Study of low loss Plasmonic Semi conductor oxide Materials as compared to lossy conventional noble metals

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ABSTRACT
Wave guiding using Plasmonics (for high density integration) has no future unless the loss problem is solved. Since noble metals such as gold and silver are lossy, new materials need to be identified and developed. Transparent oxide and transition metal nitrides are doped to provide low loss materials whose plasma frequency is in the near or mid infrared. Therefore we propose heavily doped oxide semiconductors that offer both functional and fabrication advantages in the near infrared wavelength range. So Aluminum doped Zinc oxide and Gallium doped zinc oxide are new plasmonic materials with low loss.

Keywords : Low-loss plasmonics, nano-photonics, AZO, GZO, Transparent conducting oxide (TCO), ITO

1 INTRODUCTION

Plasmonics is a very popular research area combining the fields of optics and nano electronics by confining light with relatively large free space wavelength to the nanometer scale- thereby enabling a family of novel devices [1]. Conventional photonic elements such as optical fibers require physical dimensions on the order of wavelength of light. The difference in physical size between nanometer scale electronics and micrometer scale photonic elements yields an incompatibility between two types of devices. Plasmonics merges the high bandwidth offered by photonics and nano scale integration offered by nanoelectronics by coupling a photon's energy with a free electron density, creating a sub wavelength, oscillating mode known as a Plasmon [1].

Due to the plasmon phenomenon in optical and telecommunication frequencies typically originates from the collective oscillations of free charges in a material for an applied electromagnetic field, plasmonic devices generally require metallic

components, which have an abundance of free electrons. These free electrons provide the negative real permittivity that is an essential property of any plasmonic material. However, metals are plagued by large losses, especially in the visible and ultra-violet (UV) spectral ranges. Even the metals with the highest conductivities suffer from large losses at optical frequencies. These losses are detrimental to the performance of plasmonic devices, seriously limiting the feasibility of many plasmonic applications. Because these losses are inherent to the constituent materials, alternative plasmonic materials with lower losses are required to develop robust plasmonic devices.

Plasmonics could have a large impact on applications at telecommunication and optical frequencies, and hence we offeralternative plasmonic materials with lower losses.In Section 2, we provide a framework on the various electromagnetic losses associated with solids at frequencies in and near the visible range. In Section 3, we provide an thorough investigation of alternative plasmonic materials.Lastly, We concludethe paper with a discussionof the reviewed material choicesfor various regions of the visible and near-infrared (NIR) ranges.

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2.FRAMEWORK:

Polarization describes a material's interaction with electromagnetic waves.

The electrical polarization can be described by the material's complex electrical permittivity or dielectric function, denoted by $\varepsilon(\omega)$. While the real part of the dielectricfunction (denoted by $\varepsilon_1$or ε') describes the strength of the polarization induced by anexternal electric field, the imaginary part (denoted by ε_2 or ε'') describes the lossesencountered in polarizing the material. Thus, a low loss material is associated with smallvalues of ε''[1].

According to the generalized Drude Theory [9] the permittivity of a material can be written as follows:

$$\varepsilon(\omega)'+i\varepsilon(\omega)''=\varepsilon(\omega)=\varepsilon_{int}-\omega_p^2/\omega(\omega+i\Gamma) \quad (1)$$

$$\omega_p^2=ne^2/\varepsilon_0 m^* \quad (2)$$

In equation (1) $\Gamma=1/\mathrm{r}$ where

r= mean relaxation time of conduction electron

ε_{int}= contribution due to inter band transition(it is unity for the case of a perfectly free electron gas)

ω_p=Plasma frequency(in equation 2)

n= conduction electron density

m*= effective optical mass of conduction electrons

Table 1:Drude model parameters for metals.ω_{int} is the frequency of onset for interband transitions. Drude parameters tabulated are not valid beyond this frequency.

	ε_{int}	ω_p(eV)	Γ(eV)	ω_{int}(eV)
Silver[4,5,6]	3.7	9.2	0.02	3.9
Gold[4,6]	6.9	8.9	0.07	2.3
Copper[4,5,6]	6.7	8.7	0.07	2.1
Aluminum[7,8]	0.7	12.7	0.13	1.41

Because plasmonic applications require materials with negative ε ' , Eq. (1) clearly indicates that this requirement is satisfied for materials with a plasma frequency higherthan the desired frequency of application. Because metals tend to have large plasmafrequencies and high electrical conductivity, they have traditionally been the materials ofchoice for plasmonics. In Table 1, we summarize the material parameters for highconductivitymetals as reported in the literature. Among the metallic elements, silver hasthe smallest Γ and is the best-performing choice at optical frequencies. Gold, which hasa larger Γ than silver, is often the metal of choice at lower NIR frequencies, having theadvantage of being chemically stable in many environments. However, gold has highinterband losses in the visible spectrum for wavelengths below or about 500 nm.Similarly, copper is plagued by large interband losses over most of the visible spectrum.Thus, silver and gold have predominately been the materials of choice for plasmonicapplications around the optical frequencies. However, future plasmonic applicationsdemand even lower losses to fully exploit their potential.

3.INVESTIGATION OF ALTERNATIVE PLASMONIC MATERIALS:

3.1 Metals as plasmonic materials:

Metals are candidates for plasmonic applications because of their high conductivity. Among metals, Silver and Gold are the two most often used for plasmonic applications due to their relatively low loss in the visible and near infrared region. In fact, almost all of the significant experimental work on plasmonics has used either silver or gold as the plasmonic material. While metals other than silver and gold have been used in plasmonics, their uses are quite limited, as their losses are higher than those of silver and gold.

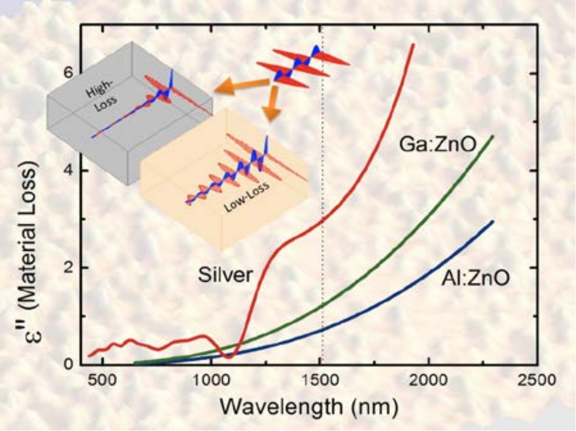

Fig: 1: Exhibition of material loss characteristicsVs Wavelength [1]

According to the fig 1, the losses of silver are still higher thanthat of Gallium doped Zinc Oxide (GZO) and Aluminum doped zinc oxide (AZO) in the visible and near infrared region (NIR).

3.2 Semiconductors:

Semiconductors are potential materials for plasmonicsbecause of the ease of fabrication and flexibility in tuning their properties such as carrier concentration.

In order to qualify as a lowlossplasmonic material, the band gap and plasma frequency of the semiconductor bothmust be larger than the frequency range of interest. While a large plasma frequencyensures a negative real permittivity, a large band gap ensures almost no interbandtransition losses. Semiconductors can exhibit negative ε ' in IR frequencies when heavilydoped(10,11). A wide band gap, heavily doped semiconductor with highcarrier mobility can qualify as a low loss plasmonic material around the opticalfrequencies. Despite the abundance of semiconductors with large bandgap values (> 1.5 eV) and highcarriermobilities, very high doping levels are necessary to bring the crossover frequencyof semiconductors into the optical range, and achieving these doping levels ischallenging[1].

Transparent conducting oxides (TCO) have been intensively investigated for optical and electrical applications, such as flat-panel displays, liquid crystal displays, organic light emitting diodes, thin film transistors and thin film solar cells. TCO thin films should have low resistivity, high transmittance in the visible region (400 to 800 nm), and high thermal/chemical stability. In most cases Indium tin oxide (ITO) has been widely employed as a TCO material because of its superb electrical and optical properties. However, ITO has low stability, high toxicity, and high cost and is a rare material, motivating efforts to develop alternatives. Recently, zinc oxide (ZnO) has been regarded as a promising candidate to replace ITO due to its low cost and excellent properties as compared with ITO. For the purpose of improving the electrical conductivity and optical transmittance of ZnO group III elements such as boron, alluminum, gallium and indium are usually introduced to ZnO.

In this paper, optical functions of one such TCO, gallium-doped zinc oxide (GZO), aluminum doped zinc oxide (AZO) arestudied.We perform theoretical studies and fundamental understanding of the connection between material, structural, and optical properties of highly doped TCOs to tailor those materials for various plasmonic applications [2].

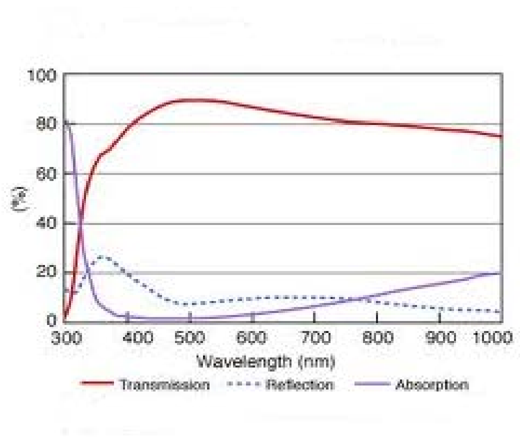

Fig2: (a) Transmissivity, reflectance and absorption of GZO

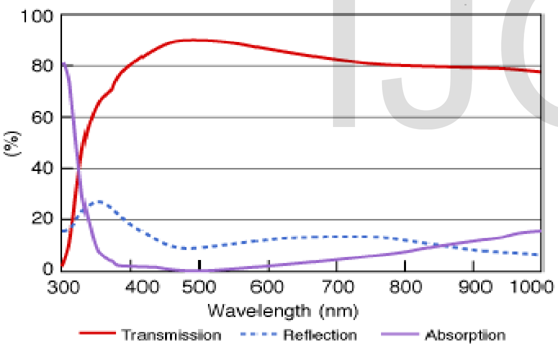

Fig2: (b) Transmissivity, reflectance and absorption of AZO

The optical properties of TCOs transmission T, reflection R, and absorption A are determined by its refractive index n, extinction coefficient k, band gap E_g and geometry. Geometry includes film thickness, thickness uniformity and film surface roughness. According to the figure 2 of AZO and GZO, the transmissivity spectrum exhibits transmission higher than 85% within the visible region, with a sharp fundamental absorption edge. In particular, absorption edge is blue shifted with increasing Al or Ga doping concentration which indicates broadening of the optical bandgap.Based on the optical characteristics of these films, we have found that AZO and GZO can have significantly lower loss than silver at telecommunication wavelengths which are of particular importance for photonics and nanophotonics applications.

CONCLUSION:

We have discussed the optical properties of AZO and GZO. AZO and GZO are at present the only TCOs with electrical conductivity close to that of ITO, and with appropriate high optical transmission in the near UV ,VIS NIR .Furthermore, these oxide semiconductor can work well at the telecommunication wavelength(1300 and1550 nm), which makes them very important substitutes for conventional materials such as gold and silver.

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