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Low-loss propagation in semiconductor $Al_xGa_{1-x}As$ Waveguide

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Abstract: We theoretically studied the effect of a metal dimensions on the propagation loss of surface plasmon polaritons (SPPs) in a metal-semiconductor-semiconductor (MSS). The propagation loss of surface plasmon polaritons (SPPs) is studied at the interfaces between metals and active media .The propagation loss is calculated at the wavelength λ=1550nm for different widths and thicknesses of a gold layer. Also it has been observed the variation of the propagation loss with the height of the $Al_xGa_{1-x}As$ which is between the gold film and high refractive semiconductor. We analyze metal-semiconductor-semiconductor (MSS) waveguide by using the effective-index method (EIM) and the finite-difference-time-domain (FDTD) methods.

Keywords: Surface Plasmon Polaritons (SPPs), Metal-Semiconductor- Semiconductor Waveguides Propagation Loss

1. Introduction

Waveguide geometrical parameters define by its dimensions and refractive indices of layers, surface plasmon polaritons (SPPs), which are electromagnetic waves that propagate along metal-dielectric interfaces and decay exponentially along the two sides [1]. Surface plasmons can be described macroscopic electromagnetic theory, if the electron mean free path in the metal is much shorter than the plasmon wavelength [2].

Surface plasmon polaritons (SPPs) are surface waves at the interface between metal and dielectric media. The propagation losses, including intrinsic and ohmic loss arising from metal absorption as well as scattering loss owing to the variations of the metal surface morphology and fabrication imperfections are inevitable in plasmonic waveguides [3]. Due to their tight binding at the interface, they can be used for controlling light at nanoscale levels Furthermore, the propagation losses may vary significantly from structure to structure [4,5].

In order to reduce the propagation loss of the SPPs mode the light must be kept in optical waveguides, the propagation loss of the SPP waveguide can be decreased to less than 1 dB/cm, not only by lowering the refractive index of the clad material, but also by optimizing the metal structure [6-8].The propagation losses are typically associated with SPPs due to the losses in the metal, and a fundamental tradeoff has to be achieved between field localization and propagation losses. [9]. To reduce the propagation loss of the SPP mode, multi-stripe configurations were proposed by [10]. Gold and silver stripe waveguides with multi-stripe configurations were investigated at a wavelength of 1.55 μm [11]. Various types of plasmonic waveguides have been analyzed. Stripe waveguides based on a single thin metal film provide a relatively high propagation length, i.e. low modal losses, but suffer from low field confinement [12]. Several theoretical studies have focused on the use of thin metal stripes such as gold or silver embedded in a dielectric material to guide light in optical waveguide devices [13,14]. Many different plasmonic waveguiding configurations have been proposed and demonstrated over the past few years [15].

This paper reports propagation loss calculation taking into account for various waveguide dimensions. Different numerical methods have previously been successfully utilized in the analysis of optical waveguides.

We study the effect of different waveguide parameters on the propagation losses of metal-semiconductor-semiconductor (MSS) waveguide devices using a two-dimensional (2D) finite-difference frequency-domain (FDFD) method [16].

2. Waveguide Structure

The waveguide geometry is composed of a metal layer, a low index dielectric layer and a high index dielectric layer as Au, $Al_{0.8}Ga_{0.2}As$ and $Al_{0.4}Ga_{0.6}As$. Its dimensions are *w, t* and *h*, as shown in Fig. 1. At a 1550 nm wavelength the refractive indices for these materials are n_1= 0.55+ 11i, n_2= 2.9755 and n_3=3.1752 respectively [10]. There are three waveguide parameters that must be taken into account for optimization of the waveguide the height *h* of the low-index dielectric, the width *w* of the metal strip and its thickness *t*. We first study the effect of the metal film width *w*, then the effect of its thickness *t*. Finally, we examine the effect of the height *h* low-index dielectric. This paper is organized as follows; the finite-difference frequency-domain (FDFD) method is used in calculations of the propagation loss.

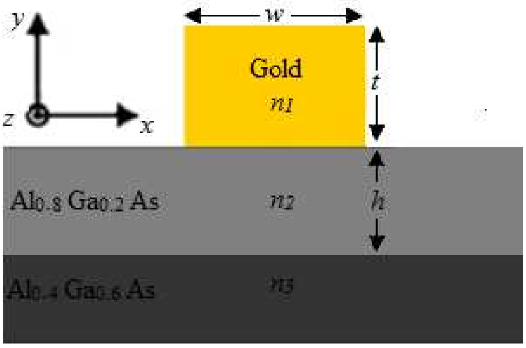

Fig. 1. *Structures of MSS waveguide.*

3. Simulation Results and Analysis

The analyzed straight waveguide structure is similar to that investigated experimentally [8]. The geometry of the SPP is simulated as shown in the Fig. 1, by the finite difference time domain (FDTD) method. We suppose the propagation direction is along the *z* axis, and the electric field can then be written in the form

$$\vec{E}(x,y,z) = \vec{E}(x,y)e^{i\beta z} \quad (1)$$

Where *E(x, y)* denotes component of the electric field in the *x y* plane and β is the propagation constant of the travelling waves in the direction of propagation. The SPP modes and their dispersion relation can be characterized by the Helmholtz equation derived from Maxwell's equations

$$(\nabla^2 + \varepsilon\, k_0^2)\vec{E} = 0 \quad (2)$$

where k_o is the wavenumber in vacuum, and ε being the complex permittivity. The propagating mode is related to the mode effective index according to $\beta = \frac{2\pi\, n_{eff}}{\lambda} = k_0 n_{eff}$, where λ is the vacuum wavelength. It is instructive to consider the SPP dispersion relation of a metal-dielectric interface is given by [1]

$$\beta = k_0\sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \quad (3)$$

where $\varepsilon_m$and $\varepsilon_d$is the complex permittivity of the metal and dielectric layers respectively. The solution of the wave equation must produce a propagating wave that is localized to the metal-dielectric interface, decaying exponentially in both perpendicular directions to the interface.

In our work, the propagation loss of a structure was calculated for different waveguide parameters by utilizing the calculated effective indexes methods n_{eff}. We simulated the structure by the finite difference time domain (FDTD) method .The important parameter that characterizes the mode is the effective index mode n_{eff} which is defined as n_{eff} = *k/* k_o, where *k* and k_o are the propagation constant of the hybrid mode and the free space wave.

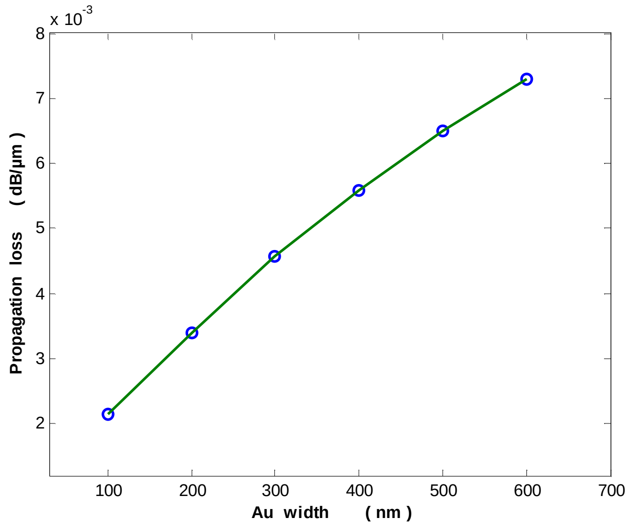

Fig. 2. *The propagation losses of the gold stripe as a function of width w.*

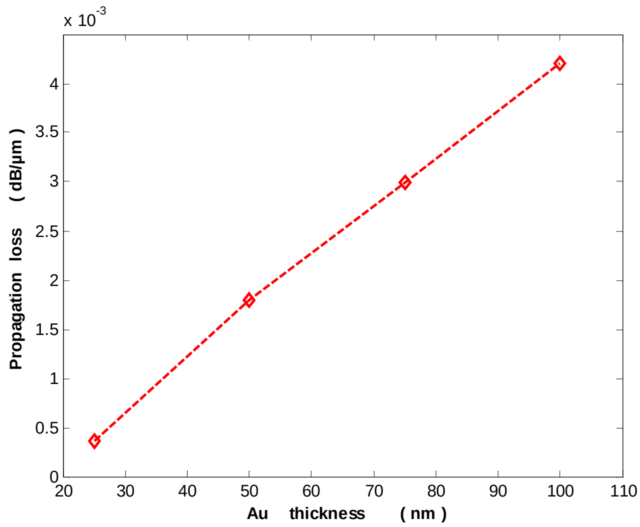

Fig. 3. *The propagation losses of the gold stripe as a function of thickness t.*

For all cases, a height of the high-index dielectric layer is fixed. To examine the effect of gold layer loss on overall propagation losses we have plotted the propagation loss in absence of high-index dielectric layer loss. While this layer plays a significant role in limiting the propagation loss, the metal loss is the main limiting factor. We will first focus on the effect of varying the widths *w* of the gold region on the propagation loss with a fixed thickness *t* of 50 nm, and show these results in figure 2. In fact, we notice that the propagation loss of the structure mode becomes strongly affected by gold width is continuously increased.

Then the propagation loss can be calculated for different gold thickness *t* over the range 25 nm to 100 nm with a fixed width *w* of 400 nm and plotted as in figure 3. We found that the propagation loss of the SPP mode becomes strongly dependence on the gold structure as its thickness is increased. For thin layer the SPPs mode is confined closer to the surface and the propagation loss is small. As the thickness is increased, the SPP is less confined and hence the propagation loss is increased. The propagation loss is in linear relationship and more effectively when the thickness increases.

In figure 4 we show the calculated propagation loss for different dielectric height *h* to be adjacent to the gold- layer and other parameters are fixed (*w* =250 nm and *t* = 50 nm). This is another possibility to control propagation loss of light in our structure by changing height of the medium.

The propagation loss increases when decreasing the core height and approaches the SPPs propagation at the gold air interface. This increasing in the propagation loss shows that a large portion of the mode spreads outward from the dielectric material.

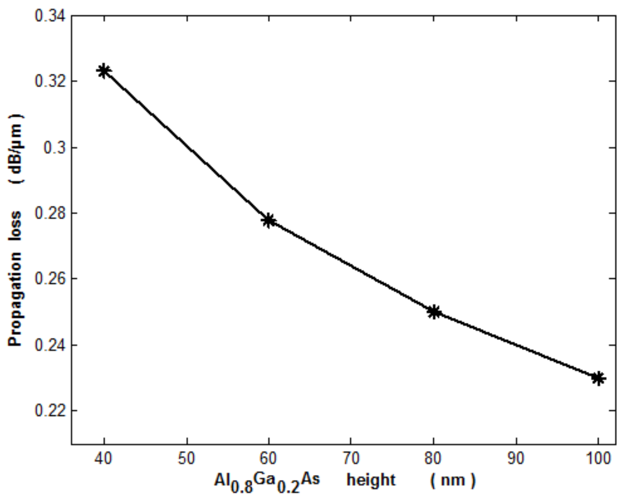

Fig. 4. *The propagation loss of the SPP with different dielectric height h.*

4. Conclusion

In conclusion, we theoretically study the propagation loss of the plasmonic waveguide through varying the width and thickness of the gold layer and also the height of the $Al_{0.8}Ga_{0.2}As$, the propagation loss of the waveguide is effectively controlled by tuning metal dimensions and core height. The propagation loss of the SPP in the structure is calculated by finding EIM of the structure. We have showed that utilizing thin metal films in a MSS waveguide can increase the propagation loss with thick layers. The propagation loss can be minimized by selecting a suitable dimension of gold layer and its adjacent semiconductor.

The results indicate that the propagation loss is also effect by the height of dielectric constant between the metal and high refractive semiconductor.

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