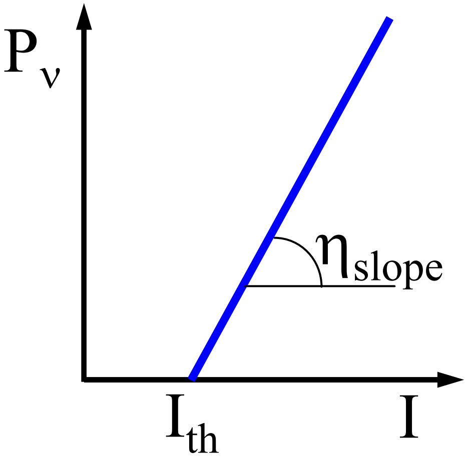
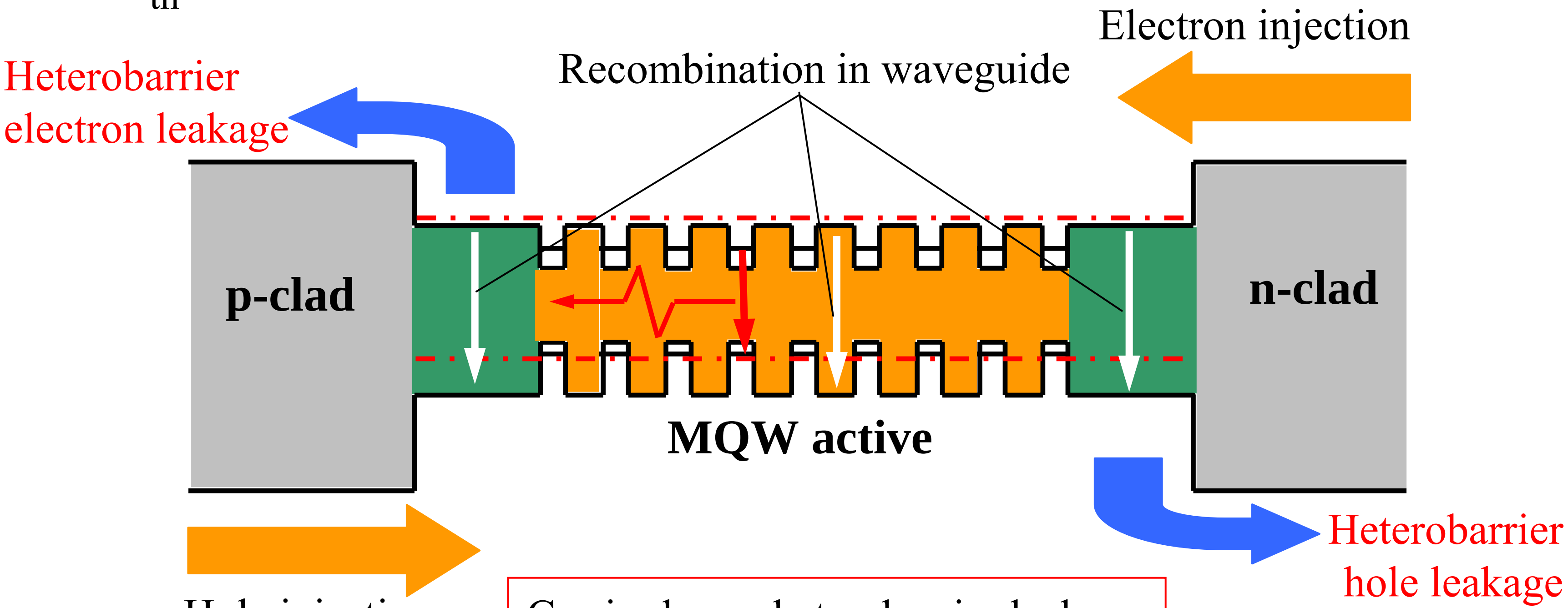
Laser injection efficiency



$$P_\nu = \eta_{slope}\cdot\left(I - I_{th}\right)$$

$$\eta_{slope} = \eta_i \cdot \frac{\alpha_m}{\alpha_i + \alpha_m}\cdot\frac{h\nu}{q}$$

$$\boxed{\eta_i = \frac{\#_{phot}}{\#_{e-h}} \le 1}$$



Electron injection

Recombination in waveguide

Heterobarrier electron leakage

p-clad

n-clad

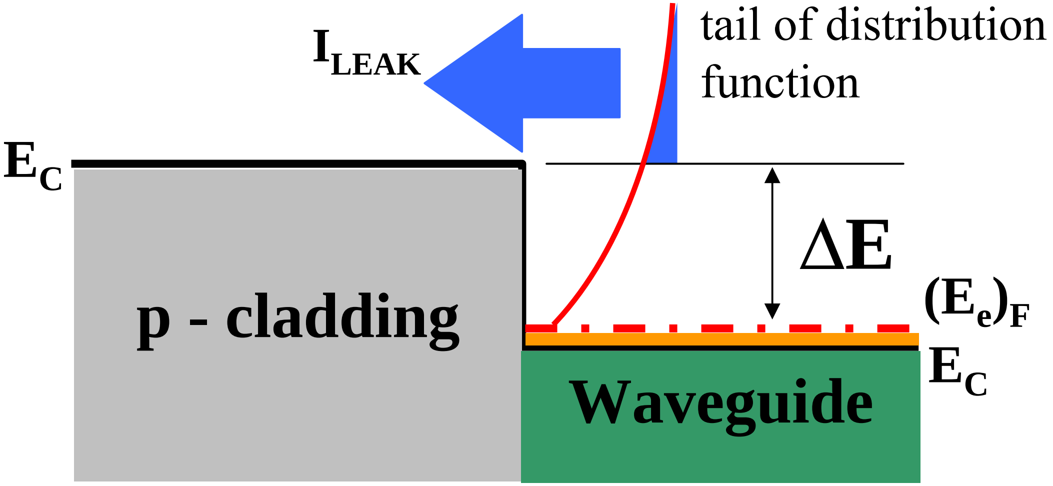
MQW active

Hole injection

Heterobarrier hole leakage

Carrier loss – heterobarrier leakage and waveguide recombination

Heterobarrier carrier leakage



Thermionic emission current density

$$\boxed{I_{LEAK} \propto T^2 \cdot \exp\left(-\frac{\Delta E}{kT}\right)}$$

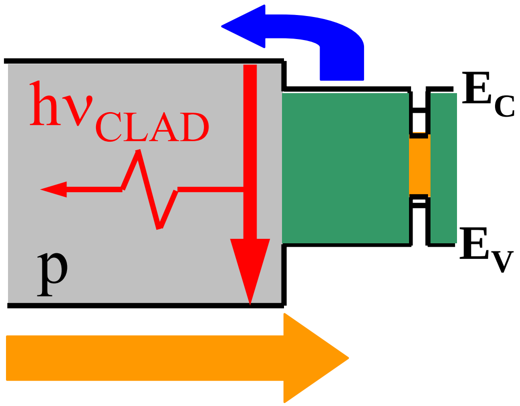
Heterobarrier carrier leakage reduces laser injection efficiency η_i.

After threshold, injected carriers can be captured into QW and recombine or be emitted from QW into the cladding.

Heterobarrier carrier leakage affects temperature dependence of the laser efficiency.

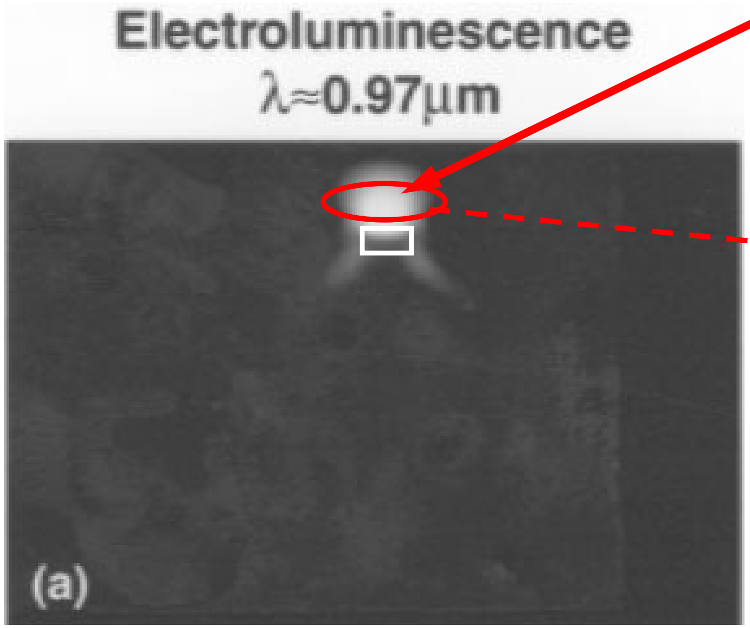
At room temperature (kT=0.026eV), the decrease of the barrier energy from 200meV to 100meV increases the thermionic emission current 55 times.

Experimental observation of the heterobarrier carrier leakage

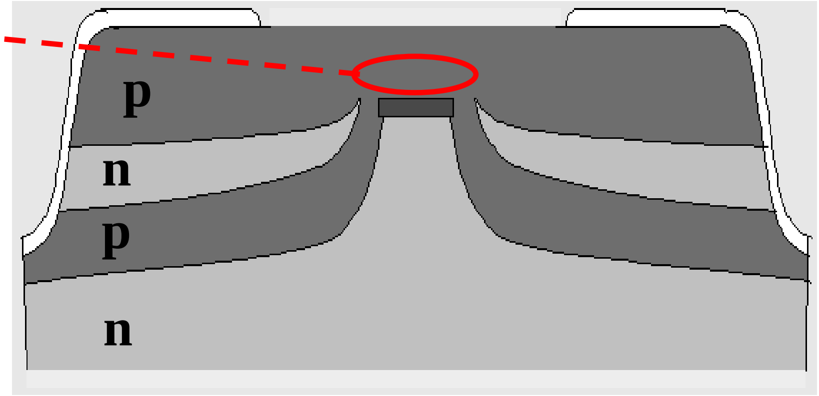


Carriers emitted into the cladding layer can recombine radiatively or nonradiatively. If the cladding layer is made of direct bandgap material the radiative recombination will be significant and spontaneous emission from cladding can be observed.

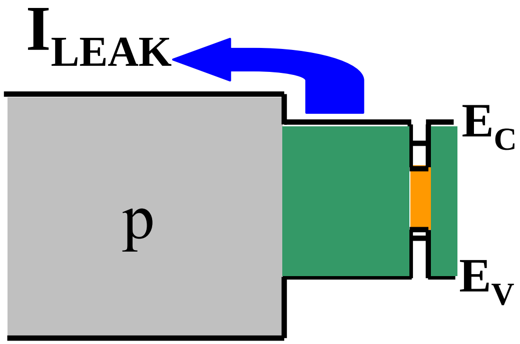
IR camera image of the CMBH laser cross-section shows electroluminescence from p-cladding evidencing significant heterobarrier leakage.



* cross-section of CMBH laser

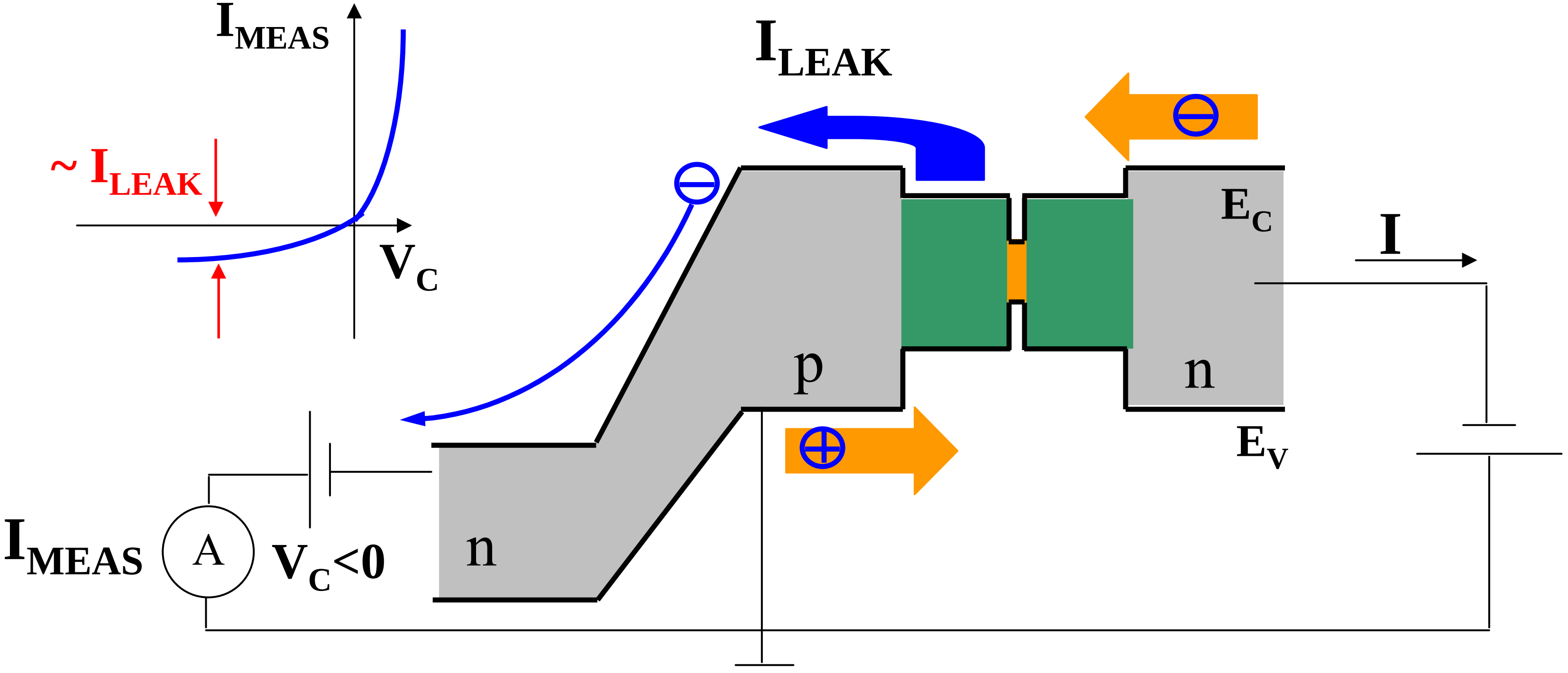


Measurements of the electron heterobarrier leakage current



I_{LEAK} can be measured by **small** n-collector which is build on top of the p-cladding layer.

* carrier lifetime in cladding should be estimated



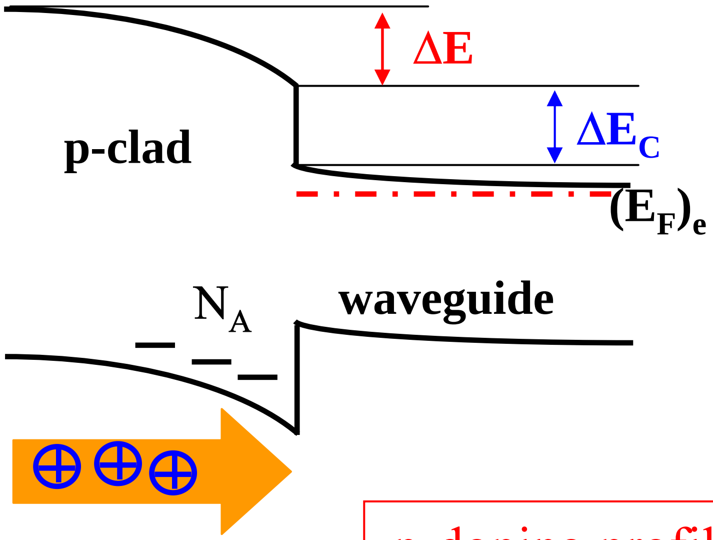
Why heterobarrier electron leakage is so important?

1.3 and 1.5μm telecom lasers are made of InGaAsP/InP. In InGaAsP/InP the ratio of the band offsets $\Delta E_C/\Delta E_V \approx 40\%$.

Typical value of the ΔE_C is less than 100meV

The heterobarrier electron leakage reduces laser efficiency, increases threshold current and enhances their temperature sensitivity (reduces T_0 and T_1).

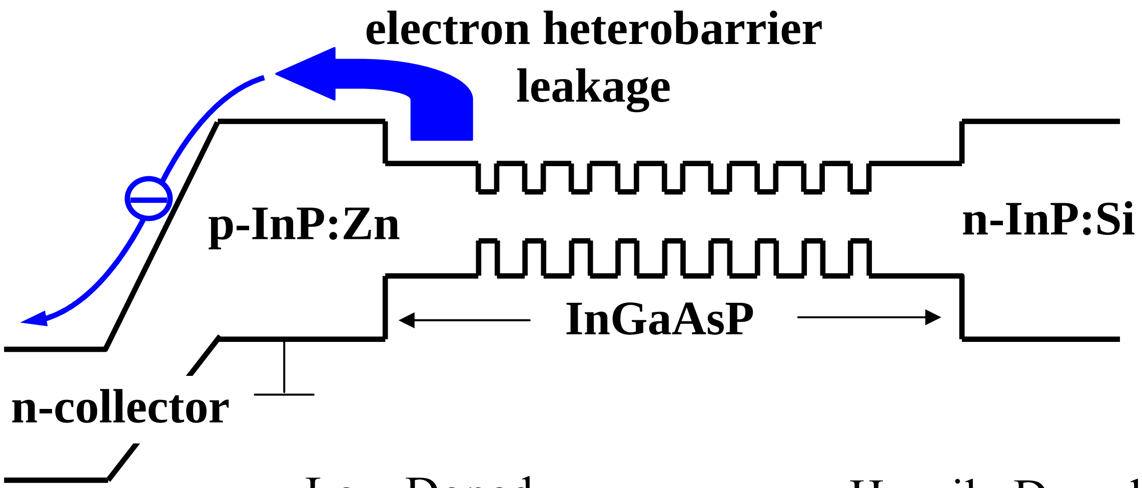
How can InGaAsP/InP laser temperature performance be improved?



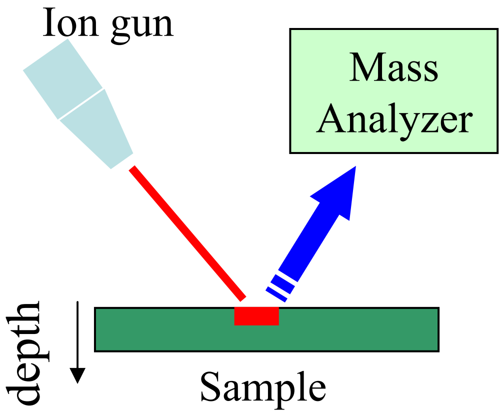
The barrier for electron thermionic emission from waveguide into p-cladding contains two contributions: **ΔE_C** ~ 100meV and modulation doping barrier **ΔE.**

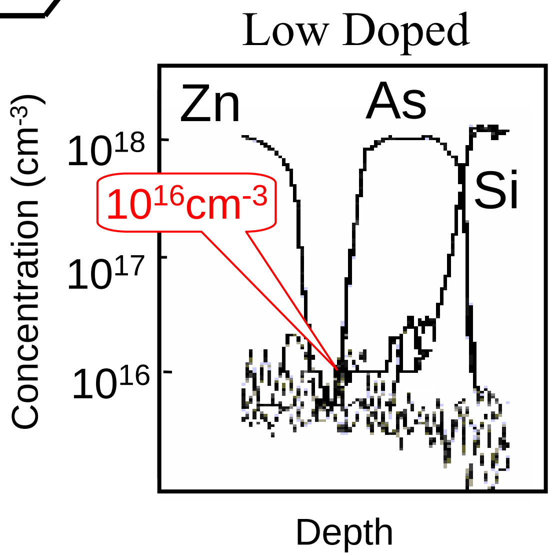
p-doping profile optimization can improve laser T_0 and T_1

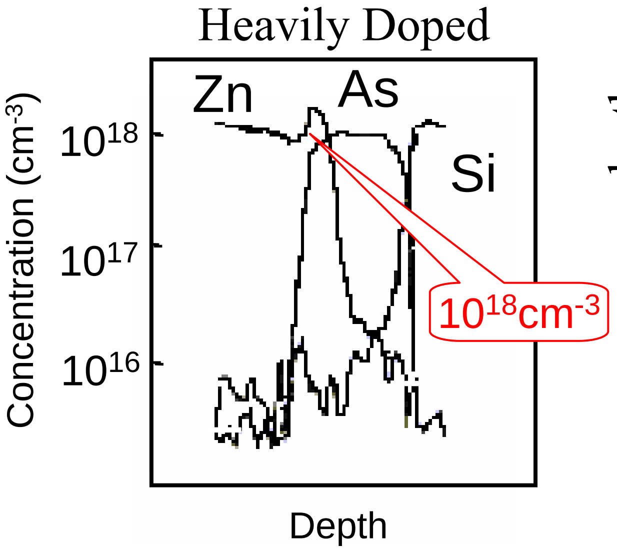
1.3μm InGaAsP/InP lasers with different doping profiles



Device doping profile is controlled by Secondary Ion Mass Spectroscopy (SIMS)



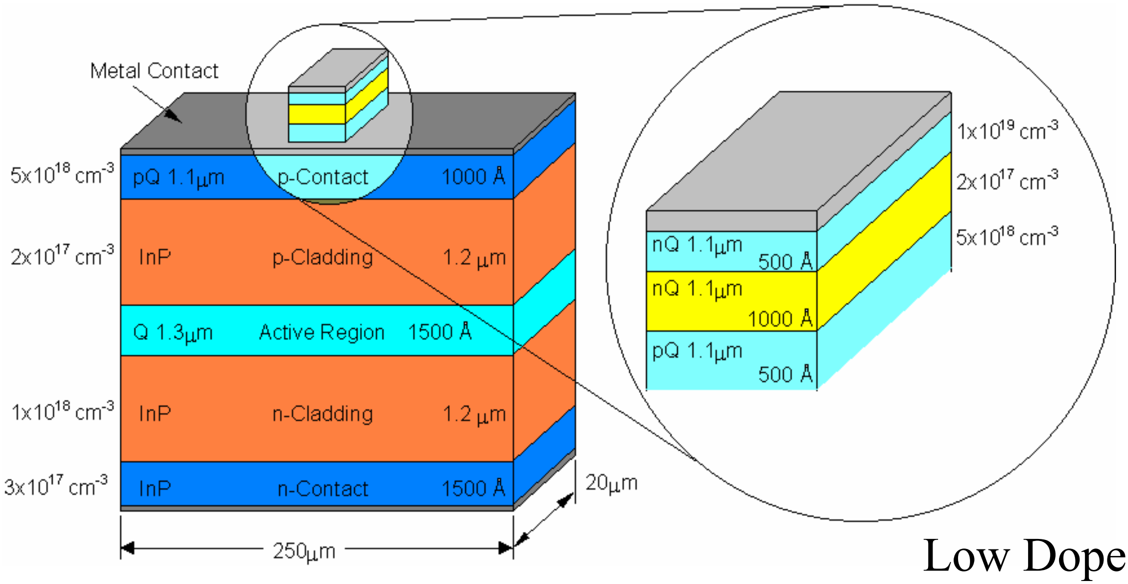


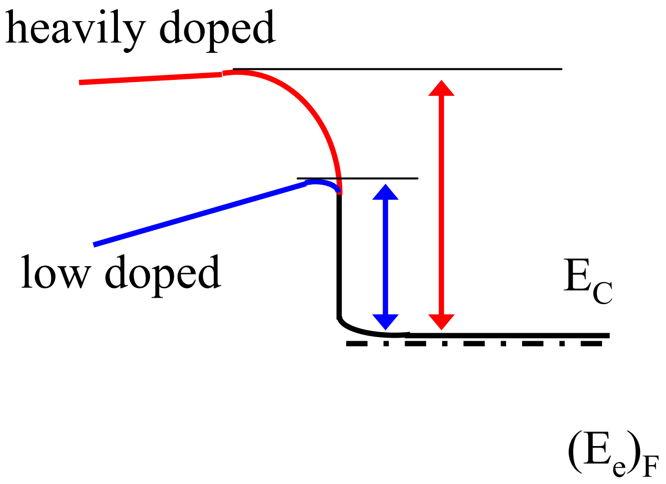


Low doped structure should have smaller ΔE and, hence, larger heterobarrier electron leakage current I_{LEAK}.

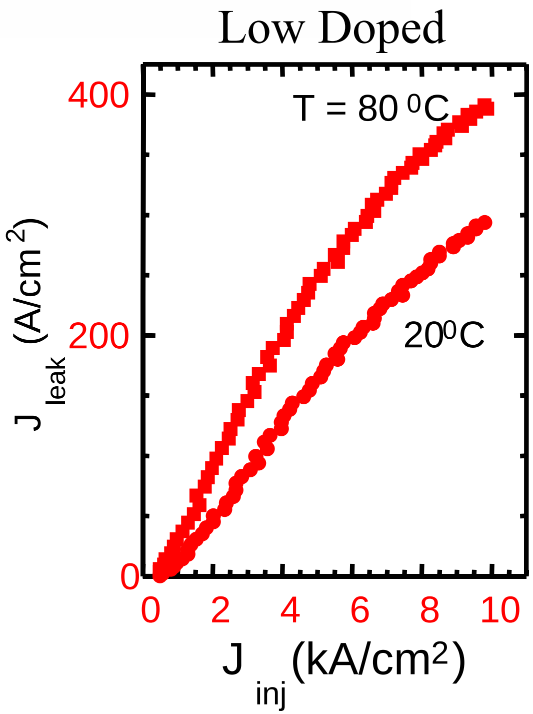
* **As** signal denotes the location of waveguide and MQW active regions

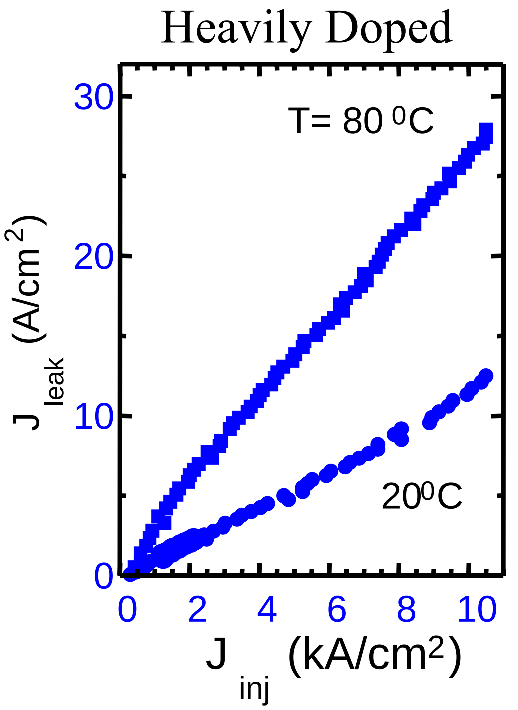
Dependence of the heterobarrier leakage current on p-doping profile



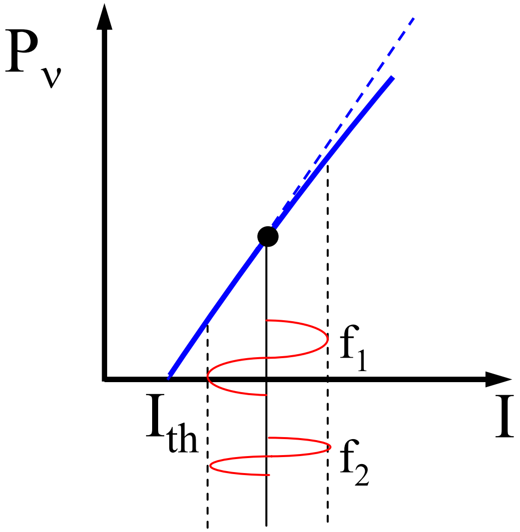


Heterobarrier electron leakage can be reduced by the order of magnitude with proper p-doping profile





Heterobarrier electron leakage and laser distortion.



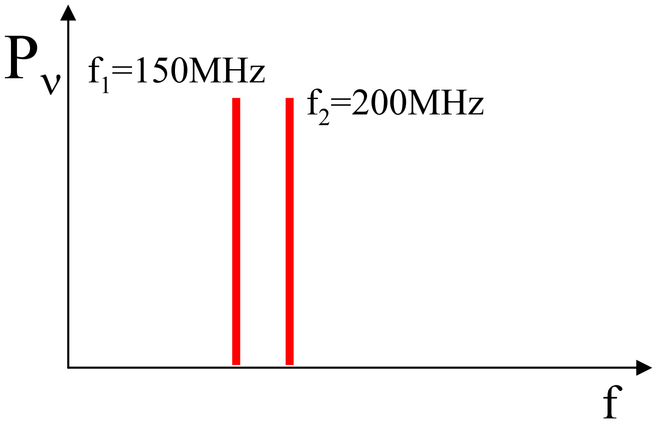
Nonlinearity of LI characteristics due to carrier leakage leads to distortions in transmitted signal

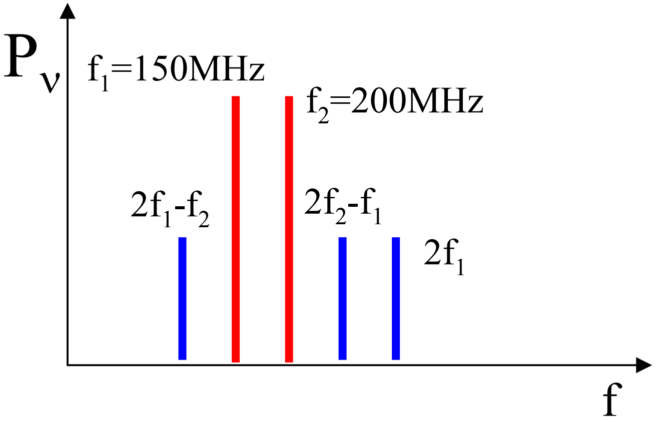
$$\delta P_\nu = \eta_d \cdot \delta I + \beta \cdot (\delta I)^2,\ \beta = \frac{1}{2} \cdot \frac{d^2 P_\nu}{dI^2}$$

1. **Harmonic**: $2f_1$ and $2f_2$, $3f_1$ and $3f_2$, …
2. **Intermodulation**: $f_1 \pm f_2$, $2f_1 \pm f_2$, $2f_2 \pm f_1$, …

TV input at two subcarriers f_1 and f_2

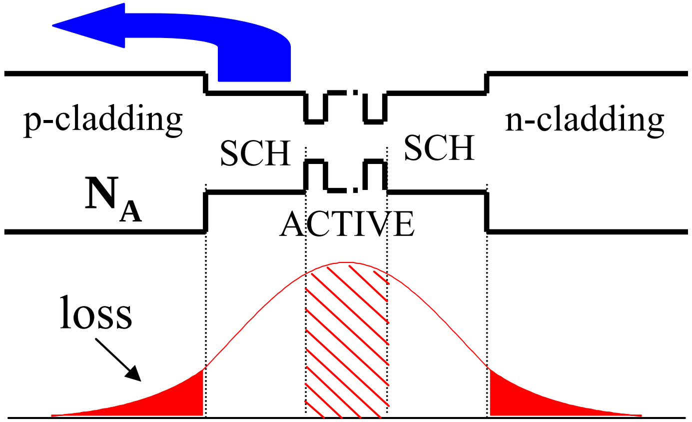
Distorted TV signal in fiber



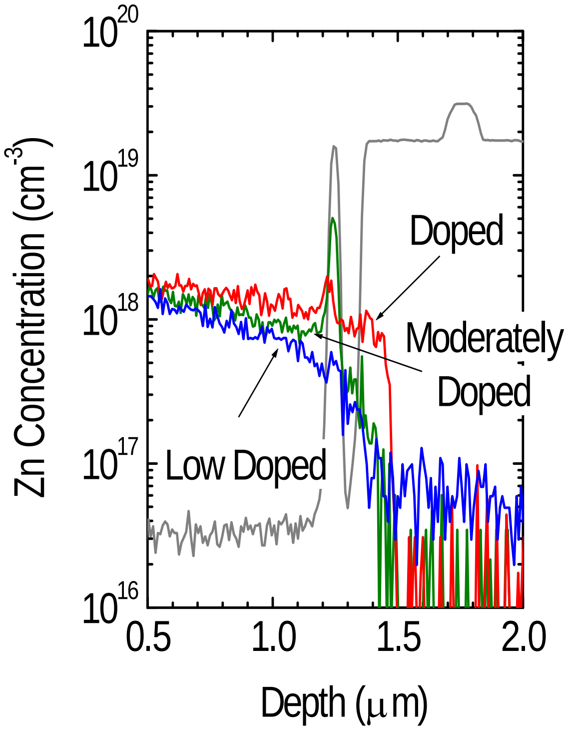


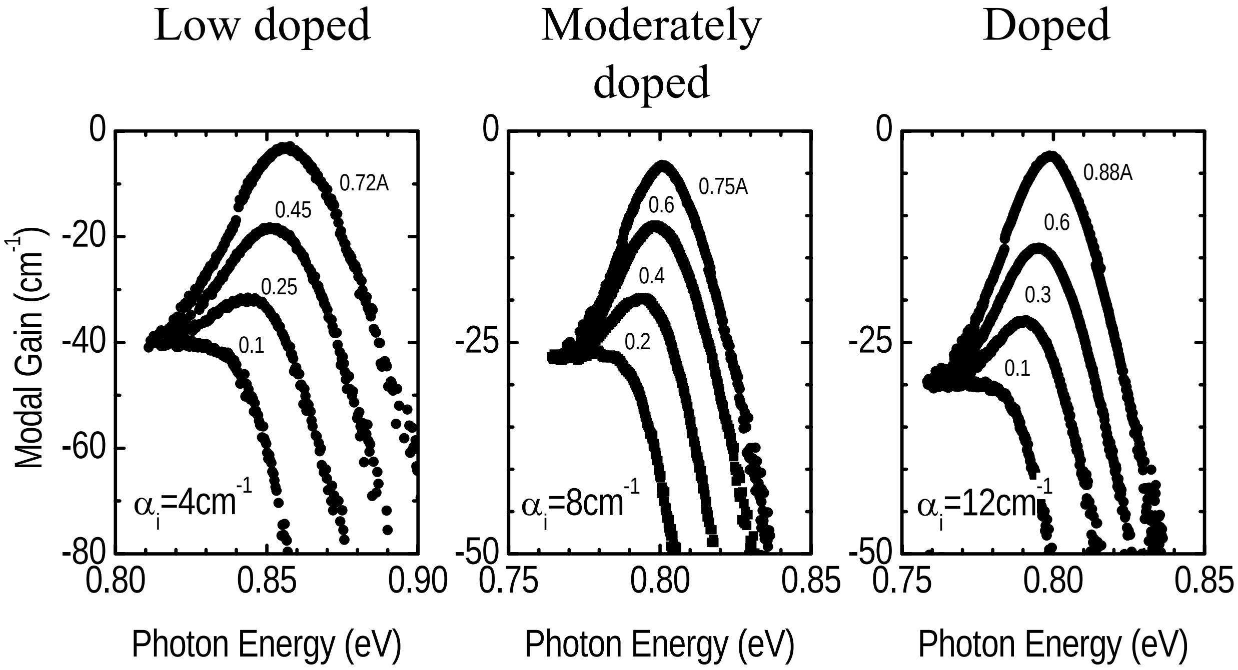
Sum of the second order distortion terms – composite second-order distortion (CSO) ~ -60dBc
Sum of the third order distortion terms – composite triple-beat (CTB) ~ -65dBc

Trade-off between leakage and loss



Doping of the p-cladding/SCH interface is a powerful tool for heterobarrier electron leakage suppression leading to high injection efficiency. The price paid for these advantages is an increased optical loss due to free carrier absorption in doped p-cladding ($\alpha_{\text{free carr.}} \sim N_A$).

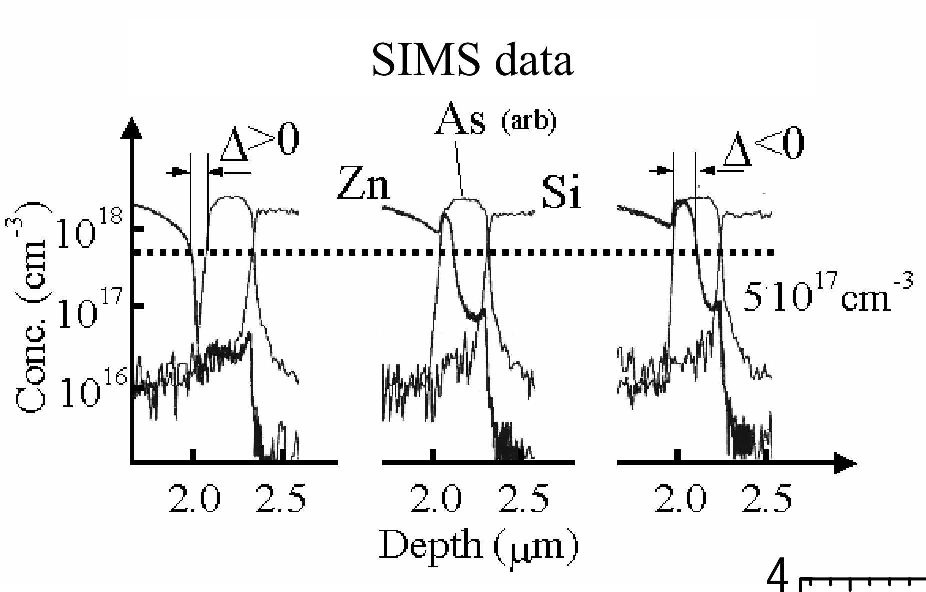



Low doped

Moderately doped

Doped

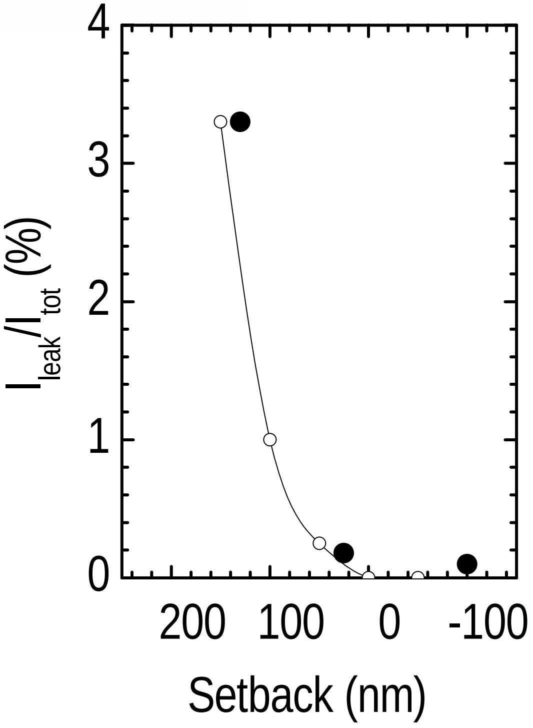
Optimization of the p-doping profile in 1.3μm InGaAsP/InP lasers

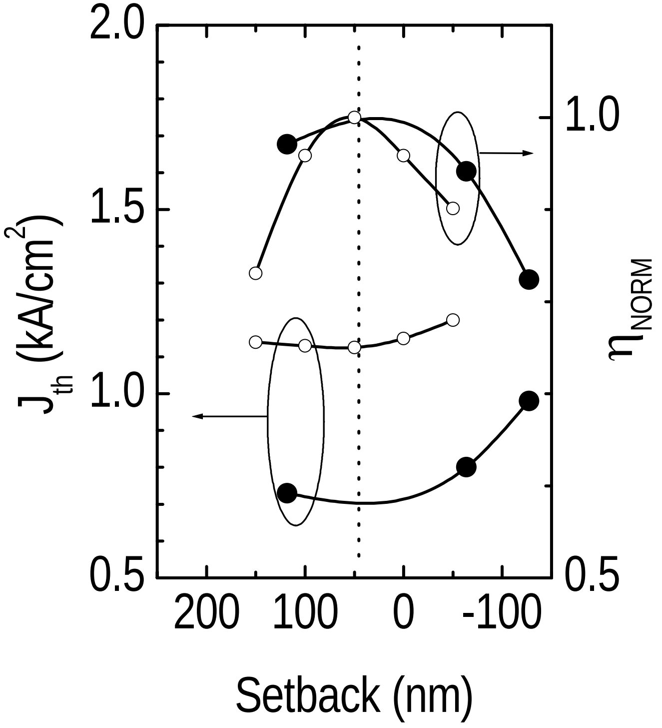


To define the placement of Zn doping within the laser structure, a setback (Δ) parameter was introduced as the distance between the Zn-doping profile edge at concentration of $5\text{x}10^{17}\text{cm}^{-3}$, and the p-cladding/SCH.

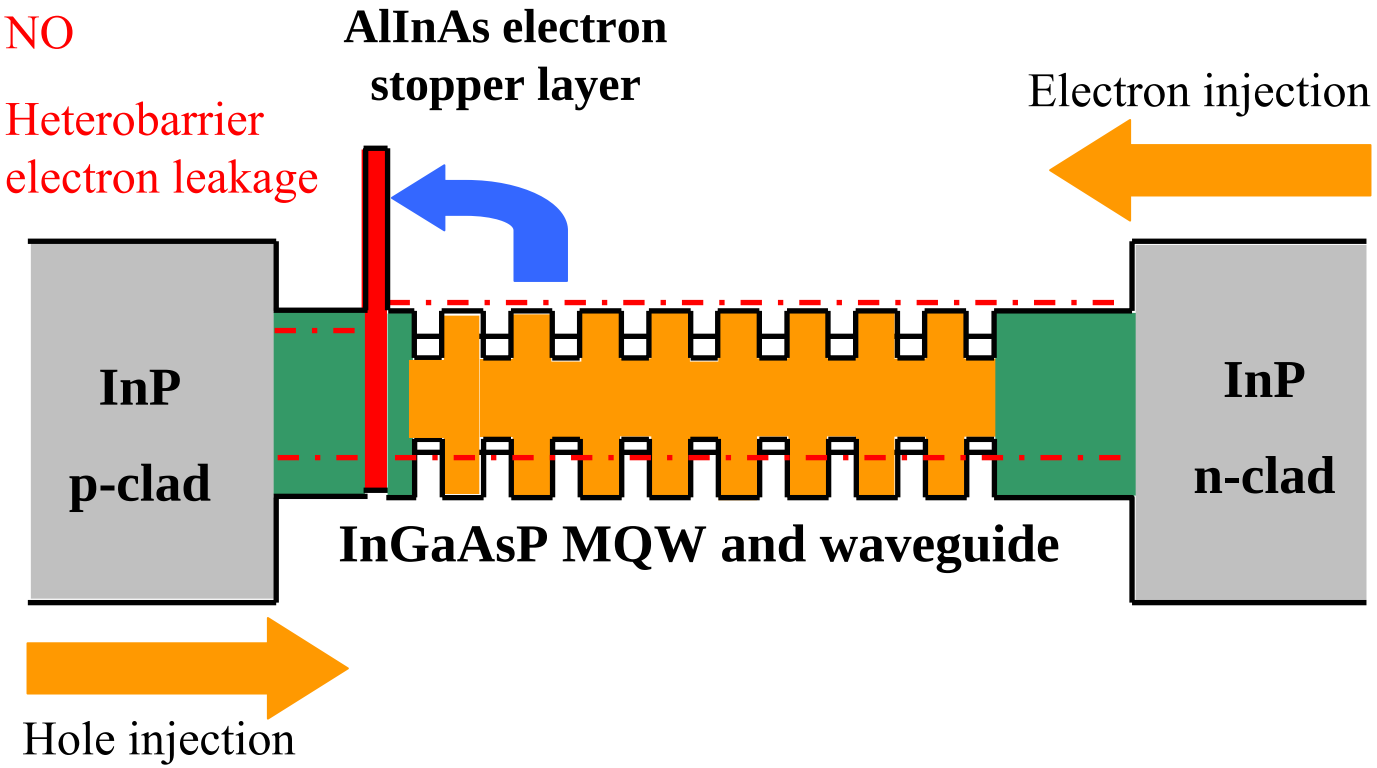
$$\eta_{slope} \propto \eta_i \cdot \frac{\alpha_m}{\alpha_i + \alpha_m},\ \eta_i \uparrow \text{and } \alpha_i \uparrow \text{with } N_A$$

Simulation (open circles) predicts and experiment (solid circles) confirms that Δ = 50nm is optimum for minimum threshold and maximum external efficiency at 300K.





Stopper layer

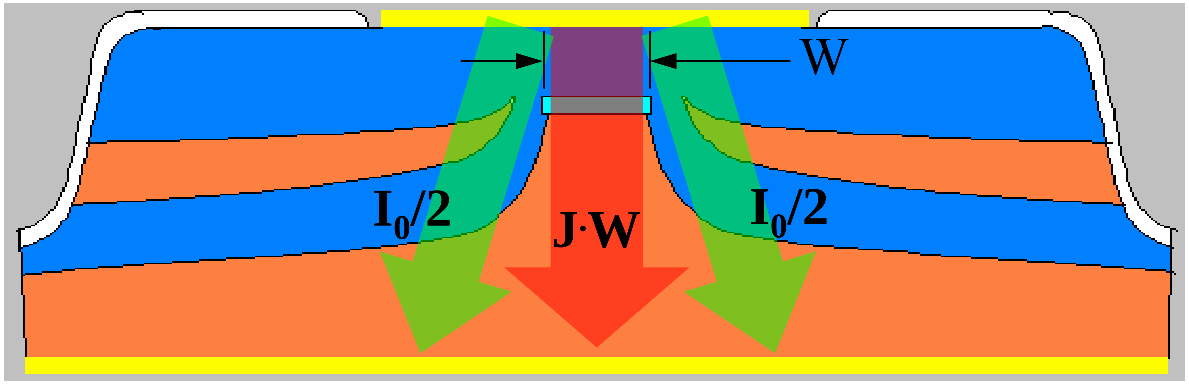


AlInAs Electron stopper layer was proposed at Bell Labs in 1995

Lasers with AlInAs electron stopper layer were realized in 1997 at Oki Electric Industry Co. Maximum operating temperature of 155^{0}C was achieved.

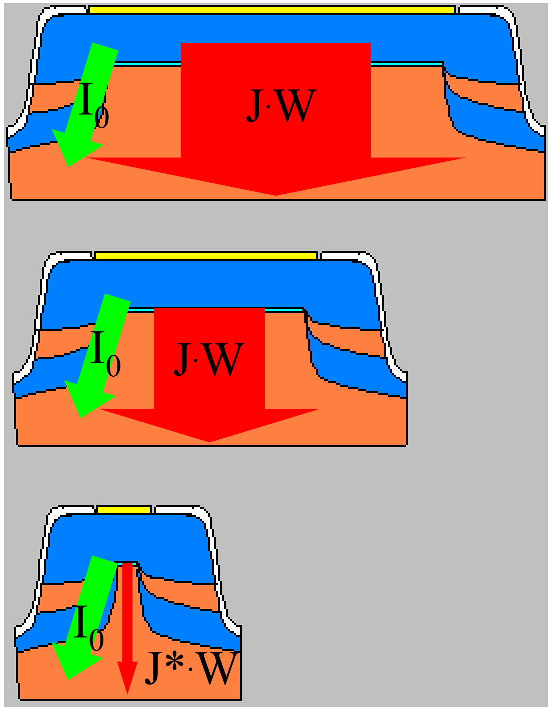
Modification of the stopper layer – AlInAs/AlGaInAs MQB layers on n- and p- sides of MQW

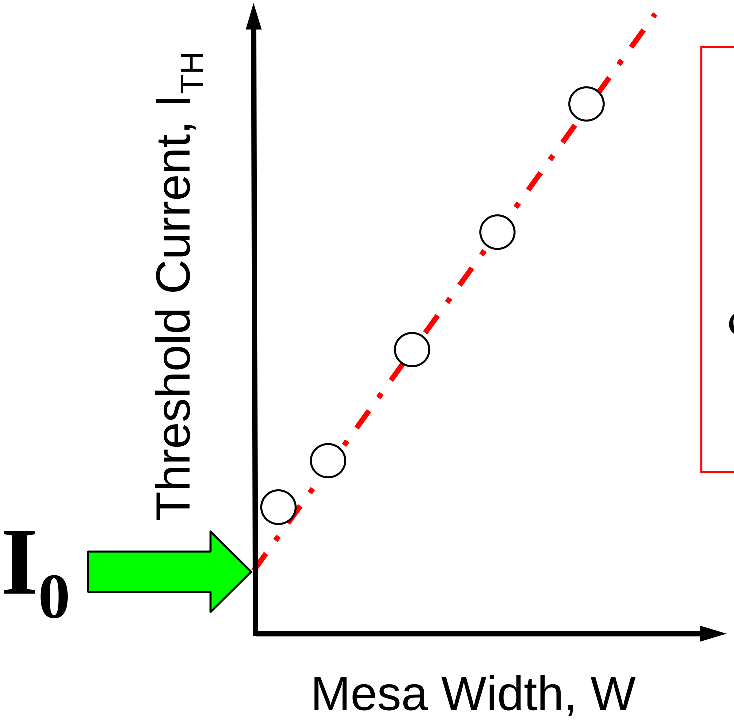
Lateral leakage in CMBH lasers



Experimental study of lateral carrier leakage in CMBH lasers can be performed using $I_{th}=I_0+J\cdot W$

Experiment idea – by changing the mesa width W, keep blocking layer structure the same.





This study was performed and it was shown that I_0 can contribute up to 30% of threshold current in W=1μm single mode CMBH devices

* Laser efficiency stays high (~95%) showing clamping of the carrier loss mechanism after threshold