Optimization of Nano-grating Structure to Reduce the Reflection Losses in GaAs Solar Cells

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***Abstract*— In this paper, finite-difference time domain (FDTD) method is used to simulate the reflection losses of subwavelength grating (SWG) structure in GaAs solar cells. The SWG structures make an excellent alternative antireflective (AR) coating due to its capacity to reduce the reflection losses in GaAs solar cells. The SWG structures allow the gradual change in refractive index that confirm excellent AR and light trapping properties, when compare with planar thin film structures. The nanorod (nano-grating) structure acts as a single layer AR coating, whereas the triangular (conical or perfect cone) and parabolic (or truncated cone) shaped grating structures act as a multilayer AR coating. Simulation results show that the reflection loss of triangular (conical or perfect cone) shaped nano-grating structure having a 300 nm grating height and a 830 nm period is ~2%, which is about 28% less than that of flat type substrates.**

***Index Terms*— Subwavelength grating (SWG), triangular or conical shaped grating, nano-structures, solar cells, reflection loss, FDTD simulation.**

I. Introduction

Subwavelength grating (SWG) structures have been identified as promising candidate for realising high conversion efficiency in solar (photovoltaics) cells due to their low reflection losses. If the pitch (or period) of a single grating structure is less than the wavelength of the incident light, it behaves like a homogeneous medium with an effective refractive index [1]. Therefore, the SWG structures provide gradual changes in refractive index that ensure an excellent antireflective and light trapping properties compared to a planar or flat type thin film [1-2]. This type of nanorod (or nano-grating) structure acts as a single layer antireflective (AR) coating, whereas the triangular (or conical) and parabolic shaped nano-grating structures act as a multilayer broadband AR coating [3-4].

As reserves of fossil fuels are used up, then need to find an alternative source of energy. The solar, hydroelectric, wind and biomass are considered as renewable energy sources that can be used in a wide range of applications from heating water and generating electricity to telecommunications and transportation, etc. Renewable energy is a clean energy being environmentally friendly. Therefore, the solar cell is a very important area of research area for the generation of renewable or green energy. The solar cell was discovered in the nineteenth century and since then scientists and researchers have been trying to improve its conversion efficiency which is currently 20.3% for the best reported silicon solar cells [5].

There are various types of losses in solar cell that always reduces the conversion efficiency of solar cells. Reflection loss is one of the most important factor that reduces or influences on the conversion efficiency of solar cells. The thin-film anti-reflection coating can minimize the reflection losses only for certain wavelengths and the formation of coating film can be a complex process as well as it has some other drawbacks, such as adhesion and thermal mismatch etc. and instability under thermal cycling [2, 4]. Therefore, the SWG structure (especially, triangular or conical shaped) cause a gradual change in refractive index that lead to a lower reflection losses over a wide range of wavelengths and angles of incidence [2, 4, 6-9].

In this paper, finite-difference time domain (FDTD) method is used to simulate the reflection losses for different types of nano-grating structures. The nano-grating profiles are rectangular and triangular (conical or perfect cone) shaped. From simulation results, an optimum nano-grating height and pitch (or period) for the SWG structures were obtained. If the nano-grating structure has a shorter pitch (or period) than the wavelength of the incident light, it acts as a homogeneous medium with an effective refractive index. The reflection loss more than 30% for a rectangular-shaped SWG structure, however, for a triangular (conical or perfect cone) shaped SWG structure, the refractive index changes gradually in several steps, finally the reflection loss becomes ~2%. However, the intermediate structures (trapezoidal or truncated cone and parabolic shaped), the reflection is lower than the rectangular shaped SWG structure but higher than the triangular (conical or perfect cone) shaped SWG structure. This reduction of reflection losses in solar cell confirms the increase of the efficiency in solar cells. The optimized SWG structures confirm that the reflection loss is ~2%, which is ~28% less than that of a flat type substrate or a rectangular shaped grating structure.

II. Antireflective Coating and SWG Structure

A) Antireflection Coating

The efficiency of a solar cell can be increased by using an anti-reflection coating that reduces the light reflection losses only for certain wavelengths (such as, IR, Visible UV gives good performance). Minimum reflectance can be achieved when the refractive index equates to the square root of the refractive indices of two medium [2]. The strength of the light reflection depends on the refractive indices of both media and the angle of the surface to the beam of light.

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Fig. 1 shows the reflection and transmission of a glass substrate with a thin film coating. Here, the light is travelling from air into a common glass substrate (upper portion). The intensity of the incident light is I, reflected light is R.I, and transmitted light is T.I. But when a thin film coating is applied on the glass substrate then it reduces the reflection of light. In this case, I is the incident light on the coating, R_{01} is the reflected light at the interface of air and thin film coating, and transmittance light is $T_{01}I$. The incident light at the coating and glass interface is $T_{01}I$, transmittance light is $T_{1s}T_{01}I$ and reflectance light is $R_{1s}T_{01}I$ (as shown in Fig. 1).

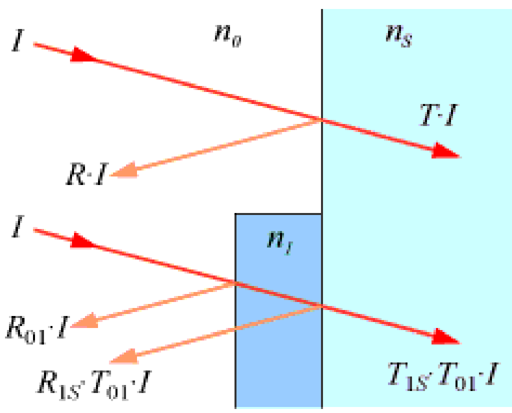


Fig. 1. Light reflection of a glass substrate (upper portion) is reduced by using a thin film on the glass substrate (lower portion).

The percentage of light reflection can be calculated by using Fresnel equations,

$$R = \left(\frac{n_0 - n_s}{n_0 + n_s} \right)^2 \qquad (1)$$

where, R is the reflection co-efficient or reflectance, n_0 is the refractive index of the first media (air), and n_s is refractive index of the second media (glass substrate).

For such a case, if visible light is travelling from the first media (i.e., air, $n_0 = 1.0$) into the second media (i.e., a common glass substrate, $n_s = 1.5$), the value of R (i.e., light reflection) is 4%. However, when a thin film is added on the glass, it reduces the reflection loss. Then, the new optimum refractive index, $n_1 = \sqrt{(n_0 n_s)} = \sqrt{(1.0*1.5)} = 1.225$. The reflection loss of each interface is 1%. i.e., the total reflection is 2%. It was calculated that an intermediate coating between the air and the glass can reduce the reflection losses by half (about 50%). However, the formation of a coating film can be a complex process and there are some drawbacks, such as adhesion, thermal mismatch and instability under thermal cycling [2, 4].

B) Moth's-eye Principle

The surface of a moth's eyes is covered with nano-structured film that absorbs the light instead of reflecting back it (as shown in Fig. 2). The nano-structured film consists of a hexagonal pattern bump ~200 nm high, which acts as an antireflective coating; this is because the bumps are smaller than the wavelength of visible light. The refractive index between the air and the surface changes gradually and this gradual change of refractive index decreases the light reflection. This model is suitable for solar cells to reduce the reflection losses and increase the conversion efficiency [6].

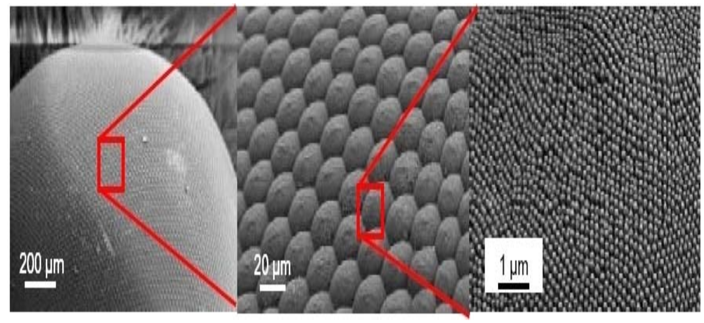


Fig. 2. Moth-eyes covered by the nano-structured film.

C) Sub-wavelength grating structure (SWG)

The subwavelength features cause a gradual change in refractive index which acts as a multilayer anti-reflective coating leading to low reflection over broadband ranges of wavelength and angle of incidence. Fig. 3 shows the gradual change of the SWG structure as well as refractive index leading to the low reflection. The nanorod structure acts as a single layer AR coating whereas the triangular (or conical) shaped SWG structure acts as a multilayer AR coating [4].

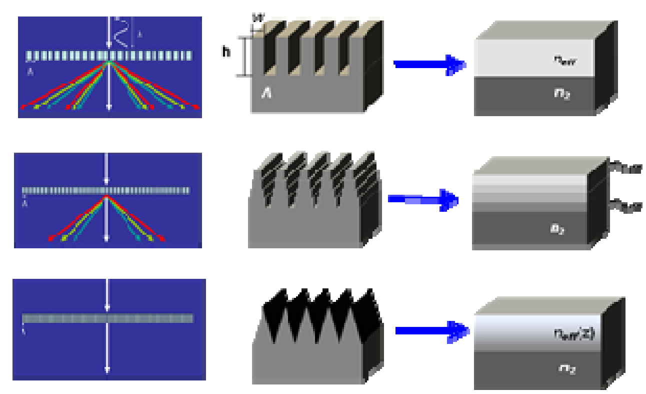


Fig. 3. Light reflection of different nano-grating shapes: such as, a rectangular (top), trapezoidal (middle) and triangular or conical (bottom) shaped SWG structures.

AR coating is an optical coating that is applied to the surface of lenses or other optical devices to reduce the reflection. The coating increases the efficiency of optical devices or lenses. Optimum reflection can be obtained when the refractive index equates to the square root of the refractive indices of two medium [2]. Multilayer AR coatings can increase the efficiency of solar cells. However, formation of coating film can be a complex process and there are some drawbacks, such as adhesion and thermal mismatch etc. and instability under thermal cycling [1-2].

The idea of SWG structures has been adopted from moths' eyes. The surface of a moths' eye is covered with nano-structured film that absorbs most of the incident light instead of reflecting. The nano-structured film consists of a hexagonal pattern bump which is 200 nm high. This acts as an AR coating, because the bumps are smaller than the wavelength of the visible light. The refractive index between the air and the surface changes gradually and that decreases the reflection of light. This model is being applied in solar cells to increase the cell conversion efficiency [2].

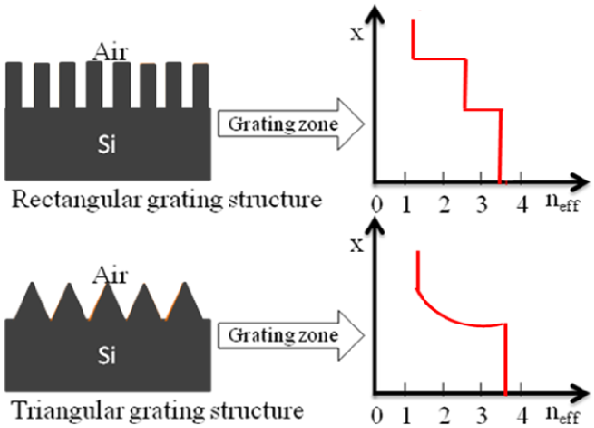


Fig. 4. Nano-structured grating geometry of rectangular (or flat type) and triangular (or conical) shaped profile and the plot of SWG height versus the effective refractive index (n) for a silicon (Si) substrate.

Figure 4 shows the nano-grating geometry of rectangular and triangular shaped profile and the plot of SWG height versus the effective refractive index (n) for silicon (Si) substrate [9]. It shows that for a rectangular-shaped SWG structure, the refractive index changes very sharply from air (n = 1.0) to the grating zone or structure (approximately 2.5 at TM mode) [1]. The reflection loss of a SWG structure can be calculated easily using Freshnell's equation (which is similar to equation (1)),

$$R = \left(\frac{n_2 - n_1}{n_2 + n_1} \right)^2 \quad (2)$$

where, n_1 is the refractive index of first medium and n_2 is the refractive index of second medium.

From Fig. 4, the total reflection of the grating structure can be calculated using the following equation,

$$R_{total} = R_1 + R_2 \quad (3)$$

where, R_1 is the reflection at the interface of the air and the grating structure and R_2 is the reflection at the interface of the grating structure and the substrate.

If the grating structure has a shorter pitch (or period) than the wavelength of the incident light, it acts as a homogeneous medium with an effective refractive index [1]. According to the Fig. 4, the calculated reflection loss is more than 20.2% for a rectangular-shaped grating structure [1]. In the triangular (or conical) shaped SWG structure, the refractive index changes gradually in several steps, the reflection becomes less than 8% [1]. In the parabolic structure, the reflection is lower than the rectangular shaped grating structure but higher than that the triangular shaped grating structure (~5%) [8].

III. Design of Nano-Grating Structures

In this section, discuss about the shape design and modeling of the nano-structured gratings (i.e., SWG structures). The modeled nanostructured gratings are: (i) rectangular-shaped nano-grating profile (as shown in Fig. 5(a)), (ii) trapezoidal-shaped nano-grating profile with different aspect ratios (i.e., 0.1 ~ 0.9), and (iii) triangular-shaped nano-grating profile (as shown in Fig. 5(b)). Here, we discussed only the rectangular and triangular shaped nano-gratings as shown in Fig. 5(a) and 5(b), respectively. For trapezoidal shaped nano-grating profile, the aspect ratio is defined as the ratios between the trapezoid-top and base lengths [3, 7]. For the rectangular-shaped nano-grating profile, the aspect ratio is '1' (i.e., the top and base length of the trapezoid is same or equal) and for the trangular-shaped nano-grating profile, the aspect ratio is '0' (i.e., the top length of the trapezoid is zero compared to the base length of the trapezoid). These shapes are used for the simulation and analyzed the results for light reflection, transmission and absorption for the SWG structures [3, 7].

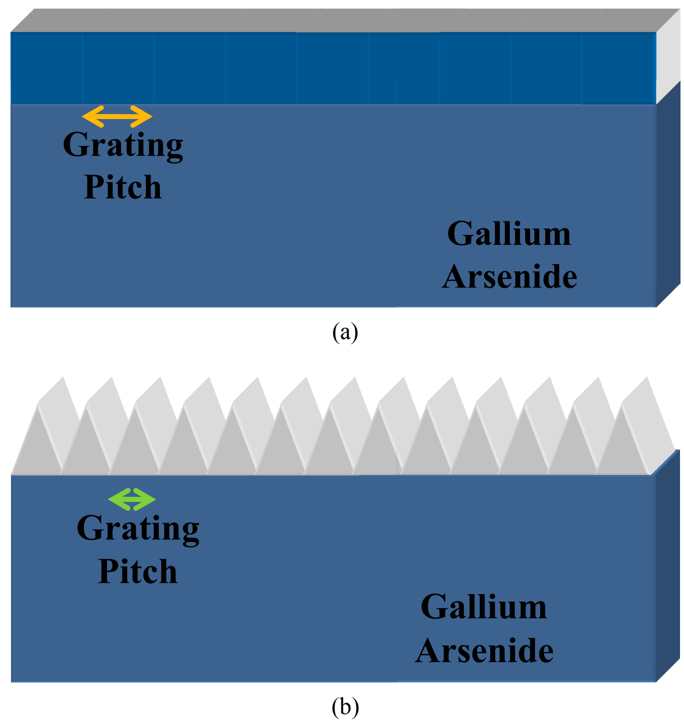


Fig. 5. Nanograting profile for the simulation of light reflection, transmission and absorption of solar cells, (a) Rectangular-shaped nano-grating profile and (b) Triangular (or conical) shaped nano-grating profile. Here, the substrate is Gallium Arsenide (GaAs).

IV. Results and Discussions

In this section, simulation results of SWG structures and reflection losses are discussed. The simulation results carried out using OptiFDTD software package, which is based on the FDTD method that developed by Optiwave Inc. [10]. This method is a powerful engineering tool for integrated and deffractive optics device simulations. Light propagation, scattering and diffraction, reflection and polarization effects can be simulated by this method. This software gives numerical solutions by using Maxwell's equation.

Fig. 6 shows a simple schematic diagram for the simulation of triangular (or conical) shaped SWG structure of Galium Arsanide (GaAs). The incident light directly hits on top of the SWG structure (or nano-structure). A major portion of light is absorbed by the grating zone (triangular shaped nano-gratings) due to the gradual change of refractive index in the grating zone, some portion of the light is reflected and the remaining portion of the light is transmitted through the GaAs substrate.

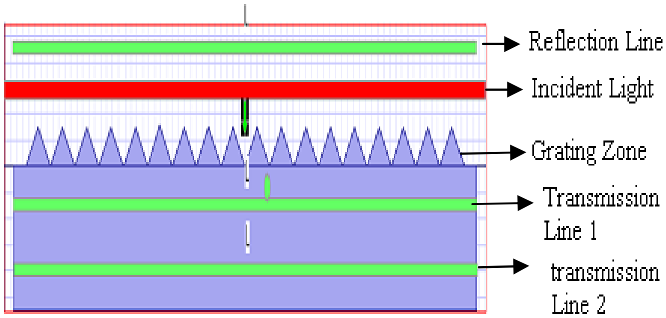
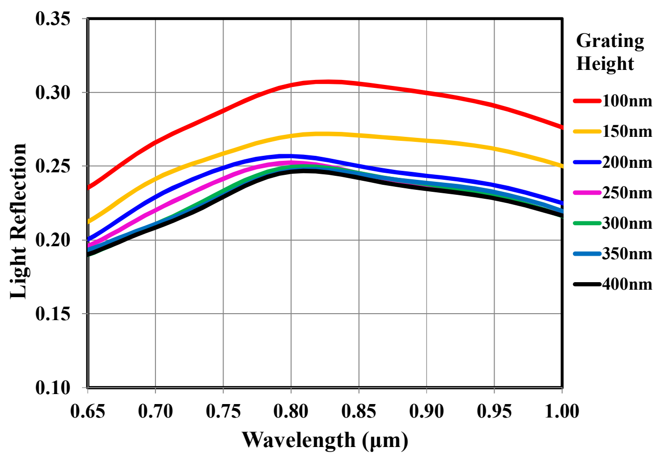
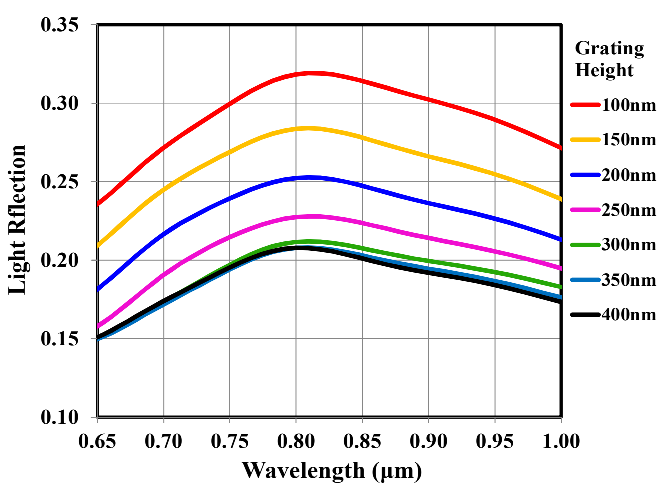


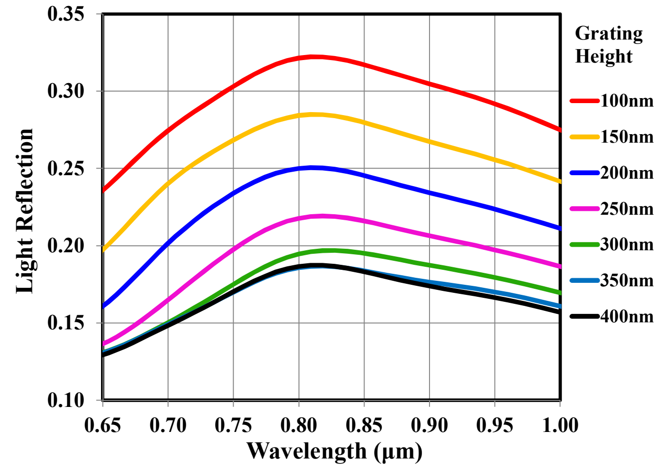
Fig. 6. A simple schematic diagram of triangular (or conical) shaped nano-grating (such as, SWG) structure. The top red line represents an incident light source (i.e., incident light that directly hits on the grating zone), uper green line respresents the reflection line that can detect the reflected light and both the lower green lines (inside the substrates) represents the transmission lines (i.e., transmission line 1 & transmission line 2).



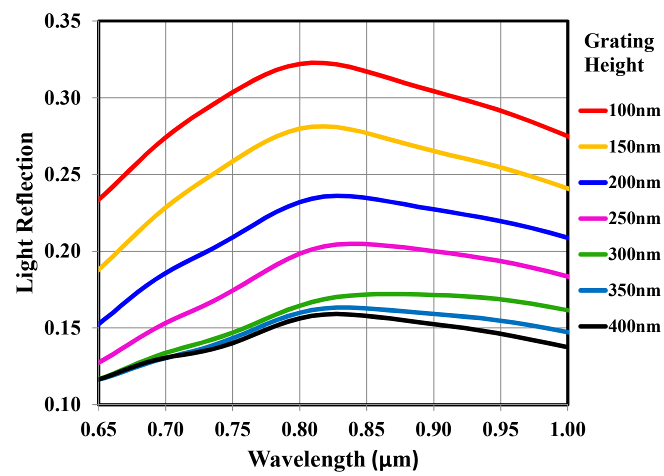
(a)Triangular (or conical) shaped nano-grating with pitch 200 nm.



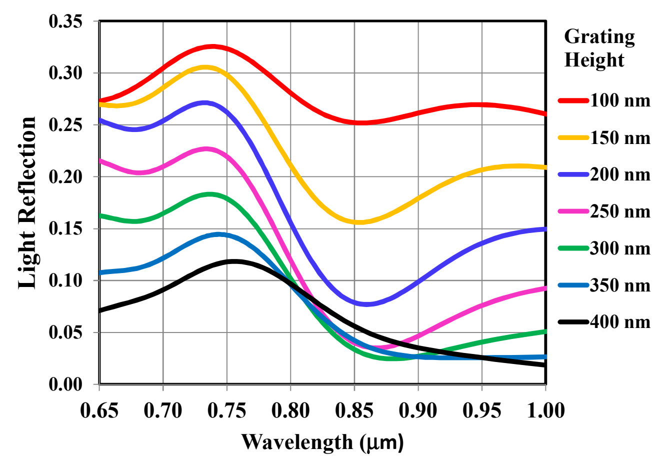
(b) Triangular (or conical) shaped nano-grating with pitch 300 nm.



(c) Triangular (or conical) shaped nano-grating with pitch 350 nm.



(d) Triangular (or conical) shaped nano-grating with pitch 400 nm.



(e) Triangular (or conical) shaped nano-grating with pitch 830 nm.

Fig. 7. Light reflection spectra for several nano-grating heights with different pitch (or period). The periods are: (a) 200 nm, (b) 300 nm, (c) 350 nm, (d) 400 nm, and (e) 830 nm. The incident light wavelength is kept constant at 830 nm.

The FDTD method is used to simulate the reflection losses on the SWG structures for high efficiency GaAs solar cells. The nano-grating pitch (or period) and height of the SWG structures were varied to achieve the minimum reflection losses in GaAs solar cells. Fig. 7 shows the light reflection losses spectra for several nano-grating heights (such as, the heights are from 100 nm to 400 nm) with different pitches (or periods). The pitches or periods are: (a) 200 nm, (b) 300 nm, (c) 350 nm, (d) 400 nm, and (e) 830 nm. For this simulation, the incident light wavelength is kept constant at 830 nm. The simulated results show that with the increase of nano-grating heifhts the light reflection reduces and reached to the satiuration of light reflection at 300 nm. The simulated results show that when the nano-grating height is ~300 nm the reflection loss is minimum. It has also observed that the light refeletion for 300 nm and 350 nm grating height is very close. This nano-grating height for light relectrion is is minimum and it is saturated, which is the similar tendency as reported [3]. When the nano-grating height inctreases further, such as 400 nm, the ligth reflection is increases.

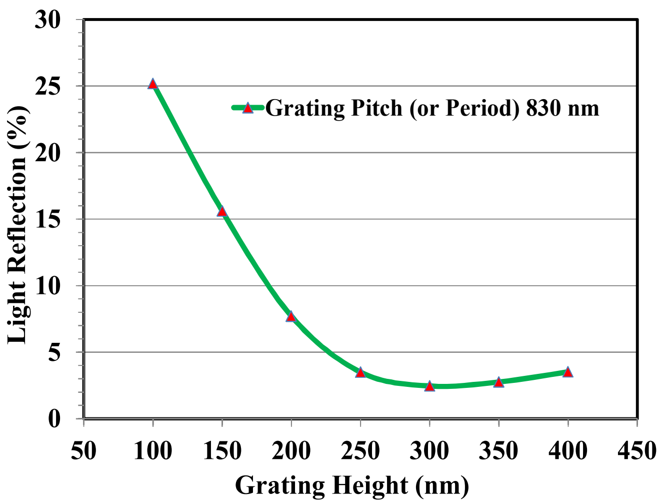


Fig. 8. Light reflection versus grating height characteristics when the grating pitch or period is kept constant at 830 nm.

Figure 8 shows the simulated light reflection versus the nano-grating height characteristics for a triangular (conical or perfect cone) shaped nano-grating structure of GaAs, having a constant period at 830 nm. The minimum reflection loss (~2%) was observed at 300 nm nano-grating height. However, when the nano-grating height is increased to 350 nm and 400 nm, then the reflection loss increases further to higher order direction. So, it indicates that the nano-grating height about 300 nm has the minimum refelection loss for the GaAs substrate. It confirms that the nano-grating height ~300 nm is the optimum nano-grating height for the minimum reflection loss of GaAs solar cells.

V. CONCLUSION

This paper presented that the light reflection is ~2%, with the optimum nano-grating height of ~300 nm and nano-grating period of ~830 nm, which is ~28% lower than that of flat type substrates. The light reflection was calculated by using the FDTD method. The simulated sresults show that the light reflection of a rectangular-shaped grating structure is ~30%, however, the light reflection becomes ~2% for a triangular (conical or perfect cone) shaped nano-grating structure, because the refractive index changes gradually in several steps and reduces the light reflection losses. It also noticed that the intermediate structures (trapezoidal and parabolic shaped), the light reflection loss is lower than the rectangular shaped nano-grating structure but higher than the triangular shaped nano-grating structure. The simulated results confirm that the reduction of light reflection losses in solar cell will increase the conversion efficiency of GaAs solar cells. Therefore, it is confirmed that the triangular (or conical) shaped nano-grating structures are an excellent alternative AR coating for the high efficiency GaAs solar cells.

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