Intersubband Devices Operating in the Restrahlen Region

Greg Sun and Jacob B. Khurgin

***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 in which operating within the restrahlen band of a cladding layer offers advantages over both traditional dielectric waveguide and metal clad waveguides using surface plasmon polaritons.**

I. Introduction

In recent years significant progress has been achieved in development of efficient sources and detectors of far-IR radiation in the range of 12-30 μm. These devices, especially quantum cascade lasers (QCLs) require efficient waveguiding structures capable of providing high degree of optical confinement with low loss. Unfortunately at wavelengths that are in excess of 10μm there is no easy way to accomplish this goal. The difference in the indices of refraction of different semiconductors in the far-IR range is typically small, unless one ventures close to one of the lattice resonances where index is large. Unfortunately, being close to resonance usually implies significant absorption. At any rate, even with a reasonably large index contrast a typical dielectric waveguide would have to be very thick, making the growth and fabrication difficult and expensive.

Therefore, typically a metal clad waveguide, in which the TM mode is evanescent in both core and metal cladding (surface plasmon polariton) is used as confinement means [1-2]. The thickness of active waveguide core thus can be made much smaller than the wavelength. Unfortunately the metal clad waveguide is not entirely problem free. First of all, the metal is strongly absorptive in the far IR region. Second, it is difficult to provide metal layer on both sides of the waveguide. For this reason highly doped semiconductors are often used in place of metal [3-4] and they suffer from high free carrier absorption.

The origin of strong absorption losses in metals and highly doped semiconductor is in extremely fast energy relaxation rates of electrons – it is about 10fs in Au and a few hundreds of femtoseconds in GaAs. One would like to identify some transitions that are less prone to scattering. Such transition can be associated with optical phonons that are known to have scattering times in the order of a few picoseconds. Due to strong optical phonon resonance there exists a Restrahlen region in the far-IR where the dielectric constant is actually negative and the material behaves just like a metal. Therefore, at the interface between two semiconductors, one of which is in Restrahlen region and the other one is not, is there exits a surface polariton TM mode which exponentially decays into both materials. This mode can be used to provide desired confinement with low loss. In this work we have considered surface phonon-polariton modes that can be used for quantum cascade lasers (QCLs) and other intersubband devices.

II. Confined TM Modes

For the purpose of demonstrating such an idea, we compare two GaAs-based QCLs operating in the Restrahlen region of GaN. One uses GaN as cladding, the other uses Au as shown

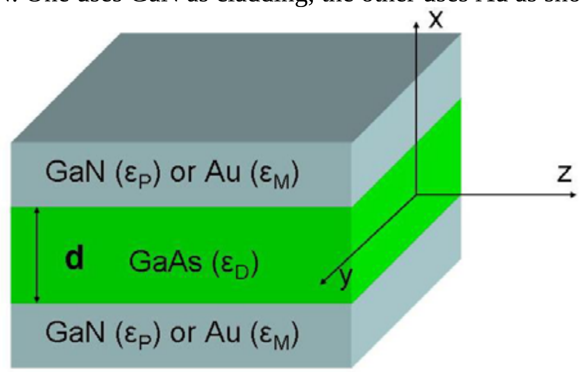

Fig. 1. Illustration of GaAs-based QCL waveguide with either GaN or Au as cladding.

in Fig.1. Both waveguides will support TM modes with an electric field

$$\mathbf{E}=\begin{cases}\dfrac{\cosh(kd/2)}{\varepsilon}E_o(j\beta\hat{\mathbf{x}}+q\hat{\mathbf{z}})e^{-q(x-d/2)}e^{j(\beta z-\omega t)}, & x>d/2\\ E_o[j\beta\cosh(kx)\hat{\mathbf{x}}-k\sinh(kx)\hat{\mathbf{z}}]e^{j(\beta z-\omega t)}, & |x|<d/2\\ \dfrac{\cosh(kd/2)}{\varepsilon}E_o(j\beta\hat{\mathbf{x}}-q\hat{\mathbf{z}})e^{q(x+d/2)}e^{j(\beta z-\omega t)}, & x<-d/2\end{cases}\quad(1)$$

where complex wave vectors $\beta=\beta'+j\beta''$ and k are related by $k^2[\varepsilon^2\tanh^2(kd/2)-1]=1-\varepsilon$ with $\varepsilon=\varepsilon_{P,M}/\varepsilon_D$, the dielectric function of GaN in Restrahlen band $\varepsilon_p=\varepsilon_\infty(1+\dfrac{\omega_{LO}^2-\omega_{TO}^2}{\omega_{TO}^2-\omega^2-j\omega\gamma_P})$ and that of Au $\varepsilon_M=1-\dfrac{\omega_P^2}{\omega^2+i\omega\gamma_M}$. The Restrahlen band of GaN is between

G. Sun is with Department of Physics, University of Massachusetts Boston, Boston, MA 02125 USA (phone: 617-287-6432; fax: 617-287-6053; e-mail: greg.sun@ umb.edu).

J. B. Khurgin is with Department of Electrical and Computer Engineering, Johns Hopkins University, Baltimore, Maryland 21218, USA (phone: 410-516-7518; fax: 410-516-5553; email: jakek@jhu.edu).

$\hbar\omega_{TO} = 67.6$ meV, and $\hbar\omega_{LO} = 89.7$ meV with $\gamma_p = 0.1$ meV. For Au, the plasmon frequency corresponds to $\hbar\omega_M = 8.11$ eV with $\gamma_M = 65.8$ meV.

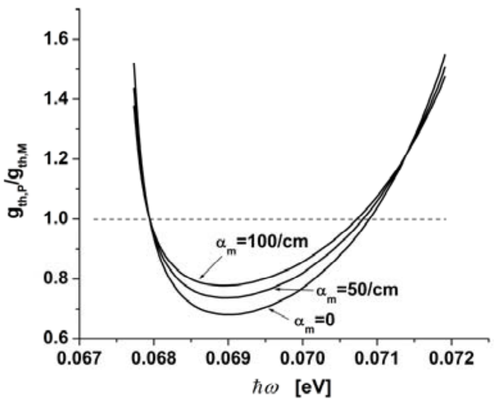

Fig. 2. Ratio of threshold optical gain between GaN Restrahlen and Au plasmon waveguide as a function of phonon energy for several values of mirror loss.

III. Comparison of Threshold Gain

We have compared the threshold optical gain of the two waveguides with an active region thickness of 1μm, using $g_{th} = (\alpha_w + \alpha_m)/\Gamma$, where Γ is the optical confinement factor, α_m is the mirror loss, and α_w is the waveguide loss which can be obtained by $\alpha_w = 2\beta''$. Assuming the same mirror loss for both waveguides, we have calculated the ratio of threshold gain

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

The result is plotted in Fig.2 as a function of the operating wavelength within the Restrahlen band of GaN for different values of mirror loss. It can be seen from Fg.2 there exists a narrow photon energy range from 68.0 to 70.7meV where this ratio is less than 1, representing a reduction of threshold.

References

[1] K. Unterrainer, R. Colombelli, C. Gmachl, F. Cappasso, H. Y. Hwang, A. M. Sergent, D. L. Sivco, and A. Y. Cho, Appl. Phys. Lett. **80**, 3060 (2002)

[2] B. S. Williams, S. Kumar, H. Callebaut, Q. Hu, and J. L. Reno, Appl. Phys. Lett. **83**, 2124 (2003)

[3] M. Rochat, M. Beck, J. Faist, U. Oesterle, Appl. Phys. Lett. **78**, 1967 (2001)

[4] R. Köhler, A. Tredicucci, F. Beltram, H. E. Beere, E. H. Linfield, A. G. Davies, D. A. Ritchie, R. C. Lotti, and F. Rossi, Nature **417**, 156 (2002)