EE 232: Lightwave Devices

Lecture #20 – Strain engineering in light emitting devices

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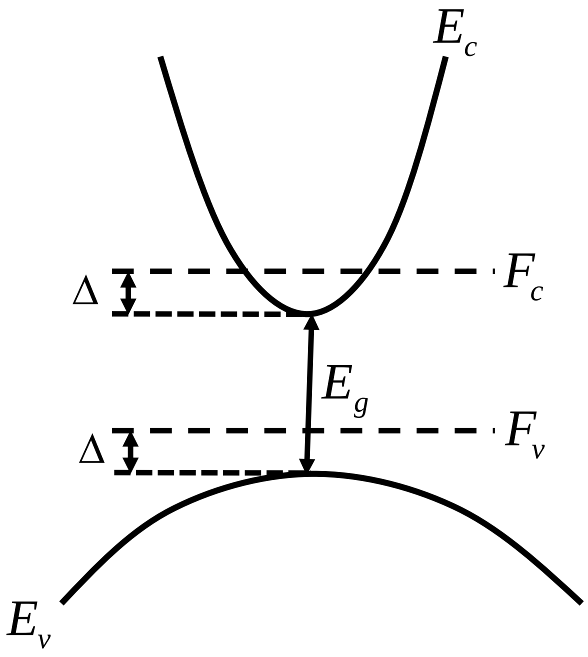
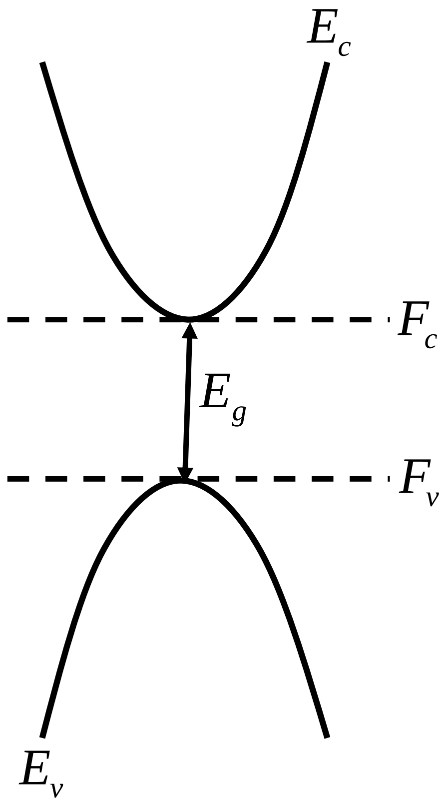
Bernard-Duraffourg Condition

Typical band structure



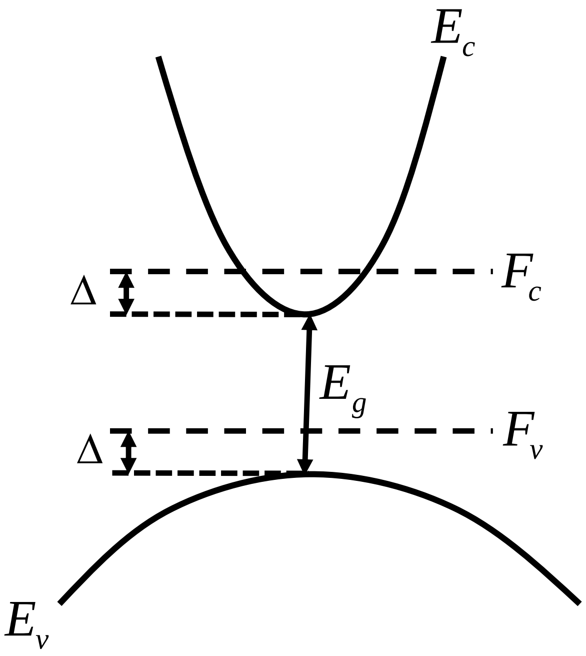
Ideal band structure



Bernard-Duraffourg Condition: $F_c - F_v = E_g$

Carrier density - typical band structure

Typical band structure



$$n = \int_{E_g}^{\infty} \frac{m_e^*}{\pi\hbar^2} \frac{1}{e^{(E-F_c)/kT}+1} dE$$

$$\text{Let } x = \frac{E-F_c}{kT}$$

$$= \int_{(E_g-F_c)/kT}^{\infty} \frac{m_e^*}{\pi\hbar^2} \frac{kT}{e^x+1} dx$$

$$= -\frac{m_e^* kT}{\pi\hbar^2} \ln\left(e^{-x}+1\right)\Big|_{(E_g-F_c)/kT}^{\infty}$$

$$\simeq \frac{m_e^*}{\pi\hbar^2}(F_c-E_g)$$

$n = \frac{m_e^*\Delta}{\pi\hbar^2}$ Similarly, $p = \frac{m_h^* kT}{\pi\hbar^2} \exp\left(-\frac{\Delta}{kT}\right)$

Since, n = p → $\frac{\Delta}{kT}\left(\frac{m_e^*}{m_h^*}\right) = \exp\left(-\frac{\Delta}{kT}\right)$

Further, $\frac{m_e^*}{m_h^*} \simeq \frac{1}{6}$ → $\Delta = 1.43kT$

$$\boxed{n = \frac{1.43kT}{\pi\hbar^2} m_e^*}$$

Transparency carrier reduction with ideal band structure

$$n = p = \int_{E_g}^{\infty} g(E)\,f(E)\,dE$$

$$= \int_{E_g}^{\infty} \frac{m_e^*}{\pi\hbar^2}\frac{1}{e^{(E-F_c)/kT}+1}dE$$ (quantum well)

$$\int_{E_g}^{\infty} \frac{m_e^*}{\pi\hbar^2}\frac{1}{e^{(E-E_g)/kT}+1}dE$$

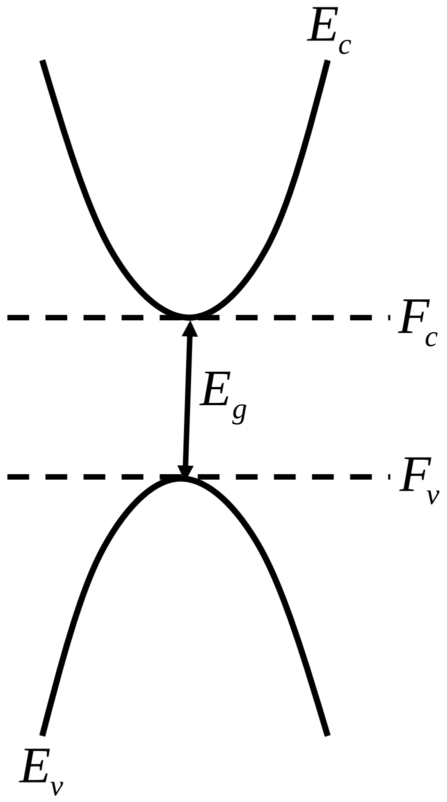
$$\boxed{n = \frac{kT}{\pi\hbar^2} m_e^* \ln 2}$$

Comparing the calculated carrier density at the Bernard-Duraffourg condition, we find

$$\frac{n_{typical}}{n_{ideal}} = \frac{\dfrac{1.43kT}{\pi\hbar^2}m}{\dfrac{kT}{\pi\hbar^2}m_e^* \ln 2} \sim 2$$

Transparency carrier density is reduced by about a **factor of two** with the ideal band structure.

Ideal band structure



Threshold current reduction with ideal band structure

$$J_{th} = J_{SRH} + J_{sp} + J_{Auger}$$

Reduction in threshold current can be significant in long-wavelength materials (λ > 1.0 μm) where Auger recombination can be dominant at laser threshold.

In that case,

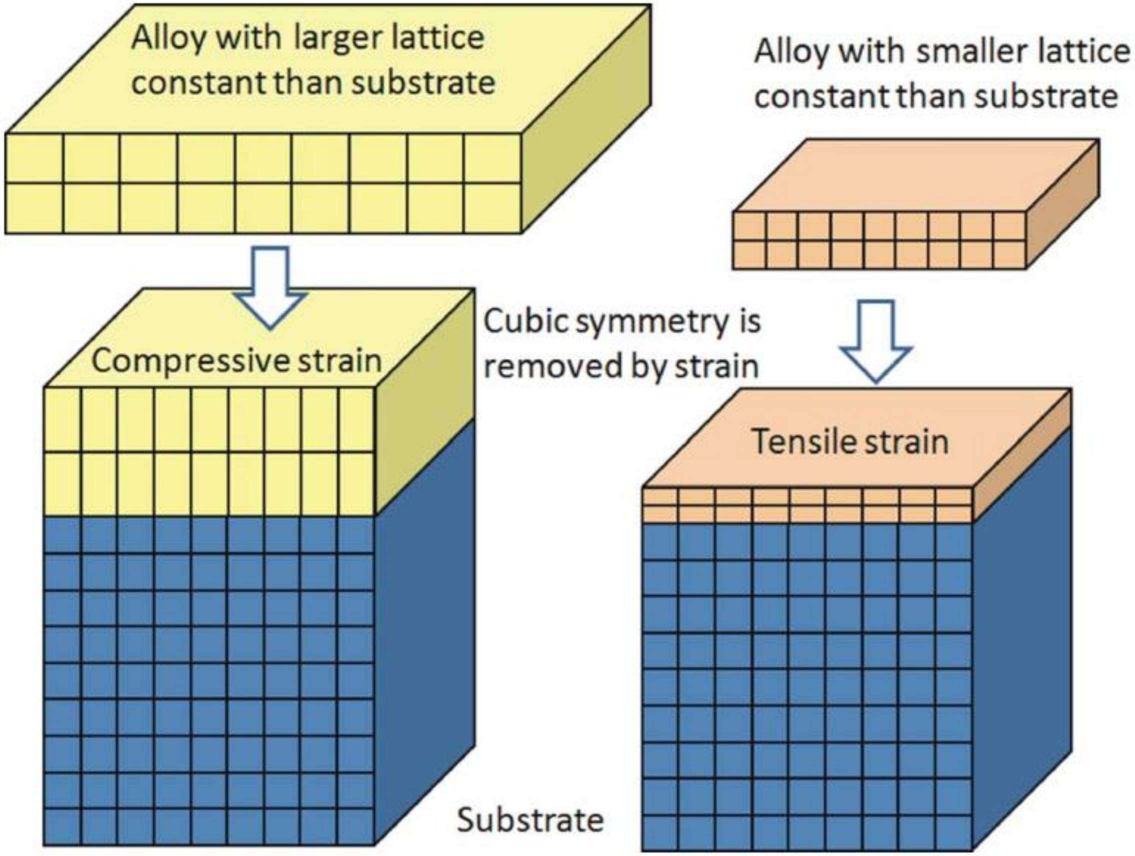
$$J_{th} \sim J_{Auger} \propto Cn^3$$

$$\frac{Cn^3_{typical}}{Cn^3_{ideal}} = 2^3 = 8$$

Threshold current is reduced by about a factor of 8.
Note: strain may also reduce the Auger "C" coefficient.

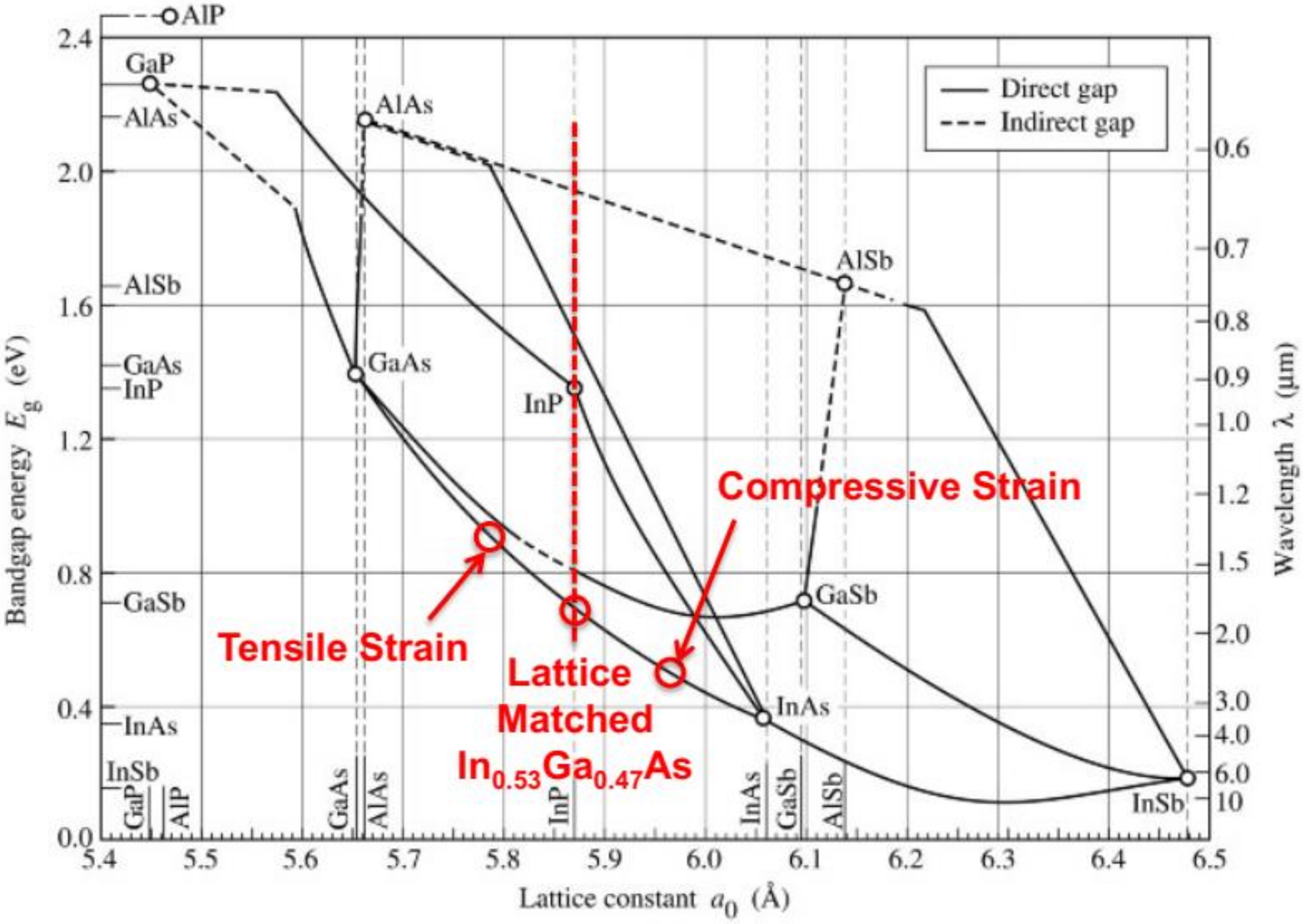
See Yablonovitch and Kane, J. Light. Tech. Vol. LT-4, No. 5, 1986 for more discussion.

Strain engineering



Alf Adams. J. Sel. Top. in Quant. Electron. Vol. 17, No. 5 (2011).

Strain engineering



Strain engineering

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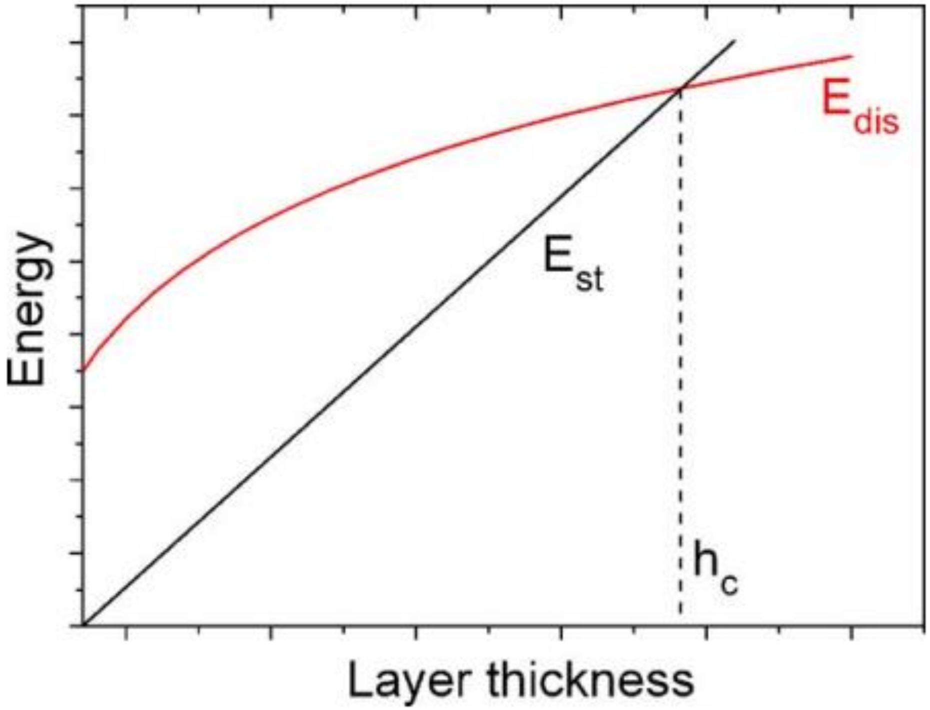


E_{st}: Energy stored in strained layer

E_{dis}: Energy to form a dislocation

h_c: critical thickness

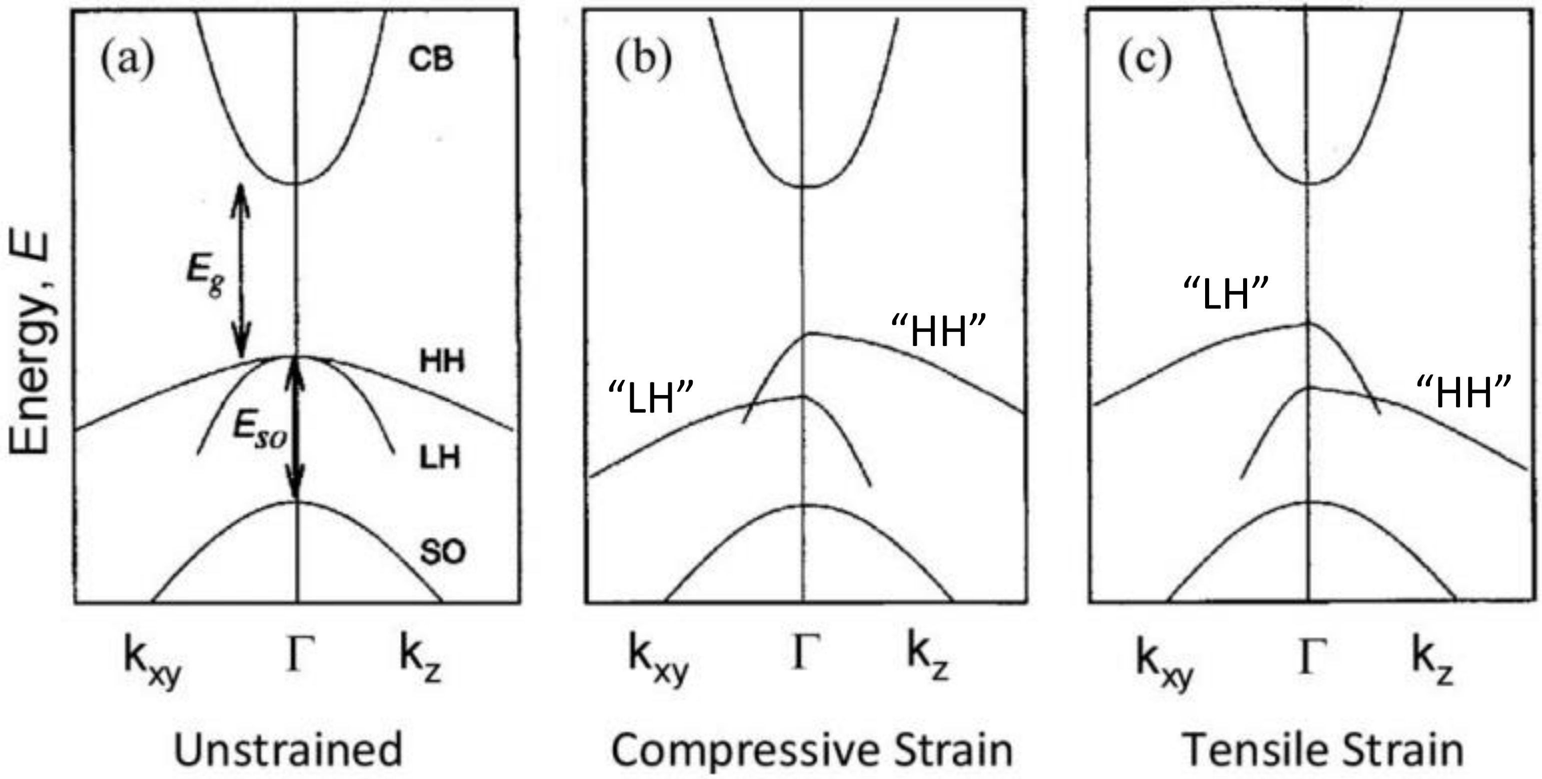
Lattice can accommodate strain until a critical thickness is reached.
Above the critical thickness, it is more energetically favorable to relax the strain through defect formation.

E.g. for $In_xGa_{1-x}As$ grown on GaAs. The critical thickness is about 20 nm%.
Usually, about 1% strain is desired therefore critical thickness is 20nm.

Given the critical thickness, strained materials are almost always quantum wells.

Band structure

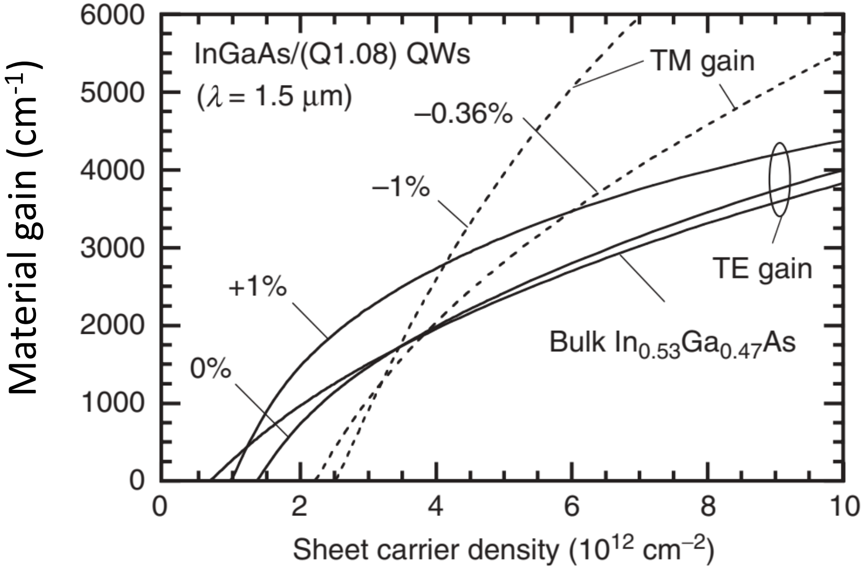
Band diagrams for III-V with and without strain



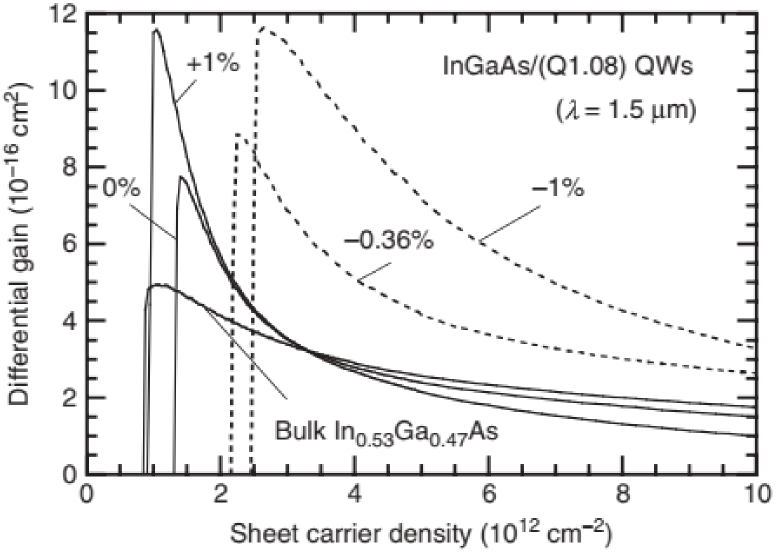
Strain breaks cubic symmetry: in-plane effective mass and longitudinal effective mass (along the growth direction) are <u>different</u>.

Longitudinal effective mass is used for quantum well eigenenergy calculation
Transverse effective mass is used for DOS and gain calculation.

Gain in strained quantum wells



Note: Negative % strain is tensile



Compressive strain → TE polarization
Tensile strain → TM polarization

Compressive and tensile strain have increased differential gain with respect to unstrained material.

Compressive strain more widely used in part because of TE mode operation

Coldren et al,. Diode Lasers and Photonic Integrated Circuits