Enhanced Light Absorption in Plasmonics-based MSM-PD with Special Design of Subwavelength Slit

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***Abstract*— A novel plasmonics-based metal-semiconductor-metal photodetector is introduced which dramatically modifies the light transmission spectra when the sub-wavelength central slit is not bare. FDTD method has been utilized to simulate the behavior of the device with significant responsivity.**

***Index terms*— FDTD simulation, Plasmonics-based MSM-PDs, Subwavelength aperture, Surface plasmon polariton.**

I. Introduction

Recently, the rapid progress in optimization of nanoscale structures to enhance surface plasmon polaritons (SPPs) coupling was helpful in developing plasmonic enhanced metal-semiconductor-metal-photodetectors (MSM-PDs) [1-3]. Implementation of optimized nano-gratings between two contacts of MSM-PDs facilitate the TM polarized light coupling to SPP modes of the grating. Design of complex plasmonic nano-sized structures opened up the new ways to improve MSM-PD's light absorption performance. Here, we report the development of a plasmonics-based MSM-PD structure via fabrication of nano-scale structures inside the central aperture of the device. This breaks the conventional barrier of diffraction limit and leads to the formation of concentrated sub-wavelength light spots on the order of nanometers. Finite-difference time-domain (FDTD) numerical method has demonstrated significant enhancement of light absorption for the design of ultrafast MSM-PDs.

II. Photodetector Structure Design

Figure 1 shows a plasmonics-based MSM-PD structure with the metal nano-gratings, subwavelength apertures and substrate. For generation of SPPs, the nano-corrugations should satisfy the dispersion relation. Coupling to SPPs results in absorption in a mode volume that is small relative to the exponential absorption profiles that occur in conventional bulk semiconductors [4]. The SPP wave vector for a metal nano-grating with period of Λ is given by equation (1).

$$K_{sp} = \frac{\omega}{c}\sin(\theta) \pm \frac{2\pi l}{\Lambda} = \frac{\omega}{c}\sqrt{\frac{\varepsilon'_m \varepsilon_d}{\varepsilon'_m + \varepsilon_d}} \qquad (1)$$

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where, ω is the angular frequency of the incident light wave, c is the speed of light in vacuum, θ is the angle of light incident to the device normal, l is an integer number. The complex dielectric permittivity of the metal is defined as $\varepsilon_m = \varepsilon'_m + i\varepsilon''_m$ which is obtained from Lorentz-Drude model and that of the air is denoted as ε_d. Focusing of light into the sub-wavelength slit occurs with the aid of nano-grating grooves. Furthermore our investigation shows that application of ultra-thin films in the central slit provides excellent condition to enhance the photocurrent in comparison with simple plasmonics-based structures of similar dimensions.

III. Results and Discussion

To analyze the effect of ultra-thin nano-fabrications in the subwavelength aperture, we designed the plasmonics-based MSM-PD structure with novel ellipse-wall nano-gratings. The light absorption enhancement factor (LAEF) can be defined as the ratio of light transmission through the device with the nano-gratings to that of the similar device without the nano-gratings [3].

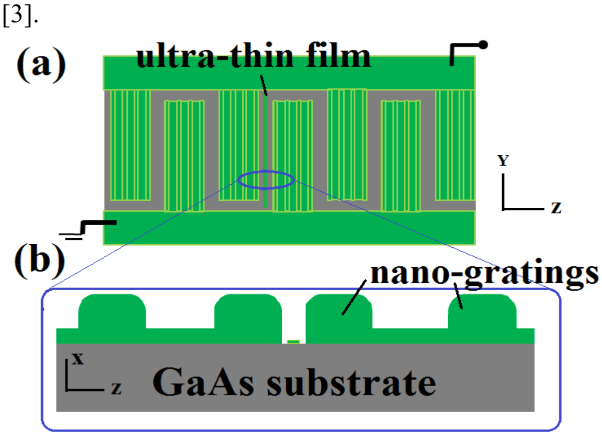

Fig. 1. Schematic diagram of MSM-PD structure with ellipse-wall nano-gratings on top of the subwavelength apertures and ultra-thin film inside the slit a bit up of the semiconductor substrate, a) top view, b) cross section.

Here, the gold (Au) metal nano-gratings were deposited on top of the subwavelength apertures, such as ellipse-wall nano-gratings which are more efficient compared to rectangular ones also they are more compatible with realistic conditions experimentally. This nonlinear design facilitates energy flow through the subwavelength aperture and therefore the energy concentration is improved inside the active region. We applied an ultra-thin film symmetrically in the center of the subwavelength slit and measured the amount of LAEF for several devices to compare their efficiency with the simple plasmonics-based MSM-PD.

a) Ellipse-wall Plasmonics-based MSM-PD

We present the absorption enhancement in a simple plasmonics-based MSM-PD with optimized parameters. Improved absorption in the semiconductor substrate can be obtained caused by best of existing design for metal nano-gratings, i.e. ellipse-wall shaped nano-gratings. In this special design, nano-grating walls satisfy the exponential function with the exponential coefficient of C=3, $x=Ce^{z}$, which is more efficient than those having straight and slanted walls. LAEF curve for rectangular shaped nano-gratings with optimized parameters are also presented in Fig. 2 to make a delicate comparison. Here, the subwavelength aperture width, and duty cycle are 50 nm, and 40%, respectively. In this case, the maximum LAEF is about 33.5-times for 140 nm height.

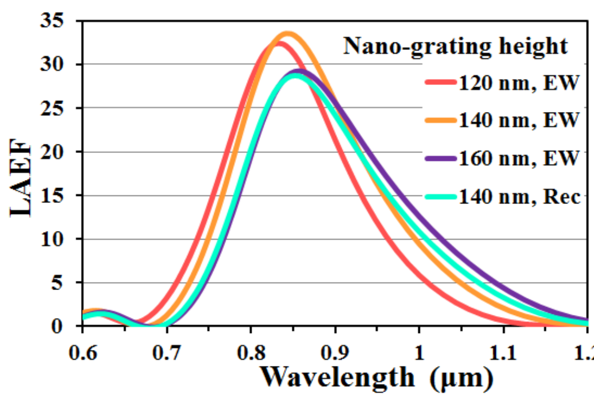

Fig. 2. LAEF spectra for ellipse-wall (EW) and rectangular (Rec) plasmon-assisted MSM-PDs with different nano-grating heights.

b) Ultra-thin film assisted ellipse-wall MSM-PD

Simulation results in Fig. 3 show that the impact of number of nano-gratings (NG) on either side of the subwavelength slit is unchanged for NG $\geq$ 4 in thin-film assisted MSM-PD. Therefore, we used NG=4, instead of NG=8 in part a, in our modeling which is an advantageous design for experimental purposes.

Application of metallic ultra-thin film inside the slit results in SP field concentration and enhances the absorption performance of ellipse-wall MSM-PD while the peaks are shifted to bigger wavelengths. The LAEF spectra are considerably improved if the ultra-thin metallic film is placed symmetrically in the sub-wavelength aperture. Figure 4 shows the calculated LAEF curves of MSM-PD with ultra-thin films for three nano-grating heights. Hence, efficient light concentration in the active region is obtained through application of ultra-thin metallic films inside the slit. The distribution of localized surface plasmon resonances corresponding to the application of thin film in the slit exceeds, and accordingly enables incident light energy to be absorbed more efficiently near the thin film surface. Hence the quality light absorption occurs for thin-film assisted ellipse-wall MSM-PDs with the maximum LAEF of about 1330 times, outstandingly higher than the simple plasmonics-based device.

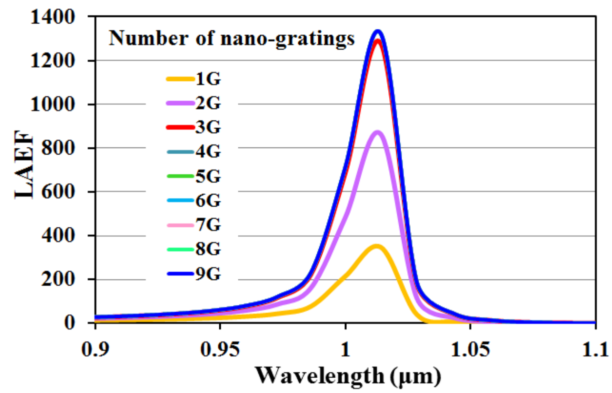

Fig. 3. LAEF spectra for ellipse-wall MSM-PDs with different nano-grating numbers on each side of slit. Nano-grating height is 140 nm.

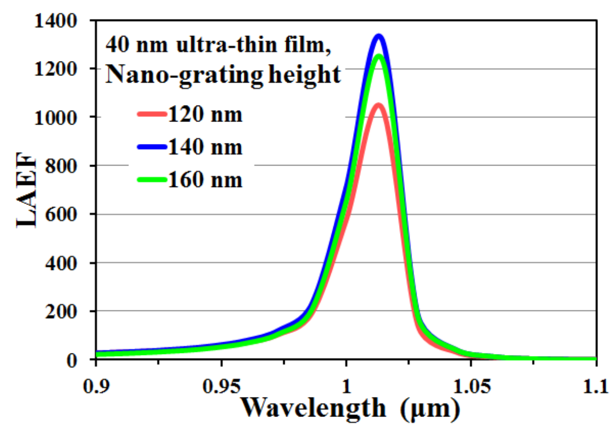

Fig. 4. Light absorption spectra for ellipse-wall nano-grating-assisted MSM-PD capped with 40nm width thin film layer.

IV. Conclusion

We have modeled the light absorption performance of a new MSM-PD structure employing ellipse-wall metal nano-gratings. We optimized nano-gratings structure and analyzed the impact of ultra-thin metallic films inside the subwavelength aperture which allows for the realization of photodetectors with improved responsivity. Hence, the sensitivity of optimized device is improved compared with simple plasmonics-based MSM-PDs. For such a device, the maximum LAEF peak of the ultra-thin structured MSM-PD is 40-times higher than the identical structure with bare central slit.

References

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