Impact of Duty Cycle and Nano-Grating Height on the Light Absorption of Plasmonics-Based MSM Photodetectors

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Abstract— **We use finite difference time-domain (FDTD) method to calculate the light absorption enhancement of nano-grating assisted metal-semiconductor-metal photo-detectors (MSM-PDs). The simulated results show that the light absorption enhancement of nano-grating assisted MSM-PD is~9-times better than conventional MSM-PD.**

Index terms— **Subwavelength aperture, duty cycle, nano-grating, surface plasmon polariton, FDTD simulation, MSM-PDs.**

I. INTRODUCTION

The application of periodic structures on the metal-semiconductor-metal photodetectors (MSM-PDs) leads to effective light absorption and transmission through the subwavelength apertures. They have significant appeal in optical fiber communication, high-speed sampling, and chip to chip interconnects. The MSM-PD is a symmetrical semiconductor device which is equivalent to two back-to-back connected Schottky diodes [1]. There are two distinct mechanisms to produce transmission in one dimensional metal grating with narrow slits, which are the excitation of horizontal and vertical surface resonances. The horizontal surface resonances are excited by the periodic structure of the nano-gratings. The vertical surface resonances correspond to Fabry–Perot-like resonances of the fundamental TM guided wave in the slits [2]. The metallic gratings can exhibit absorption anomalies. One of these particularly remarkable anomalies is observed for p-polarized light only, and is due to surface plasmon polaritons (SPPs) excitations [3]. The light incident on the metal nano-grating is converted into propagating SPPs that can absorb the light efficiently in extremely thin (10's~100's of nm's thick) layers. The extremely thin absorbing layers can act as a light concentrator which is essential for triggering the extra ordinary absorption (EOA) of light [4]. Subwavelength apertures have also been used to efficiently concentrate light into the deep subwavelength regions [5]. Finite-difference time-domain (FDTD) simulation results have demonstrated significant enhancement of light absorption for the design of ultrafast MSM-PDs [5-6].

II. DESIGNOF MSM-PD STRUCTURE

Figure 1 shows a simple plasmonics-based MSM structure with gold (Au) nano-gratings etched on top of a layer of the same metal. The structure design is shown with three separate parts, namely, the metal nano-gratings (top part), the subwavelength apertures (middle part) and the substrate (bottom part). The momentum of surface plasmons can be easily changed by adding thin layers of material on the metal surface or by changing the dielectric constant of the material deposited on it. Here, the gold (Au) metal nano-gratings were deposited on top of the layer containing subwavelength apertures and the layer is only on the semiconductor (GaAs) substrates.

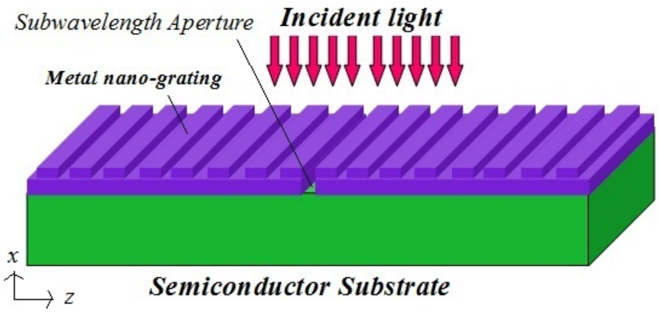

Fig. 1. Schematic diagram of the MSM-PD structure with rectangular shaped nano-gratings on top of the subwavelength apertures. The subwavelength apertures are just on top of the semiconductor (GaAs) substrates.

For a metal nano-grating period of Λ, the conservation of momentum in the direction parallel to the nano-gratings lead to the following relationship.

$$k_{x(out)}.\sin\theta = k_{x(in)}.\sin\theta \pm mk_g = \frac{\omega}{c}\sqrt{\frac{\varepsilon_m^{'}\varepsilon_d}{\varepsilon_m^{'}+\varepsilon_d}} \qquad (1)$$

When the plasmonic excitations occur then the left side of equation (1) matches the wave vector of the excited SPP (K_{SPP}). Here, m is an integer corresponding to the order of the outgoing diffracted beam, $k_g = 2\pi/\Lambda$ is the grating wave vector, ω is the angular frequency of the incident light wave with θ as the angle of incidence and c is the speed of light.

III. RESULTS AND DISCUSSION

A. *Impact of nano-grating height on LAEF*

In this sub-section, we will discuss the influence of nano-grating height on the light absorption enhancement. Fig. 2 shows the light absorption enhancement factor (LAEF) spectra for different nano-grating heights with 60% duty cycle and the

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subwavelength aperture width is 100 nm. The assumed grating period is 810 nm. The TM mode of light was perpendicularly incident on the grooves with θ=0°. Different sets of results show that the amount of light transmitted into the active area of the MSM-PD changes with the variation of nano-gratings height. The peak wavelength is red shifted and it behaves like a sinusoidal manner.

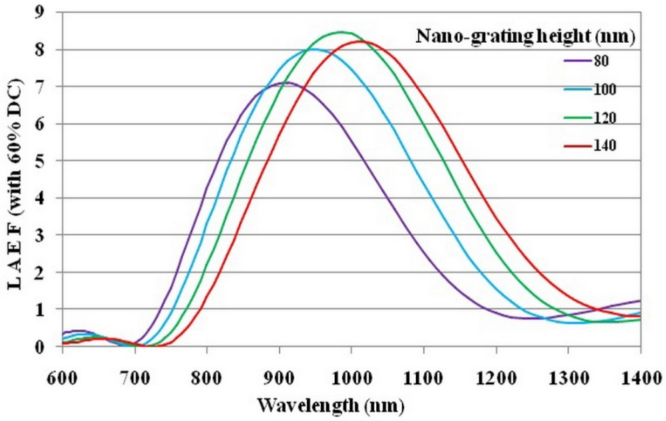

Fig.2. LAEF spectra for different nano-grating heights. Here, the duty cycle is 60% and subwavelength aperture width is 100 nm.

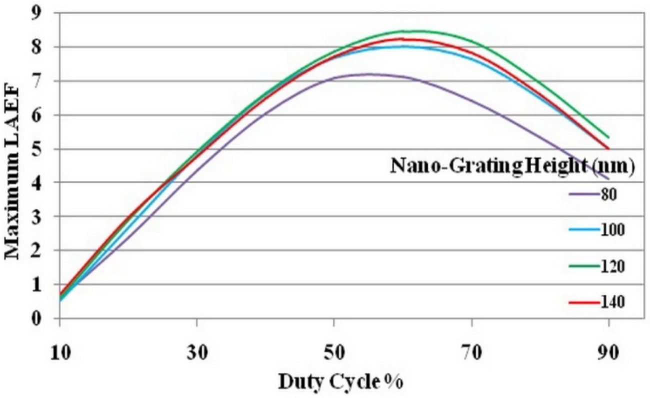

Fig. 3. Maximum (or peak) LAEF versus duty cycle characteristics with several nano-grating heights.

B. Influence of the duty cycles on LAEF with different nano-grating heights

In this sub-section, the LAEF spectra for several duty cycles which affect the amount of light flux transmitted into the active area is discussed. The duty cycle was varied from 10% to 90% while the subwavelength aperture was kept constant at 100 nm and the metal nano-grating heights were varied from 80 ~ 140 nm. The results illustrate that the amount of the LAEF grows gradually towards to 60% duty cycle and falls down moderately. The effects of the duty cycle on the transmitted power into the active region become more noticeable by plotting the value of the maximum LAEF as a function of the duty cycle, as shown in Fig. 3. It can be inferred that the maximum LAEF for each specific duty cycle increases from 80 nm to 120 nm of nano-grating height and decreases for 140 nm. It is clear that the duty cycle can affect the peak wavelength also the amount of light transmitted into the active area of the MSM-PDs.

C. Impact of nano-grating height and duty cycles on LAEF of MSM-PDs

It is noticed that the change of metal nano-grating height also affects the phase of the transmitted electric field, which is evident from the red shift exhibited when the metal nano-grating heights are increased. The LAEF for MSM-PD structure with different duty cycles is shown in Fig. 4. The maximum LAEF for each duty cycle can be obtained when the metal nano-grating height is around 120 nm that is the optimum nano-grating height for this typical device structure. As it was expected, the amount of power transmitted into the active region not only depends on the duty cycle but also on the nano-grating height which can be interpreted by changes in phase of the transmitted electric field.

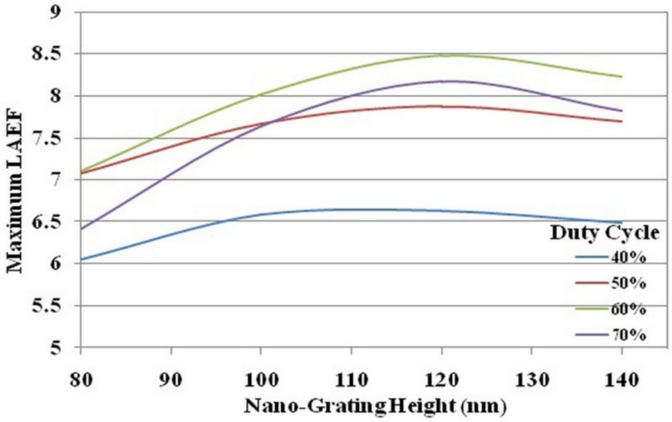

Fig. 4. Maximum (or peak) LAEF versus nano-grating height characteristics with several duty cycles.

IV. CONCLUSION

We have modeled the light absorption enhancement performance of a new MSM-PD structure with rectangular-shaped metal nano-gratings. The impact of metal nano-grating height and duty cycle on the LAEF of MSM-PD structures was analyzed using the FDTD technique to optimize these design parameters. Our simulation results show that the LAEF is ~9-times better than the conventional MSM-PDs with the subwavelength aperture width of 100 nm. These simulated results are useful for the design and development of high responsivity MSM-PDs.

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