Thin dielectric layers in active plasmonic devices

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In this paper a design study on active plasmonic lasers is presented. In active plasmonic devices the semiconductor layer stack needs to be electrically isolated from the metal cladding that supports the plasmon modes. Secondly, surface states, created during processing of the devices, need to be passivated. Thin dielectric layers can fulfill both functions. These layers however have overlap with the optical field and therefore influence the optical mode structure of the device. The influences of the layer thickness and the refractive index are investigated.

Introduction

Over the last years, the subject of plasmonics has received considerable attention. It offers the possibility to confine light on a sub-wavelength scale. Until now, most research in plasmonics concentrated on investigating the behavior of passive optical structures [1,2]. Their behavior is well understood. Active plasmonic devices, such as lasers, are relatively new [3]. Their structure, and also their behavior, design and fabrication, are more complex.

The passive plasmonic structures, discussed in most papers, can be divided in two types: the M-I-M (metal-insulator-metal) structures and the I-M-I (insulator-metal-insulator) structures [4]. In active plasmonic devices, the insulator is replaced by a semiconductor layerstack. Also, additional dielectric layers are required. These dielectric layers are located between the metal and the semiconductor layerstack. This M-I-S-I-M structure is shown in figure 1.

The dielectric layers have two important functions. First they serve to electrically shield the semiconductor layerstack from the metal, preventing a shortcut of the device. Secondly these layers have to passivate any surface states created during dry etching of the structure. In order to fulfill these functions the dielectric layers have to be in direct contact with the optical field. They will therefore have a considerable influence on the optical characteristics of the structure.

Until now PECVD deposited layers, such as silicon nitride, have been used in our work to fulfill the functions mentioned above. It is expected that layers deposited by means of atomic layer deposition will have an improved performance. Before we can resort to ALD deposited layers, we have to study the effect of the thickness and of the refractive index of the dielectric layer on the optical characteristics of the active, plasmonic structure. We have done so by means of finite difference mode calculations. For these calculations we have used the structure as depicted in figure1 and taken ε_{metal}=-129.0 - 3.3i. In this paper we present the results of these calculations.

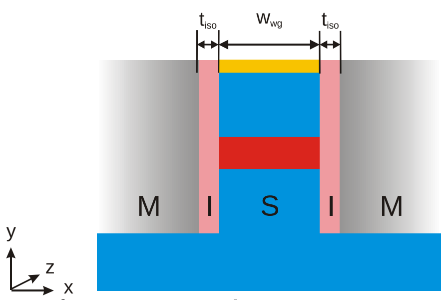

figure 1: An active plasmonic structure

Layer thickness

The first parameter under investigation is the thickness of the dielectric layer, t_{iso}. Since the layer has to provide sufficient electrical isolation, the thickness of the layer is limited at the lower end by the dielectric strength of the material. The dimension w_{wg} of our plasmonic devices are between 50-300 nm; the thickness of the dielectric layers, t_{iso}, is typically an order of magnitude smaller, between 0-20 nm. The refractive index of the dielectric layer is 1.9.

The influence of varying the thickness of the layer and waveguide width on the effective mode index is shown in figure 2. From this figure we can see that as the layer thickness increases, the geometrical dispersion characteristics of the structure change. For example, we can see that for a layer thickness of approximately 10 nm, the effective mode index does not change with waveguide width.

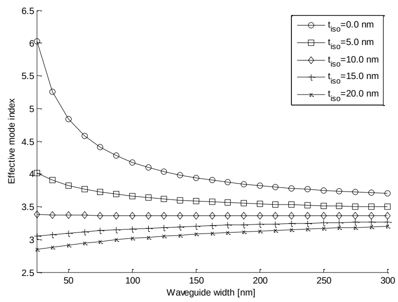

figure 2: Effective mode index as a function of waveguide width (n_{iso} = 1.9)

Refractive index

The refractive index of the material used for the dielectric layer partly determines the properties of the optical mode in the plasmonic waveguide. The influence on the effective mode index is presented in figure 3. The different line styles indicate a different n_{iso}. In these calculations the dielectric layer thickness, t_{iso}, was 15 nm. By comparison of figures 2 and 3 we can see that changing the refractive index of the layer has a similar effect on the dispersion as changing the thickness of the layer.

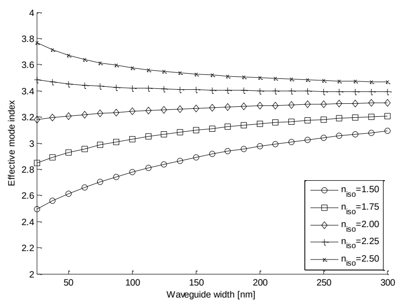

figure 3: Effective mode index as a function of waveguide width (t_{iso}=15 nm)

It is clear that both the layer thickness and its refractive index have a significant influence on the optical behavior of the structure. Both can be used to achieve the desired dispersion characteristics for the total structure.

Confinement and loss

Loss in plasmonic waveguides limits the propagation distance to several hundreds of micrometers [5, 6]. In these waveguides the biggest part of the optical field is located near the junction with the metal. Good overlap with a gain medium, required for amplification or lasing, is therefore not trivial. In this section we will have a look at the confinement and loss as a function of the thickness and refractive index of the dielectric layer.

In figures 4 and 5 the confinement in the active layer is shown as a function of waveguide width. The different lines in figure 4 and 5 indicate, respectively, the different refractive indices and the different layer thicknesses of the isolation layer. From figure 4 ($t_{isolation}$ = 15 nm) it can be seen that a higher refractive index of the dielectric layer leads to a higher confinement in the active region (the red region in figure 1) of the structure.

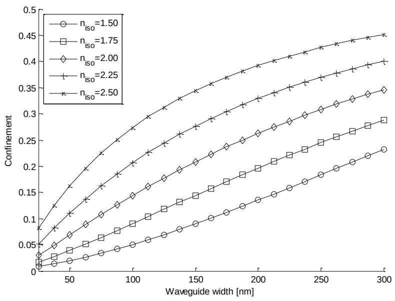

figure 4: Confinement for various $n_{isolation}$

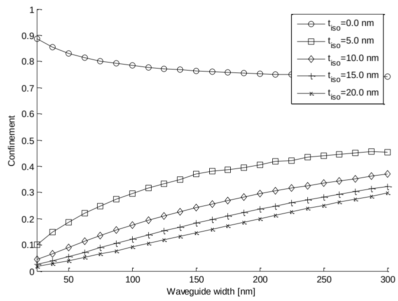

figure 5: Confinement for various $t_{isolation}$

In figure 5 (n_{iso}=1.9) we can see that if the thickness of the dielectric layer increases, the confinement in the active layer decreases. This is caused by the fact that, due to the interaction with the free electron gas in the metal, the maximum field intensity is located at the interface with the metal. As the layer thickness increases, most of the light will thus be in the dielectric layer. This is demonstrated in figures 6 and 7.

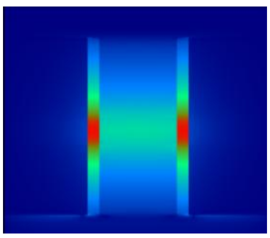

figure 6: Field distribution, structure with dielectric layers

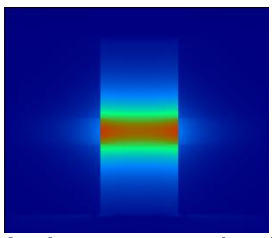

figure 7: Field distribution, structure without dielectric layers

From figure 5 we can also see that for t_{iso} < 0 nm, an increasing width of the total structure results in a higher confinement in the active region of the structure. This is because the interaction between the free electrons in both metal slabs becomes less as the distance between the slabs grows. Light can still travel along the independent metal interfaces, but the total structure starts behaving more and more like an ordinary, dielectric waveguide.

Finally, the loss of structure has been investigated. Figure 8 shows that for higher refractive indices of the dielectric layer the loss increases. For an increasing refractive index of the layer, the effective mode index will increase as well, causing the light to travel slower and allowing more interaction with the metal. The same effect is found when decreasing the thickness of the dielectric layer.

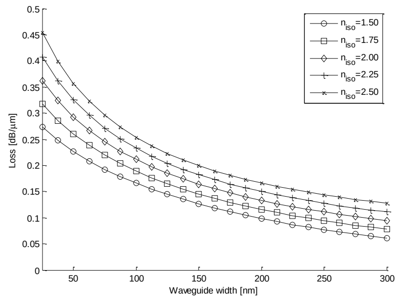

figure 8: Loss as a function of n_{iso}

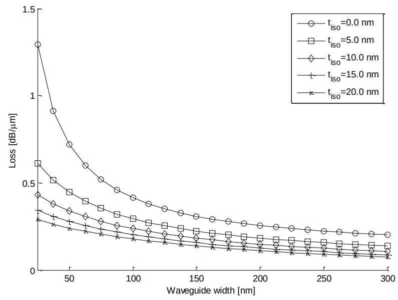

figure 9: Loss as a function of t_{iso}

Conclusions

We have seen that the thickness and the refractive index of the dielectric layers determine the confinement and loss of the active plasmonic structure. These parameters can be used to tune the dispersion of the structure. A change of the refractive index from 1.5 to 2.5 results in a change in the effective mode index from 2.5 to 3.8, for a w_{wg} of 25 nm. A change in layer thickness from 20 nm to 0 nm leads to a change in effective mode index from 2.9 to 6.0. This is particularly useful when designing a grating.

The confinement of the mode in the core region of the structure improves slightly for higher refractive indices of the dielectric layer. The biggest increase in confinement can be achieved by decreasing the thickness of the dielectric layer (an 80% increase for $t_{iso} \leq 5$ nm).

Increasing the refractive index from 1.5 to 2.5 leads to higher optical losses (from 0.27 dB/µm to 0.45 dB/µm). Decreasing the thickness of the dielectric layer from 20 nm to 0 nm has the same effect, be it a lot stronger (from 0.3 dB/µm to 1.3 dB/µm). Both lead to a higher effective mode index causing the light to propagate slower and allowing more interaction with the lossy metal. On the other hand, this also leads to a higher confinement in the active layer of the structure, thus providing a higher modal gain.

More calculations could be performed to determine whether there exists an optimal balance between the loss and the confinement for the plasmonic structure described in this paper.

References

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