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

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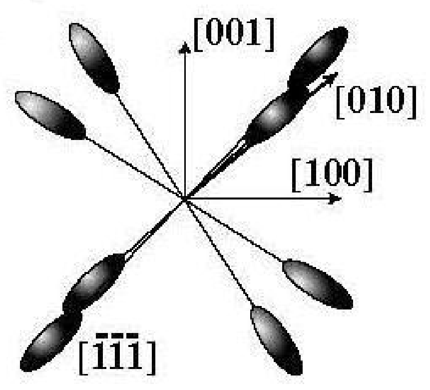
Advantages of Si Lasers

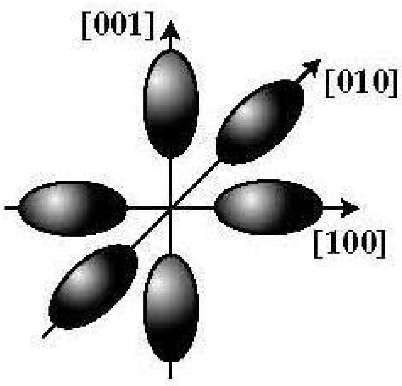
- Availability of lowest cost, largest size Si wafers
- Leveraging the infrastructure of the huge, global silicon microelectronics industry in order to make highly sophisticated silicon photonic devices
- Integrating silicon photonics monolithically on a chip containing fast VLSI silicon electronics 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

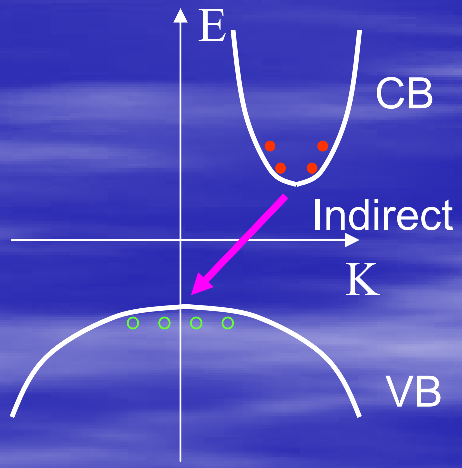
- Indirect bandgap



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:

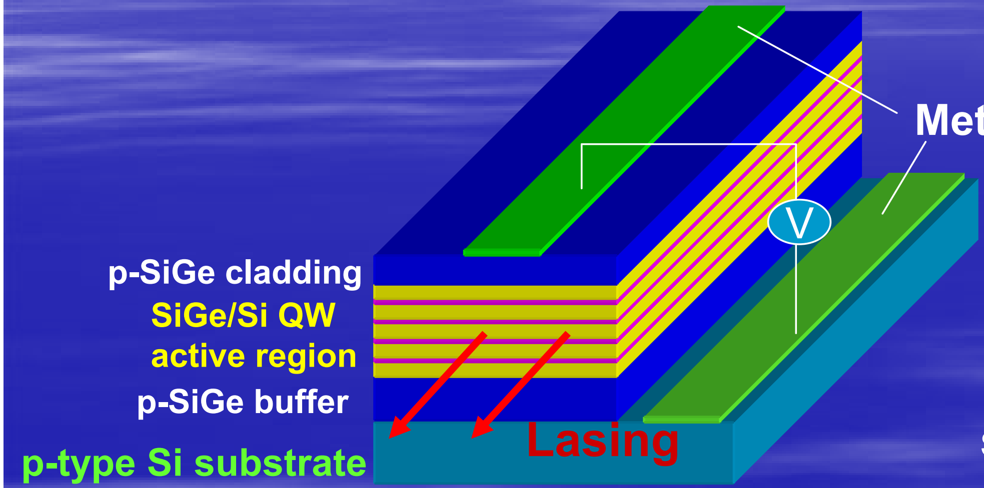
  G. Dehlinger et al (Switzerland, 2000)

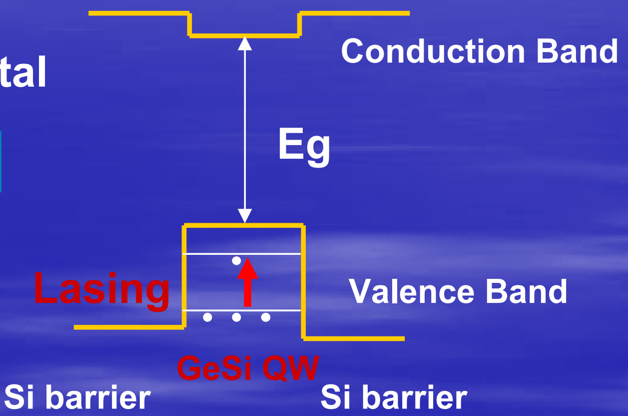
  I. Bormann et al (Germany, 2002)

  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





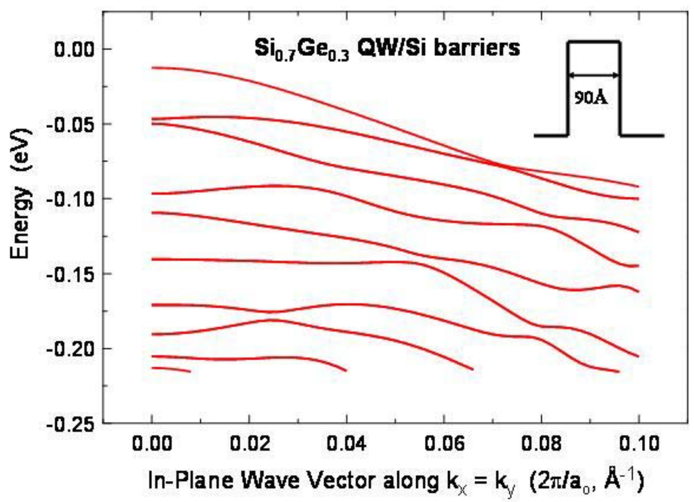
- SiGe quantum wells with Si barriers
- Small offset in conduction band
- Large offset in valence band – p-i-p structure
- Electro-luminescence demonstrated but no lasing so far

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

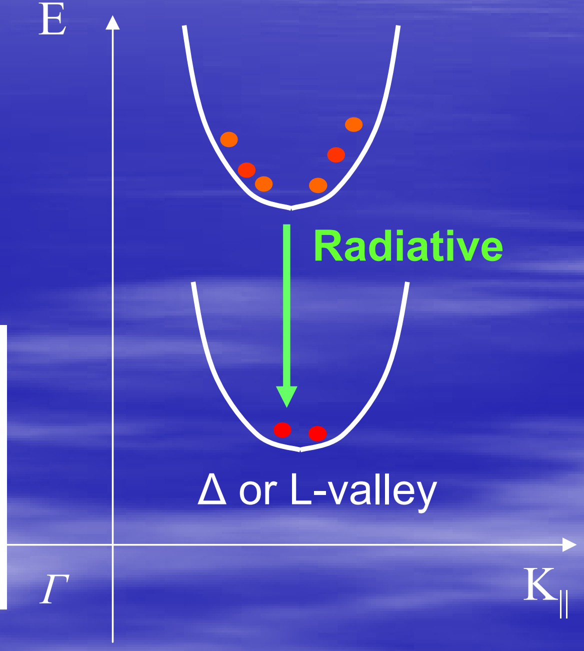


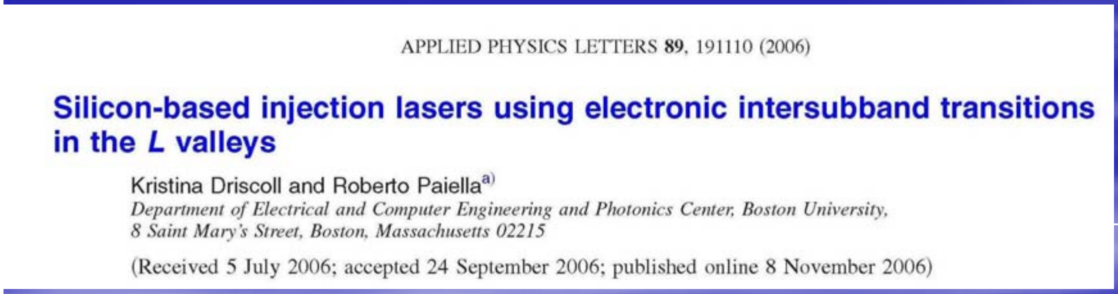
Opportunities:

- **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

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- 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

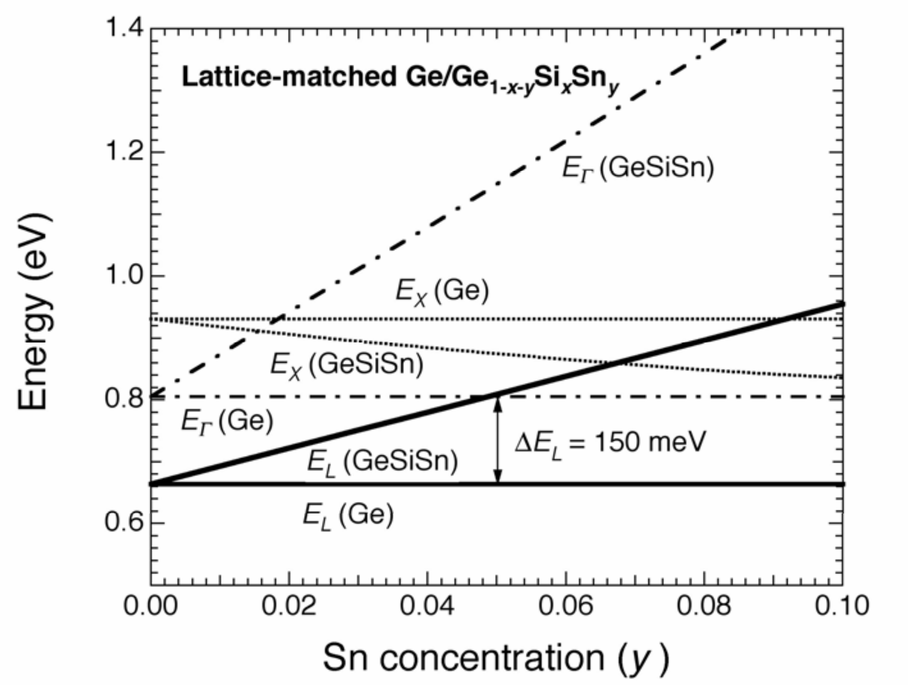
Advantages:

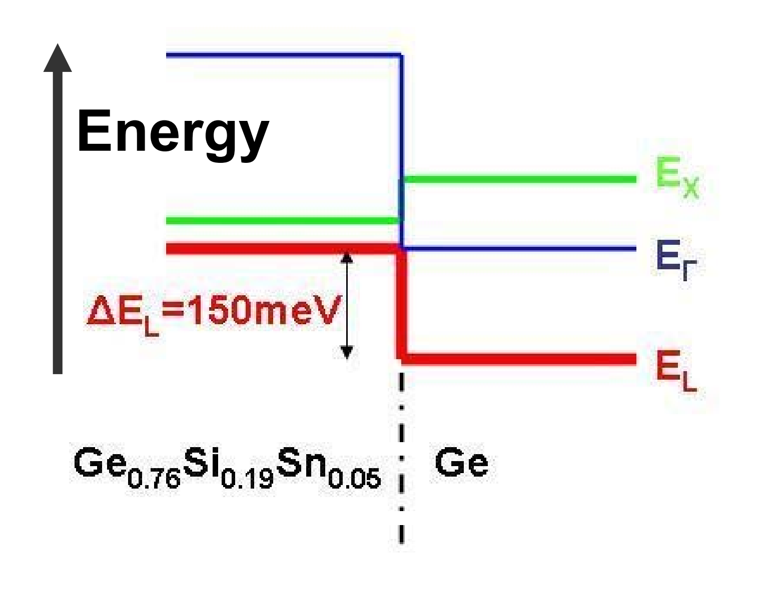
- Another degree of freedom
  - Strain modulation by incorporating Sn into the system
  - Lattice constant of SiGeSn alloys either above or below Ge
- Direct bandgap predicted in tensile strained Ge type-I QW with $Ge_{1-x-y}Si_xSn_y$ (y>20%) barriers
- Increase of conduction band offset – CB QCLs

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

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

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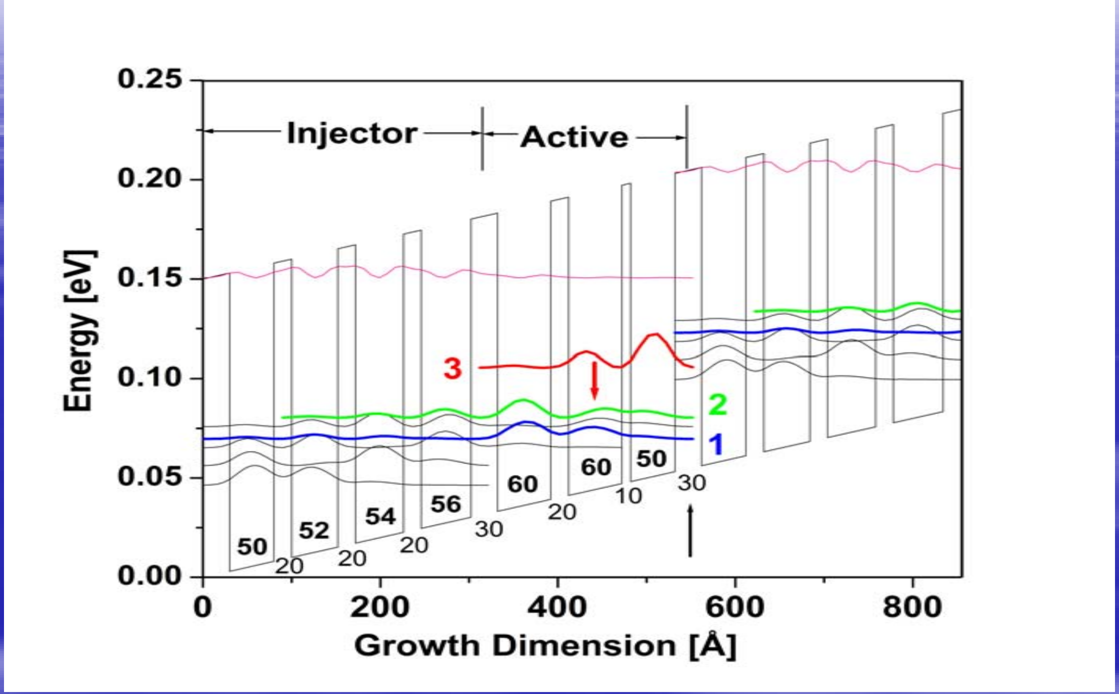
(Received 16 November 2006; accepted 3 January 2007; published online 23 February 2007)

- 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



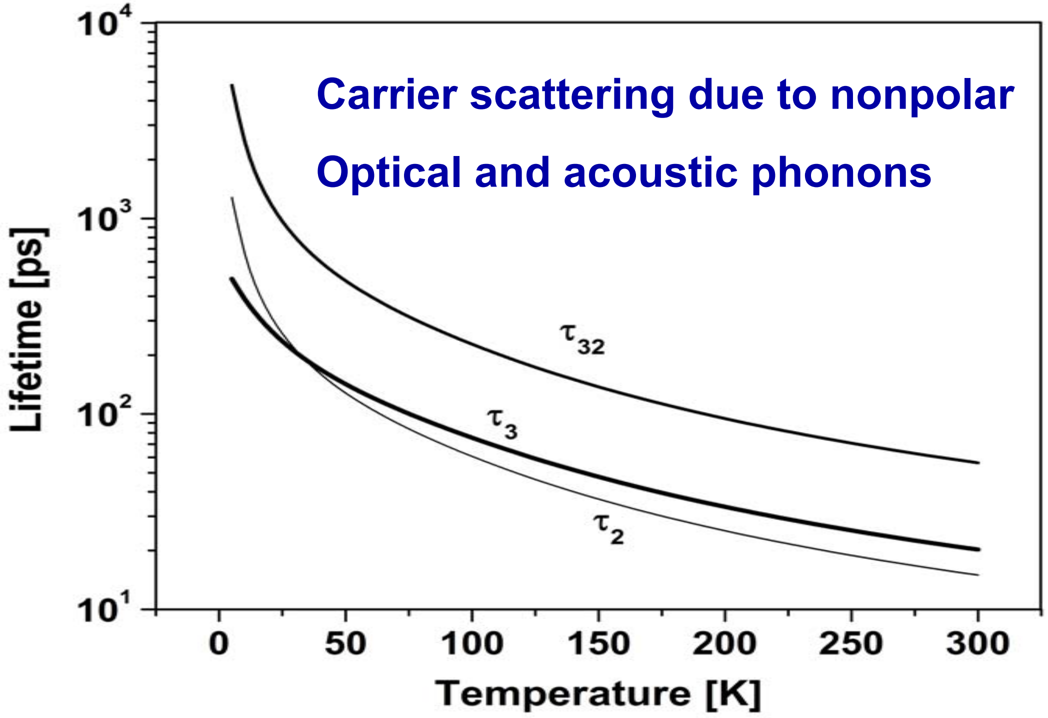
L-valley CB offset: 150meV; Effective mass: $0.12m_o$; Electric field: 10kV/cm

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



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

Population dynamics and optical gain

Population rate equation at threshold

$$\begin{cases} \dfrac{\partial N_3}{\partial t} = \dfrac{\eta J}{e} - \dfrac{N_3 - \bar{N}_3}{\tau_3} \\[2ex] \dfrac{\partial N_2}{\partial t} = \dfrac{N_3 - \bar{N}_3}{\tau_{32}} - \dfrac{N_2 - \bar{N}_2}{\tau_2} \end{cases}$$

Current injection

Depopulation

$3 \rightarrow 2$ Carrier scattering

Optical gain

Lifetime requirement for inversion

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

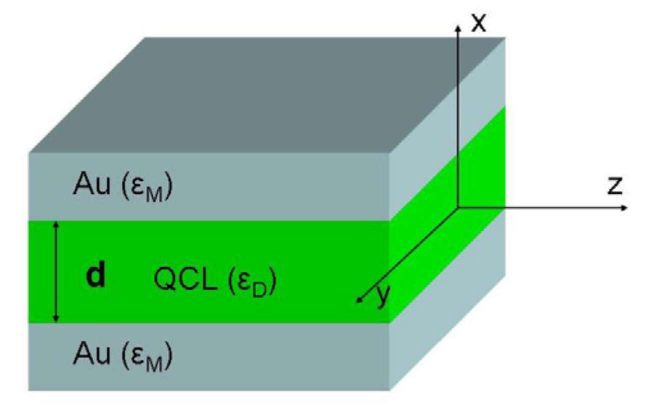
Dipole matrix overlap

Thermal population

Plasmon Waveguide

- Conventional dielectric waveguides unsuitable for far-IR QCLs ($d \ll \lambda$)
- 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

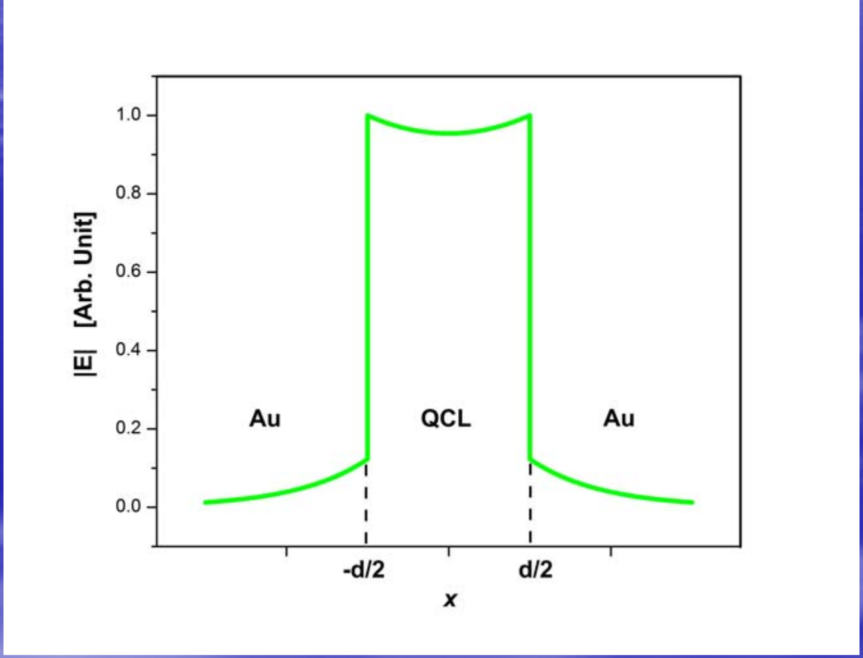
$$H_y = \begin{cases} a e^{-q(x-d/2)} e^{j(\beta z-\omega t)}, & x > d/2 \\ b\cosh(kx) e^{j(\beta z-\omega t)}, & |x| < d/2 \\ a e^{q(x+d/2)} e^{j(\beta z-\omega t)}, & x < -d/2 \end{cases}$$

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

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

Plasmon Waveguide Results

Electric field Profile:



Optical confinement Γ≈1.0

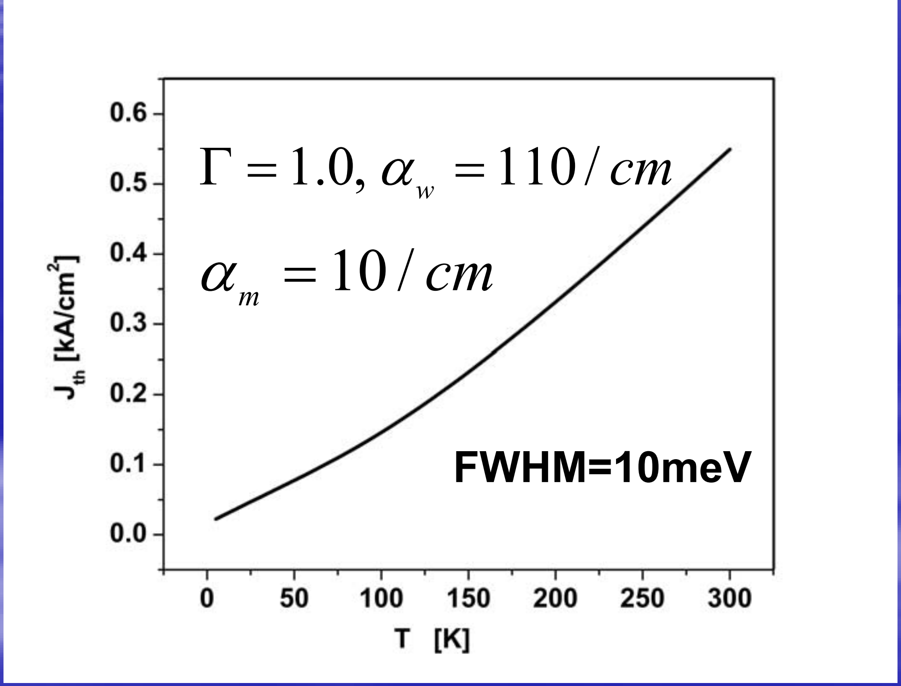
For d=2.1μm (40 periods of QCL)

Waveguide loss: α_W=110/cm

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