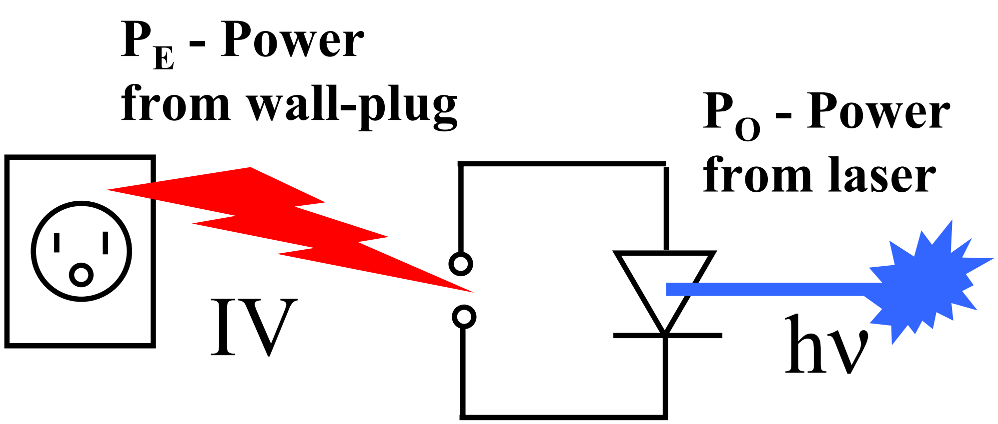
Semiconductor laser is an electrical to optical converter



Power-conversion or wall-plug efficiency – η_{WP} *is the measure of ability of the laser to convert electrical power to optical power.*

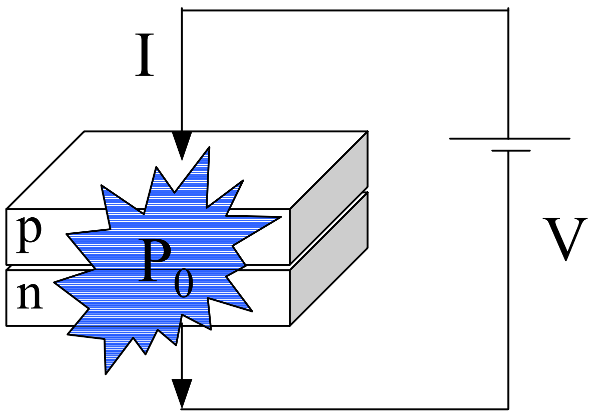
Power produced by semiconductor laser is proportional to the rate of carrier supply into the active region. Carrier supply rate is proportional to the electrical current flowing through the laser. As a result, electrical current I, but not electrical power P_E*, is a natural parameter to characterize laser output power* P_O*.*

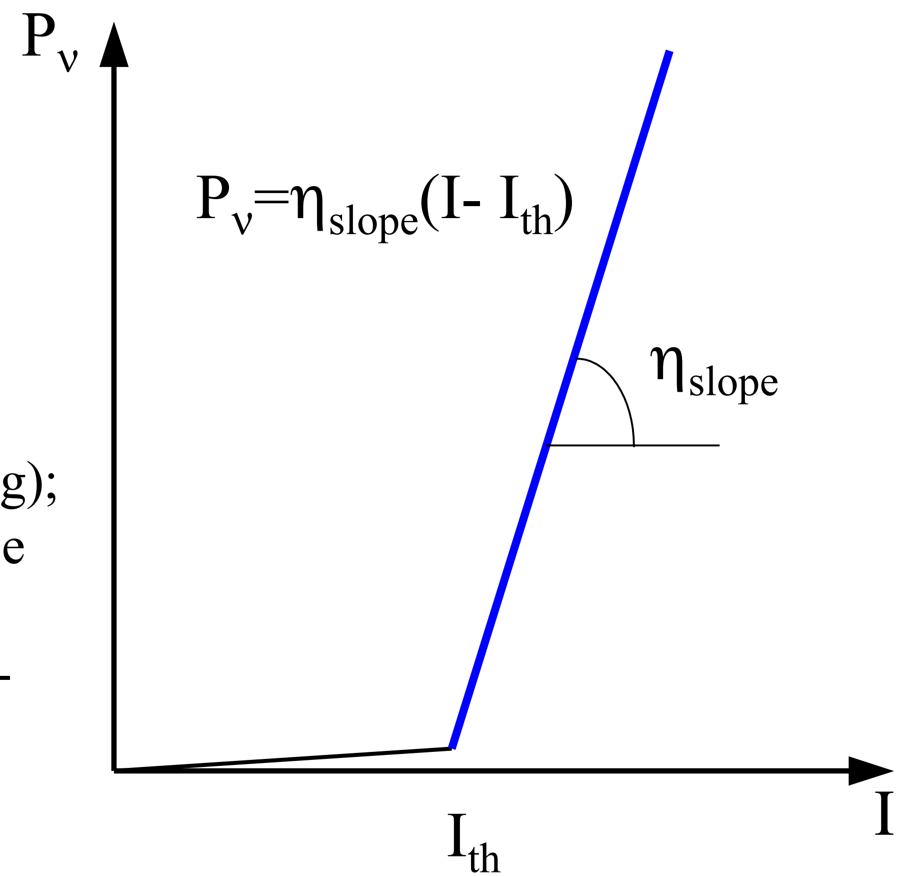
$$\eta_{WP} = \frac{P_O}{P_E}$$

Laser wall-plug efficiency depends on current through the laser $\eta_{WP}(I)$ *and usually decreases with I, since the voltage drop across laser heterostructure increases with current.*

$$\eta_{WP} = \frac{P_O}{P_E} \sim \frac{I}{IV} \sim \frac{1}{V}$$

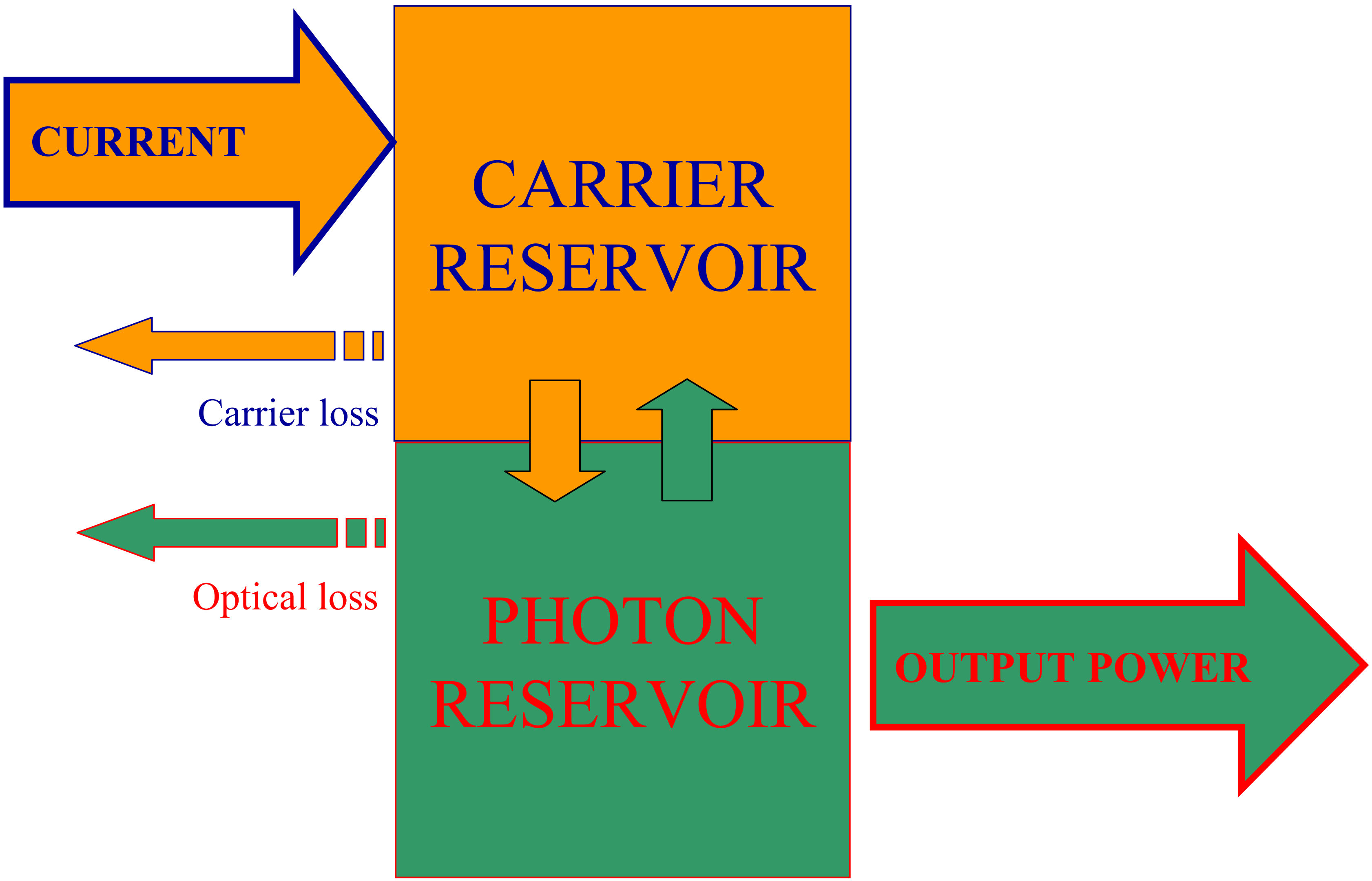
Parameters of semiconductor lasers



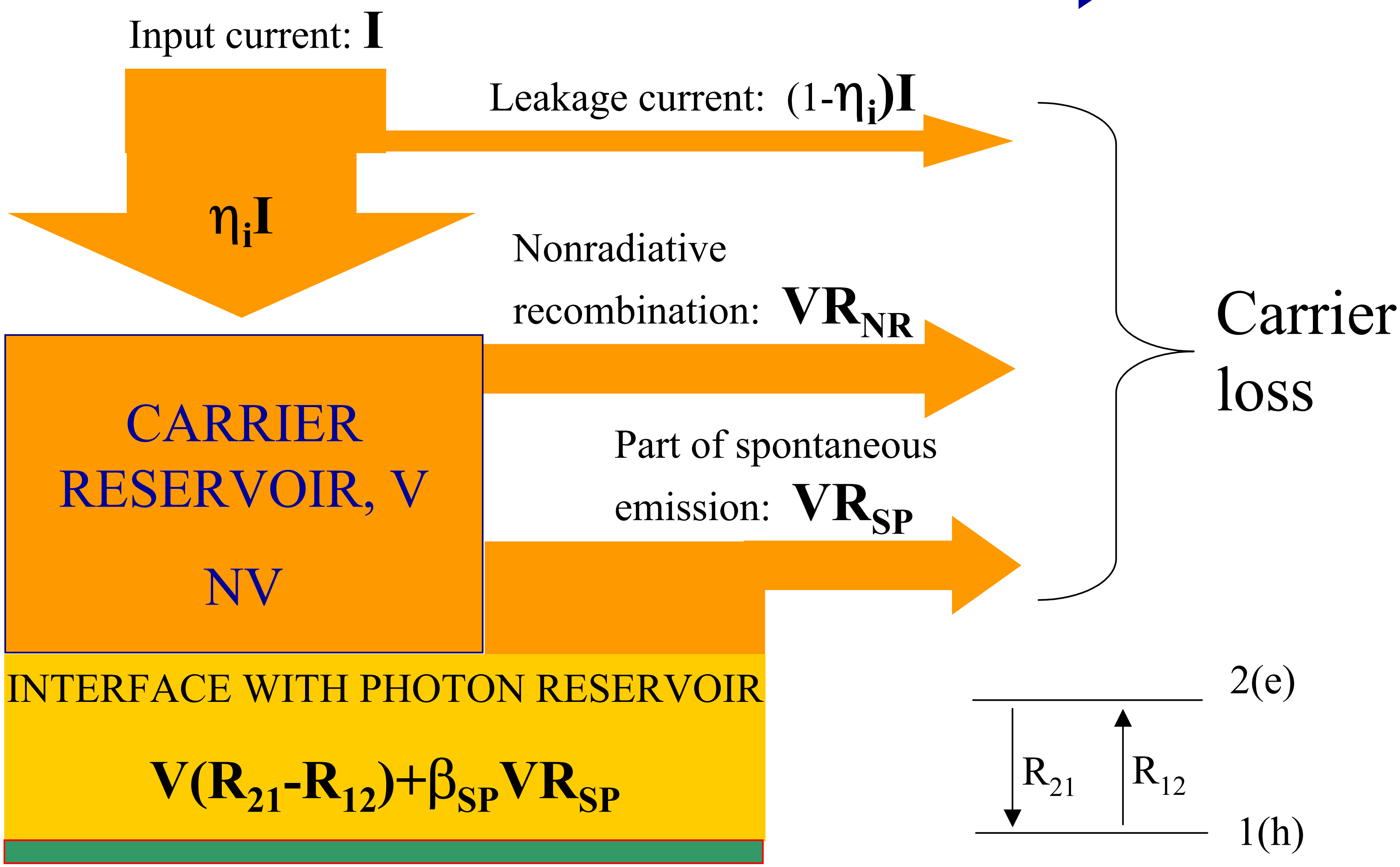


I_{th} – threshold current (start of lasing);
η_{slope} – rate of output power increase with current when $I > I_{th}$;
P_{output} optical/P_{input} electrical = wall-plug efficiency (power conversion efficiency)

"Reservoir" analogy of semiconductor lasers



Carrier loss and carrier balance eq



$$\frac{d(N\cdot V)}{dt} = \frac{\eta_i \cdot I}{q} - (R_{SP} + R_{NR})\cdot V - (R_{21} - R_{12})\cdot V$$

stimulated emission

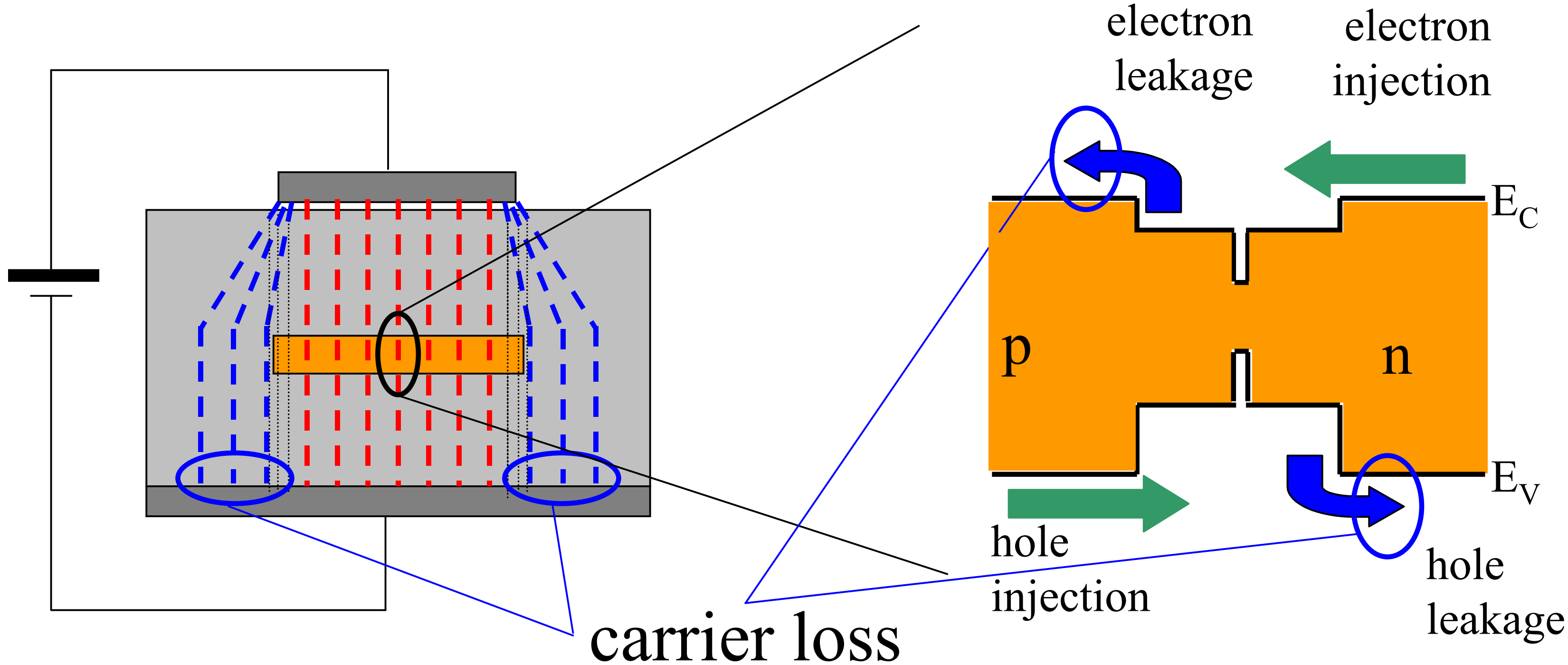
Carrier leakage current and internal efficiency, η_i

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

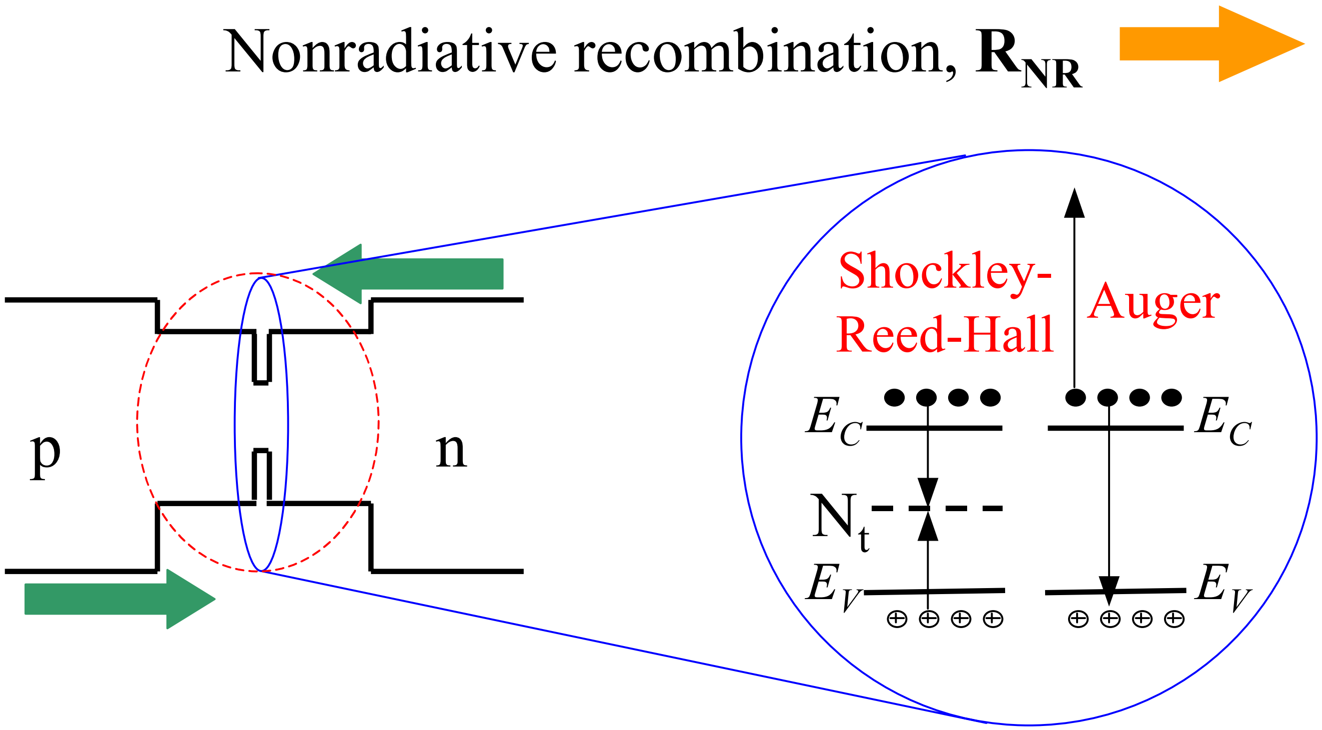
Carrier loss by any mechanism which is not fixed at threshold leads to decrease of η_i **- carrier leakage -**

Lateral leakage

Heterobarrier leakage



Nonradiative recombination, $\mathbf{R_{NR}}$



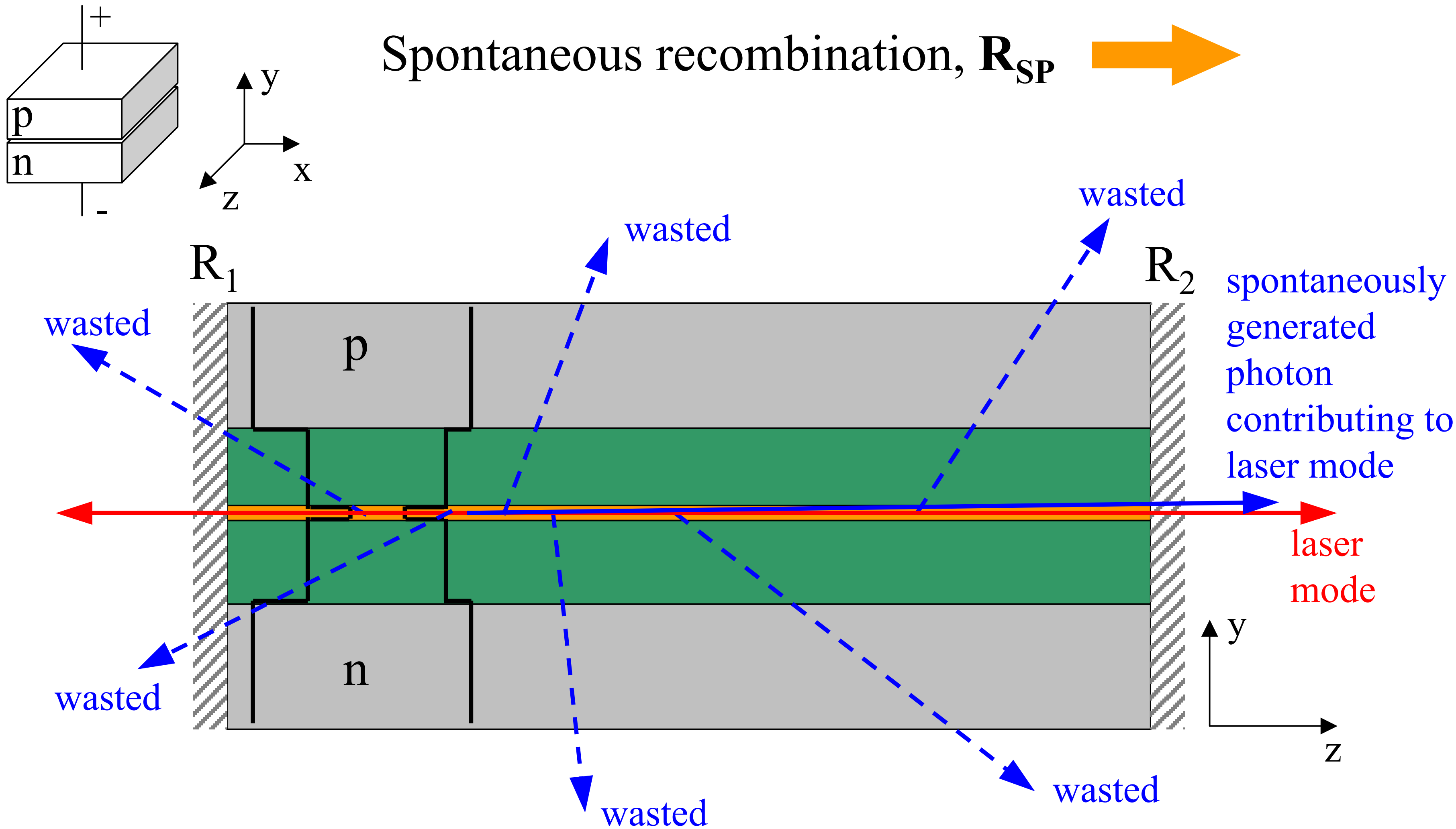
Nonradiative recombination removes carriers that could have been recombined radiatively.

Nonradiative recombination decreases carrier lifetime in the active region.

$$\frac{1}{\tau_{TOTAL}} = \frac{1}{\tau_{RAD}} + \frac{1}{\tau_{NR}}$$

$$\frac{1}{\tau_{NR}} = \frac{1}{\tau_{SRH}} + \frac{1}{\tau_{AUG}}$$

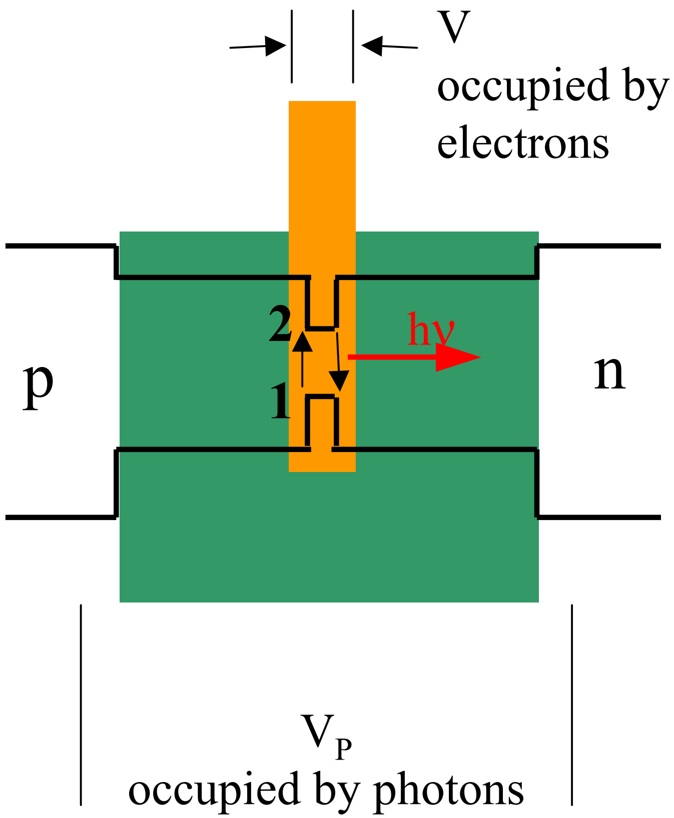
Spontaneous recombination, $\mathbf{R_{SP}}$



Spontaneous recombination generates photons with random momentum. Only a small part of them (β_{SP}) contribute to the lasing mode. Most of the spontaneously generated photons are wasted.

Interaction between electron and photon reservoir
Stimulated recombination

Modern lasers have separate confinements for electrons and photons



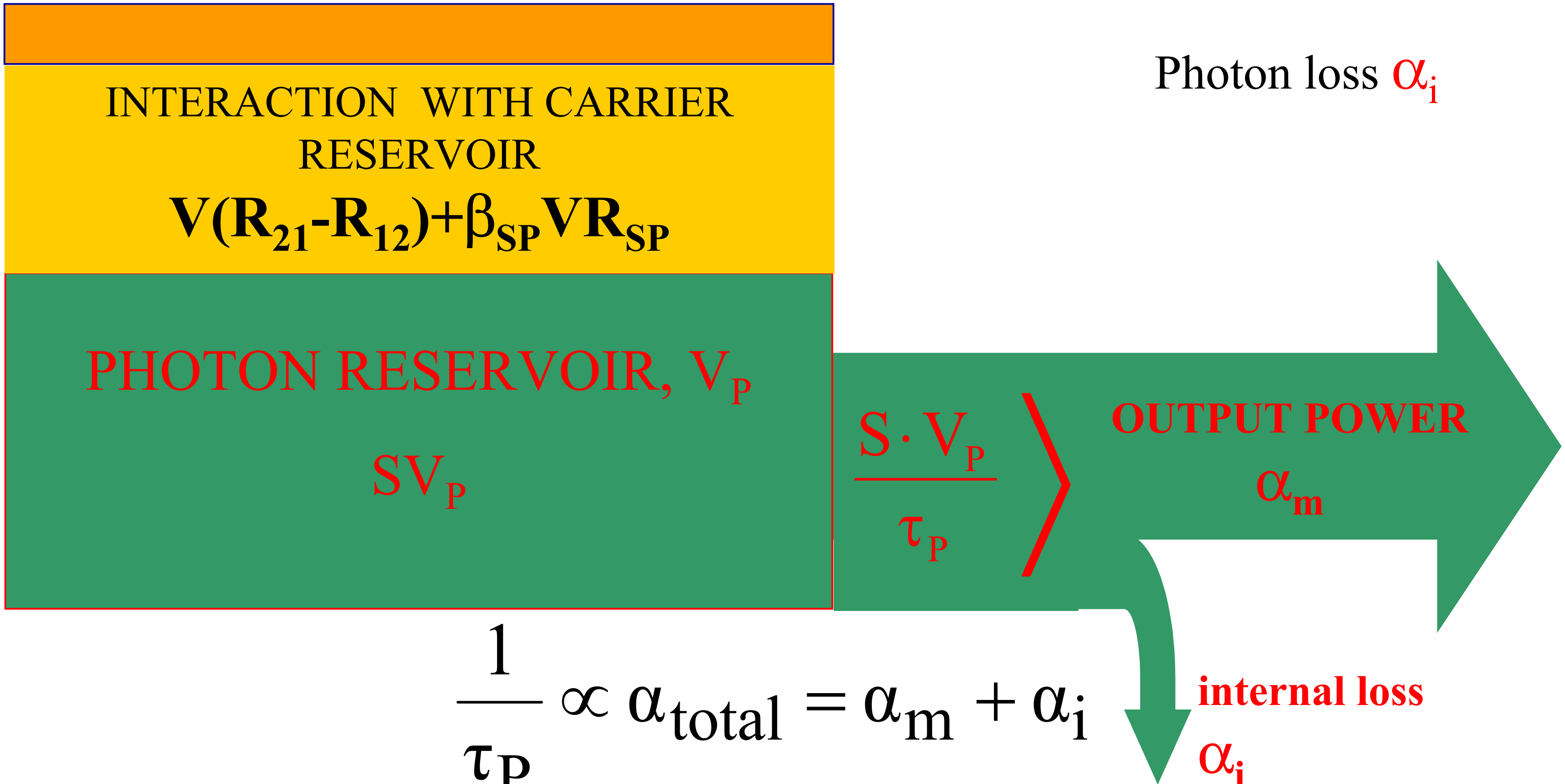
The net number of photons generated by stimulated recombination is equal to

Generation Rate VR_{21}	minus	Absorption Rate VR_{12}

Carrier lifetime with respect to stimulated recombination process is

$$\tau_{STIM} \propto \frac{1}{(R_{21} - R_{12})} \propto \frac{1}{\#_{phot}}$$

Photon balance equation



$$\frac{1}{\tau_P} \propto \alpha_{total} = \alpha_m + \alpha_i$$

$$\frac{d(S \cdot V_P)}{dt} = V \cdot (R_{21} - R_{12}) + \beta_{SP} \cdot V \cdot R_{SP} - \frac{S \cdot V_P}{\tau_P}$$

Optical loss at mirrors, α_m

$$\alpha_m = \frac{1}{2L} \cdot \ln\left(\frac{1}{R_1 R_2}\right)$$

This is the loss of photons through mirrors from laser cavity. However, unlike internal loss, mirror loss provide laser output.

Uncoated laser: $R_1 = R_2 = R,\ \alpha_m = \frac{1}{L} \cdot \ln\left(\frac{1}{R}\right),\ R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$

$R \approx 0.3$

Coated laser:

High reflection (HR) – R=0.95

Anti reflection (AR) – R=0.03-0.05

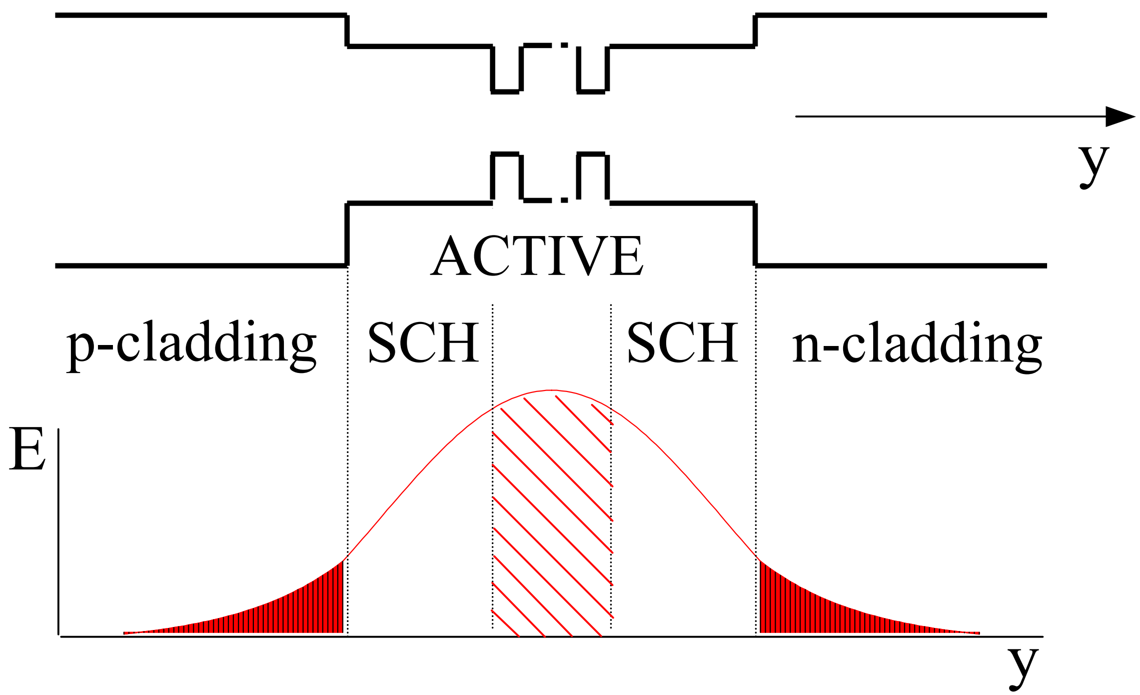
Neutral reflection (NR) – R=0.32

Choice of coating type depends on application.

* Example:

$R\uparrow \rightarrow \alpha_m\downarrow \rightarrow I_{th}\downarrow$ but $\eta_{ext}\downarrow$

Internal optical loss, α_i



$$\Gamma_i = \frac{\int_{a_i}^{b_i} E^2(y)\,dy}{\int_{-\infty}^{+\infty} E^2(y)\,dy}$$

$$\alpha_i = \Gamma \cdot \alpha_{act} + \Gamma_{SCH} \cdot \alpha_{SCH} + \Gamma_p \cdot \alpha_p + \Gamma_n \cdot \alpha_n$$

Photon scattering and Free carrier absorption are the two main causes of the photon loss