A Study on the Suitability of Indium Nitride for Terahertz Plasmonics

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Abstract: Gold (Au), the most commonly used plasmonic material demonstrates excellent performance at optical frequencies. However, as interest in the electromagnetic spectrum and plasmonic phenomenon expands towards the infrared and terahertz range, the distinct advantages of using semiconductors instead of metals for plasmonic applications must be understood. Plasmonic resonances in gold (Au) and indium nitride (InN) are studied, in the terahertz (λ=30μm) regime and their performances are compared. Plasmonic grating structures are investigated. The electromagnetic properties of Au and InN are described by the Drude model using values reported in literature. InN, has a lower plasma resonance frequency of $f_p \approx 52 \times 10^{12}$ Hz (Far IR) as compared to that of Au which has $f_p \approx 2.18 \times 10^{15}$ Hz (optical range). This leads to InN plasmonics structures demonstrating a greater confinement of surface plasmon waves to the interface and also show greater field enhancement (upto 1.4 times) as compared to Au in the THz regime.

Keywords: Plasmonics, Semiconductors, Indium Nitride, Terahertz, field confinement

1. Introduction

Since the discovery of extraordinary optical transmission (EOT) by Ebbesen et al [1] in 1998, the desire to manipulate photons in a manner analogous to the control of electrons in solids has inspired interest in topics like localisation of light, plasmonics and near field optics [2,3]
Metals are the natural choice for plasmonic applications because of their high conductivity. Among metals, silver and gold have been used most often for plasmonic applications due to their relatively low loss in the visible and NIR ranges.
Recently, interest in plasmonic phenomena has extended beyond the visible spectrum on both sides into the UV [4,5] and the IR [6,7] to THz [8,9] regime. This shift from the natural plasmon resonance frequency of silver and gold has led to a search for new materials that have a plasma frequency more suited to UV or THz part of the spectrum [10].
Semiconductors have a much lower plasmonic resonant frequency than metals, typically in the IR to THz range. This allows semiconductors to confine THz waves to the semiconductor surface (surface plasmon polaritons) and exhibit interesting electromagnetic properties in the IR and THz regime [11,12].
This paper will look at the potential of semiconductors like InN as an alternative material for plasmonics in THz to IR range. There have been earlier reports of such studies on related semiconductors like indium arsenide (InAs) [13]. InN with a bandgap of 0.7eV is seen as a potential candidate for IR photodetectors. Also, InN is a strong emitter of THz [14]. These properties make InN a unique and interesting material for its substantial potential applications in plasmonics in the IR and THz regimes.
The performance of InN is compared with that of Au, the most commonly used plasmonic material. Plasmonic resonances at a frequency of 10THz in Au and InN are explored in the simulations. Grating geometries with a periodicity of 0.8μm and a grating height of 50nm are modelled and the field enhancement in the subwavelength apertures are compared for the case of metal and semiconductor. The electromagnetic properties of the metal and semiconductor are simulated using Drude model. Indium nitride shows greater field enhancement (~1.4 times that of gold) in the IR and THz regimes.
Considering the various irregular geometries and nanostructures that are usually employed in advanced plasmonic applications, a full wave solution of Maxwell's equations is essential. Comsol Multiphysics being an FEM solver is expected to be better suited for a wider range of geometries as compared to other conventional FDTD solvers.

2. Theoretical Model and Governing Equations:

Drude model for permittivity:

The Drude model [15] is commonly used to understand the frequency dependence of ε for metals and recently, even semiconductors [16]. The most general form of the equation is,

$$\varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\gamma\omega}$$

where ε_∞ is the dielectric constant at high frequency, $\omega_p = 2\pi f_p$ is the plasma frequency, $\gamma = \frac{1}{\tau}$ is a damping factor with τ being the relaxation time of the free electron gas.

In our simulations, we have used the values reported in literature for Au (ε_∞= 9.2, f_p = 2.18×10^{15}Hz, $\gamma = 6.46\times10^{12}s^{-1}$) [17] and InN ($\varepsilon_\infty$ = 6.7, f_p = 52×10^{12}Hz, $\tau = 52\times10^{-15}$s) [18,19].

Figures 1 and 2 shows the plot of real and imaginary parts of the complex permittivity ε for Au and InN in the THz range. As seen, Au has large negative real values and large imaginary component of complex permittivity in the THz range as compared to InN. Au has a plasma frequency in the optical range and the ω^{-3} dependence of the imaginary part of relative permittivity results in Au having a large value of the imaginary part of permittivity. The low values of plasma frequency for InN result in InN having a lower magnitude values for both the real and imaginary part of relative permittivity. The smaller value of imaginary component for InN in the THz indicates lower losses and suggests the suitability of InN for plasmonics in this frequency range.

The dispersion relation for surface plasmon waves at the interface of a metal and dielectric for the case of a grating is given by [20],

$$\beta = k_0\sqrt{\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1 + \varepsilon_2}}$$

where β is the propagation constant of the surface wave, k_0 is the wave vector of the free space wave. ε1 and ε2 are dielectric constants of the two materials forming the interface where the surface wave is travelling. In our simulations,

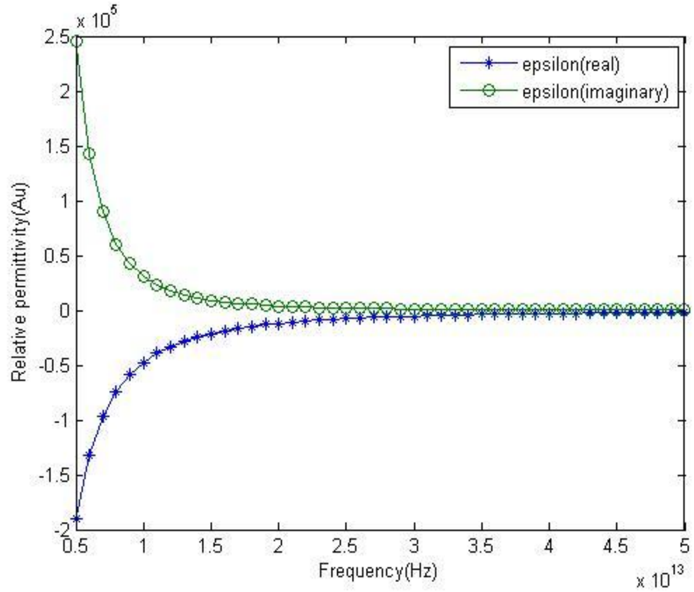

Figure 1: Relative permittivity of Au (from 5THz to 50THz)

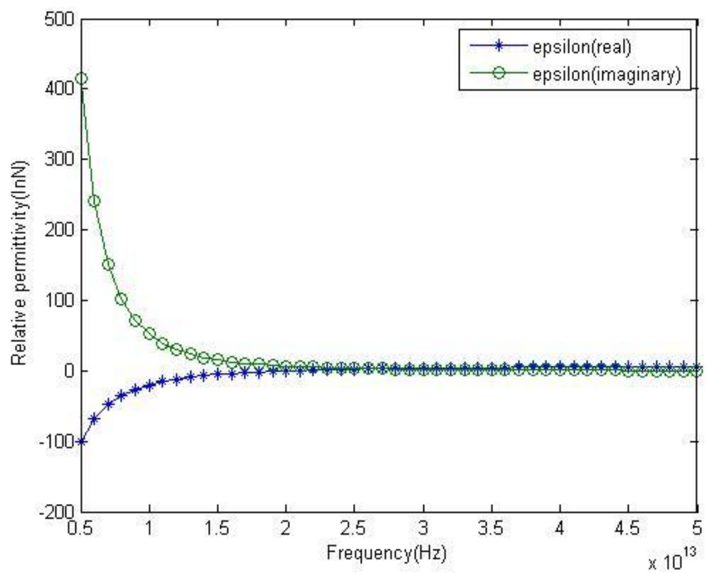

Figure 2: Relative permittivity of InN (from 5THz to 50THz)

one material is the grating (either Au or InN) and the other material is free space.

Another governing equation for the case of surface waves on gratings is [20],

$$\beta = k_0 \sin\theta \pm \nu g$$

where, $g = \frac{2\pi}{a}$ is the reciprocal vector of the grating and β is the propagation constant of the surface wave, k_0 is the wave vector of the free space wave, θ is the angle of incidence and a is the periodicity of the grating.

Solving both the equations simultaneously, we get the values of β and θ for particular values for k_0, ε1 and ε2 for which the surface plasmon wave is excited.

In our simulations, we have chosen values of incident wave λ = 30μm for the THz range. The grating periodicity if 0.8μm and the grating height is 50nm.

3. Use of COMSOL Multiphysics

We will be using the RF module of Comsol Multiphysics for full wave solutions of Maxwell's equations for the case of Au and InN. The electromagnetic properties of Au and InN are modelled using the Drude model.

The structure is as shown in figure 3. We are modelling a single period of the grating.

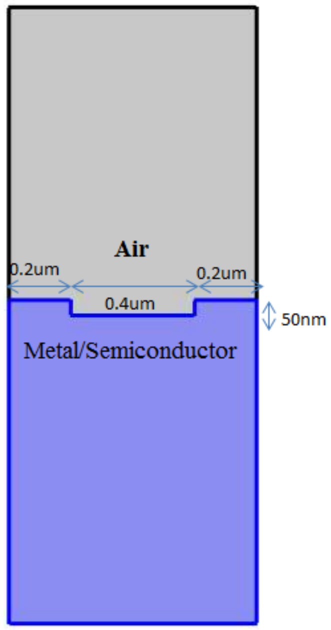

Figure 3: Grating structure being modelled

Boundary conditions: The periodicity of the gratings is taken care of by considering Floquet periodicity on vertical boundaries of the model. Floquet periodicity boundary condition ensures that the solution at one boundary is a phase shifted version of the solution at the other boundary. Floquent boundary condition enables us to consider the periodicity in the structure while effectively modeling a single period of the entire structure. The top boundary is considered as a port and the incident wave is applied from this port. The bottom boundary is modeled using a perfectly matched layer to minimise reflections and scattering. The rest of the boundaries in the structure are modeled using continuous field conditions.

4. Simulation Results

The resulting electric field distribution for the case of Au and InN gratings are shown in figures 4 and 5. The magnitude of the electric fields in the case of InN gratings are higher than those in the case of Au gratings.

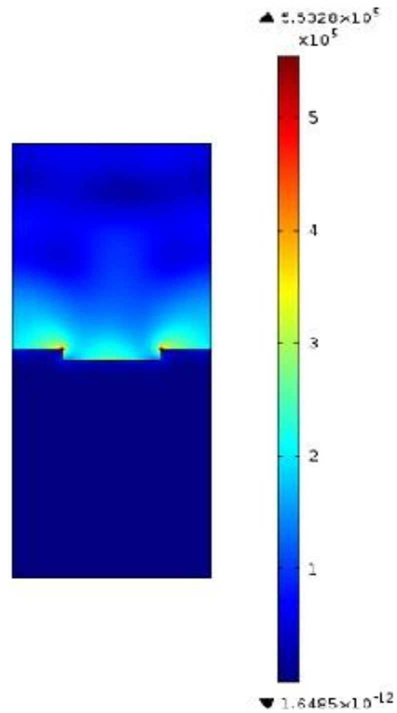

Figure 4: Electric field distribution (Au grating)

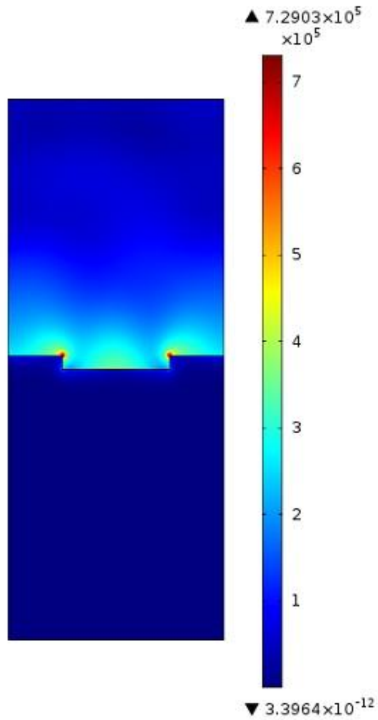

Figure 5: Electric field distribution (InN grating)

To get a better understanding of the electric field distribution, we use a horizontal cutline along the 0.4μm grating aperture to plot the exact electric field distribution within the grating gap in the two cases. The electric field magnitude variation is plotted in figures 6 for the case of Au and InN. It is seen that InN leads to greater field enhancement in the subwavelength aperture

Another measure of the effectiveness of plasmon excitation is the extent of confinement of the electromagnetic wave to the metal-air interface. If the surface waves are strongly excited then the field tends to confine itself more closely to the interface, exhibits a greater magnitude close to the interface and decays faster as we move away from the interface. To study the distribution of electric field as we move away from the interface, we use a vertical cutline and plot the magnitude of the electric field as we move away from the interface. The plot of field versus distance from the interface is given in figures 7 for the case of Au and InN. This clearly indicates that in the case of InN, the field has a higher magnitude close to the interface, the field is more tighly confined to the interface and also decays faster as compared to Au gratings. This again shows, superior performance by InN as a plasmonic material as compared to Au.

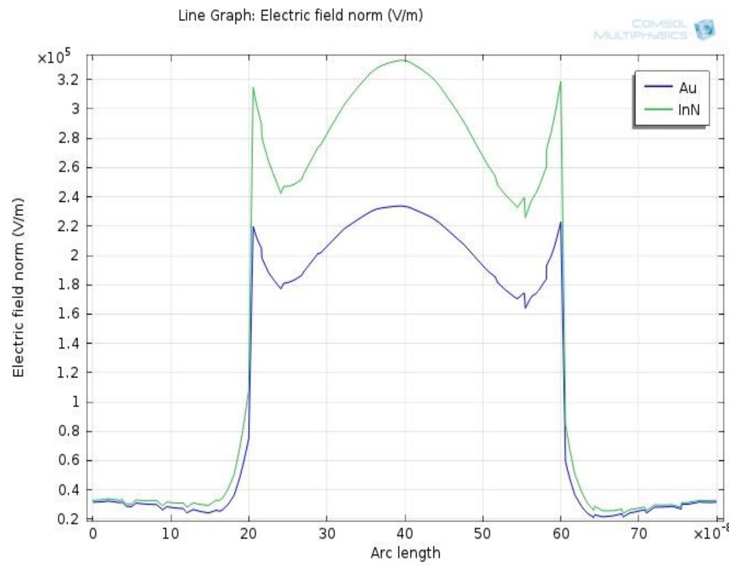

Figure 6: Field distribution within the grating for the case of Au and InN

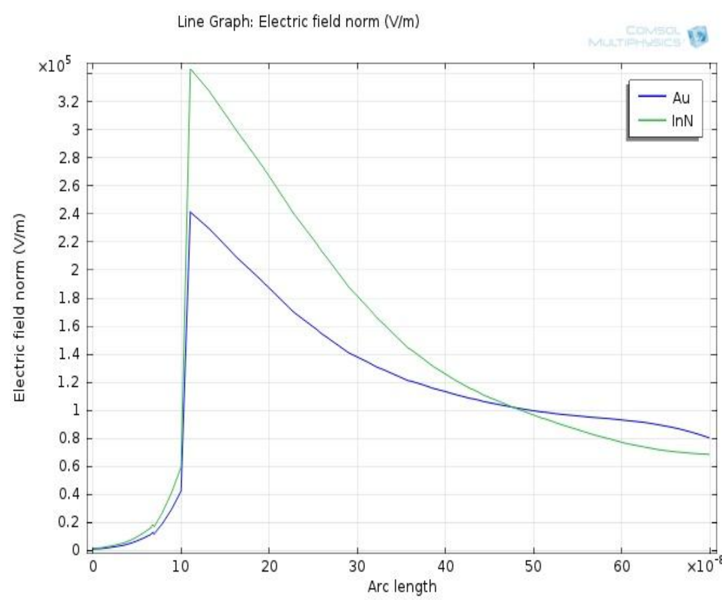

Figure 7: Field distribution as a function of distance from the interface for Au and InN.

6. Conclusions

Results clearly indicate the suitability of InN for plasmonics in the THz range. The plasma frequency of InN lies in the THz whereas the plasma frequency of Au lies in the optical range. The higher plasma frequency of Au leads to a higher value of imaginary part of the dielectric constant. This indicates greater losses in Au for the THz part of the spectrum as compared to InN. Full wave solutions of Maxwell's equations using the RF module of Comsol Multiphysics confirm our predictions. Results indicate greater field enhancement (upto 1.4 times) for the case of InN gratings as compared to Au gratings. These results indicate that InN shows substantial potential as an alternative plasmonic material to metals like Au in the IR and THz range.

7. References

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