Influence of Array Arrangement on Scattering Characteristics of Metal Circular Hole Nanostructures

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Abstract. The key problem to improve the efficiency of solar cells by using the effect of surface plasmon is to select the parameters such as the material, shape, size, surface coverage, and the film thickness correctly. Much effort has been devoted to one-dimensional periodic arrays of slits and two-dimensional periodic arrays of holes with different shapes. However, little attention has been paid to the arrangement of the periodic arrays. In this article, we mainly analyze the scattering of gold circular hole arrays arranged in triangles, squares, rectangles and circles with the same thickness, aperture and period, and the results shows that scattering is affected by the arrangement of hole array. This will have certain potential significance to design metal dielectric structure properly for improving the absorption rate of photovoltaic devices.

1. Introduction
Photovoltaics technology, which converts the sunlight directly into electrical energy without emitting carbon dioxide [1], is generally considered to be a promising alternative technology that can solve the energy problems faced by modern society. However, for photovoltaic technology to compete with fossil fuel technology and gain widespread adoption, the key issue is to improve the efficiency of solar energy conversion while reducing the manufacturing costs. At present, the cost of solar cells mainly depends on the material (silicon) and processing technology. As a result, thin-film solar cells, especially monocrystalline silicon cells, which can be deposited on inexpensive substrates such as glass and plastic to further reduce the material costs, have attracted a lot of attention. The substantial reduction in production consumable also allows large-scale use of a few semiconductor materials, such as indium and tellurium which are scarce in Earth’s crust, to improve the performance of solar cells. However, the reduction in thickness inevitably reduces its ability to absorb incident photons, especially for the indirect band gap semiconductor silicon, whose near-band gap light absorption is very small. Therefore, for thin-film solar cell, it appears to be particularly important to increase the light absorption rate. And when the thickness is less than 1μm, usual methods such as surface texturing is no longer applicable. For this reason, various methods have been proposed to extend the path of photons through the absorption layer so as to increase the absorption rate. These methods include surface grating [2], photonic crystal [3, 4], antireflection coating [5,6], and moth-eye nanostructure [7].

The emergence of a large number of tools that can be used for nanoscale manufacturing and nanophotonics characterization, as well as powerful and efficient electromagnetic simulation methods, has greatly promoted people’s understanding and utilization of plasmon excitation. Nowadays, the plasmonics has rapidly expanded into a new filed of materials and device research [8]. For thin-film
solar cells, the use of metal nanostructures is an effective new method to enhance light capture. Proper engineering design of the metal nanostructure can concentrate light and fold it into a thin semiconductor layer, which result in the enhancement of light capture. A lot of research and optimization has been carried out on the parameters of metal nanostructure such as material, shape, size, surface coverage, local dielectric environment, and how to conduct the electrical design of solar cell [9-12]. In addition, due to the Fabry-Perot interference effect [13, 14], the thickness is also an important external factor affecting the performance of solar cells. Therefore, the key issue to improve the performance of solar cells is how to select these parameters correctly. In recent years, various metal gratings with sub-wavelength microstructures, such as one-dimensional periodic arrays of slits [15–18] and two-dimensional periodic arrays of holes with different shapes [19–21] have been extensively studied. However, the arrangement of periodic arrays, such as triangular, rectangular, and circular, is rarely discussed. In this article, we mainly analyze the scattering of Au circular hole arrays arranged in triangles, squares, rectangles and circles with the same thickness, aperture and period, and discuss the influence of the array distribution on the scattering. This will have certain potential significance for improving the absorption rate of photovoltaic devices, reducing the thickness of the photovoltaic absorption layer, and providing a new option for the design of high-efficiency solar cell.

2. Model and simulation
A gold film of thickness 30 nm centered at $z = 0$ is perforated with circular hole array in different arrangements, as indicated in figure 1, (a) is circular hole array structure arranged in equilateral triangle; (b) is square-arranged circular hole array structure; (c) is circular hole array structure arranged in rectangular; (d) is circular hole array structure. The radius of the circular hole is $r$, the distance $d$ between adjacent circular holes is 800 nm, and the long side $d'$ of the rectangular arrangement in the figure 1(c) is 1200 nm. The surrounding medium is the air with the permittivity $\varepsilon_0$ and the permeability $\mu_0$. A plane wave is incident on the metal plane along the positive direction of the $z$ axis. Then we simulate the scattering of four kinds of circular hole arrays with different radius, including the distribution of transmitted field, and the reflectivity, transmittance, and absorptivity varying with incident wavelength.

Figure 1. Circular hole array structure with different arrangements in $xy$ plane. (a) Circular hole array structure arranged in equilateral triangle; (b) Square-arranged circular hole array structure; (c) Rectangular arrangement of circular hole array structure; (d) Circular hole array structure.

Figure 2 shows the distribution of transmitted electric field of gold circular arrays with different arrangements. Here, for simplicity, we only consider one period in the periodic structure, that is, only the area of one unit centered on the circular hole is considered. And, we can clearly see the difference in the electric field intensity distribution. The upper left corner of the figure 2 is the distribution of transmitted electric field of the gold circular hole array arranged in triangle, corresponding to the (a) in figure 1. The electric field is at its weakest in the center of the hole. Around the hole, the electric field changes periodically. The upper right corner of the figure 2 is the distribution of transmitted electric field of the gold circular hole array arranged in a square, corresponding to the figure 1 (b). Similarly, the electric field is the weakest in the center of the circular hole. The lower left corner of the figure 2
indicates the distribution of the transmitted field of the gold circular hole array arranged in a rectangle, corresponding to the figure 1 (c). In particular, the electric field at the center is stronger, and the electric field around the hole is weakened. The lower right corner of the figure 2 indicates the distribution of transmitted electric field of hole array arranged in a circle, corresponding to the diagram (d) in Figure 1. Obviously, the electric field gradually decreases from the outside to the inside.

Figure 2. Distribution of transmitted electric field of gold circular arrays with different arrangements. The radius of the circular hole \( r \) is 300nm. (a) triangle; (b) square; (c) rectangle; (d) circle.

Figure 3 shows the variation of reflectivity, transmittance and absorptivity of the gold circular array versus the incident wavelength. The range of wavelength is from 0.2 micron to 1 micron. The radius of circular hole is 300 nm, and thickness of the film is 30 nm. As shown in this figure, the four curves with different colors correspond to the array structure with four arrangement ways. When the wavelength is in the range of 0.2 micron to 0.55 micron, the reflectivity and absorptivity of the metal array structure increases in the order of triangle, square and rectangle, while the transmissibility changes in the opposite way. In this range, the reflectivity, transmittance and absorptivity of the circular array structure are almost the same with the triangular array structure. As the incident wavelength is about 0.5 micron, the normalized reflectance of these four arrays are all at the trough, while the transmittances are all at the peak. Observing the distribution curves, it can be seen that, when the incident wavelength is about 0.7 microns, for the triangularly arranged metal array structure, the reflectivity reaches the maximum value, which is close to 0.8, and the transmittance reaches the minimum value, which is close to zero. Furthermore, depending on the arrangement, the number of peaks and troughs appearing on the reflectance and transmittance curves is also different. In the range of 0.2 micron to 1 micron, there are two distinct peaks and troughs on the curves of the rectangular...
array structure; On the other hand, there is only one obvious peak and trough on the curve of triangular array structure. As the wavelength is greater than 0.6, the reflectance, transmittance, and absorptivity of these four structures have no obvious laws, so further refinement is needed to study their changes.

Figure 3. The reflectance, transmittance and absorptivity of the gold circular array versus the wavelength. The radius of the circular hole $r$ is 300nm. The color of the curve corresponds to the array structure of the four arrangements.

3. Conclusion
Our results show that the arrangement of the array structure has a certain effect on reflectance, transmittance and absorptivity. As shown in the figure, in the range of 0.2 to 0.5, the reflectance and absorptivity increase in the order of triangle, square, and rectangle, and the change in transmittance is just the opposite. When the wavelength is near 0.7, the reflectance of the gold round hole array structure arranged in a triangle, square, and rectangle is at the peak, and the transmittance is at the trough. Therefore, it is necessary to consider the effect of array arrangement in order to increase the absorption rate of photovoltaic device and reduce the thickness of the solar photovoltaic absorption layer.

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References
[1] P. Würfel, Physics of Solar Cells: From Principles to New Concepts, Wiley VCH, 2005.
[2] K. Yu and J. Chen, Enhancing Solar Cell Efficiencies through 1-D Nanostructures, Nanoscale Res. Lett., 4: 1-10, 2009.

[3] L. Zeng, P. Bermel, Y. Yi, B. A. Alamariu, K. A. Broderick et al., Demonstration of enhanced absorption in thin film Si solar cells with textured photonic crystal back reflector, Appl. Phys. Lett., 93, 221105, 2008.

[4] A. Bielawny, J. Üpping, P. T. Miclea, R. B. Wehrspohn, C. Rockstuhl, F. Lederer, 3D photonic crystal intermediate reflector for micromorph thin-film tandem solar cell, Phys. Stat. Sol. (a), 205 (12), 2796-2810, 2008.

[5] Y. Wang, L. Chen, H. Yang, Q. Guo, W. D. Zhou, and M. Tao, Hemispherical Antireflection Coatings by Large Area Convective Assembly of Monolayer Silica Microspheres, Solar Energy Materials & Solar Cells, 93(1), 85-91, 2009.

[6] Y. Wang, R. Tummala, L. Q. Guo, W. D. Zhou and M. Tao, Solution-Processed Omnidirectional Antireflection Coatings on Amorphous Silicon Solar Cells, J. Appl. Phys. 105, 103501, 2009.

[7] J. Zhu, Z. Yu, G. F. Burkhard, C. Hsu, S. T. Connor, Y. Xu, Optical Absorption Enhancement in Amorphous Silicon Nanowire and Nanocone Arrays, Appl. Phys. Lett. 93, 221105, 2008.

[8] A. Polman, Plasmonics Applied. Science 322(5903), 868-869, 2008.

[9] S. Pillai, K. R. Catchpole, T. Trupke, and M. A. Green, Surface plasmon enhanced silicon solar cells, J. Appl. Phys. 101(9), 093105, 2007.

[10] K. R. Catchpole and A. Polman, Plasmonic solar cells, Optics express, 16(26), 21793, 2008.

[11] Yu. A. Akimov, K. Ostrikov and E. P. Li, Surface Plasmon Enhancement of Optical Absorption in Thin-Film Silicon Solar Cells, Plasmonics, 4(2), 107-113, 2009.

[12] Yu. A. Akimov, W. S. Koh, and K. Ostrikov, Enhancement of optical absorption in thin-film solar cells through the excitation of higher-order nanoparticle plasmon modes, Optics express 17(12), 10195, 2009.

[13] C. Rockstuhl and F. Lederer, Photon management by metallic nanodiscs in thin film solar cells, Appl. Phys. Lett. 94(21), 213102, 2009.

[14] K. R. Catchpole and S. Pillai, Absorption enhancement due to scattering by dipoles into silicon waveguides, J. Appl. Phys. 100(4), 044504, 2006.

[15] J. A. Porto, F. J. Garcia-Vidal, J. B. Pendry, Transmission Resonances on Metallic Gratings with Very Narrow Slits, Phys. Rev. Lett. 83(14), 2845-2848, 1999.

[16] K. G. Lee, Q. H. Park, Coupling of Surface Plasmon Polaritons and Light in Metallic Nanoslits, Phys. Rev. Lett. 95(10), 103902, 2005.

[17] Y. Xie, A. R. Zakharian, J. V. Moloney, M. Mansuripur, Transmission of light through a periodic array of slits in a thick metallic film, Opt. Express 13(12), 4485, 2005.

[18] B. Hu, B. Y. Gu, B. Z. Dong, Y. Zhang, Optical transmission resonances tuned by external static magnetic field in an n-doped semiconductor grating with subwavelength slits, Opt. Commun. 281(24), 6120-6123, 2008.

[19] H. F. Ghaemi, T. Thio, D. E. Grupp, T. W. Ebbesen, H. J. Lezec, Surface plasmons enhance optical transmission through subwavelength holes, Phys. Rev. B, 58(11), 6779-6782, 1998.

[20] K. J. K. Koerkamp, S. Enoch, F. B. Segerink, N. F. van Hulst, L. Kuipers, Strong Influence of Hole Shape on Extraordinary Transmission through Periodic Arrays of Subwavelength Holes, Phys. Rev. Lett. 92(18), 183901, 2004.

[21] A. Mary, S. G. Rodrigo, L. Martin-Moreno, F. J. García-Vidal, Theory of light transmission through an array of rectangular holes, Phys. Rev. B, 76(19), 195414, 2007.