Strain Free Ge/GeSiSn Quantum Cascade Laser Based on L-Valley Intersubband Transitions

Greg Sun
Physics Department
University of Massachusetts Boston

Jacob B. Khurgin
Department of Electrical and Computer Engineering
The Johns Hopkins University

Richard A. Soref
Sensors Directorate
Air Force Research Laboratory

Advantages of Si Lasers

- Availability of lowest cost, largest size Si wafers
- Leveraging the infrastructure of the huge, global silicon microelectronics industry in order to make highly sophisticated silicon photonic devices
- Integrating silicon photonics monolithically on a chip containing fast VLSI silicon electronics to create an Opto-Electronic IC
- High quality SOI wafers with large index contrast between Si (3.45) and SiO_2 (1.45) – an ideal platform for planar wavguide circuits (hundreds of nm scale) that are truly compatible with IC
- Superior material properties:

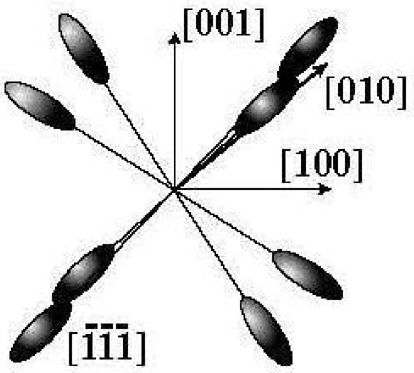
  High thermal conductivity (10X higher than GaAs)

  High optical damage threshold (10X higher than GaAs)

  High third-order optical nonlinearities

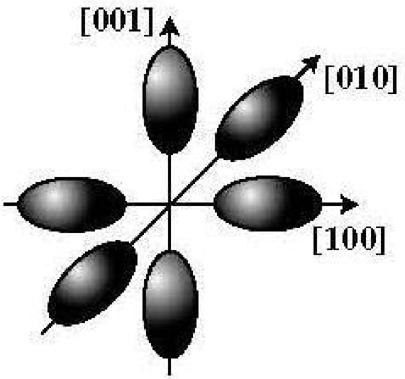
Group IV Semiconductors Unsuitable for Interband Lasers

- Indirect bandgap



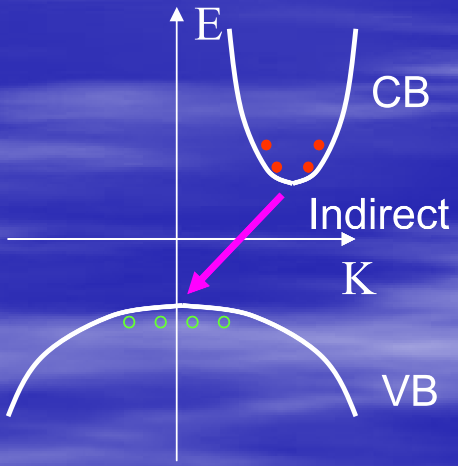
L-valleys in Ge

or Ge-rich SiGe



Δ-valleys in Si

or Si-rich SiGe



Development of Si-based Lasers

- **Si nanocrystals formed in Si-rich SiOx**

  -Optically pumped gain observed (Univ. of Trento, 2003, Univ. of Rochester, 2005)

  -Observations highly dependent on sample preparation – poor reproducibility
- **Er-doped Si motivated by light amplification at 1.55µm in Er-doped optical fibers made of SiO_2**

  -LEDs with 10% efficiency on par with commercial GaAs LEDs

  -Si is not a good host of Er – only low concentration of Er can be accommodated
- **Optically pumped Si Raman laser** (UCLA, Intel, 2003)

  - High optical pumping power and large device size – unlikely to be integrated with Si ICs
- **Hybrid of III-V lasers on Si wafer**

  InGaAs QD laser grown on Si (Univ. Michigan, 2005)

  InP laser bounded on Si (Intel, UCSB, 2006)

Si-based Intersubband Lasers

- Bandgap indirectness irrelevant for intersubband lasers, making Si a promising candidate
- Intersubband approach proposed with SiGe/Si QWs (G. Sun et al, 1995)
- Intersubband EL demonstrated in SiGe/Si Quantum cascade structures:

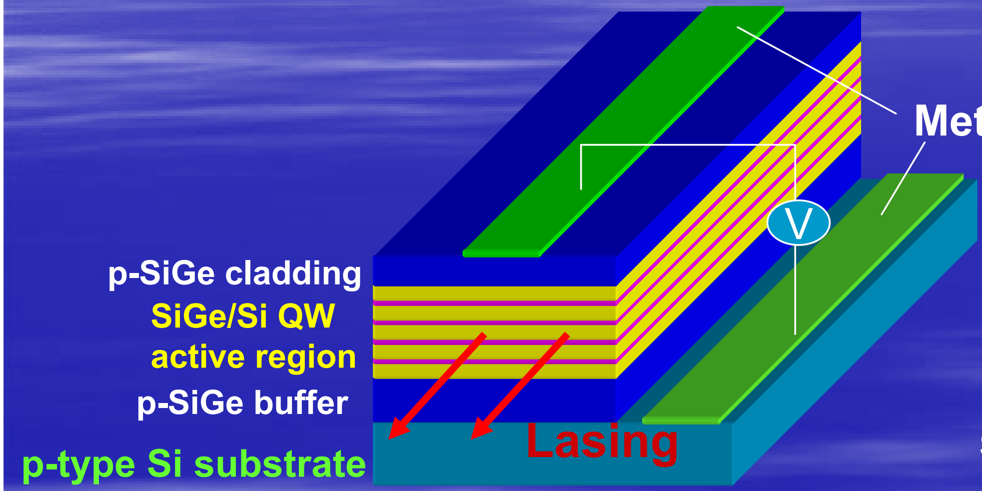
  G. Dehlinger et al (Switzerland, 2000)

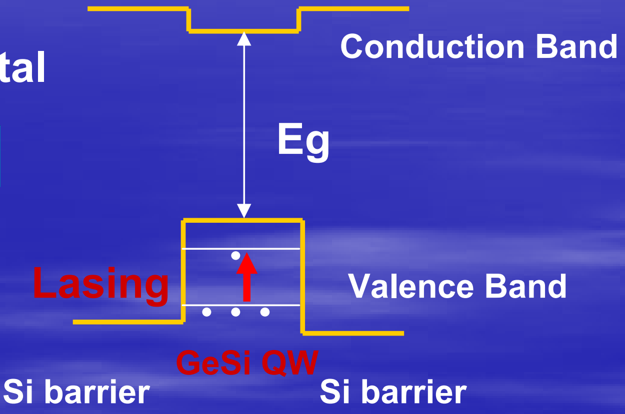
  I. Bormann et al (Germany, 2002)

  S. A. Lynch et al (England, 2002)
- **One scheme in common – Intersubband transitions in valence band**

SiGe Intersubband Devices

- Intersubband transitions within the valence band of GeSi/Si quantum Wells





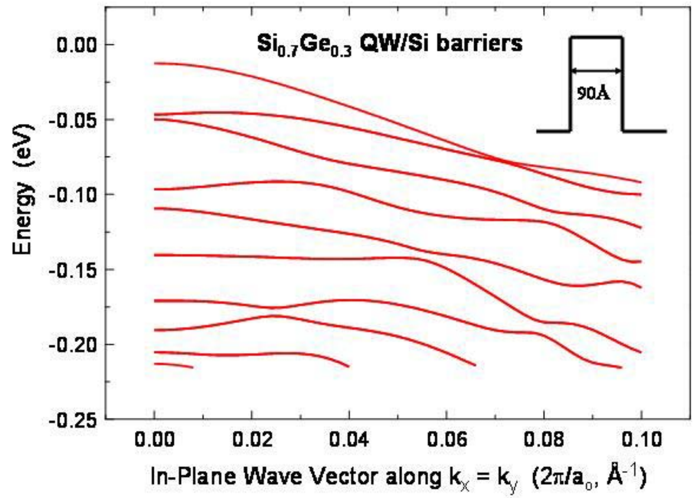
- SiGe quantum wells with Si barriers
- Small offset in conduction band
- Large offset in valence band – p-i-p structure
- Electro-luminescence demonstrated but no lasing so far

G. Sun, L. Friedman, and R. A. Soref, APL, vol.66, 3425 (1995)

Challenges and Opportunities of Si Based Intersubband Lasers

Challenges:

- Unparallel valence subband dispersion due to light hole – heavy hole coupling
- Difficulty in growing multiple QWs of large thickness due to large lattice mismatch (4%) between Si and Ge
- Low carrier transport and small oscillator strength due to large hole effective mass

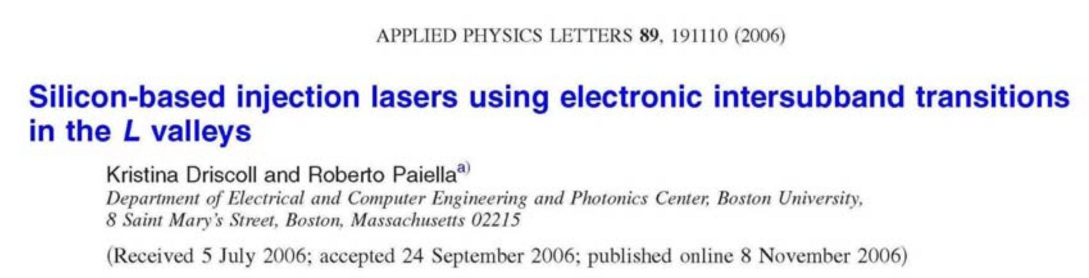


Opportunities:

- **Lower threshold** because of longer subband lifetimes due to weaker scattering of nonpolar optical phonons
- Strain and band offset engineering by incorporating yet another group-IV element **Sn** into the system

Possibility of Group-IV Intersubband Lasers in Conduction Band

Transitions between subbands within either Δ- or L-valleys are direct.

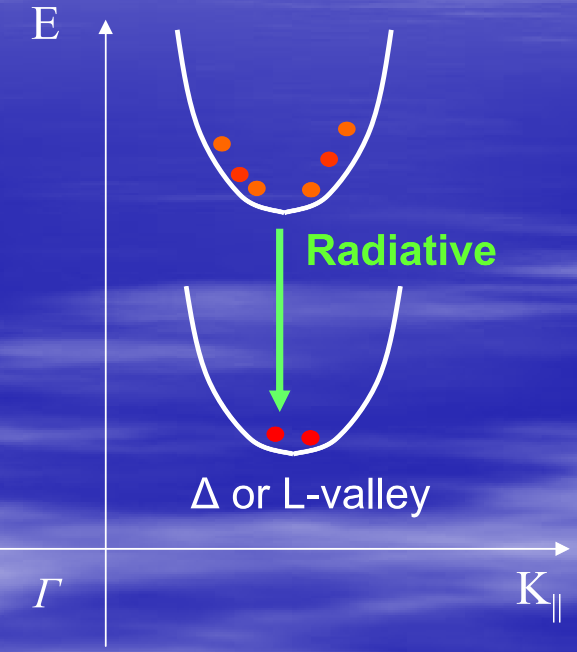


APPLIED PHYSICS LETTERS **89**, 191110 (2006)

Silicon-based injection lasers using electronic intersubband transitions in the *L* valleys

Kristina Driscoll and Roberto Paiella[a)]
Department of Electrical and Computer Engineering and Photonics Center, Boston University, 8 Saint Mary's Street, Boston, Massachusetts 02215

(Received 5 July 2006; accepted 24 September 2006; published online 8 November 2006)



- Proposed a CB QCL operating in L-valleys of Ge/SiGe QW structure
- L and Δ valleys are entangled - possible nonradiative decay channels

SiGeSn Material System

Incorporation of Sn:

- Initially motivated by the prediction of possible direct bandgap in Ge-Sn alloy
- Difficulty in growth due to large lattice mismatch (17% with Ge), instability of α-Sn, and solubility of Sn in Ge is very low (<0.5%)
- CVD Growth of SiGeSn alloys on (001) Si substrate at ASU since 2002

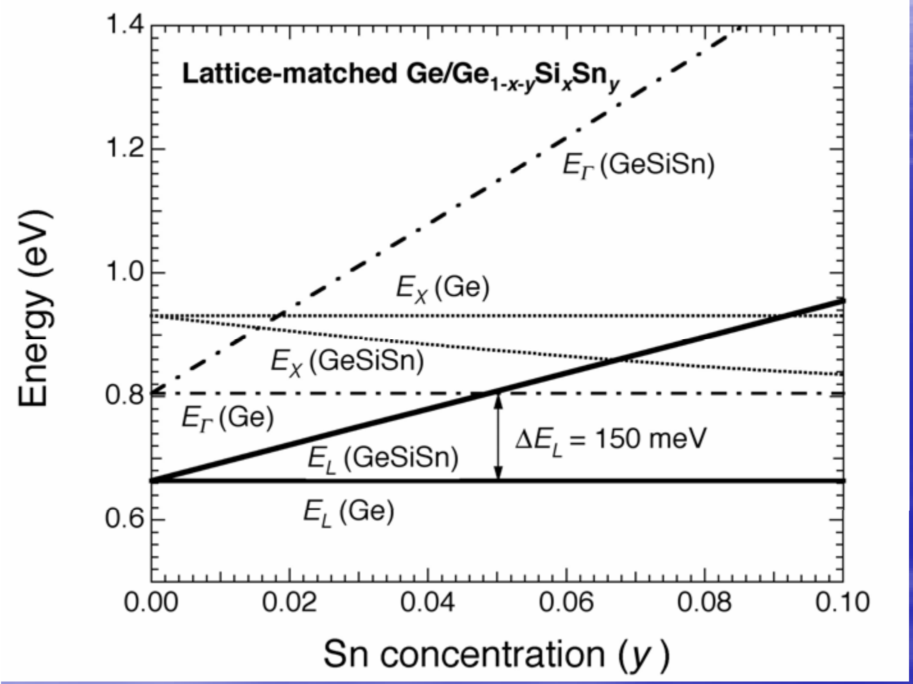
Advantages:

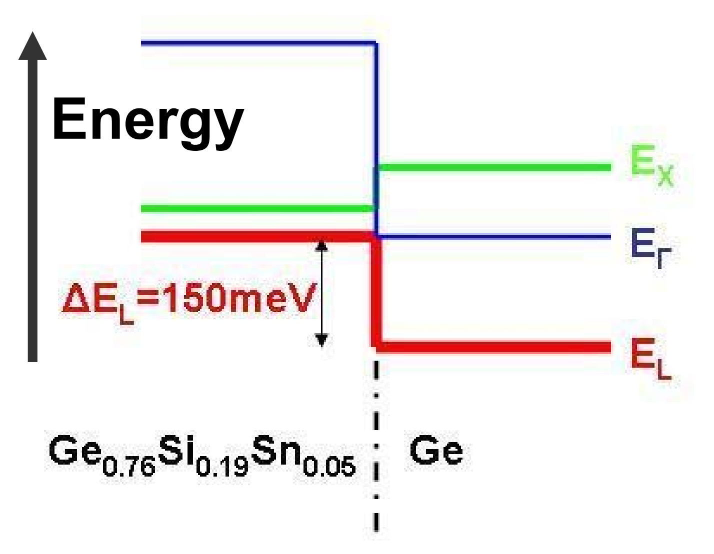
- Another degree of freedom
  - Strain modulation by incorporating Sn into the system
  - Lattice constant of SiGeSn alloys either above or below Ge
- Direct bandgap predicted in tensile strained Ge type-I QW with $Ge_{1-x-y}Si_xSn_y$ (y>20%) barriers
- Increase of conduction band offset – CB QCLs

GeSiSn/Ge Strain Free QCLs

- Lattice matched structure
  no limitations on number of layers and thickness
- Large L-valley offset
  conduction band intersubband lasers
- “Clean” L-valley offset
  no entangling with other valleys

Ge/GeSiSn Conduction Band Offset

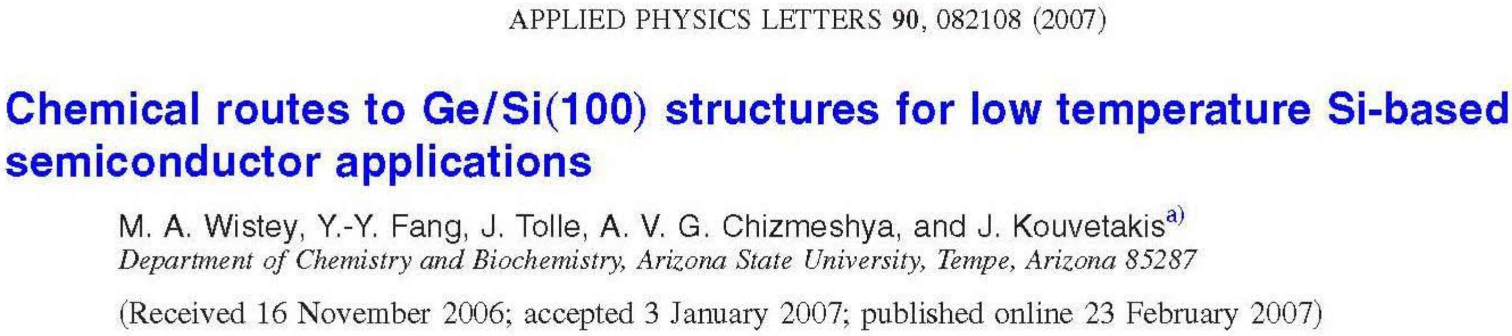




- Calculated based on Jaros' Band offset theory Phys. Rev. B **37**, 7112 (1988)
- Conduction Γ, X, and L valleys for lattice matched GeSiSn alloy with Ge
- L-valleys for both GeSiSn and Ge below all others for Sn < 5%

  ΔE_L=150meV between Ge well and Ge$_{0.76}$Si$_{0.19}$Sn$_{0.05}$ barrier

Ge/GeSiSn QCL on Si substrate



APPLIED PHYSICS LETTERS **90**, 082108 (2007)

Chemical routes to Ge/Si(100) structures for low temperature Si-based semiconductor applications

M. A. Wistey, Y.-Y. Fang, J. Tolle, A. V. G. Chizmeshya, and J. Kouvetakis[a)]
Department of Chemistry and Biochemistry, Arizona State University, Tempe, Arizona 85287

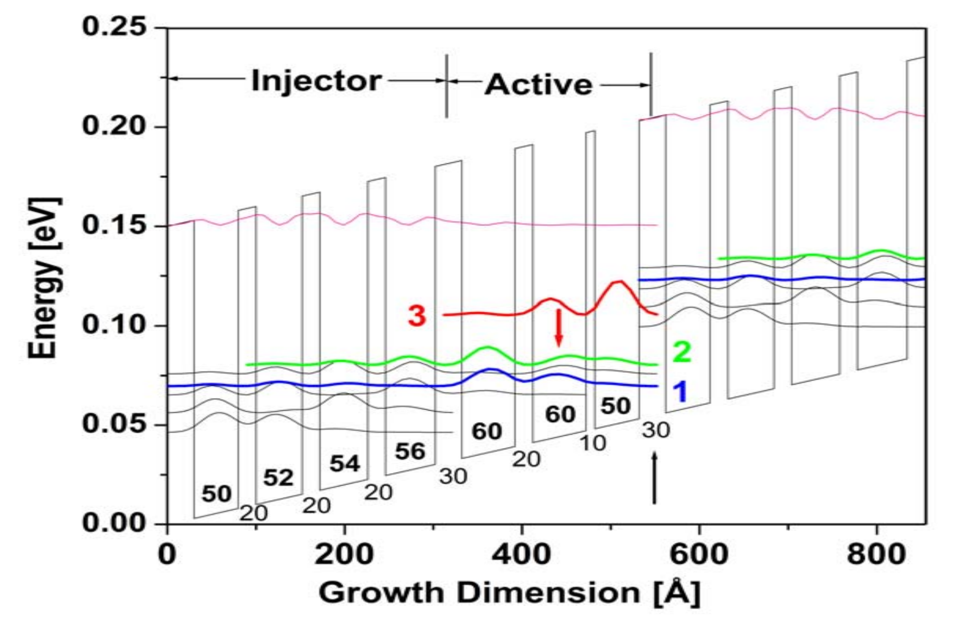
(Received 16 November 2006; accepted 3 January 2007; published online 23 February 2007)

- **Growth of relaxed Ge layers directly on Si substrate**
- **Ge layers in 40nm -1µm thickness**
- **Edge dislocations formed at interface**
- **Low threading dislocation density < $10^5/cm^2$**

Strain Free Ge/GeSiSn QCLs can be lattice matched

to relaxed Ge buffer layer on Si substrate

L-Valley Ge/GeSiSn QCL



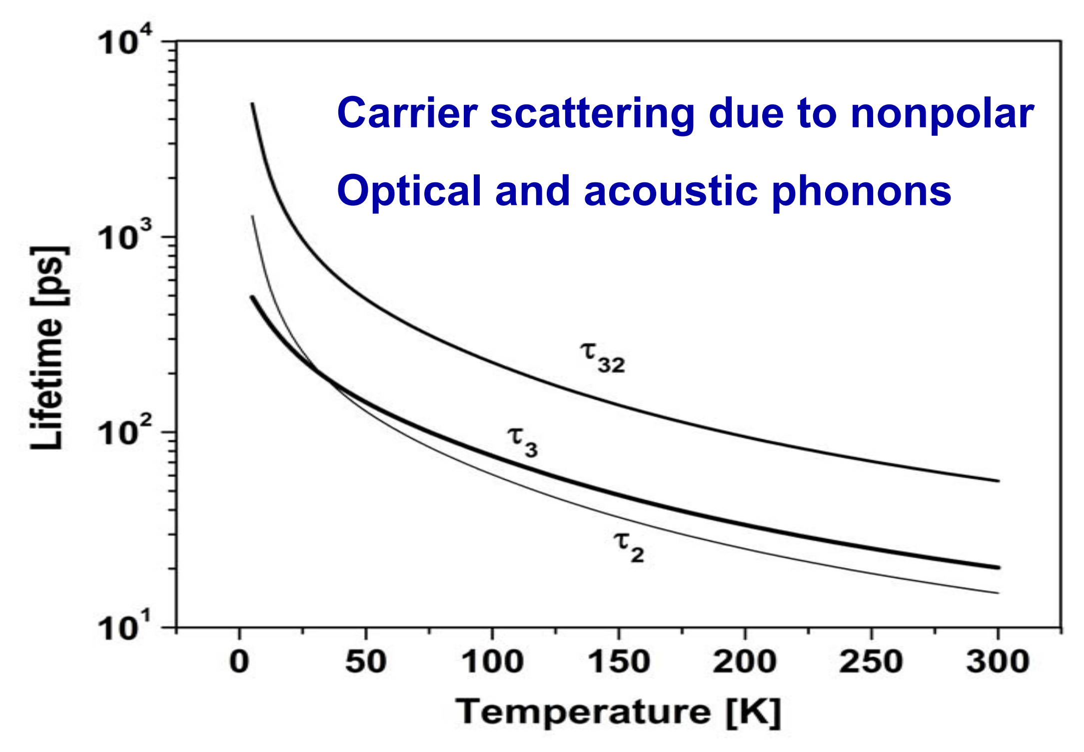
L-valley CB offset: 150meV; Effective mass: $0.12m_o$; Electric field: 10kV/cm

Active region: 3 states with 3 QWs; lasing transition: 3 → 2 (49μm)

Injector region: miniband formed with 4 QWs; upper state 3 in miniband gap; strong overlap between state 2 and miniband.

$\tau_{32} > \tau_2$

Lifetimes



Carrier scattering due to nonpolar

Optical and acoustic phonons

Population inversion: $\tau_{32} > \tau_2$

Population dynamics and optical gain

Population rate equation at threshold

$$\begin{cases} \dfrac{\partial N_3}{\partial t} = \dfrac{\eta J}{e} - \dfrac{N_3 - \bar{N}_3}{\tau_3} \\ \dfrac{\partial N_2}{\partial t} = \dfrac{N_3 - \bar{N}_3}{\tau_{32}} - \dfrac{N_2 - \bar{N}_2}{\tau_2} \end{cases}$$

Current injection

Depopulation

3 → 2 Carrier scattering

Optical gain

Lifetime requirement for inversion

$$g = \frac{2e^2(\hbar\omega_L)|<3|z|2>|^2}{\varepsilon_o c\hbar n\Gamma L_p}[\tau_3(1-\frac{\tau_2}{\tau_{32}})\frac{\eta J}{e} - (\bar{N}_2 - \bar{N}_3)]$$

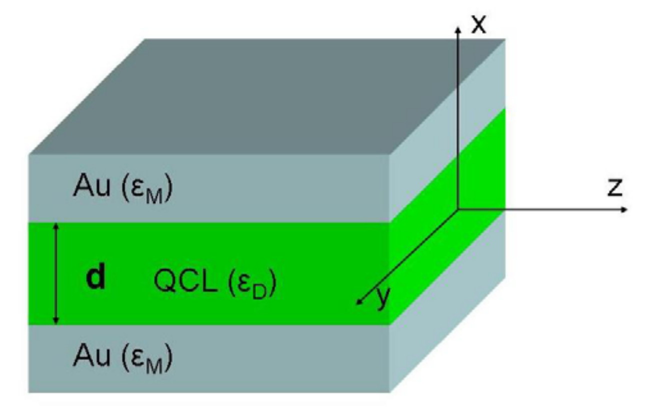
Dipole matrix overlap

Thermal population

Plasmon Waveguide

- Conventional dielectric waveguides unsuitable for far-IR QCLs (d<<λ)
- Plasmon waveguides with metal cladding layers effective for mode confinement
- Only TM-polarized modes allowed
- Waveguide loss associated with metal absorption

Plasmon Waveguide Analysis



TM mode

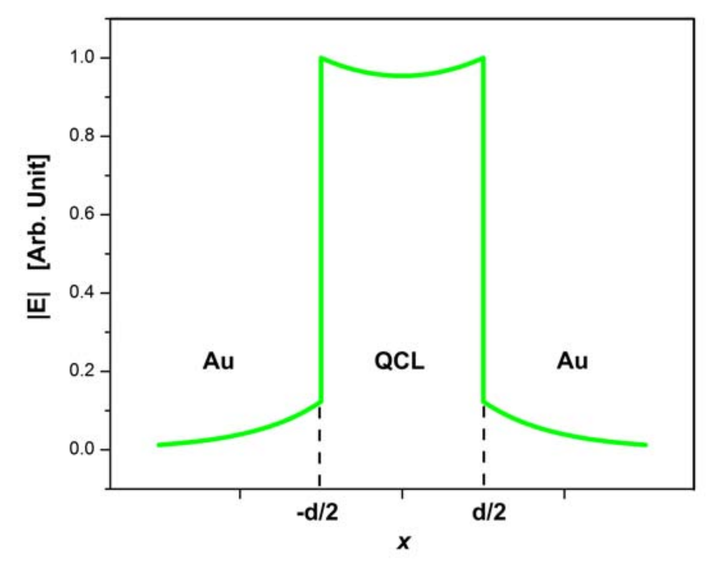
$$H_y = \begin{cases} a e^{-q(x-d/2)} e^{j(\beta z-\omega t)}, & x > d/2 \\ b\cosh(kx) e^{j(\beta z-\omega t)}, & |x| < d/2 \\ a e^{q(x+d/2)} e^{j(\beta z-\omega t)}, & x < -d/2 \end{cases}$$

$$\mathbf{E} = \begin{cases} \dfrac{\cosh(kd/2)}{\varepsilon} E_o (j\beta\hat{\mathbf{x}} + q\hat{\mathbf{z}}) e^{-q(x-d/2)} e^{j(\beta z-\omega t)}, & x > d/2 \\ E_o[j\beta\cosh(kx)\hat{\mathbf{x}} - k\sinh(kx)\hat{\mathbf{z}}] e^{j(\beta z-\omega t)}, & |x| < d/2 \\ \dfrac{\cosh(kd/2)}{\varepsilon} E_o (j\beta\hat{\mathbf{x}} - q\hat{\mathbf{z}}) e^{q(x+d/2)} e^{j(\beta z-\omega t)}, & x < -d/2 \end{cases}$$

$$\varepsilon_M = 1 - \frac{\omega_P^2}{\omega^2 + i\omega\gamma_M} \quad \rightarrow \quad \beta = \beta' + j\beta''$$

Plasmon Waveguide Results

Electric field Profile:



Optical confinement Γ≈1.0

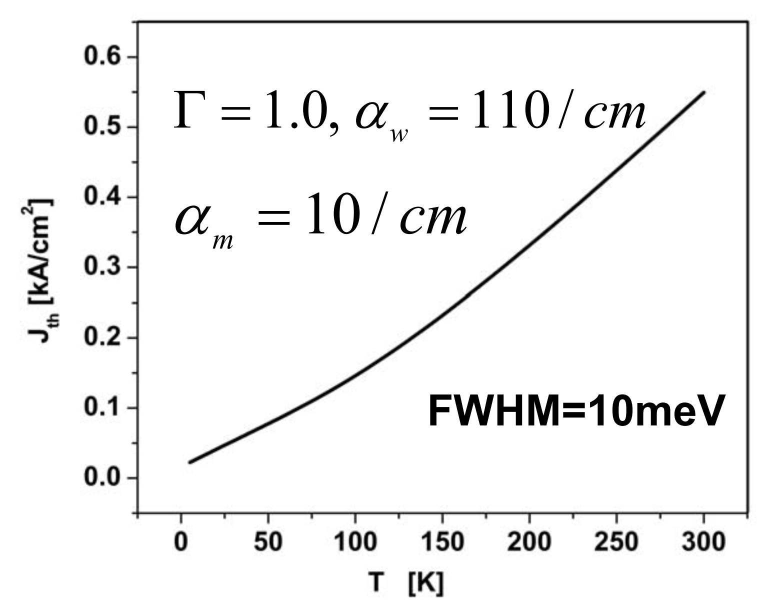
Waveguide loss: α_W=110/cm

For d=2.1μm (40 periods of QCL)

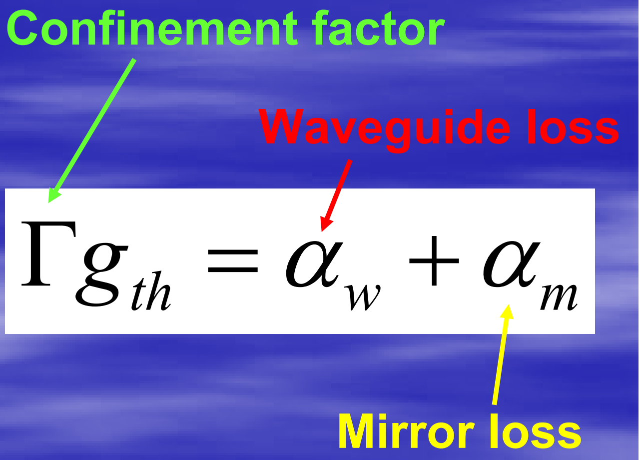
Threshold Current

Optical Gain:

$$g = \frac{2e^2(\hbar\omega_L)|<3|z|2>|^2}{\varepsilon_o c\hbar n\Gamma L_p}[\tau_3(1-\frac{\tau_2}{\tau_{32}})\frac{\eta J}{e} - (\bar{N}_2 - \bar{N}_3)]$$



$$<3|z|2>= 3.3nm$$



Confinement factor

Waveguide loss

$$\Gamma g_{th} = \alpha_w + \alpha_m$$

Mirror loss

In comparison with GaAs-based QCLs, this represents a reduction in threshold current density!

Summary

GeSiSn/Ge Strain Free QCLs

- Lattice matched structure
  no limitations on number of layers and thickness
- Large L-valley offset
  conduction band intersubband lasers
- “Clean” L-valley offset
  no entangling with other valleys