2010

Absorption Enhancement of MSM Photodetector Structure with a Plasmonic Double Grating Structure

Chee Leong Tan

Volodymyr V. Lysak

Narottam Das
Edith Cowan University

Ayman Karar
Edith Cowan University, ayman_karar@hotmail.com

Kamal Alameh
Edith Cowan University, k.alameh@ecu.edu.au

See next page for additional authors

10.1109/NANO.2010.5697989
This article was originally published as: Tan, C., Lysak, V., Das, N. K., Karar, A. , Alameh, K. , & Lee, Y. T. (2010). Absorption Enhancement of MSM Photodetector Structure with a Plasmonic Double Grating Structure. *Proceedings of IEEE NANO 2010 10th International Conference on Nanotechnology.* (pp. 849-853). . Seoul, Korea. IEEE. Original article available here

Authors
Chee Leong Tan, Volodymyr V. Lysak, Narottam Das, Ayman Karar, Kamal Alameh, and Yong Lee

Absorption Enhancement of MSM Photodetector Structure with a Plasmonic Double Grating Structure

Chee Leong Tan[1]*, Volodymyr V. Lysak[2], Narottam Das[4], Senior Member, IEEE, Ayman Karar[4], Kamal Alameh[3,4], Senior Member, IEEE and Yong Tak Lee[1,2,3]*

[1]School of Photon Science and Technology, Gwangju Institute of Science and Technology (GIST), 261 Cheomdan-gwagiro (Oryong-dong), Buk-gu, Gwangju, 500-712, Republic of Korea
[2]Department of Information and Communications, GIST,
[3]Department of Nanobio Materials and Electronics, GIST, Republic of Korea
[4]Electron Science Research Institute, Edith Cowan University, Joondalup, WA 6027, Australia
*E-mail: ytlee@gist.ac.kr, ccheelong@gist.ac.kr

***Abstract*-We present finite difference time domain simulation to analyze the optical absorption enhancement of metal-semiconductor-metal photodetector employing double plasmonic grating structures. Simulation results show that the combination of a subwavelength aperture and a double nano-structured metal grating results in up to 25 times enhancement in optical absorption, in comparison to MSM photodetector structures employing only a subwavelength aperture. This improvement of the absorption enhancement is due to the coupling out function of the bottom grating structure which distributes the light to both side of the subwavelength aperture.**

***Index Terms*—FDTD simulation, MSM photodetectors, surface plasmon polaritons, plasmonic nano-gratings, nanophotonics.**

I. INTRODUCTION

Interesting phenomena between metal and dielectric interaction known as surface plasmon effects have attracted great interest in recent years. Basically surface plasmon excitations can be categorized into two groups namely; Localized Surface Plasmon Resonance (LSPR) and Surface Plasmon Polariton (SPP). The impact of Surface Plasmon Polaritons (SPP) on light diffraction and absorption using subwavelength apertures can lead to large enhancement in light transmission. In the past decade, there have been several experimental and theoretical research activities reported on the extraordinary optical transmission (EOT) through a metallic aperture [1] as well as through periodic metal grating structures [2, 3]. Simulation results based on finite-difference time-domain (FDTD) software have shown significant enhancement of light absorption through SPPs, and this has direct application to the design of MSM structures. Accurate modeling of MSM will open the way for the development of high responsivity-bandwidth-product photodetector that are attractive for many practical applications.

In this paper, we continue the work reported in a previous paper [4] to investigate the absorption enhancement of a plasmonics-based double grating subwavelength aperture MSM photodetector structure and compare its performance to a single subwavelength aperture and a single grating subwavelength aperture structure. In depth analyses of the electric field distribution across the MSM photodetector structure are presented, and the optimized metallic grating dimensions for maximizing the optical absorption enhancement at 980 nm are determined.

II. MSM-PD STRUCTURE DESIGN

The MSM photodetector structure consists of four parts, namely, the top metal grating, the subwavelength aperture, bottom metal grating and the substrate, as shown in Fig 1. The light is coupled to the top plasmonic grating structure, then transmitted through the subwavelength aperture with surface plasmon enhancement, and finally coupled out using the bottom plasmonic grating structure. Similar structures have also been reported in [7] but the authors did not study any parameters of the grating structure. Both top and bottom metal gratings consist of perfect conductors whose grooves are parallel in the x direction. Their dimensions are optimized to couple light at a design wavelength and trigger SPPs along the x direction. For a metal grating period of Λ the wave vector of SPPs is given by [3]

$$k_{sp} = \omega/c \sin\theta \pm j\, 2\pi/\Lambda = \omega/c \sqrt{\varepsilon_m^{'}\varepsilon_d / (\varepsilon_m^{'}+\varepsilon_d)} \qquad (1)$$

where ω , θ and c are the angular frequency, the light incidence angle and the speed of light in vacuum, respectively. The permittivity of the metal is defined as $\varepsilon_m = \varepsilon_m^{'} + i\varepsilon_m^{''}$ and that of the air is ε_d . Each groove of the metal grating triggers surface plasmon polaritons, which propagate along both positive and negative x directions, and are represented by a

978-1-4244-7031-0 ©2010 IEEE

E_{spp}

electric field, E_{spp}. This SPP wave can also be composed of diffracted evanescent waves (CDEW), as described in [1]. The detail explanation of the enhancement phenomena is explained in a previous paper [4]. When the incident light is at resonance, the metal grating acts as a wave collector or a focusing lens. The light transmission enhancement of the single grating structure is highly dependent on the metal grating parameters, such as the grating period (x_m) and the grating thickness (h_g), which are discussed in detail in previous paper [4].

The coupling of the SPP wave (E_{spp}) with the incident wave (E_i) results in a combined transmission of t_{12} .The combined waves then propagate into the subwavelength aperture whose width and depth are x_d and L. We had shown in [4] that when the subwavelength aperture width (x_d) is much smaller than the propagating wavelength (λ_0), light transmission enhancement and improved absorption in the semiconductor substrate can be obtained in addition to the light transmission absorption caused by the metal grating. In this paper, we show that further light absorption enhancement is achieved by adding another grating structure between the single metal grating structure and the substrate. This enhancement is due to the distribution of the surface plasmon polaritons created between the interaction of the bottom metal grating and substrate interface. It is obvious that the resonance wavelength of the top grating structure will be different from the bottom grating, as evident from Equation 1. We can notice the wavelength shift by comparing the transmission spectra of the single plasmonic grating structure and the double plasmonic grating structure. It is important to simulate each parameter and adjust the wavelength shift based on the wavelength of interest. In the next Section, we investigate the design of the bottom grating by optimizing the following parameters: the first bottom grating metal width pitch (χ_{bm}), the bottom grating period (Λ_b) , the metal duty cycle (χ_{bmp}) and also the bottom grating high (h_{bg}).

III. Results and Discussion

The 2D MSM-photodetector metal structure shown in Fig. 1 was simulated using Opti-FDTD software package developed by Optiwave. In the design a Gold (Au) metal grating and a gallium arsenide (GaAs) substrate were assumed. The gold permittivity ε_m was obtained from the Lorentz-Drude model [5], and the GaAs permittivity ε_{sub} was assumed real of value 12.25, since the imaginary permittivity of GaAs was negligible for mid infrared wavelengths [6]. For the FDTD simulation, we used a grid step size of $\delta x = 10nm$ and a time step of $\delta t < 0.1\delta x / c$. This high-resolution sampling yielded solutions that converged at reasonable computation times. A periodic boundary condition was assumed along the x direction since the incident light propagated along the normal direction. The anisotropic perfectly matched layer (APML) boundary condition was assumed along the z-direction to accurately simulate the absorption of the light reflected from the bottom as well as light transmitted from the top boundaries of the simulated MSM photodetector structure. We assumed that if the light transmission through the double metal grating and subwavelength aperture increases, the absorption of the GaAs increases or structure below GaAs, mainly due to a larger amount of light reaching the GaAs. We define the absorption enhancement factor as the ratio of the normalized power transmittance of the double metal-grating MSM photodetector to the normalized power transmittance of an MSM photodetector structure without a metal grating. The absorption enhancement factor is defined as the amount of light absorption from the free space (air) to the substrate of the structure.

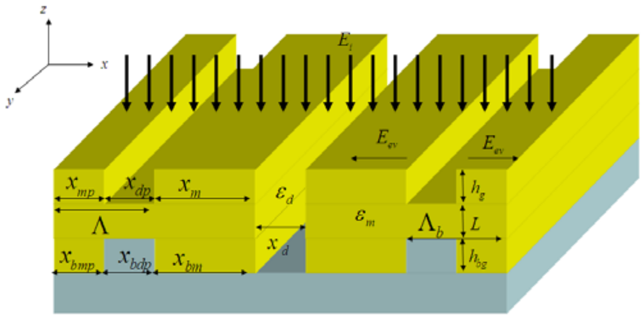


Fig. 1. MSM photodetector structure with a top metal grating, a subwavelength aperture and a bottom metal grating for optical absorption enhancement

The FDTD simulation was first verified by evaluating the absorption enhancement factor versus the subwavelength aperture thickness for the single plasmonic grating structure, as shown in Fig. 2. These results are in excellent agreement with the results published in [8], which confirm that the maximum absorption enhancement occurs when the relation $\phi_{21} + \phi_{23} + 2k_z^{'}L = 2m\pi$ is satisfied, where m is the order of the resonance, ϕ_{21} and ϕ_{23} are the reflection phases when the light reflected from region 2 to region 1, and region 1 to region 2, respectively, and $k_z^{'}$ is the propagation wave vector along the z-direction.

Fig. 2. Absorption enhancement spectrum for different subwavelength aperture thicknesses.

The simulation results in Fig 3 show that the combination of a subwavelength aperture, a nano-structured metal grating on top and bottom of the metal results in up to 25 times enhancement in optical absorption, in comparison to MSM photodetector structures employing only a subwavelength aperture. This is 1.6 times more absorption compared to the single subwavelength grating structure as presented in previous paper [4]. This increase in absorption can be achieved by setting the design parameters as shown in Table 1. As the top grating subwavelength structure has been optimized in [4], in this paper we use the same parameter for the top subwavelength grating structure and the aperture width. The increase of the absorption enhancement of the double grating structure is mainly due to the coupling out of the bottom grating structure. This is clearly illustrated in Fig. 4 that the second grating will distribute out the enhanced light through the subwavelength aperture to a wider length of the substrate and metal interface. It is notice that in Fig 4a, the wave distribution is only concentrated on the exit of the subwavelength aperture and the intensity of the wavelength decreases exponentially. In comparison with the double grating plasmonic structure (Fig 4b) it is noticed that the light distribution is wider in the substrate and the metal interface. (Note that the red color indicated the highest intensity of the wavelength).

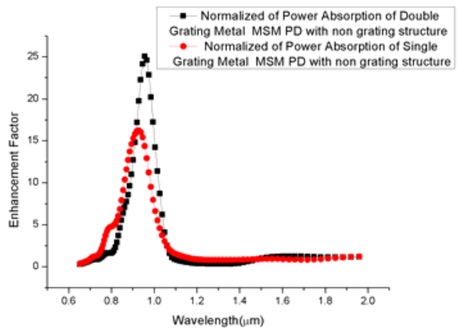
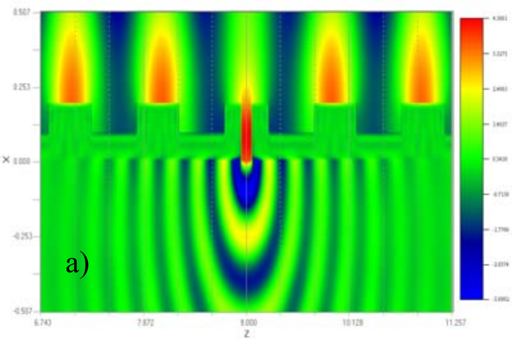


Fig. 3. Comparation enhancement absorption of double subwavelength grating metal MSM PD structure and single subwavelength grating metal MSM PD



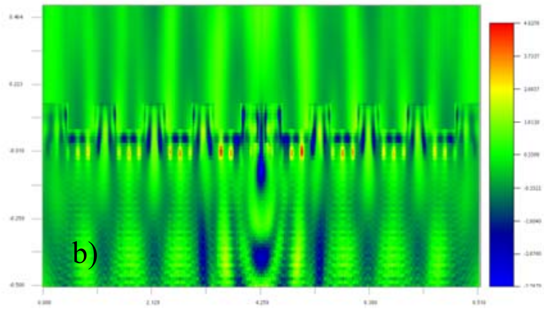


Fig.4. Comparation of light enhancement distribution on substrate/ metal interface of a) double subwavelength grating metal MSM PD structure and b) single subwavelength grating metal MSM PD in FDTD simulation

Table 1: Parameter of the double metal grating MSM PD structure

Symbol	Description	Value
χ_{mp}	Top metal grating duty cycle	0.5
χ_{m}	Top first grating width	300nm
χ_{d}	Subwavelength aperture width	50nm
χ_{bmp}	Bottom metal grating duty cycle	0.5
χ_{bdp}	Bottom first grating width	50nm
h_g	Top grating high	60nm
L	Subwavelength aperture high	100nm
h_{bg}	Bottom grating high	60nm
Λ	Top grating period	950nm
Λ_b	Bottom grating period	200nm

The parameters of the bottom grating structure were also investigated and optimized. First we varied the bottom grating period while kept other parameters value. Fig. 5 shows that the bottom grating period structure has minimum impact on the absorption enhancement but maximum enhancement can be achieved for a bottom grating period of 200nm. This slight enhancement is mostly due to the change of the refractive index in Equation 1 compared to the index of air. The surface Plasmon wave vector should change with respect to the top grating structure but it is noticed that there are only a little change inlight transmission enhancement.

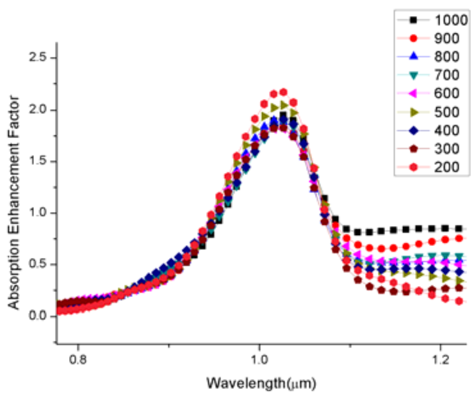


Fig. 5. Absorption enhancement spectrum for different bottom metal grating period.

The first pitch of metal grating structure played an important role on the coupling the light into the subwavelength grating structure. Here similar simulation was carried out to investigate the impact of the bottom grating structure. Fig 6 shows the simulated absorption enhancement when the width of the first bottom grating structure was varied while maintaining other parameters unchanged. The results show that the first pitch of the bottom grating structure does not significantly affect the absorption enhancement of the MSM PD structure

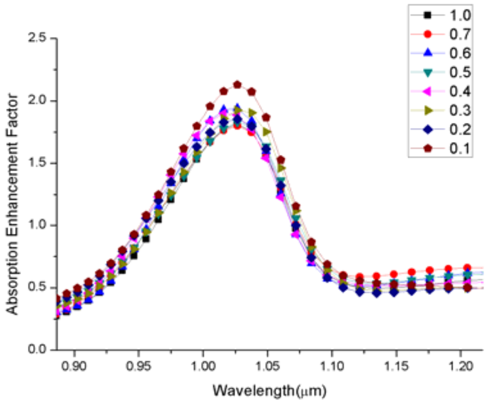


Fig. 6. Absorption enhancement spectrum for different width of the first pitch of the bottom metal grating.

The duty cycle of the metal grating of the bottom grating structure was also simulated. Fig. 7 shows the absorption enhancement spectra for different duty cycles of the bottom metal grating structure. It is interesting to notice that the impact of the duty cycle on the absorption enhancement of the double plasmonic grating structure is negligible. This result is actually very similar to the experiment results reported on pure double plasmonic grating structures where similar gratings on both sides were considered with the input and output coupling media being the air [7, 9].

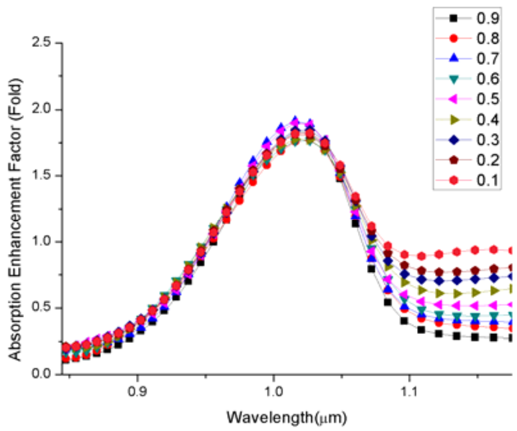


Fig. 7. Absorption enhancement spectrum for different duty cycles of the bottom metal grating.

Finally, we simulated the impact of bottom grating thickness on the performance of the MSM PD structure. Fig. 8 shows the simulated absorption enhancement spectra for different bottom grating thicknesses. Here we see that the bottom grating thickness plays an important role on the enhancement of the light absorption of the double plasmonic grating structure MSM PD. As the thickness increases the optimum SPP wavelength is a blue-shifted. The peak intensity also varies sinusoidal with the peak absorption enhancement shifted 80nm from the optimum wavelength around 1000nm. For an input wavelength of 980nm the optimum bottom grating thickness is 60 nm.

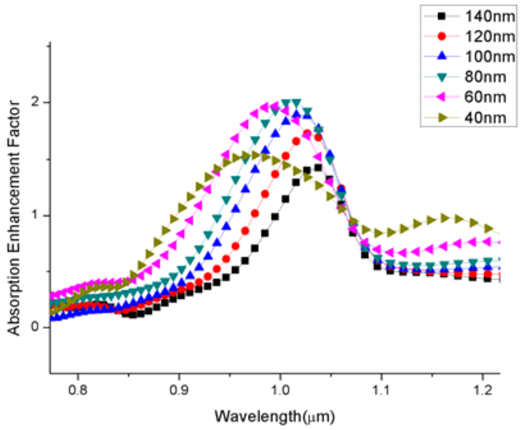


Fig. 8 Absorption enhancement spectrum for different width of the first pitch bottom metal grating.

IV. Conclusion

In this paper, we have carried out FDTD simulations to optimize the different parameters of an MSM photodetector structure employing a double metal grating structure in conjunction with subwavelength aperture. We have simulated the impact of the different parameters such as the subwavelength aperture, bottom metal grating period, width of the first pitch of the bottom metal grating, duty cycle of the bottom metal grating, and the width of the first pitch bottom metal grating. We have shown that an absorption enhancement factor of 25 times is theoretically feasible when the various parameters of the MSM photodetector structure are optimized. It is interesting to note that the top plasmonic grating have complete different properties in comparison to the bottom grating structure. All parameters of the top grating structure have impacts on the absorption enhancement, either in shifting the optimum wavelength or changing the maximum absorption enhancement. However, for the bottom grating of the double plasmonic grating structure only the bottom grating thickness has significant impact on the light absorption enhancement.

Acknowledgment

This work was partially supported by the GIST Systems Biology Infrastructure Establishment Grant, by the World Class University (WCU) program at GIST through a grant provided by MEST of Korea (R31-20008-000-10026-0) and by the Core Technology Development Program for Next-generation Solar Cells of Research Institute for Solar and Sustainable Energies (RISE), GIST.

REFERENCES

[1] G. Lévêque, O. J. F. Martin, and J. Weiner, “Transient behavior of surface plasmon polaritons scattered at a subwavelength groove,” *Phys. Rev. B* **76**, 155418, 2007.

[2] F. J. García-Vidal, H. J. Lezec, T. W. Ebbesen, and L. Martín-Moreno, “Multiple paths to enhance optical transmission through a single subwavelength slit,” Phys. Rev. Lett. **90**, 213901, 2003.

[3] J. A. Shackleford, R. Grote, M. Currie, J. E. Spanier, and B. Nabet, “Integrated plasmonic lens photodetector,” *Appl. Phys. Lett.* **94**, 083501, 2009.

[4] C. L. Tan, V. V. Lysak, K. Alameh, and Y. T. Lee, “Absorption enhancement of 980 nm MSM photodetector with a plasmonic grating structure,” *Opt. Commun*. **283**, pp. 1763-1767, 2010.

[5] A. D. Rakić, A. B. Djurišić, J. M. Elazar, and M. L. Majewski, “Optical properties of metallic films for vertical- cavity optoelectronic devices,” Appl. Opt. **37**, 5271, 1998.

[6] W.E Courtney , IEEE Transactions on Microwave Theory and Techniques, Vol25, 8, (1977).

[7] A. Degiron and T. W. Ebbesen, "Analysis of the transmission process through single apertures surrounded by periodic corrugations," Opt. Express 12, 3694-3700(2004).

[8] J. S. White, G. Veronis, Z. Yu, E. S. Barnard, A. Chandran, S. Fan, and M. L. Brongersma, “Extraordinary optical absorption through subwavelength slits,” Optics Letters, 34, Issue 5, 686-688, 2009.

[9] L. Wang, J.X. Cao, Y. Lv, L. Liu, T.Y. Niu and Y.C. Du“Experimental study of surface-wave-assisted microwave transmission through a single subwavelength slit” Journal of Applied Physics,105, 093115,(2009)