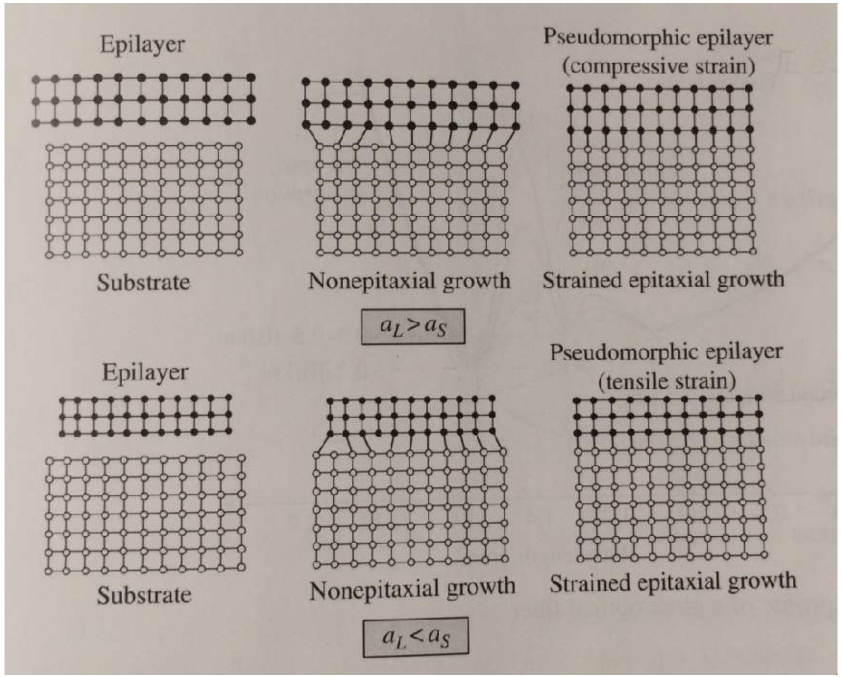
Lecture 12

- Active materials and characteristics

Strained materials

- Strain occurs in lattice mismatched systems. When the lattice constant of the active region is smaller than the substrate, it is tensile strain. If it is larger, it is compressive strain.
- There is a critical thickness beyond which the strained latticce will begin to revert back to its native state, causing high densities of lattice defects. In practice, this critical thickness is on the order of a few tens nm, thus limiting the thickness of the strained active layers to a few Qwells.



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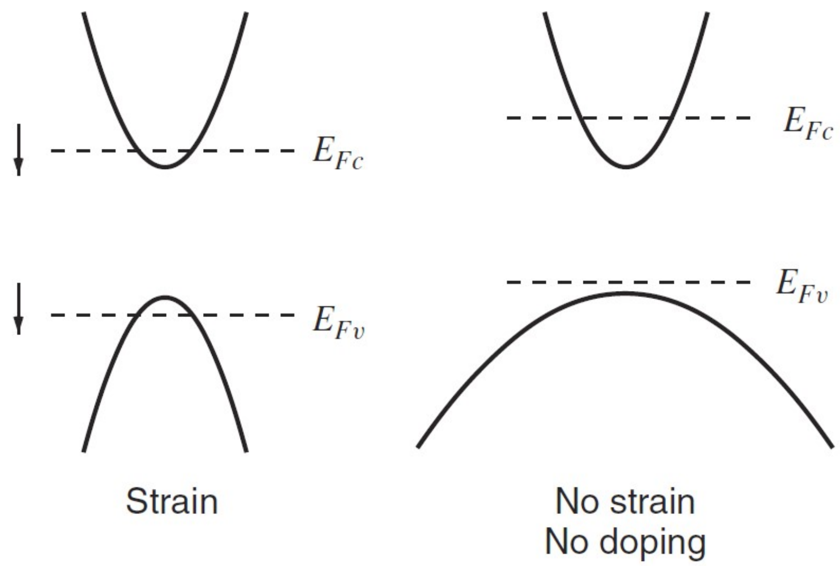
Strained materials

- Both strains increase the curvature of the valence band structure, greatly reducing the effective mass of holes. However, compressive strain is better to do this.

- Therefore, the quasi-Fermi levels separate more symmetrically than those without strain.
- For a given quasi-Fermi level separation, the electron carrier density is always lower in the strain case. Therefore, the transparency carrier density can be reduced in strained materials.



- The reduction of transparency current can be up to a factor of 2.

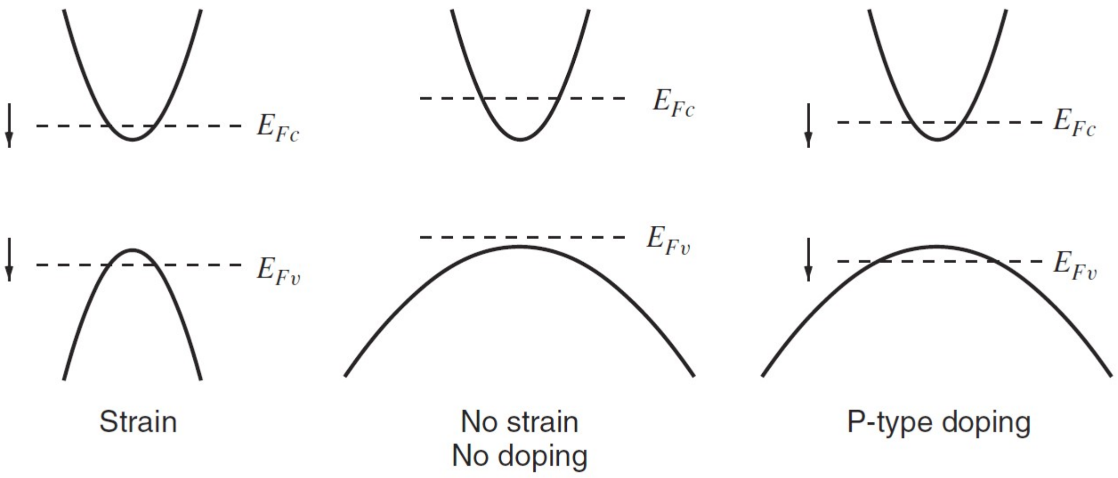
Strained materials

- Strain increases the differential gain dg/dN as well, that is, the gain increases faster with carrier density.
- The differential gain depends on how quickly the band-edge carrier density changes in response to movements in the quasi-Fermi levels. It is maximized when the quasi-Fermi level is aligned with the band edge. In order to enhance the differential gain, it is critical to bring both quasi-Fermi levels as close to the band edges as possible.
- The improvement in differential gain in strained materials can be as much as a factor of 2.

P-doping materials

- P-type doping of the active region pull down the quasi-Fermi levels down to a more symmetrical position as the strain does. Thus, the differential gain is improved.

- However, p-type doping increases the transparency current density: while the electron density can be reduced at transparency, the hole density is increased. Because the hole density is nondegenerate, the downward shift of quasi-Fermi levels increases hole density faster than it decreases the electron density. Thus, the NP product increases, resulting in a higher transparency current density.



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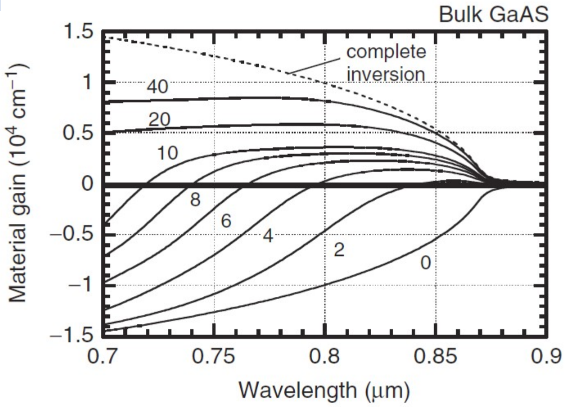
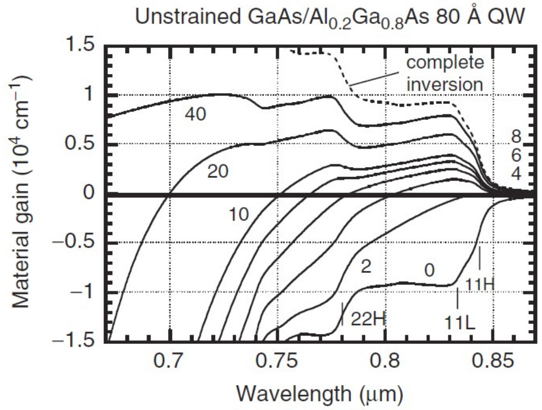
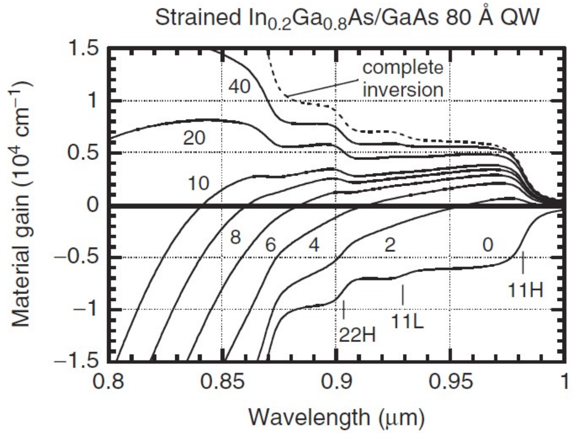
Gain spectra of GaAs system

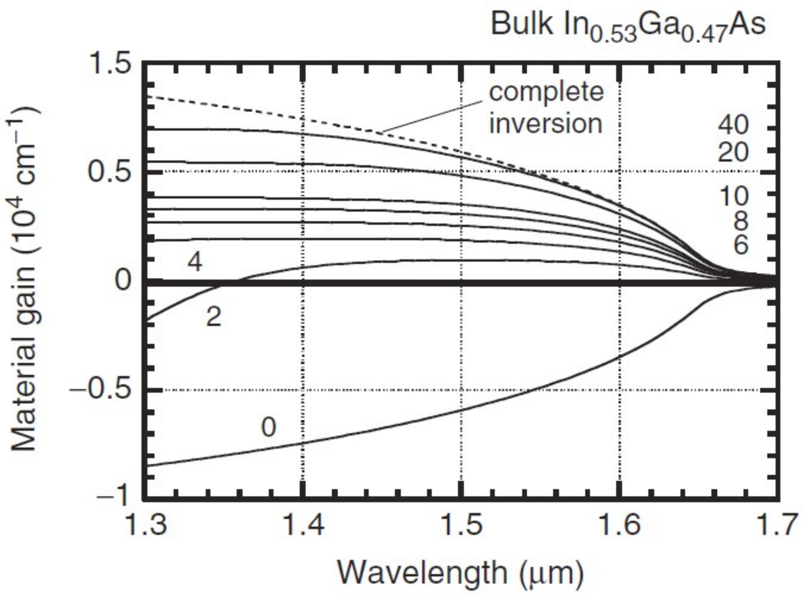
- Using the gain expression and considering the lineshape broadening effect. Assuming the charge neutrality and considering the TE polarization, the gain spectra are calculated.
- The bulk gain spectra are smoother than the Qwell gain spectra.
- The Qwell gain near the band edge is higher.
- The unstrained Qwell provides higher maximum gain than the strained one, but requires more carriers to reach complete inversion.
- The Qwell gain spectra include various subband transitions.
- For very high carrier density, the barrier can be also inverted to produce gain.
- Positive gain requires a minimum density of ~2e12 cm^{-2}.

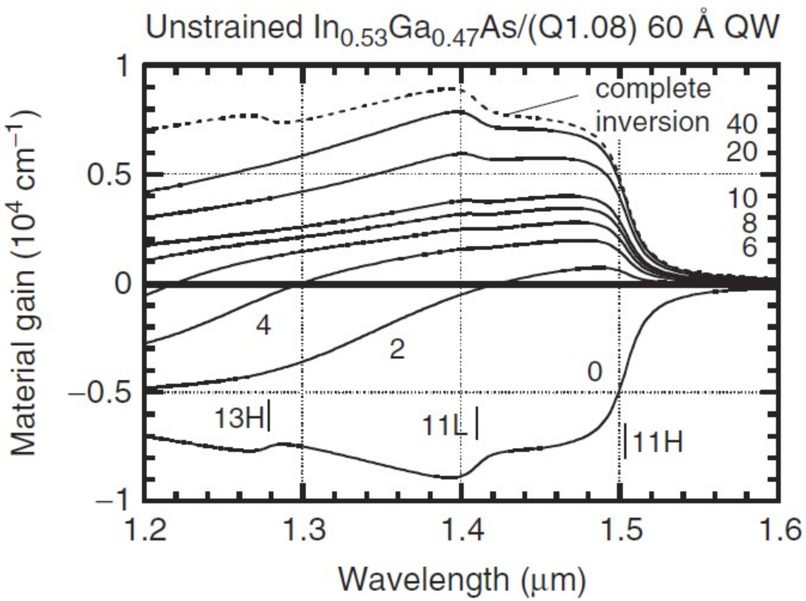


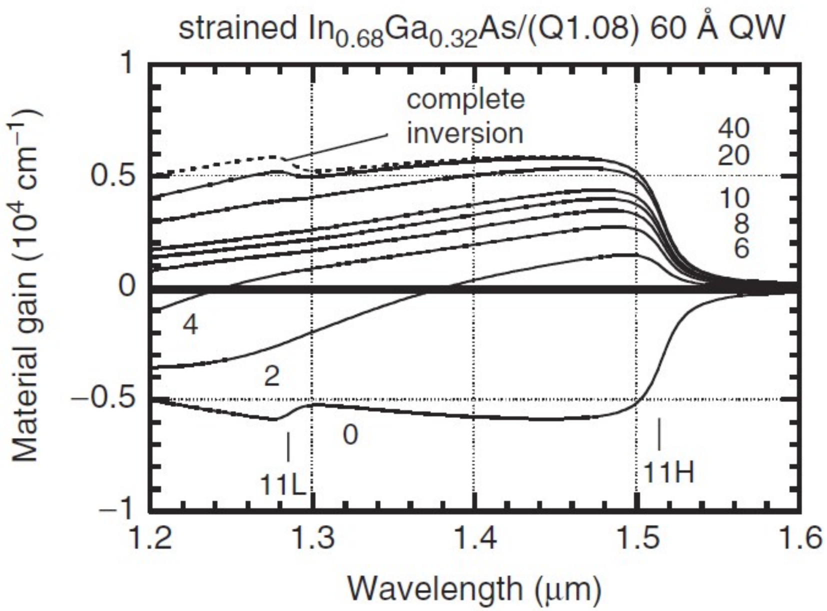




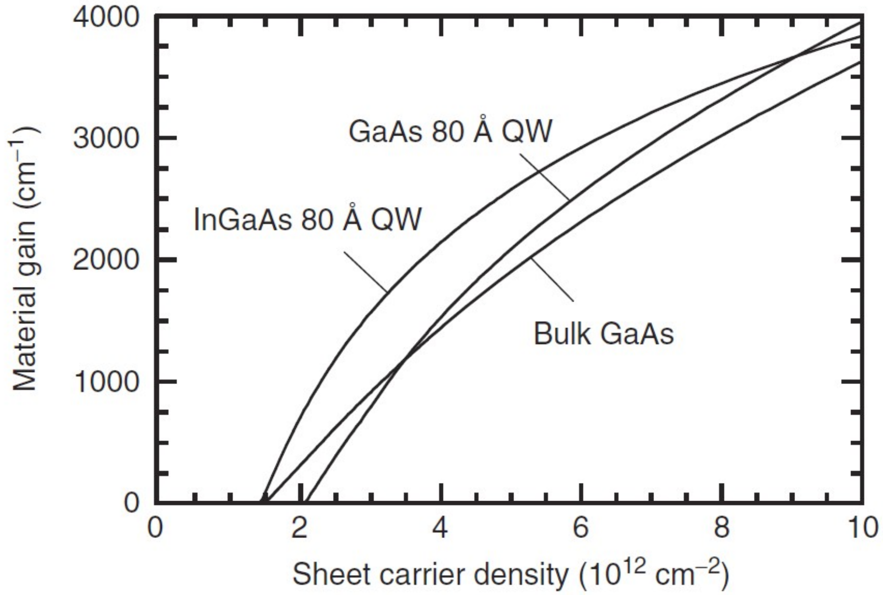
Gain spectra of InP system





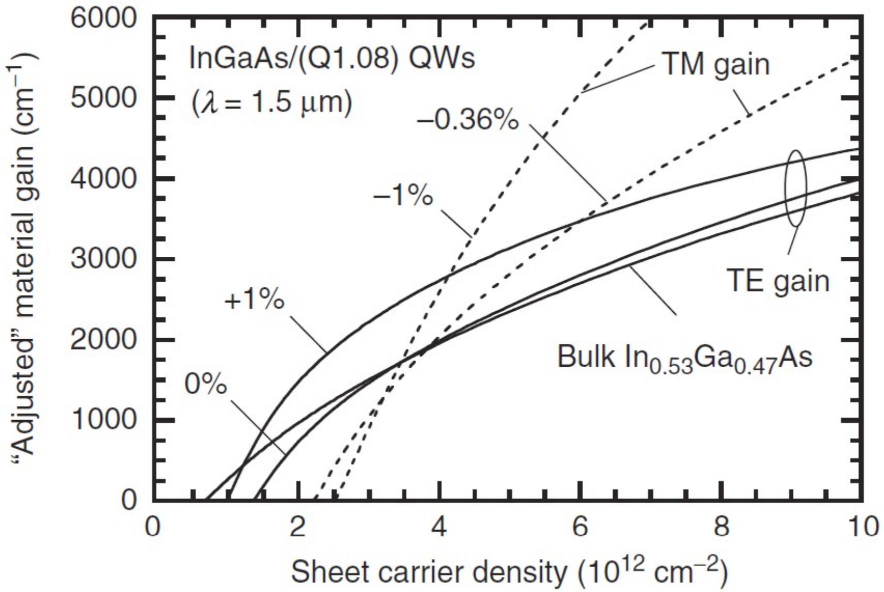


Gain versus carrier density (GaAs)



- The peak TE gain increases with the carrier density, the transparency carrier density is around 2e-12 cm^{-2}.
- 8 nm GaAs Qwell is similar to GaAs bulk, the improved performance is gained from the volume reduction, rather than the quantum effect.
- The strained InGaAs Qwell has the lowest N_{tr}, and the highest differential gain.

Gain versus carrier density (InP)



- In the tensile strain case (-), the C-LH transition dominates, leading to higher TM gain.
- The tensile strain results in higher N_{tr}, and higher differential gain.
- The compressive strain has lower threshold, and the gain saturates faster.
- The bulk has the lowest N_{tr}.

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Gain versus carrier density model

	$g = g_0 \ln\left[\frac{N+N_s}{N_{tr}+N_s}\right]$			$g = g_0 \ln[N/N_{tr}]$	
Active Material	N_{tr}	N_s	g_0	N_{tr}	g_0
Bulk GaAs	1.85	6	4200	1.85	1500
GaAs/$Al_{0.2}Ga_{0.8}As$ 80 Å QW	2.6	1.1	3000	2.6	2400
$In_{0.2}Ga_{0.8}As$/GaAs 80 Å QW	1.8	−0.4	1800	1.8	2100
Bulk $In_{0.53}Ga_{0.47}As$	1.1	5	3000	1.1	1000
InGaAs 30 Å QW (+1%)	3.3	−0.8	3400	3.3	4000
InGaAs 60 Å QW (0%)	2.2	1.3	2400	2.2	1800
InGaAs 120 Å QW (−0.37%)	1.85	0.6	2100	1.85	1800
InGaAs 150 Å QW (−1%)	1.7	0.6	2900	1.7	2300
$In_{0.15}Ga_{0.85}N$ 25 Å QW [42]	—	—	—	8	2400

Inverse Relation

$$N = (N_{tr} + N_s)e^{g/g_0} - N_s$$

Differential Gain

$$\frac{dg}{dN} = \frac{g_0}{N + N_s}$$

$[N] = 10^{18}\ \mathrm{cm}^{-3}$, $[g] = \mathrm{cm}^{-1}$.

- Usually, the gain follows a logarithmic relation with the carrier density.
- A third parameter N_s is introduced to better fit more linear gain curves.

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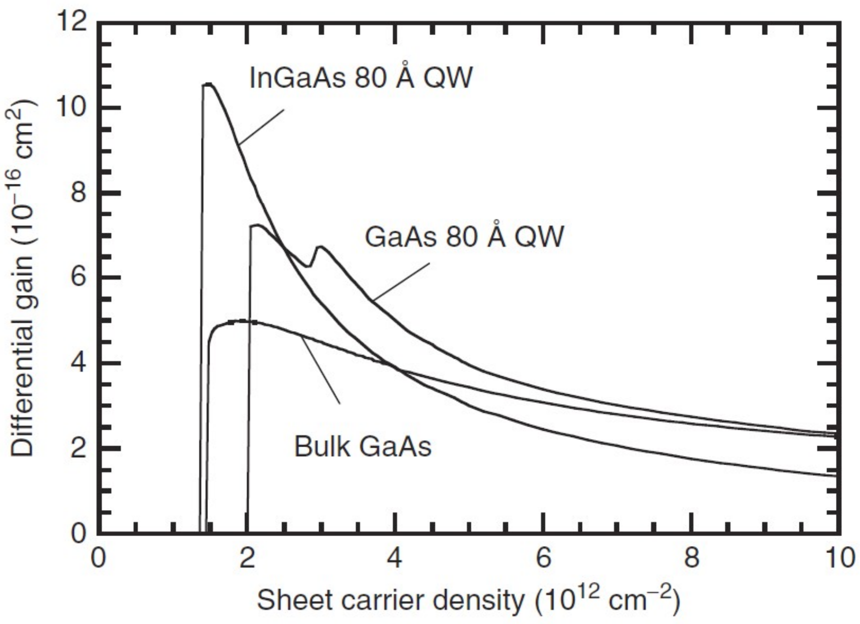
The differential gain

- The differential gain is crucial for determining the resonance frequency, and higher value is expected. Thus, it is important to operate the laser close to transparency when designing high-speed lasers.



- The strain (InGaAs) enhances the differential gain value by about 50%.
- The bulk has the lowest differential gain.
- The secondary peak in the GaAs QW is due to the switch from C-HH(11) to C-LH(11), with slightly shorter wavelength.
- The differential gain is on the order of 10^{-16} /cm.

P226, example 4.7

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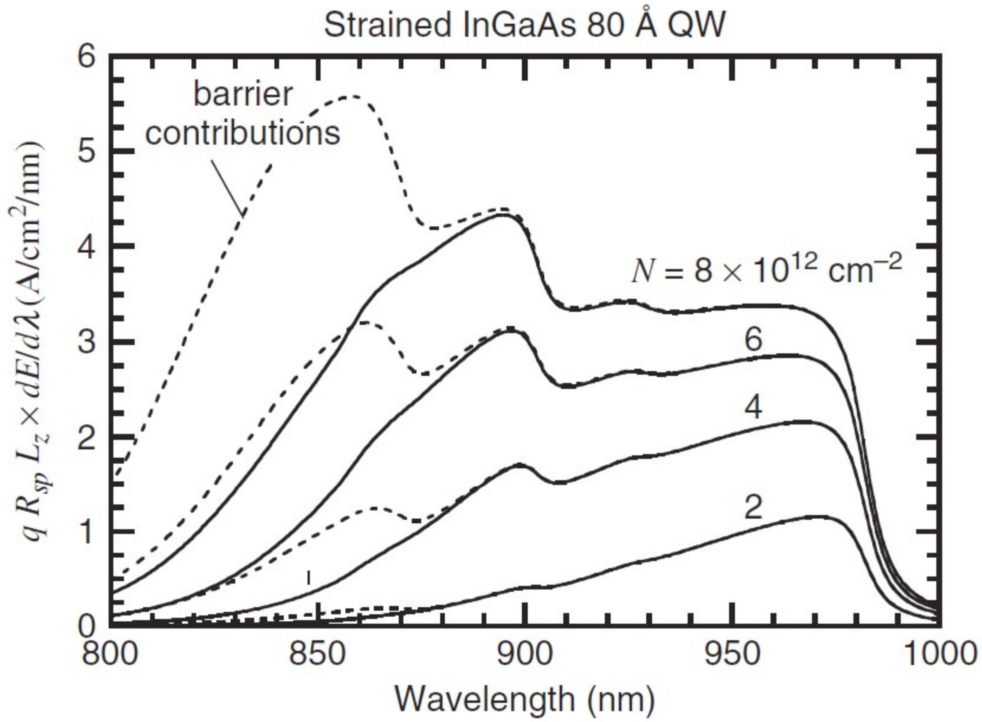
Spontaneous emission spectra



- The n=1 transition step height is much higher than the n=2 transition, due to its larger transition matrix element.
- The barrier of GaAs contributes to the spontaneous emission spectra at high carrier densities (dashed lines).

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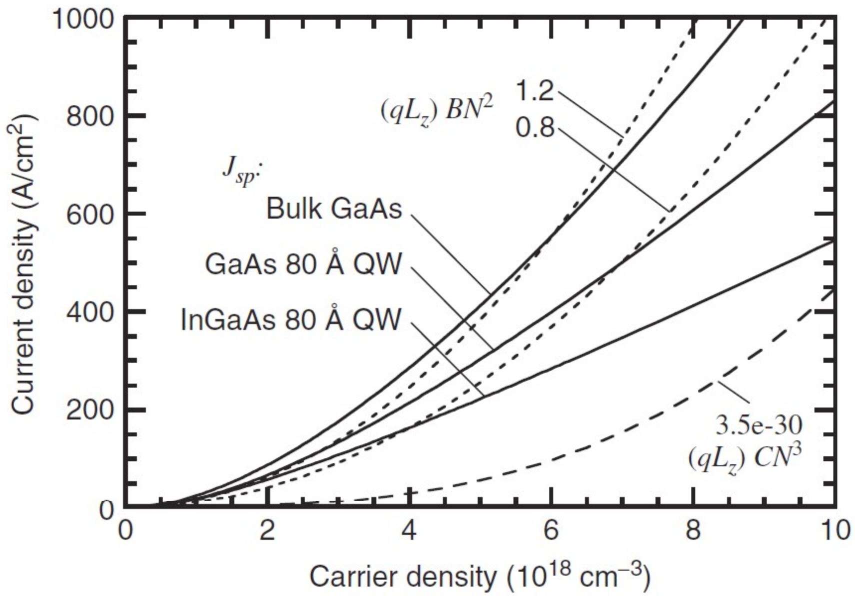
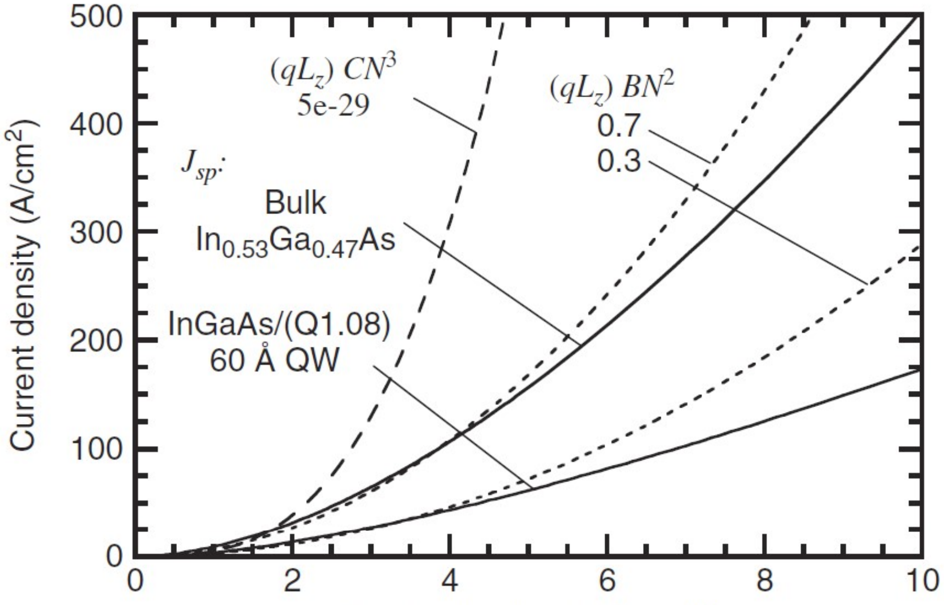
Spontaneous emission current density



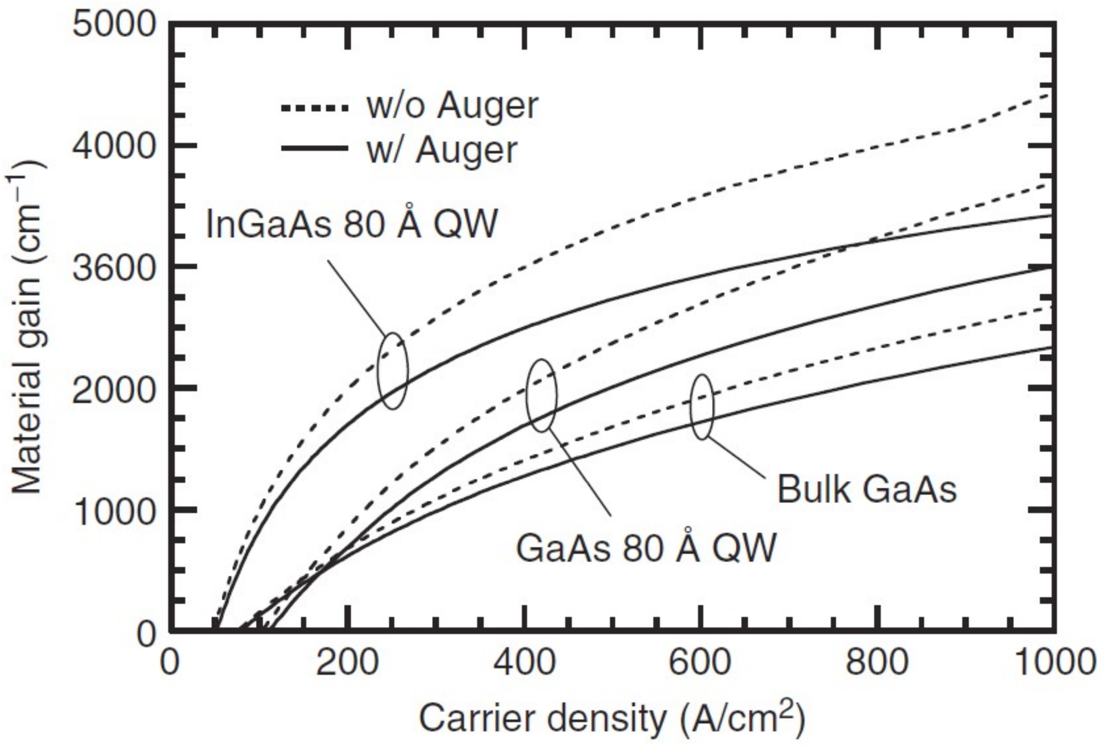
- For low carrier densities, the current density roughly follows the BN^2 law.
- For high carrier densities, the BN^2 law overestimates the current density, because it is only valid within the Boltzmann approximation. As the injection level becomes highly degenerate, the rate does increase so rapidly.
- The QWs have lower B coefficients than the bulks.
- In GaAs system, the Auger recombination is much smaller than the spontaneous emission.

Spontaneous emission current density



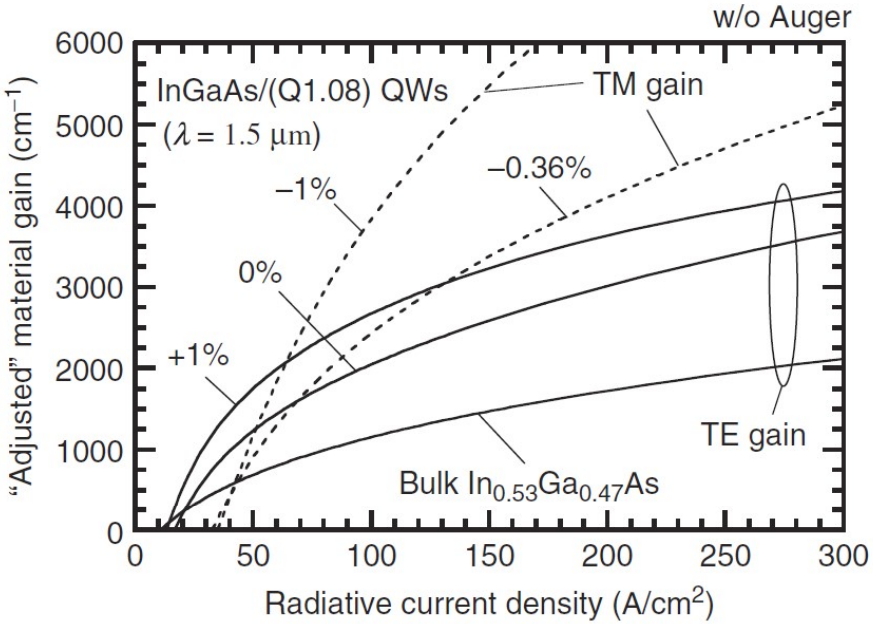
- The InP-based system has lower B coefficients than the GaAs-based system, due to the lower optical mode density a longer wavelengths (less modes, less spontaneous emission).
- In InP system, the Auger current is much higher than the spontaneous emission current due to its smaller bandgap.
- Therefore, the radiative efficiency is usually below 50%.

Gain versus current density



- The strained QW has the best performance, with lower transparency carrier density and higher material (TE) gain.
- For a given (threshold) gain, the strained QW requires roughly half the current required by the unstrained QW.

Gain versus current density



- The compressive strained QW has similar transparency current density as the bulk, around 10-15 A/cm^2.
- The tensile stained QW has higher transparency current density around 30-35 A/cm^2.
- However, the Auger recombination prevents such low threshold current densities.

Gain versus current density model

	$g = g_0 \ln\left[\frac{J + J_s}{J_{tr} + J_s}\right]$			$g = g_0 \ln[J/J_{tr}]$	
Active Material	J_{tr}	J_s	g_0	J_{tr}	g_0
$J_{sp} + J_{bar} + J_{Aug}$					
Bulk GaAs	80	140	1400	80	700
GaAs/$Al_{0.2}Ga_{0.8}As$ 80 Å QW	110	50	1600	110	1300
$In_{0.2}Ga_{0.8}As$/GaAs 80 Å QW	50	−10	1100	50	1200
InGaAsP/InGaAsP 65 Å QW [36]	—	—	—	44	1040
$In_{0.15}Ga_{0.85}N$ 25 Å QW [37]*	—	—	—	300	1200
$In_{0.15}Ga_{0.85}N$ 25 Å QW [38]*	900	31 K	5403	—	—
J_{sp}					
Bulk GaAs	75	200	1800	75	800
GaAs/$Al_{0.2}Ga_{0.8}As$ 80 Å QW	105	70	2000	105	1500
$In_{0.2}Ga_{0.8}As$/GaAs 80 Å QW	50	0	1440	50	1440
J_{sp}					
Bulk $In_{0.53}Ga_{0.47}As$	11	30	1000	11	500
InGaAs 30 Å QW (+1%)	13	2	2800	13	2600
InGaAs 60 Å QW (0%)	17	11	1500	17	1200
InGaAs 120 Å QW (−0.37%)	32	18	1400	32	1100
InGaAs 150 Å QW (−1%)	35	10	1700	35	1500

Inverse Relation

$$J = (J_{tr} + J_s)e^{g/g_0} - J_s$$

$[J] = \text{A/cm}^2, [g] = \text{cm}^{-1}$

Differential Gain

$$\frac{dg}{dJ}L_z = \frac{g_0}{J + J_s}L_z$$

P232, example 4.8

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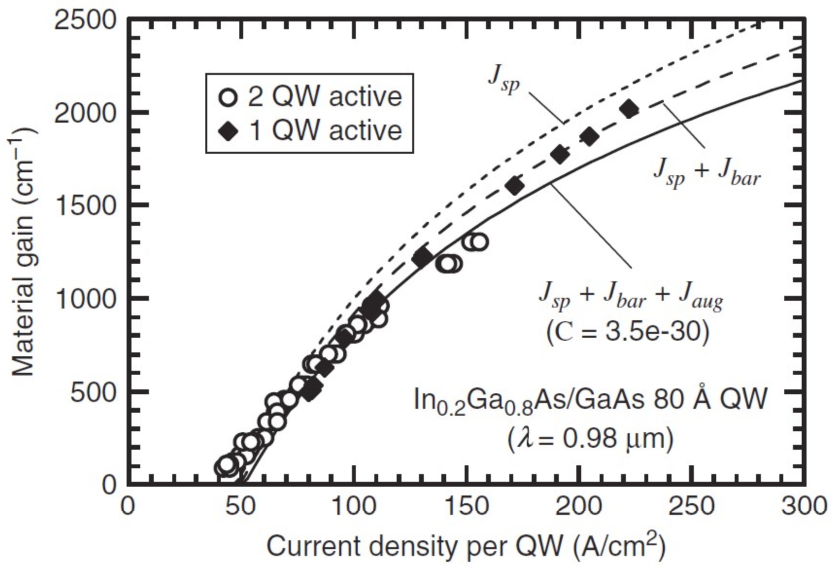
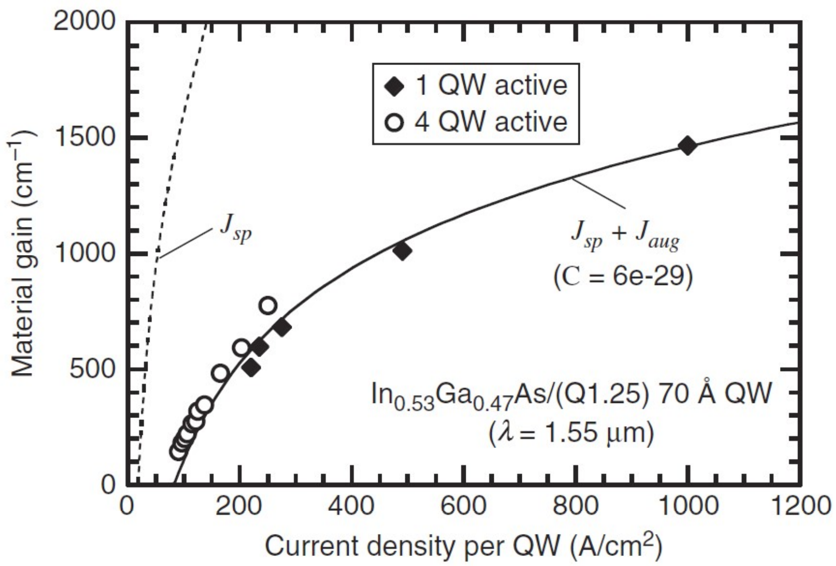
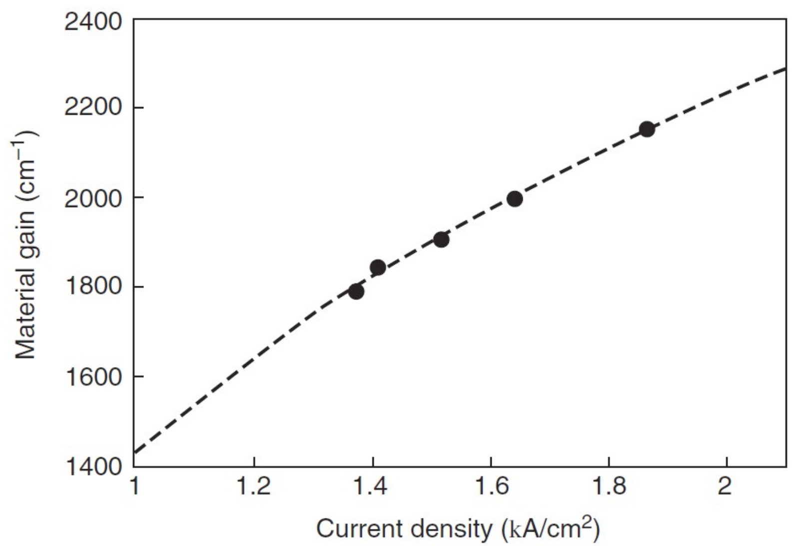
Experimental gains

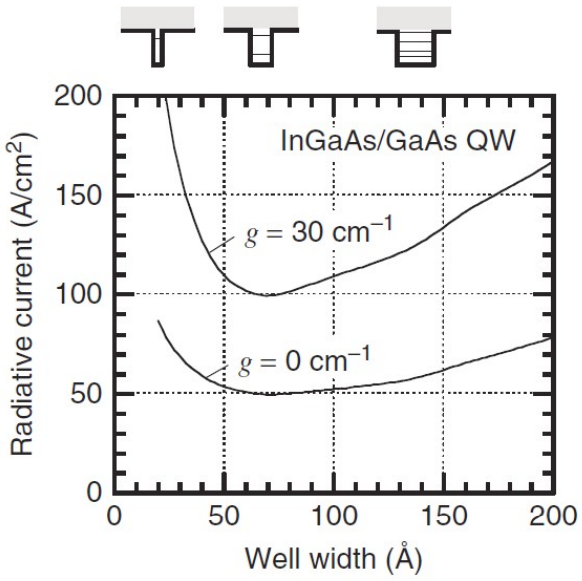


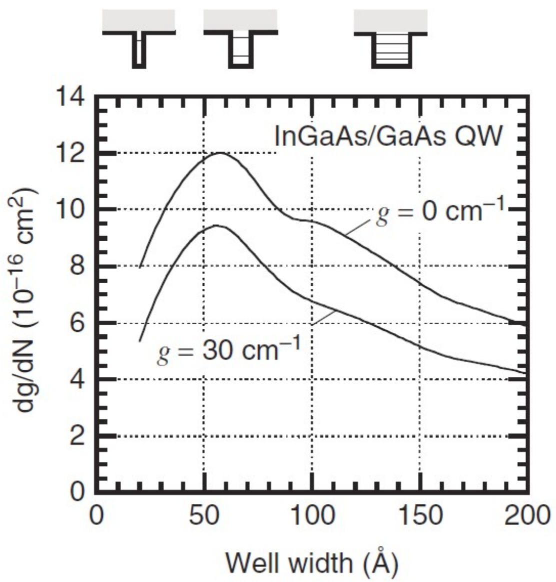




- The theory is in good agreement with the experiments for 980nm GaAs, 1550 nm InP, and 445 nm GaN-based systems.

Dependence on the well width





- The minimum required current for a certain gain is in the range of 5-10 nm.
- Larger width reduces the subband spacing, and higher subandbs can be populated.
- Smaller width levers the lowest suband up to close to the barrier, and barrier states can be populated.

- The maximum gain occurs around 6 nm.

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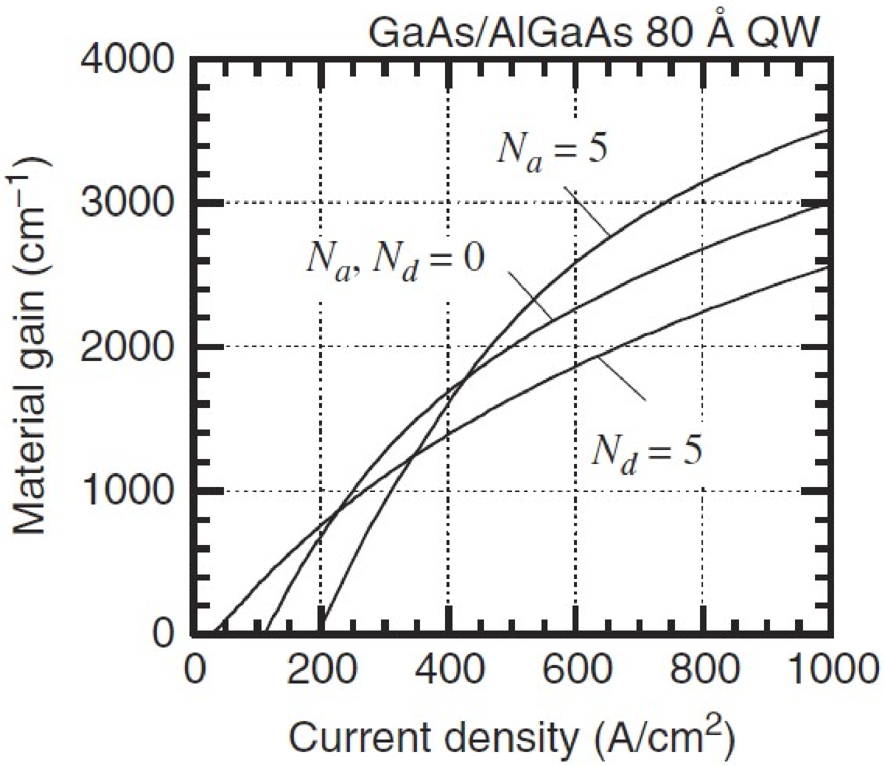
Dependence on the doping

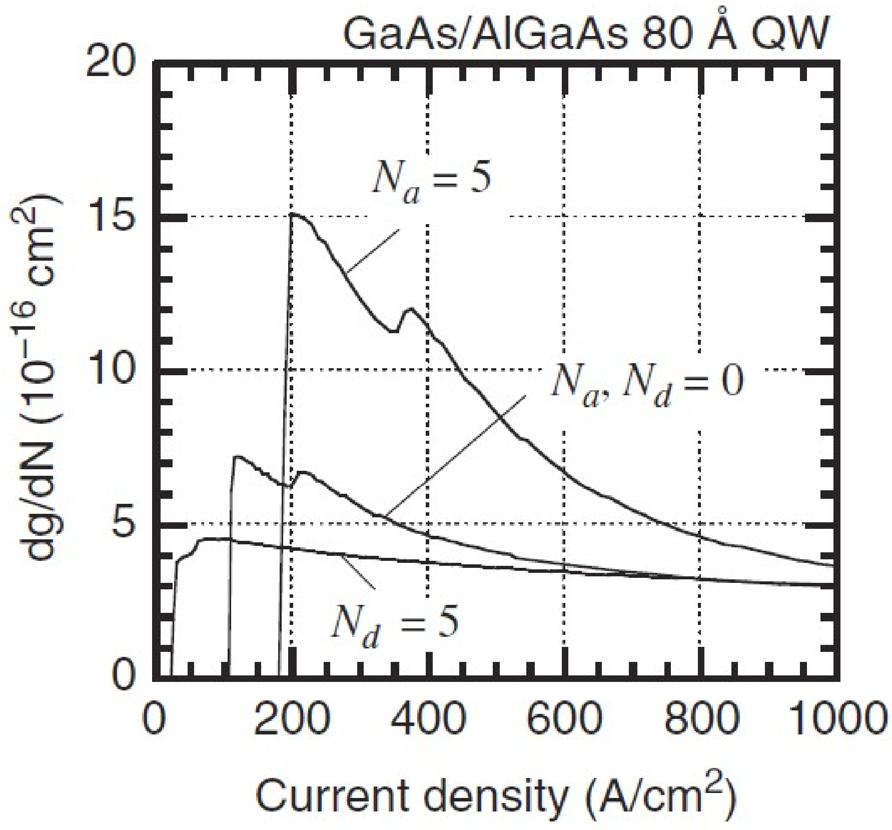
- Doping in the barrier instead of active region (modulation doping) changes the the charge neutrality condition:

$$N + N_A^- = P + N_D^+$$



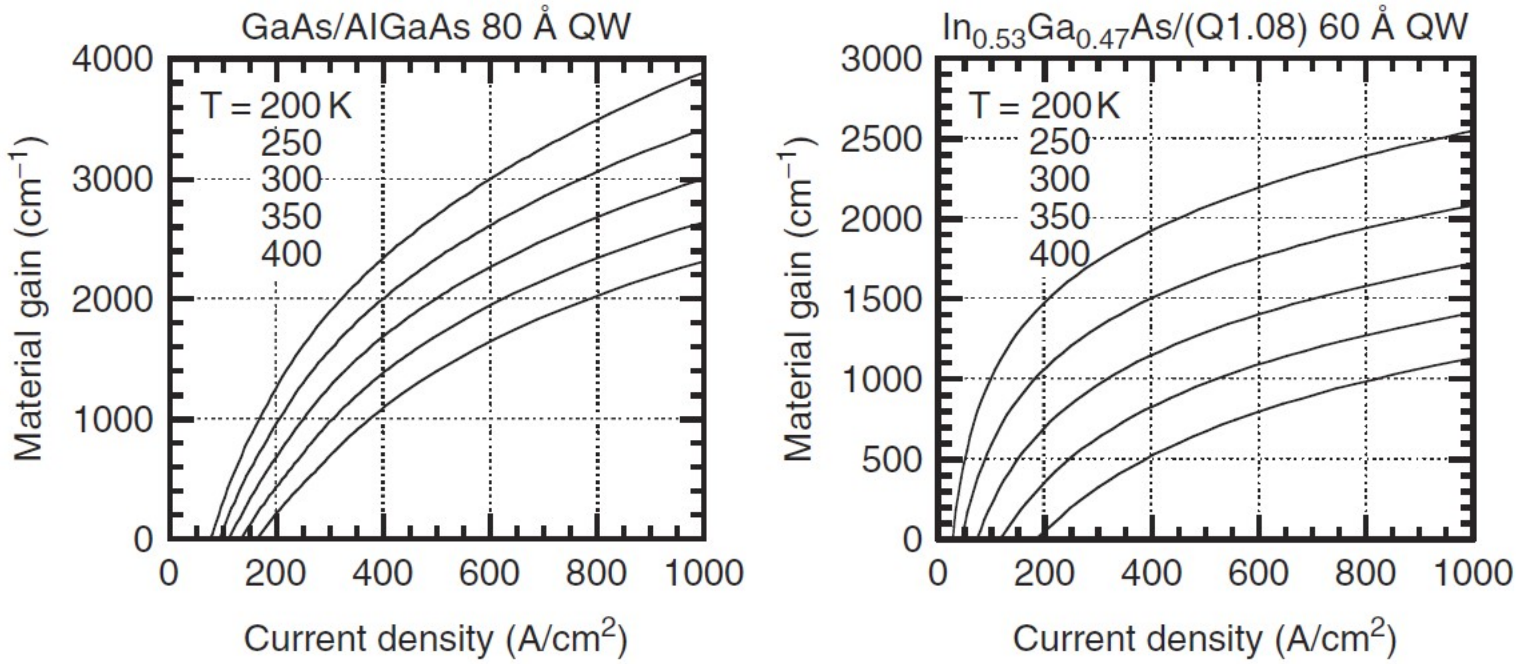
- For the p-doping, the downward shift of the quasi-Fermi levels increases the NP product (N is degenerate and P is nondegenerate at transparency).
- For the n-doping, the upward shift of the quasi-Fermi levels reduces the NP product.
- Therefore, the n-doping reduces the current density, while the p-doping increases the current density.

Dependence on the doping



- Due to the alignment of the quasi-Fermi levels with respect to the band edges, p-type doping increases the differential gain dramatically, whereas n-doping reduces the differential gain.
- Therefore, ultra-high-speed laser design favors p-doping, while ultra-low-threshold current laser design favors n-doping.
- Note that the strain can reduce the threshold current density, while increase the differential gain。

Dependence on the temperature



- The current required to reach a given gain increases with increasing temperature. The dominate cause is the broadening of the Fermi occupation probability function, which spreads the carriers over a larger energy range for a given overal carrier density. The result is a lower spectral concentration of the inverted carriers, which leads to a broadening and flattening of the gain spectrum.
- In addition, non-radiative recombination and internal loss increase as well.

P237, example 4.9