Energy Flow in Semiconductor Devices and its Applications for Semiconductor Laser Diodes

6.772/SMA5111 Term Paper

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Outline

- Motivation
- Energy Source in Semiconductor Devices
- Internal Cooling in a p-n Diode
- Applications to Laser Design (ICICLE)
- Summary

Heat/Energy Flow in Semiconductor Devices

Mid-IR laser SOI MOSFET Thermoelectric Cooler

Smaller, Faster, Denser & more powerful ⇨ More Heat

Understanding heat/energy flow in semiconductor devices, helps understanding of:

- **Thermal-induced failure in semiconductor devices**
- **Energy conversion in thermoelectric / thermionic devices**

Approaches:

- **Coupled Electron-phonon Boltzmann Transport Equation**
- **Electrohydrodynamics or Energy Transport Equations**
- **Drift-Diffusion Equations (Thermodynamic Approach)**

Heating Effects in Semiconductor Lasers

Maximum optical output power limited by active layer temperature rise

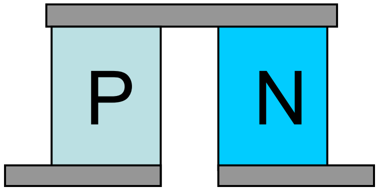
Threshold current density (left axis) and lasing wavelength (right axis) versus operating temperature for λ=1.2μm InGaAs laser.

T. K. Sharma, et al. IEEE Phot. Tech. Lett. **14**, 887 (2002).

High temperature leads to:

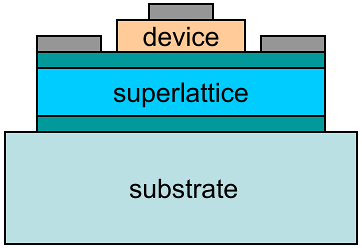
- Increased threshold current
- Wavelength drift
- Decreased output power
- Decreased device lifetime

Temperature Control in Optoelectronic Devices



Traditional BiTe Thermoelectric Cooler

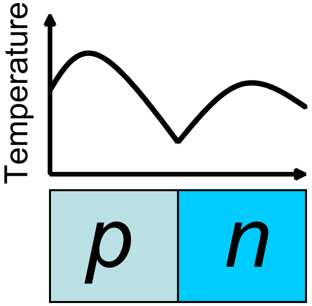
- Cooling power density ~10 W/cm^2
- Difficult to integrate due to lack of processing technology
- Device mounted on cooler



Integrated Superlattice Cooler

- Cooling power density of several hundred W/cm^2
- Integration possible
- Cooler can be grown near device

A. Shakouri and J. E. Bowers, *Appl. Phys. Lett.* **71**, 1234 (1997)
R. Venkatasubramanian, et. al, *Nature* **413**, 597-602 (2001)
T.C. Harman, et al, *Science* **297**, 2229-2232 (2002)



Internal Cooling Effects

- Device structure is such that the operating current also produces cooling

K. P. Pipe, R. J. Ram, and A. Shakouri. *Phys. Rev. B*, Sept 15 2002.

Non-isothermal Carrier Flow
- Thermodynamics Approach

Transport under both Electrical and Temperature Field

Particle Flux: $\vec{J}_h = \mu_h p(\nabla E_{fh} - P_h \nabla T)$ $\qquad$ $\vec{J}_e = -\mu_e n(\nabla E_{fe} + P_e \nabla T)$

Current Flux: $J_h = e\vec{J}_h$ $\qquad$ $J_e = -e\vec{J}_e$

Heat Flux: $\vec{J}_h^Q = eP_h T\vec{J}_h - k_h \nabla T$ $\qquad$ $\vec{J}_e^Q = eP_e T\vec{J}_e - k_e \nabla T$

Energy Flux: $\vec{J}_h^u = \vec{J}_h^Q - eE_{fh}\vec{J}_h$ $\qquad$ $\vec{J}_e^u = \vec{J}_e^Q + eE_{fe}\vec{J}_e$

Energy Conservation Equation: $$\frac{\partial u}{\partial t} + \nabla \vec{J}^u = 0$$

$\Downarrow$

Energy Source

Heat Conduction Equation: $$C\frac{\partial T}{\partial t} = \nabla(k\nabla T) + \dot{q}$$

Energy Source in Semiconductor Devices

$$\dot{q} = -e\nabla[(\pi_e + E_{fe})\vec{J}_e + (\pi_h + E_{fh})\vec{J}_h] + e[E_{fh} - T\frac{\partial E_{fh}}{\partial T}]\frac{dp}{dt} - e[E_{fe} - T\frac{\partial E_{fe}}{\partial T}]\frac{dn}{dt}$$

Definition of Peltier Coefficient:

$$\pi = PT = \frac{\int v^2 \tau (E - E_f)\frac{\partial f_o}{\partial E} D(E)dE}{e\int v^2 \tau \frac{\partial f_o}{\partial E} D(E)dE}$$

Maxwell-Boltzmann

$$\pi_e = P_e T = \frac{E_c - E_{fe}}{k_B T} + \frac{3}{2}k_B T + \pi_e^0 \qquad \pi_h = P_h T = \frac{E_{fh} - E_v}{k_B T} + \frac{3}{2}k_B T + \pi_h^0$$

where

$$\pi_e^0 = (r+1)\frac{k_B T}{e} \qquad \pi_h^0 = (r+1)\frac{k_B T}{e}$$

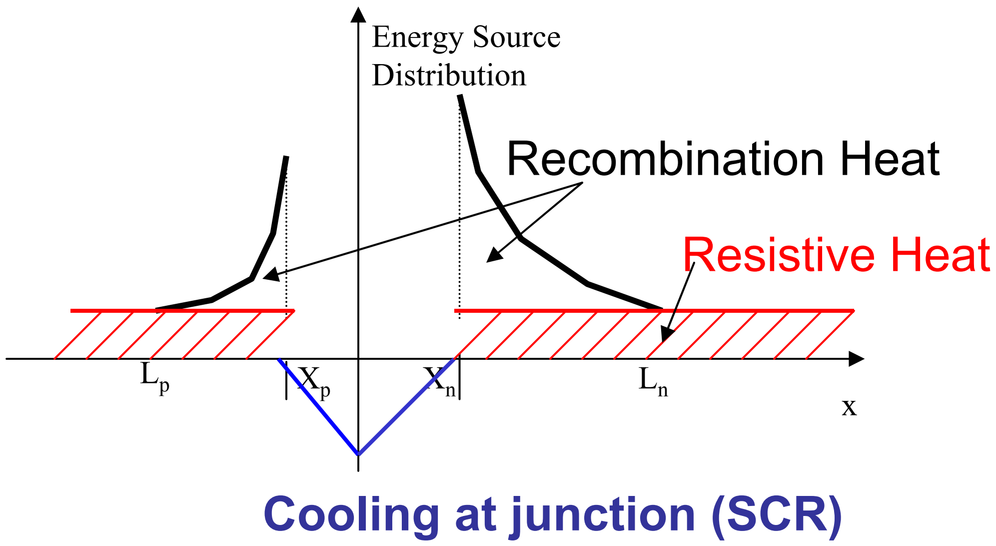
This r is related to the energy-dependent electron relaxation time
r=-1/2 for acoustic-phonon scattering and r =3/2 for impurity scattering

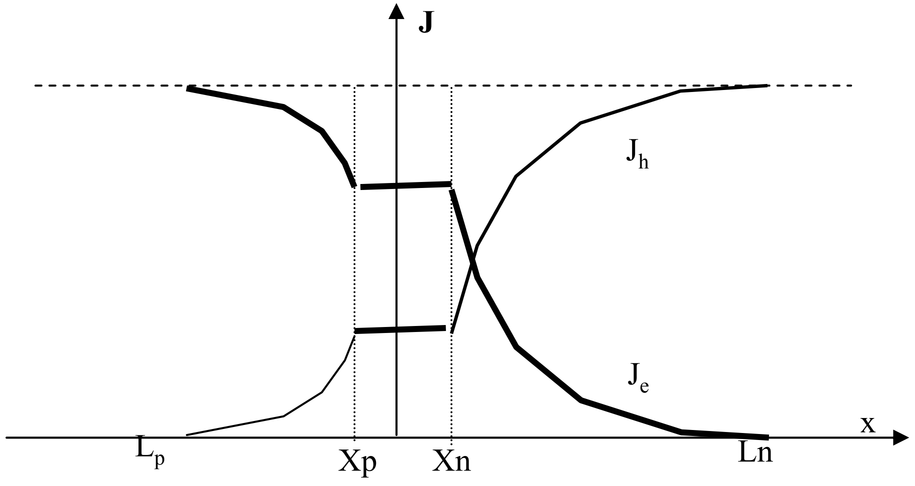
Steady State, Homojunction

$$\dot{q} = -(E_g + 3k_B T)\nabla\vec{J}_e - \nabla(\pi_h^0\vec{J}_h + \pi_e^0\vec{J}_e) + \frac{\nabla E_v}{e}J$$

Recombination Thompson Resistive heat

p-n Diode under Forward Bias



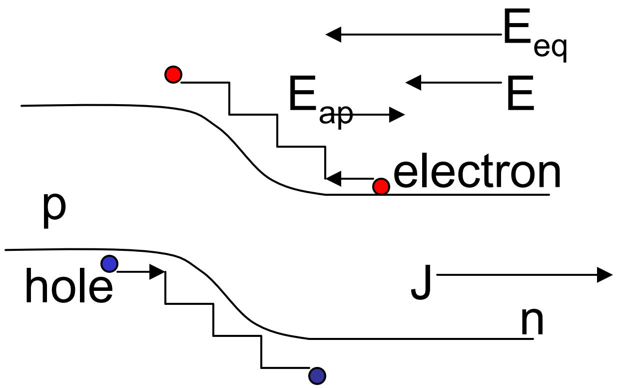


Increase Net Cooling

- Short diodes
- Radiative recombination

Why & How Large is the Cooling

Cooling at the Junction



In SCR: $\dot{q} = \vec{E} \cdot \vec{J}$

Total Cooling in the junction:

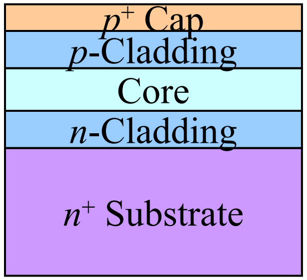
$$Q = \int_{-x_p}^{x_n} \dot{q}\, dx = \frac{1}{2} E_{\max} J_{\max}$$

$$= J(\phi_{bi} - V)$$

- **Every junction causes heating or cooling.**
- **Cooling at the *p-n* junction is bias-dependent**

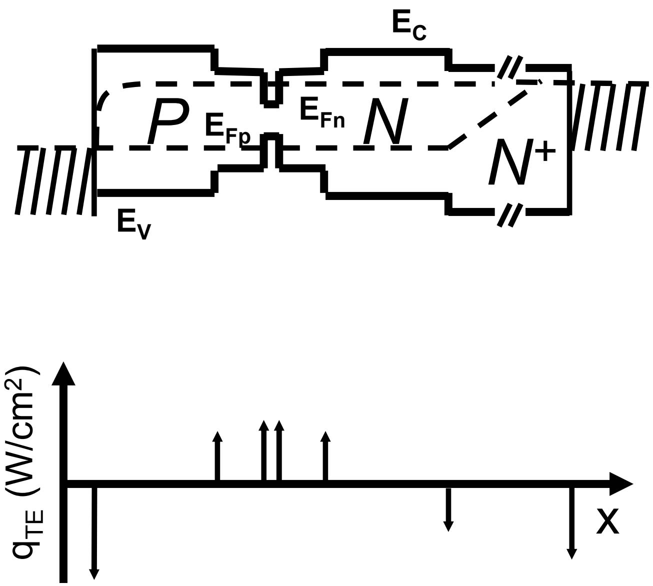
✓ Cooling under forward bias
✓ Heating under reverse bias

Optimizing Cooling Effect in Lasers

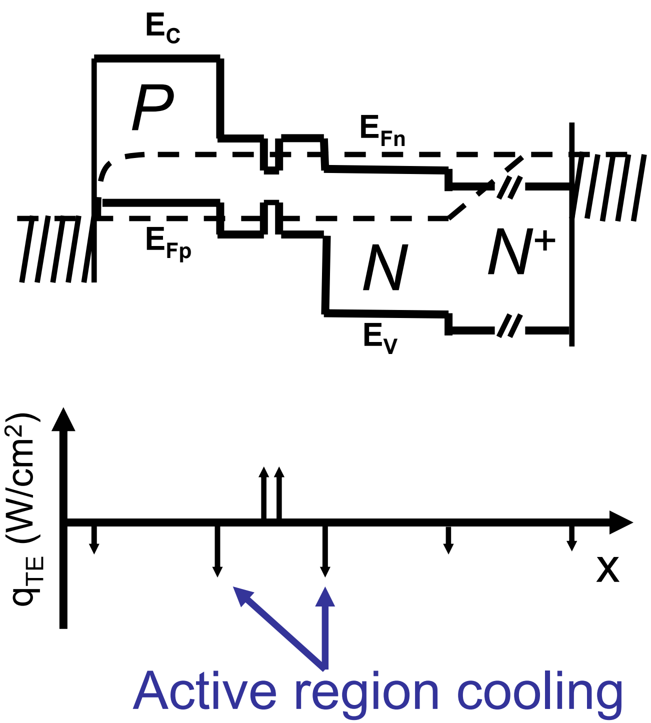


Structure

Conventional SCH



Injection Current Internally Cooled Light Emitter



Conclusions

- Thermal effects is very important for active devices, such as transistors and lasers
- Energy source term is derived based on the thermodynamic approach
- Internal cooling effect is found in p-n diode under forward bias
- The internal cooling effect has been utilized for semiconductor laser design.

Thank you for your attention!