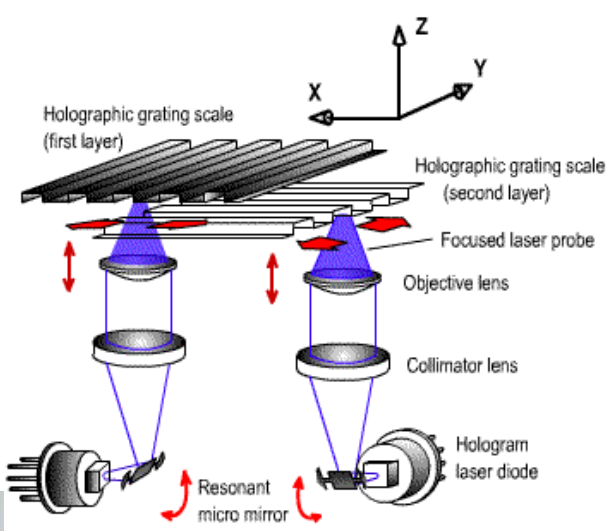
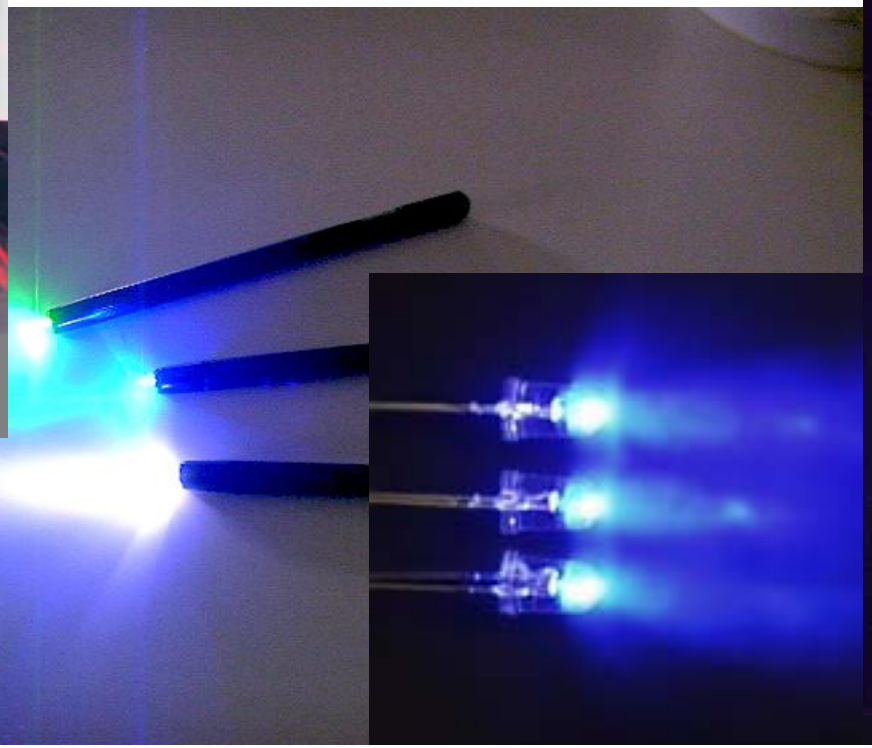
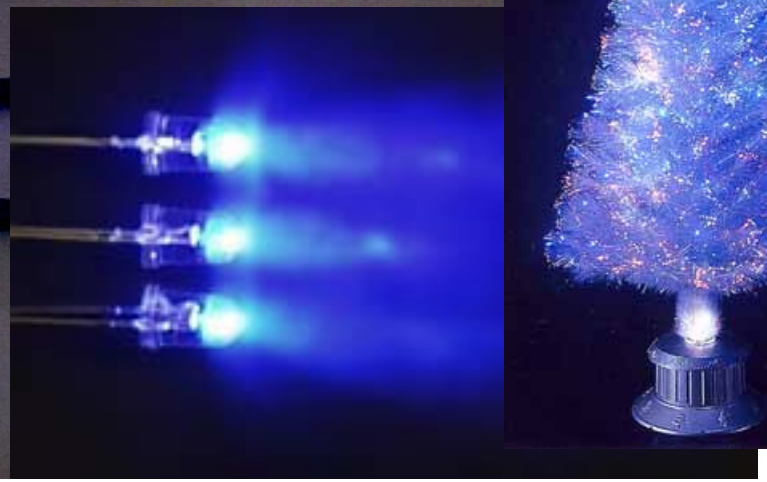
Domieszki w półprzewodnikach

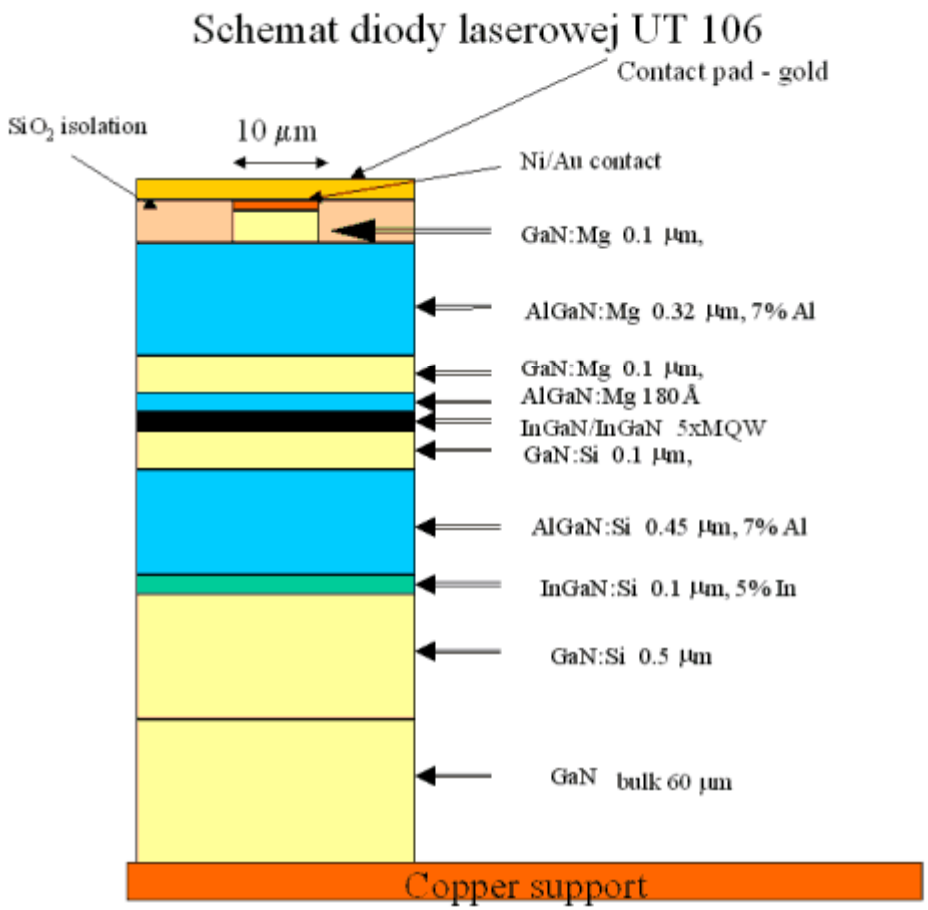
Niebieska optoelektronika



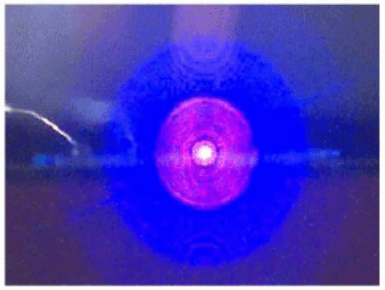


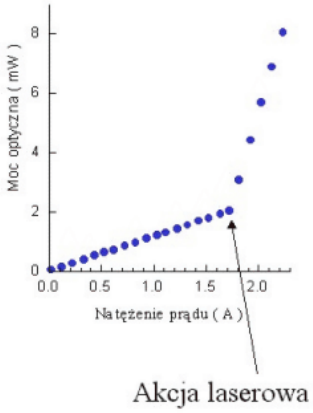


Niebieski laser

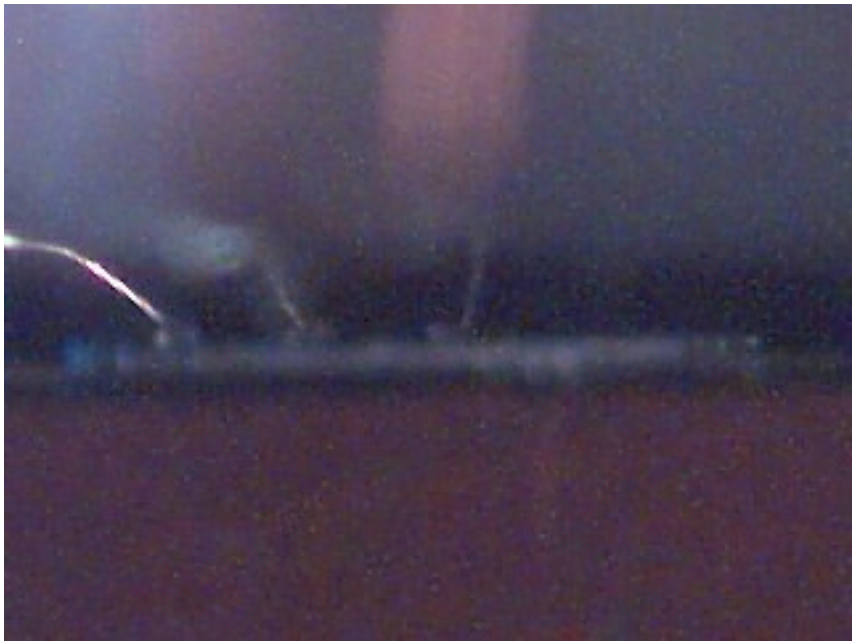


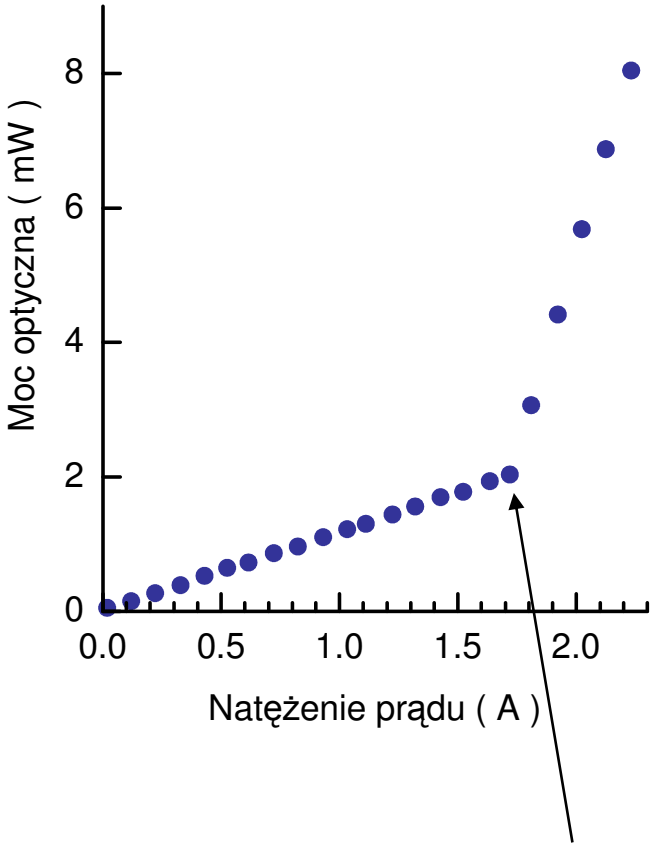
Elektryczne pobudzanie struktury laserowej „UT 106"





Elektryczne pobudzanie struktury laserowej „Unipress 106”

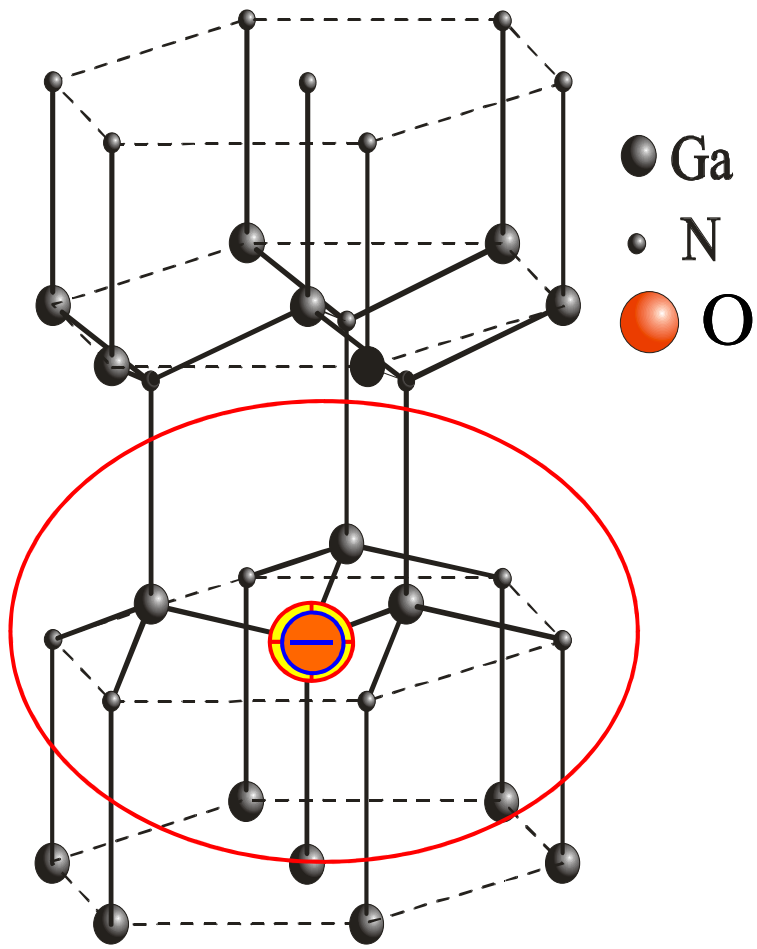




Akcja laserowa

Domieszkowanie…

m*



Neutralny donor
w przybliżeniu masy efektywnej

$$\left(-\frac{\hbar^2}{2\,\mathrm{m}^*}\,\Delta-\frac{e^2}{4\pi\varepsilon_0\,\varepsilon_s\,r}\right)\Phi_n(\mathbf{r})=E\;\Phi_n(\mathbf{r})$$

$$E_n=-\frac{R^*}{n^2};\;\; n=1,2,\ldots;\; R^*=13.6eV\,\frac{m^*}{\varepsilon_s{}^2}$$

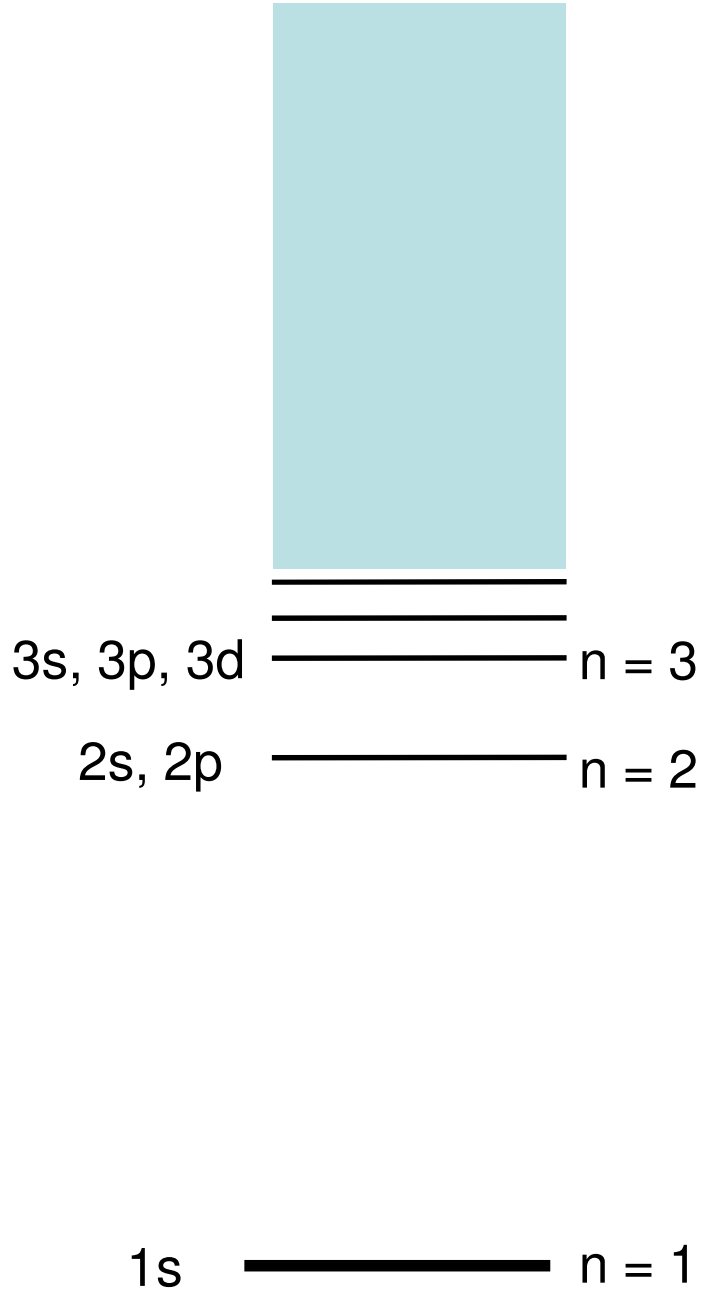
Problem bardzo zbliżony do rozważań ekscytonowych!

J. Luttinger and W. Kohn, Physical Review **97** ,869 (1955)

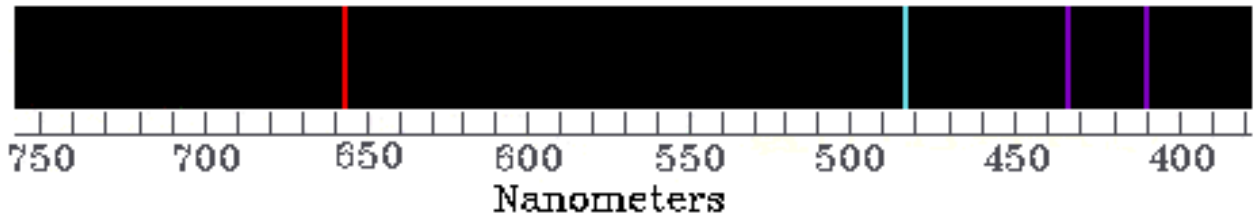
Atom wodoru

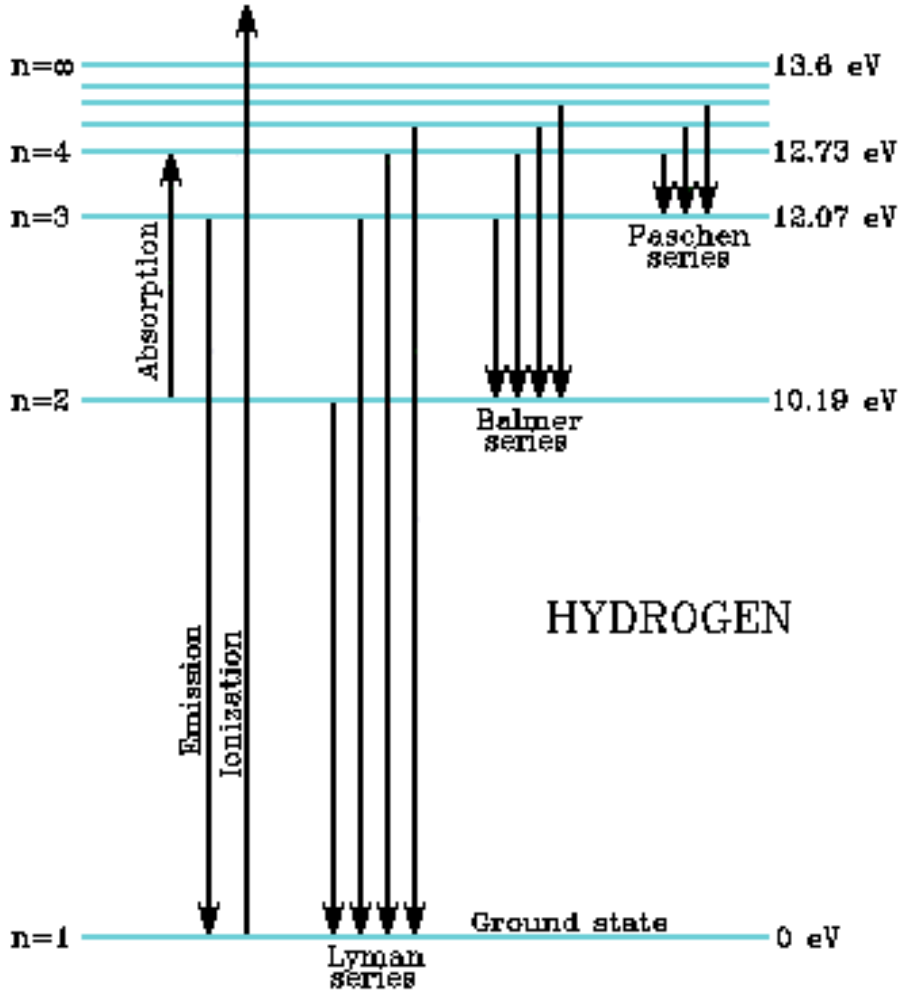
$$E_n = -\frac{m_0 e^4}{2(4\pi\varepsilon_0)^2 \hbar^2}\frac{1}{n^2} = -R\frac{1}{n^2}$$

$$R = 13{,}6 \text{ eV}$$



Widmo atomu wodoru





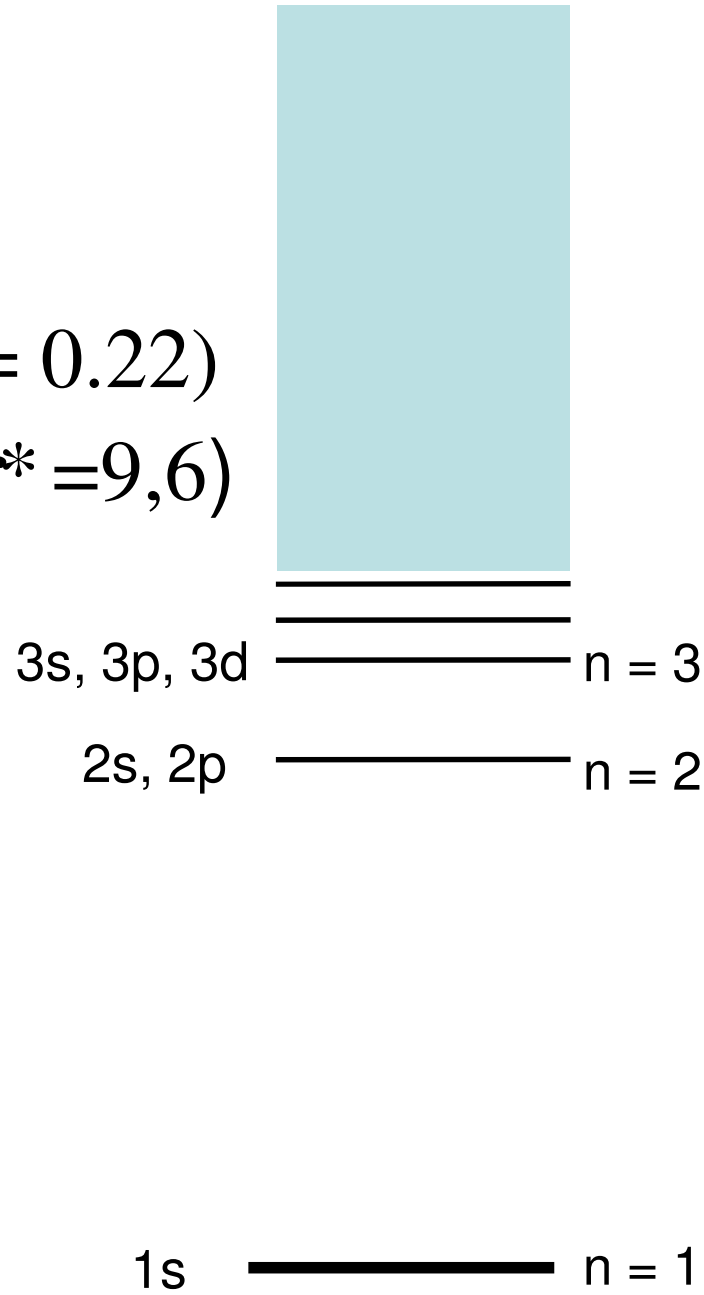
Donor

$m_0 \rightarrow m = m^* m_0$ (dla GaN $m^* = 0.22$)

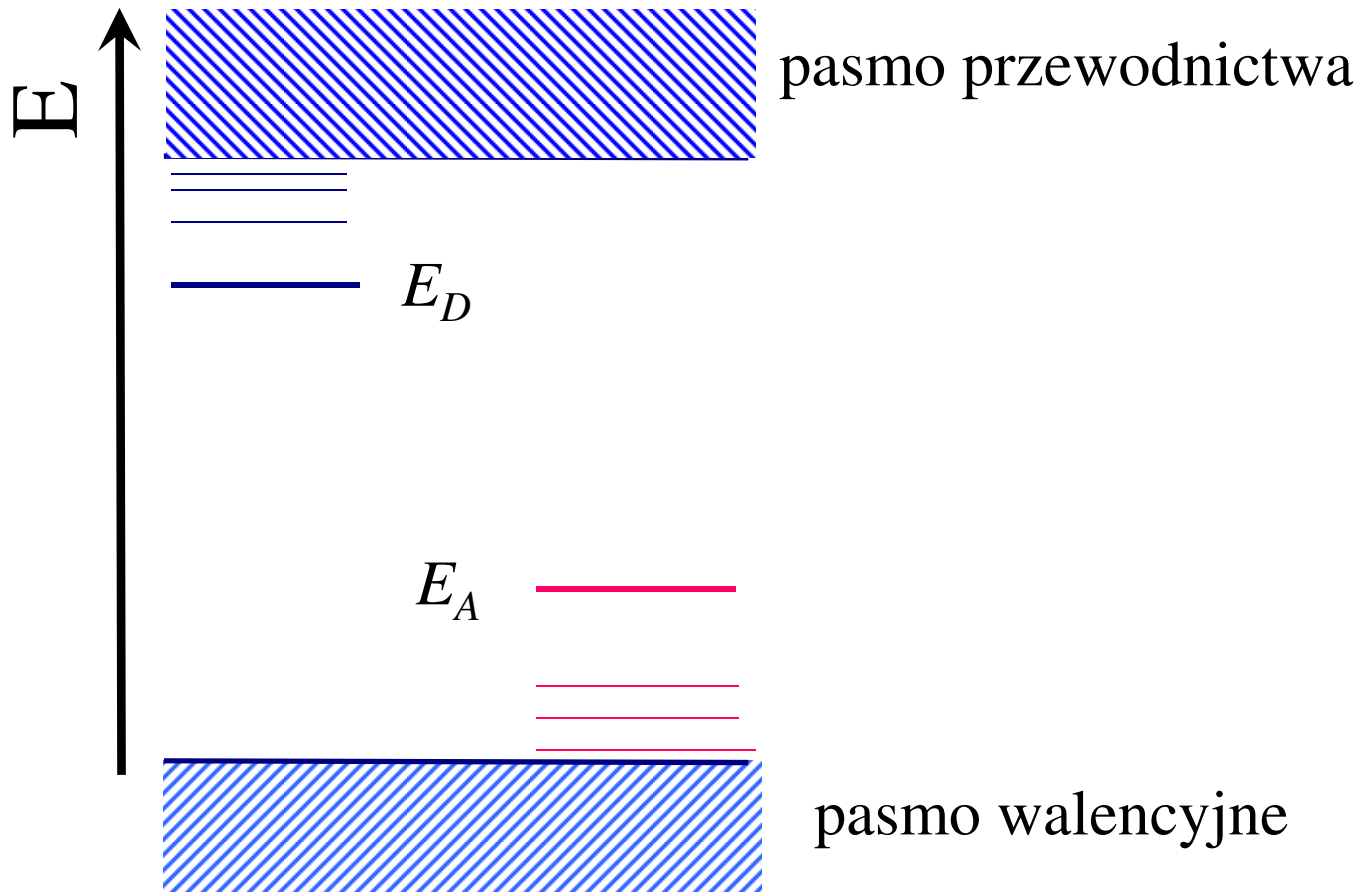
$\varepsilon_0 \rightarrow \varepsilon = \varepsilon^* \varepsilon_0$ (dla GaN $\varepsilon^* = 9{,}6$)

$$R^* = R \frac{m^*}{(\varepsilon^*)^2}$$

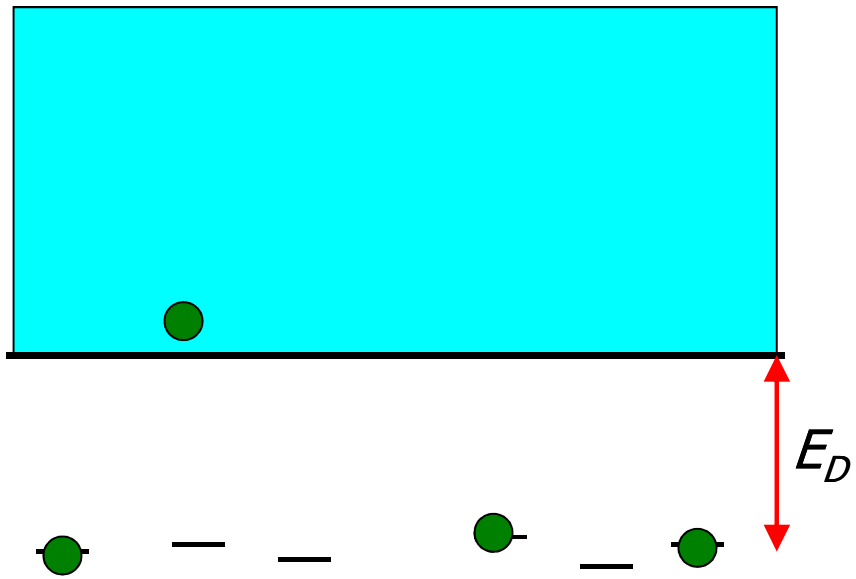
$R^* = 30$ meV

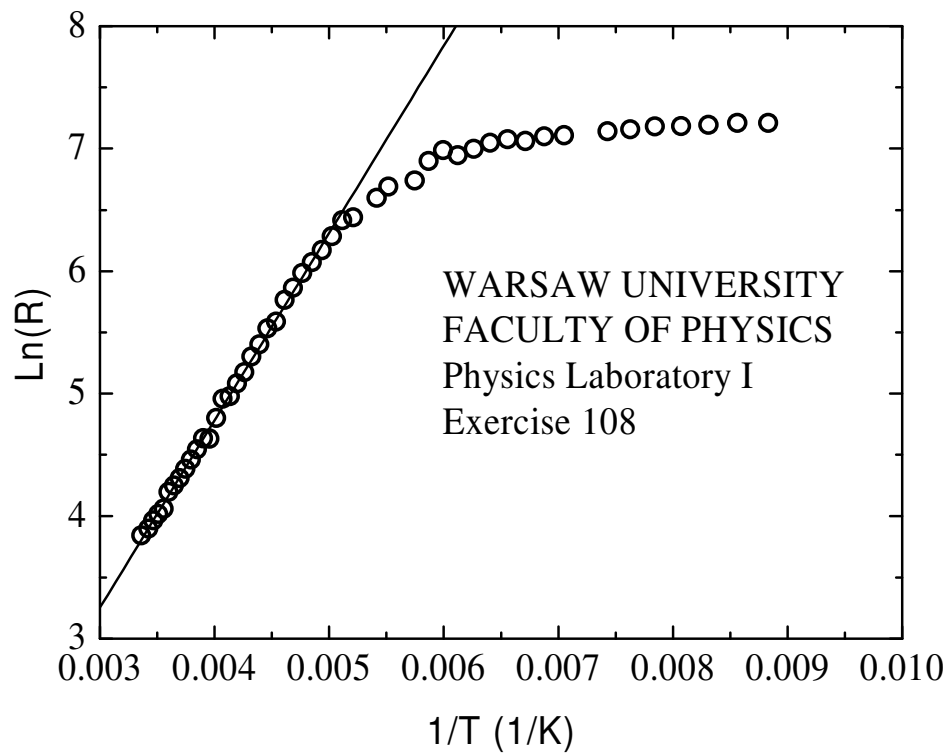


Stany domieszkowe



Energia wiązania donora

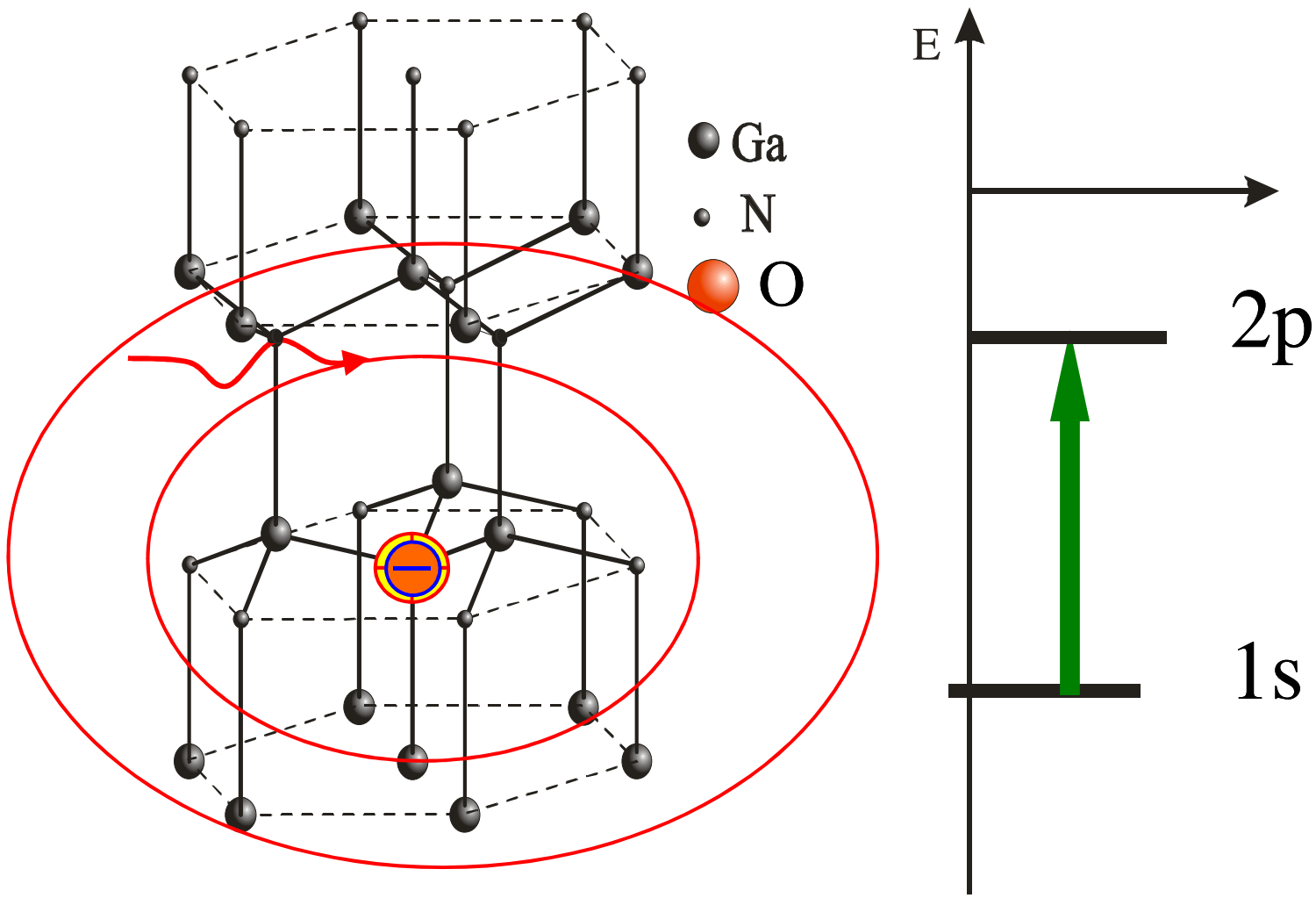




$$R = R_\infty \exp(E_D / k_B T)$$

Neutralny donor

m*



Wodór w polu magnetycznym

$$\hat{H} = \frac{1}{2m^*}(\hat{\mathbf{p}} + e\mathbf{A})^2 - \frac{e^2}{4\pi\varepsilon_0\varepsilon_s}\frac{1}{r}$$

$$\vec{A} = 1/2(\vec{B} \times \vec{r})$$

(Cechowanie cylindryczne)

Charakterystyczne jednostki długości i energii:

$$a^* = \frac{4\pi\hbar^2\varepsilon_0\varepsilon}{e^2 m^*} \qquad \mathrm{Ry}^* = \frac{m^* e^4}{2\hbar^2(4\pi\varepsilon_0\varepsilon_s)^2}$$

$$E_0 = 2Ry^*$$

$$\gamma = \frac{1/2\hbar\omega_c}{Ry^*}$$

We współrzędnych biegunowych (ρ, φ, z)

$$\boxed{\hat{H} = -\nabla^2 - \frac{2}{r} - i\gamma\frac{\partial}{\partial\varphi} + \frac{1}{4}\gamma^2\rho^2}$$

$$r = \sqrt{\rho^2 + z^2}$$

Rachunek wariacyjny

$$\Psi = \sum_j C_j \psi_j$$

Funkcje bazowe

$$\psi_i = \rho^{|m|} e^{i\varphi m} z^q e^{-\alpha_i\rho^2} e^{-\beta_i z^2}$$

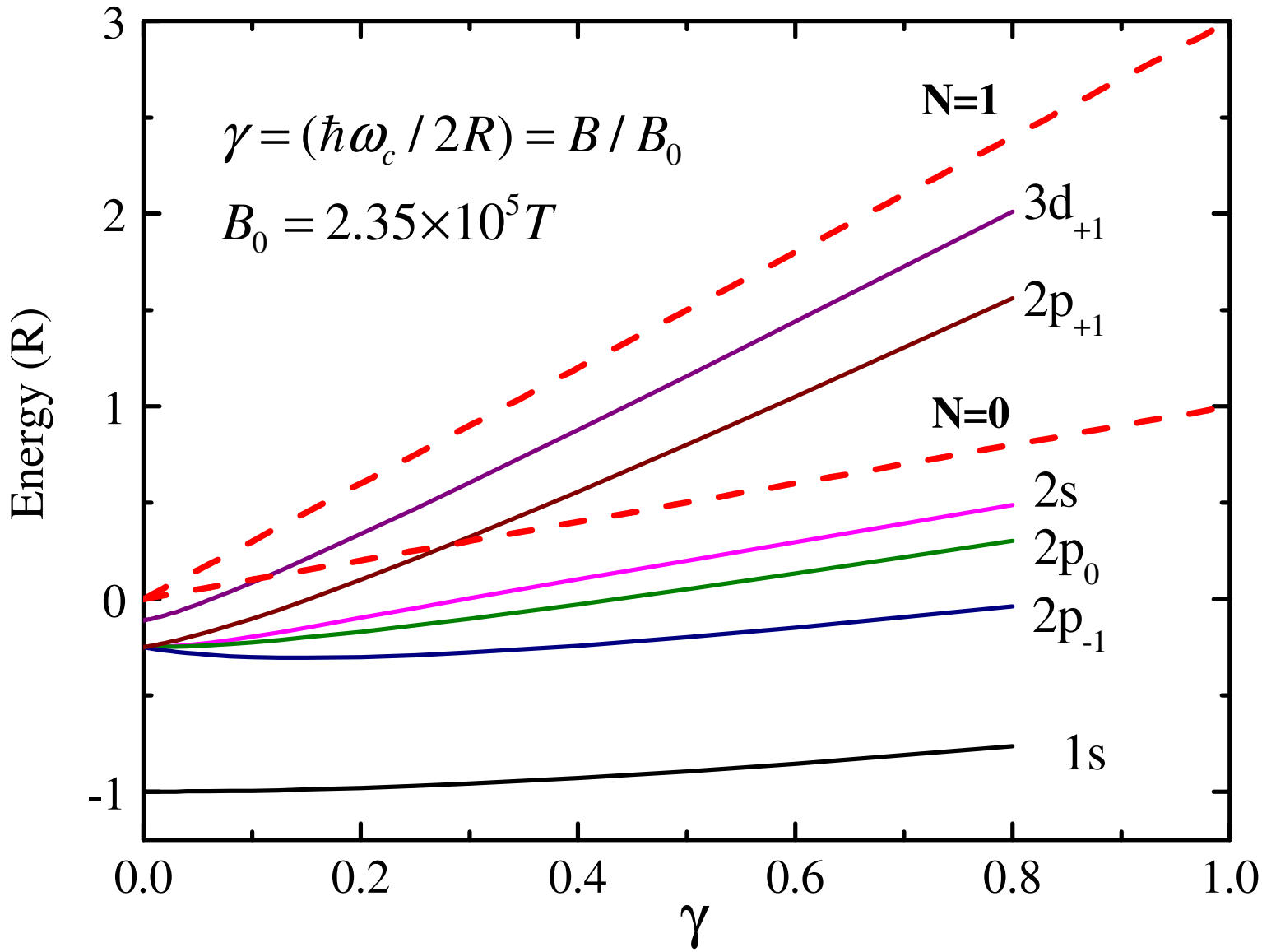
Symetria Hamiltonianu:

$$\boxed{E_{-|m|} = E_{|m|} - 2|m|\gamma}$$

P.C. Makado and N. C. McGill, J. Phys. C **19**, 873 (1986)

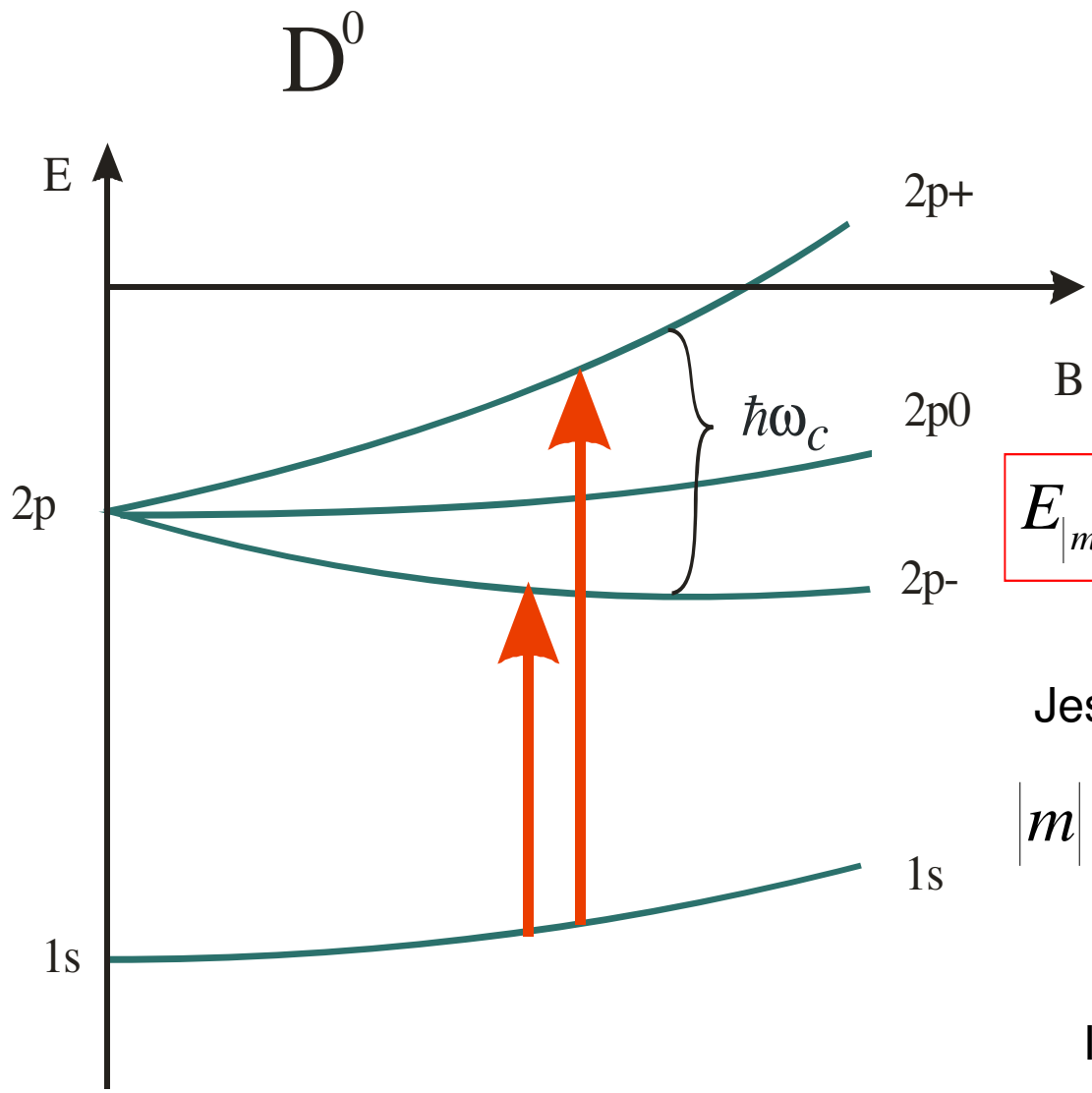
Wodór w polu magnetycznym

- P. C. Macado and N. C. McGill,
  J. Phys. C: Solid State Physics **19**, 873 (1986)
- W. Rösner, G. Wunner, H. Herold and H. Ruder,
  J. Phys. B: At. Mol. Phys. **17,** 29 (1984)
- A. V. Turbiner,
  J. Phys. A: Math. Gen. **17**, 858 (1984)
- Y. P. Kravchenko, M.A. Liberman, B. Johanson,
  PRB **54**, 287 (1996)



Y. P. Kravchenko, M.A. Liberman, B. Johanson, PRB **54**, 287 (1996)

Transmisja w dalekiej podczerwieni



$$E_{-|m|} = E_{|m|} - 2|m|\gamma$$

$$E_{|m|} - E_{-|m|} = 2|m|\gamma = |m|\hbar\omega_c$$

Jeśli

$$|m| = 1 \quad E_{2p_{+1}} - E_{2p_{-1}} = \frac{\hbar e B}{m^*}$$

Informacja o masie efektywnej!

Płytki donor w GaN

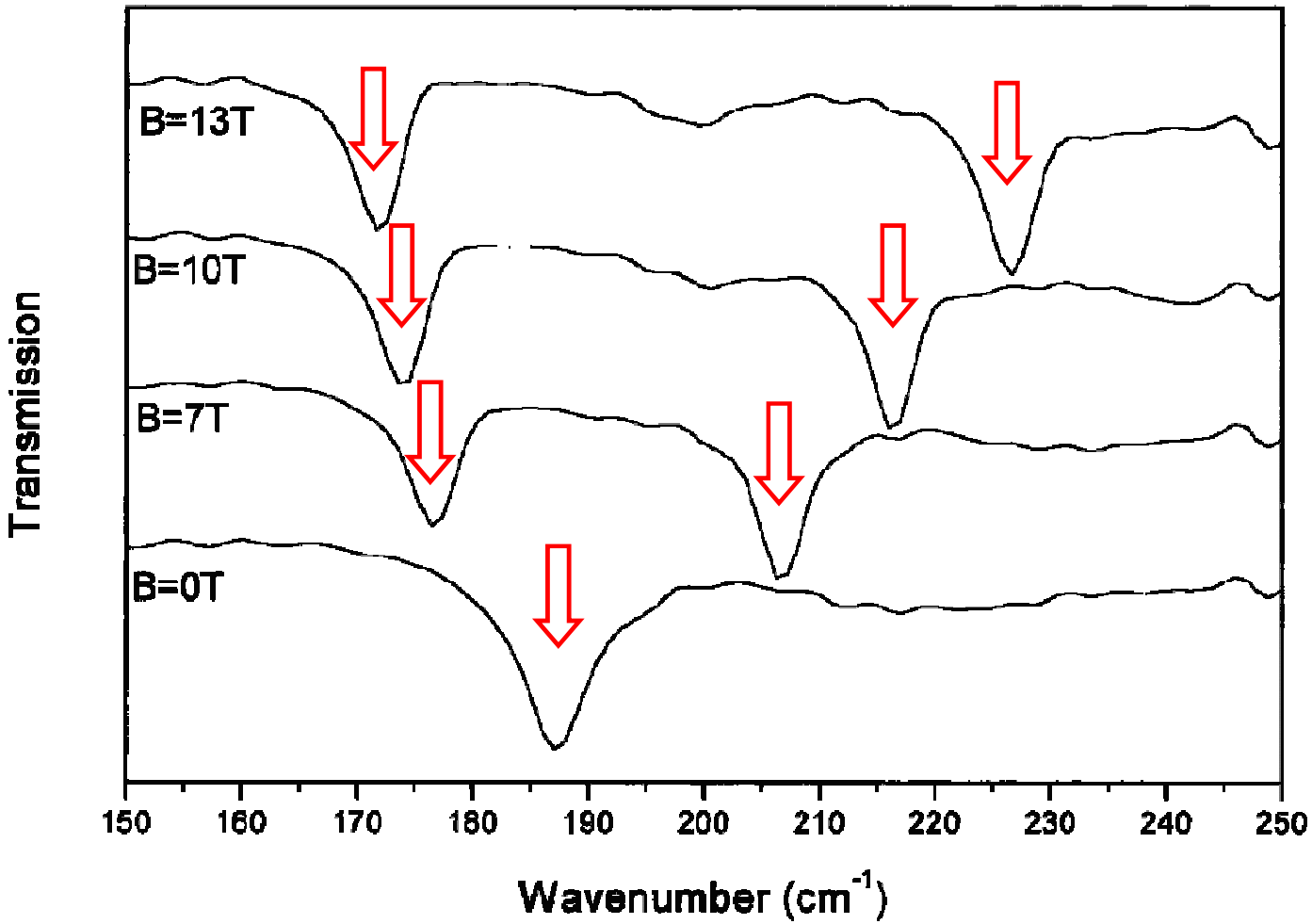
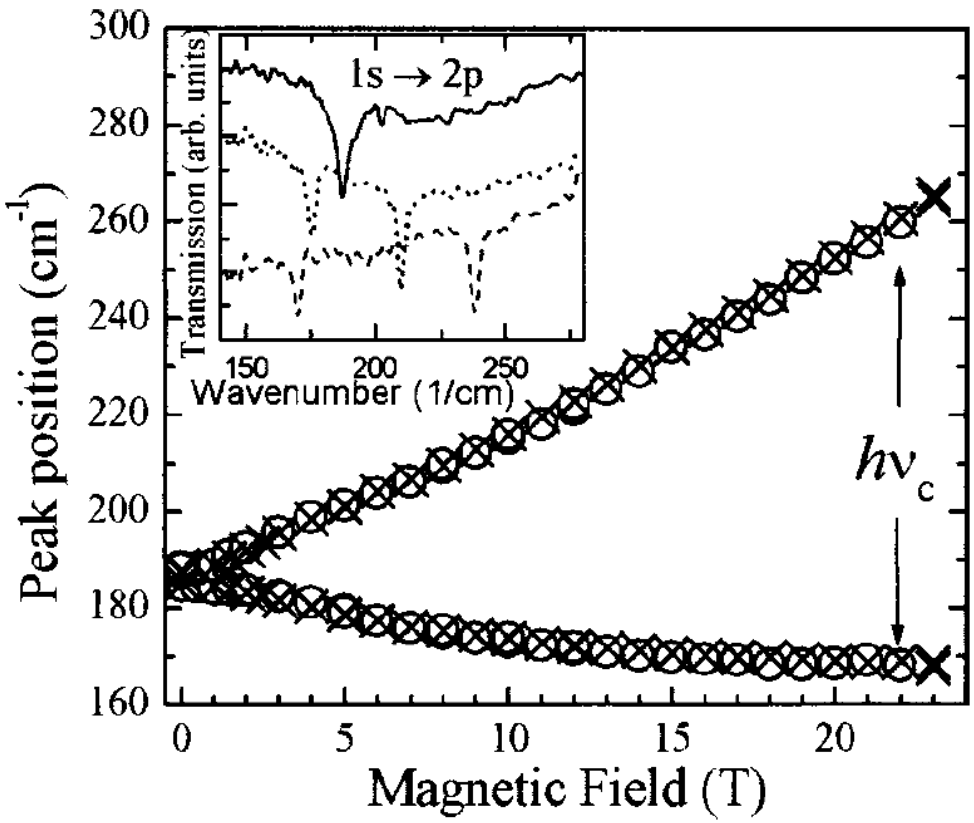


Fig. 1. Transmission spectra of an undoped GaN layer on sapphire, measured at 2K, normalised by the transmission of a sapphire slab identical to the substrate

„Far-Infrared Magnetospectroscopy of Shallow Donors in GaN"
A.M. Witowski et al., phys. stat. sol. (b) ***210****, 385 (1998)*



$$\hbar\omega = \hbar eB/m^*$$

$$m^* = 0.222(2)\, m_0$$

FIG. 1. Positions of $1s \rightarrow 2p_-$ (lower set of points) and $1s \rightarrow 2p_+$ transitions (upper set) vs external magnetic fields measured at 4.5 K. Crosses (circles) denote data for undoped (Si doped) GaN layers grown on sapphire. In the inset transmission of the doped sample normalized by the transmission of a sapphire slab is presented measured at 0 (solid line), 8 (dotted line), and 16 T (dashed line).

A. M. Witowski, K. Pakuła, J. M. Baranowski, M. L. Sadowski and P. Wyder, APL 75, 4154 (1999)

Zobaczyć funkcję falową donora –

np. przy użyciu mikroskopu tunelowego

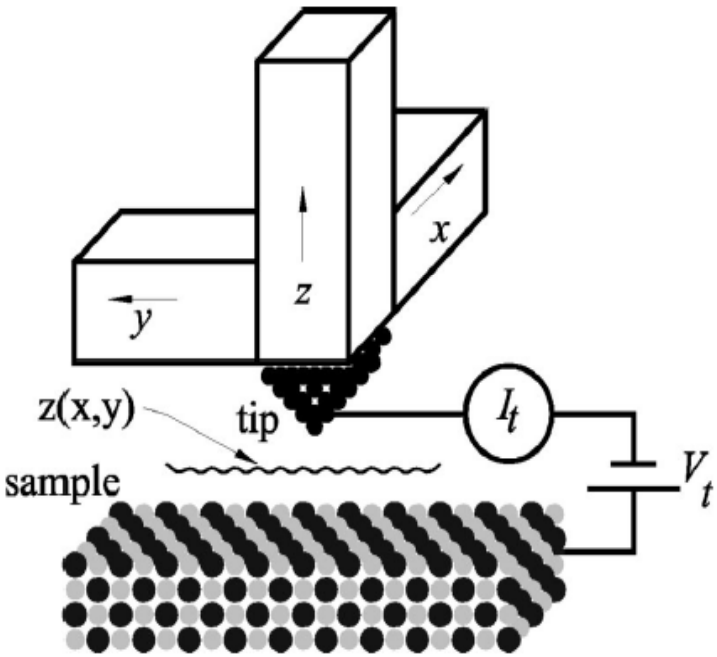


FIG. 2. A scanning tunneling microscope (schematic).

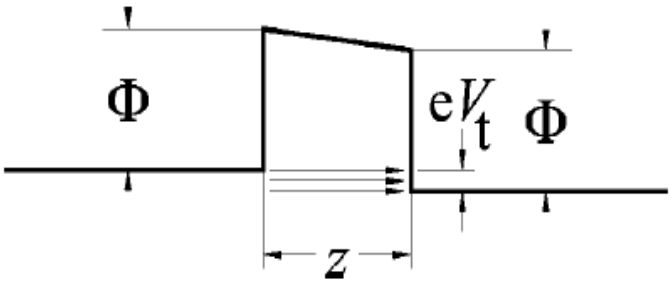
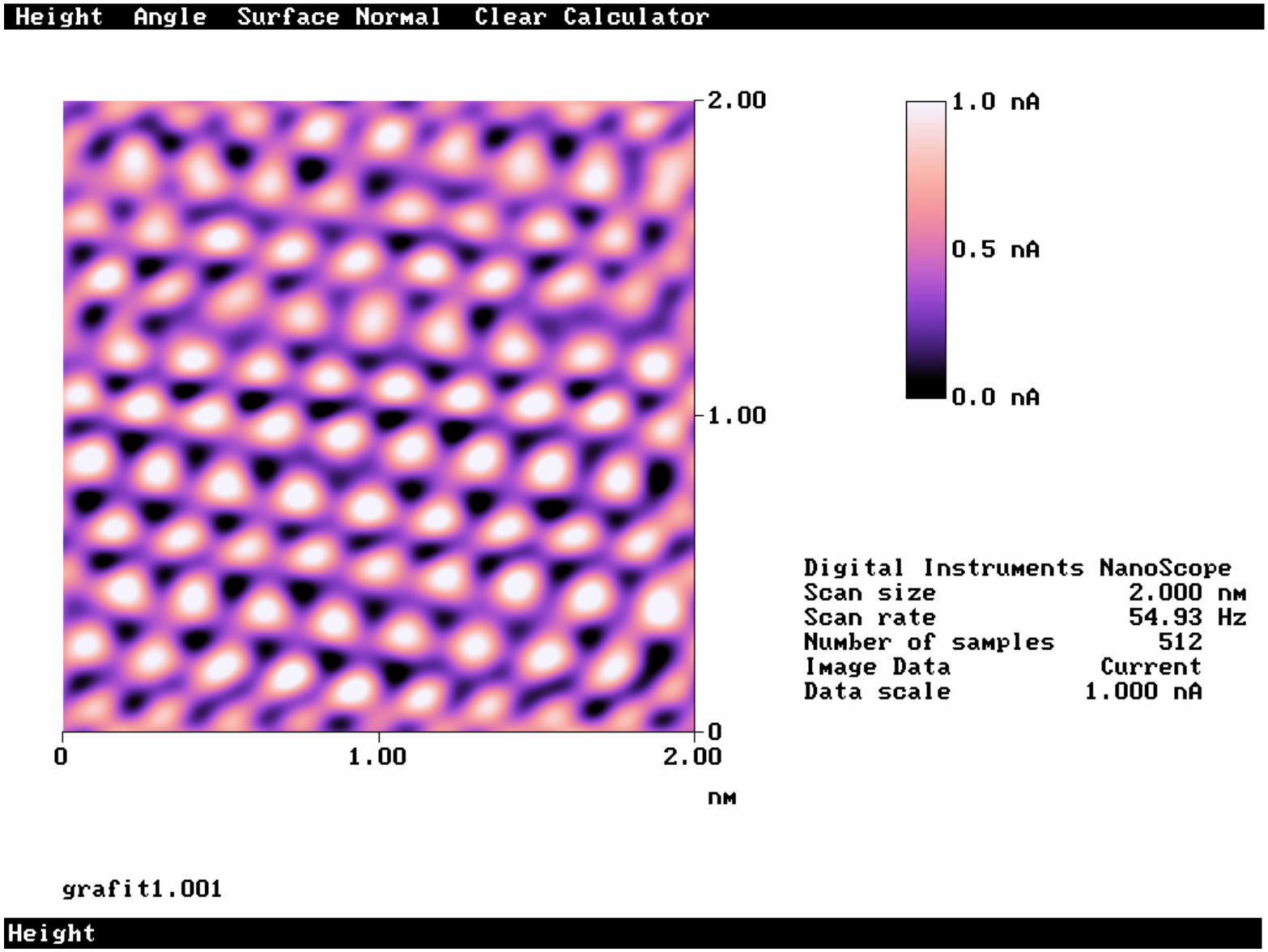


FIG. 3. Energy diagram of an idealized tunneling gap. The image charge effect (see Chen, 1993) is not taken into account here.

a width z and a height given by the work function Φ. According to elementary quantum mechanics, the tunneling current is given by

$$I_t(z) = I_0 e^{-2\kappa_t z}. \quad (1)$$

Sprawdzenie mikroskopu tunelowego – na graficie HOPG …



HOPG (Highly Oriented Pyrolitic Graphite)

Igły muszą być ostre…

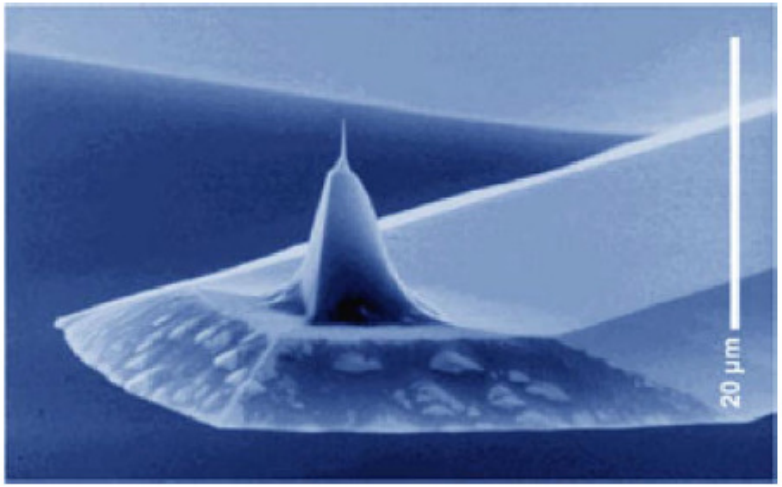


FIG. 8. (Color in online edition) Scanning electron micrograph of a micromachined silicon cantilever with an integrated tip pointing in the [001] crystal direction (Wolter *et al.*, 1991). This is a Pointprobe sensor made by Nanosensors GmbH und Co. KG, Norderfriedrichskoog, Germany D-25870. Photo courtesy of Nanosensors GmbH & Co. KG.

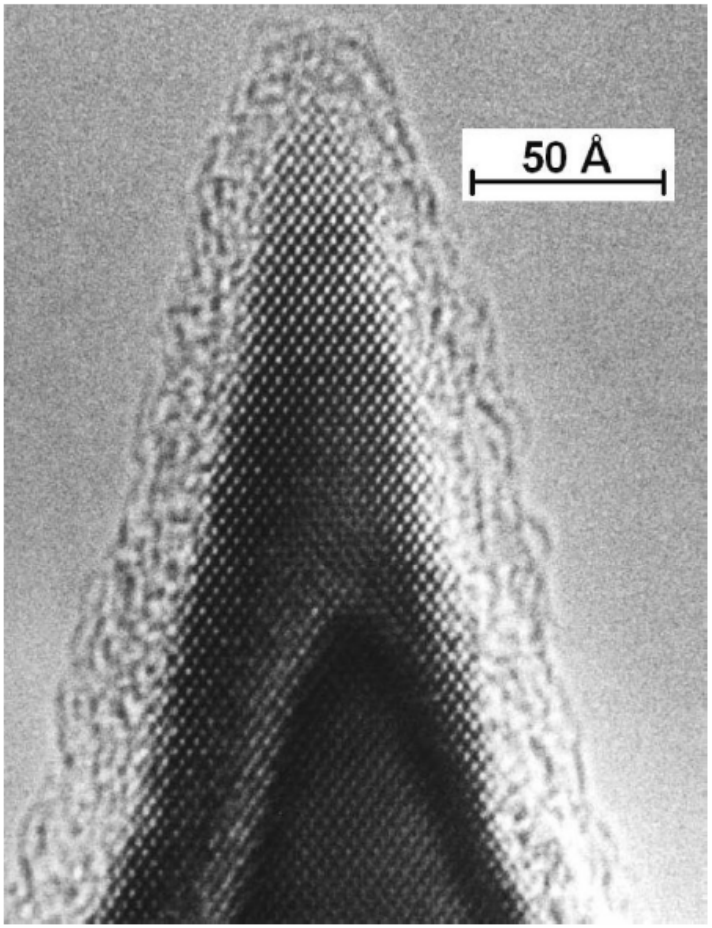


FIG. 13. Transmission electron micrograph of an extremely sharp silicon tip. The native oxide has been etched away with hydrofluoric acid before imaging. The 15–20-Å-thick coating of the tip is mostly due to hydrocarbons which have been polymerized by the electron beam. Interestingly, the crystal structure appears to remain bulklike up to the apex of the tip. From Marcus *et al.*, 1990.

Scanning Tunneling Microscopy Studies of Si Donors (Si_{Ga}) in GaAs

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[1]*Department of Materials Science, University of California at Berkeley, Berkeley, California 94720*
[2]*Materials Science Division, Lawrence Berkeley Laboratory, Berkeley, California 94720*
(Received 26 July 1993)

We report scanning tunneling microscopy (STM) studies of Si substitutional donors (Si_{Ga}) in GaAs that reveal delocalized and localized electronic features corresponding to Si_{Ga} in the top few layers of the (110) cleavage surface. The delocalized features appear as protrusions a few nm in size, superimposed on the background lattice. These features are attributed to enhanced tunneling due to the local perturbation of the band bending by the Coulomb potential of subsurface Si_{Ga}. In contrast, STM images of surface Si_{Ga} show very localized electronic structures, in good agreement with a recent theoretical prediction [J. Wang *et al.*, Phys. Rev. B **47**, 10 329 (1993)].

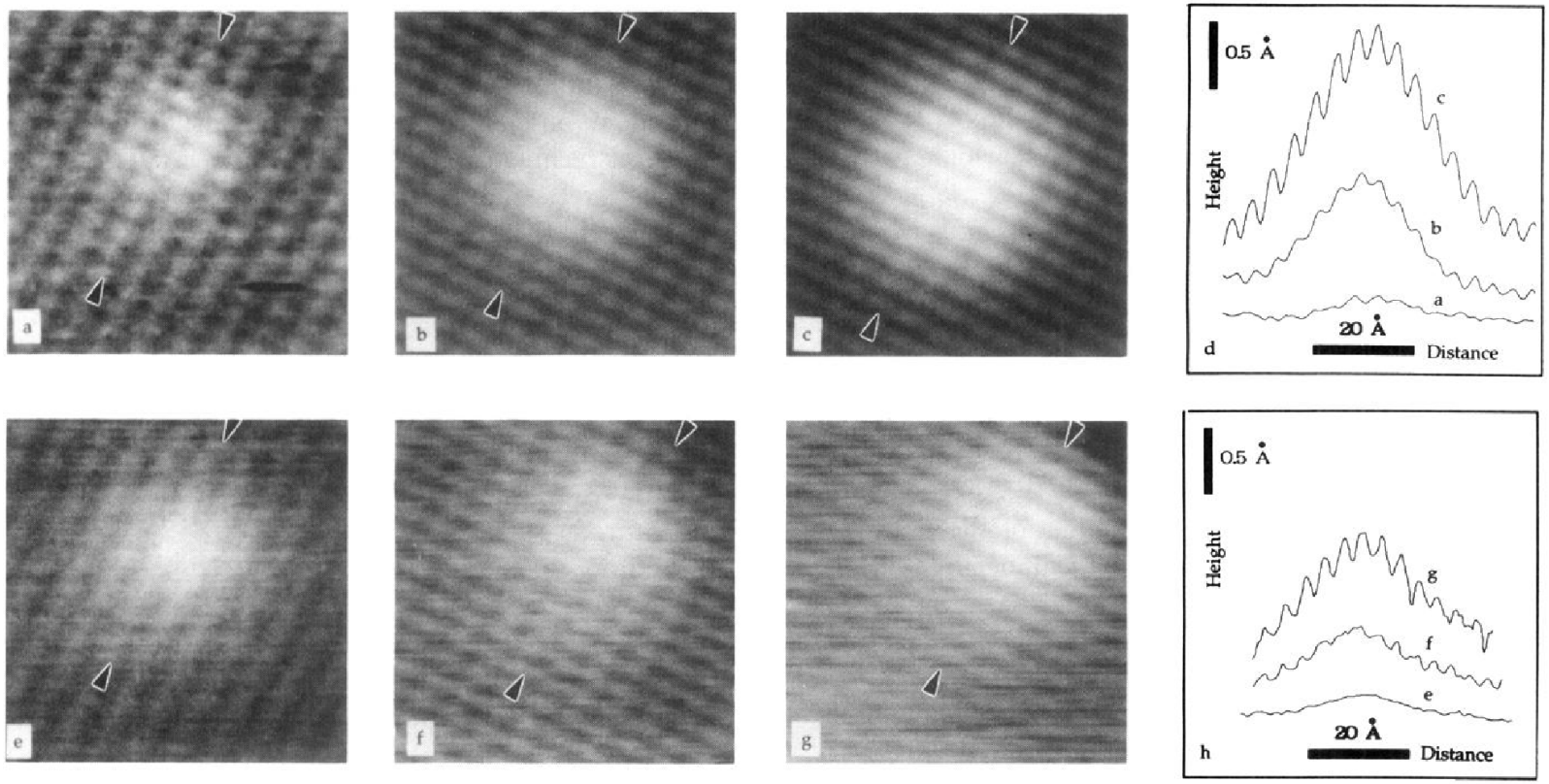


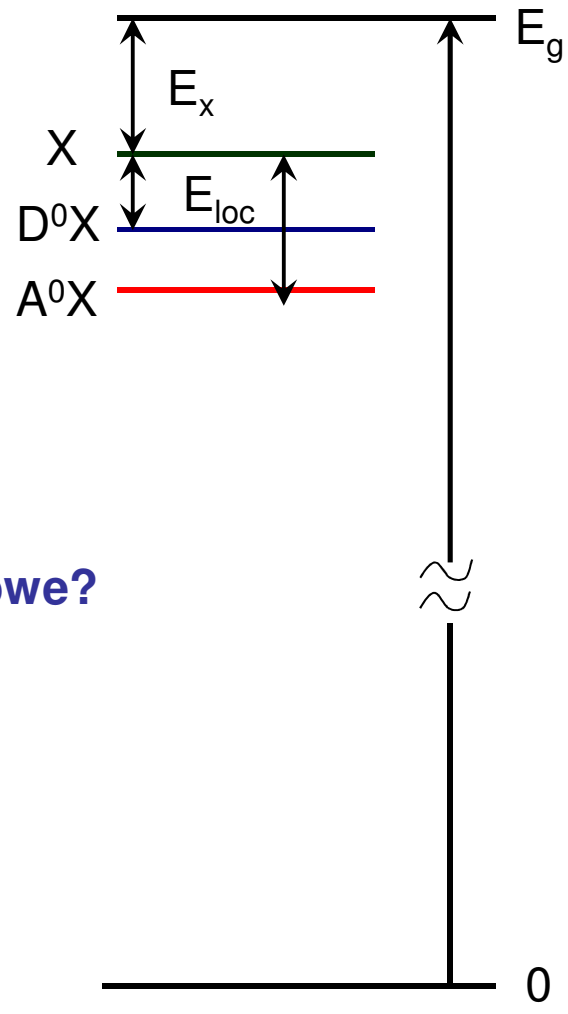
FIG. 3. STM images of the protrusion region *D* in Fig. 1 taken with tunneling current of 0.5 nA at various sample voltages. The sample voltages are (a) −3 V; (b) −2.0 V, (c) −1.5 V; (e) +3.0 V; (f) +2.0 V; and (g) +1.5 V. The topographic profiles along the [1$\bar{1}$0] direction (indicated by the arrows) across the features are shown in (d) and (h). All images are 60 Å×60 Å in size.

Rekombinacja ekscytonow związanych jako narzędzie badań domieszek...

Przegląd kompleksów ekscytonowych

Ekscyton zwiazany

- na neutralnym donorze D^0X
- na neutralnym akceptorze A^0X
- na zjonizowanym donorze D^+X
- na zjonizowanym akceptorze A^-X

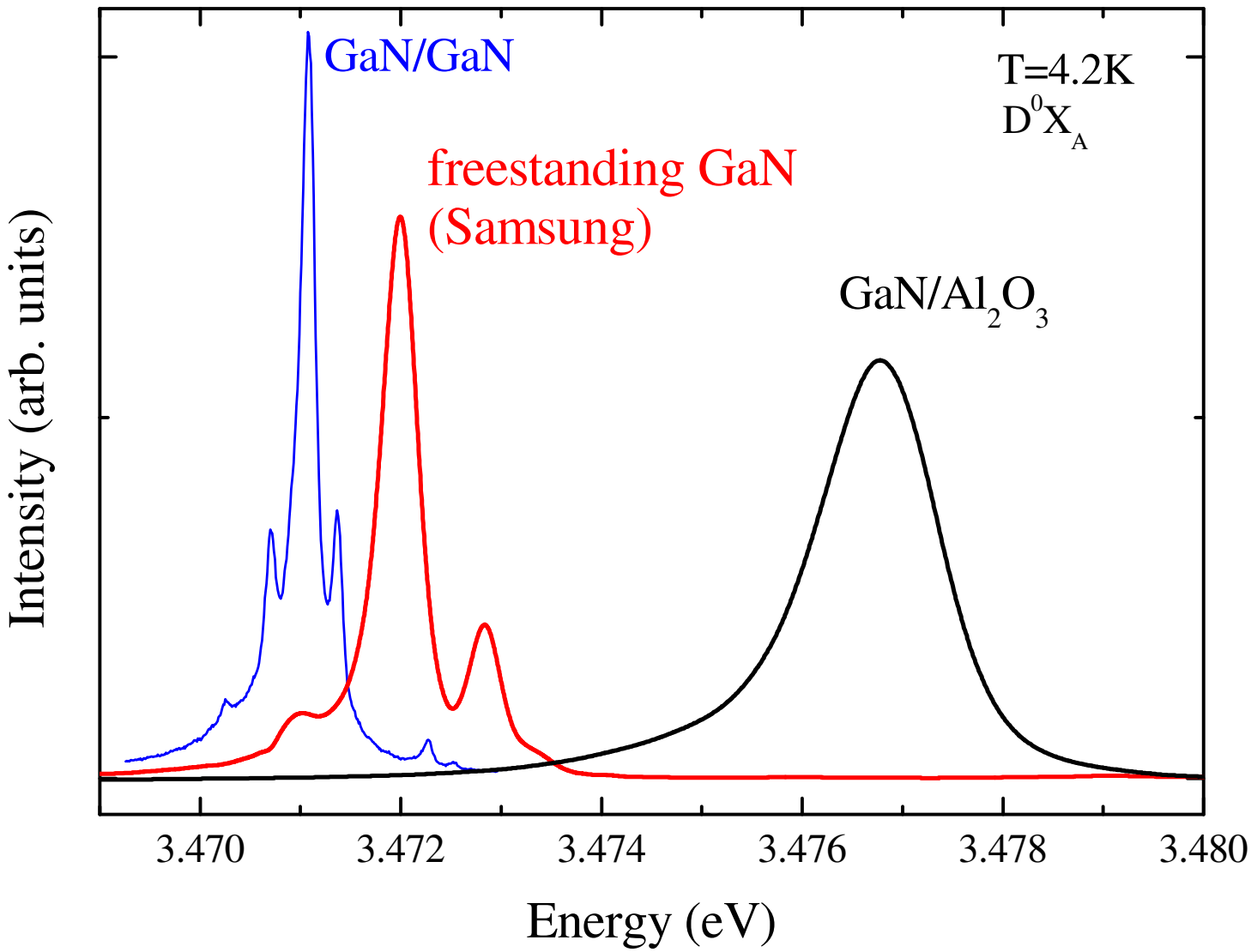


Jak zidentyfikować poszczególne linie ekscytonowe?

Nie jest to łatwe!

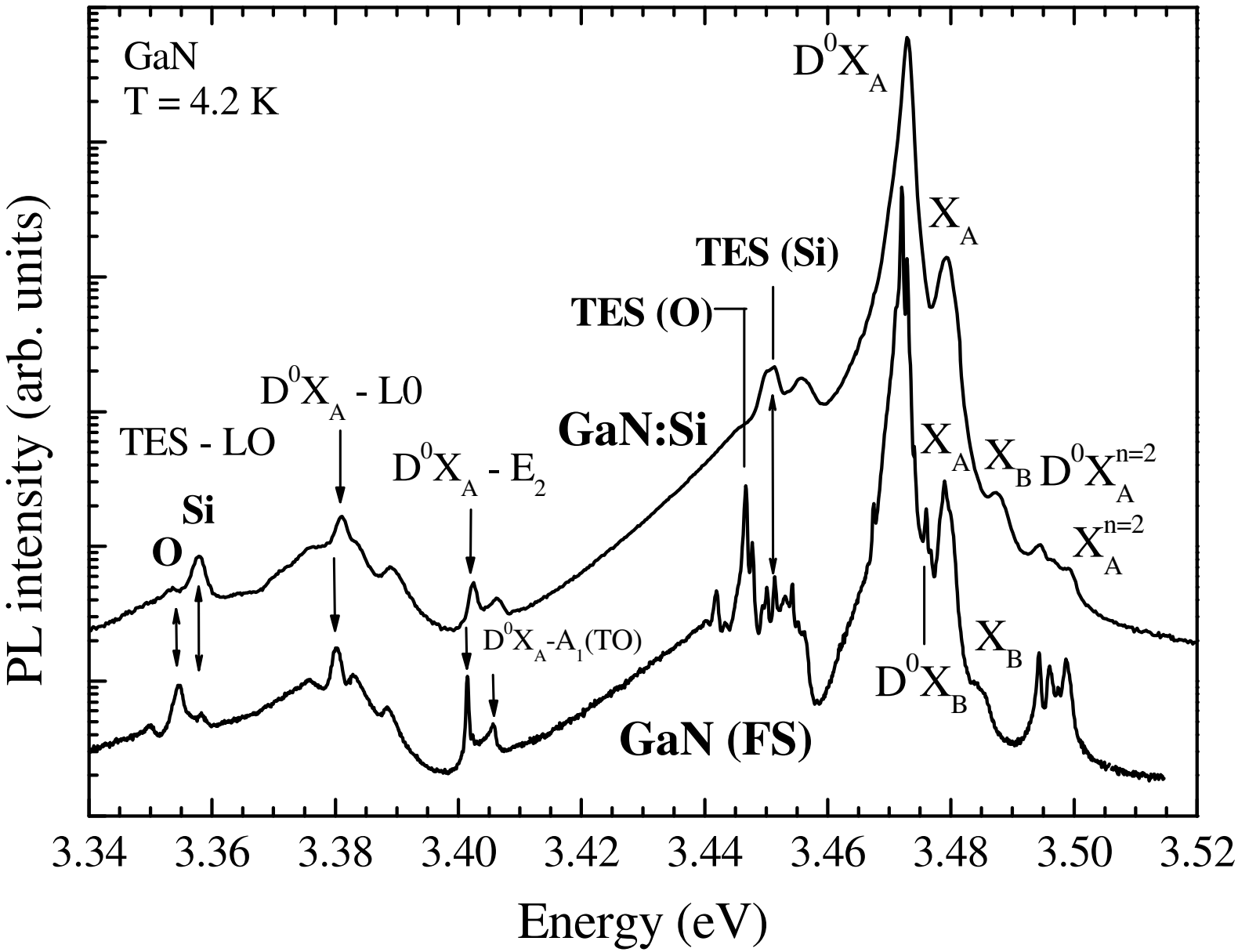
Pomaga pole magnetyczne…

Luminescencja ekscytonowa w GaN

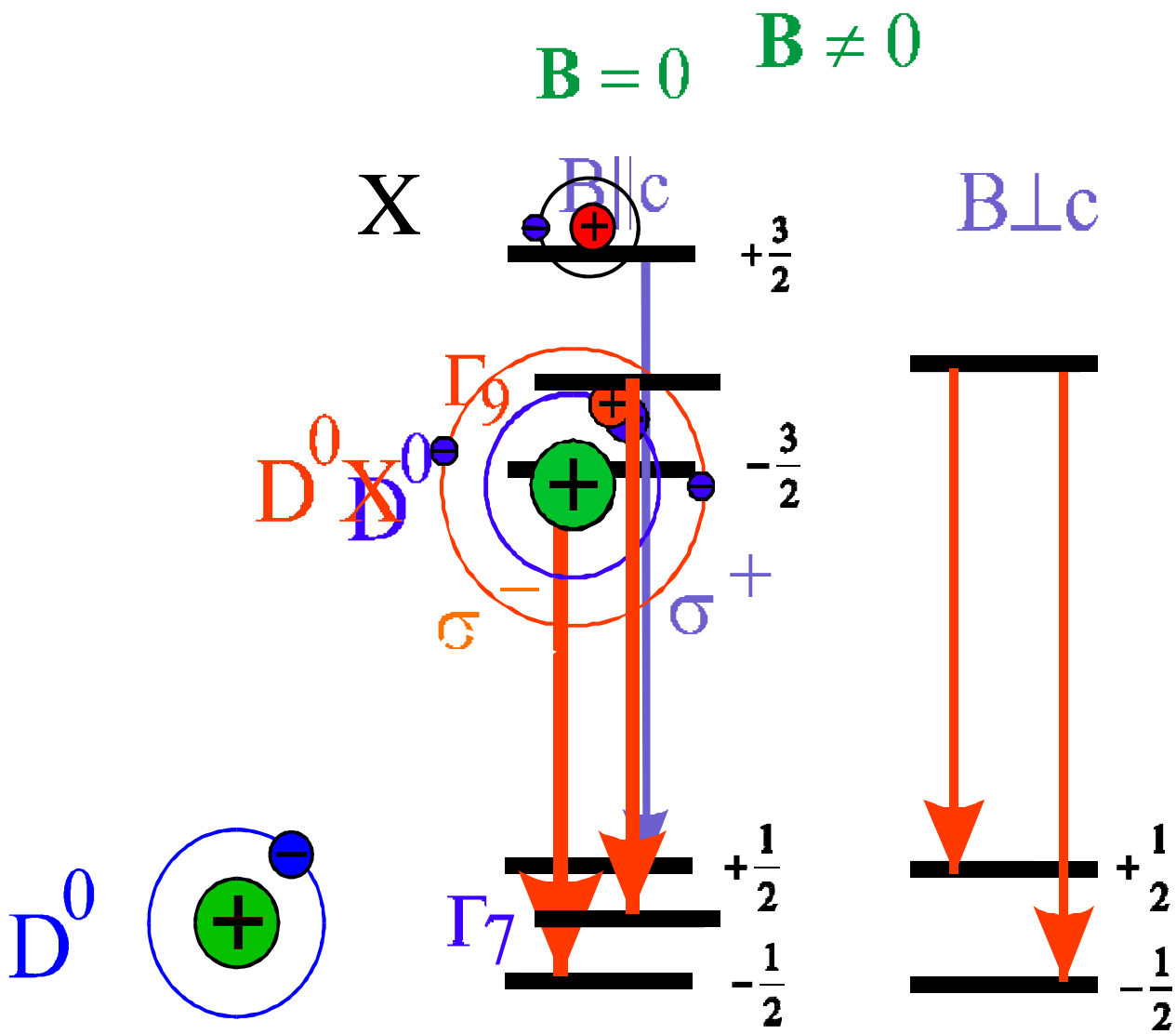


A. Wysmolek et al. PRB 74, 195205 (2006)

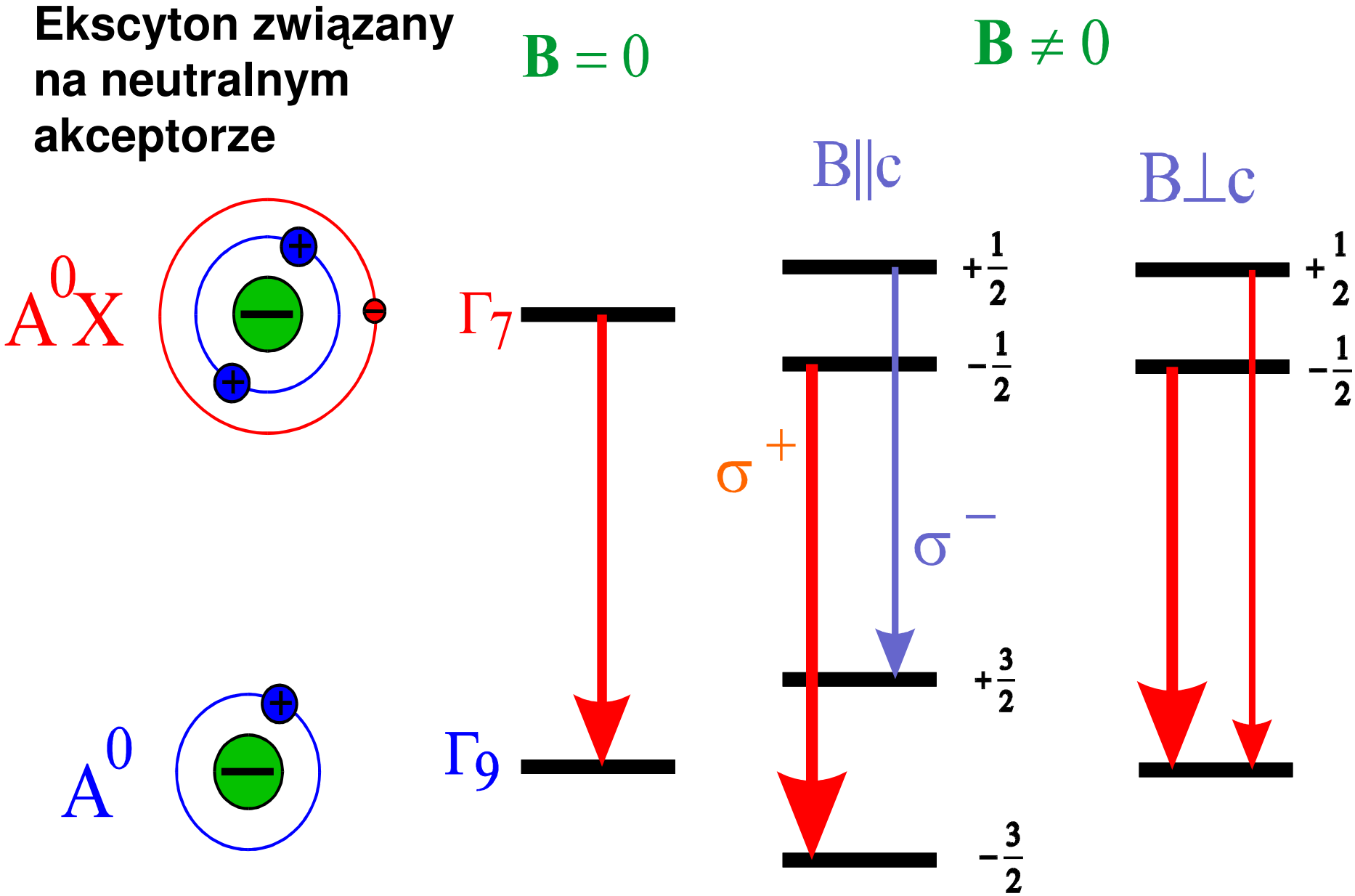
Donor tlenowy donor krzemowy



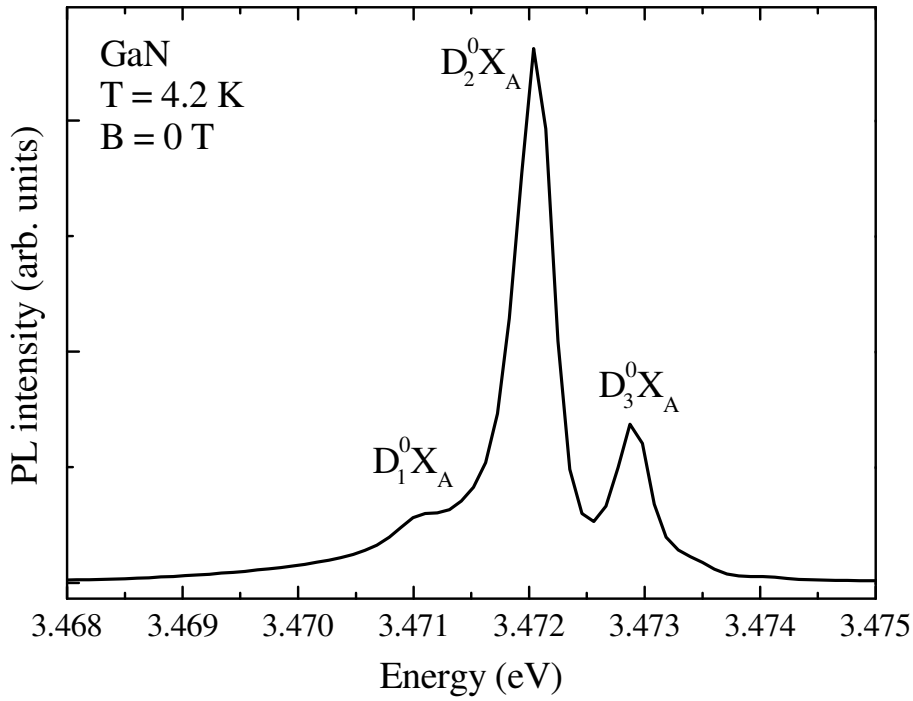
Ekscyton związany na neutralnym donorze (D^0X)

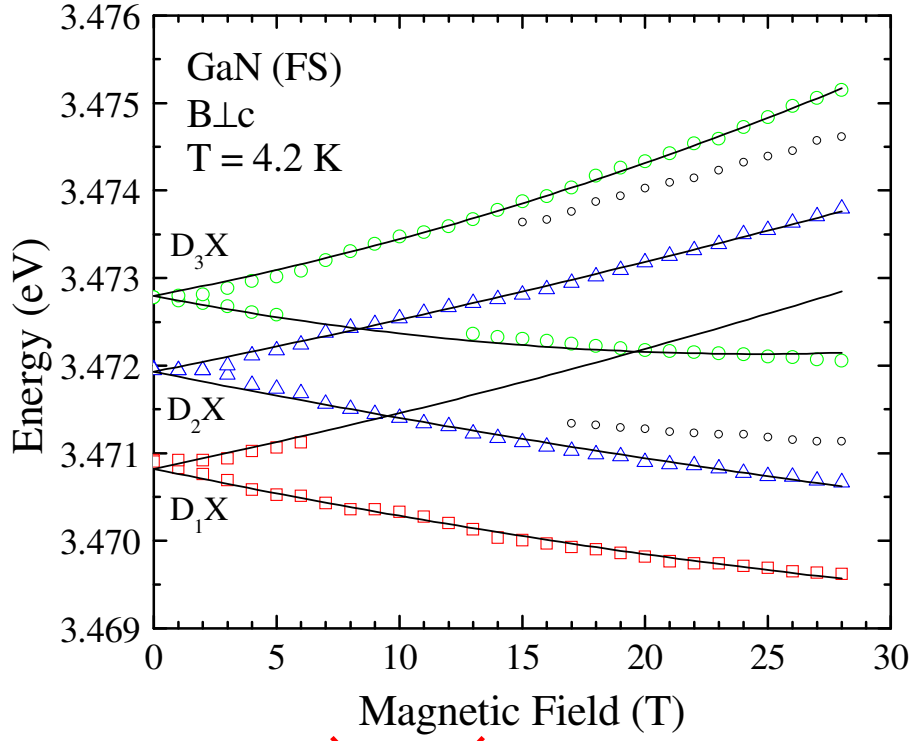


Ekscyton związany na neutralnym akceptorze



Rozszczepienia spinowe – konfiguracja B⊥c





$D_1{}^0X_A$ – O_N

$D_2{}^0X_A$ – Si_{Ga}

$D_3{}^0X_A$ – ?(V_N)

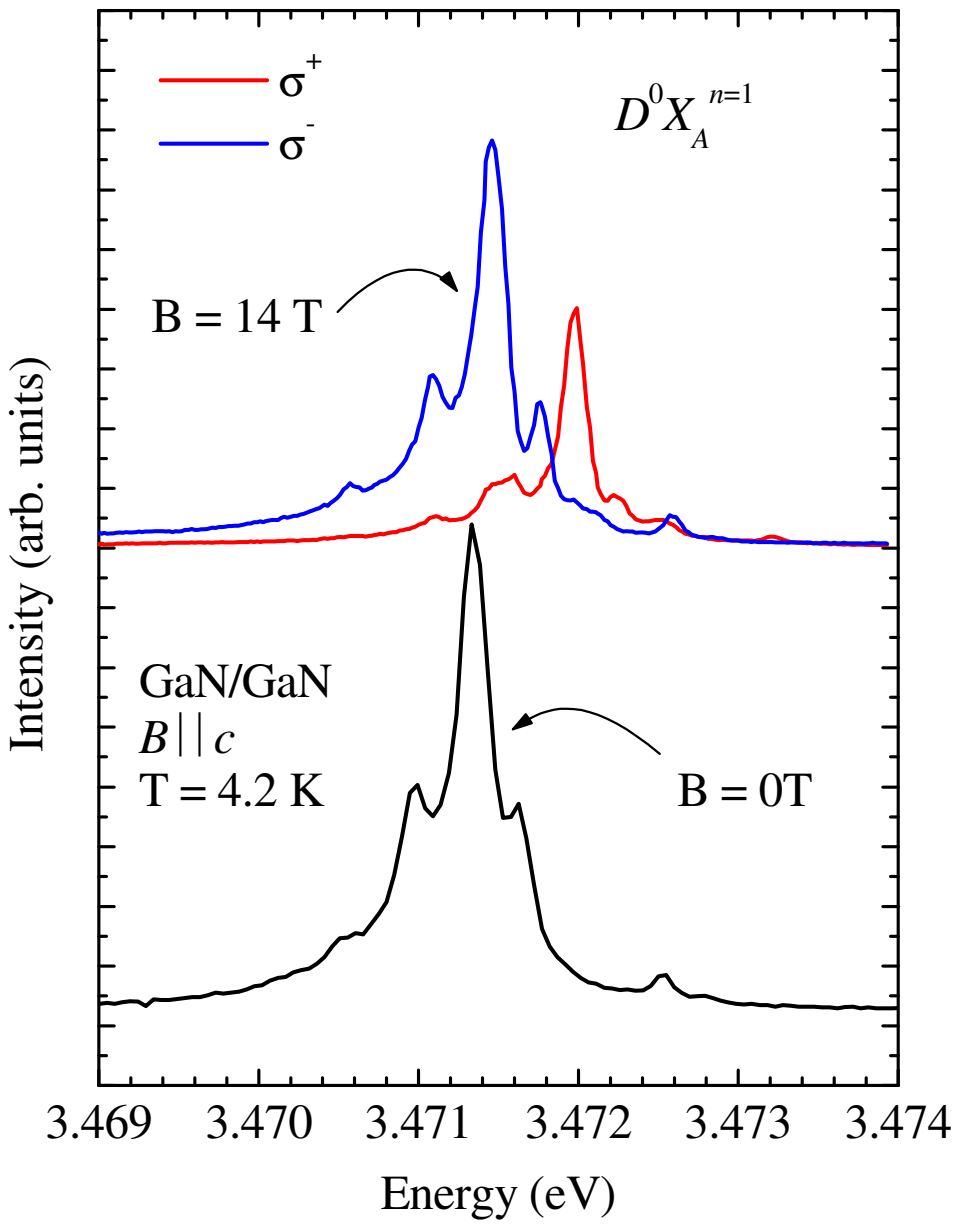
Wysmolek et al. PRB 66, 245317 (2002)

$D_1{}^0X_A$ – ~~D^+X~~

$D_2{}^0X_A$ – O_N

$D_3{}^0X_A$ – Si_{Ga}

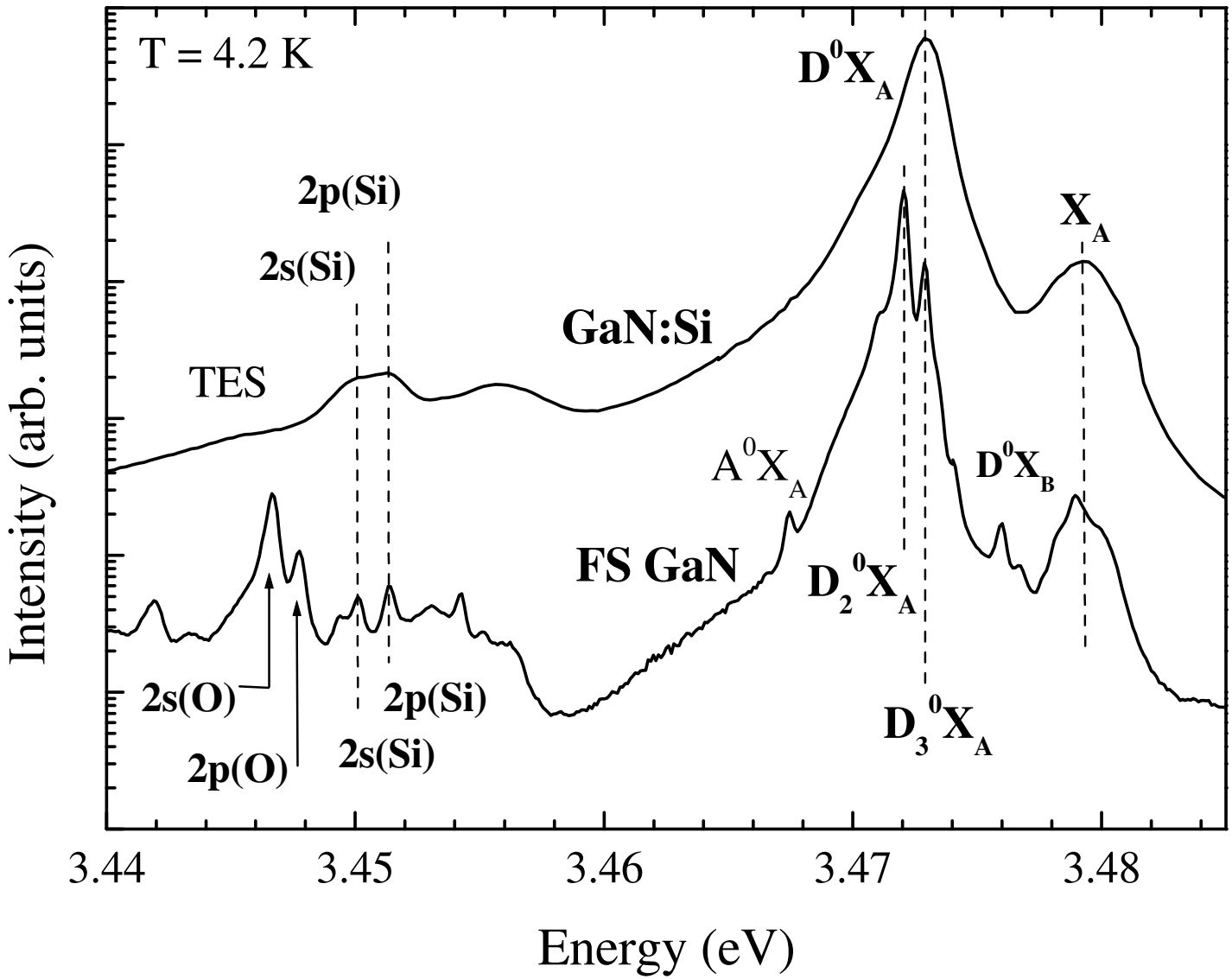
A. Freitas, Jr., PRB **66**, 233311 (2002).



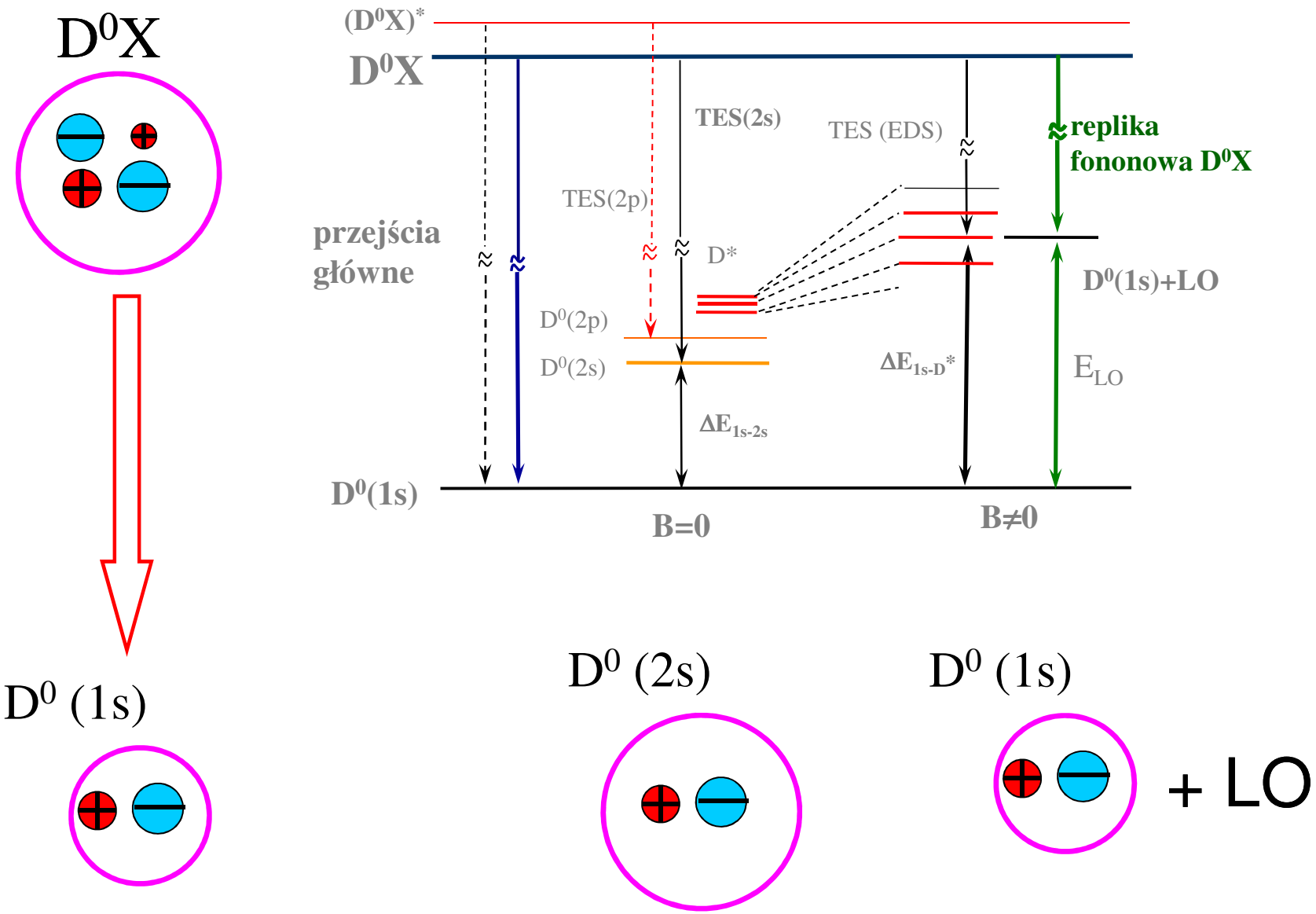
Konfiguracja B II c

Zachowanie typowe dla D^0X!

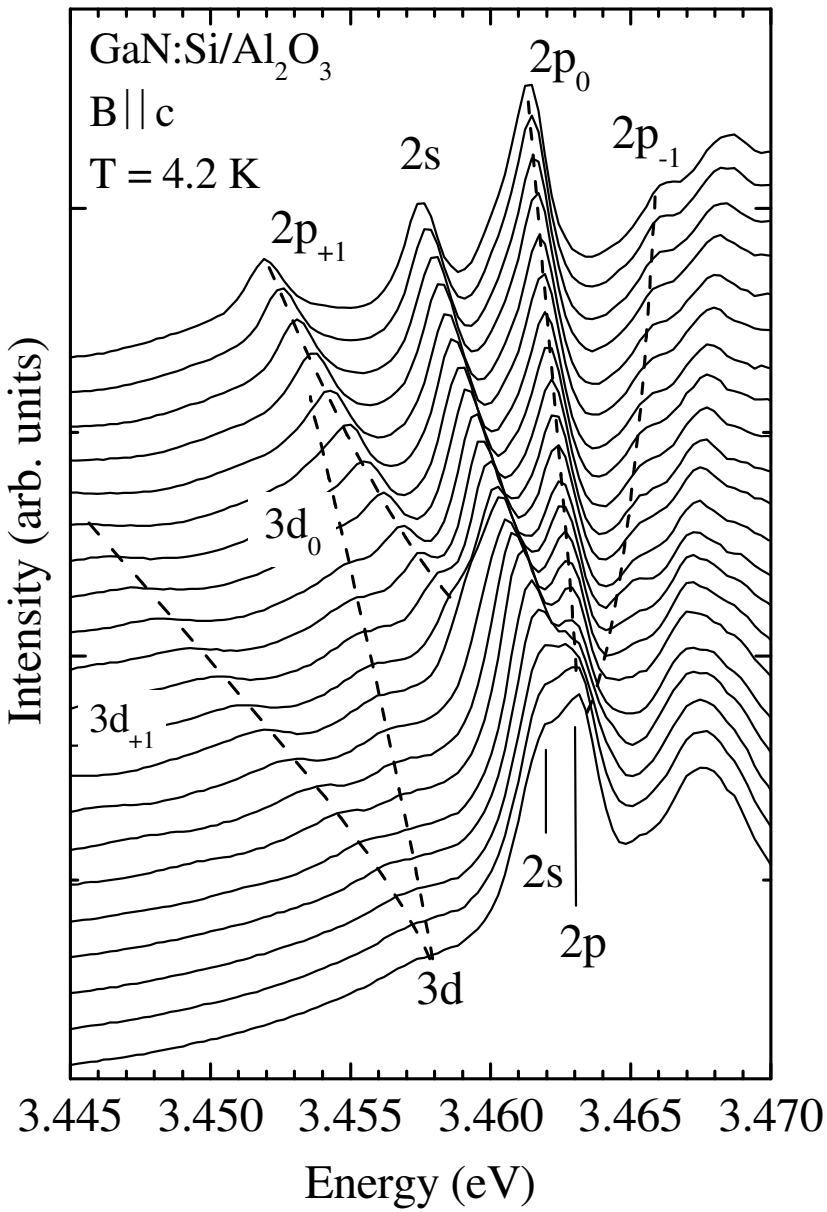
Rozróżniamy donory o różnych energiach wiązania…

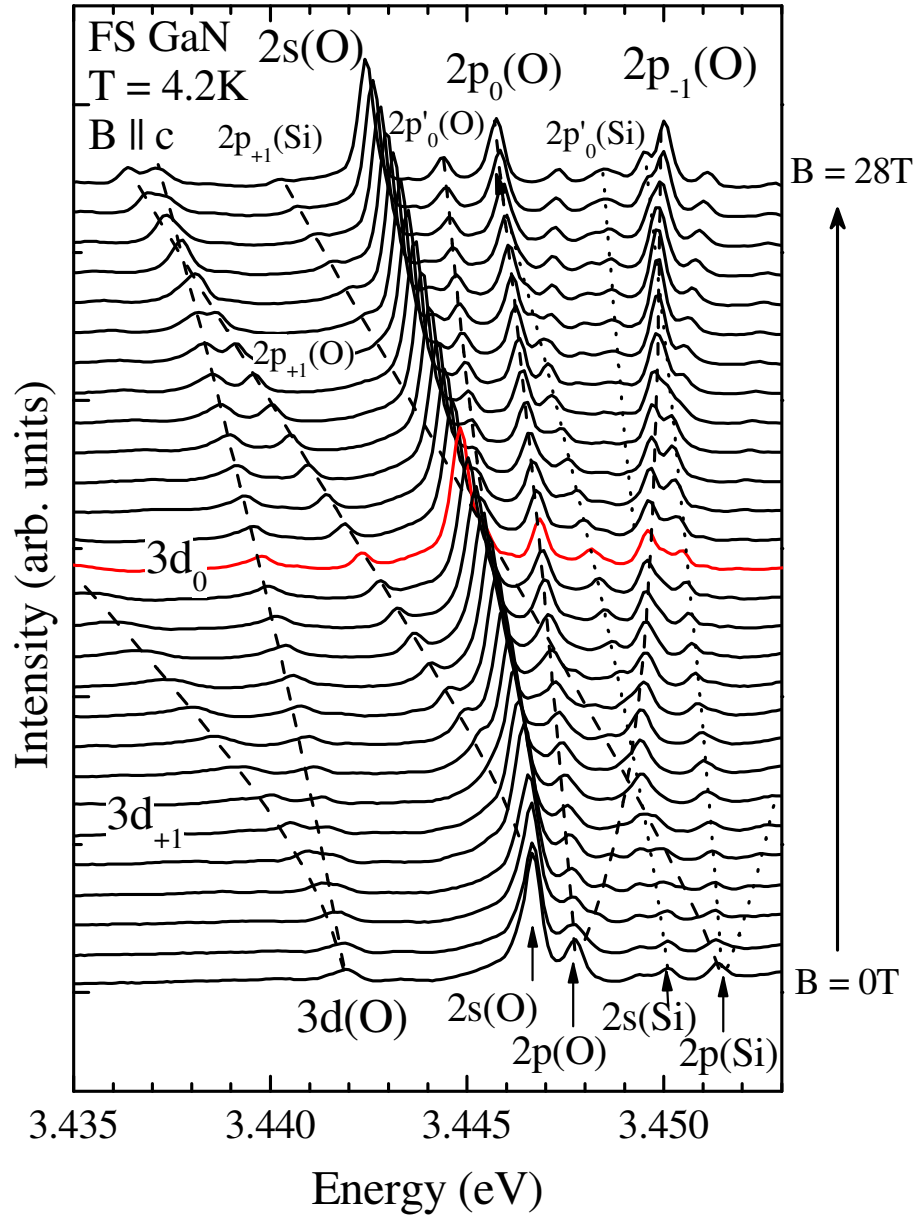


Różne kanały rekombinacji D^0X

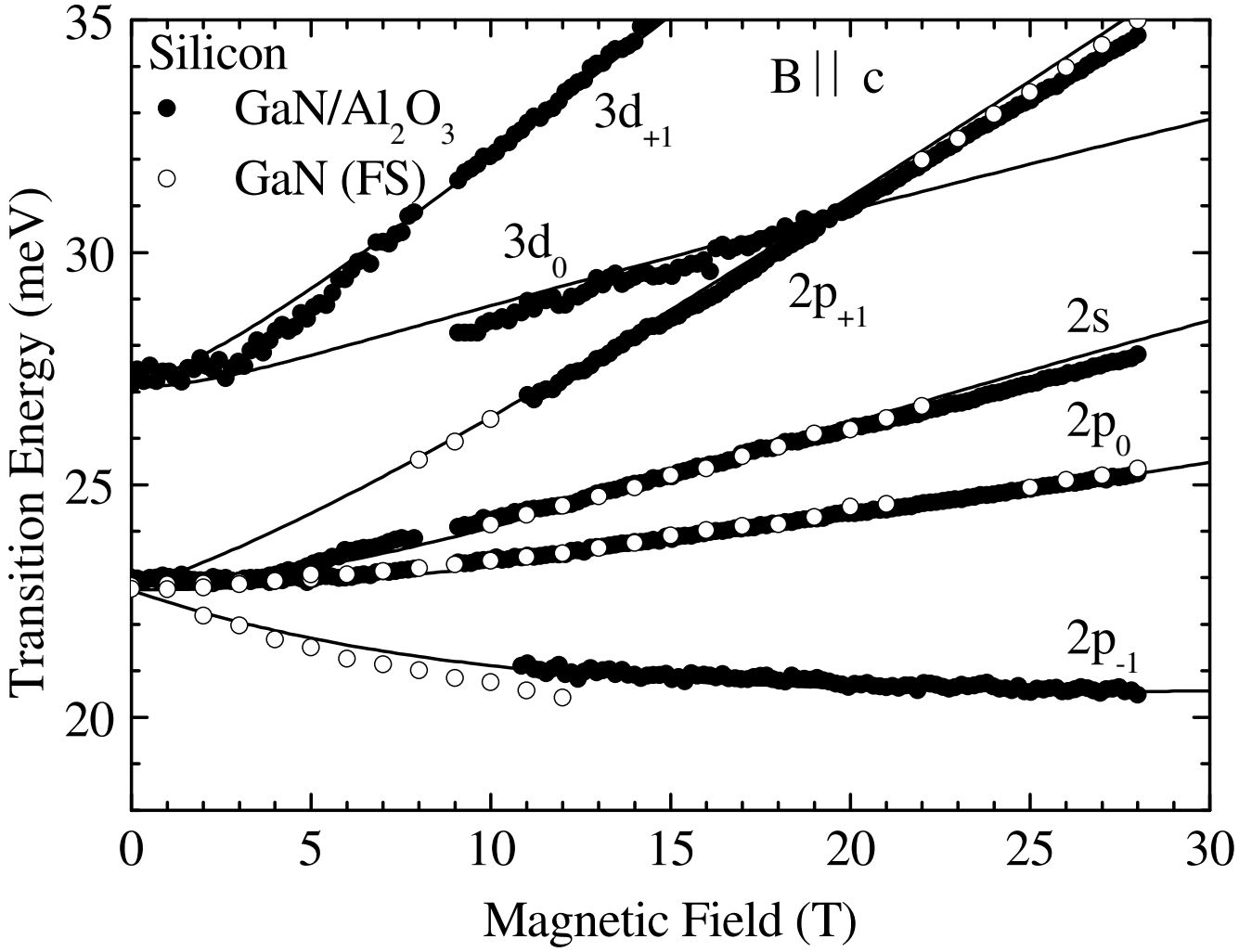


Identyfikujemy przejścia używając pola magnetycznego





Donor krzemowy



R_y=30.28(5) meV

Δ_{1s}= 0

E_b=30.28meV

m^*=0.214m_0

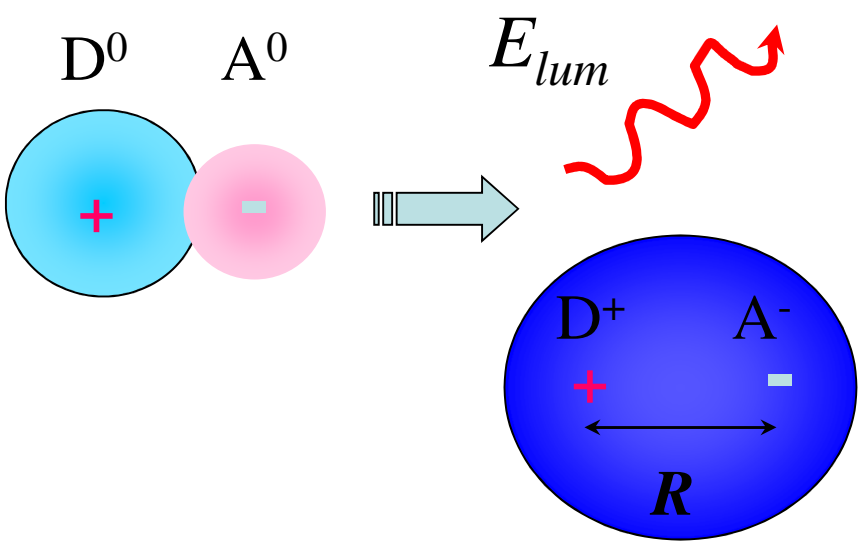
A. Wysmolek et al. PRB 74, 195205 (2006)

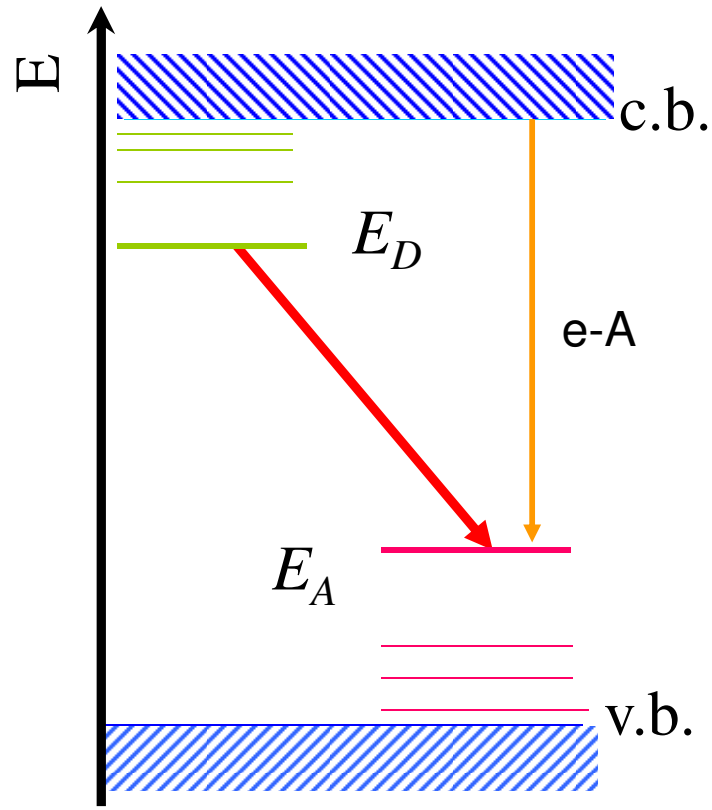
Rekombinacja par donor-akceptor

(jeden z podstawowych kanałów rekombinacji promienistej

półprzewodnikach domieszkowanych)

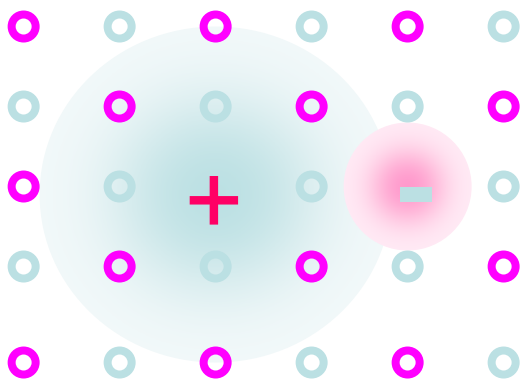
Pary donor-akceptor





$$E_{lum} = E_g - E_A - E_D + e^2/(\varepsilon R)$$

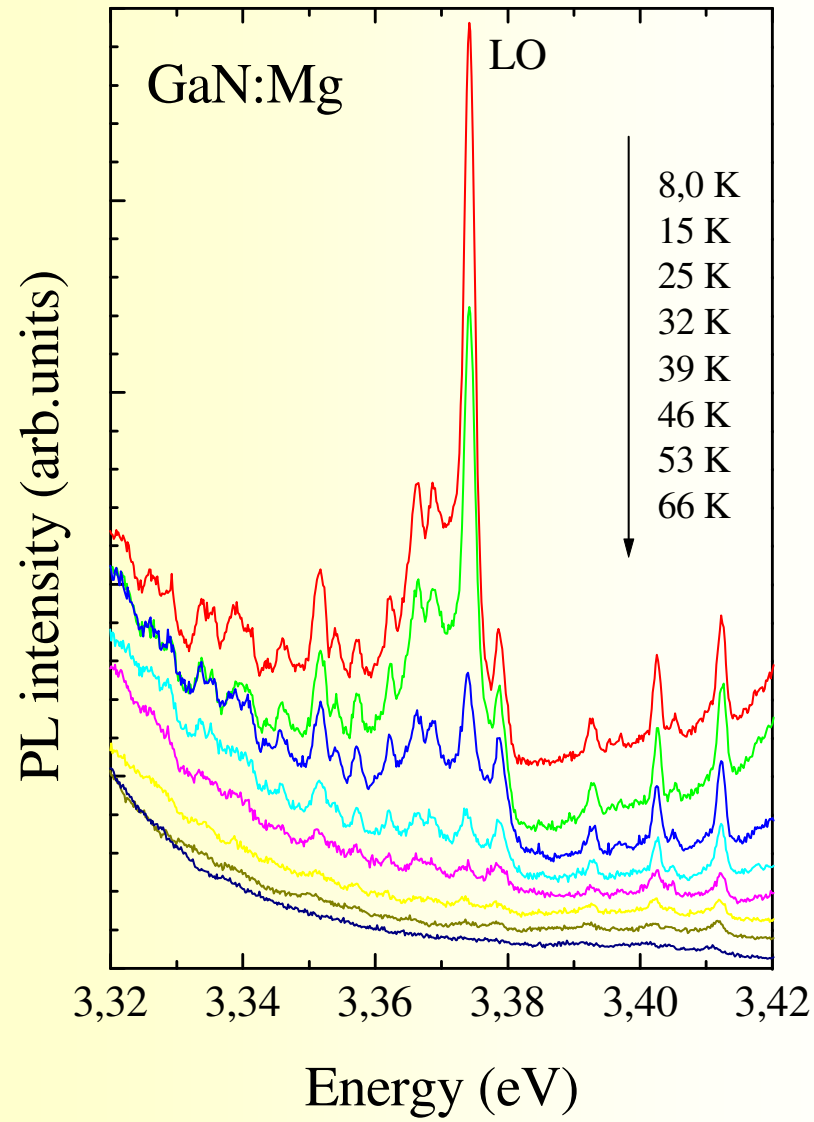
Emisja par donor-akceptor



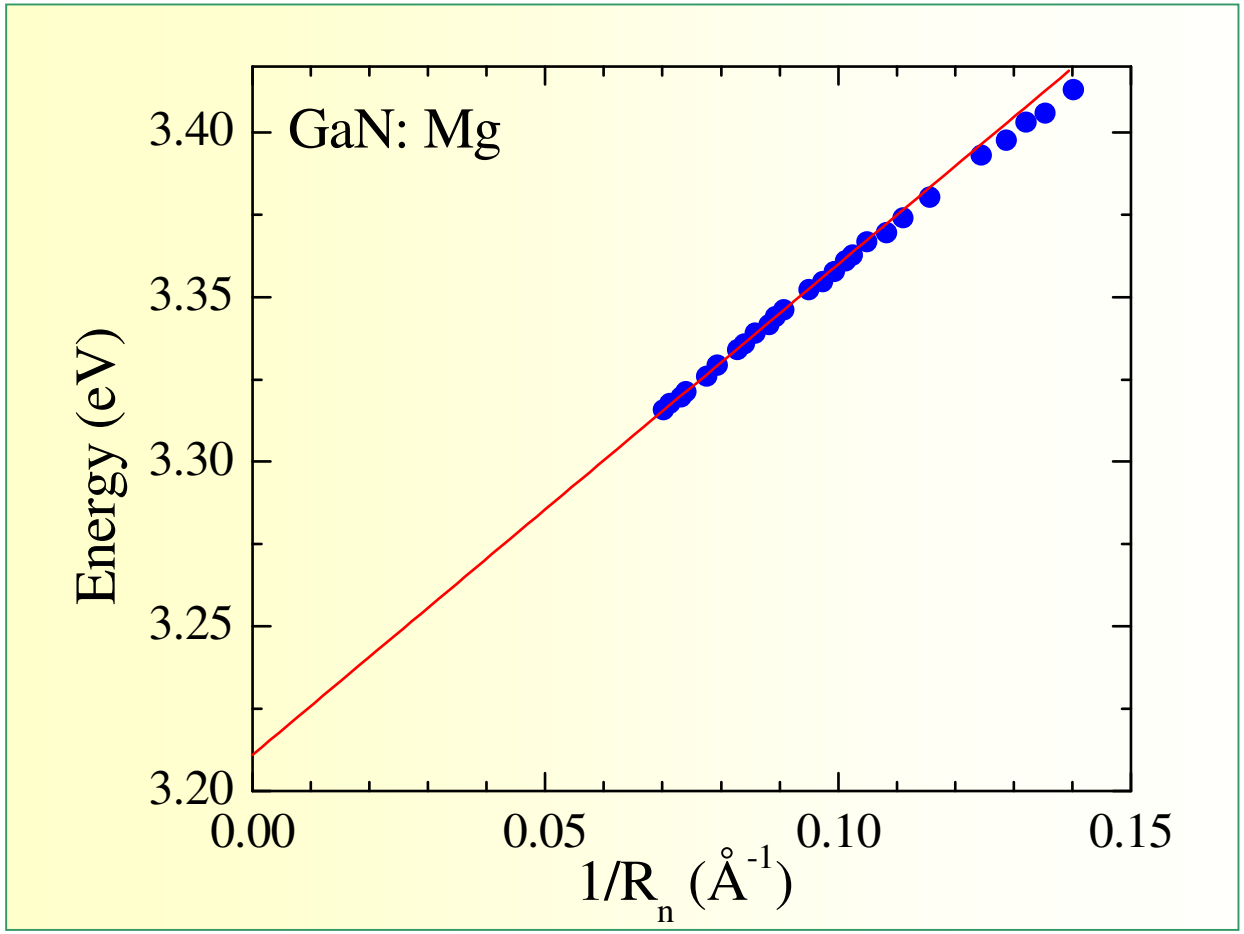
R_n

dyskretne odległości D-A

dyskretne linie emisyjne



Emisja par donor-akceptor w GaN



$$E_{lum} = E_g - E_A - E_D + e^2/(4\pi\, \varepsilon_0 \varepsilon_s\ R_n) \Rightarrow E_D, E_A, \varepsilon_s$$

„Historyczne” widma par w GaP

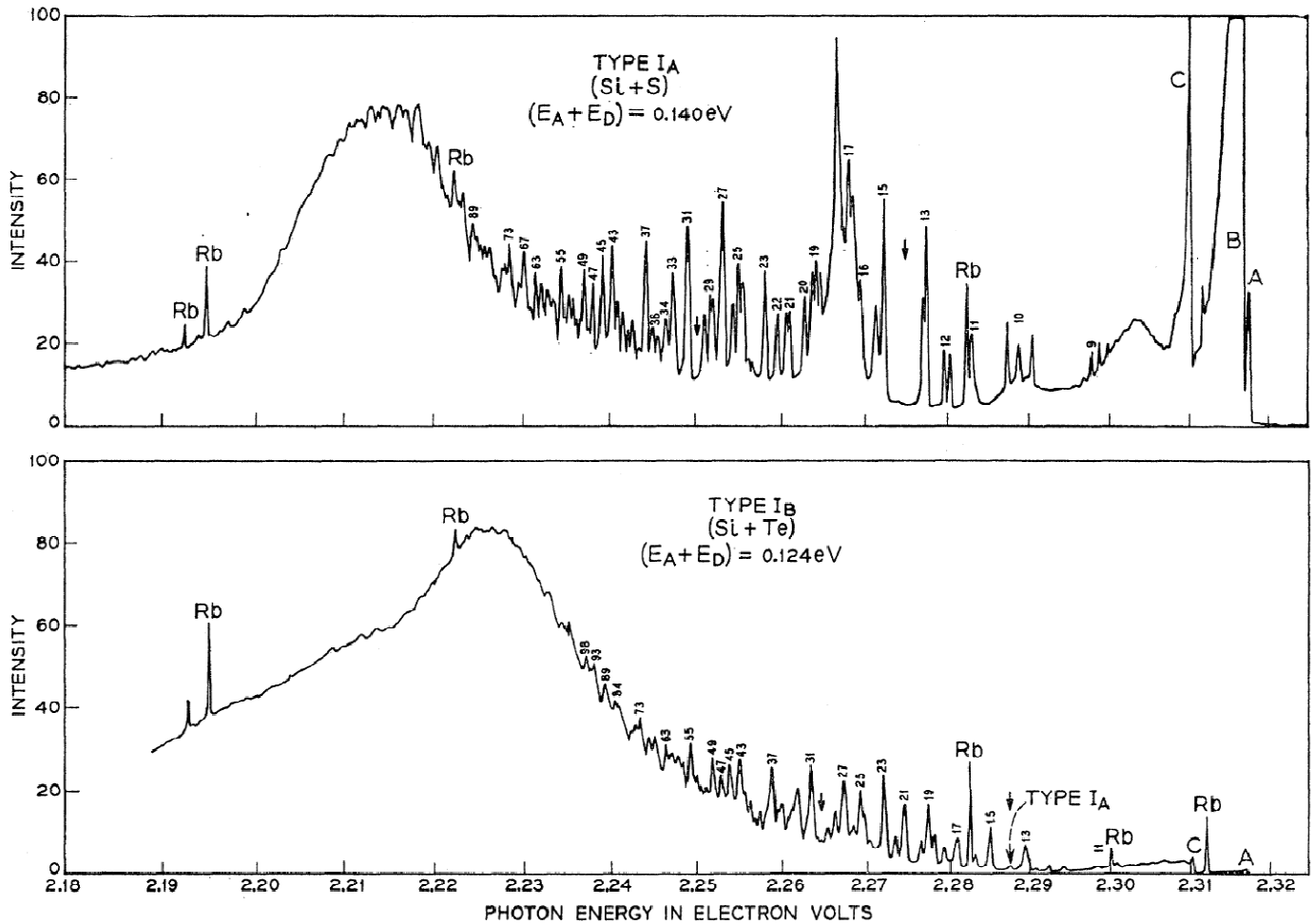
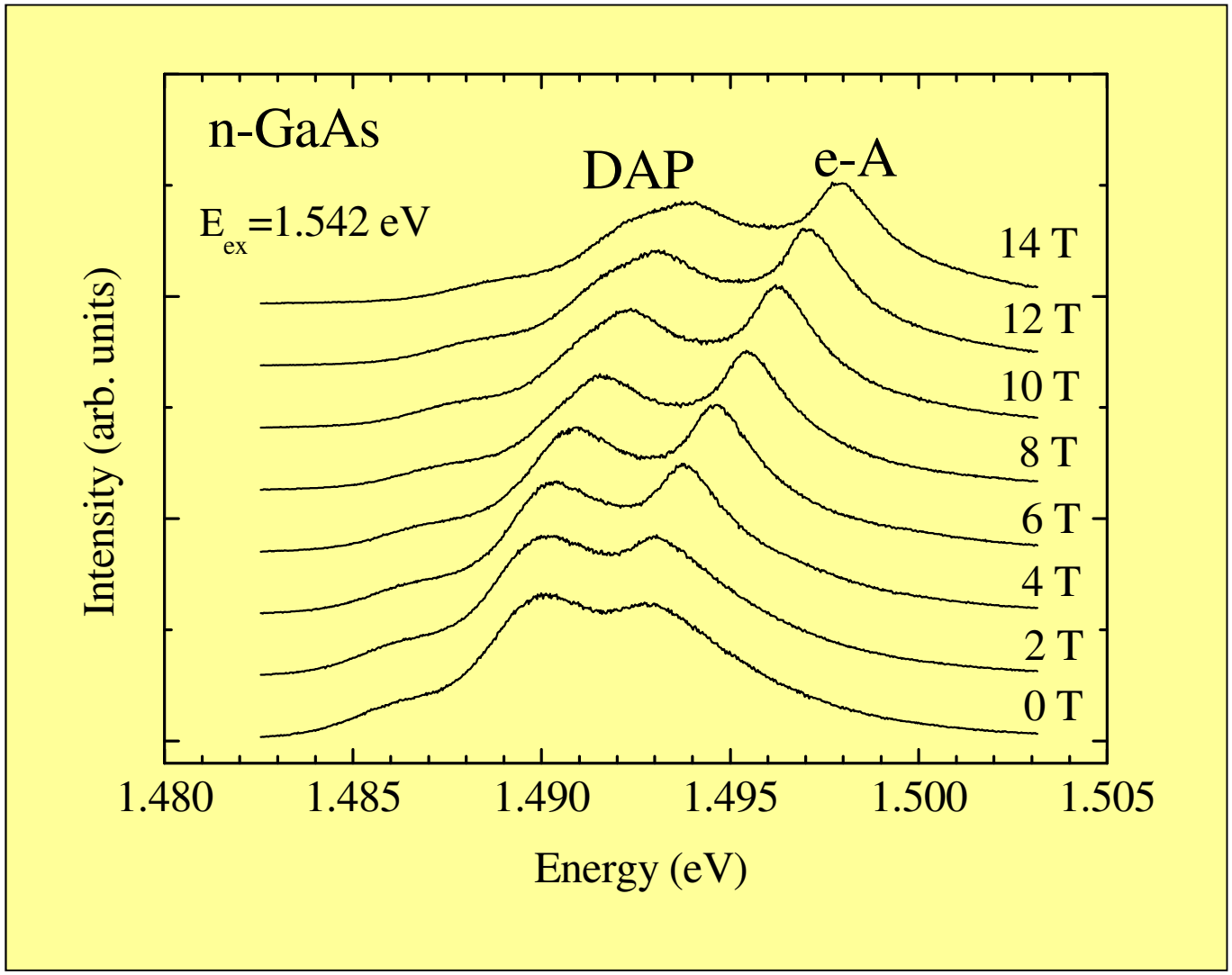


FIG. 2. The photoluminescent spectra (on arbitrary scales) of type I_A and I_B crystals taken at 1.6°K. The lines marked Rb are rubidium calibration lines. The small numbers indicate the shell numbers of the pair spectra. A, B, and C are bound exciton lines. The arrows indicate some positions for which $N(r)=0$, and mark a gap in the spectra. The type I_A crystals are grown without the addition of impurities; the I_B crystals are produced by adding Te.

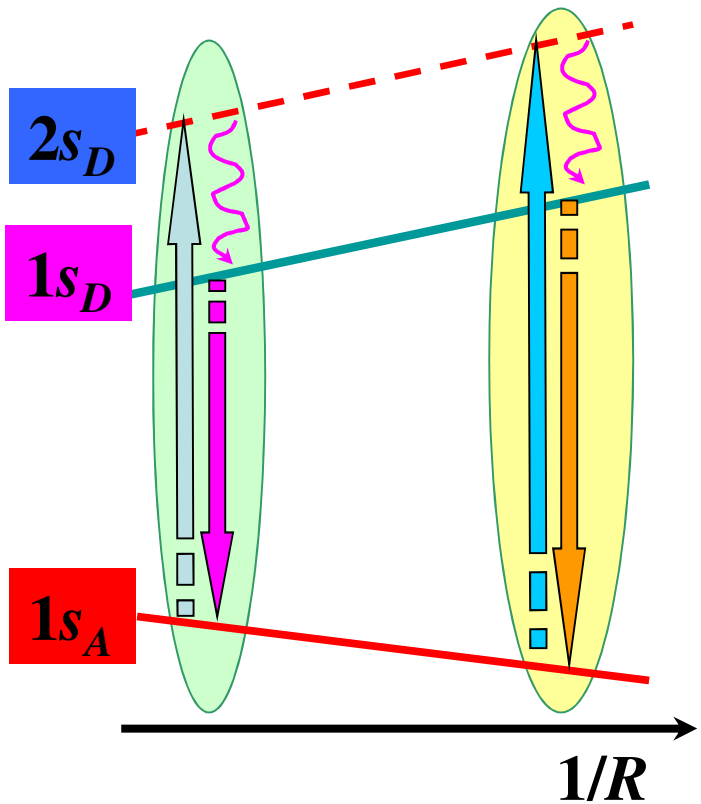
D. G. Thomas et al. Phys. Rev. **133**, A269 (1964)

Luminescencja par donor-akceptor w GaAs

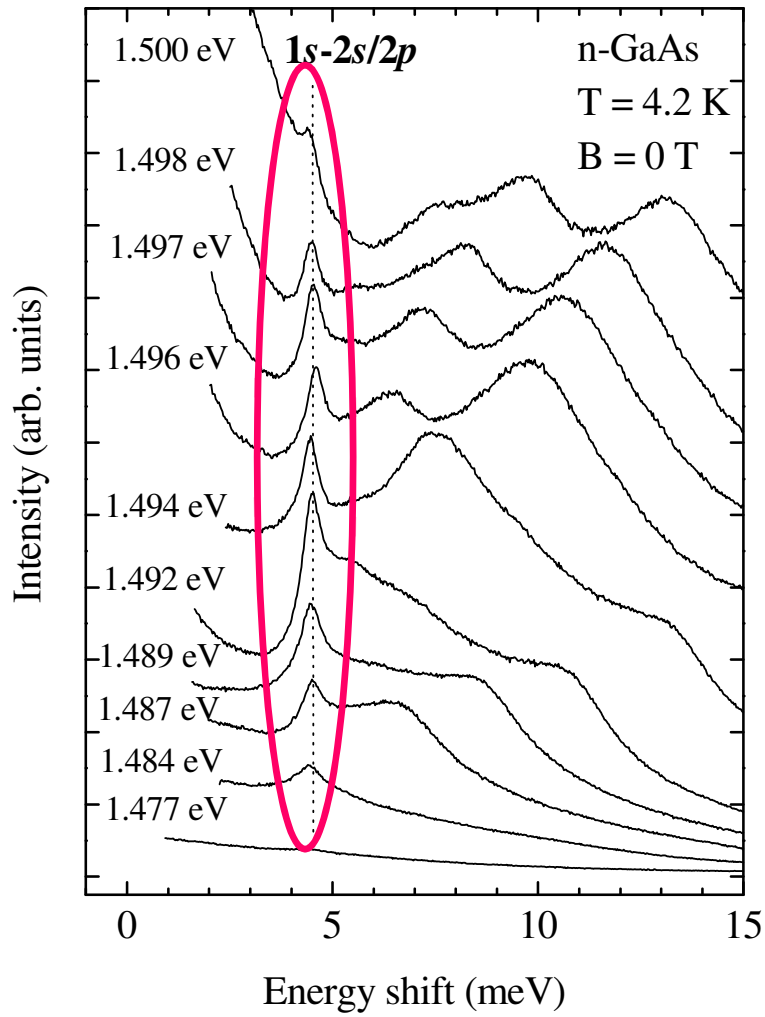
Szerokie linie luminescencyjne! Czy z tego można cos wydobyć?



Selektywne pobudzanie – użyteczna technika rezonansowa (SPL)



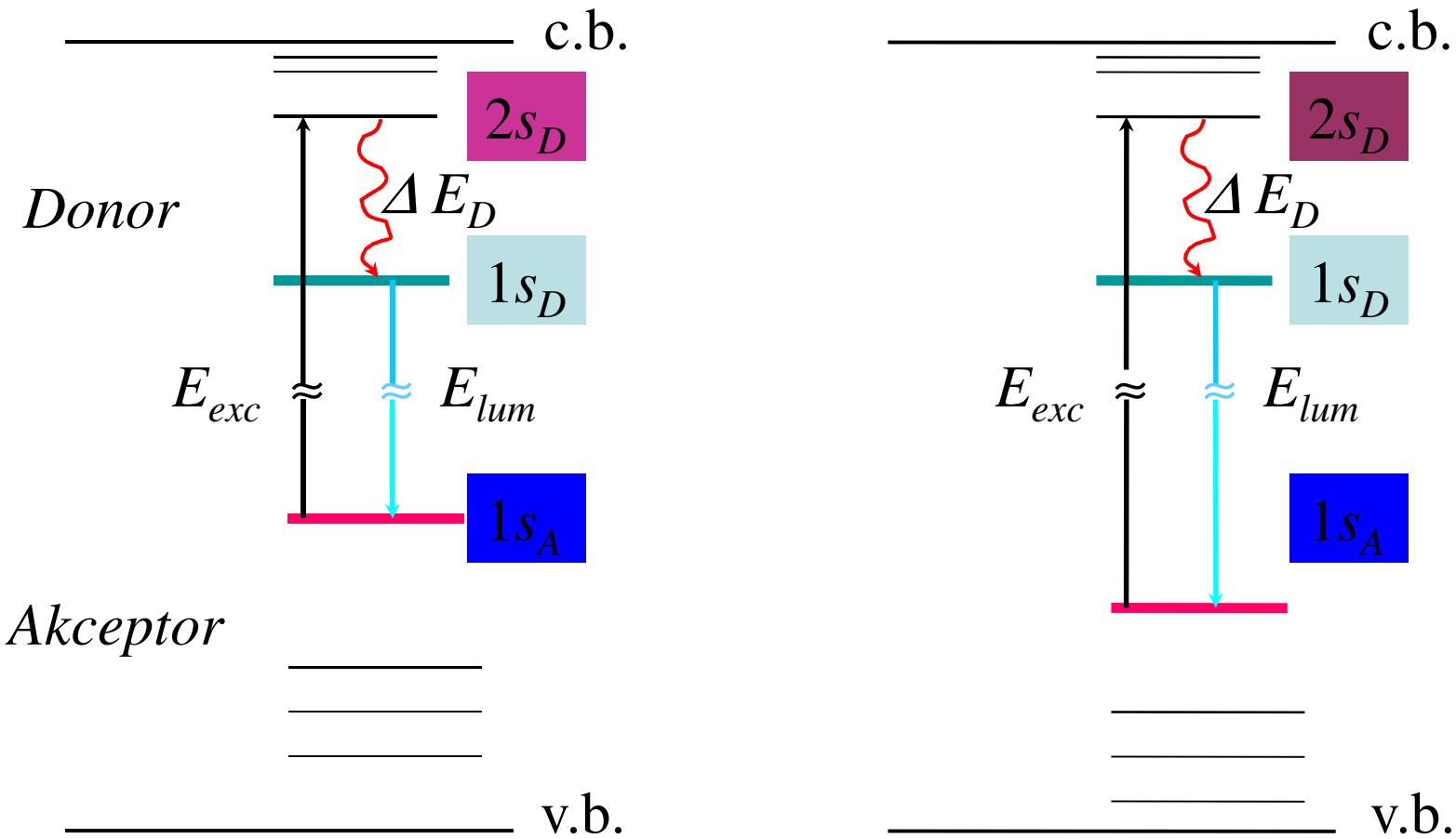
$$E_{exc} - E_{lum} = \Delta E_D$$



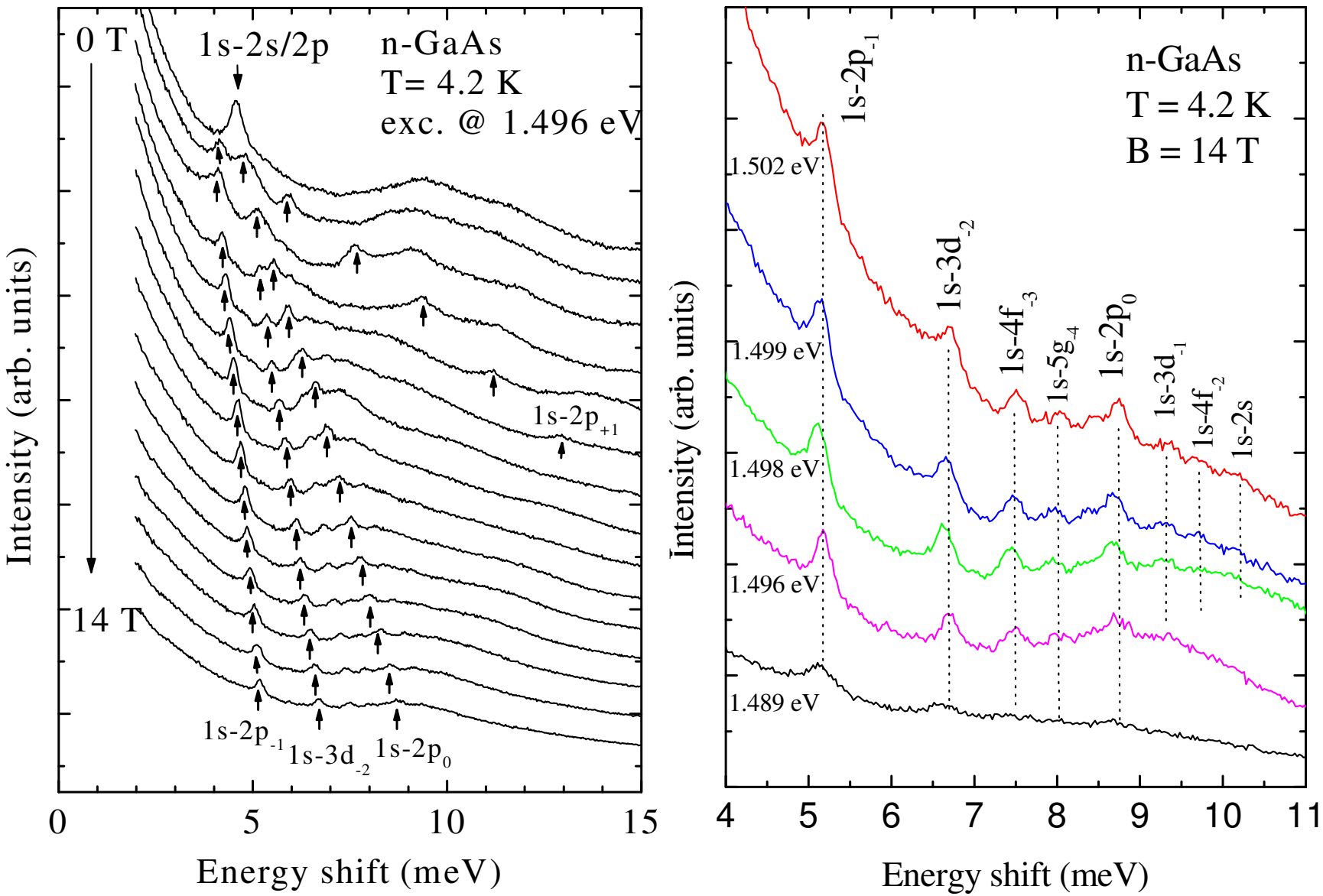
Selektywna spektroskopia par donor-akceptor

$$E_{lum} = E_g - E_A - E_D + e^2/(4\pi\, \varepsilon_0 \varepsilon_s\ R_n)$$

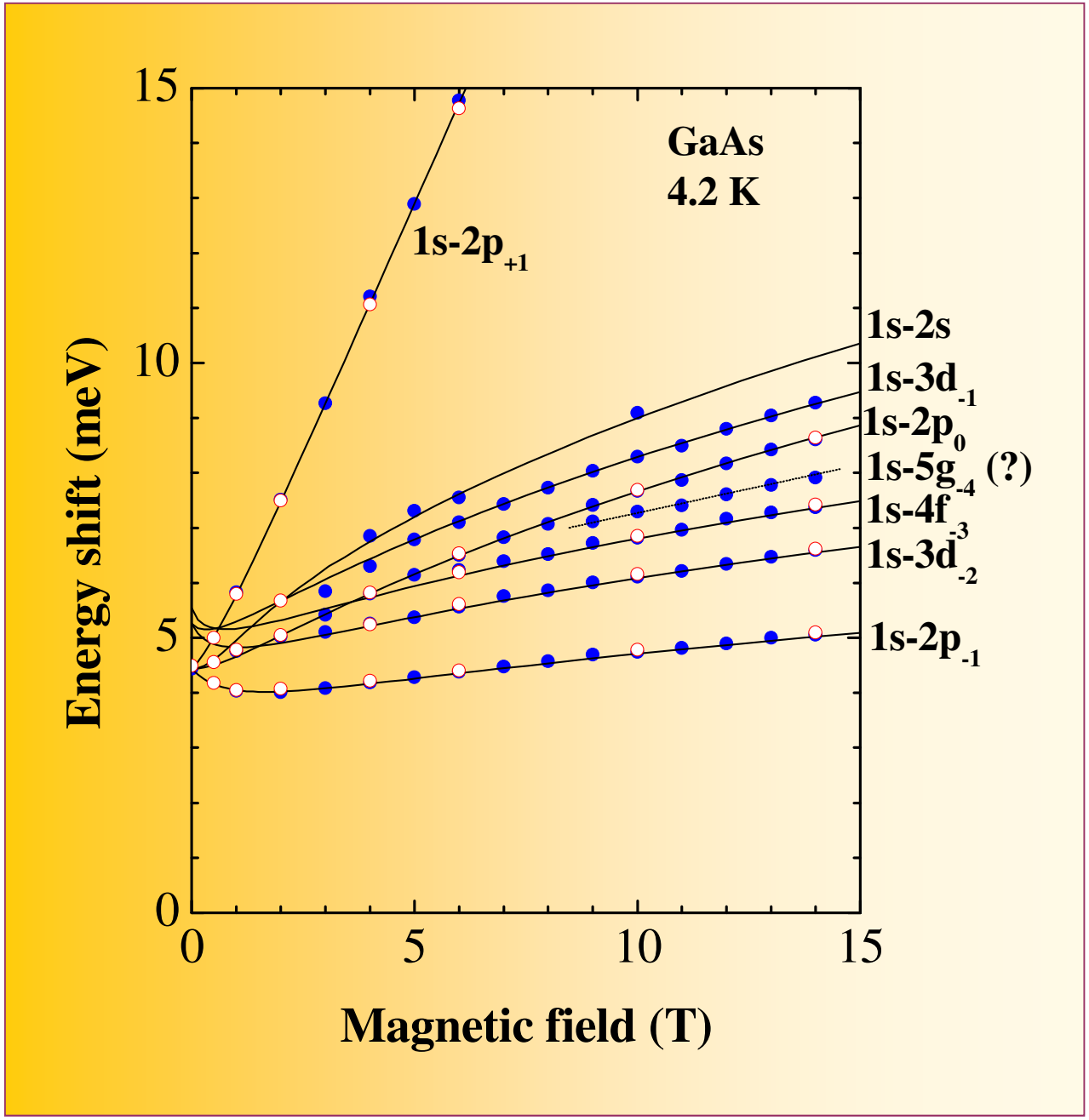
$$R_1 > R_2$$



SPL w polu magnetycznym



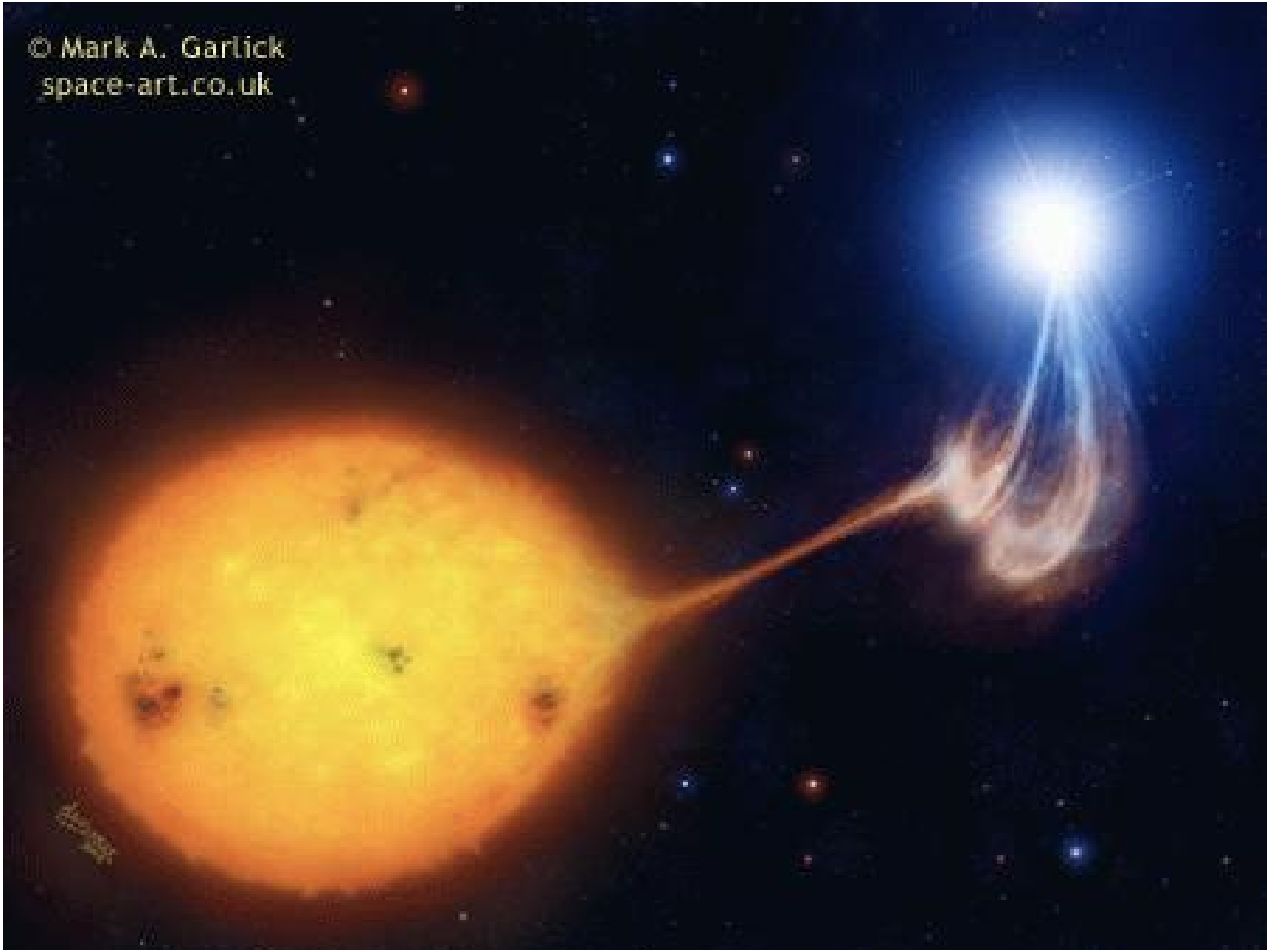
Donor w GaAs



Teoria:

P. C. Makado and N. C. Mc. Gill,

J. Phys. C ***19****, 873 (1986)*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B=230 T, γ=0.01

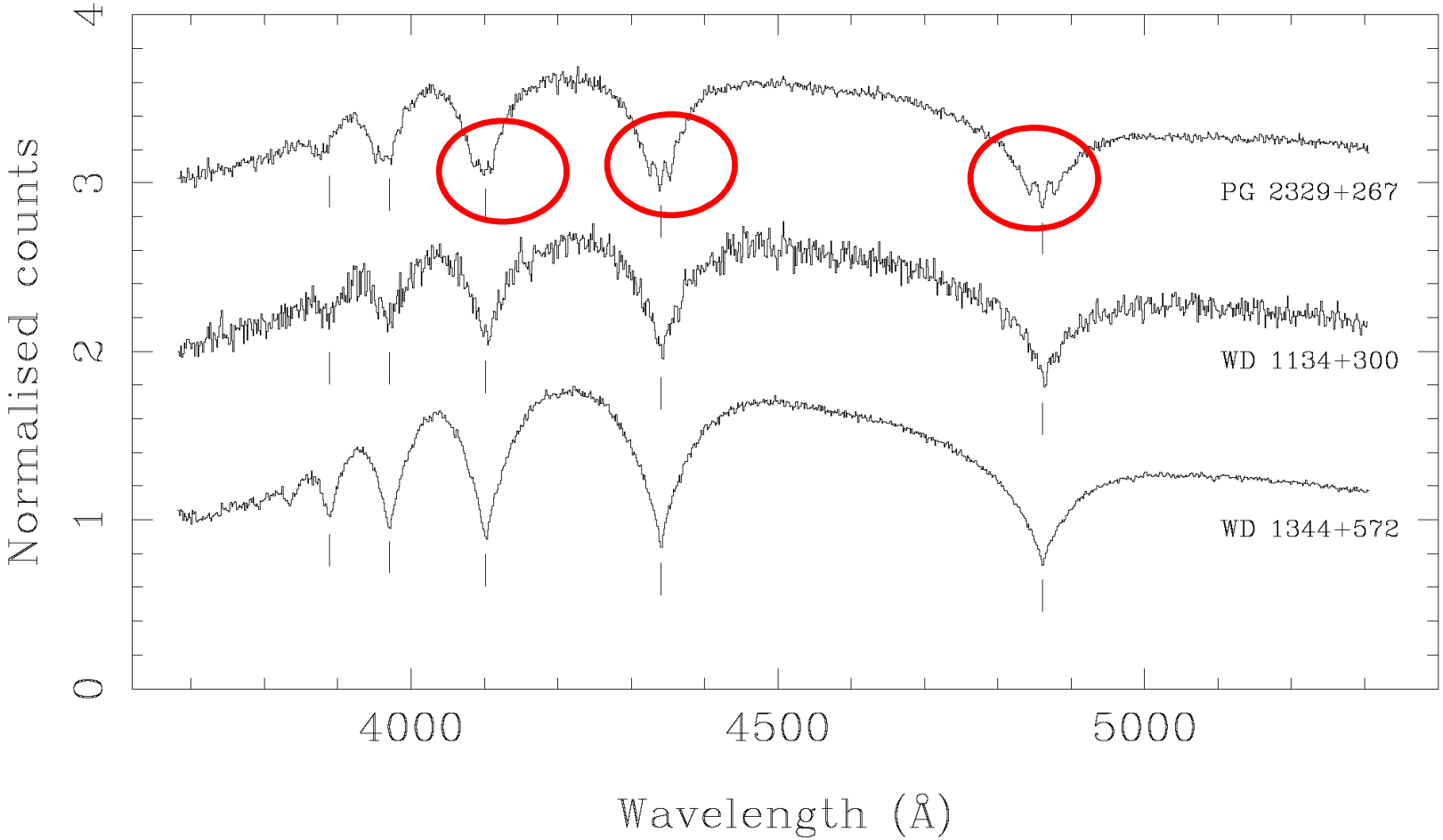

Figure 1. The spectrum of PG 2329+267 (top) taken with the INT clearly shows Zeeman splitting of the hydrogen Balmer lines due to the presence of a magnetic field. The spectra of two non-magnetic white dwarfs are offset below for comparison. The vertical lines are placed at the rest wavelengths of the Balmer lines and aid detection of the quadratic zeeman shift in the spectrum of PG 2329+267.

C. Moran, T. R. Marsh, and V. S. Dhillon (1998)