Strong quantum-confined Stark effect in germanium quantum-well structures on silicon

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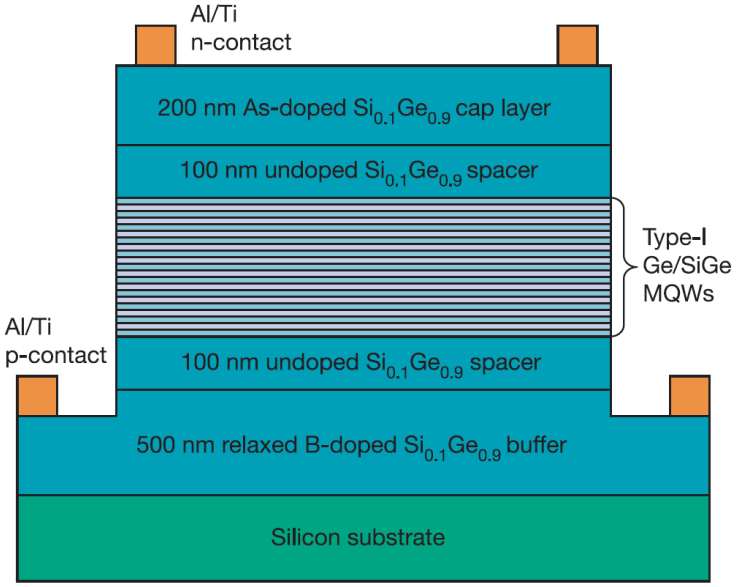
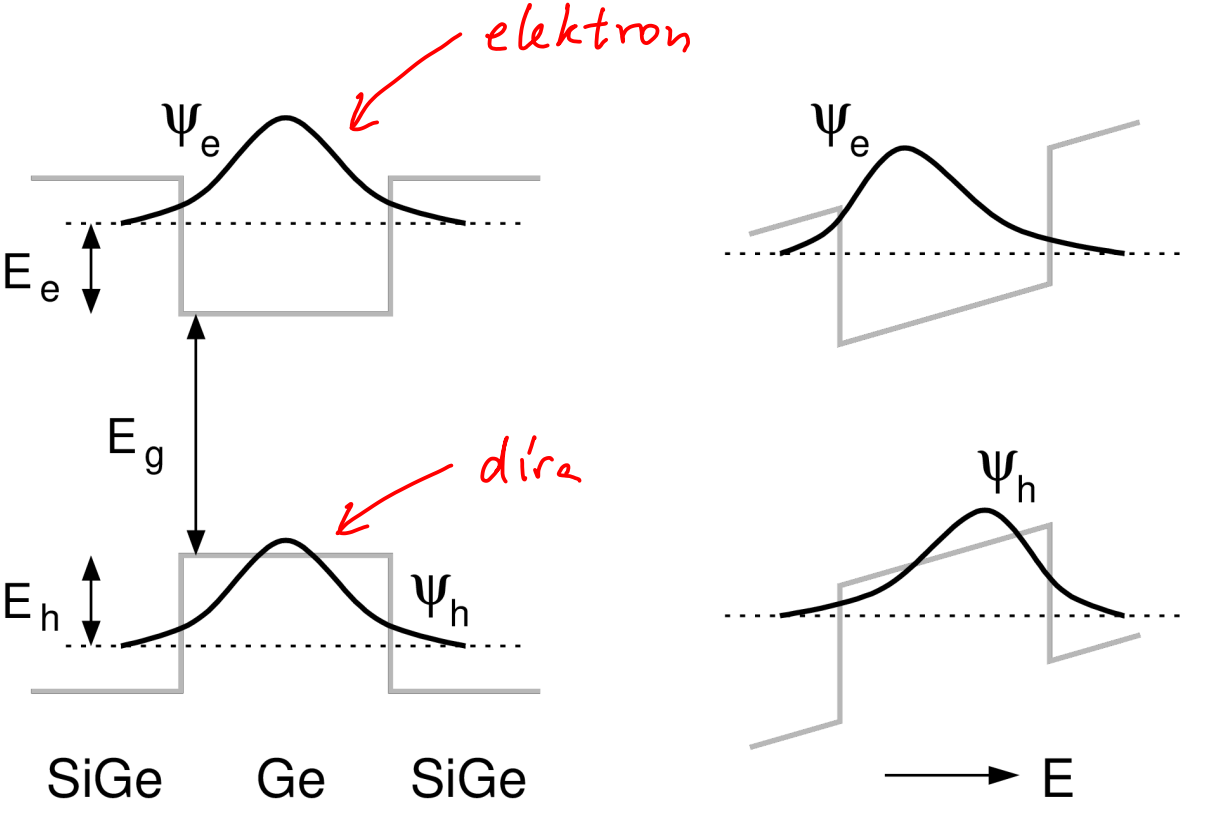


Figure 2 | **Schematic diagram of a p-i-n diode.** The cross-sectional view shows the structure of strained Ge/SiGe multiple quantum wells (MQWs) grown on silicon on relaxed SiGe direct buffers (not to scale). In the measurements, light from a monochromator is incident on the top surface (that is, in 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).



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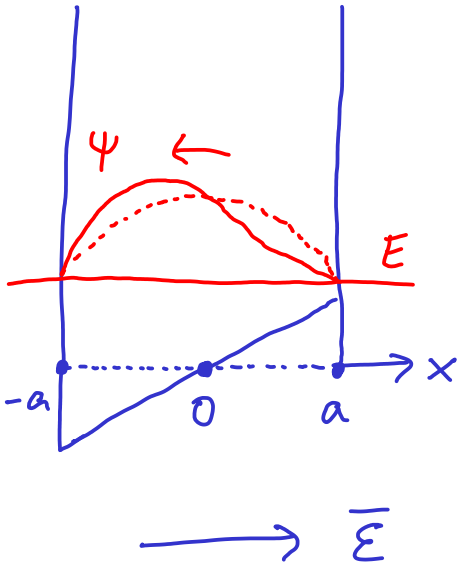
Kvantová jáma v elektrickém poli



1) zkušební vlnová funkce $\psi(x) = N\left(1+\lambda\frac{\pi x}{a}\right)\cos\frac{\pi x}{2a}$

posouvá vpravo pro $\lambda>0$; ψ bez pole

2) normování

$$\int_{-a}^{+a} |\psi(x)|^2 = 1 \quad \rightarrow \quad N$$

3) střední hodnota $\hat{H}$

$$\langle H\rangle = \int_{-a}^{+a} \psi^*(x)\left(-\frac{\hbar^2}{2m}\frac{d^2}{dx^2} + e\mathcal{E}x\right)\psi(x)\,dx$$

$$\approx \frac{\hbar^2}{2ma^2}\left(\frac{\pi^2}{4}+\pi^2\lambda^2\right) + e\mathcal{E}a\,\frac{2(\pi^2-6)}{3\pi}\lambda$$

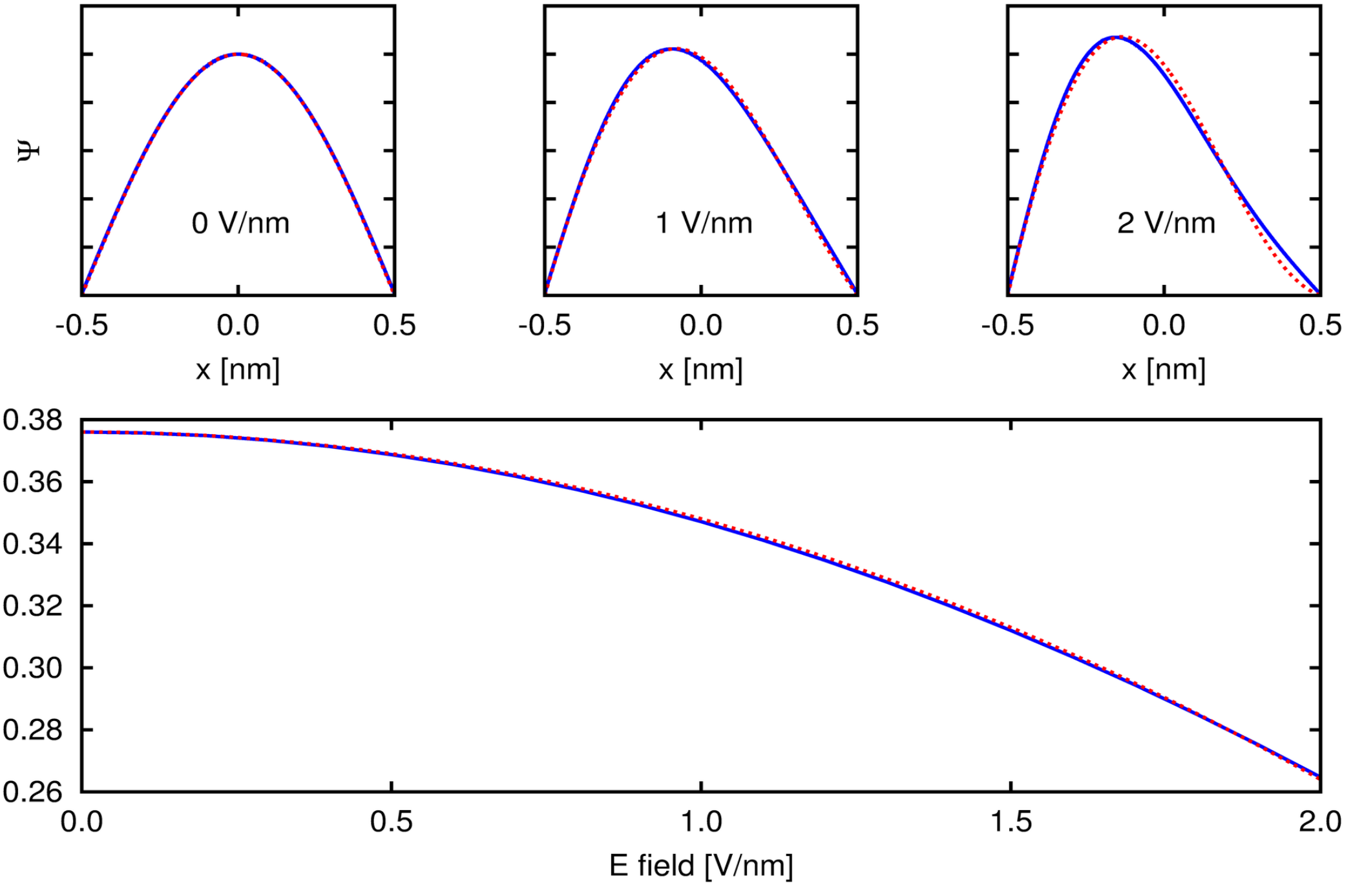
4) minimalizace

$$\frac{\partial\langle H\rangle}{\partial\lambda} = 0 \rightarrow \lambda \approx -\frac{\pi^2-6}{3\pi^3}\,\frac{e\mathcal{E}a}{\frac{\hbar^2}{2ma^2}}$$

posuv $\sim \mathcal{E}$

$$\langle H\rangle_{opt} \approx E_0 - \left(\frac{1}{3}-\frac{2}{\pi^2}\right)^2 \frac{(e\mathcal{E}a)^2}{\frac{\hbar^2}{2ma^2}}$$

snížení energie $\sim \mathcal{E}^2$


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]

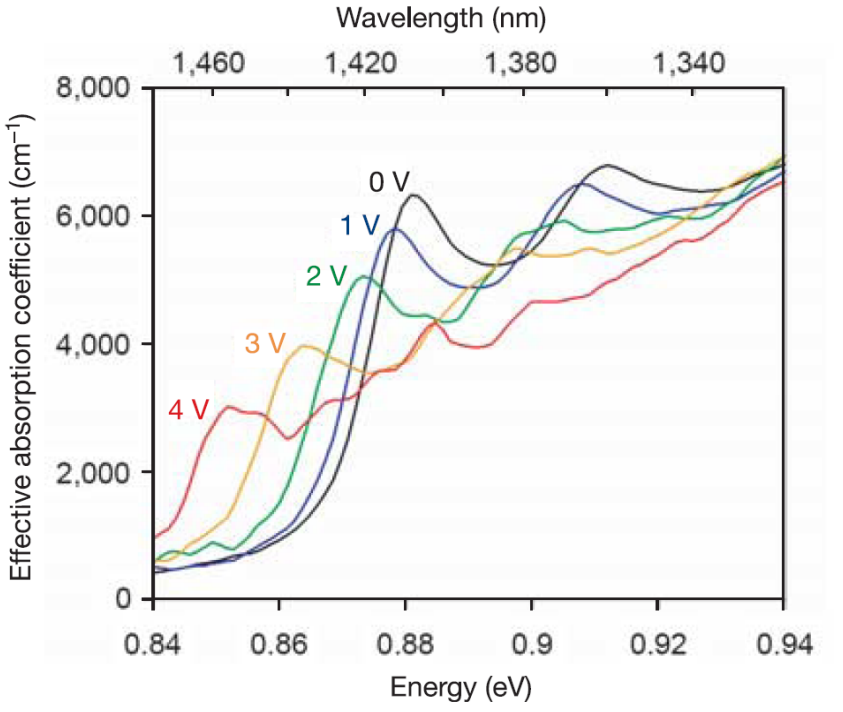
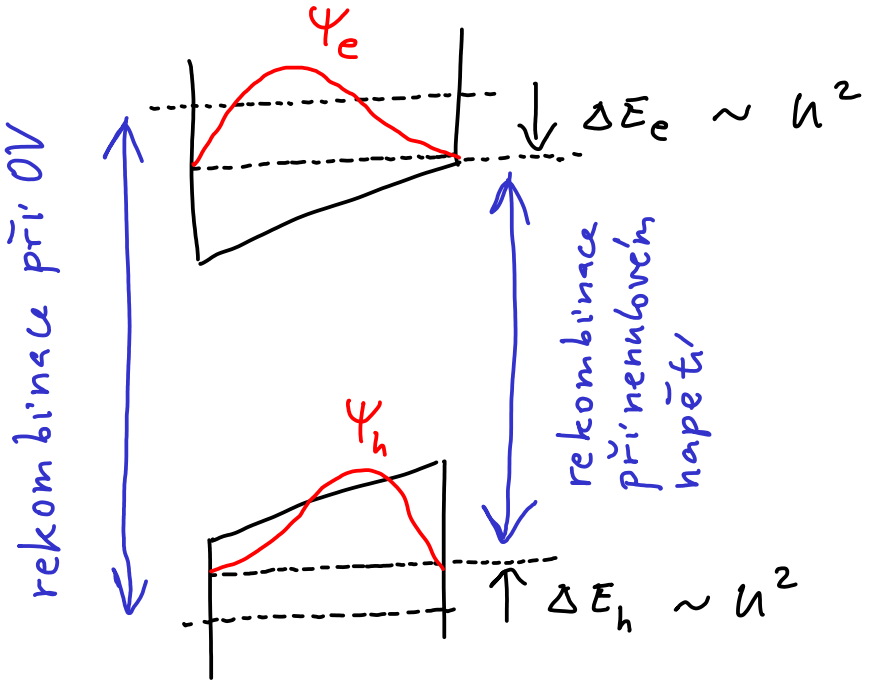


Figure 3 | Effective absorption coefficient spectra. Strong QCSE is observed at room temperature with reverse bias from zero to 4 V. The thickness for effective absorption coefficient calculations is based on the combination of Ge well and SiGe barrier thicknesses.



1) poloha absorpčního píku

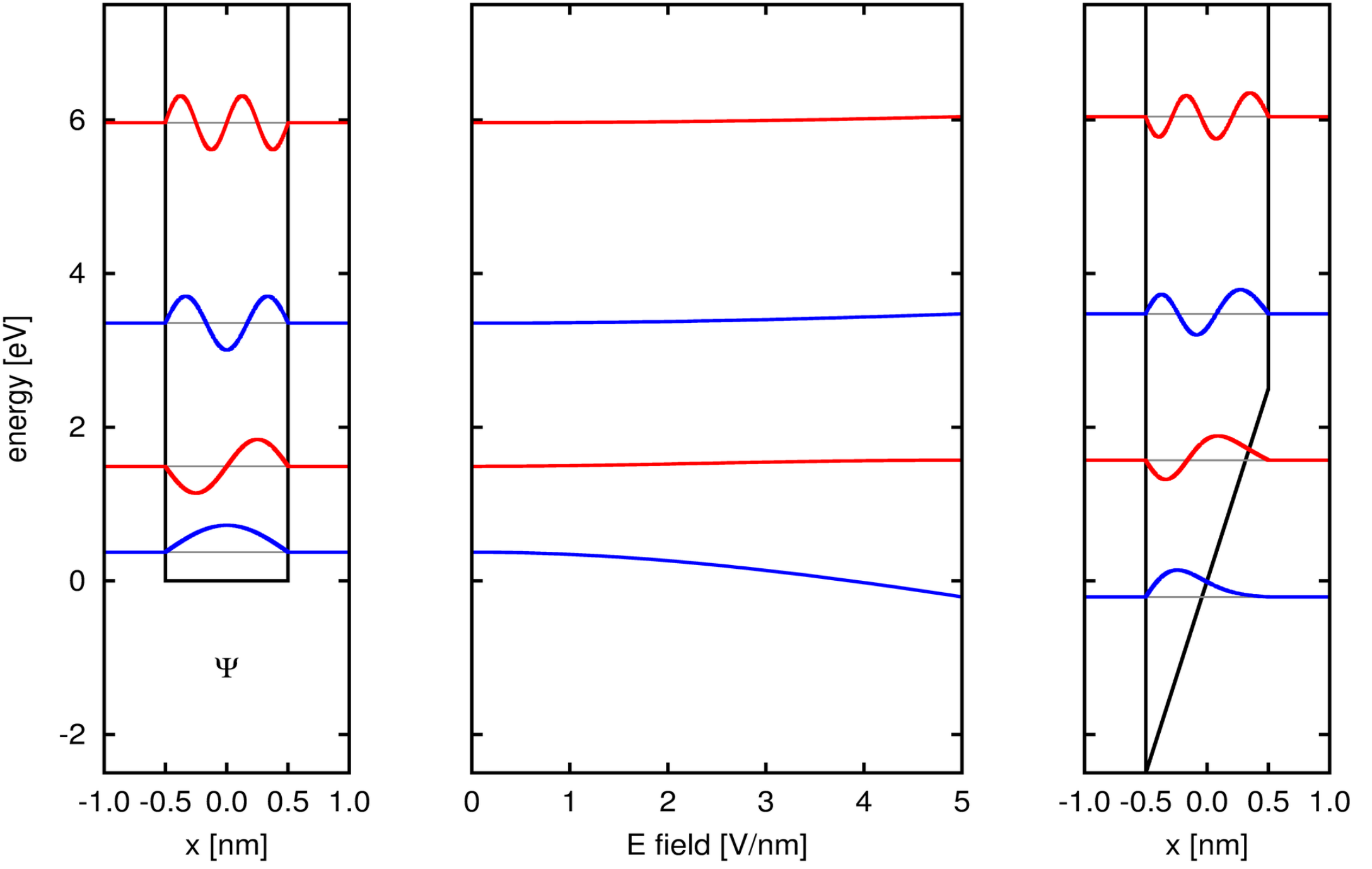
$$E_{rec} = E_{rec}(0V) - \alpha u^2$$

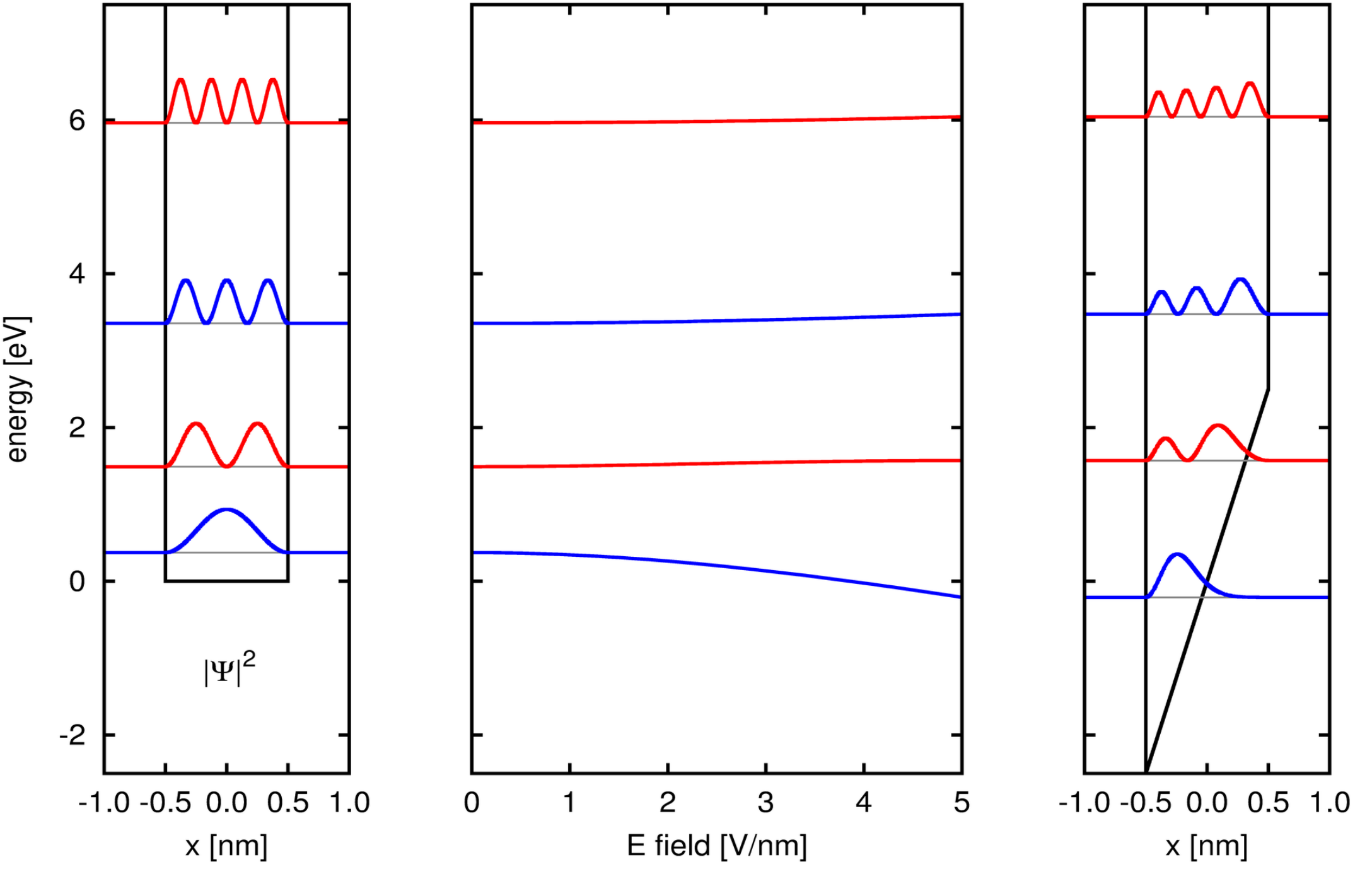
2) velikost absorpční struktury

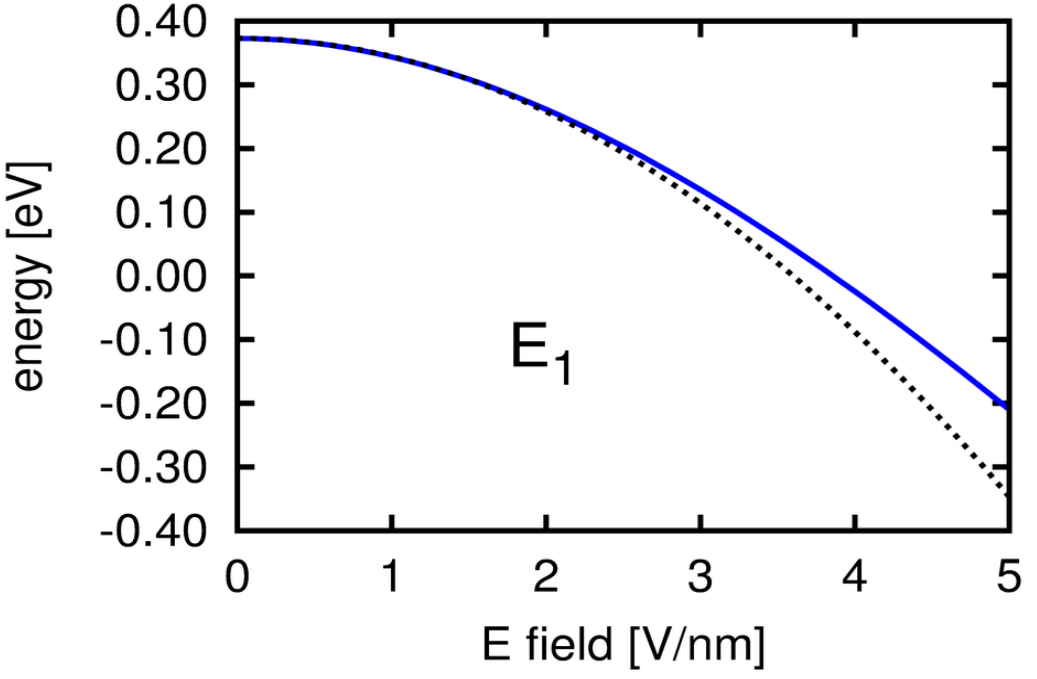
$$\sim \left| \int \Psi_e^*(x)\, \Psi_h(x)\, dx \right|^2 \sim \left| 1 - \frac{2(\pi^2-6)}{3} \lambda^2 \right|^2 \approx 1 - \frac{4(\pi^2-6)}{3} \lambda^2$$

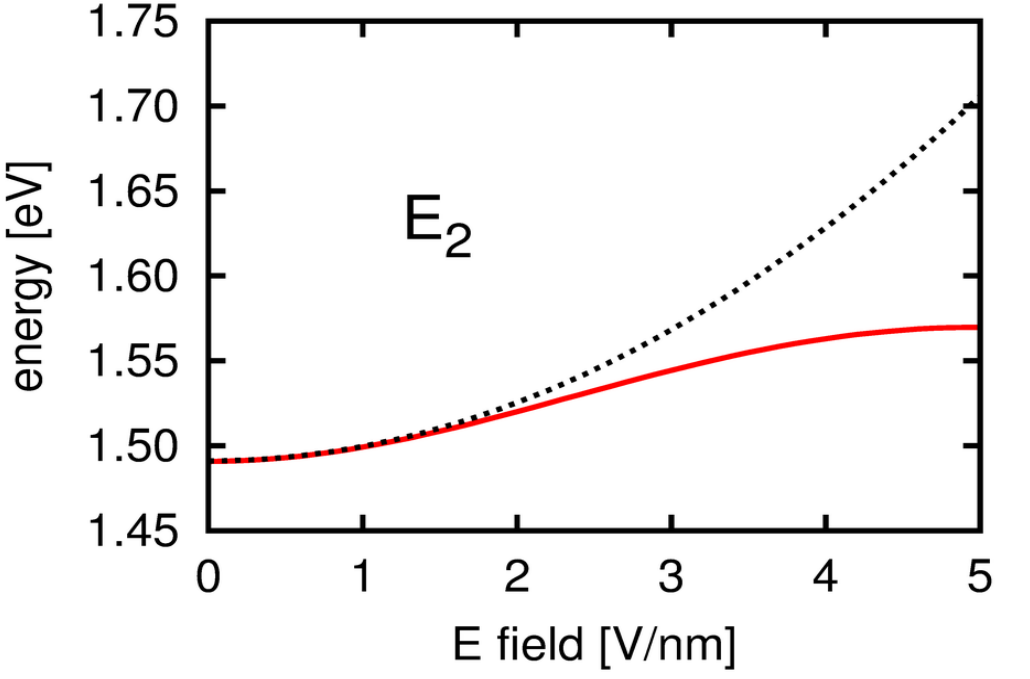
překryvový integrál

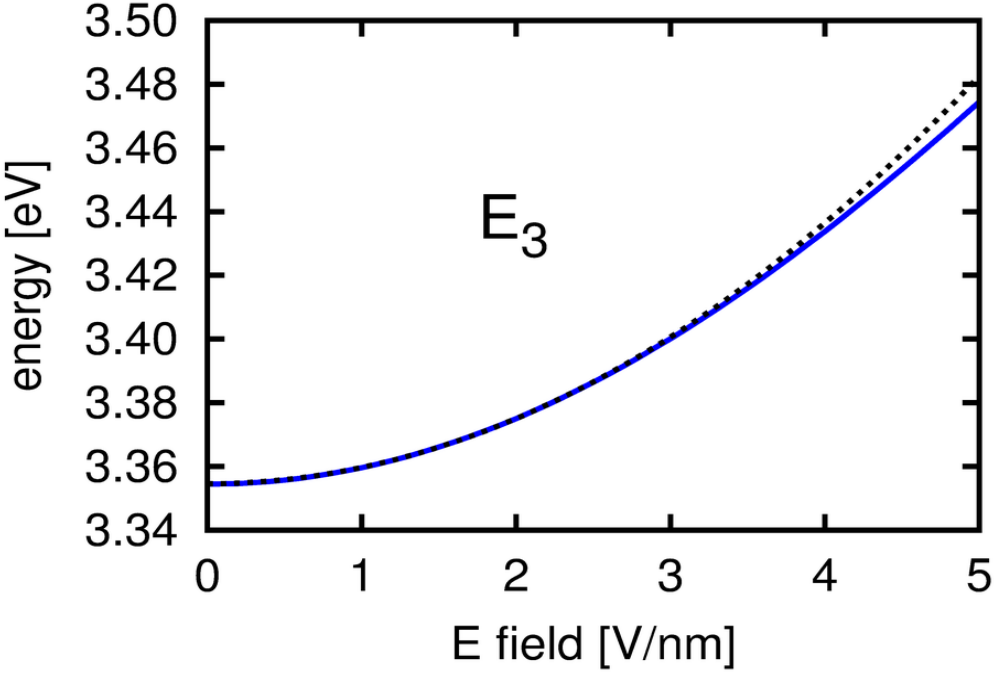
$\lambda \sim u \rightarrow$ úbytek absorpce $\sim u^2$

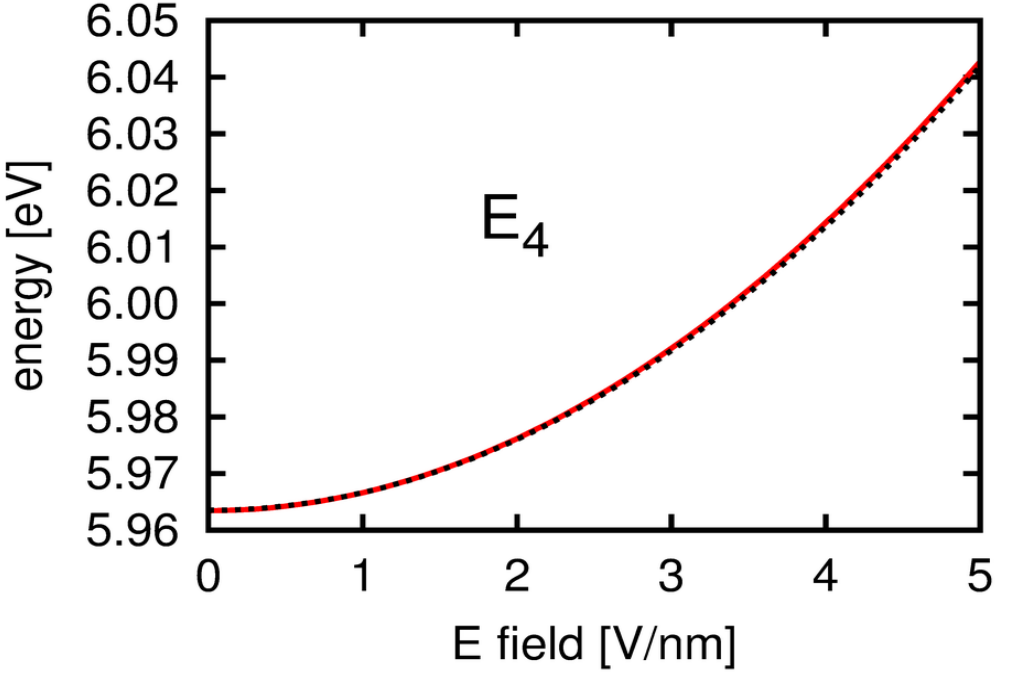

energy [eV]
6
4
2
0
-2
Ψ
-1.0 -0.5 0.0 0.5 1.0
x [nm]
0 1 2 3 4 5
E field [V/nm]
-1.0 -0.5 0.0 0.5 1.0
x [nm]

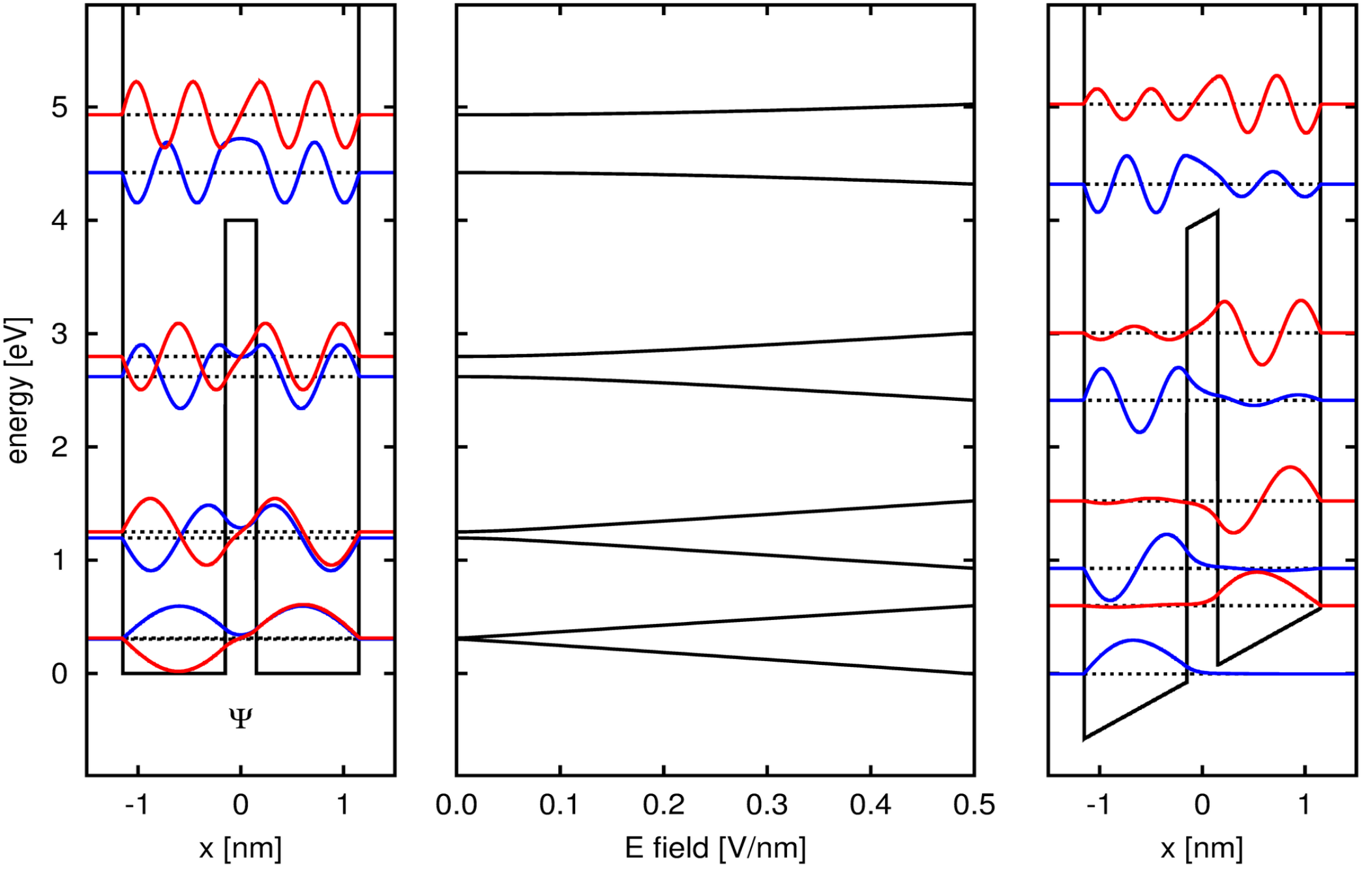

energy [eV]
6
4
2
0
-2
$|\Psi|^2$
-1.0 -0.5 0.0 0.5 1.0
x [nm]
0 1 2 3 4 5
E field [V/nm]
-1.0 -0.5 0.0 0.5 1.0
x [nm]

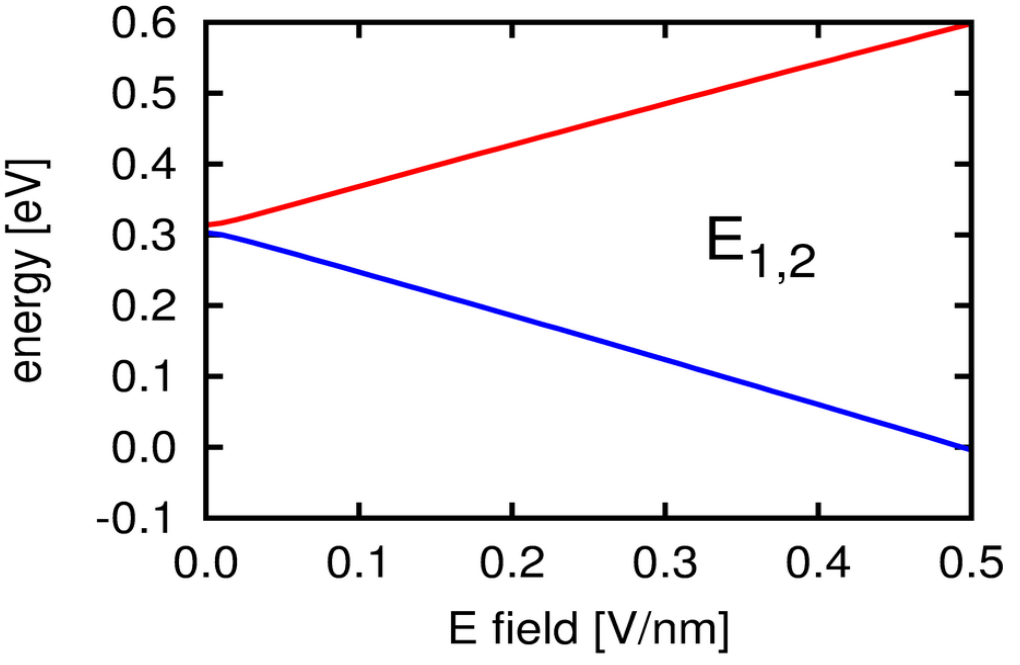

0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
-0.40
energy [eV]
E1
0
1
2
3
4
5
E field [V/nm]

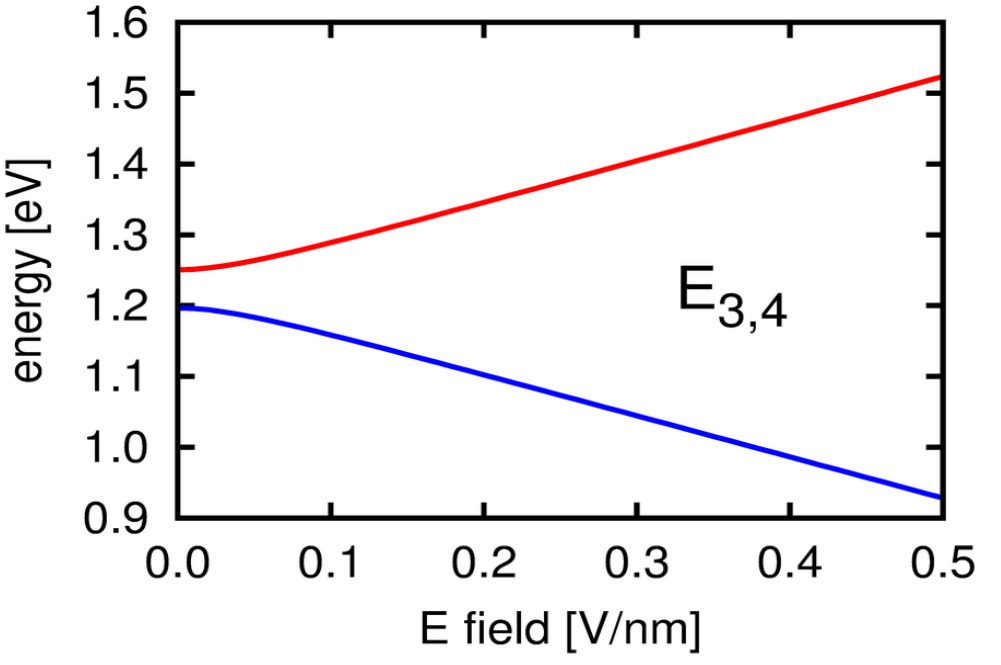

1.75
1.70
1.65
1.60
1.55
1.50
1.45
energy [eV]
E2
0
1
2
3
4
5
E field [V/nm]

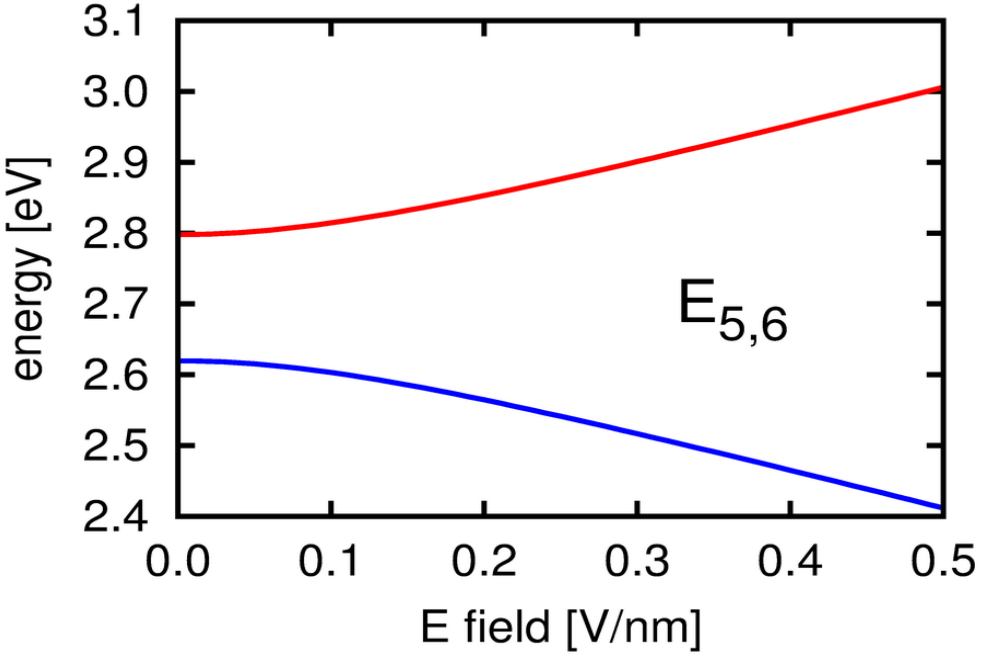

3.50
3.48
3.46
3.44
3.42
3.40
3.38
3.36
3.34
energy [eV]
E3
0
1
2
3
4
5
E field [V/nm]

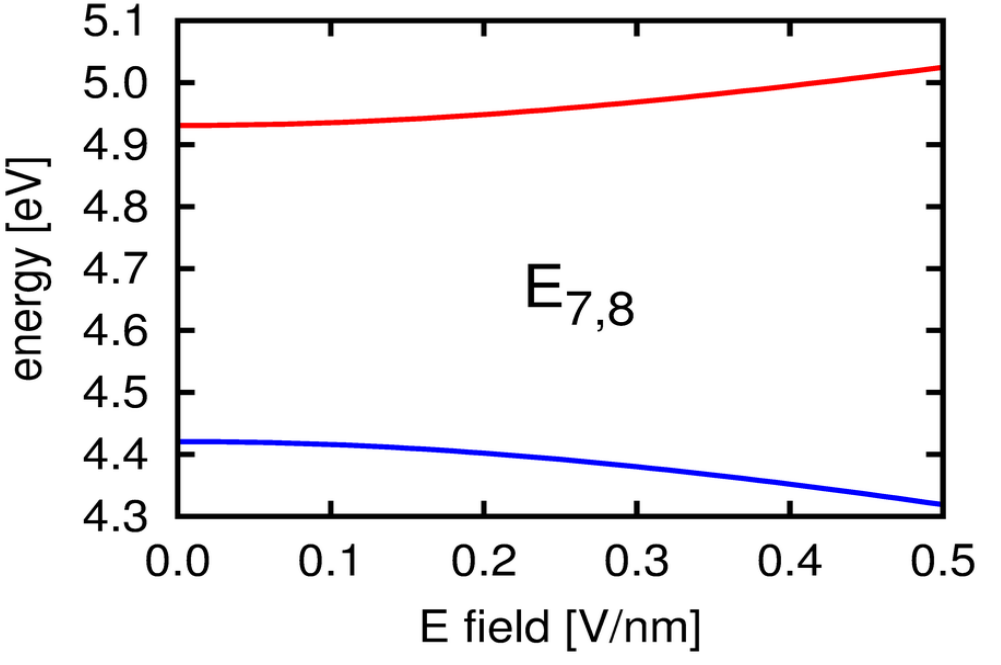

6.05
6.04
6.03
6.02
6.01
6.00
5.99
5.98
5.97
5.96
energy [eV]
E4
0
1
2
3
4
5
E field [V/nm]

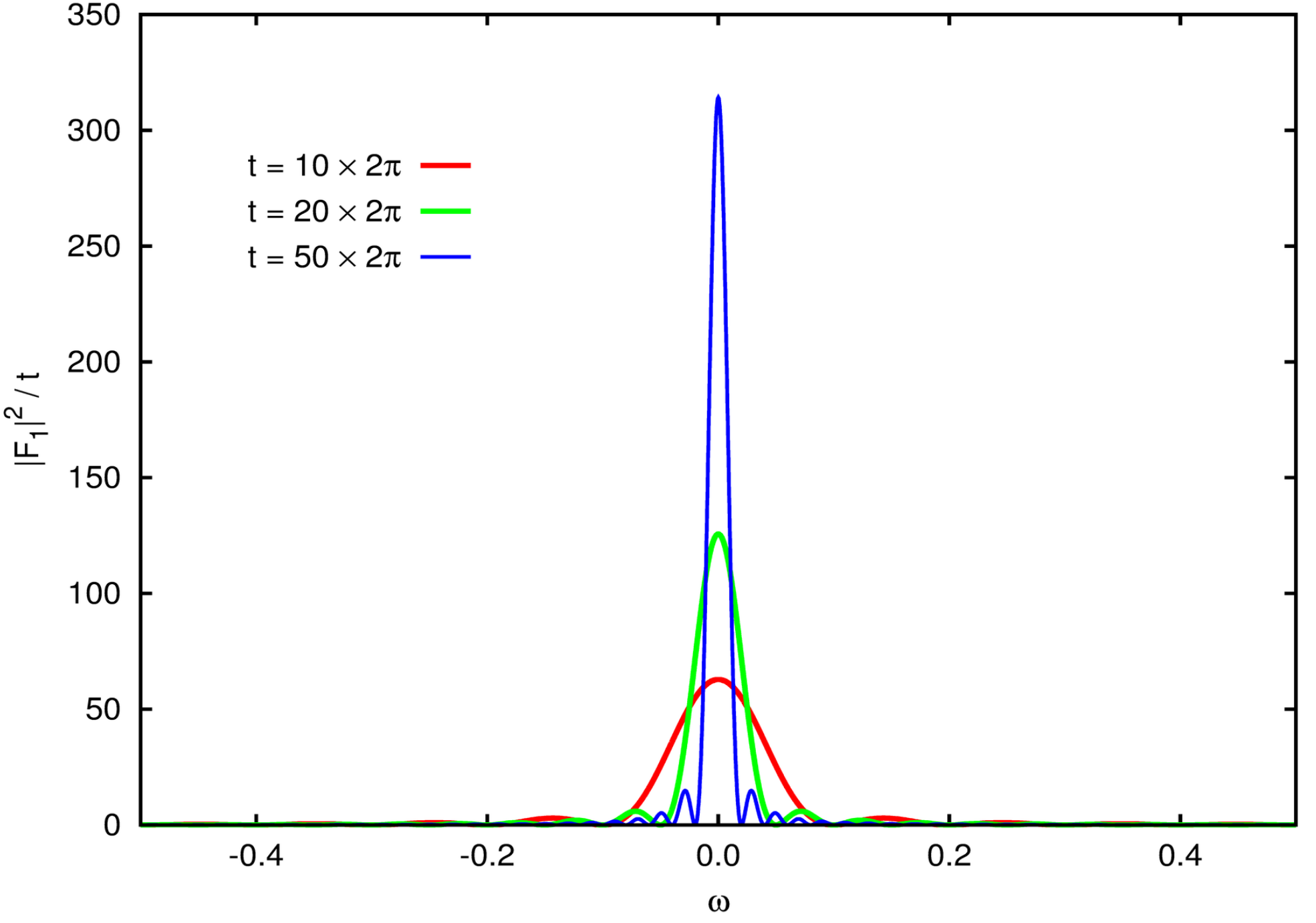

energy [eV]
5
4
3
2
1
0
Ψ
-1
0
1
x [nm]
0.0
0.1
0.2
0.3
0.4
0.5
E field [V/nm]
-1
0
1
x [nm]

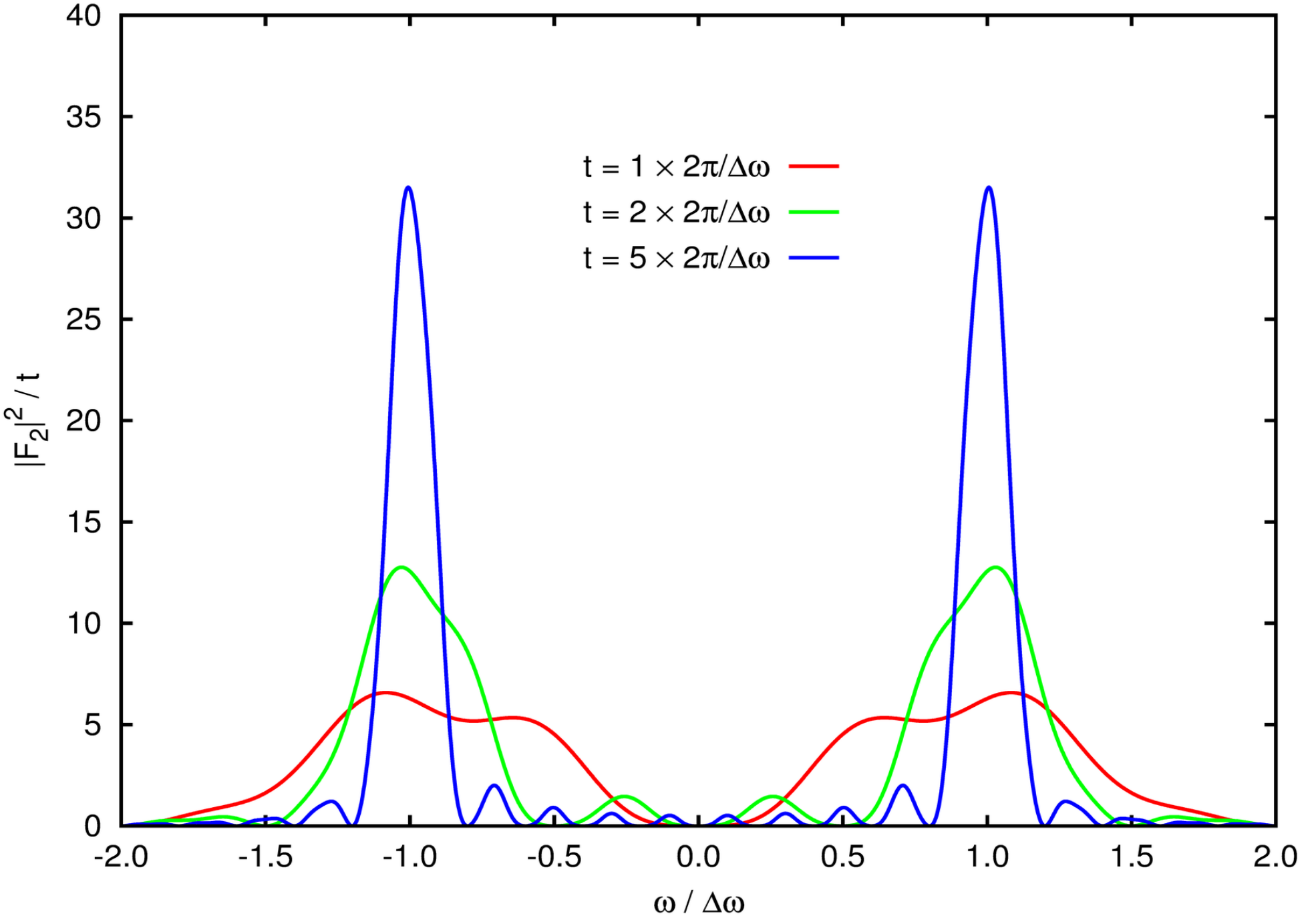

energy [eV]
E field [V/nm]
$E_{1,2}$

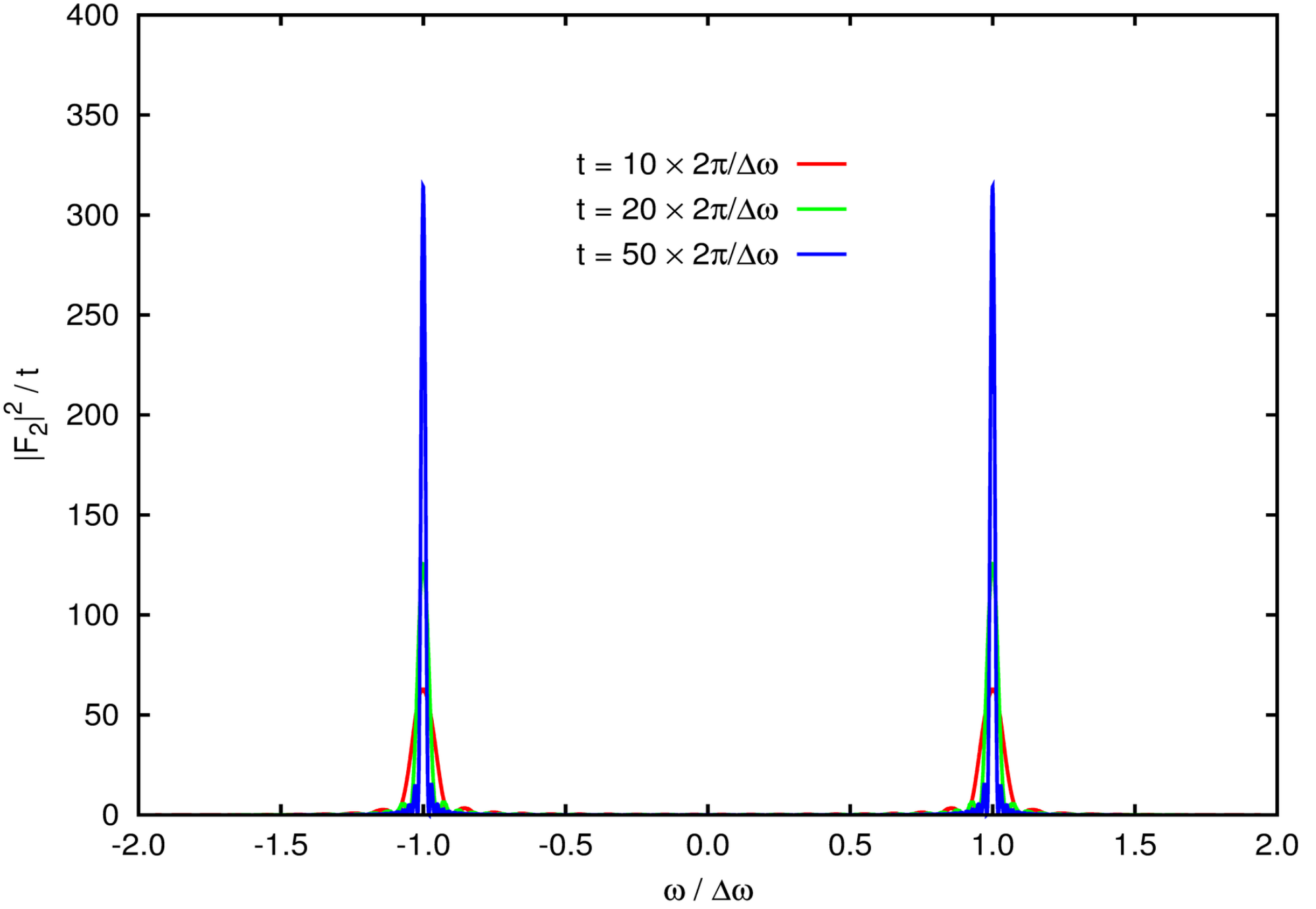

energy [eV]
E field [V/nm]
$E_{3,4}$

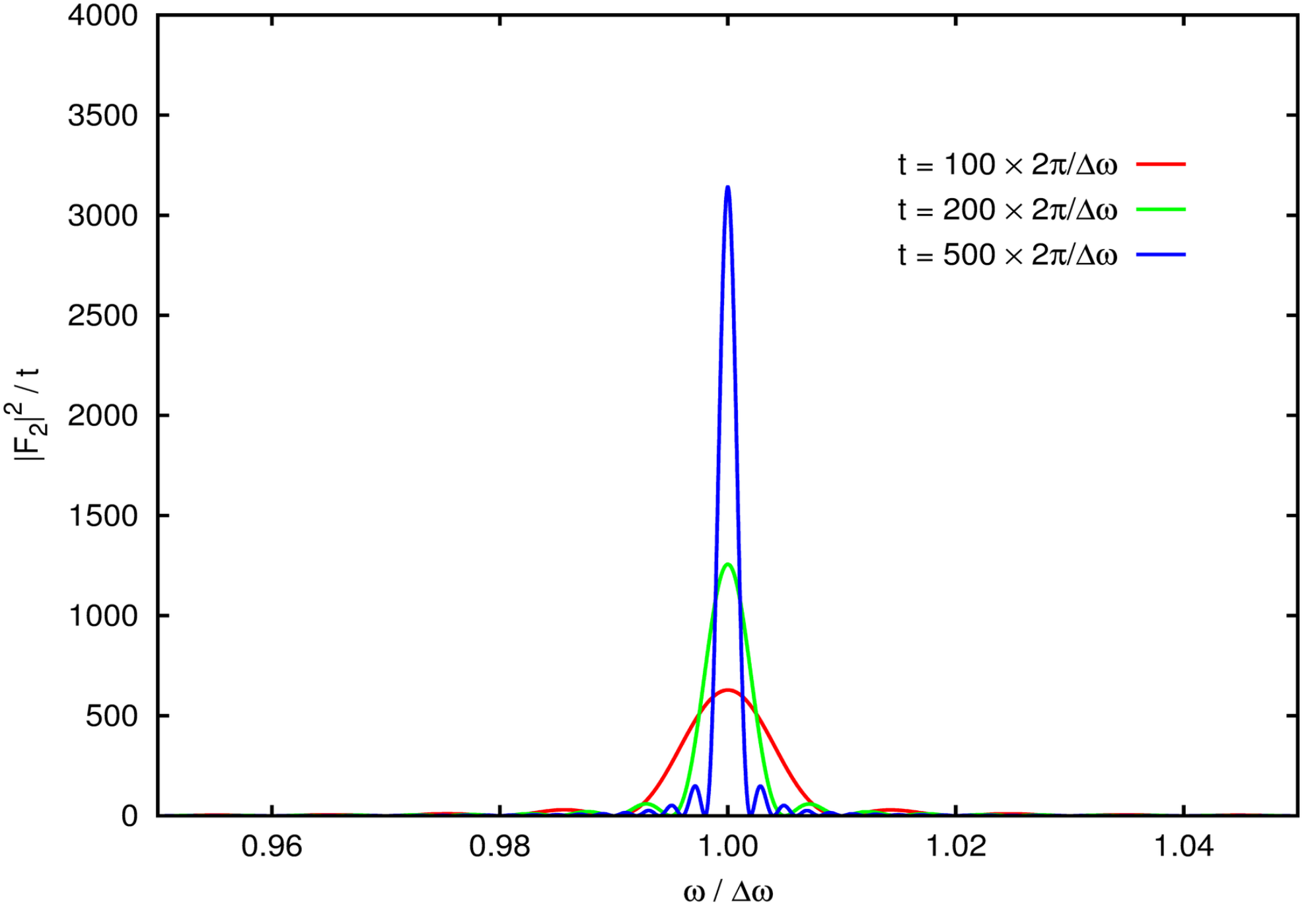

energy [eV]
E field [V/nm]
$E_{5,6}$

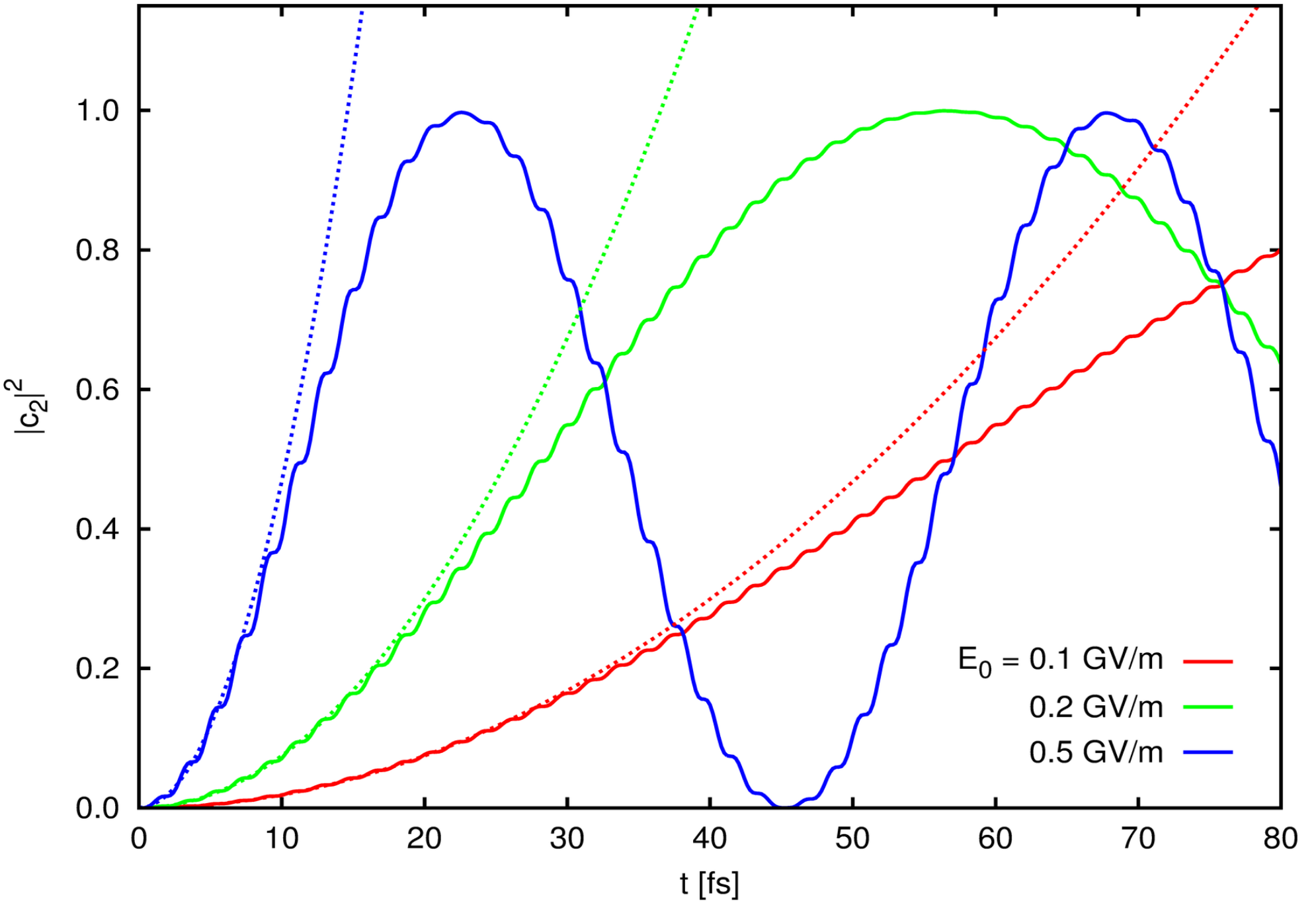

energy [eV]
E field [V/nm]
$E_{7,8}$

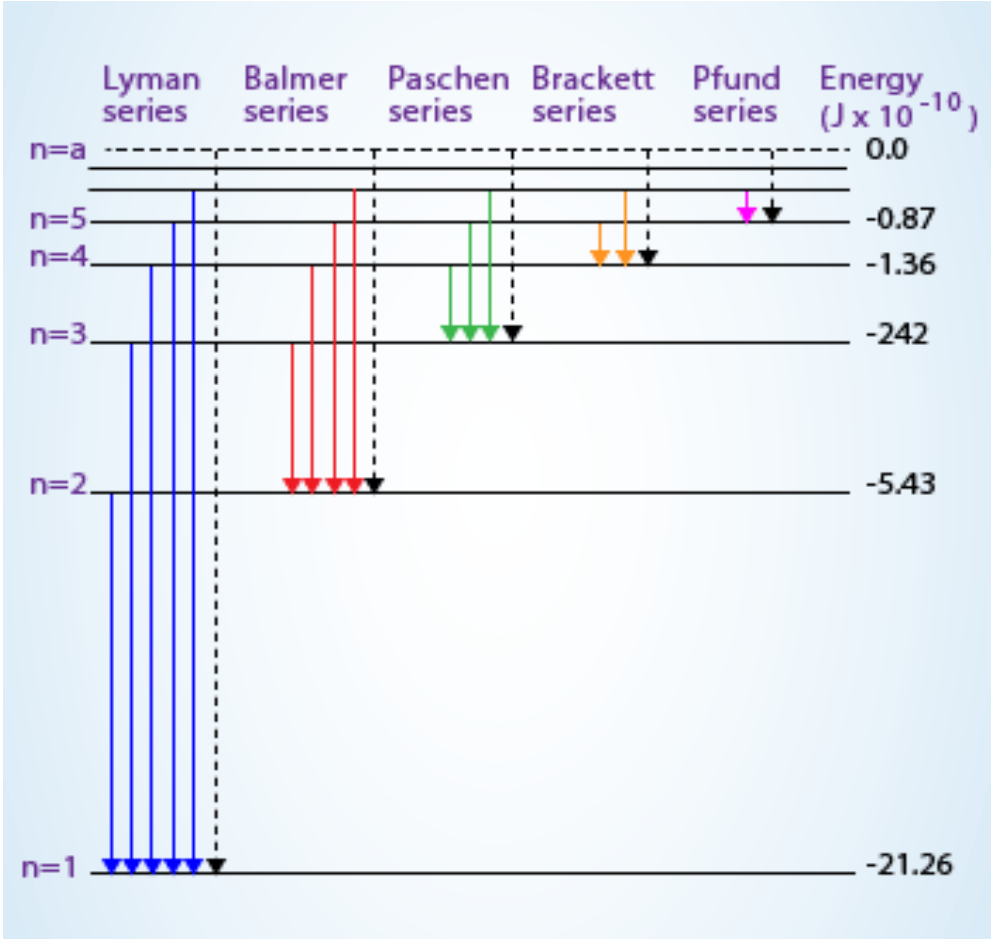

350
300
250
200
150
100
50
0
-0.4
-0.2
0.0
0.2
0.4
ω
$|F_1|^2 / t$
t = 10 × 2π
t = 20 × 2π
t = 50 × 2π

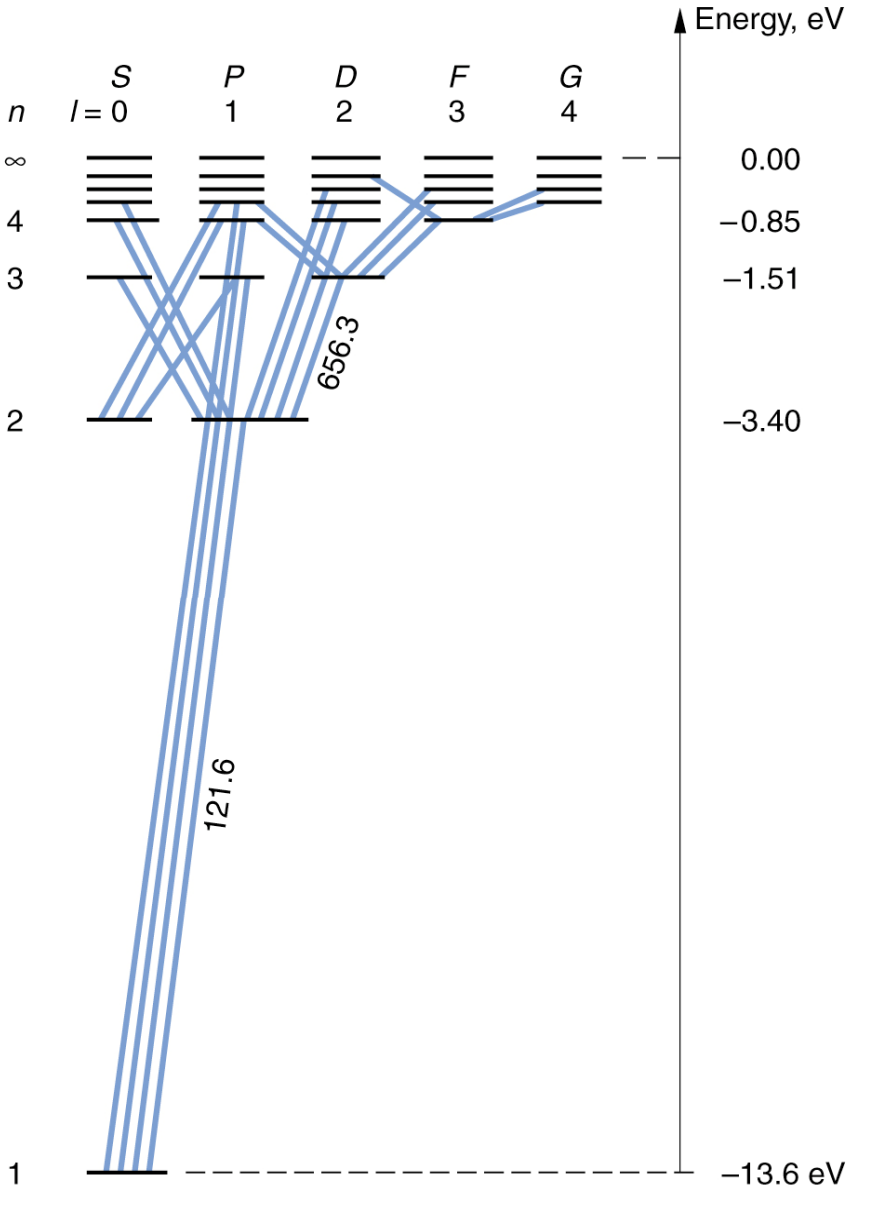

40
35
30
25
20
15
10
5
0
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
$|F_2|^2 / t$
$\omega / \Delta\omega$
$t = 1 \times 2\pi/\Delta\omega$
$t = 2 \times 2\pi/\Delta\omega$
$t = 5 \times 2\pi/\Delta\omega$


400
350
300
250
200
150
100
50
0
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
$|F_2|^2$ / t
ω / Δω
t = 10 × 2π/Δω
t = 20 × 2π/Δω
t = 50 × 2π/Δω


4000
3500
3000
2500
2000
1500
1000
500
0
0.96
0.98
1.00
1.02
1.04
|F2|2 / t
ω / Δω
t = 100 × 2π/Δω
t = 200 × 2π/Δω
t = 500 × 2π/Δω


1.0
0.8
0.6
0.4
0.2
0.0
$|c_2|^2$
0
10
20
30
40
50
60
70
80
t [fs]
E_0 = 0.1 GV/m
0.2 GV/m
0.5 GV/m


Lyman series
Balmer series
Paschen series
Brackett series
Pfund series
Energy (J x 10^-10)
n=a
n=5
n=4
n=3
n=2
n=1
0.0
-0.87
-1.36
-242
-5.43
-21.26


Energy, eV
S
P
D
F
G
n
l = 0
1
2
3
4
∞
0.00
–0.85
–1.51
–3.40
–13.6 eV
656.3
121.6

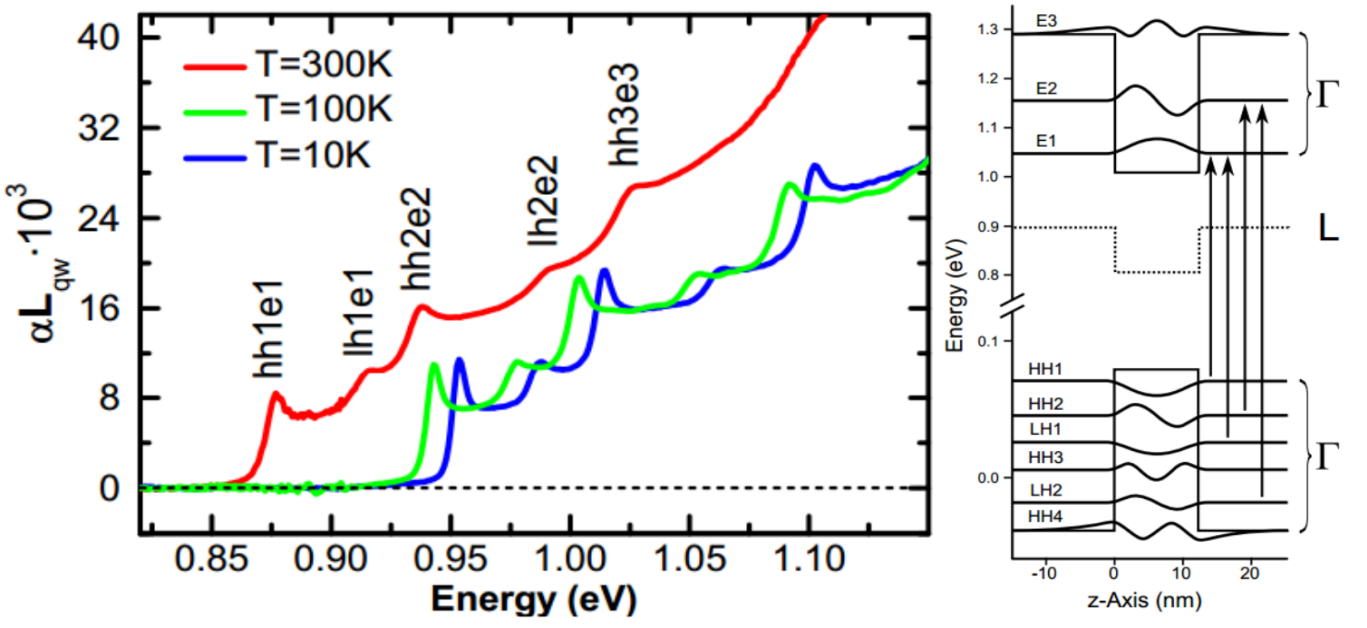


Figure 2. Linear absorption spectrum of the Ge multiple quantum well structure. A schematic sketch of the electronic structure according to [18] is given on the right-hand side.