2010

Groove shape-dependent absorption enhancement of 850 nm MSM photodetectors with nano-gratings

Narottam Das
Edith Cowan University

Ayman Karar
Edith Cowan University, ayman_karar@hotmail.com

Mikhail Vasiliev
Edith Cowan University, m.vasiliev@ecu.edu.au

Chee Leong Tan

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

See next page for additional authors

10.1109/NANO.2010.5697754
This article was originally published as: Das, N. K., Karar, A. , Vasiliev, M. , Tan, C., Alameh, K. , & Lee, Y. T. (2010). Groove Shape-Dependent Absorption Enhancement of 850 nm MSM Photodetectors with Nano-Gratings. *Proceedings of IEEE Conference on Nanotechnology IEEE-NANO. (pp. 289-293). . Seoul, Korea. IEEE.* doi:10.1109/NANO.2010.5697754. Original article available here

Authors
Narottam Das, Ayman Karar, Mikhail Vasiliev, Chee Leong Tan, Kamal Alameh, and Yong Tak Lee

Proceedings of 10th IEEE International Conference
on Nanotechnology Joint Symposium with Nano Korea 2010
August 17~20, KINTEX, Korea

Groove Shape-Dependent Absorption Enhancement of 850 nm MSM Photodetectors with Nano-Gratings

Narottam Das[1]*, *Senior Member, IEEE*, Ayman Karar[1], Mikhail Vasiliev[1], Chee Leong Tan[2], Kamal Alameh[1,3]*, *Senior Member, IEEE* and Yong Tak Lee[2,3]

[1]Electron Science Research Institute, Edith Cowan University, Joondalup, WA 6027, Australia
[2]Department of Information and Communications, Gwangju Institute of Science and Technology (GIST), 261 Cheomdan-gwagiro (Oryong-dong), Buk-gu, Gwangju, 500-712, Republic of Korea
[3]Department of Nanobio Materials and Electronics, GIST, Republic of Korea
*E-mail: k.alameh@ecu.edu.au and n.das@ecu.edu.au

***Abstract*— Finite difference time-domain (FDTD) analysis is used to investigate the light absorption enhancement factor dependence on the groove shape of the nano-gratings etched into the surfaces of metal-semiconductor-metal photodetector (MSM-PD) structures. By patterning the MSM-PDs with optimized nano-gratings a significant improvement in light absorption near the design wavelength is achieved through plasmon-assisted electric field concentration effects. Simulation results show about 50 times light absorption enhancement for 850 nm light due to improved optical signal propagation through the nano-gratings.**

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

I. Introduction

Subwavelength plasmonic nanostructure gratings have recently been proposed for the development of high-speed improved-responsivity metal-semiconductor-metal photo-detectors (MSM-PDs). The strong interaction of the nano-structured metal gratings with incident light enables trapping the light inside the subsurface region of semiconductors [1], leading to substantial improvement in light absorption. MSM-PDs have a wide range of potential applications, including optical fiber communications, high-speed chip-to-chip interconnects, and high-speed sampling.

An MSM-PD comprises interdigitated metal fingers deposited onto a semiconductor substrate. Upon detection of photons, it collects the electric currents generated by photo-excited charge carriers in the semiconductor region, which drift under the electric field applied between the fingers. The speed of MSM-PDs can either be intrinsically limited by the carrier transit time between the electrodes or by the carrier recombination effects. The interdigitated electrodes in MSM-PDs result in a huge increase in bandwidth and reduction in dark current, in comparison to conventional PIN photodiodes with active areas of similar size [2-3]. In recent years, the use of surface plasmon-assisted effects for the design of such photodetectors has been reported for the development of MSM-PDs having a high responsivity-bandwidth product, well beyond that of conventional PIN photodetectors, therefore attracting a great deal of interest [4].

Several theoretical and experimental research and development activities have recently been reported on the extraordinary optical transmission through the subwavelength metallic apertures [5-10] as well as through periodic metal grating structures [11-13]. Simulation results using finite-difference time-domain (FDTD) have shown significant enhancement of light absorption through interaction with SPPs, and this has direct application to the design of MSM-PDs [1, 4-6].

In this paper, we adopt the FDTD technique to optimize the performance of a novel GaAs MSM-PD structure where the metal fingers are structured to form a metal nano-grating above an unperturbed part of the same metal fingers. Simulation results show that theoretically it is possible to attain about 50 times enhancement in light trapping near the wavelength of 850nm in comparison to conventional MSM-PDs. This enhancement in absorption is due to the extraordinary optical wave propagation through the metal nano-gratings.

II. MSM-PD Structure Design

Figure 1 illustrates a novel MSM-PD structure, which consists of three separate layers, namely 1) top layer (metal nano-grating), 2) unperturbed metal layer (underlayer) containing conventional

978-1-4244-7032-7/10/$26.00 ©2010 IEEE

subwavelength apertures, and c) semiconductor (GaAs) substrate. The metal nano-grating is formed by etching or focussed ion-beam (FIB) milling the lines inside a metal (Au or Ag) layer with the grooves being perpendicular to the x-axis, and its dimensions and geometry are optimized to in-couple light near the design wavelength and trigger SPPs propagating along the z-axis. For a metal nano-grating period of Λ, the wave vector of the excited SPPs is given in [1].

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

where ω is the angular frequency of the incident light wave, c is the speed of light in vacuum and θ is its angle of incidence with respect to the device normal, l is an integer number i.e., l = 1, 2, 3, ……..N. In our analysis, we denote the complex dielectric permittivity of the metal as $\varepsilon_m = \varepsilon_m^{'} + i\varepsilon_m^{''}$, where $\varepsilon_m^{'}$ and $\varepsilon_m^{''}$ are the real and imaginary part of the dielectric permittivity, respectively, and i is a complex (or an imaginary) number, i.e., $i = \sqrt{-1}$, and the dielectric permittivity of air (or the incidence medium) is denoted as ε_d. Therefore, the metal nano-grating with a period Λ is required to match the surface plasmons' wavevector to that of the normally-incident light (θ = 0) of the angular frequency ω. Using Eq. (1) to design the absorption enhancement peak spectrally located near 850 nm for the Au grating/Au/GaAs material system and air as incidence medium, we found that a grating periodicity of Λ = 810 nm was optimum. Following the approach reported in [1], we have also selected the duty cycle of grating corrugations to be 50%. Different types of nano-grating groove shape designs, shown in Fig. 1, were considered and specifically, the dependency of the plasmon-assisted light absorption enhancement on the geometric shape of the nano-grating corrugations cross-sections was investigated using FDTD analysis.

Figure 1(a) shows a schematic diagram of an MSM-PD with plasmonic rectangular-shaped nano-gratings etched inside the top part of Au layer. The thickness of the unperturbed metal layer containing subwavelength apertures is shown as h_s (typically about 10-50 nm) and the height of the metallic nano-gratings, h_g (varied between 50-100 nm in our modeling). A single grating period (Λ) of 810nm (fixed in our design and modeling) contains a metal nano-grating and a cut-out (free space) with a duty cycle of 50%. The subwavelength aperture width is x_w and its value was varied between 50-250 nm.

Figure 1(b) shows a trapezoidal-shaped nano-grating profile that was used for the simulation. It is the closest cross-sectional profile to that developed using FIB lithography in the case of small-feature-size (sub-100 nm) nano-patterned grooves. The modeled trapezoidal shapes had different aspect ratios (trapezoid-top to base length ratios) of 0.9, 0.8, 0.7, 0.6 and 0.5.

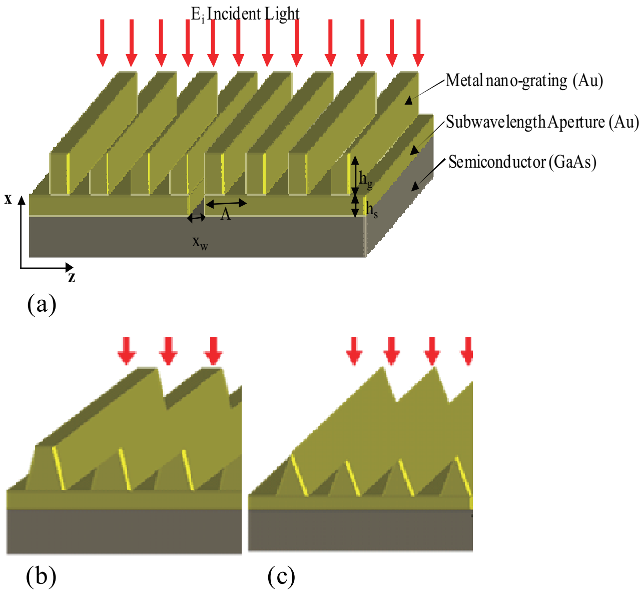

Fig. 1. Schematic diagrams of different MSM-PD structures with plasmonic nano-gratings etched inside the top part of Au layer. (a) rectangular-shaped metal nano-grating profile, (b) trapezoidal-shaped nano-grating profile, and (c) the metal nano-gratings having a triangular cross-sectional profile.

Figure 1(c) shows a triangular-shaped nano-grating profile. Figure 1 [(a), (b) and (c)] all show that a metal (Au) layer is deposited on top of the semiconductor (GaAs) substrate; the thickness of this layer was kept constant at 100 nm throughout the analysis. In the simulation, a range of grating profile-shape variations was considered, keeping the unperturbed part of metal layer (underlayer) thickness at 10 nm and the metal nano-grating height h_g at 90nm. The light is normally incident on top of the plasmonic nano-grating, which assists the light absorption within the sub-surface region of GaAs substrate.

An SEM image of the plasmonic nano-grating etched inside the top part of Au layer using FIB milling system is shown in Fig. 2(a) and Fig. 2(b). From SEM imaging, it was found that the FIB milling was better than conventional photo-lithography processes for cutting sharp-edge profiles. Moreover, the SEM images showed that the nano-grating's profile is trapezoidal rather than rectangular. The trapezoidal groove shape is formed due to the re-deposition of the etched gold atoms and the truncation of nano-grating edges due to the ion beam. An AFM system (XE-100 from Park Systems) was used to analyze the surface topography. The AFM image, shown in Fig. 2(c) confirmed the shape of the nano-grating is nearly trapezoidal profiles. We also measured the top and base lengths of trapezoid, and calculated the aspect ratio of the trapezoid is in the range 0.5 - 0.6. Based on these experimental results, the shape of the nano-grating was taken into account in the simulation of the shape dependency of light absorption enhancement in MSM-PDs.

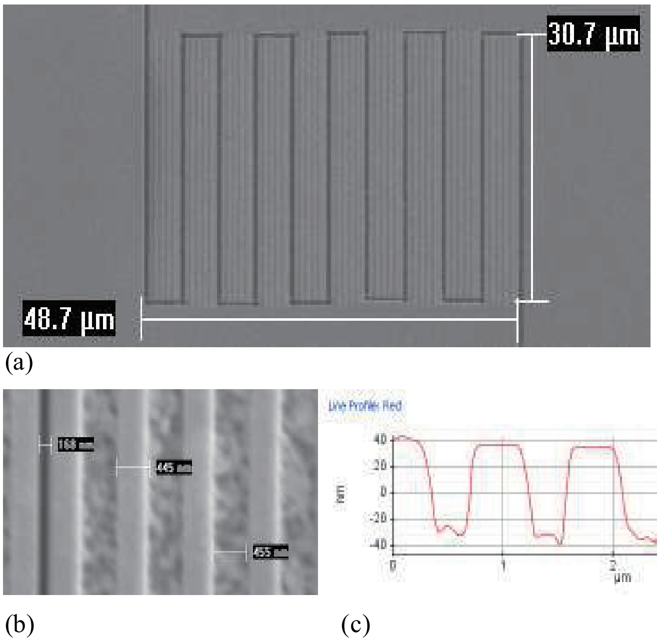

Fig. 2. Experimental results: (a) A typical SEM image of the nano-grating fabricated with FIB lithography process, (b) a detailed image of a portion of the fabricated nano-grating, and (c) AFM image of the nano-grating profile.

The incident light normally passes through the sub-wavelength apertures and reaches into the GaAs substrate, and therefore, generating electron-hole pairs. In addition, the light absorption within GaAs is assisted by the SPPs excited near the metal-semiconductor interface in the nano-grating regions. The energy of light incident on the metal nano-grating is coupled partially into propagating SPPs that can improve the light absorption efficiency in thin sub-surface regions of semiconductor under the subwavelength apertures. The improvement of light absorption of nano-grating is due to SPP-generated localized regions of high-intensity electric field distribution (as shown in Fig. 3). Therefore, the nano-grating acts as light concentrators (plasmonic lenses) or collectors, which is necessary for triggering the extraordinary optical absorption (EOA) of light within the active regions of photodetectors.

2-dimensional FDTD models of several groove shape designs of MSM-PDs (with and without the metal nano-grating) were generated using Opti-FDTD software package developed by Optiwave Inc. In the simulation, we used a mesh step size of $\delta x = 5$nm and a time step of $\delta t < 0.1\ \delta x/c$. The excitation field was modeled as a Gaussian-modulated continuous wave. The incident light wave was TM-polarized (its electric field oscillation direction was along z-axis, perpendicular to the nano-grating grooves). The anisotropic perfectly matched layer (APML) boundary conditions were applied in both x- and z-directions. The gold (Au) dielectric permittivity was defined by the Lorentz-Drude model [15] and the dielectric permittivity data of GaAs was taken from [16].

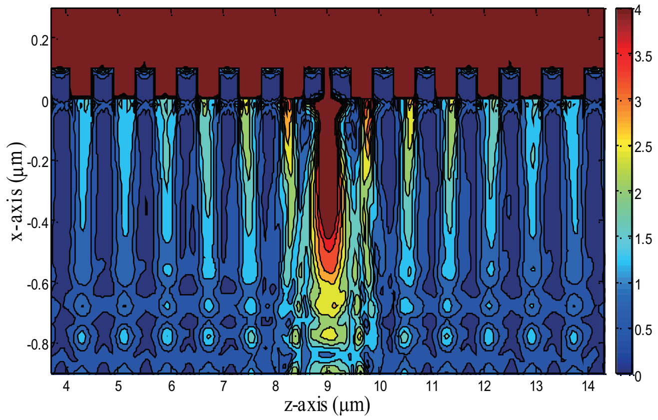

Fig. 3. Total electric field intensity distribution in the cross-section of computational volume behind the nano-grating with rectangular grooves cross-section and the following grating parameters: the nano-grating height is 90 nm, unperturbed gold layer thickness is 10 nm, grating period is 810 nm, and the subwavelength aperture width is 100 nm. The color scale has been optimized for representing small weak-field intensity variations.

A density plot of the total (transmitted) electric field strength within the substrate cross-section is shown in Fig. 3. We used a custom-designed Matlab algorithm to calculate the total electric field intensity distribution, as a result of vector summation of the modeled complex electric field component distributions along the x-direction (E_x) and z-direction (E_z). From Fig. 3, it is clearly seen that the significant amount of light is passing through the region of subwavelength aperture width is mainly due to the plasmon-assisted effects, which result in propagating SPPs excited by the incident light waves and the energy concentration (by plasmonic lenses) within small material volumes near the photodetector's active region.

III. Results and Discussion

In this section, we discuss the simulation results of different MSM-PD structures having several types of nano-grating groove-geometry designs as well as the light absorption enhancement dependency on the subwavelength aperture width. We particularly modeled the nano-grating groove shape dependency as well as the aperture width dependency of the light absorption enhancement factor, defined as the ratio of the normalized power transmittance of MSM-PD with metal-nano-grating to the normalized power transmittance of the MSM-PD without grating [5-6]. The propagation of light through the MSM-PD structures of the described type was modeled for a range of subwavelength aperture widths whilst keeping the values of h_s = 10 nm and h_g = 90 nm (optimized separately for devices operating near the wavelength 830nm) constant.

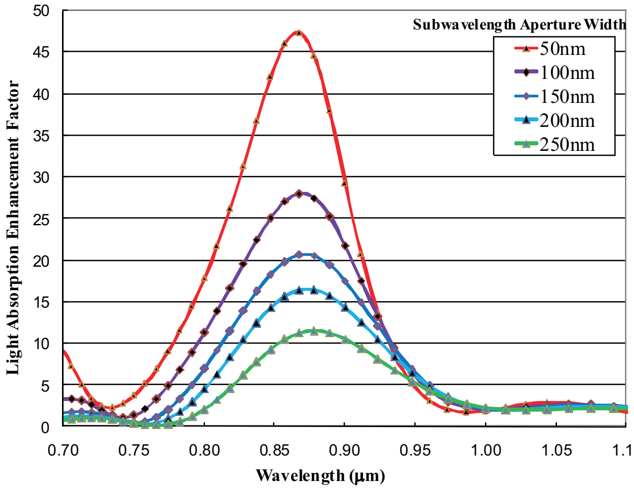

Fig. 4. Light absorption enhancement factor spectra for MSM-PDs with plasmon-assisted operation. For this simulation, the subwavelength aperture widths were varied between 50-250 nm, and all the groove shapes were rectangular-profile.

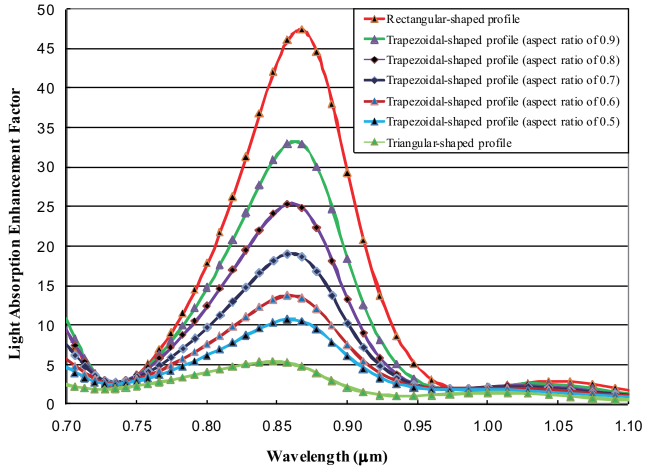

Fig. 5. Light absorption enhancement factor spectra for different nano-grating groove shapes. In this case, the subwavelength aperture width was kept constant at 50nm.

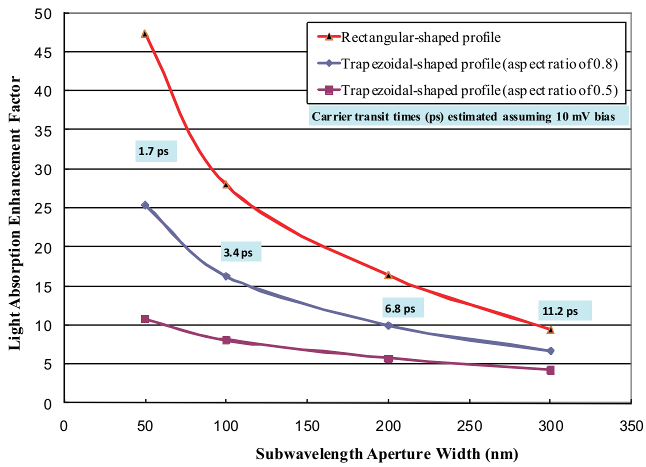

Fig. 6. Maximum (peak) light absorption enhancement factor versus the subwavelength aperture width for different groove geometries.

Figure 4 shows the calculated light absorption enhancement factor spectra of several optimized MSM-PD structures. For this case, the grooves of the nano-grating are rectangular-shaped in their cross-section. We varied the subwavelength aperture widths between 50-250 nm and kept the grating period constant at 810 nm. The results show that the light absorption enhancement factor decreases rapidly with the increasing of subwavelength aperture widths. We obtained the light enhancement factor about 50 times for 50 nm-wide subwavelength aperture width and about 12 times for 250 nm aperture width. The simulation results shown in Fig. 4 is in excellent agreement with the results reported in references [12, 14], therefore confirming the FDTD simulation model used in this paper.

The spectral distribution of the light absorption enhancement factor for different nano-grating groove shapes are shown in Fig. 5. For this simulation, the aperture width was kept constant at 50nm (already optimized with respect to the device bandwidth and light absorption), and the grating period was fixed at 810nm. We modeled the effects of different types of nano-grating groove geometries on light propagation and obtained the following results. These are: (a) the predicted light absorption enhancement factor was at its maximum about 50 times for a rectangular-shaped nano-grating, and (b) the absorption enhancement factor was reduced progressively with the decreasing aspect ratios for the trapezoidal-shaped nano-grating. For the trapezoidal-shaped profile with the aspect ratio of 0.8, the light enhancement factor was reduced about 50% compared to its "ideal-case" maximum. We also simulated the light absorption enhancement factor for the aspect ratios of 0.9, 0.7, 0.6, and 0.5 as shown in Fig. 5. Therefore, this groove-shape dependency of light absorption enhancement is the primary importance in practical manufacturing situations. Furthermore, the triangular-shaped nano-grating groove geometry shown in Fig. 5 generates the minimum (but still significant) light absorption enhancement of only a factor of 5.

The maximum (peak) light absorption enhancement factor versus the subwavelength aperture width for different groove shapes are shown in Fig. 6. It is clear that the light absorption enhancement factor was decreasing exponentially with increasing the subwavelength aperture width for all groove shapes; however, the decreasing rate is different for different groove shapes. Furthermore, we calculated the lower-limits for the carrier transit time for different subwavelength aperture widths, using a simplified kinematics-based carrier drift model. From the transit-time estimates obtained as shown in Fig. 6, it is clear that using very short subwavelength aperture widths, carrier drift-limited device operation in the sub-terahertz frequency range is possible.

IV. Conclusions

We have modeled the light-capture performance of novel MSM-PD structures employing metal nano-gratings of different cross-sectional shapes in terms of the light absorption enhancement and hence the responsivity-bandwidth products. FDTD technique has been used to optimize the different device parameters, such as subwavelength aperture width, nano-grating's height and other structure parameters (corrugation shapes) for maximized light absorption enhancement. Our simulation results have shown that the novel MSM-PD structures can attain a maximum light absorption enhancement near 850 nm of almost 50 times better than the conventionally-designed MSM-PDs. Also, we have analyzed the reality of different nano-grating groove shapes for practical device manufacturing considerations and modeled the light absorption enhancement dependency on these nano-grating groove shapes in MSM-PDs. The results reported are useful for the design and development of MSM-PDs with high responsivity-bandwidth products.

REFERENCES

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

[2] J. B. D. Soole and H. Schumacher, "InGaAs metal-semiconductor-metal photodetectors for long wavelength optical communication," *IEEE J. Quantum Electron.*, **27**(3), pp. 737–752, Mar. 1991.

[3] M. Ito and O. Wada, "Low dark current GaAs metal-semiconductor-metal (MSM) photodiodes using WSi contacts," *IEEE J. Quantum Electron.*, **22**(7), pp. 1073–1077, Jul. 1986.

[4] J. Hetterich, G. Bastian, N. A. Gippius, S. G. Tikhodeev, G. von Plessen, and U. Lemmer, "Optimized design of plasmonic MSM photodetector," *IEEE J. Quantum Electron.*, **43**(10), pp. 855-859, 2007.

[5] N. Das, C. L. Tan, V. V. Lysak, K. Alameh and Y. T. Lee, "Light absorption enhancement in metal-semiconductor-metal photodetectors using plasmonic nanostructure gratings," in Proc. HONET'09, Alexandria, Egypt, Dec. 28~30, 2009.

[6] 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.

[7] F. J. García-Vidal and, L. Martín-Moreno, "Transmission and focusing of light in one-dimensional periodically nanostructured metals," Phys. Rev. B **66**, 155412, 2002.

[8] 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.

[9] B. Sturman, E. Podivilov, and M. Gorkunov, "Theory of extraordinary light transmission through arrays of subwavelength slits," Phys. Rev. B 77, 075106, 2008.

[10] L. Martín-Moreno, F. J. García-Vidal, H. J. Lezec, K. M. Pellerin, T. Thio, J. B. Pendry, and T. W. Ebbesen, "Theory of extraordinary optical transmission through subwavelength hole arrays," Phys. Rev. Lett. **86**, 1114, 2001.

[11] 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.

[12] L. Martín-Moreno, F. J. García-Vidal, H. J. Lezec, A. Degiron, and T. W. Ebbesen, "Theory of highly directional emission from a single subwavelength aperture surrounded by surface corrugations," Phys. Rev. Lett. **90**, 167401, 2003.

[13] H. J. Lezec, and T. Thio, "Diffracted evanescent wave model for enhanced and suppressed optical transmission through subwavelength hole arrays," Opt. Express **12**, 3629-3651, 2004.

[14] 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.

[15] 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.

[16] E. D. Palik, "Galllium Arsenide (GaAs)" in *Handbook of Optical Constants of Solids,* E. D. Palik, ed. (Academic, San Diego, USA, 1985).