Auger recombination in $A^{III}B^{V}$ compound semiconductors: non-radiative losses in quantum wells and superlattices

Georgii Samsonidze

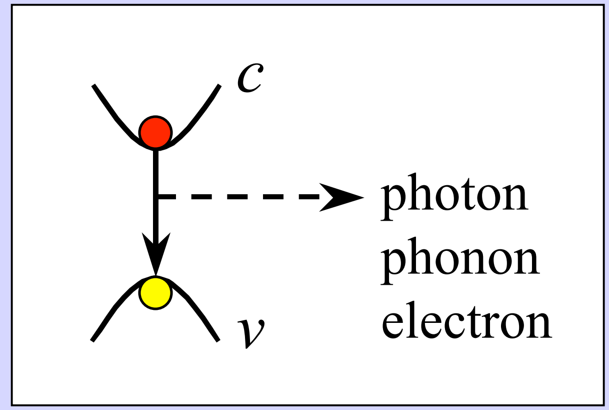
Department of Electrical Engineering and Computer Science
Massachusetts Institute of Technology, Cambridge, MA 02139-4307

May 15, 2003

Outline

- Carrier recombination mechanisms in semiconductors
  - non-radiative channel: Auger recombination
  - source of dark current in lasers and detectors
  - optimized laser structure to reduce Auger
- Auger recombination enhancement in heterostructures
  - narrow-gap semiconductor
  - high doping level
  - high injection level
  - wavefunction localization
  - breaking momentum conservation
- Theoretical model for direct-gap $A^{III}B^{V}$ semiconductors
- Experimental measurements of lifetime for Auger process

Carrier Recombination in Semiconductors



❖ Radiative recombination

recombination rate: $R_{rad} = B(T)\, n\, p$

n-type ⇒ lifetime: $\tau_{rad} = (\, B(T)\, n_0 \,)^{-1}$

$R_{rad} = p \,/\, \tau_{rad}$

direct bandgap: photon $h\nu \approx E_g$

indirect bandgap: photon $h\nu \approx E_g$ + phonon $h\nu << E_g$

❖ Non-Radiative recombination

✓ phonon: $h\nu << E_g$ ⇒ trap-assisted (middle-gap, Shockley-Read-Hall)

rate: $R_{trap} = A(T)\, p = p \,/\, \tau_{trap}$ where $\tau_{trap} = A(T)^{-1}$

✓ electron: Auger recombination

rate: $R_{Auger} = C(T)\, n^2\, p = p \,/\, \tau_{Auger}$ where $\tau_{Auger} = (\, C(T)\, n_0^2 \,)^{-1}$

V. N. Abakumov, V. I. Perel, and I. N. Yassievich, *Nonradiative recombination in semiconductors*, vol. 33 of *Modern Problems in Condensed Matter Sciences*, North-Holland, Amsterdam (1991,1997)

Auger Recombination in Semiconductors

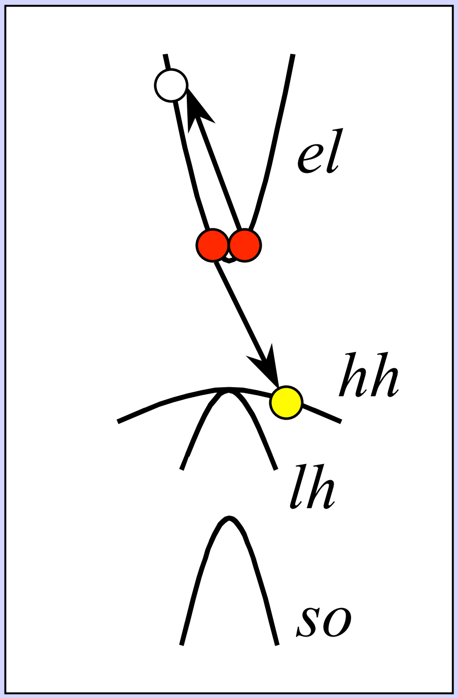
$\tau_{trap}^{-1} = A \quad << \quad \tau_{Auger}^{-1} = C\, n_0^2 \quad << \quad \tau_{rad}^{-1} = B\, n_0$

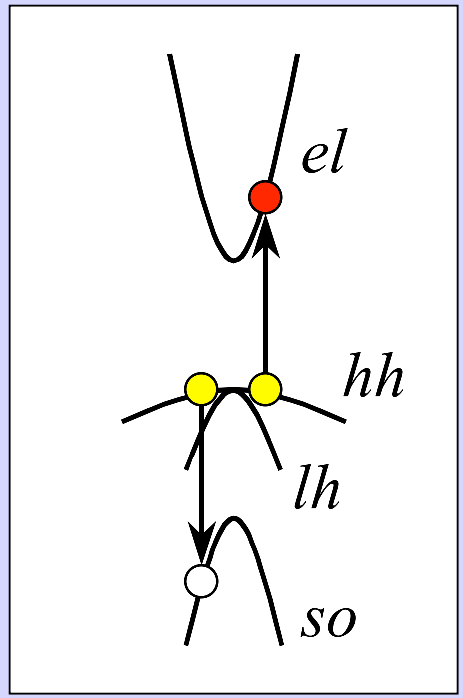
high doping level ⇒ dominant: radiative + Auger

CHCC
Auger
process

energy is
transferred
to an enectron

direct
processes





CHHS
Auger
process

energy is
transferred
to a hole

enhancement
$E_g = \Delta_{SO}$

momentum conservation ⇒ temperature threshold ⇒ photon-assisted

V. N. Abakumov, V. I. Perel, and I. N. Yassievich, ***Nonradiative recombination in semiconductors*****,**
vol. 33 of ***Modern Problems in Condensed Matter Sciences*****, North-Holland, Amsterdam (1991,1997)**

Auger Recombination in Heterostructures

wavefunction localization within the quantum well □
□ enhancement of coefficients A(↑), B(↑↑), C(↑↑↑)

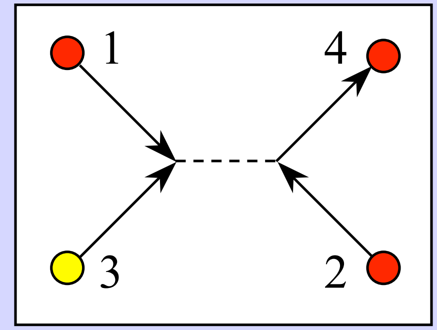
direct Auger process

1) CHCC
2) CHHS

phonon-assisted
higher-order
impurity scattering
etc

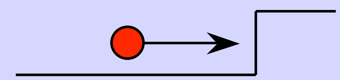
http://www.ioffe.rssi.ru/SVA/NSM/Auger/model.html
http://www.wsi.tu-muenchen.de/nextnano3/input_parser/database/Auger-recombination.htm

Direct Auger Recombination Mechanism

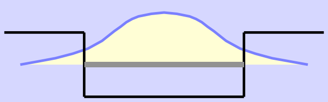


Auger coefficient in heterostructures: $C = C_1 + C_2 + C_3$

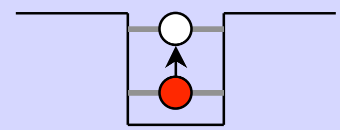
C_1: electronic scattering on a single heterobarrier



C_2: Coulomb interaction within the quantum well



C_3: Auger electron in the bound state (deep QW)



quantum well □ momentum non-conservation □ thresholdless

A. S. Polkovnikov and G. G. Zegrya, Phys. Rev. B 64, 073205 (2001)
ibid, Phys. Rev. B 58, 4039 (1998)

Direct Auger Recombination Calculation

Auger coefficients (C_1, C_2, C_3) different origin □
different dependencies on QW width, temperature, bandgap, barriers
(temperature thresholdless □ breaking momentum conservation)

A. S. Polkovnikov and G. G. Zegrya, Phys. Rev. B 64, 073205 (2001)
ibid, Phys. Rev. B 58, 4039 (1998)

Phonon-Assisted Auger Recombination

Theoretical calculation for n-type InGaAsP lattice matched to InP

$\tau_{Auger}=(Cn^2)^{-1}$

Auger recombination processes:
narrow-gap : direct (dominant)
wide-gap : phonon-assisted

Auger theory: the sensitivity of the calculation to the band model, wavefunctions, and other approximations used

$\Rightarrow$ disagreements…

N. K. Dutta and R. J. Nelson, J. Appl. Phys. 85, 74 (1982)
M.Takeshima, Phys. Rev. B 23, 6625 (1981)

Recombination Lifetime in narrow-gap InGaAs

$$\tau = [\, A + B\,n + C\,n^2 \,]^{-1}$$

- A — trap-assisted [phonon]
- B — radiative [photon]
- C — Auger [electron]

n-type
$In_xGa_{1-x}As$
$0.53<x<1$

$\tau \propto n^{-x}$

direct:
$x = 1$
phon-assist:
$x = 2$
second-order:
$x = 7/3$

W. K. Metzger, M. W. Wanlass, R. J. Ellingson, R. K. Ahrenkiel, and J. J. Carapella, Appl. Phys. Lett. 79, 3272 (2001)

Auger lifetime in GaInAsSb/GaSb compounds

Auger coefficient increases with decreasing band-gap

Auger coefficient increases when $E_g=\Delta_{SO}$ (CHHS process) as observed experimentally

M. Muñoz, K. Wei, F. H. Pollak, J. L. Freeouf, C. A. Wang, and C. W. Charache, J. Appl. Phys. 87, 1780 (2000)

Carrier lifetime is measured by the standard small-signal optical response technique

J. M. Pikal, C. S. Menoni, H. Temkin, P. Thiagarajan, G. Y. Robinson, Rev. Sci. Instrum. 69, 4247 (1998)

I. Riech, M. L. Gomez-Herrera, P. Díaz, J. G. Mendoza-Alvarez, J. L. Herrera-Pérez, E. Marín, Appl. Phys. Lett. 79, 964 (2001) ***and references therein***

Temperature Dependence of Recombination

InAsP/InGaAsP multiple QW laser with band-gap wavelengths

— 1.15 μm (shallow gap)

— 1.06 μm (deep gap)

$$\tau = [\, A + B\,n + C\,n^2 \,]^{-1}$$

Nearly 50% of threshold current is due to Auger at room temperature

enhancement

Analysis	Shallow well Bulk	Shallow well QW	Deep well Bulk	Deep well QW
$A\times10^{-7}$	3.3	4.5	3.5	3.5
$B\times10^{11}$	3.1	7.2	4.9	6.8
$C\times10^{29}$	.058	5.1	1.0	3.4

x100 (.058 → 5.1)

J. M. Pikal, C. S. Menoni, P. Thiagarajan, G. Y. Robinson, and H. Temkin, Appl. Phys. Lett. 76, 2659 (2000)

Narrow-gap InAs/GaSb/AlSb Superlattices

$$R = A + B\,n + C\,n^2$$

Experimental (solid diamonds) and computed (hollow squares) total recombination rates per electron-hole pair for the four systems. The dashed lines are fits of the experimental data to the equation shown above.

optimal lasing density for structures (a)–(c) is close to 10^{18} cm^{-3} and **$C\,n^2 > 10$ □ A** for these densities

the structure (d) is optimized for Auger suppression
(sensitive to layer thicknesses □ errors in growth & band model)

C. H. Grein, M. E. Flatté, J. T. Olesberg, S. A. Anson, L. Zhang, T. F. Boggess,
J. Appl. Phys. 92, 7311 (2002)

Summary

- Theoretical modeling of Auger recombination
  - ✓ contradictory results from different groups
  - ✓ very sensitive to band structure models
- Experimental measurements of Auger coefficient
  - ✓ confirms many theoretical predictions
  - ✓ increase in QWs of narrow-gap materials
- Optimize long-wavelength lasers and detectors to minimize Auger recombination (reduce threshold and dark current)