Intersubband Devices Operating in the Restrahlen Region

Jacob B. Khurgin
The Johns Hopkins University
Baltimore, Maryland 21218, USA

Greg Sun
University of Massachusetts Boston
Boston, Massachusetts 01887, USA

Abstract

- We investigate characteristics of intersubband optical devices in which waveguiding is provided by highly-reflective semiconductor in the restrahlen band.
- We identify spectral regions within the restrahlen band of a cladding layer that offers advantages over both traditional dielectric waveguide and metal clad waveguides.

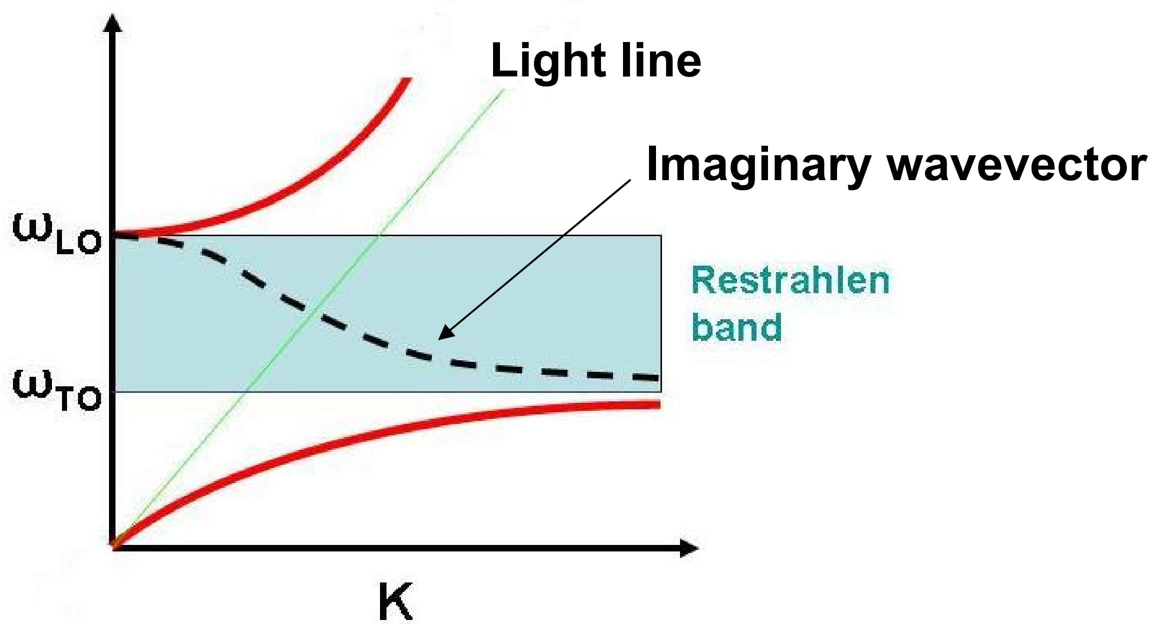
Far-IR Waveguide Challenges

- QCLs require waveguides of high optical confinement with low loss
- Conventional dielectric waveguides are unsuitable due to low index contrast and difficulty in growing thick layers
- Plasmon waveguides are highly absorptive due to fast energy relaxation rates of electrons (~10fs for Au)

Waveguides Using Surface Phonon Polaritons

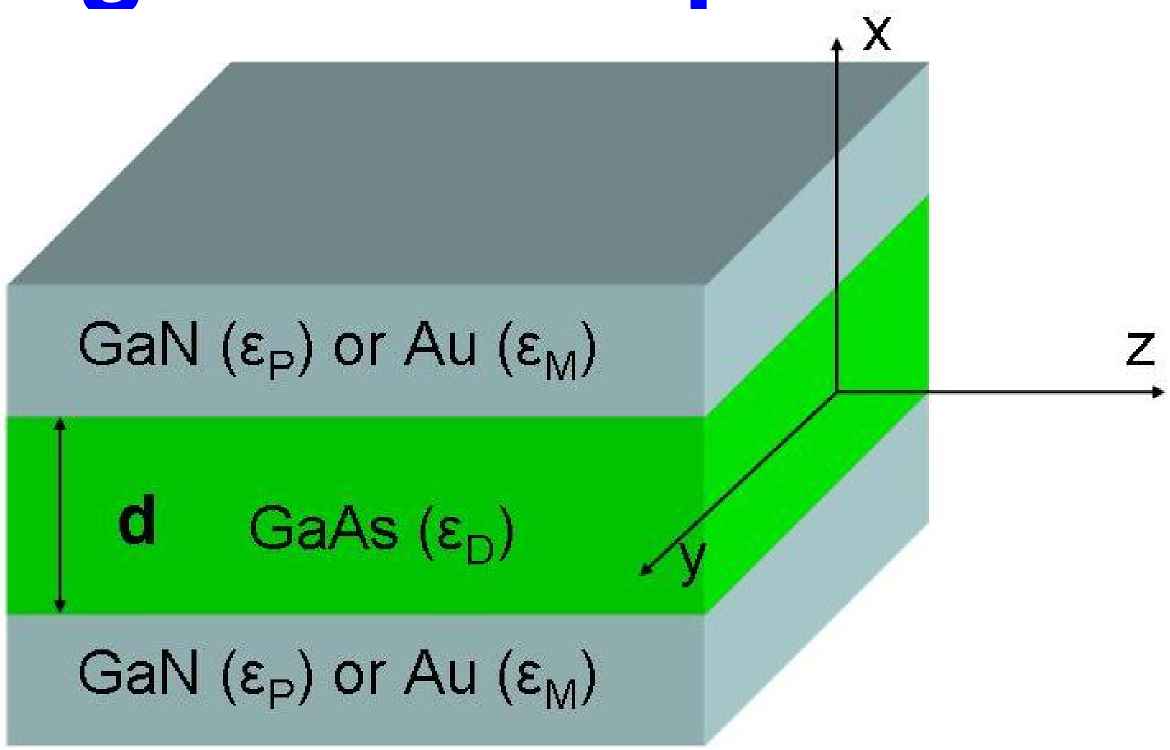
- Transitions associated with optical phonons with scattering times ~ps are less prone to scattering
- Materials with negative dielectric constant in the far-IR Restrahlen region behave just like a metal
- Waveguides formed with cladding material in Restrahlen region, can support surface phonon polariton TM modes that are evanescent in both core and cladding
- Such waveguides offer desired confinement with less loss

Surface Phonon Polaritons



Restrahlen band between TO and LO phonons with negative dielectric function

Waveguide Comparison



Two GaAs-based QCLs operating in the Restrahlen region of GaN are compared:

a) GaN as cladding (surface phonon polarions)

b) Au as cladding (surface plasmon polaritons)

TM Modes

Both waveguides will support TM modes:

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

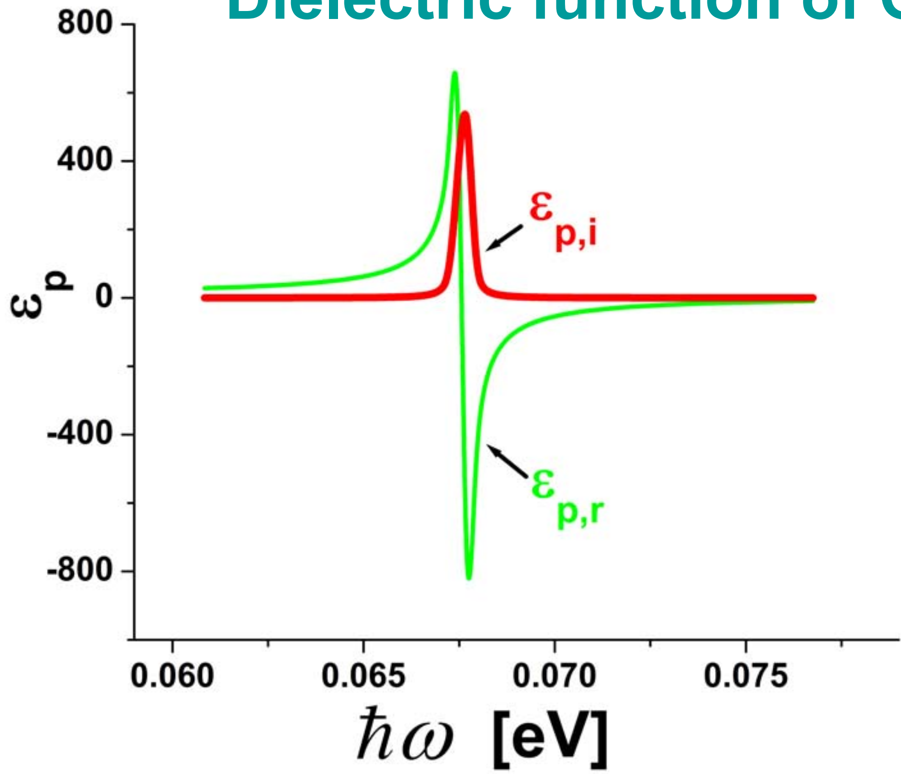
$\beta = \beta' + j\beta''$ **Complex wave vector**

$\varepsilon = \varepsilon_{P,M} / \varepsilon_D$ Dielectric functions of GaN (ε_p) and Au (ε_M)
Dielectric constant of GaAs (ε_D)

$k^2[\varepsilon^2 \tanh^2(kd/2) - 1] = 1 - \varepsilon$ **Confined modes**

Dielectric Functions

Dielectric function of GaN in Restrahlen band



$$\varepsilon_p = \varepsilon_\infty \left(1 + \frac{\omega_{LO}^2 - \omega_{TO}^2}{\omega_{TO}^2 - \omega^2 - j\omega\gamma_P}\right)$$

$\hbar\omega_{TO} = 67.6$ meV

$\hbar\omega_{LO} = 89.7$ meV

$\gamma_p = 0.1$ meV

Dielectric function of Au

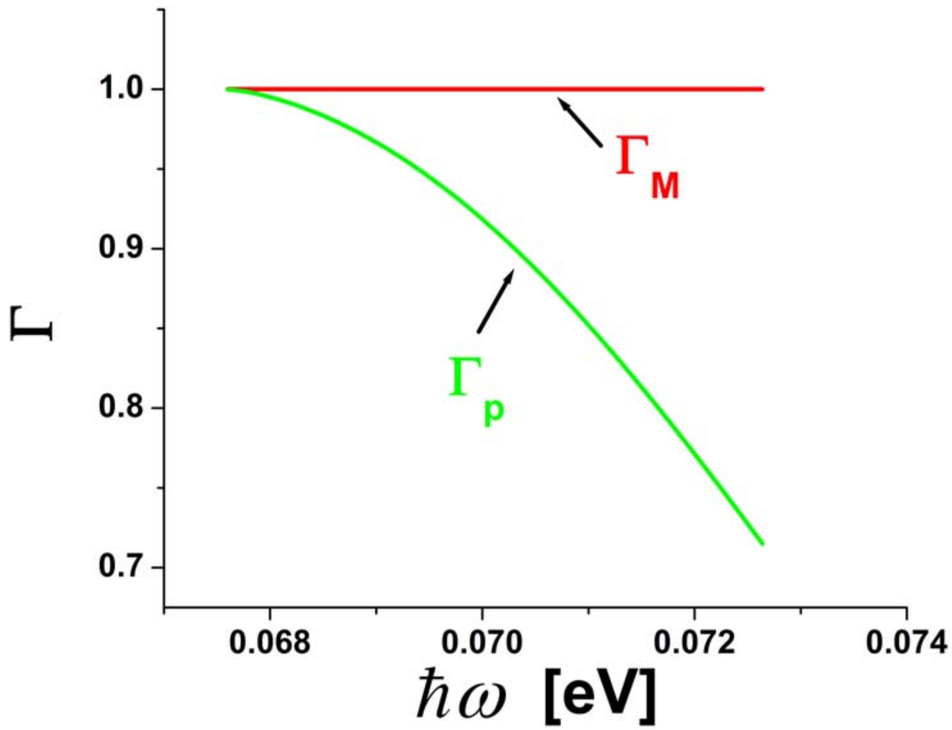
$$\varepsilon_M = 1 - \frac{\omega_P^2}{\omega^2 + i\omega\gamma_M}$$

$\varepsilon_{M,r} \approx -7000$

$\varepsilon_{M,i} \approx 6000$

$\hbar\omega_M = 8.11$ eV $\quad \gamma_M = 65.8$ meV

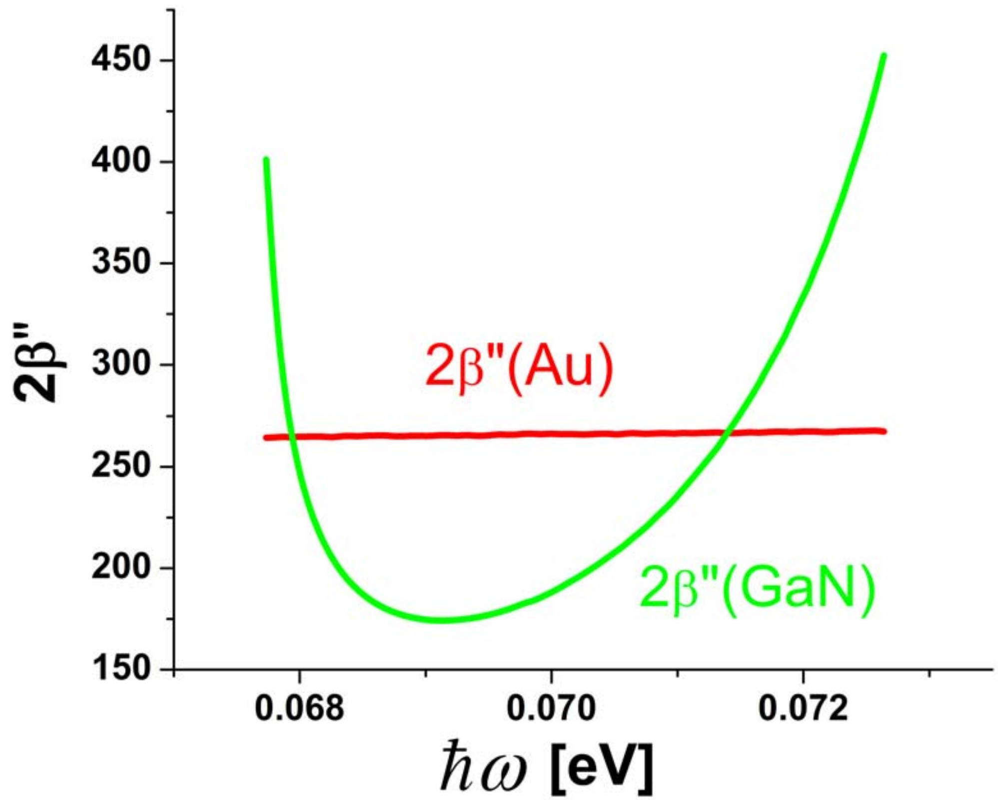
Optical Confinement



d=1μm

In general, plasmon waveguides provide better optical confinement

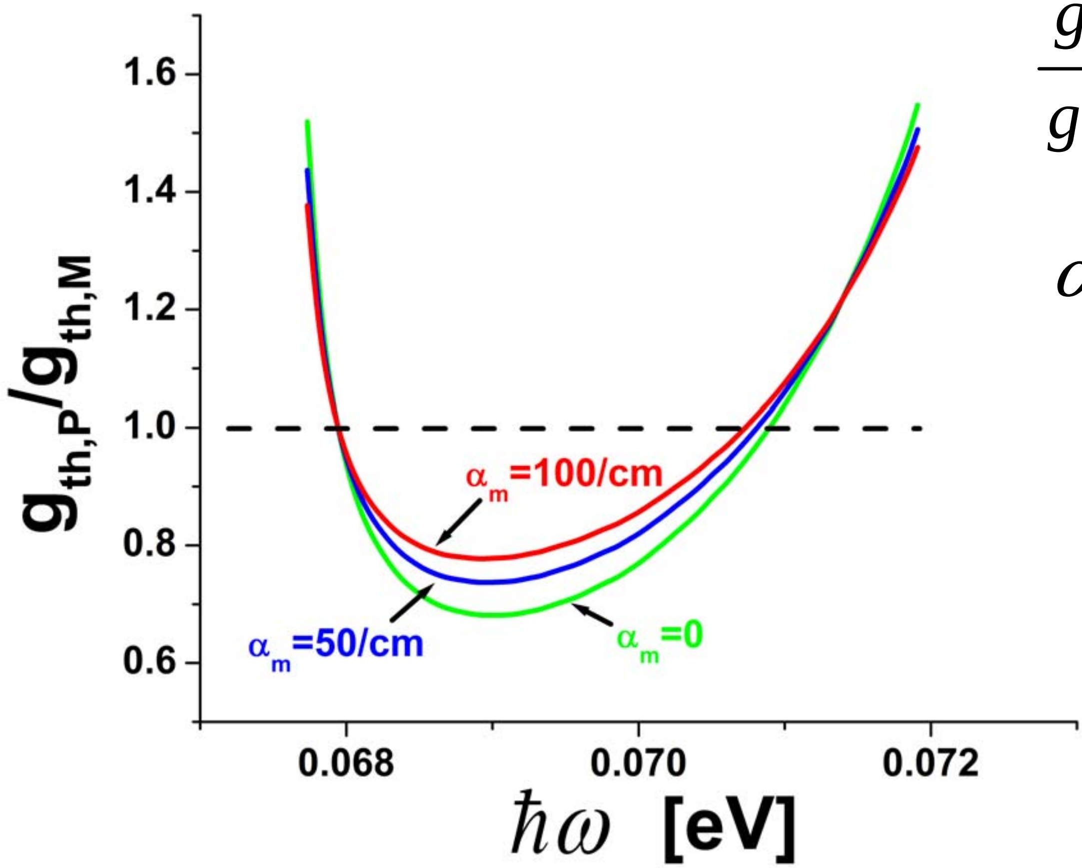
Waveguide Loss



d=1μm

Smaller waveguide loss in the narrow spectral range within the Restrahlen region of the GaN cladding is the result of slower scattering time of the optical phonons

Threshold Gain



$$\frac{g_{th,P}}{g_{th,M}} = \frac{\Gamma_M}{\Gamma_P} \frac{2\beta_P'' + \alpha_m}{2\beta_M'' + \alpha_m}$$

α_m: **mirror loss**

The region where the ratio is less than 1 represents a reduction in threshold

Conclusion

There exists a narrow spectral range within the Restrahlen region of the cladding material where a reduction in threshold can be obtained using surface phonon polariton waveguide.