Investigating valley degeneracy in AlAs two dimensional systems and split-gate structures

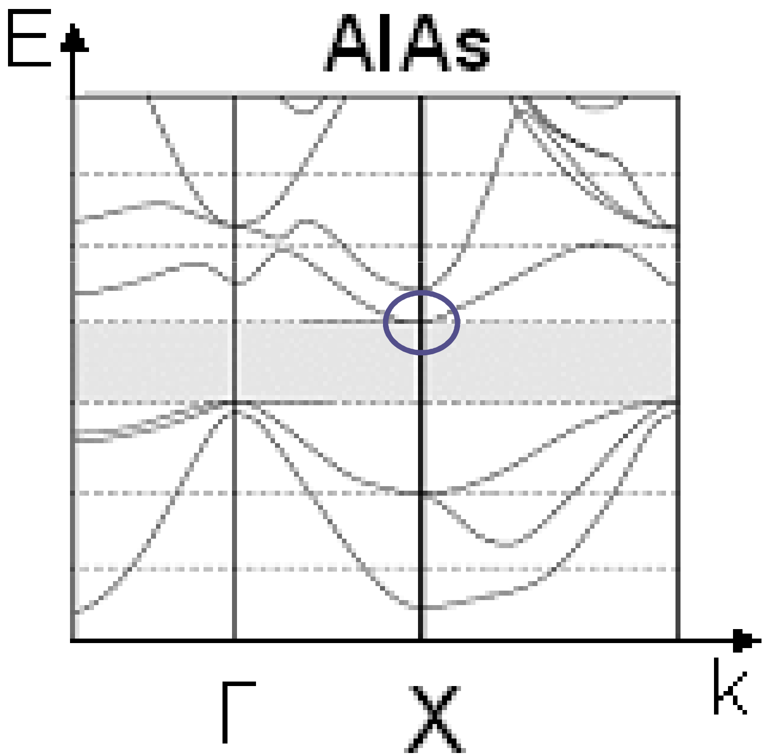
Claudius Knaak

Outline

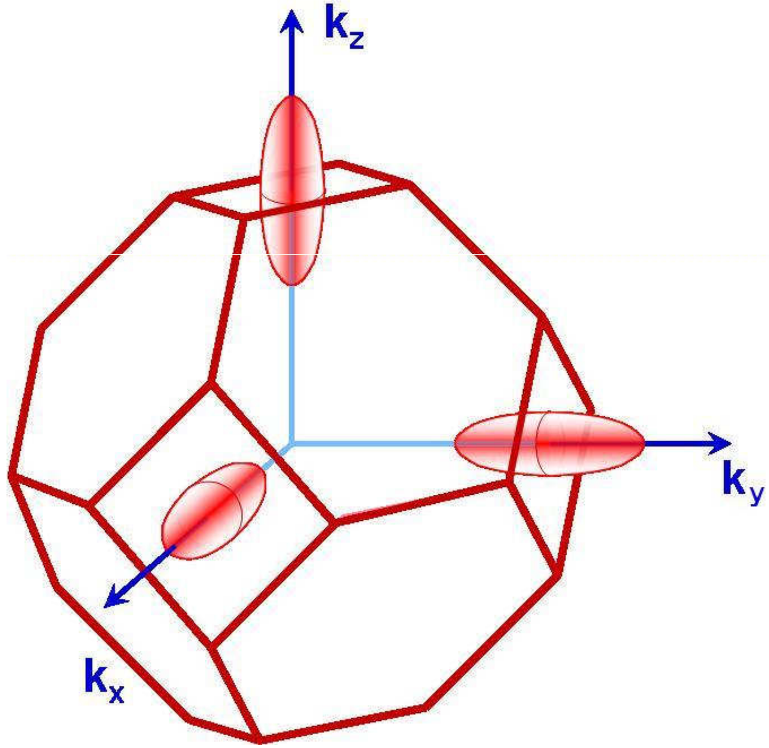
- Introduction to 2D AlAs
- Optimization
  - (001) AlAs
  - (110) AlAs
- Gate induced strain in AlAs
  - Breaking valley degeneracy
  - Strain simulations with nextnano^3

Valley degeneracy

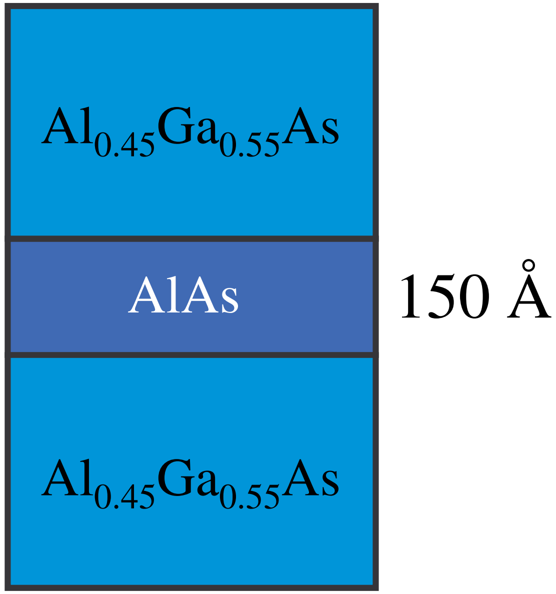
AlAs : indirect bandgap



Leads to a bulk valley degeneracy:



Confinement in AlAs (001)

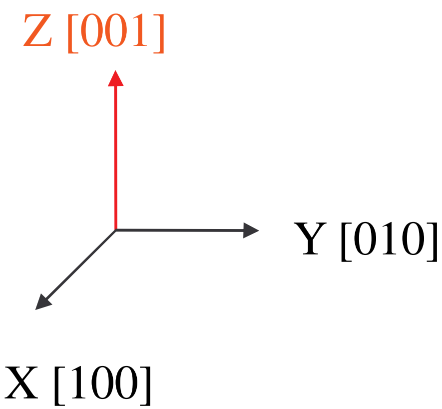


Confinement energy:

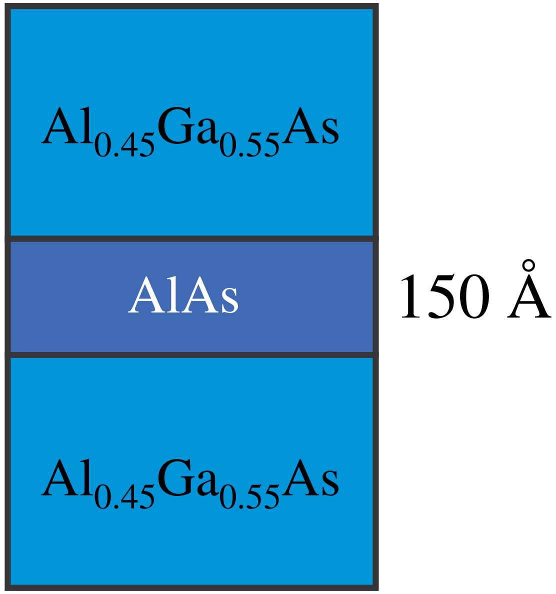
$$E_{con} = \frac{\hbar^2 k^2}{2m^*} = \frac{\hbar^2 \pi^2}{2m^* W^2}$$

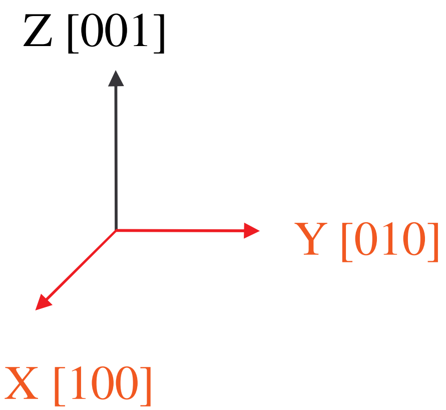
$$\frac{m_H^*}{m_L^*} = 5.8$$

$E_{con}\ (m_H) \approx 2$ meV



Kinetic energy, AlAs (001)

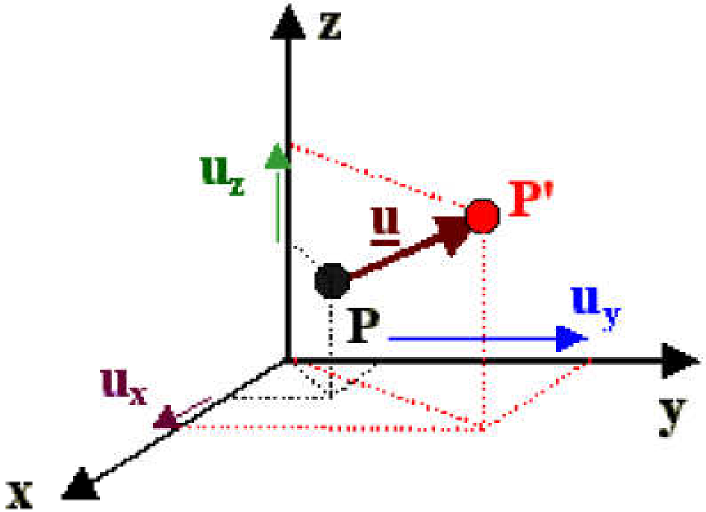




Kinetic energy:

$$E_{kin} = \frac{\hbar^2}{2}\left(\frac{k_x^2}{m_x^*} + \frac{k_y^2}{m_y^*}\right)$$

Definition of strain



$$\epsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

$\underline{u}$ = displacement vector

Uniaxial strain and energy:

$$\Delta_x = \Xi_u \epsilon_{xx}$$

$$\Delta_y = \Xi_u \epsilon_{yy}$$

$$\Delta_z = \Xi_u \epsilon_{zz}$$

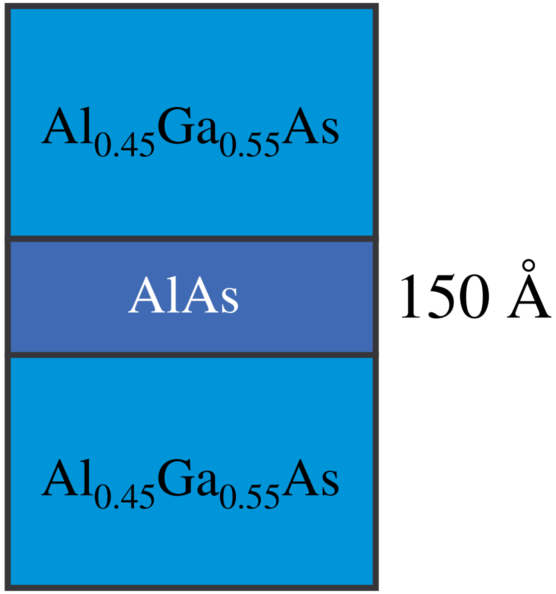
Strain splitting:

$$\Delta = (\Delta_z - \Delta_x)$$

Ξ_u = uniaxial deformation potential

Image : www.tf.uni-kiel.de/matwis/amat

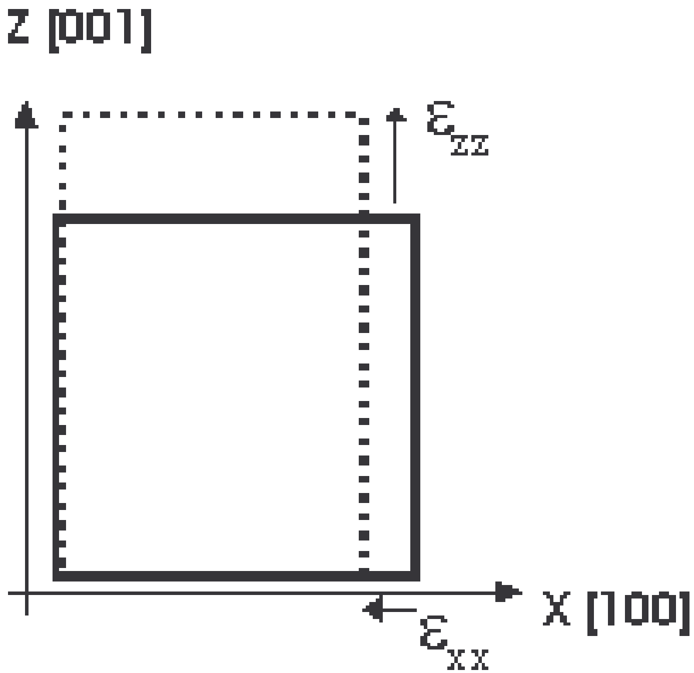
Strain in AlAs (001)



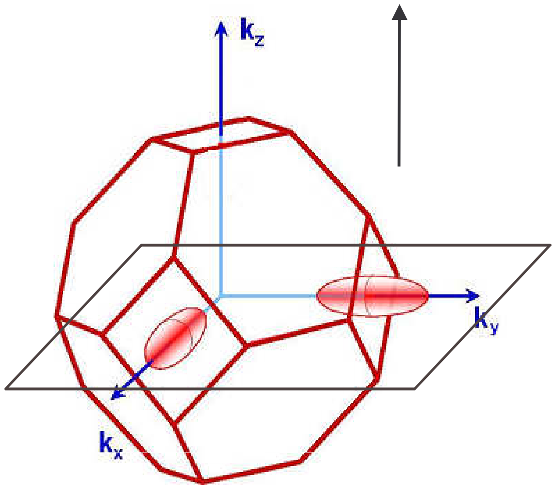
Lattice constants: AlAs > $Al_{0.45}Ga_{0.55}As$

(0.26% @ T = 4K)

$$\Delta = (\Delta_z - \Delta_x) \approx 12 \text{ meV}$$



Energy, AlAs (001)



Expectation: double valley system, isotropic conductance

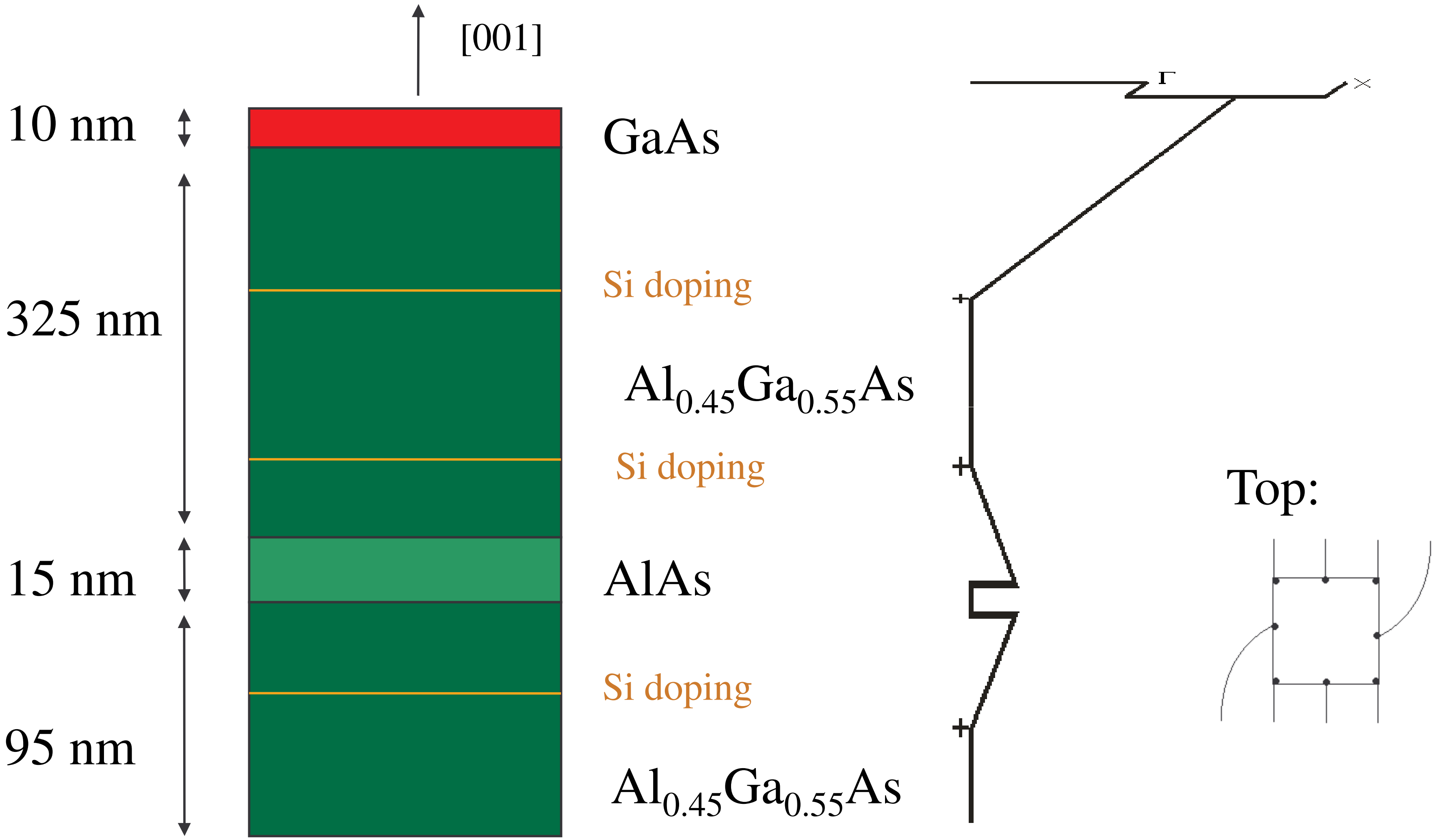
$$E_i = E_{kin} + E_{con} + \Delta_i$$

$$E_x = \frac{\hbar^2}{2}\left(\frac{k_x^2}{m_H} + \frac{k_y^2}{m_L}\right) + \frac{\hbar^2\pi^2}{2m_L W^2} + \Delta_x$$

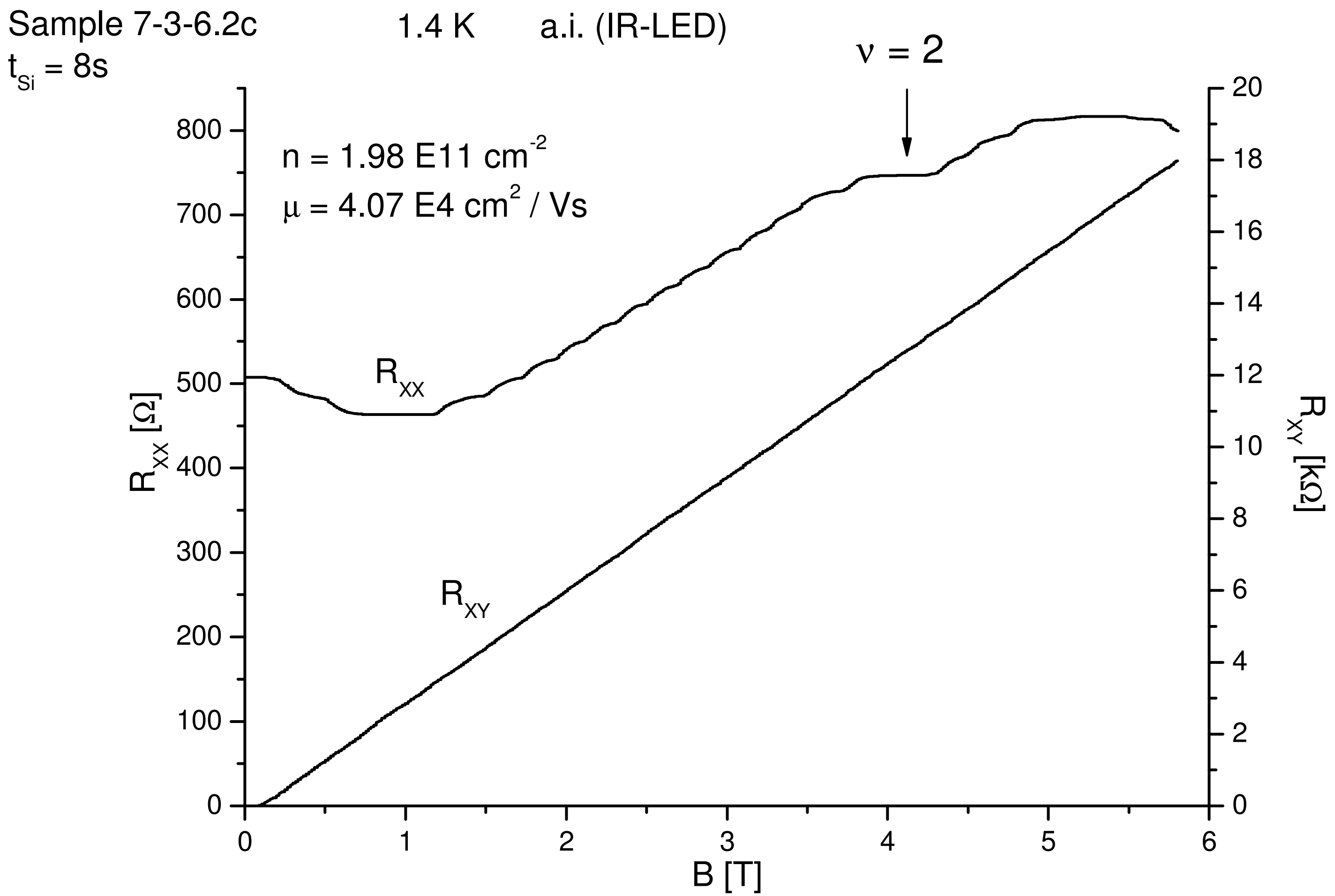
$$E_y = \frac{\hbar^2}{2}\left(\frac{k_x^2}{m_L} + \frac{k_y^2}{m_H}\right) + \frac{\hbar^2\pi^2}{2m_L W^2} + \Delta_y$$

$$E_z = \frac{\hbar^2}{2m_L}\left(k_x^2 + k_y^2\right) + \frac{\hbar^2\pi^2}{2m_H W^2} + \Delta_z$$

Measurements - sample structure AlAs (001)

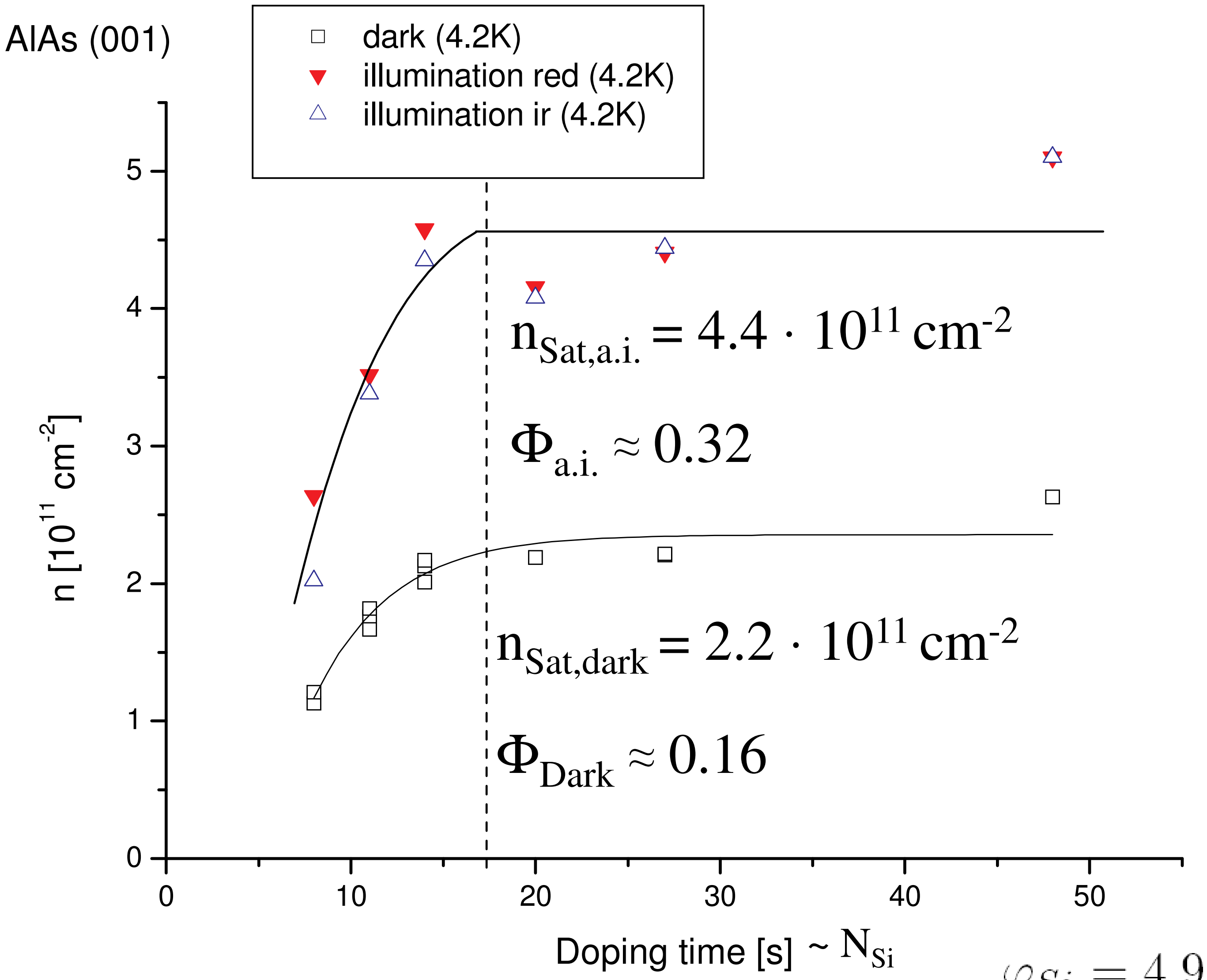


AlAs (001), VdP measurement



$$\frac{R_{xy}}{B} = \frac{1}{n \cdot e}$$

AlAs (001) QW - density dark and a.i.



Doping efficiency:

$$\Phi = \frac{N_{active}}{N_{Si}}$$

Active donors:

$$N_{active} = \frac{n_{Sat}}{2}$$

Si donors:

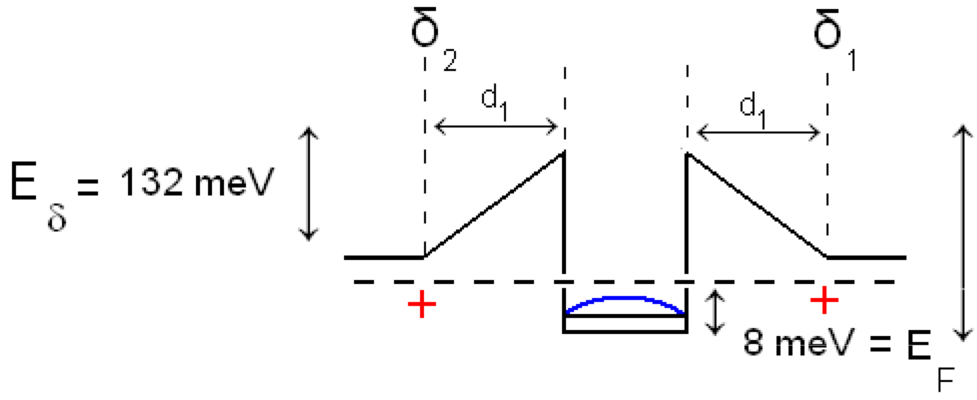
$$N_{Si} = \varphi_{Si} \cdot t_{Si}$$

$$\varphi_{Si} = 4.94 \cdot 10^{10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

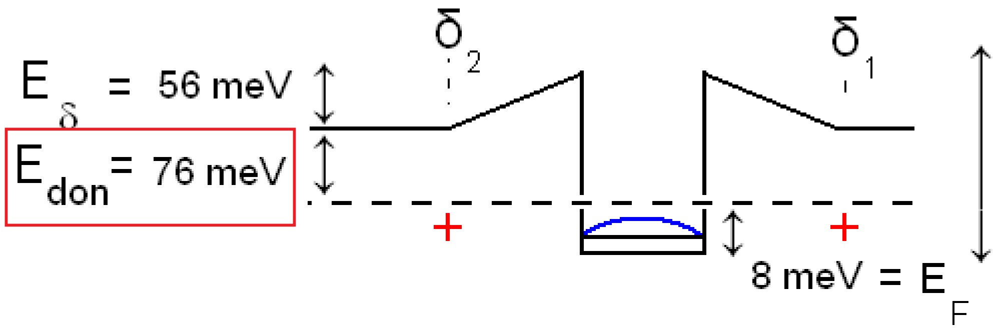
AlAs (001) QW - Donor binding energy

a.i.: expected $n = 4.4 \cdot 10^{11}\ cm^{-2}$

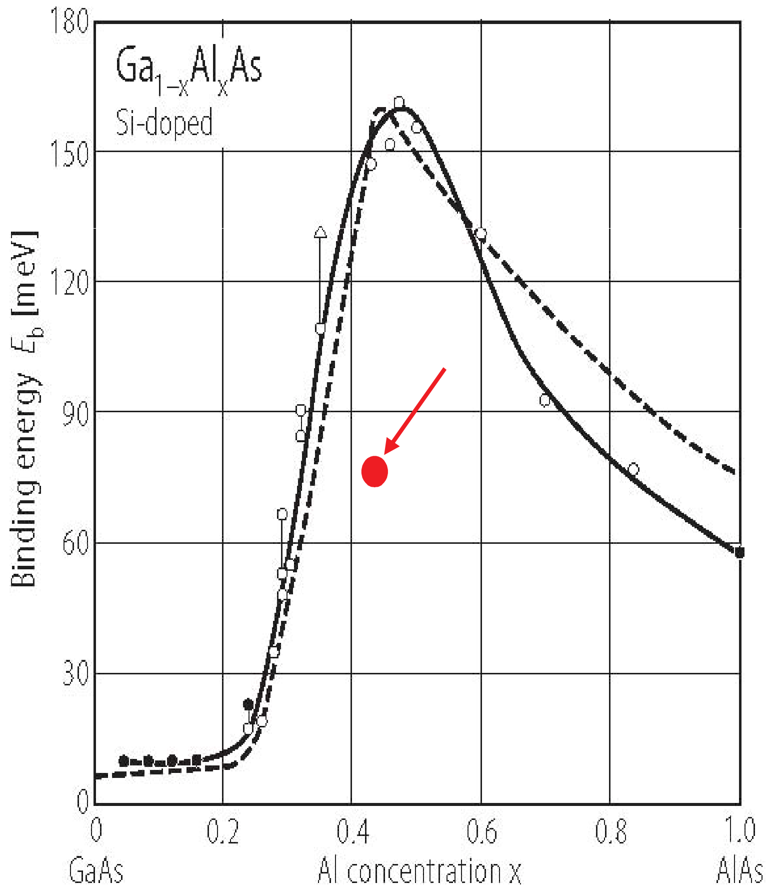
Pavesi *et al*, JAP **75**, 4779 (1994)



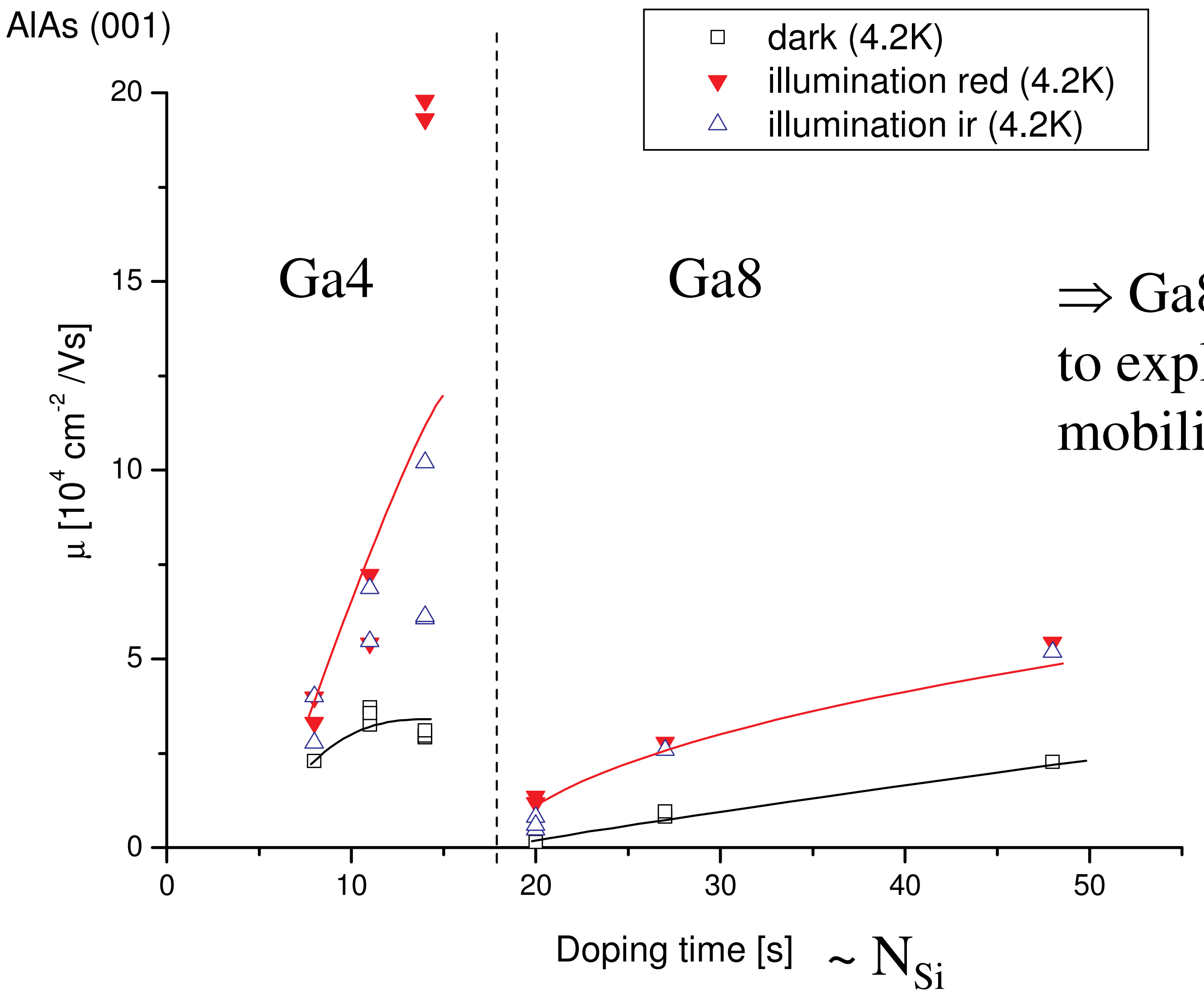
Dark: $n_{sat} = 2.2 \cdot 10^{11}\ cm^{-2}$



$Al_{0.45}Ga_{0.55}As$ AlAs $Al_{0.45}Ga_{0.55}A$

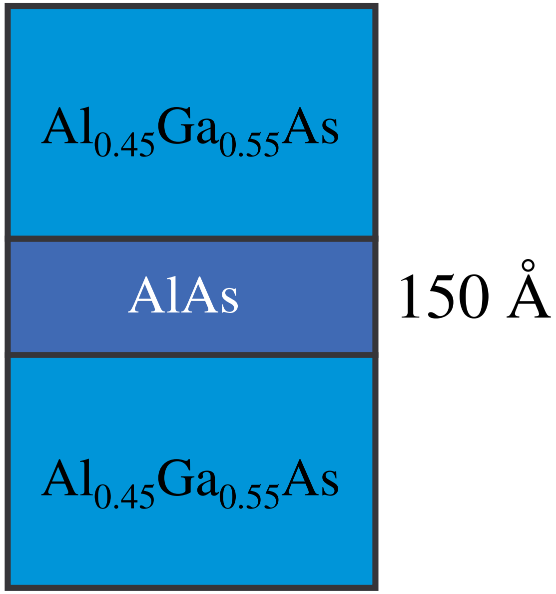


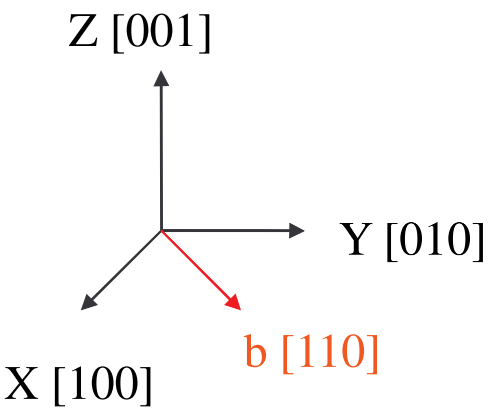
AlAs (001) QW - mobility



⇒ Ga8 seems to explain low mobility

Confinement in AlAs (110)

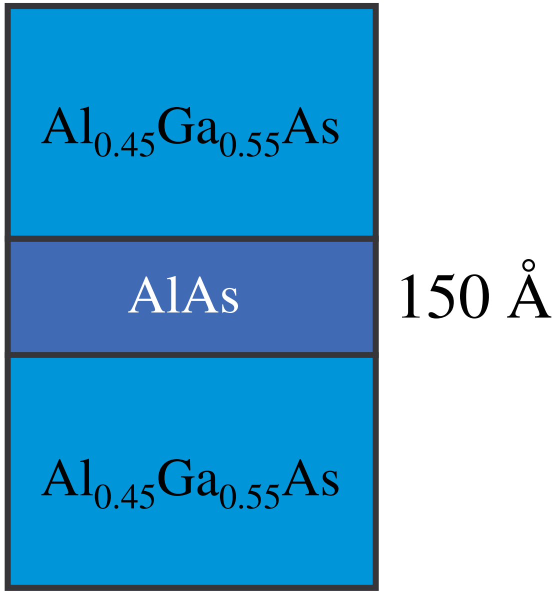


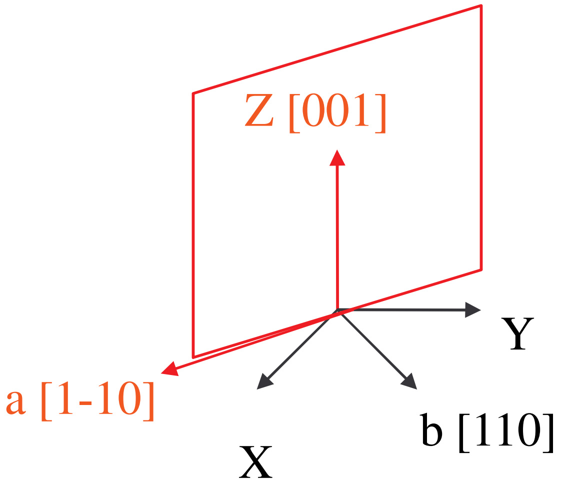


Confinement energy:

$$E_{con} = \frac{\hbar^2 k^2}{2m^*} = \frac{\hbar^2 \pi^2}{2m^* W^2}$$

Kinetic energy, AlAs (110)





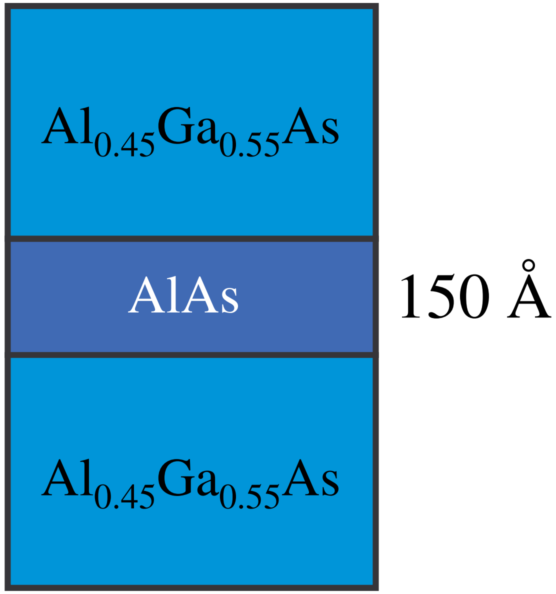
Kinetic energy:

$$E_{kin} = \frac{\hbar^2}{2}\left(\frac{k_x^2}{m_H} + \frac{k_a^2}{2m_L}\right) = \frac{\hbar^2}{2}\left(\frac{k_a^2}{2m_H} + \frac{k_y^2}{m_L}\right)$$
$$= \frac{\hbar^2}{2}k_a^2\left(\frac{m_H + m_L}{2m_H m_L}\right)$$

$$m_a = \frac{2m_H m_L}{m_H + m_L}$$

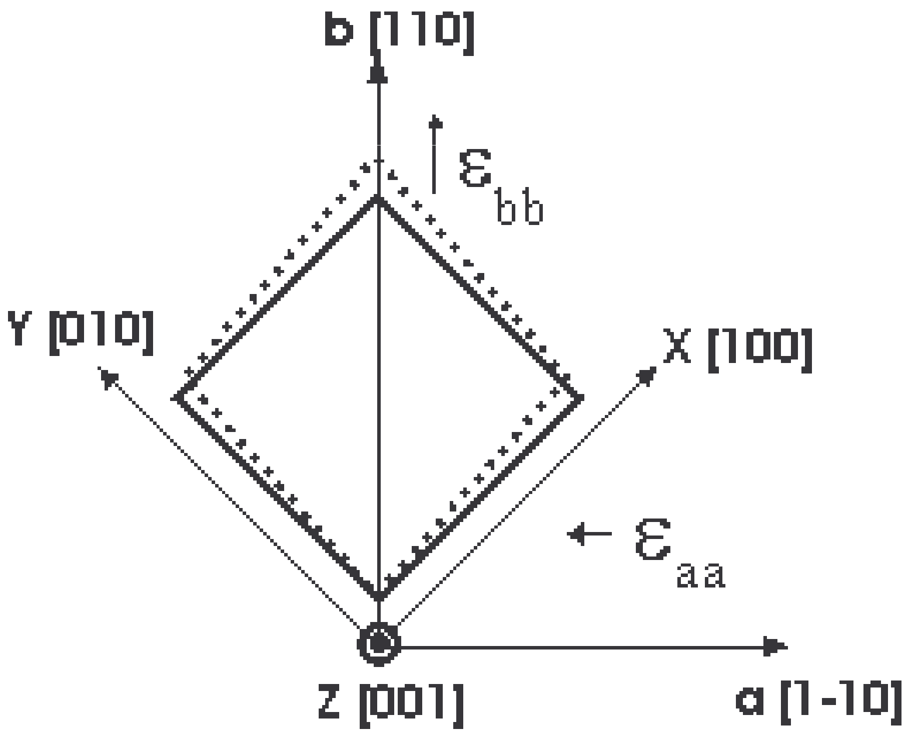
$$(k_x, k_y) = \left(\frac{k_a}{2}, \frac{k_a}{2}\right)$$

Strain in AlAs (110)

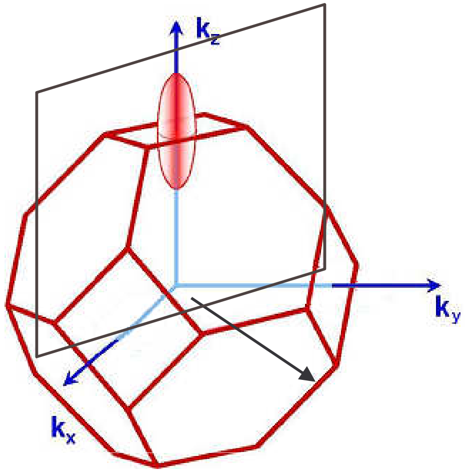


Lattice constants: AlAs > $Al_{0.45}Ga_{0.55}As$

(0.26% @ T = 4K)



Energy, AlAs (110)



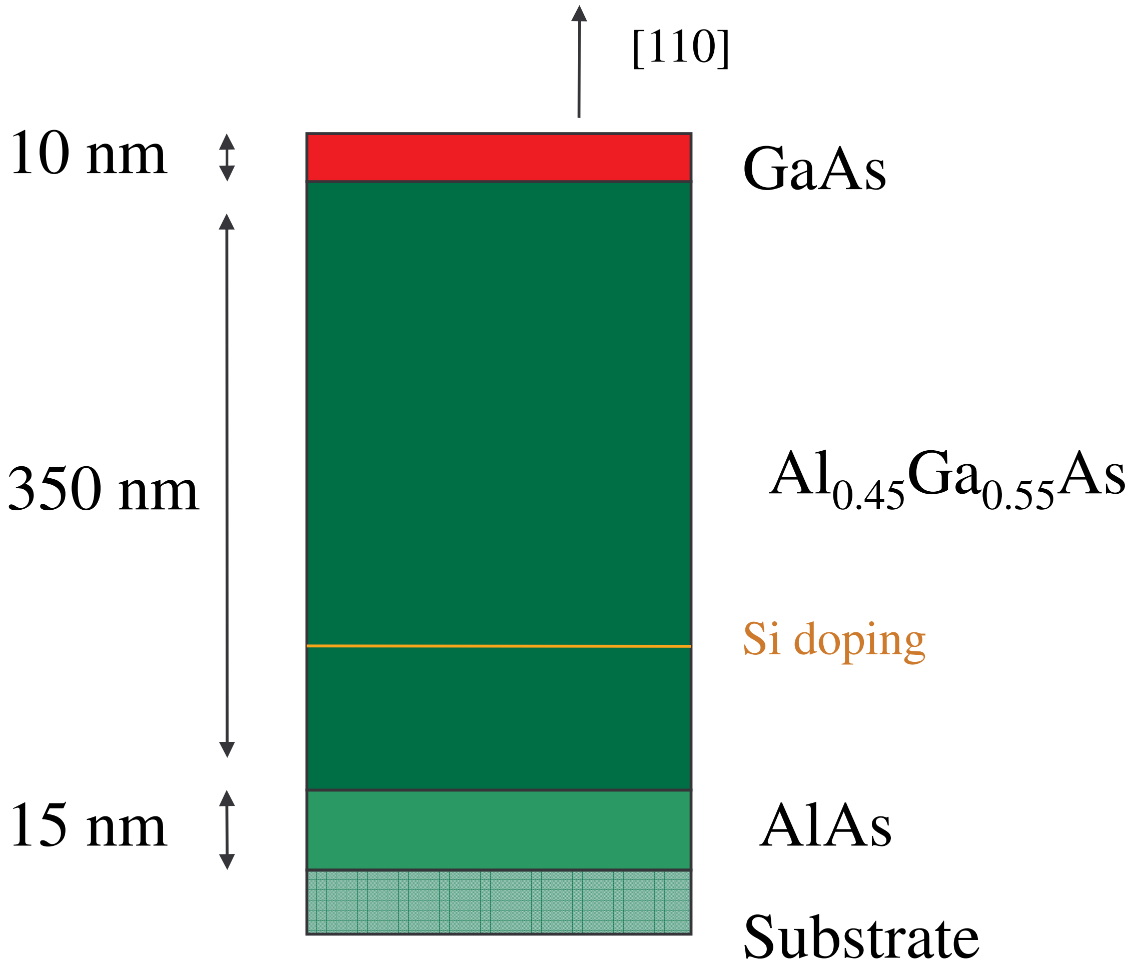
Expectation: single valley system, anisotropic conductance

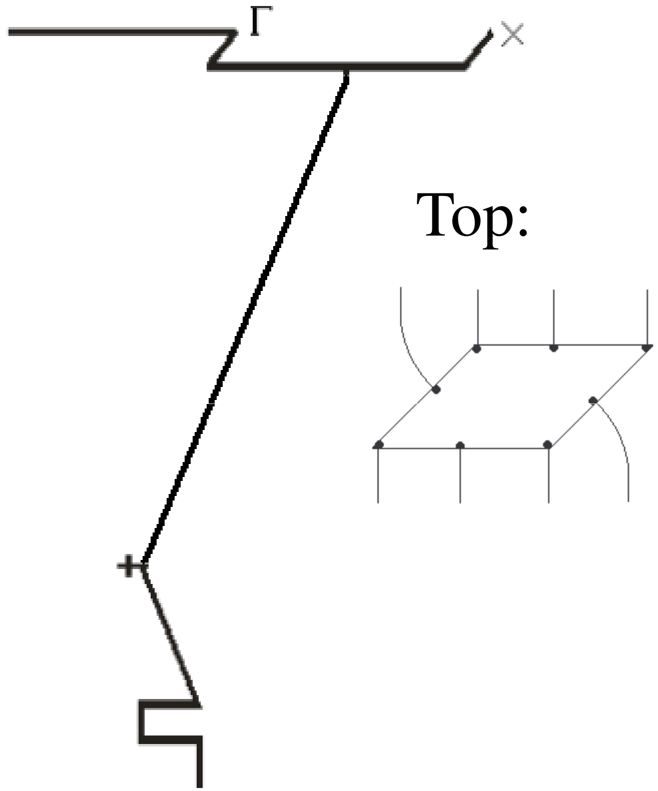
$$E_i = E_{kin} + E_{con} + \Delta_i$$

$$E_z = \frac{\hbar^2}{2}\left(\frac{k_z^2}{m_H} + \frac{k_a^2}{m_L}\right) + \frac{\hbar^2\pi^2}{2m_L W^2} + \Delta_z$$

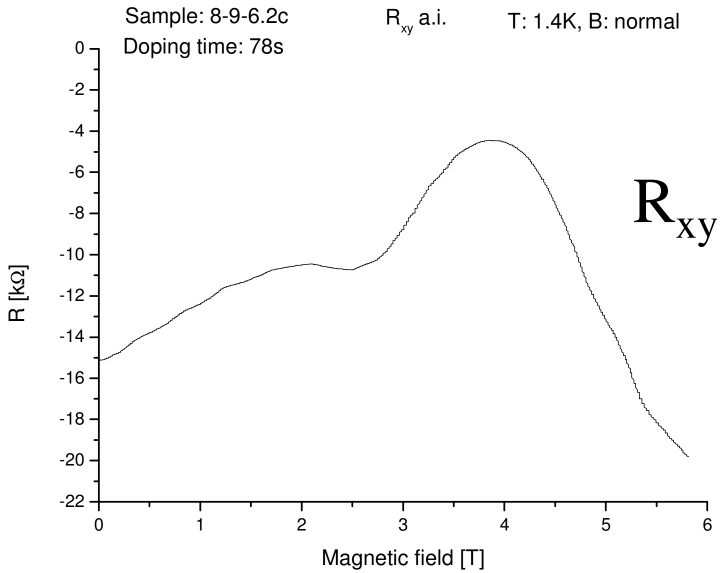
$$E_y = E_x = \frac{\hbar^2}{2}\left(\frac{k_z^2}{m_L} + \frac{k_a^2}{m_a}\right) + \frac{\hbar^2\pi^2}{2m_L W^2} + \Delta_{x,y}$$

Measurements - sample structure AlAs (110)

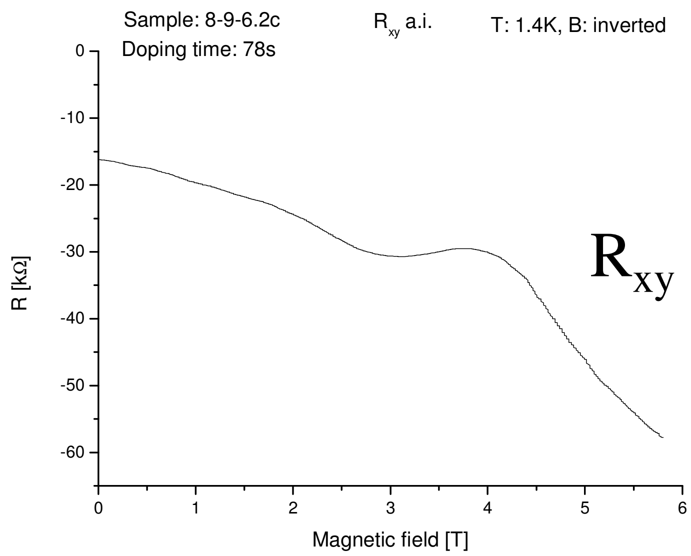




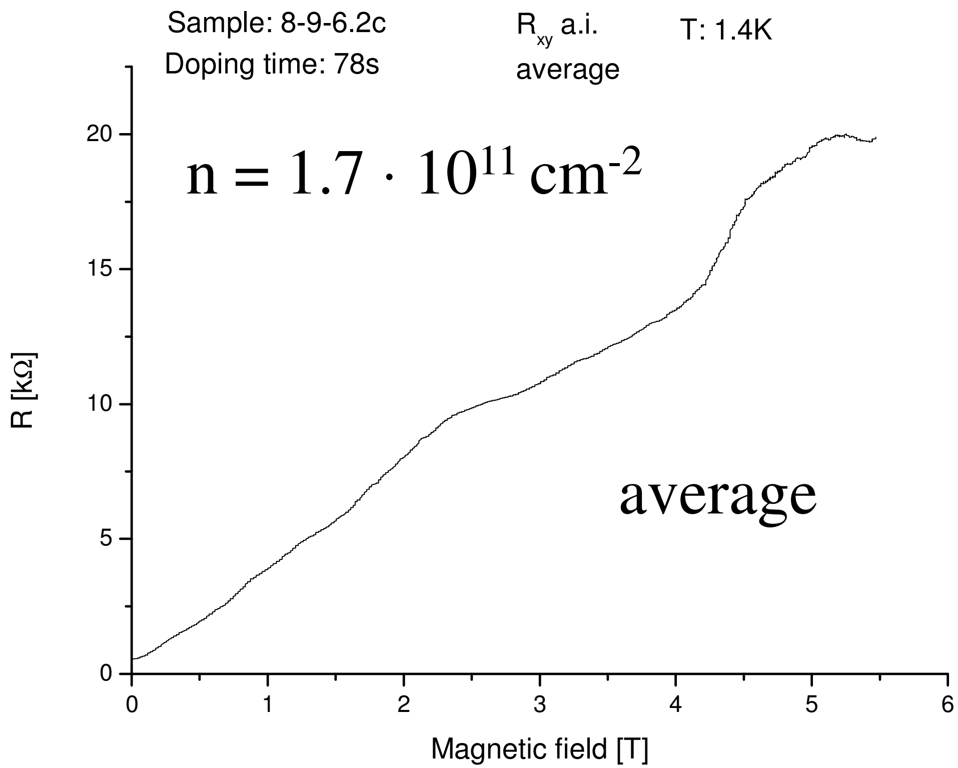
AlAs (110) - anisotropic resistances ($R_{xx} \neq R_{yy}$)



R_{xy} (+B)



R_{xy} (-B)



$n = 1.7 \cdot 10^{11}\ cm^{-2}$

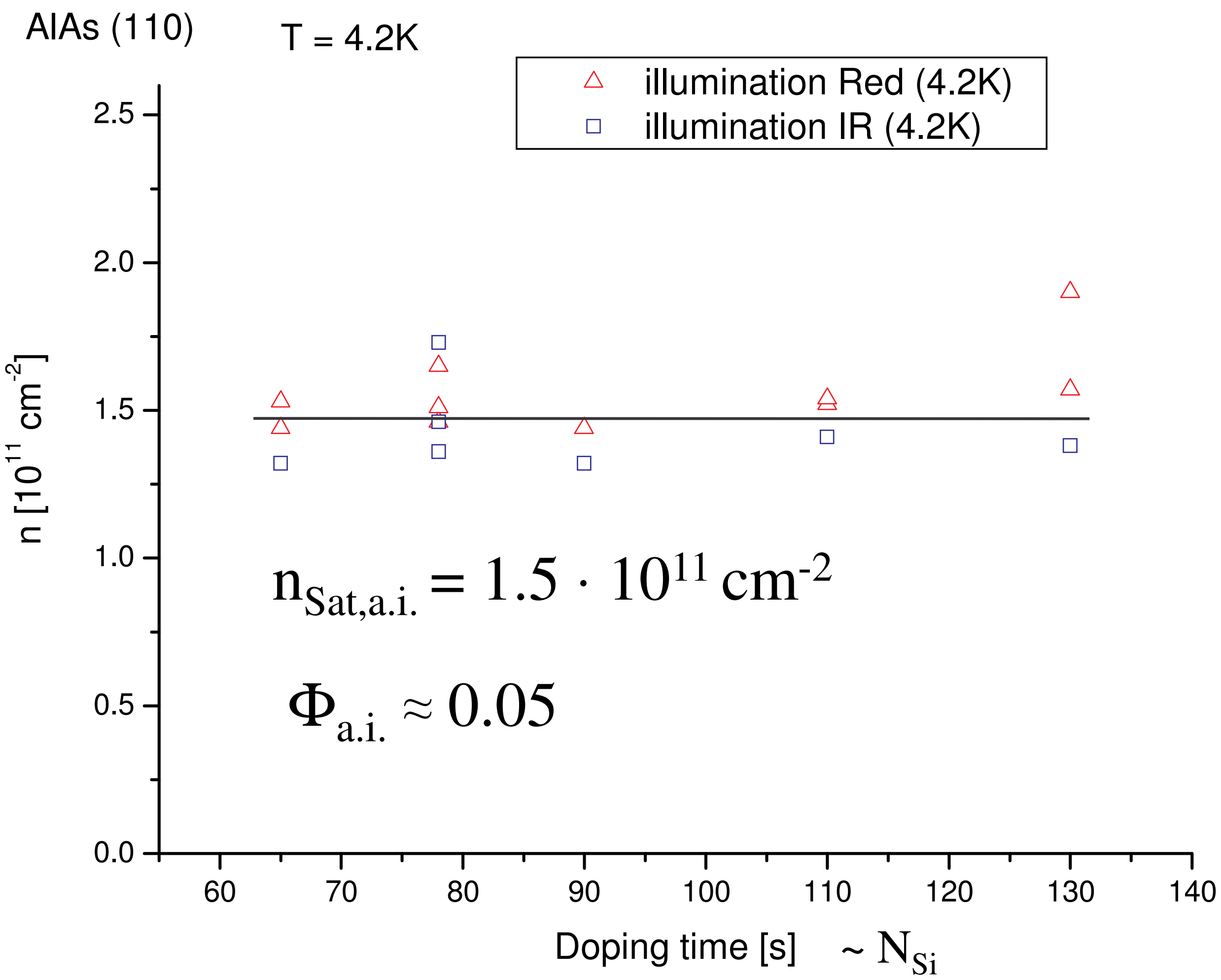
average

$$R_H = \frac{R_{xy}(+B) - R_{xy}(-B)}{2} \cdot \frac{1}{B}$$

$$\frac{R_{xy}}{B} = \frac{1}{n \cdot e} = R_H$$

Van der Pauw; Phil. Res. Rep. 16 (1961)

AlAs (110) QW - density a.i.



$n_{Sat,a.i.} = 1.5 \cdot 10^{11}\,\mathrm{cm}^{-2}$

$\Phi_{a.i.} \approx 0.05$

Doping efficiency:

$$\Phi = \frac{N_{active}}{N_{Si}}$$

Active donors:

$$N_{active} = n_{Sat}$$

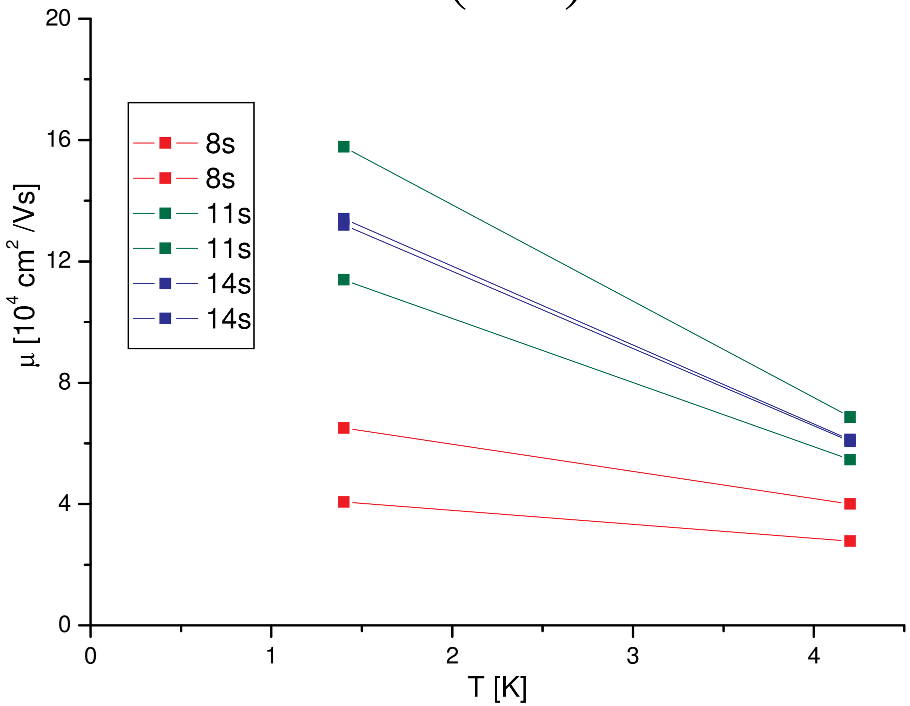
Si donors:

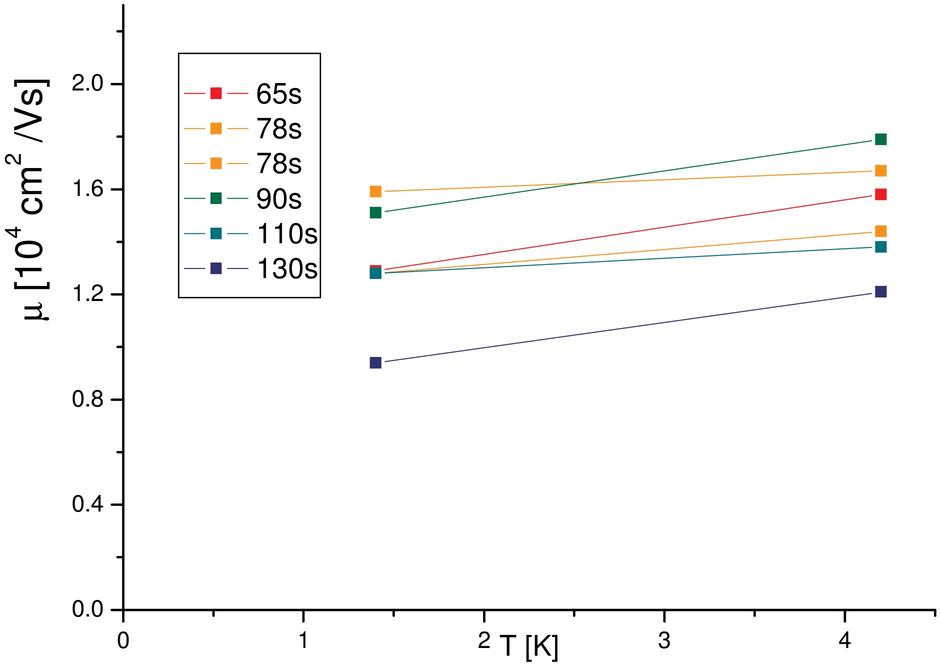
$$N_{Si} = \varphi_{Si} \cdot t_{Si}$$

$$\varphi_{Si} = 4.94 \cdot 10^{10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

AlAs (001) and (110) - mobility vs. temperature

AlAs (001) (after illumination) AlAs (110)





Temperature falls - mobility rises

Temperature falls - mobility falls

Double valley: $\mu = \mu_{xx} = \mu_{yy}$

Single valley: $\mu = \sqrt{\mu_{xx}\mu_{yy}}$

Van der Pauw; Phil. Res. Rep. 16 (1961)

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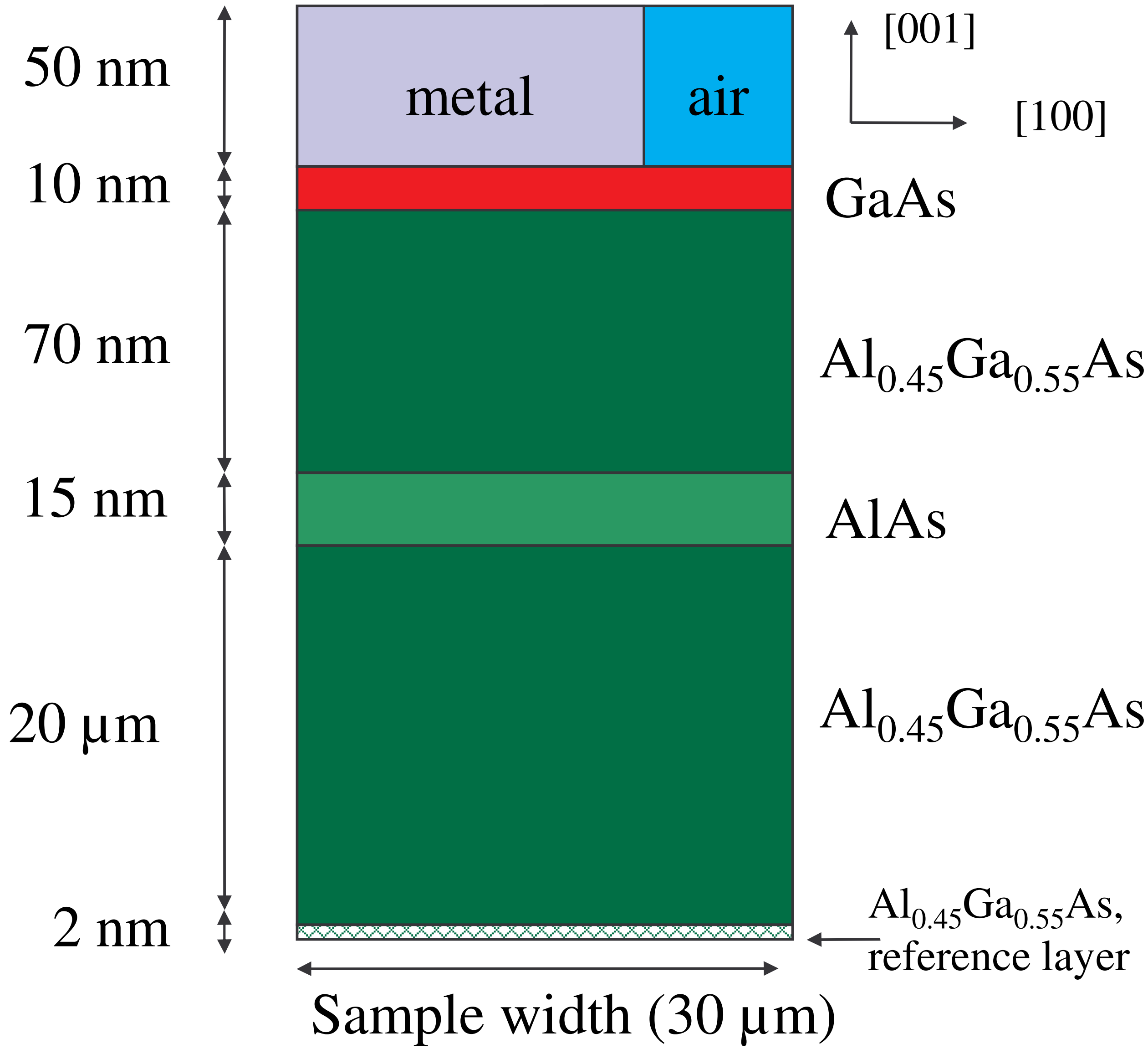
  - (110) AlAs
- Gate induced strain in AlAs
  - Breaking valley degeneracy
  - Strain simulations with nextnano^3

3D simulation - device structure

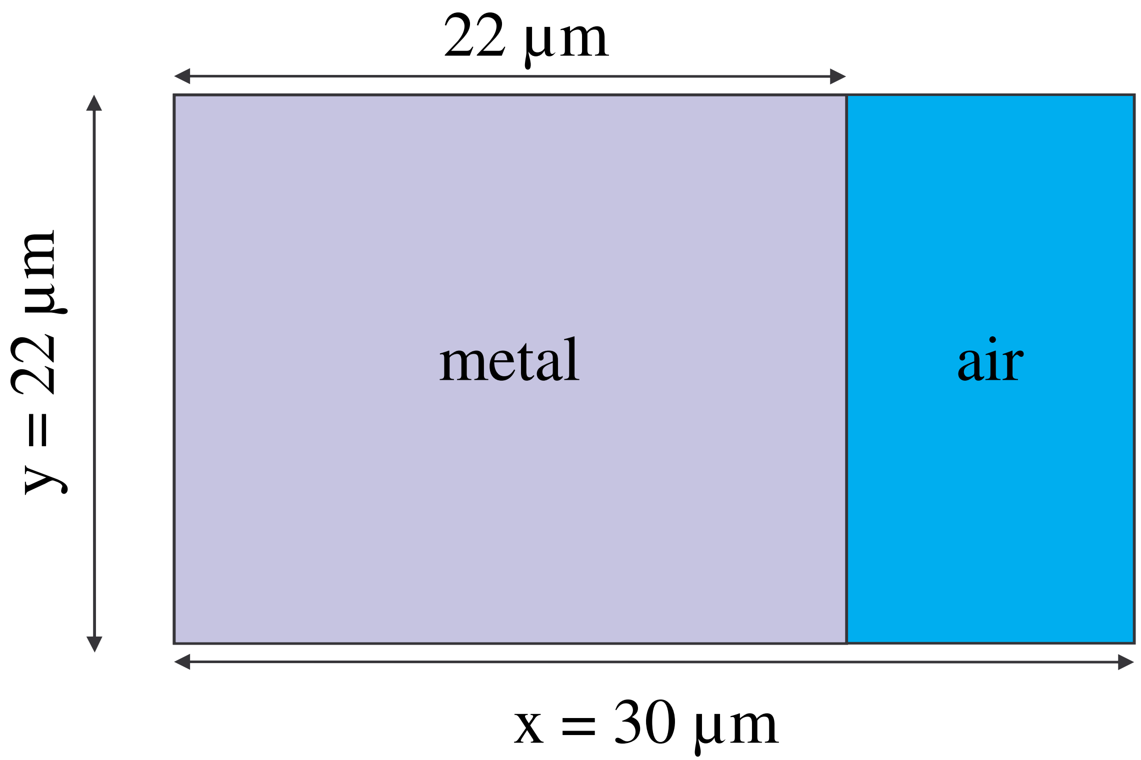


Metal to GaAs strain:

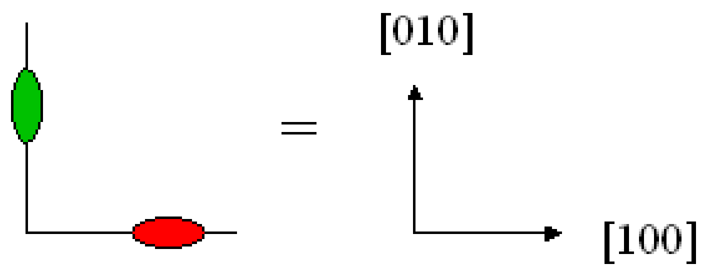
In, Al ≈ -1.0%

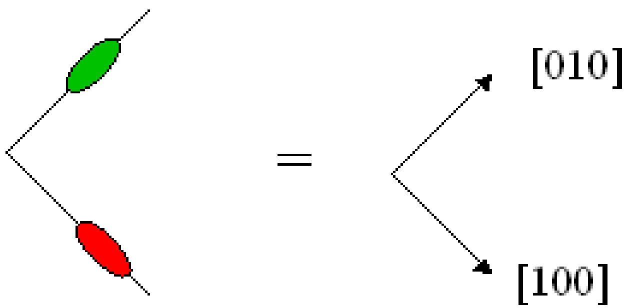
Ta, Cr ≈ 0.1%

3D simulation - device structure (top)

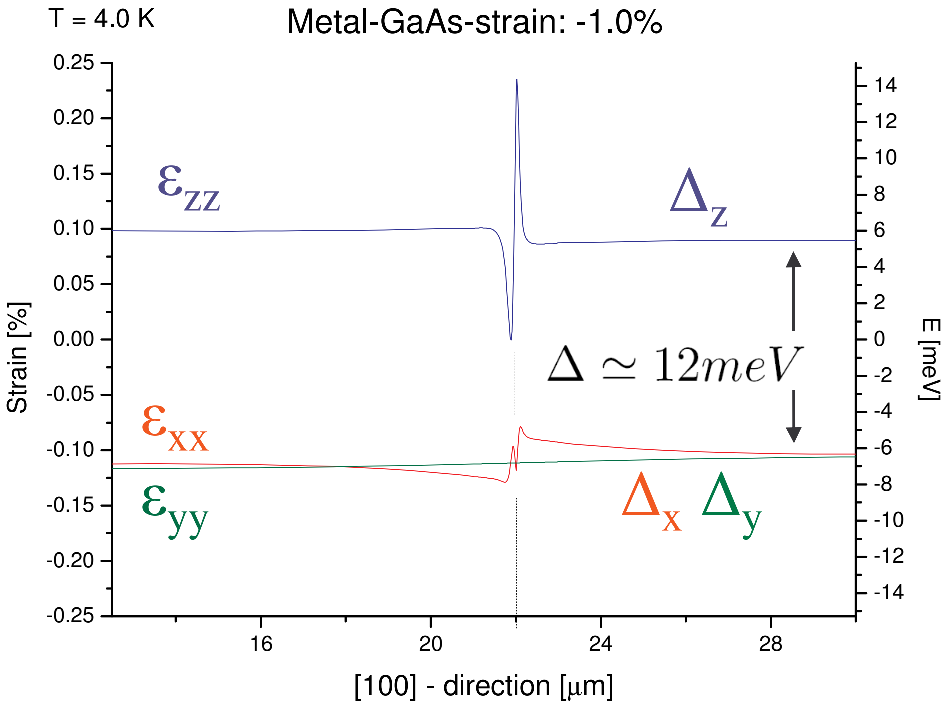


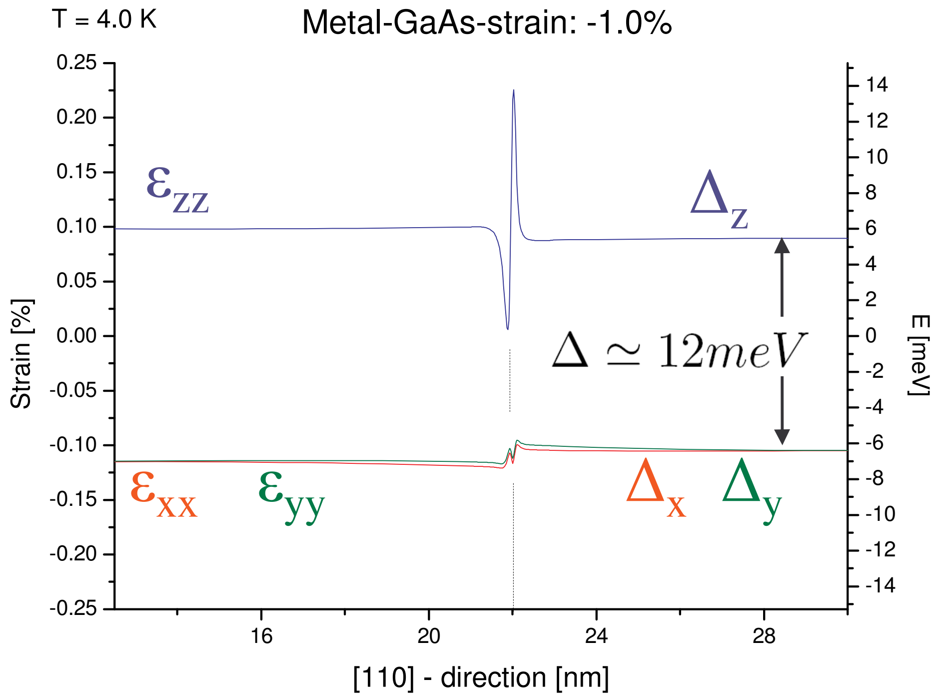
Structure: metal - air

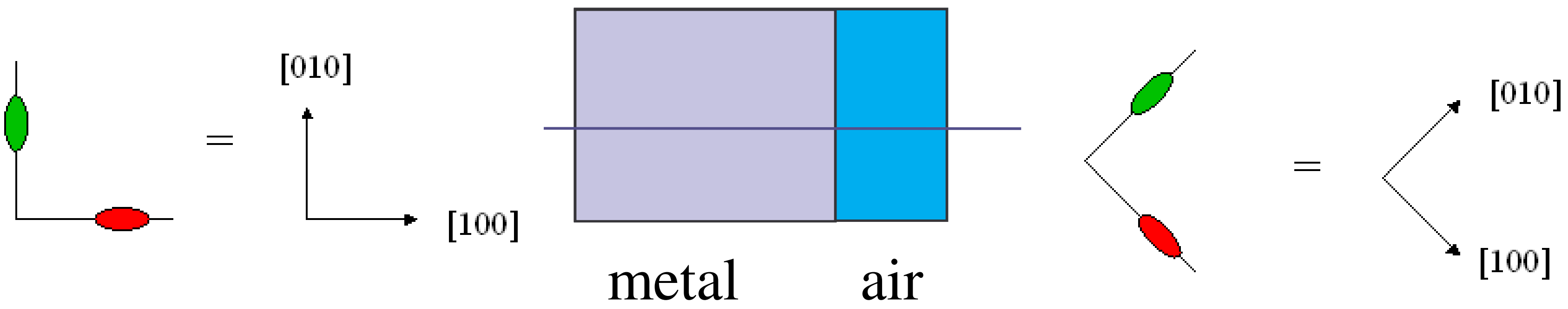




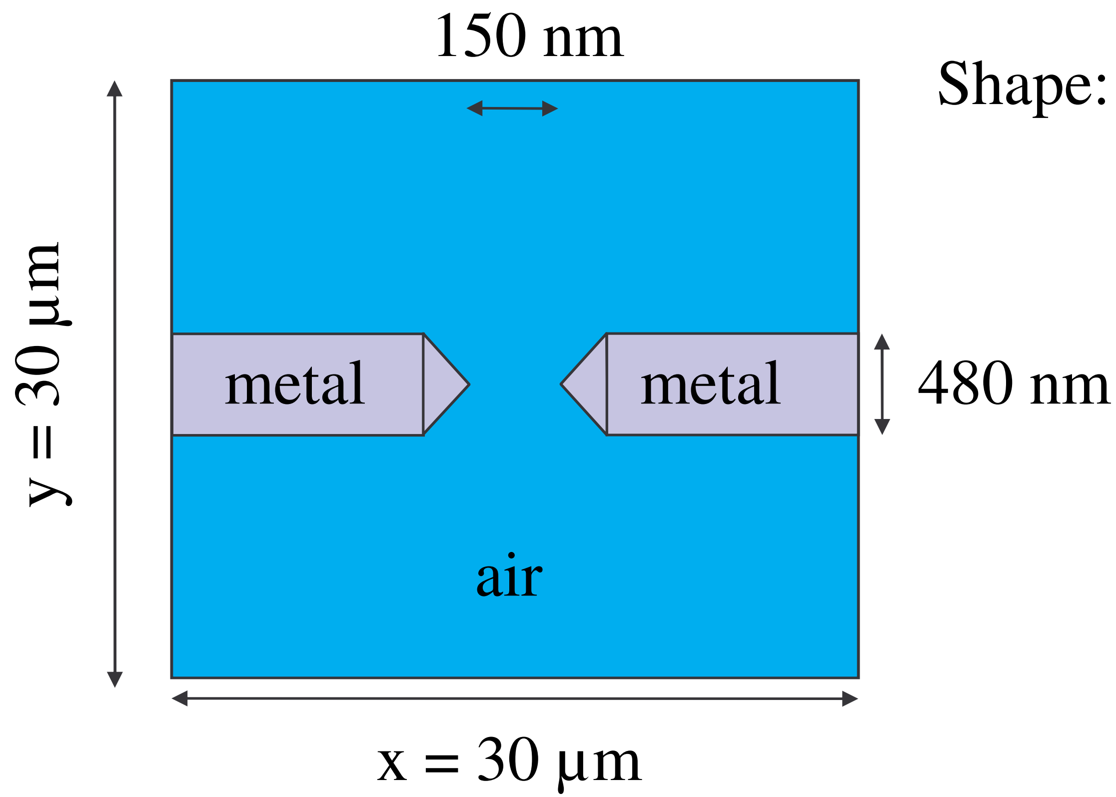
3D simulation, structure: metal-air





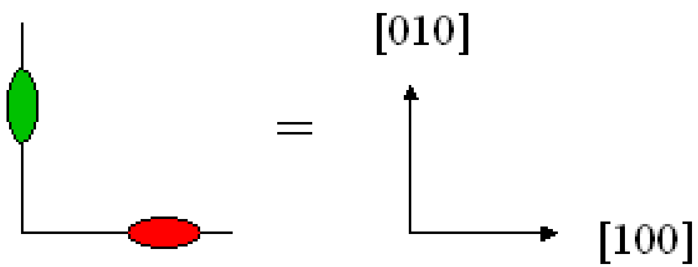


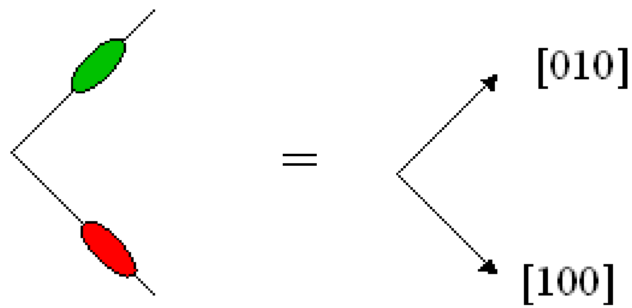
3D simulation - 2. device structure (top)



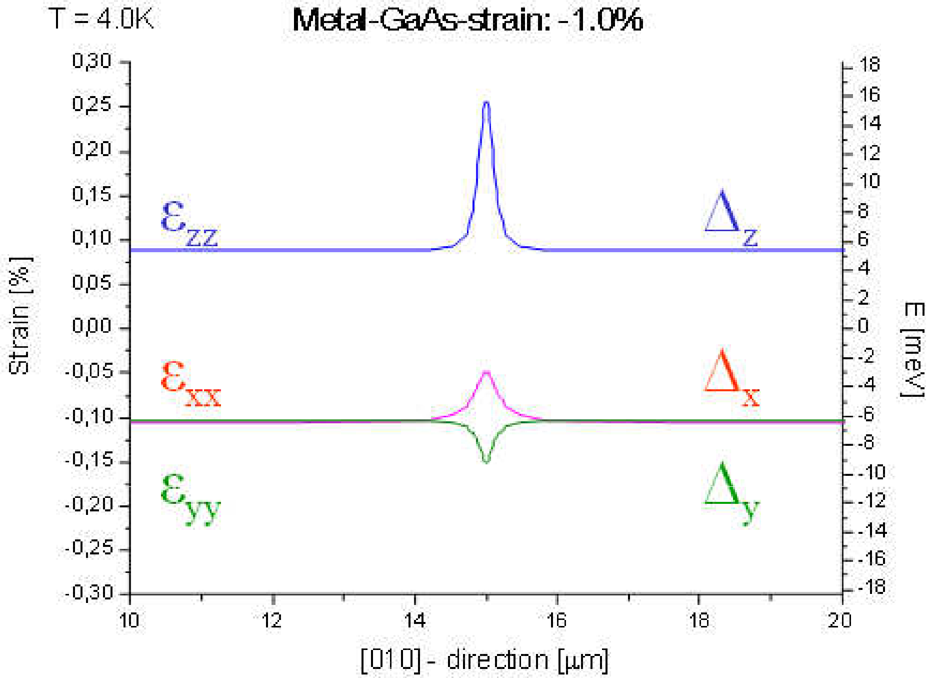
Shape: needle

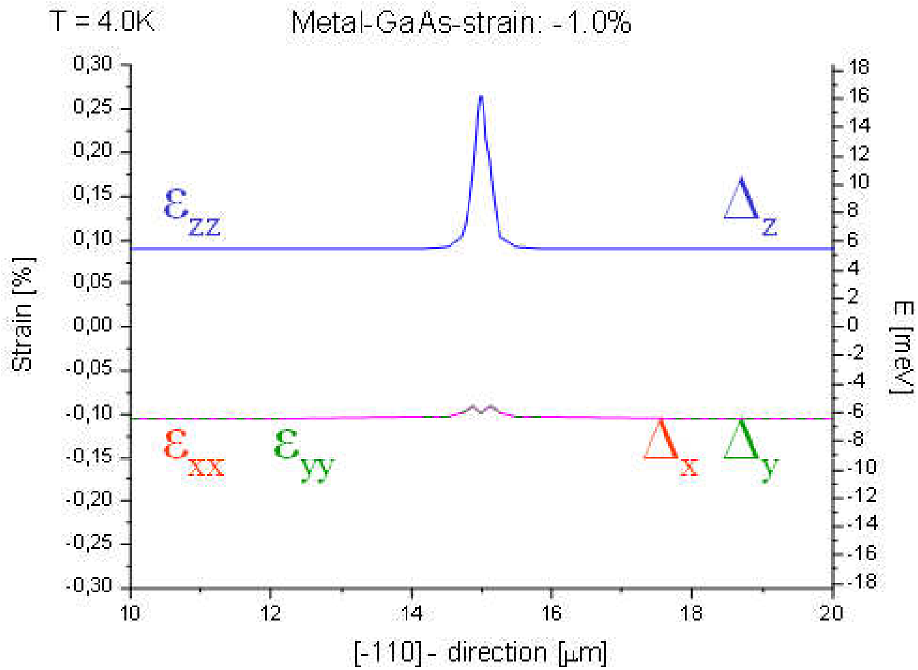
Does strain help or hurt selecting valleys between splitgate?

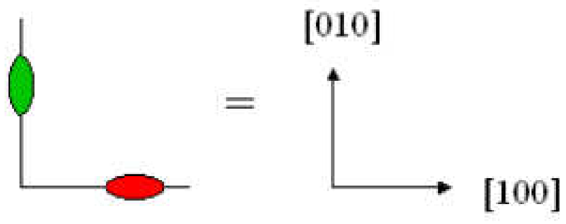


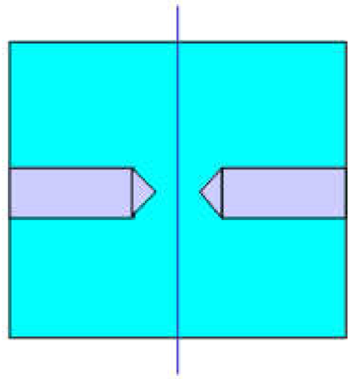


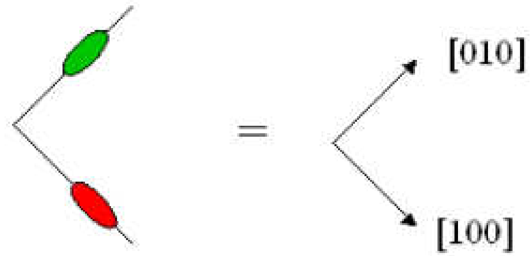
3D, air - air - air, y direction



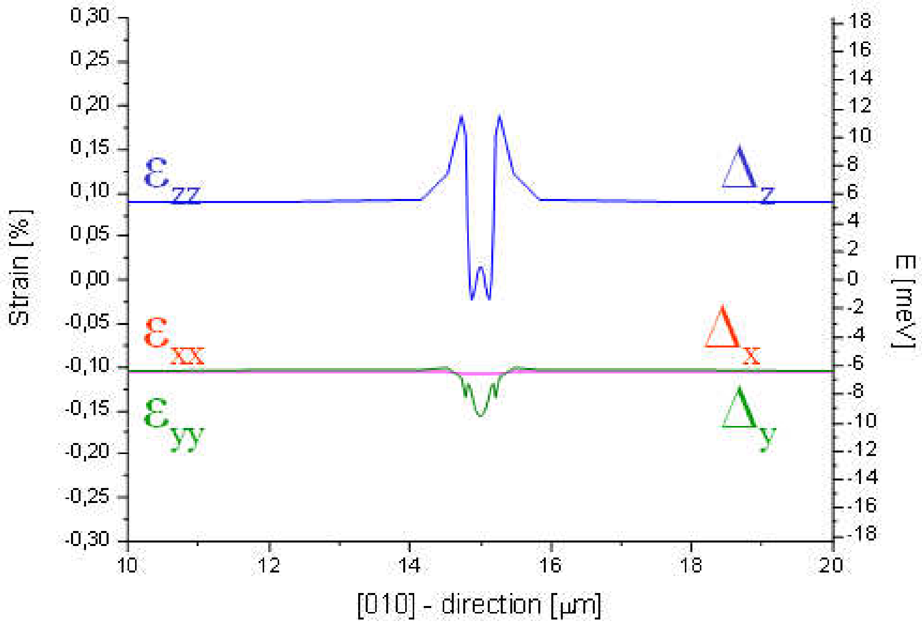


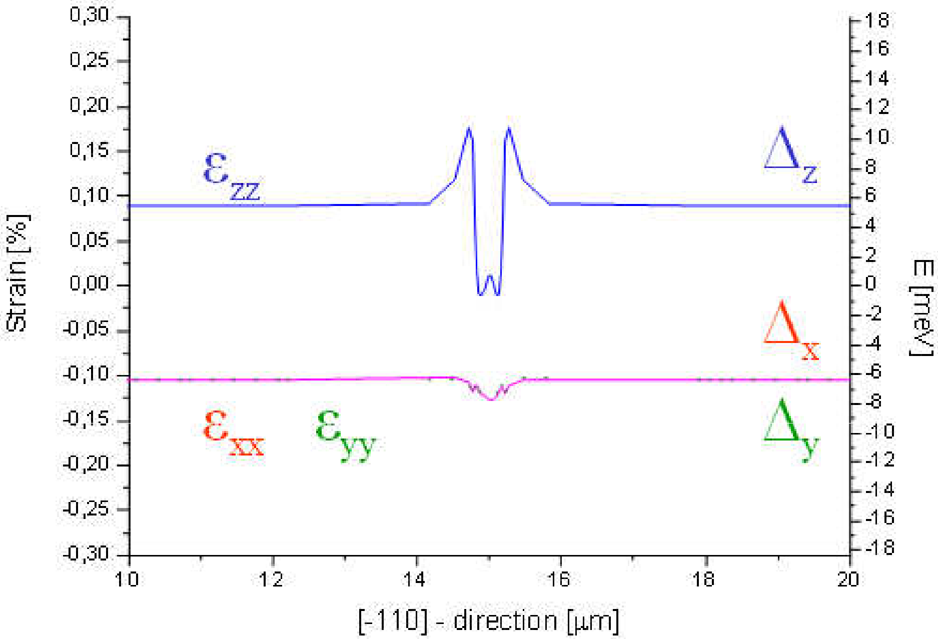


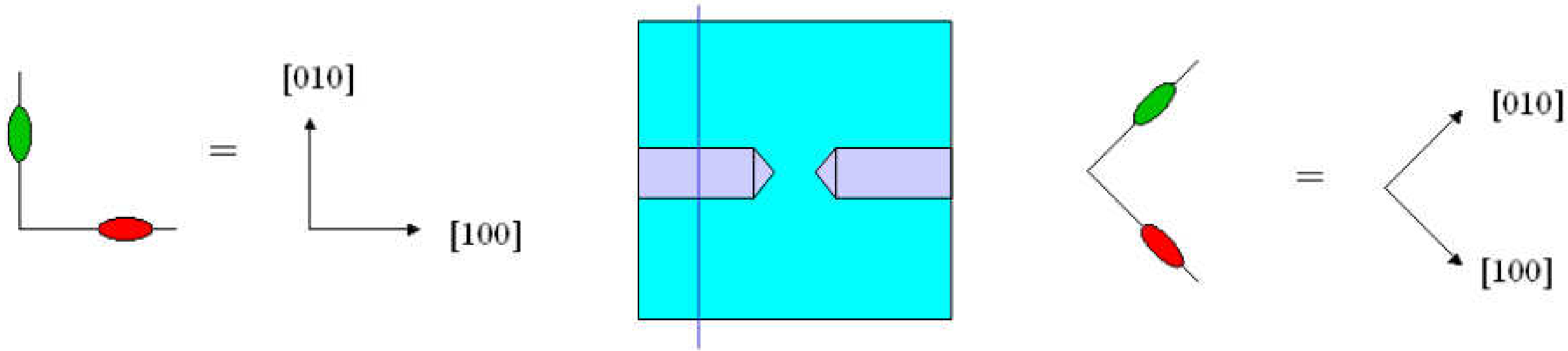




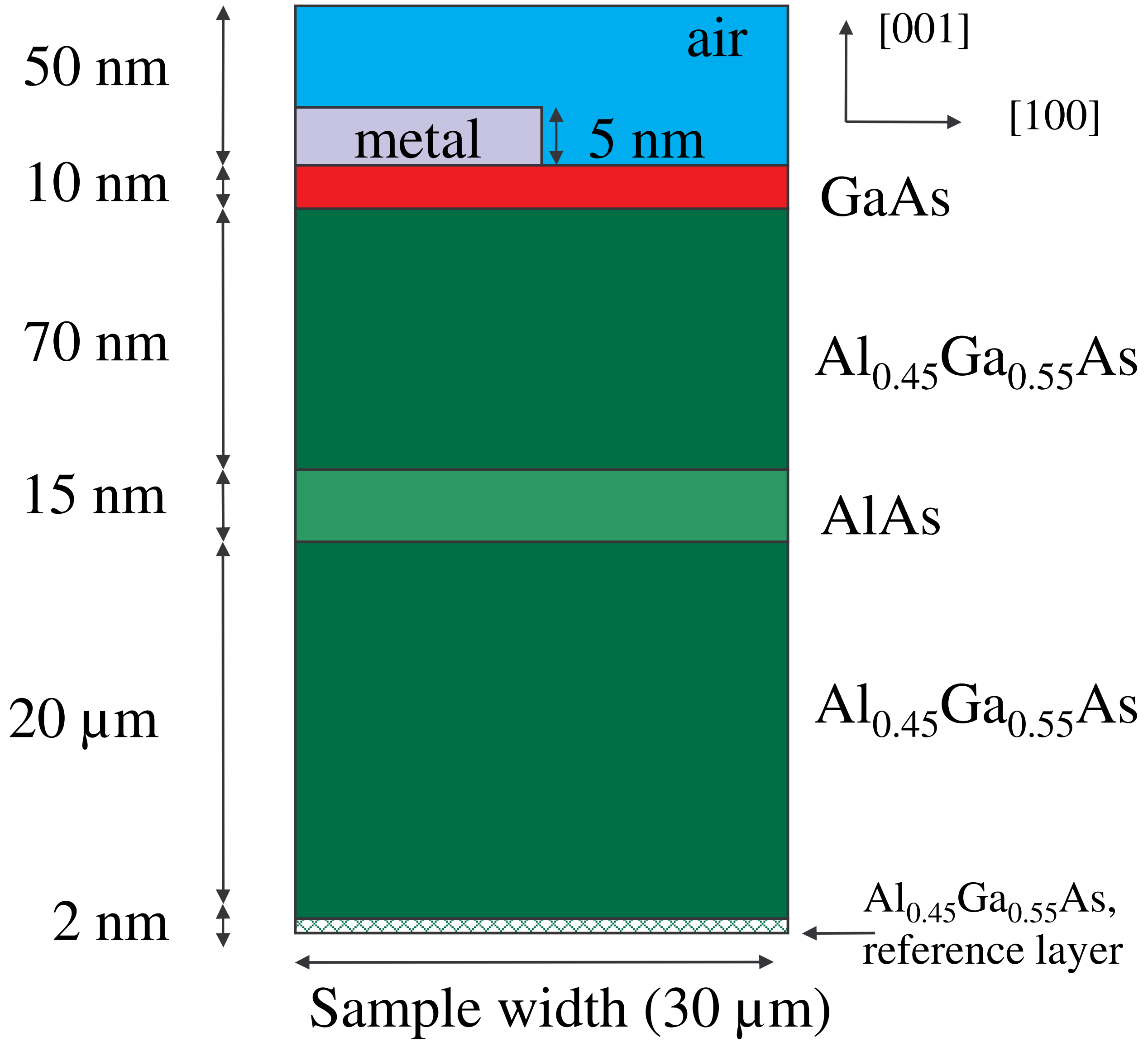
3D, air – gate - air, y direction





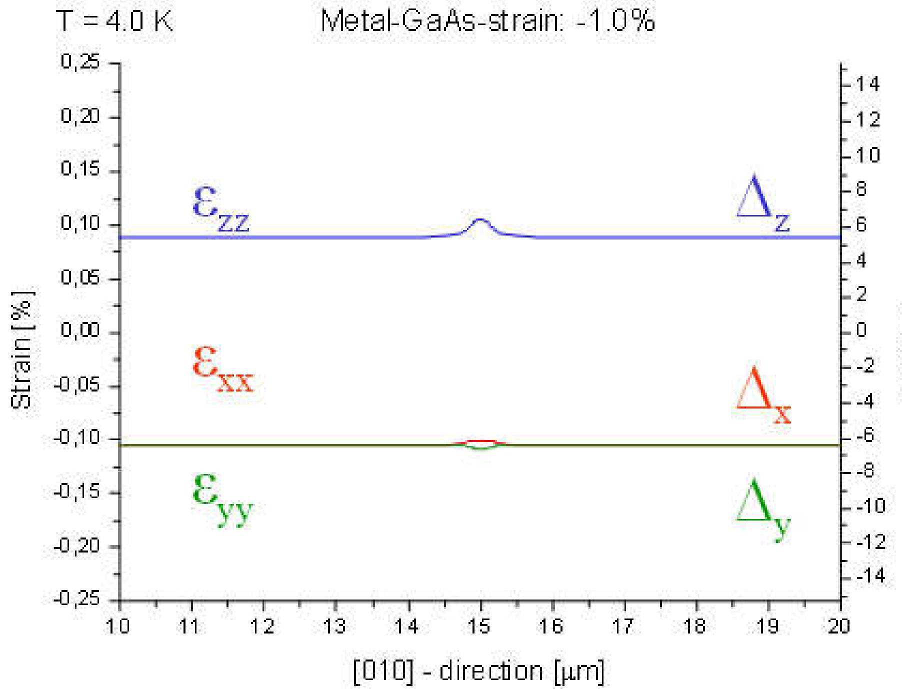


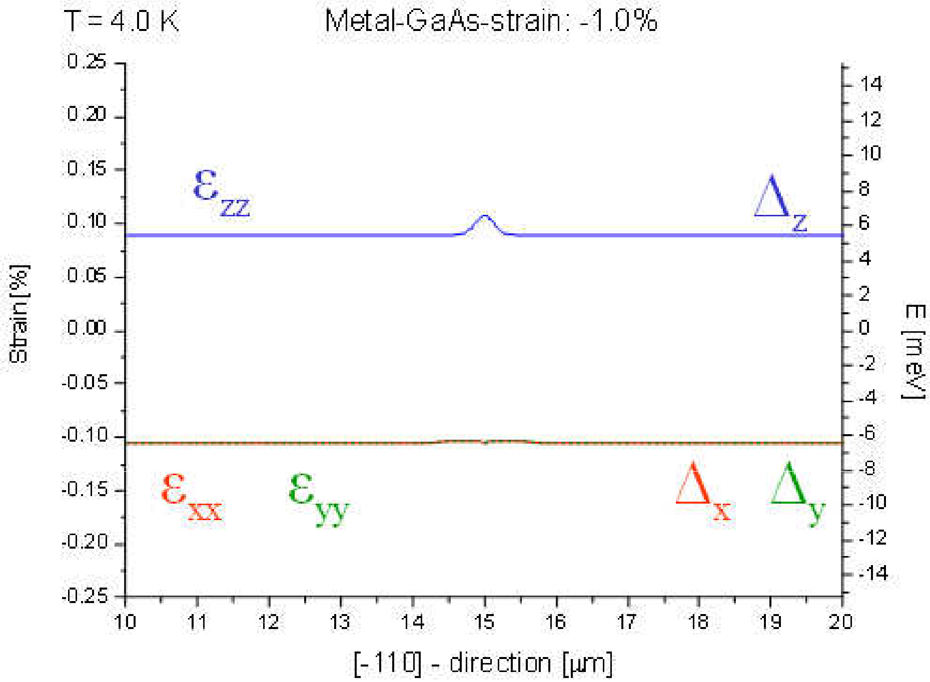
3D device structure - reduced gate thickness

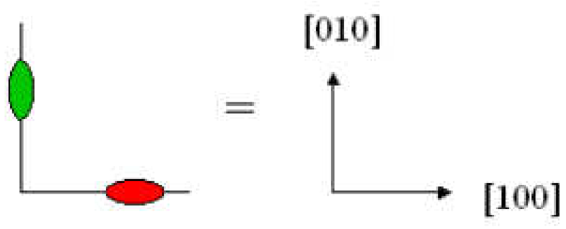


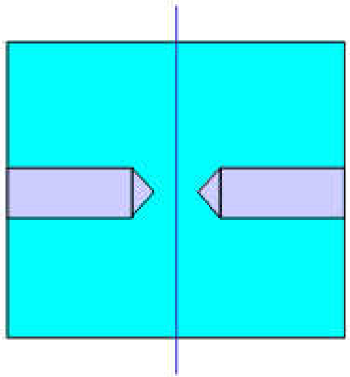
metal thickness reduced to 5 nm

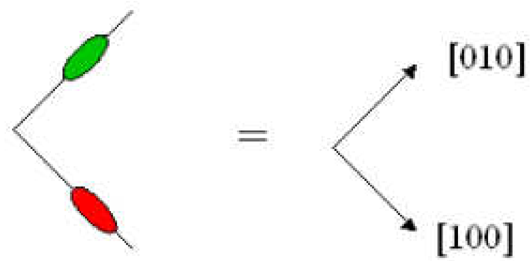
3D, air - air - air, y direction, reduced thickness











Conclusions

- Strain alone cannot make a valley QPC filter
- Strain and electrostatics can make one
- $\Rightarrow$ Strain is important
- measurements in AlAs QWs show interesting dependence of μ on T

Future Work

- L-hallbars on (110) AlAs - determine μ_{xx}, μ_{yy}
- Grow (110) AlAs with doping time < 65s
- Grow (110) AlAs with different structures
- Experimental verification of strain simulations

Acknowledgements

E24:

Gerhard Abstreiter, Matthew Grayson, Shivaji Dasgupta, Max Bichler, Anna Fontcuberta i Morral, Joel Moser

All members of the „transport group“

T33:

Peter Vogl, Tobias Zibold, Stefan Birner (nextnano^3)

nanoQUIT

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PROJEKTTRÄGER FÜR DAS Bundesministerium für Bildung und Forschung