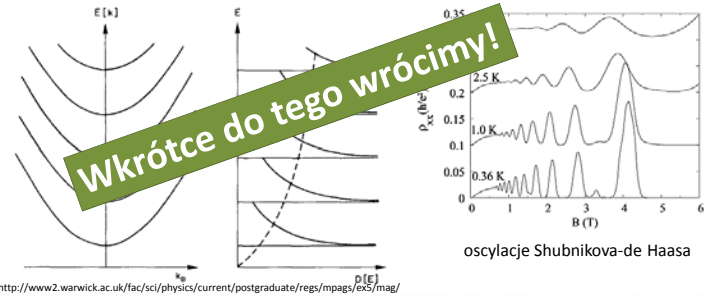
$n, m = 0,1,2...$
$L = n - m$ (elektron)

Adam Babiński

Potencjał harmoniczny 2D

$$\left[-\frac{\hbar^2}{2m}\frac{d^2}{dx^2}+\frac{1}{2}m\omega_0^2x^2\right]\psi(x)=E\psi(x) \qquad \omega_0=\omega_c=\frac{eB}{m^*}$$

Ważny przykład – cząstka w polu magnetycznym. Częstość cyklotronowa ω_c

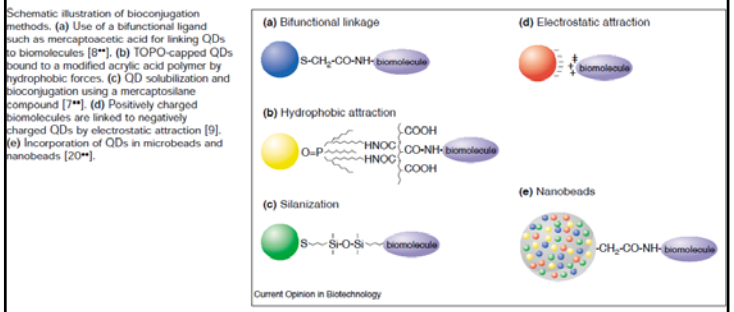


Wkrótce do tego wrócimy!

oscylacje Shubnikova-de Haasa

http://www2.warwick.ac.uk/fac/sci/physics/current/postgraduate/regs/mpags/ex5/mag/

Sferyczne kropki kwantowe



Luminescent quantum dots for multiplexed biological detection and imaging
W. Chan et al. Current Opinion in Biotechnology 2002, 13:40–46

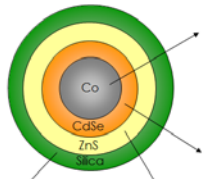
Sferyczne kropki kwantowe

Magnetic Quantum Dot

What is MQD ?

Justin Galloway

Composite with A Novel Structure for Active Sensing in Living cells



① **Cobalt core** : active manipulation
- diameter : ~10 nm
- superparamagnetic NPs

→ manipulated or positioned by an external field without aggregation in the absence of an external field

② **CdSe shell** : imaging with fluorescence
- thickness : 3-5 nm
- visible fluorescence (~450 – 700 nm)
- ability to tune the band gap

→ by controlling the thickness, able to tune the emission wavelength, i.e., emission color

③ **ZnS shell** : electrical passivation
- thickness : 1-2 nm
- having wider band gap (3.83 eV) than CdSe (1.91 eV)
- enhancement of QY

→ CdSe (5-10%) ⇒ CdSe/ZnS (~50%)

④ **Silica shell** : bio-compatibility & functionalization with specific targeting group
- thickness : ~10 nm
- bio-compatible, & non-toxic to live cell functions
- stable in aqueous environment
- ability to functionalize its surface with specific targeting group

Przejścia optyczne

E_f energia końcowa
E_i energia początkowa

$E_f = E_i + \hbar cQ$ zasada zachowania energii
$K_f = K_i + Q$ zasada zachowania pędu

Pęd fotonu $\hbar\omega = \hbar cQ$. Gdy $\hbar\omega = 1$ eV dostajemy $Q \approx 10^7 m^{-1}$. Rozmiar strefy Brillouina to ok. $\frac{\pi}{a} \approx \frac{\pi}{0.5\,nm} = 10^{10} m^{-1}$. Stąd najczęściej $K_f = K_i + Q \approx K_i$

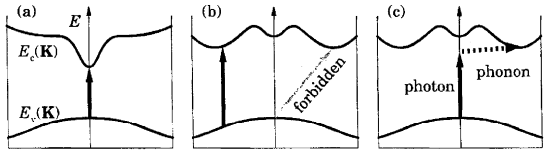
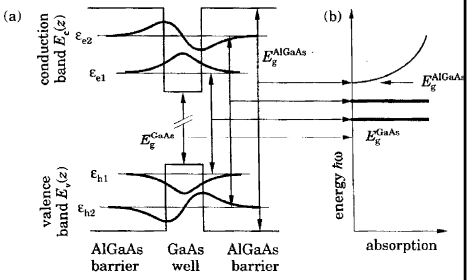


FIGURE 2.20. Optical absorption across the band gap in different types of semiconductor. (a) Absorption across a direct band gap at Γ. (b) Absorption across an indirect band gap is forbidden but vertical transitions occur for all **K**. (c) Transition across an indirect band gap with absorption of both a phonon and a photon.

Przejścia optyczne

$$\varepsilon_{e,n_e} = E_c^{GaAs} + \frac{\hbar^2\pi^2 n_e^2}{2m_0 m_e a^2}$$

$$\varepsilon_{h,n_h} = E_v^{GaAs} - \frac{\hbar^2\pi^2 n_h^2}{2m_0 m_h a^2}$$



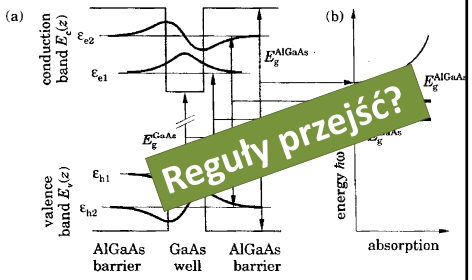
$$\hbar\omega_n = \varepsilon_{e,n_e} - \varepsilon_{h,n_h} = E_g^{GaAs} + \frac{\hbar^2\pi^2 n^2}{2m_0 a^2}\left(\frac{1}{m_e} + \frac{1}{m_h}\right) = E_g^{GaAs} + \frac{\hbar^2\pi^2 n^2}{2m_0 m_{eh} a^2}$$

Optyczna masa efektywna: $\frac{1}{m_{eh}} = \frac{1}{m_e} + \frac{1}{m_h}$

Przejścia optyczne

$$\varepsilon_{e,n_e} = E_c^{GaAs} + \frac{\hbar^2\pi^2 n_e^2}{2m_0 m_e a^2}$$

$$\varepsilon_{h,n_h} = E_v^{GaAs} - \frac{\hbar^2\pi^2 n_h^2}{2m_0 m_h a^2}$$



$$\hbar\omega_n = \varepsilon_{e,n_e} - \varepsilon_{h,n_h} = E_g^{GaAs} + \frac{\hbar^2\pi^2 n^2}{2m_0 a^2}\left(\frac{1}{m_e} + \frac{1}{m_h}\right) = E_g^{GaAs} + \frac{\hbar^2\pi^2 n^2}{2m_0 m_{eh} a^2}$$

Optyczna masa efektywna: $\frac{1}{m_{eh}} = \frac{1}{m_e} + \frac{1}{m_h}$

Przejścia optyczne

$$\varepsilon_{e,n_e} = E_c^{GaAs} + \frac{\hbar^2\pi^2 n_e^2}{2m_0 m_e a^2}$$

$$\varepsilon_{h,n_h} = E_v^{GaAs} - \frac{\hbar^2\pi^2 n_h^2}{2m_0 m_h a^2}$$

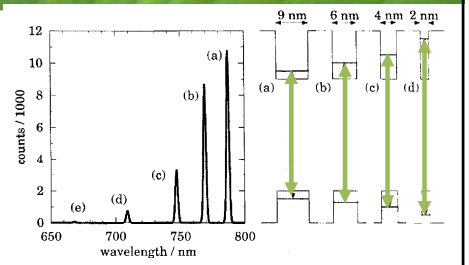


FIGURE 1.4. Photoluminescence as a function of wavelength for a sample with four quantum wells of different widths, whose conduction and valence bands are shown on the right. The barriers between the wells are much thicker than drawn. [Data kindly supplied by Prof. E. L. Hu, University of California at Santa Barbara.]

$$\hbar\omega_n = \varepsilon_{e,n_e} - \varepsilon_{h,n_h} = E_g^{GaAs} + \frac{\hbar^2\pi^2 n^2}{2m_0 a^2}\left(\frac{1}{m_e} + \frac{1}{m_h}\right) = E_g^{GaAs} + \frac{\hbar^2\pi^2 n^2}{2m_0 m_{eh} a^2}$$

Optyczna masa efektywna: $\frac{1}{m_{eh}} = \frac{1}{m_e} + \frac{1}{m_h}$

THE ARTICLE

Hidden symmetries in the energy levels of excitonic 'artificial atoms'

M. Bayer*, O. Stern*, P. Hawrylak*†, S. Fafard† & A. Forchel*

* *Technische Physik, Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany*
† *Institute for Microstructural Science, National Research Council of Canada, Ottawa, K1A OR6, Canada*

NATURE | VOL 405 | 22 JUNE 2000 | www.nature.com

THE ARTICLE

- jakie są to kropki, jakich energii luminescencji się spodziewamy?
- jaką metodą otrzymano te kropki? Jak je przygotowano do eksperymentu i dlaczego było to konieczne?
- dlaczego pomiary są w temperaturach helowych? Jakie są skale energii?
- w jaki sposób opisane są procesy zachodzące w kropkach? Czy umiesz przeczytać hamiltonian „słowami"?
- jakiej energii używamy do pobudzania?
- co się zmienia z mocą pobudzania?
- widmo emisyjne opisane jest „złotą regułą Fermiego" – o co chodzi?
- dlaczego niektóre linie „gasną", a inne „się pojawiają" jak świecimy coraz mocniej?
- dlaczego jest mowa o „sztucznych atomach"? Jaki jest czas życia (rozpadu?) takiego atomu? Jak wygląd „szereg promieniotwórczy" sztucznych atomów?
- o jakie ukryte symetrie chodzi w artykule?
- do czego można by wykorzystać obserwowane efekty?

THE ARTICLE

ARTICLE

The charge and energy of a sufficiently small particle of metal or semiconductor are quantized just like those of an atom. The current through such a quantum dot or one-electron transistor reveals atom-like features in a spectacular way.

Marc A. Kastner

M A Kastner, *Phys. Today* , **46**, 24 (1993)

REVIEW ARTICLE

Electrons in artificial atoms

R. C. Ashoori

Progress in semiconductor technology has enabled the fabrication of structures so small that they can contain just one mobile electron. By varying controllably the number of electrons in these 'artificial atoms' and measuring the energy required to add successive electrons, one can conduct atomic physics experiments in a regime that is inaccessible to experiments on real atoms.

R C Ashoori, *Nature* , **379**, 413 (1996)

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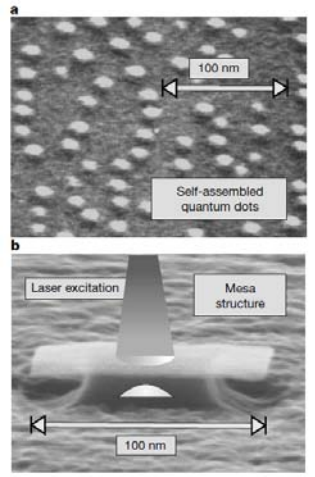


Figure 1 Scanning electron micrographs illustrating the experimental technique used for studying single self-assembled quantum dots. **a**, Scanning electron micrograph of a GaAs semiconductor layer on which $In_{0.60}Ga_{0.40}As$ self-assembled quantum dots with a density of about 10^{10} cm^{-2} have been grown by molecular beam epitaxy. To permit their microscopic observation these dots—unlike those used for spectroscopy—have not been covered by a GaAs cap layer. To a good approximation, all quantum dots have the same shape exhibiting rotational symmetry. However, their size varies by a few nanometres around an average diameter of 15 nm. This inhomogeneity results in a considerable broadening of the emission lines in spectroscopic studies. **b**, To avoid this broadening we have studied the emission of a single quantum dot. Lithographic techniques were used to fabricate small mesa structures on samples capped by a GaAs layer. The lateral mesa size was reduced to such an extent (<100 nm) that only a single dot is contained in it. These mesa structures have been studied by photoluminescence spectroscopy at low temperature. A laser beam (shown schematically as a truncated cone above the mesa) injects a controlled number of electrons and holes into the dot indicated by the lens shape, and the emission spectrum of this complex is recorded. To reduce sample heating under optical excitation, the structures are held in superfluid helium at about 1.2 K. After dispersion by a monochromator, the emission is detected by a CCD (charge-coupled device) camera.

Harmonic potential 2D

$E_n^x = \hbar\omega_0\left(n_x + \frac{1}{2}\right)$ in x direction and the same in y

$E_n^y = \hbar\omega_0\left(n_y + \frac{1}{2}\right)$

$E_n = E_n^x + E_n^y = \hbar\omega_0(N+1)$

Degeneracy? $N = n_x + n_y$

$g_N = N + 1$

N	(n_x, n_y)
0	(0,0)
1	(1,0) (0,1)
2	(2,0) (1,1) (0,2)
3	(3,0) (2,1) (1,2) (0,3)

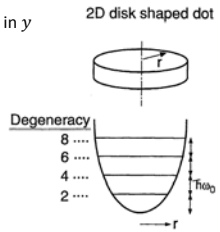


Fig. 5. Schematic model for the vertical dot with a harmonic lateral potential. The single-particle states are laterally confined into discrete equidistant 0D levels whose degeneracies are 2, 4, 6, 8, ⋯ including spin degeneracy from the lowest level.

Jpn. J. Appl. Phys. Vol. 36 (1997) pp. 3917–3923
Part 1, No. 6B, June 1997

Harmonic potential 3D

$E_n^x = \hbar\omega_0\left(n_x + \frac{1}{2}\right)$ in x, y i z

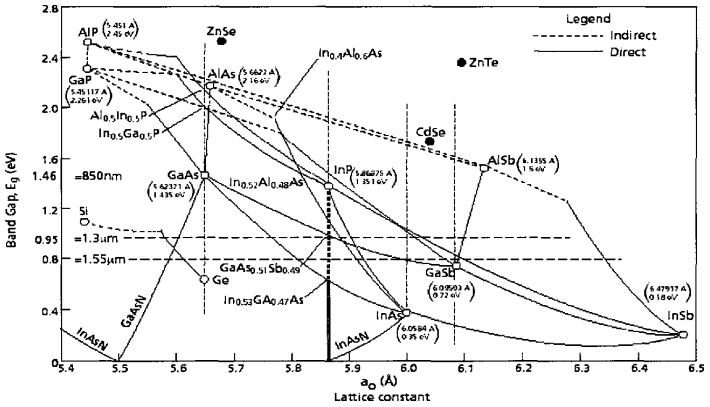
$E_n = E_n^x + E_n^y + E_n^z = \hbar\omega_0\left(N + \frac{3}{2}\right)$

Degeneracy? $N = n_x + n_y + n_z$

$g_N = \frac{(N+1)(N+2)}{2}$

N	(n_x, n_y, n_z)
0	(0,0,0)
1	(1,0,0) (0,1,0) (0,0,1)
2	(2,0,0) (0,2,0) (0,0,2) (1,1,0) (1,0,1) (0,1,1)
3	3x(3,0,0) 1x(1,1,1) 6x(2,0,1)

Semiconductor heterostructures



Investigation of high antimony-content gallium arsenic nitride-gallium arsenic antimonide heterostructures for long wavelength application

THE ARTICLE

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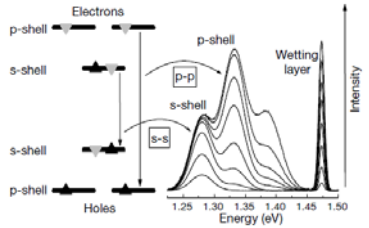

Figure 2 State filling spectroscopy on quantum dots. On the left is a scheme of the dot energy levels, their occupation by carriers and the radiative transitions. Spin orientations of electrons and holes: grey triangles, spin-down; black triangles, spin-up. On the right are typical emission spectra resulting from these transitions for an ensemble of $In_{0.60}Ga_{0.40}As$ quantum dots; these spectra were recorded at different excitation powers (an Ar-ion laser was used).

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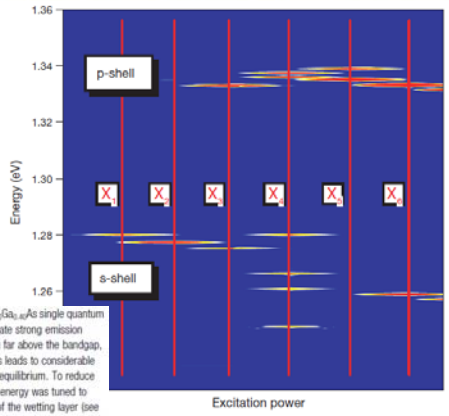

Figure 3 Contour plot of the variation of the emission of an $In_{0.60}Ga_{0.40}As$ single quantum dot with excitation power and with energy. Bright regions indicate strong emission intensities, blue regions low intensities. When optically exciting far above the bandgap, carrier relaxation involving multiple phonon emission processes leads to considerable sample heating, which causes the system to be in strong non-equilibrium. To reduce heating, a Ti-sapphire laser was used as excitation source. Its energy was tuned to $E = 1.470$ eV, corresponding to emission close to the bottom of the wetting layer (see Fig. 2). The excitation power P_{ex} was varied between 50 nW and 5 mW.

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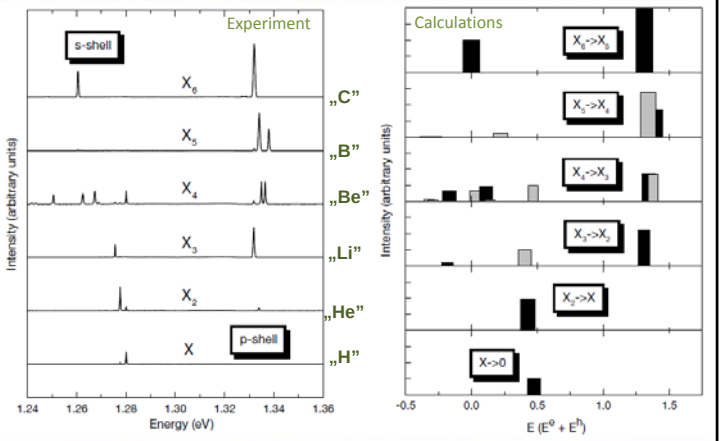

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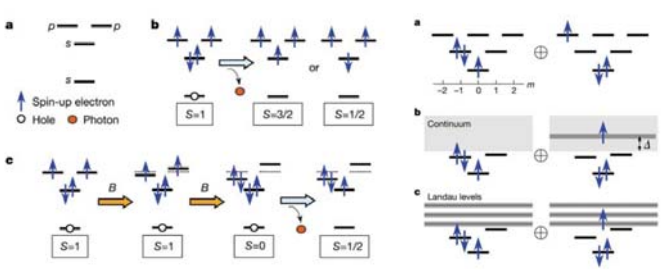
$$H = \sum_i E_i^e c_i^+ c_i + \sum_i E_i^h d_i^+ d_i - \sum_{ijkl} \langle ij|V_{eh}|kl\rangle c_i^+ d_j^+ d_k c_l$$

$$+ \frac{1}{2}\sum_{ijkl} \langle ij|V_{ee}|kl\rangle c_i^+ c_j^+ c_k c_l + \frac{1}{2}\sum_{ijkl} \langle ij|V_{hh}|kl\rangle d_i^+ d_j^+ d_k d_l$$

where c_i^+ and d_i^+ (c_i and d_i) are the creation (annihilation) operators for electrons and holes. $E_i^{e/h}$ are the electron/hole single particle energies and V_{mn}, m,n = e,h are the interparticle Coulomb interactions.

The interband optical processes are described by the polarization operator $P^+ = \Sigma_i c_i^+ d_i^+$, where P^+ annihilates a photon and creates an electron–hole pair. The main question arises when populating

$$L_N(\omega) = \sum_f |\langle N-1, f|P^-|i, N\rangle|^2 \cdot \delta(E_N^i - E_{N-1}^f - \hbar\omega)$$



K.Karrai et al., *Nature* **427,** 135 (2004)