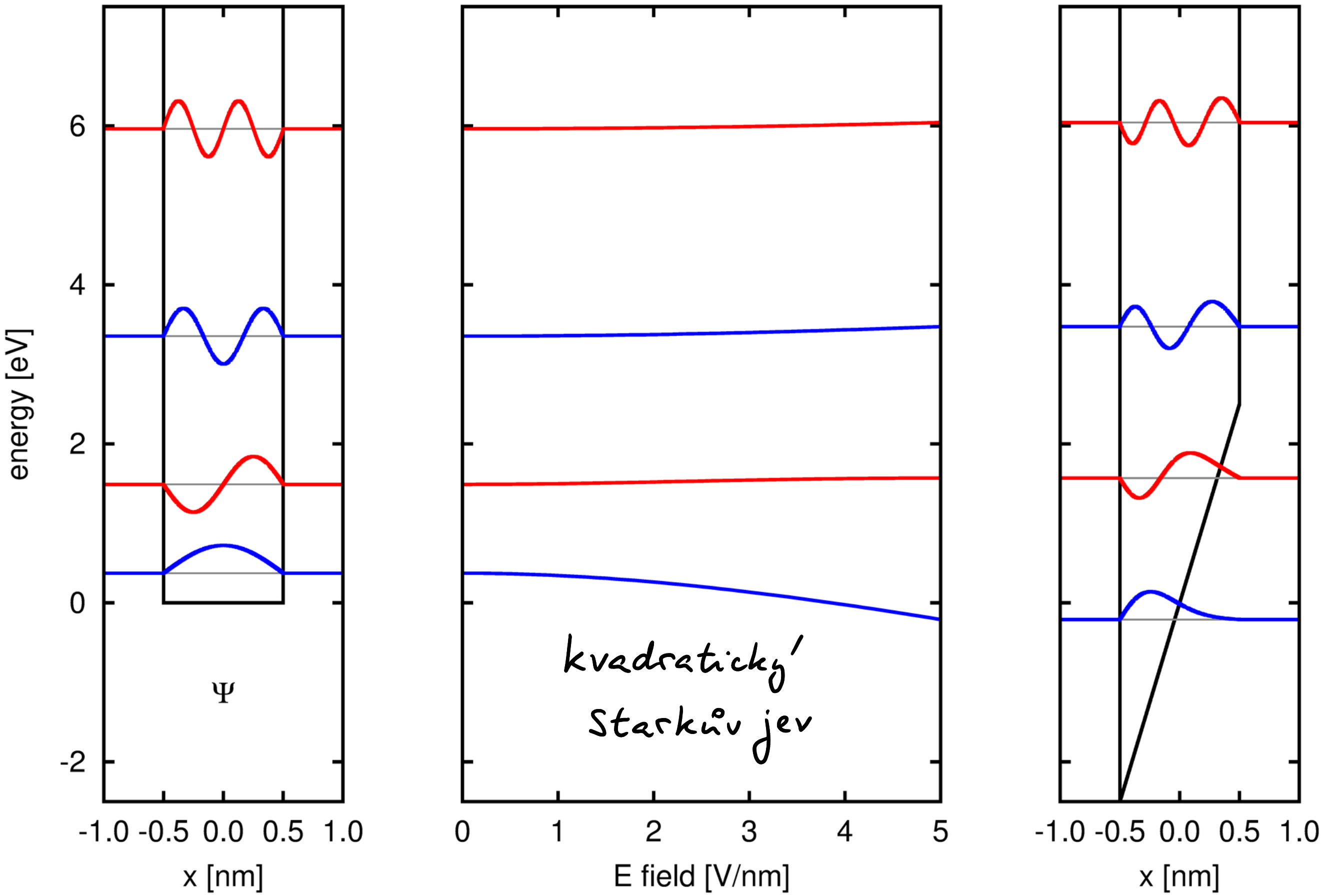
Nekonečně hluboká potenciálová jáma v elektrickém poli



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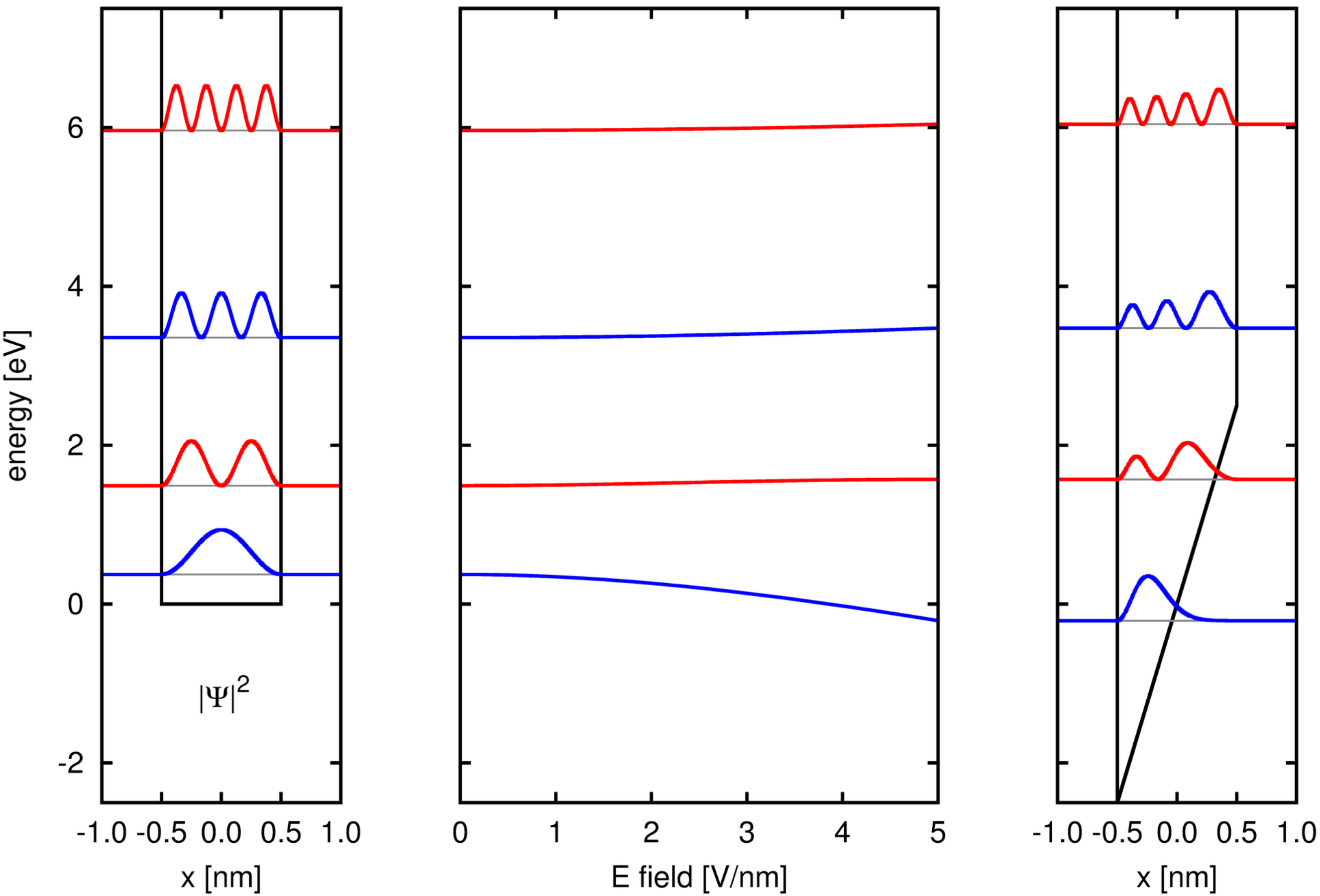
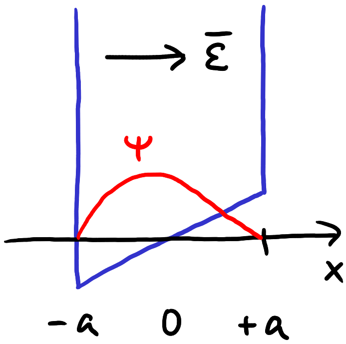


Nekonečně hluboká potenciálová jáma v elektrickém poli - variační metoda



dno jámy popsáno potenciálem $V(x) = e\mathcal{E}x$

zkušební vlnové funkce elektronu

$$\psi_\lambda(x) = N\left(1+\lambda\frac{x}{a}\right)\cos\frac{\pi x}{2a}$$

vychýlení pro $\mathcal{E} \neq 0$ přesný profil pro $\mathcal{E} = 0$

střední hodnota Hamiltoniánu

$$E(\lambda) = \frac{\langle\psi_\lambda|\hat{H}|\psi_\lambda\rangle}{\langle\psi_\lambda|\psi_\lambda\rangle} = \frac{\int\psi_\lambda^*\hat{H}\psi_\lambda dx}{\int\psi_\lambda^*\psi_\lambda dx} = \frac{-\frac{\hbar^2}{2m}\int\psi_\lambda^*\frac{d^2}{dx^2}\psi_\lambda + \int\psi_\lambda^* V\psi_\lambda}{\int\psi_\lambda^*\psi_\lambda}$$

$$= \frac{\pi^2\hbar^2}{8ma^2} + \frac{\hbar^2}{2ma^2}\frac{\lambda^2}{1+B\lambda^2} + e\mathcal{E}a\frac{2B\lambda}{1+B\lambda^2}$$

minimalizace $\rightarrow$ λ_{min}, E_{min}

$E(\lambda)$ nahradíme aproximací pro malé $\mathcal{E}$ a tedy λ

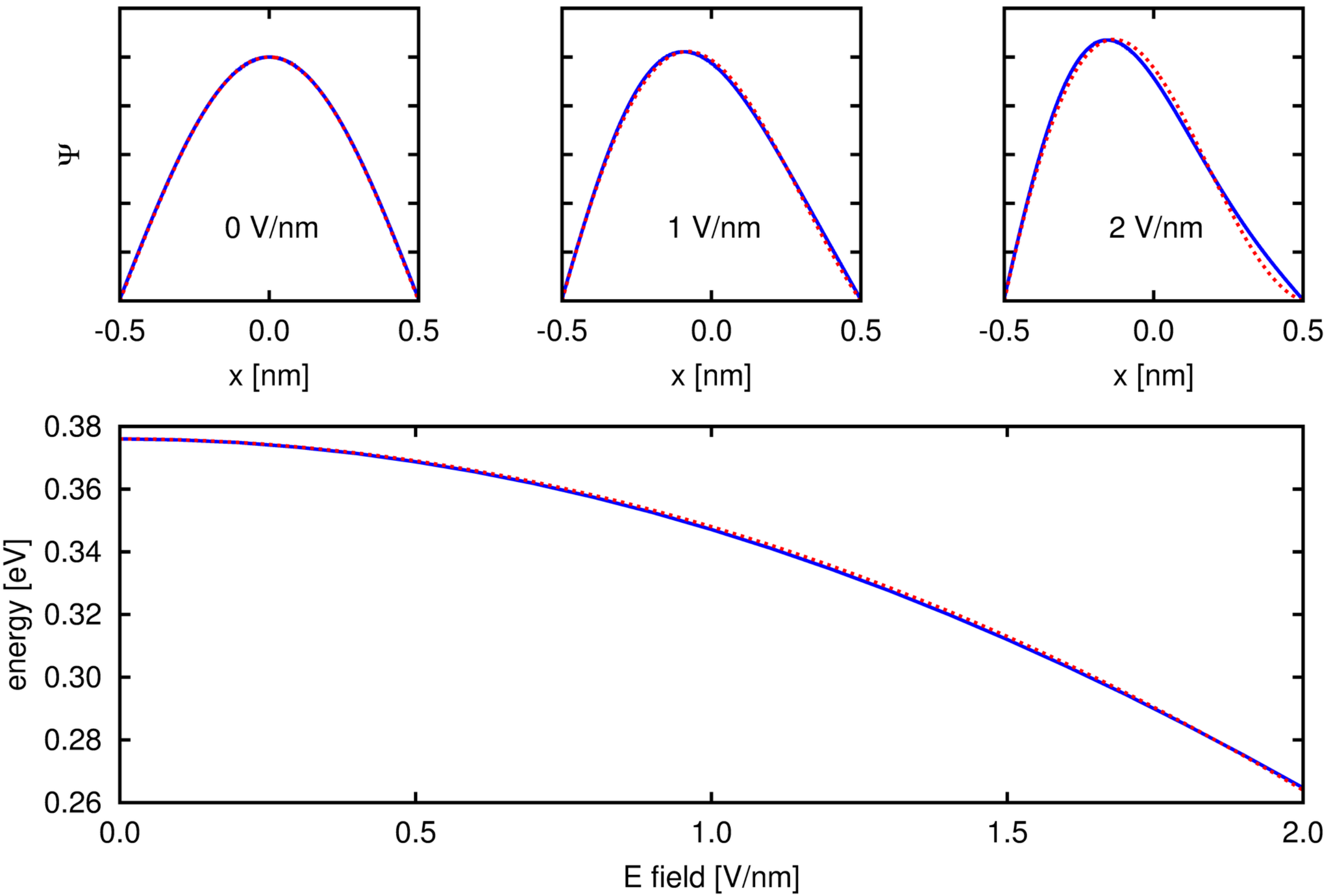
$$E(\lambda) \approx \frac{\pi^2\hbar^2}{8ma^2} + e\mathcal{E}a\ 2B\lambda + \frac{\hbar^2}{2ma^2}\lambda^2 \quad \rightarrow \quad \lambda_{min} \approx -2B\frac{e\mathcal{E}a}{\hbar^2/ma^2}$$

- odhad energie základního stavu

$$E_{min} \approx \underbrace{\frac{\pi^2\hbar^2}{8ma^2}}_{\text{energie pro } \mathcal{E}=0} \underbrace{- 2\left(\frac{1}{3}-\frac{2}{\pi^2}\right)^2\frac{(e\mathcal{E}a)^2}{\hbar^2/ma^2}}_{\text{korekce úměrná } \mathcal{E}^2}$$

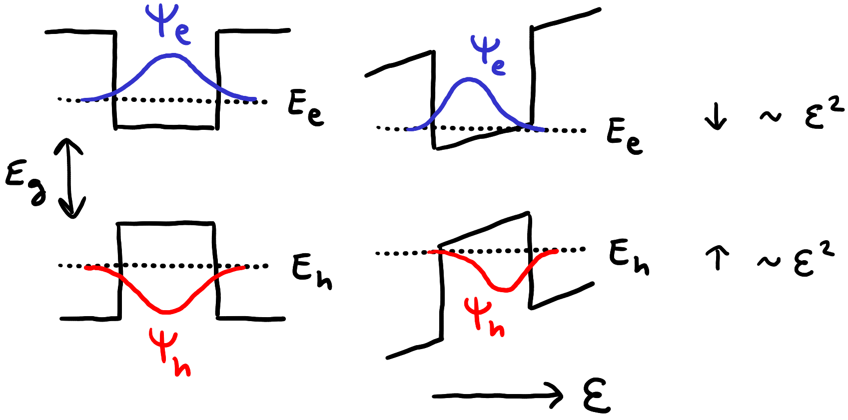
- odhad vlnové funkce

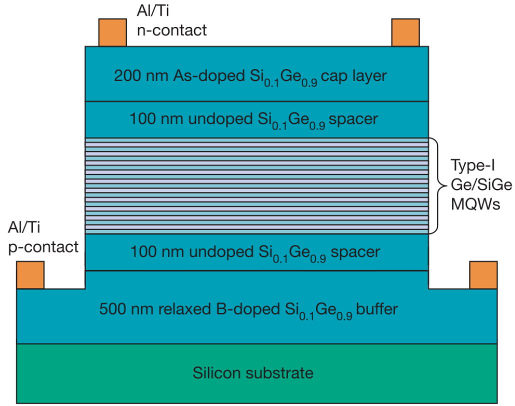
$$\psi_{min}(x) = N\left(1+\lambda\frac{x}{a}\right)\cos\frac{\pi x}{2a} \quad \text{s} \quad \lambda_{min} \approx -2B\frac{e\mathcal{E}a}{\hbar^2/ma^2} = -\left(\frac{2}{3}-\frac{4}{\pi^3}\right)\frac{e\mathcal{E}a}{\hbar^2/ma^2}$$



Ψ
0 V/nm
1 V/nm
2 V/nm
-0.5
0.0
0.5
x [nm]
energy [eV]
0.38
0.36
0.34
0.32
0.30
0.28
0.26
0.0
0.5
1.0
1.5
2.0
E field [V/nm]

Quantum-confined Stark effect (QCSE)





1) energie fotonu < vyzářeného při rekombinaci páru elektron-díra
absorbovaného za vzniku páru elektron-díra

$\hbar\omega = E_e - E_h$ ← posun úměrný ε^2

2) intenzita daná překryvem vlnových funkcí elektronu a díry

$$I \sim \left|\int \psi_e^* \psi_h\right|^2 = \left|\int_{-a}^{a} \underbrace{N\left(1+\lambda\frac{x}{a}\right)\cos\frac{\pi x}{2a}}_{\psi_e^*}\ \underbrace{N\left(1-\lambda\frac{x}{a}\right)\cos\frac{\pi x}{2a}}_{\psi_h}\,dx\right|^2 \approx 1 - \alpha\varepsilon^2$$

Elektroabsorpční modulátory

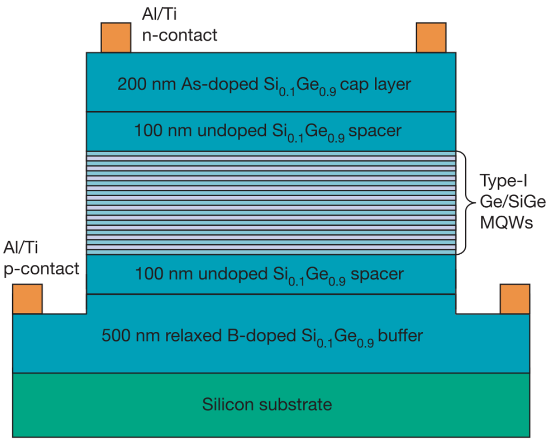


Figure 2 | Schematic diagram of a p-i-n diode. The cross-sectional view shows the structure of strained Ge/SiGe multiple quantum wells (MQWs) grown on silicon on relaxed SiGe direct buffers (not to scale). In the measurements, light from a monochromator is incident on the top surface (that is, in a 'surface-normal' configuration) on the open area inside the rectangular frame top electrode (that is, between the portions of the AlTi n-contacts shown in this cross-section).

Kuo et al., Nature <u>437</u>, 1334 (2005)

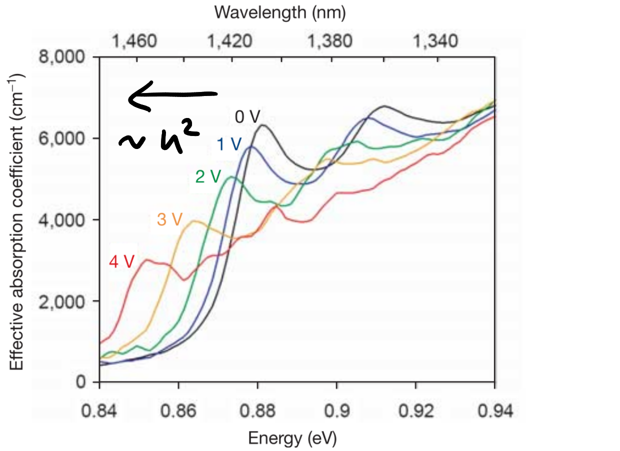


Figure 3 | Effective absorption coefficient spectra. Strong QCSE is observed at room temperature with reverse bias from zero to 4 V. The thickness for effective absorption coefficient calculations is based on the combination of Ge well and SiGe barrier thicknesses.

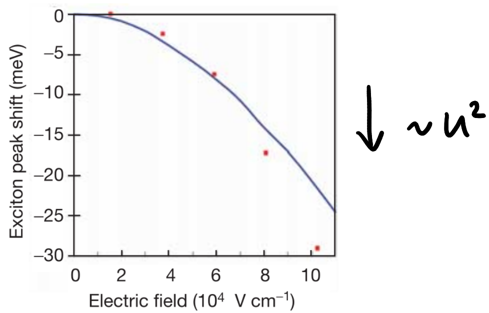
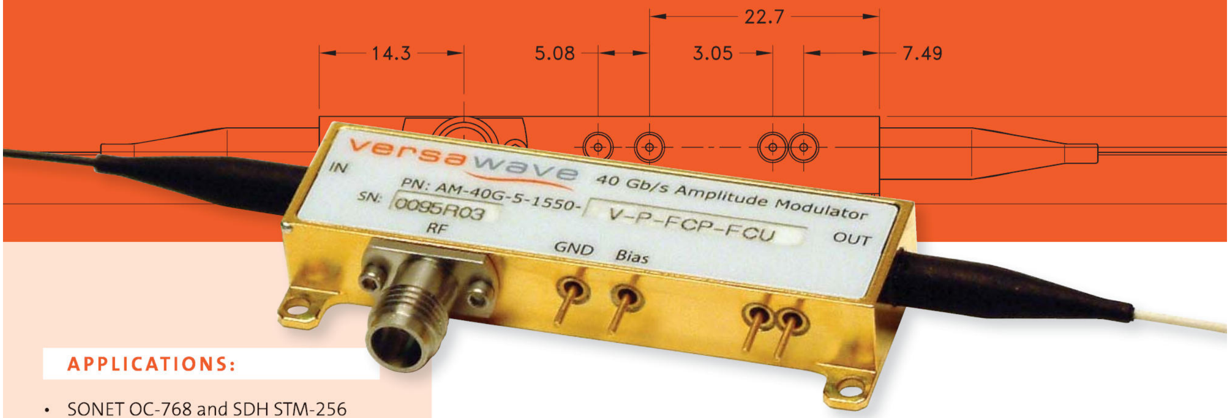


Figure 4 | Shifts of exciton peaks. Comparison of heavy-hole exciton peak shift from measurements (filled squares) and tunnelling resonance calculations (sum of electron and hole level shifts) (line).

Elektrooptické modulátory

40 Gb/s Amplitude Modulator

Electro-Optic Mode Converter



APPLICATIONS:

- SONET OC-768 and SDH STM-256 transmissions
- 40 Gb/s transponders
- High-speed Internet routers
- DWDM, high-speed Ethernet and TDM
- High-speed test equipment

FEATURES:

DESCRIPTION:

The Versawave 40 Gb/s Amplitude Modulator represents a revolutionary method for modulating CW laser light into data-carrying optical pulse trains. By employing proprietary GaAs technology, the Versawave modulator establishes new benchmarks for low drive voltage, ultra-wide bandwidth and chirp-free operation within a small footprint.

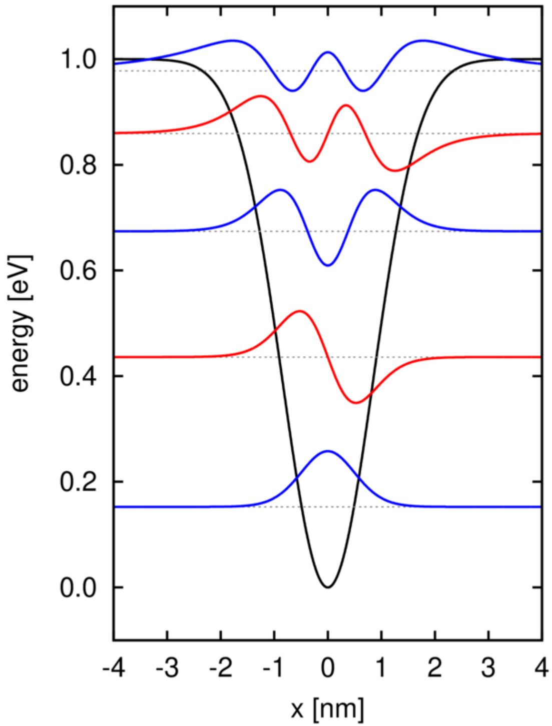
Gaussovská potenciálová jáma - Ritzova variační metoda

- jáma s potenciálem $V(x) = V_0\left(1 - e^{-\frac{x^2}{a^2}}\right)$
- sada bázových funkcí

$$\varphi_n(x) = \frac{1}{\sqrt{\sigma}}\left(\frac{x}{\sigma}\right)^n e^{-\frac{x^2}{\sigma^2}}$$

→ zkušební funkce

$$\Psi(x) = \sum_{n=0}^{n_{max}} c_n \varphi_n(x) = \text{polynom} \times e^{-\frac{x^2}{\sigma^2}}$$



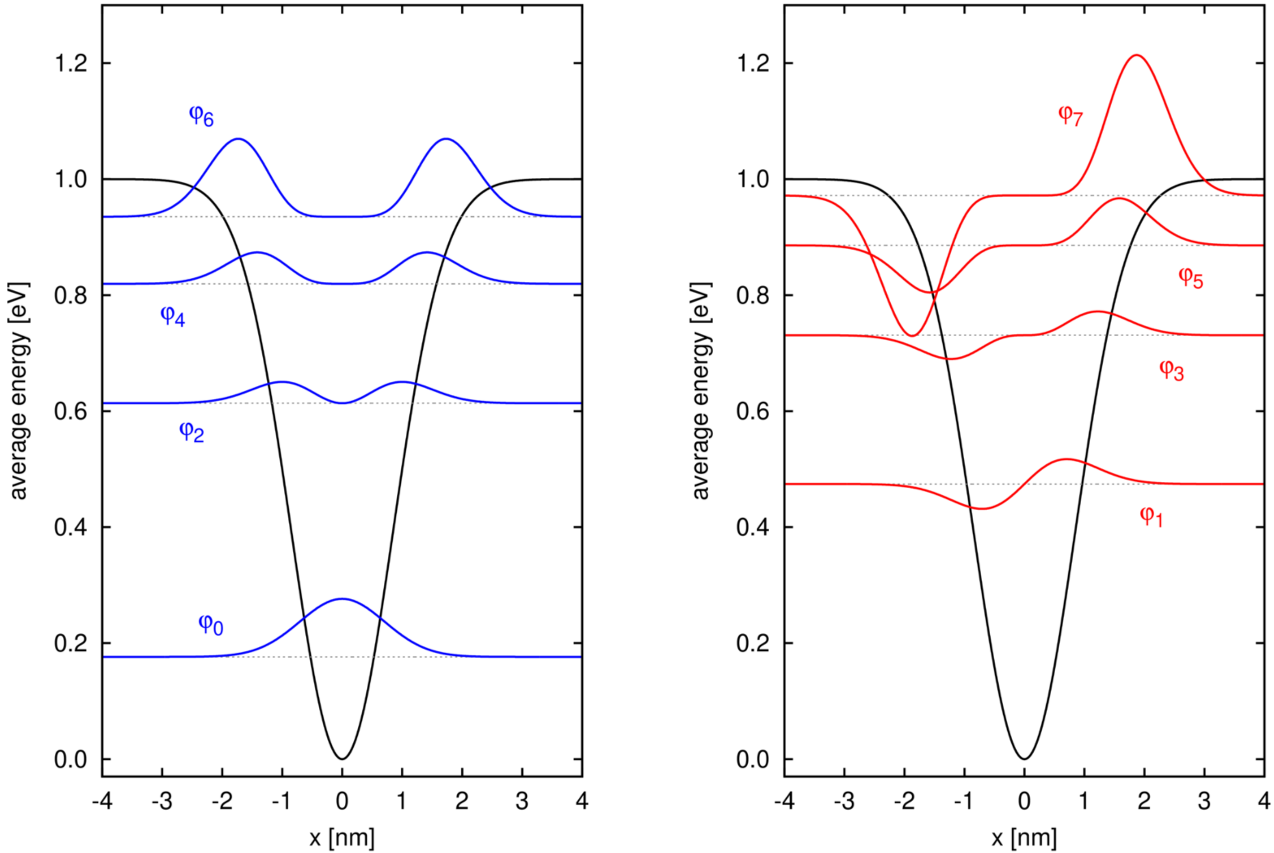
- hledání stacionárního bodu funkcionálu $E[\Psi]$

$$H_{nn'} = \int_{-\infty}^{\infty} \varphi_n^*(x)\left[-\frac{\hbar^2}{2m}\frac{d^2}{dx^2} + V(x)\right]\varphi_{n'}(x)\,dx$$

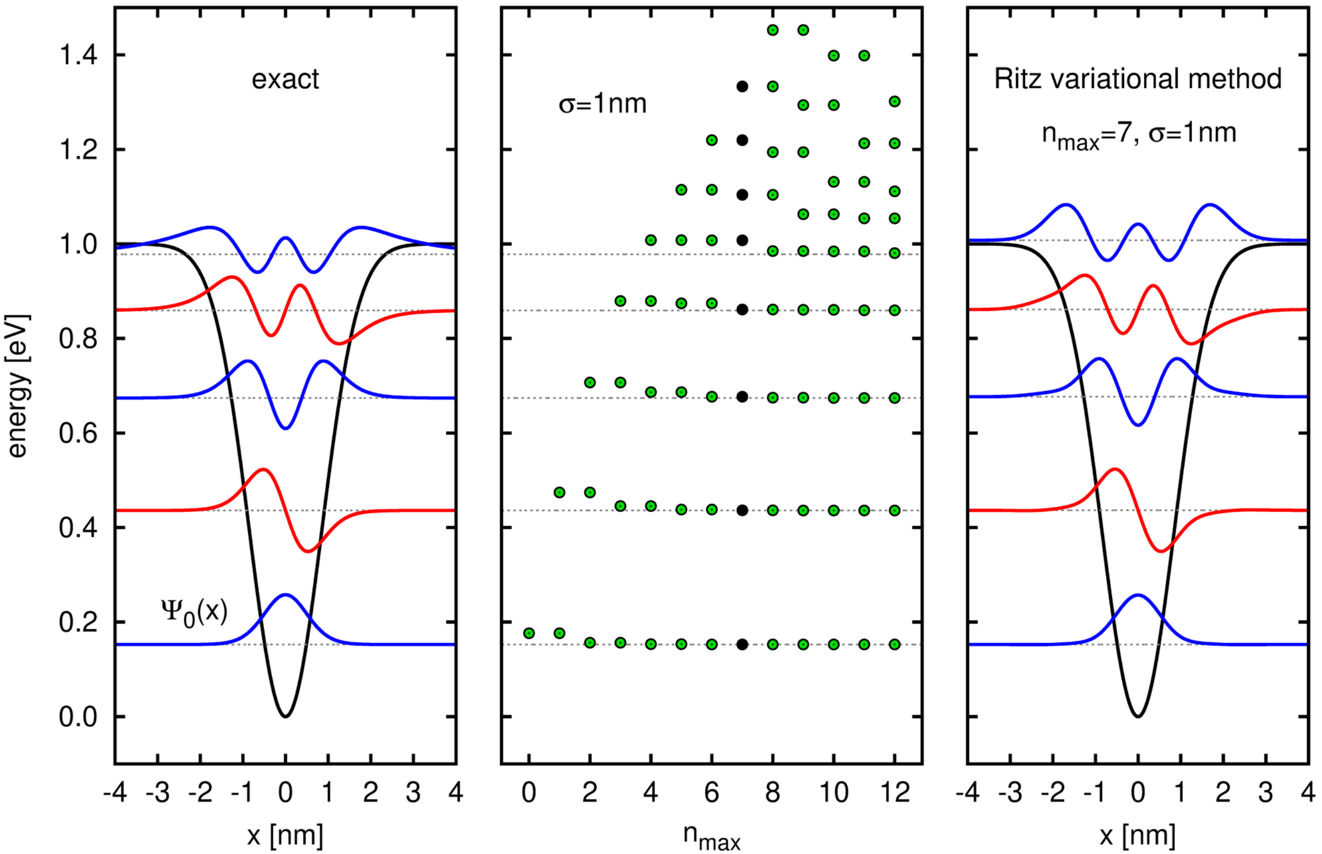
$$S_{nn'} = \int_{-\infty}^{\infty} \varphi_n^*(x)\,\varphi_{n'}(x)\,dx$$

$$\rightarrow \quad \sum_{n'=0}^{n_{max}} H_{nn'} c_{n'} = E \sum_{n'=0}^{n_{max}} S_{nn'} c_{n'} \quad \rightarrow \quad \det(H - ES) = 0$$

$$\text{sada} \quad \varphi_n(x) = \frac{1}{\sqrt{\sigma}} \left(\frac{x}{\sigma}\right)^n e^{-\frac{x^2}{\sigma^2}} \quad \longrightarrow \quad \text{zkušební funkce} \quad \Psi(x) = \sum_{n=0}^{n_{max}} c_n \varphi_n(x)$$



$$\text{sada}\quad \varphi_n(x) = \frac{1}{\sqrt{\sigma}}\left(\frac{x}{\sigma}\right)^n e^{-\frac{x^2}{\sigma^2}} \quad \longrightarrow \quad \text{zkušební funkce}\quad \Psi(x) = \sum_{n=0}^{n_{max}} c_n \varphi_n(x)$$



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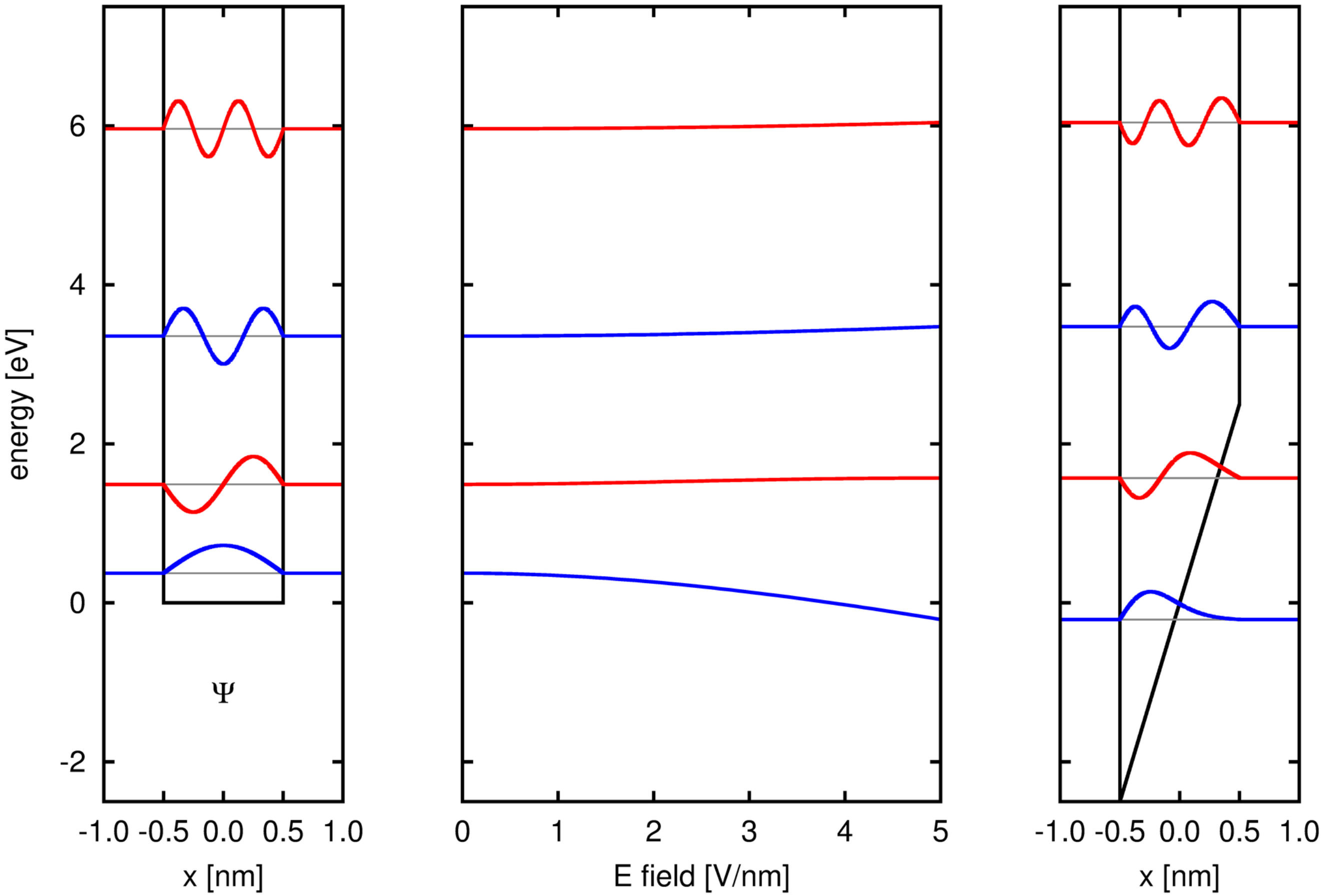


Nekonečně hluboká jáma v elektrickém poli - poruchová teorie

$$\psi_n^{(0)}(x) = \begin{cases} \sqrt{\frac{1}{a}} \cos \frac{n\pi x}{2a} & n \text{ liché} \\ \sqrt{\frac{1}{a}} \sin \frac{n\pi x}{2a} & n \text{ sudé} \end{cases} \qquad E_n^{(0)} = \frac{\pi^2 \hbar^2}{8ma^2} n^2$$

oprava energie 1. řádu

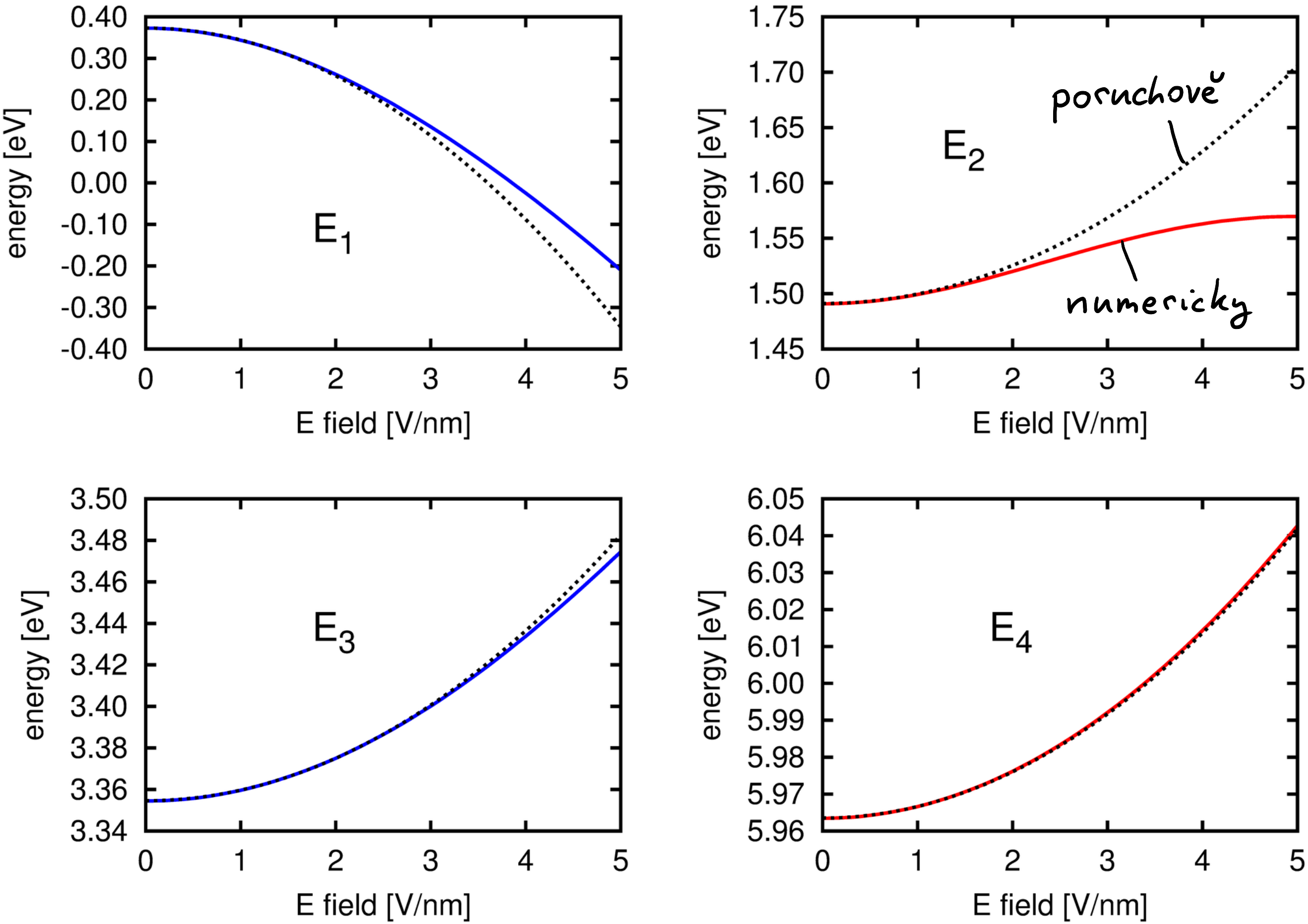
$$E_1^{(1)} = \langle \psi_1^{(0)} | \hat{W} | \psi_1^{(0)} \rangle = \int_{-a}^{+a} e\mathcal{E}x \, |\psi_1^{(0)}(x)|^2 dx = 0$$

oprava energie 2. řádu

$$E_1^{(2)} = -\sum_{n=2}^{\infty} \frac{|\langle \psi_n^{(0)} | \hat{W} | \psi_1^{(0)} \rangle|^2}{E_n^{(0)} - E_1^{(0)}}$$

maticový prvek $\hat{W}$ $\quad \langle \psi_n^{(0)} | \hat{W} | \psi_1^{(0)} \rangle = e\mathcal{E}a \frac{16}{\pi^2} \frac{n}{(n^2-1)^2}$ (sudé n)

$$E_1^{(2)} = -\sum_{\text{sudá } n \geq 2}^{\infty} \left[e\mathcal{E}a \frac{16}{\pi^2} \frac{n}{(n^2-1)^2} \right]^2 \frac{1}{\frac{\pi^2\hbar^2}{8ma^2}(n^2-1)} \quad \rightarrow \quad E_n \approx E_n^{(0)} + E_n^{(2)}$$



E1
E2
E3
E4
energy [eV]
E field [V/nm]
0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
-0.40
1.75
1.70
1.65
1.60
1.55
1.50
1.45
3.50
3.48
3.46
3.44
3.42
3.40
3.38
3.36
3.34
6.05
6.04
6.03
6.02
6.01
6.00
5.99
5.98
5.97
5.96
0
1
2
3
4
5
poruchově
numericky

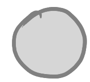
Atom vodíku v elektrickém poli - poruchová teorie pro degenerované stavy

- neporušené stavy

4× degenerovaná hladina s $n = 2$ $\qquad E_2 = -\frac{me^4}{2(4\pi\varepsilon_0)^2\hbar^2}\frac{1}{2^2}$

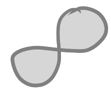
$$\psi_{2s} = \frac{1}{\sqrt{8\pi a^3}}\left(1 - \frac{r}{2a}\right)e^{-\frac{r}{2a}}$$

sféricky symetrický



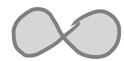
2s

$$\psi_{2p_x} = \frac{1}{\sqrt{8\pi a^3}}\frac{r}{2a}e^{-\frac{r}{2a}}\sin\vartheta\cos\varphi \quad \sim x e^{-r/2a}$$



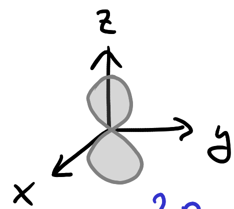
$2p_x$

$$\psi_{2p_y} = \frac{1}{\sqrt{8\pi a^3}}\frac{r}{2a}e^{-\frac{r}{2a}}\sin\vartheta\sin\varphi \quad \sim y e^{-r/2a}$$



$2p_y$

$$\psi_{2p_z} = \frac{1}{\sqrt{8\pi a^3}}\frac{r}{2a}e^{-\frac{r}{2a}}\cos\vartheta \quad \sim z e^{-r/2a}$$



$2p_z$

- porucha $\hat{W} = e\mathcal{E}\hat{z} = e\mathcal{E}r\cos\vartheta$

(elektrické pole s intenzitou $\mathcal{E}$ ve směru osy z)

- maticové prvky poruchy

nulové: $\langle 2s|\hat{W}|2s\rangle, \langle 2p_x|\hat{W}|2p_x\rangle, \langle 2p_y|\hat{W}|2p_y\rangle, \langle 2p_z|\hat{W}|2p_z\rangle$

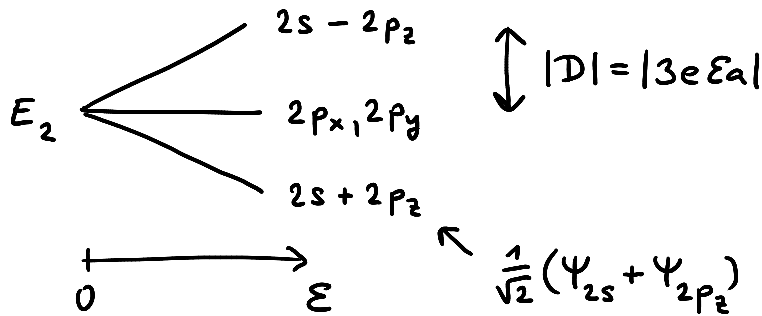
$\langle 2s|\hat{W}|2p_x\rangle, \langle 2s|\hat{W}|2p_y\rangle, \langle 2p_x|\hat{W}|2p_y\rangle, \langle 2p_x|\hat{W}|2p_z\rangle, \langle 2p_y|\hat{W}|2p_z\rangle$

nenulové pouze $\langle 2s|\hat{W}|2p_z\rangle = \langle 2p_z|\hat{W}|2s\rangle = 3e\mathcal{E}a = D$

$$\langle 2s|\hat{z}|2p_z\rangle = \frac{1}{8\pi a^3} \underbrace{\int_0^\infty dr\, r^2\left(1-\frac{r}{2a}\right) e^{-\frac{r}{2a}}\, r\, \frac{r}{2a}\, e^{-\frac{r}{2a}}}_{-18a^4 \text{ užitím } \int_0^\infty \xi^n e^{-\lambda\xi} d\xi = \frac{n!}{\lambda^{n+1}}} \underbrace{\int_0^\pi d\vartheta \sin\vartheta \cos^2\vartheta}_{\frac{2}{3}} \underbrace{\int_0^{2\pi} d\varphi}_{2\pi} = -3a$$

- oprava energie 1. řádu diagonalizací poruchy – štěpení $n=2$ hladiny

$$W = \begin{pmatrix} 0 & D & 0 & 0 \\ D & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \rightarrow$$



pořadí $2s$ $2p_z$ $2p_x$ $2p_y$