Design and Simulation of Dual band metamaterial absorber for single junction solar cells

Victor Du John. H, Jackuline Moni. D, Sneha Ann Philip, Joicey Elezabeth Sam, Berachah J

Abstract: - In this work, a metamaterial absorber is designed with the concept of step impedance resonator (SIR) structure for solar cell applications. The rate of absorption can be improved with the use of metamaterial. The designing concept of the metamaterial and the medium is very important when more efficient properties are needed. This proposed design has the capability to increase the absorption rate over a range of frequency 470THz to 570THz and getting the peak absorption at 520THz. This is a unit cell, consists of three layers, which is the substrate, the intrinsic material and also it consists of the top conducting layer which is filled with other materials. The metamaterial absorber is designed and its parametric study is done in the overall range of frequency 450THz to 750THz with various dimensions and filling materials. The materials like silicon dioxide (SiO2), gallium arsenide (GaAs) and aluminium nitride (AlN) are used as the filling materials with the top conducting layer as it is designed in such a way that can provide better absorption rate. And the variations are represented with the help of absorption and reflection parameters.

Index Terms: Absorber, Energy harvesting, Metamaterial (MTM), Solar cell.

I. INTRODUCTION

The use of energy provided by fossil fuels has increased widely and which results in the instability of the ecosystem. Due to which, the pollution emitted from such source causes global warming and also affected mankind and many animal species [2]. Fewer amounts of fossil fuels will be a dramatic issue for a future generation. So, it is very important to reduce the usage of such energy sources. Then the alternative renewable energies got more attention and one such promising renewable energy is the solar energy which is from the sun. This photovoltaic energy is nontoxic and it is cost effective. It does not contain any fluids and gasses and also it can operate at a moderate temperature [4]. There are many advantages with solar energy, since it is abundant in nature, clean, cheap and non-exhaustible. And also the sun can provide enough energy for the entire world if we are using the right method to fetch it. We know the fact that light is energy. The light from the solar cell is made out of different colors so that together forms a white color [1]. The solar spectrum usually ranges from IR to UV range, but the intensity won't be uniform. Some part of the light spectrum will get attenuated by the atmosphere, so the direct sunlight will not incident on the atmosphere. The light incident on the solar cell will get converted into electrical energy.

The process of converting light energy into electrical energy can be considered as a phenomenon called the photovoltaic effect. The photovoltaic cells are actually an electrical and semiconductor device, which consist of both N-type and P-type materials [3]. So that both electrons and holes are present. Usually, the N regions are doped heavily and this region will be very thin to make easy penetration of light. The light, which is energy falls on the photovoltaic cell, will knock the electrons and then the electrons will get energized. As a result, this will make the negatively charged atomic particles free and create electron-hole pairs in the depletion region. The energized electrons will shift from the valence band to the conduction band or from the lower energy state to the higher energy state. The mobility of the electrons mainly depends on the photon energy [3]. The photon energy can be represented as Eph. In between the valence band and the conduction band, there is a gap, which is called a band gap. This band gap is actually the difference of energy in between the lower part of the conduction band and the top part of the valence band. If the photon energy is greater than the band gap energy, then the electrons can easily shift from the valence band to the conduction band [5]. This mobility of electrons will result in the flow of current and the energy can be harvested. It is very important to absorb maximum light in order to create more electron-hole pairs. For the maximum absorption of light, the good absorber can be designed and an anti-reflective coating can be applied. In terms of absorption, the photon energy, and band gap energy play a major role. More light can be absorbed only if the energy of a photon is much higher than the energy between the valence band and the conduction band. The light absorption should do in the active region, which is near the band gap region. When the photon energy is much lower than the energy between the valence band and the conduction band, then the interaction level with the semiconductor may be weak [5]. When the energy of photon and the band gap energy are equal, then the absorption will be efficient. The optical loss will come into consideration when the light incident on the solar cell surface has a higher reflection [6]. This optical loss can make a restriction for solar cell efficiency.

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When the absorption level is enhanced, then the efficiency can be improved. The solar cell performance is also depending on the recombination rate, which can reduce the current that can be harvested from the cell. The main factors which provide losses in the solar cell include heat loss, loss with reflection and recombination losses [5]. The rate of absorption can be improved with the use of metamaterial. Metamaterial are actually artificial materials which are not found in nature. These materials are engineered to add up some more properties of the material. These metamaterials are considered for implementing in solar cell applications to get maximum absorption parameters [7]. Metamaterials are man-made with negative permittivity (ε) and negative permeability (μ), which can give many changes to the materials. By the geometrical properties like size and shape can provide many properties to the metamaterial by just varying its dimensions. The designing concept of the metamaterial and the medium is very important when more efficient properties are needed [9]. With the metamaterials, it is possible to improve the absorption rate and it can boost the efficiency of the solar cell [8]. Unlike natural materials, metamaterials can show magnetic responses at high frequencies [15].

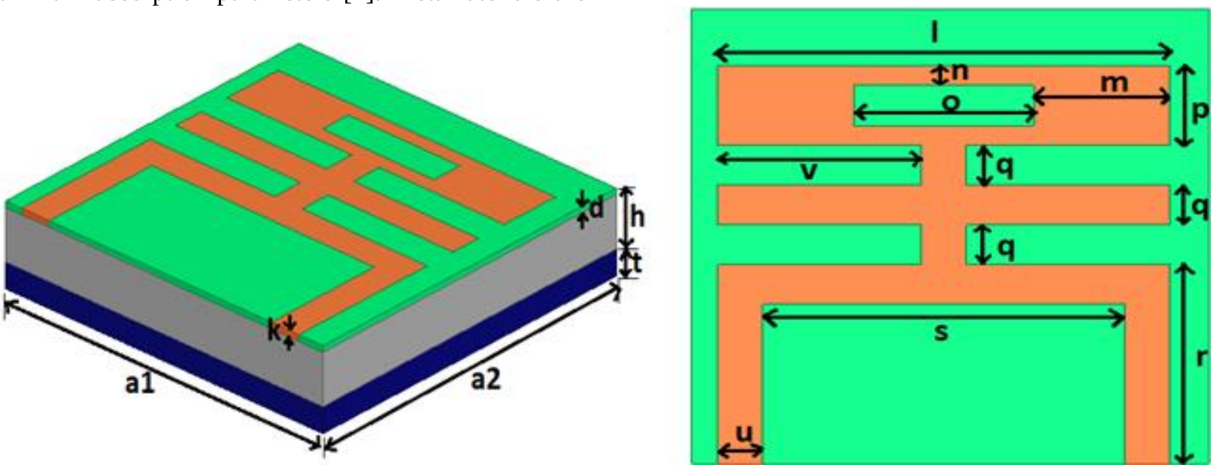

Fig. 1 – Proposed MTM Structure for solar cell absorber

II. PROPOSED DEVICE STRUCTURE

The designed absorber with the metamaterial is shown in fig. 1. This is a unit cell, which consists of three layers, which is the substrate and the intrinsic material and also it consists of the top conducting layer which is filled with other material. The material used for the bottom layer is the silicon; it has a relative permittivity of 11.9, the relative permeability of 1 and a mass density of 2330. The material above the silicon, which is the intrinsic layer is the Gallium Arsenide which consists of the relative permittivity of 12.9, the relative permeability of 1 and mass density of 53290. The top conducting layer is designed with the metamaterials, which provide a high rate of absorption. In this proposed design, gold and silver are used. For Gold, the relative permittivity is 1, the relative permeability is 0.99996 and mass density is 19300. And for the silver, the relative permittivity is 1 and relative permeability is 0.99998 and mass density is 10500. The region between the intrinsic layer gallium arsenide and the top conducting layer is filled with a material. In this paper, as the filling material, three materials are used. They are Silicon dioxide ($SiO2$), Gallium Arsenide (GaAs) and Aluminium Nitride (AlN). The coefficient of absorption A (ω) always rely on the parameter of transmission T (ω) and parameter of reflection R (ω). These parameters can be calculated with the scattering parameters. It can be represented mathematically as given in the equations 1-6. [13].

Table 1: Dimension of the designed metamaterial absorber in nm

Top conducting layer	l	m	n	o	p	q	r	s	u	v
Dimensions (nm)	350	105	17.5	140	70	35	175	280	35	157.5

Table 2: Dimension of the designed metamaterial absorber in nm

Top conducting layer	a1	a2	d	h	k	t
Dimensions (nm)	400	400	5	50	5	25

$$A(\omega) = (1 - R(\omega) - T(\omega) \quad (1)$$

$$S_{11}(\omega) = \frac{\sqrt{Power\ reflected\ from\ port1}}{\sqrt{Power\ incident\ on\ port\ 1}} \quad (2)$$

$$S_{12}(\omega) = \frac{\sqrt{Power\ delivered\ to\ port\ 2}}{\sqrt{Power\ incident\ on\ port\ 1}} \quad (3)$$

$$R(\omega) = S_{11}(\omega)^2 \quad (4)$$

$$T(\omega) = S12(\omega)^2 \quad (5)$$

$$A(\omega) = (1 - |S11(\omega)|^2 - |S12(\omega)|^2) \quad (6)$$

III. PARAMETRIC STUDY

The unit cell of the metamaterial absorber is designed in the software called Ansys HFSS. It is actually software for the simulation of high-frequency electromagnetic structures. The bottom layer is silicon, the intrinsic layer is gallium arsenide, the filling in the top layer is chosen randomly as silicon dioxide, gallium arsenide, and aluminium nitride and the top conducting layer is silver or gold. The analysis is prepared and illustrated in the following departments.

Analysis done with varying dimensions:

The variations in each dimension will give out different absorption level with respect to the assigned material. For the result with a higher absorption rate will be the optimized output. With various dimensions (400nm×400nm, 450nm×450nm, and 500nm × 500nm) AlN is filled in the top conducting layer. Silver and gold materials are delegated to the top conducting layer. Figure 2 and Figure 3 represents the result for gold and silver conducting layer respectively **[12]**. From the above analysis, the absorption is at peak level for 400nm×400nm with top conducting layer as silver. So for the further analysis 400nm×400nm dimension is considered.

Variation based on the thickness of the top conducting layer

The thickness of the top conducting layer for the proposed model is varied as 2.5nm, 5nm, 7.5nm, and 10nm for the dimension 400×400.

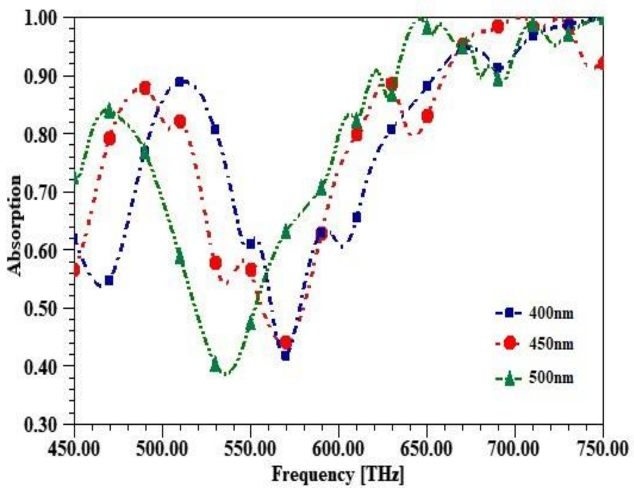

Fig.2 With various dimensions (400×400, 450×450, 500×500) Al_N is filled in the top conducting layer (Gold).

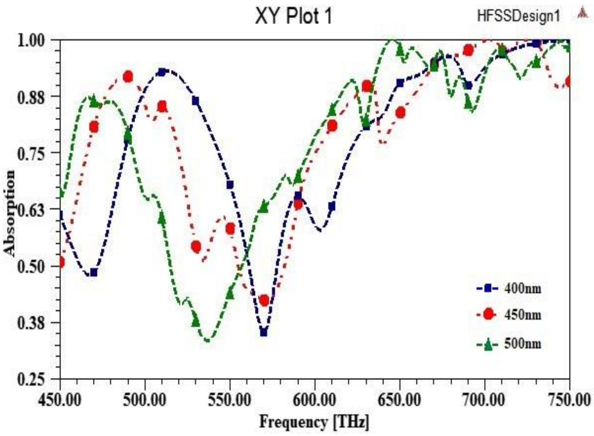

Fig.3 With various dimensions (400nm×400nm, 450nm×450nm, 500nm×500nm) Al_N is filled in the top conducting layer (Silver)

In this model, the design has three layers with a thickness of about 25nm for the bottom layer (Silicon), 50nm for the intrinsic layer (Gallium Arsenide), and the thickness of the filling material (Aluminium Arsenide) is varied with respect to the thickness of the top conducting layer (Silver). The thickness of the top conducting layer can be represented as "k". With this thickness, the variations are taken and illustrated in Figure 4. From the analysis, it is possible to observe that the absorption rate is more when the thickness of the top conducting layer is 5nm.

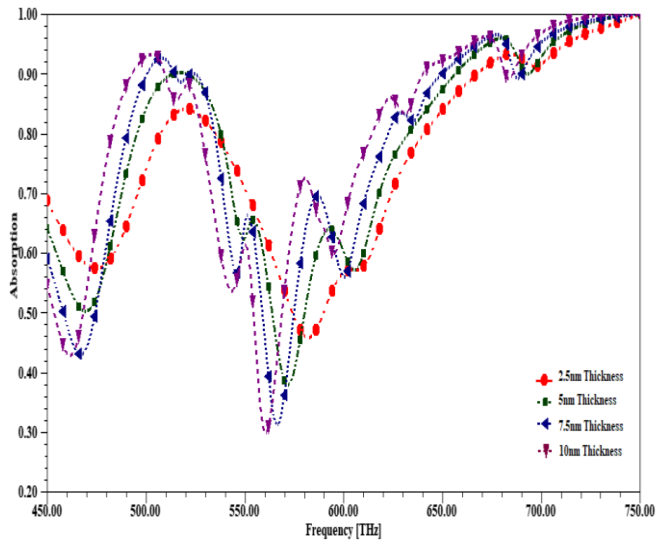

Fig.4 Analysis for absorption versus frequency, for the varying thickness of thetop conducting layer (k=2.5nm, 5nm, 7.5nm, and 10nm) in the dimension 400*400, with the dielectric material Aluminium Arsenide and Silver as top conducting layer.

Analysis for the designed metamaterial absorber based on the filling and top conducting layer.

The dimensions from 400nm to 500nm with step size 50nm is taken into consideration for the analysis. In 400nm×400nm dimension, the top conducting layer is given as silver for various filling materials like silicon dioxide, gallium arsenide, and aluminium nitride. Similarly, with the above filling material and dimension, the top conducting layer is given as gold. By varying the top conducting layer and the filling material, the absorption will vary accordingly **[12]**.

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A similar process is carried out for 450nm×450nm and 500nm×500nm with top conducting layer as silver and gold. The thickness of the bottom layer (25nm) and intrinsic layer (50nm) is not varying. In Fig 5, the absorption rate for 450nm×450nm is given. And the absorption rate for 500×500nm is given. The analysis is done and illustrated below.

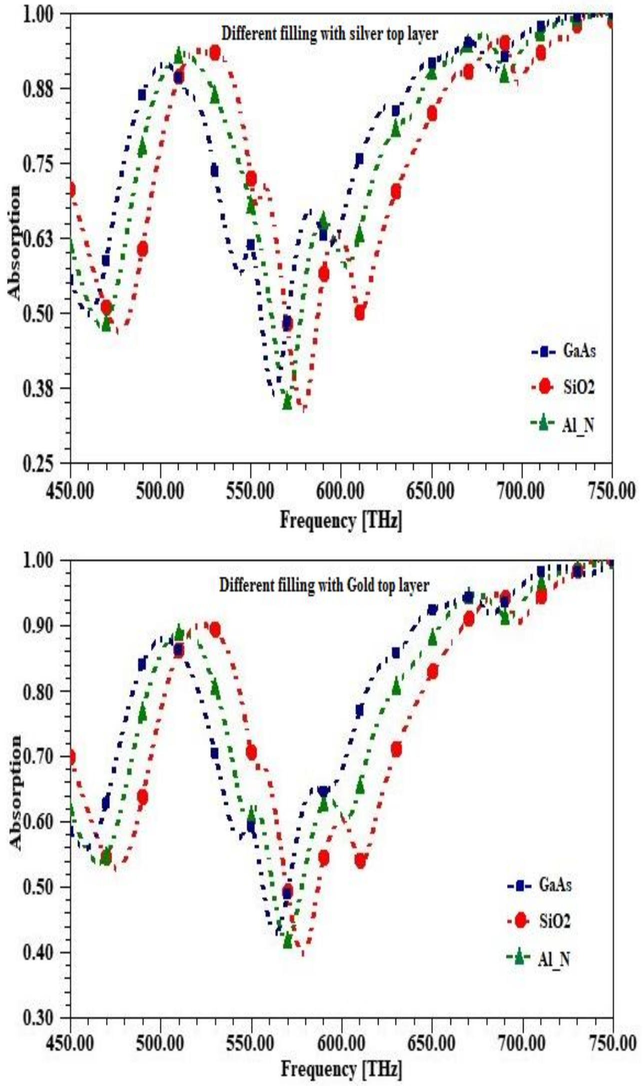

Fig.5 In 400nmX400nm, silver and gold is given as top conducting layer for different fillings.

From all the analysis done based on the filling material, the design having dimension 400nm ×400nm with silver as top conducting layer and Aluminium Nitride (AlN) as filling material is giving better absorption rate than 450nm×450nm and 500nm×500nm.

IV. RESULTS AND DISCUSSIONS

With all the analysis done, Aluminium nitride is considered as the intrinsic layer and silver is taken as the top conducting layer. This metamaterial absorber is designed in such a manner, with the proportions noted in Table 1. And the absorption versus reflection graph is illustrated below [Fig.6].

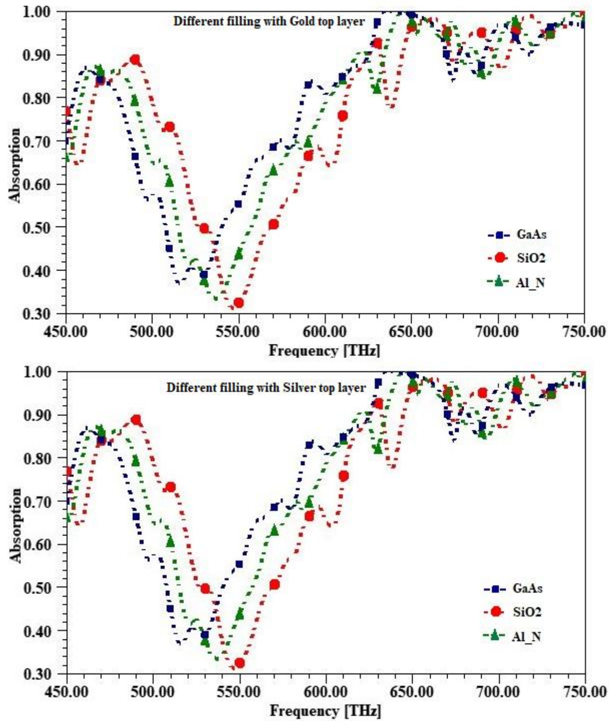

Fig. 6 In 500nmX500nm, silver and gold is fiven as top conducting layer for different fillings

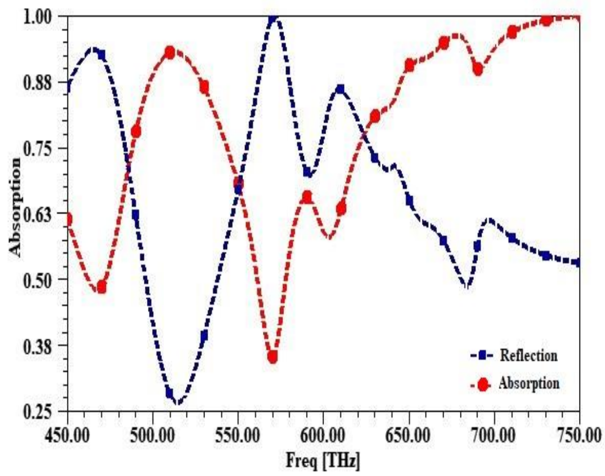

Fig.7 Absorption verses reflection graph for 400nm×400nm dimension with silver as top conducting layer and filled with AlN

The field Absorption verses reflection is represented in Fig 7 which shows the dual band from 450 to 550 and 550 to 560 THz frequency. This metamaterial absorber is compared with other previous works, which is tabulated and given below. The electric field distribution and current distribution is illustrated in fig.8. When the light strikes the solar cell, the electrons will get charged and it will move from lower energy level to higher energy level. The presence of higher electric field will result in more absorption rate and can provide more current distribution [11].

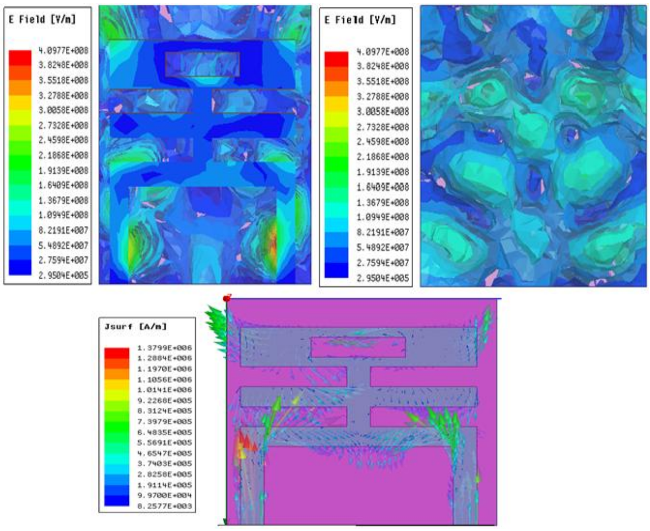

Fig.8 The proposed metamaterial absorber filed. Electric field distribution (Top view), Electric field distribution (Bottom view). Current distribution (for the MTM structure with Silver top conducting layer).

When compared to other works, this proposed design is having less size which will reduce the fabrication cost. So that the usage of material is also less. As a result, the total cost of the design will get reduced when compared to other works mentioned above in the table.

Table 3 Comparison with previous works (Abbreviations: MTM: metamaterial, SIR: step impedance resonator, FA: point of frequency at which high absorption is obtained.)

References	Total dimension(nm)	Thickness of intrinsic layer(nm)	Thickness of top layer(nm)	Type of metamaterial resonator	F_a (THz)
12	550	50	15	Plus shaped resonator	549
13	600	93.5	1.28	Metallic patch resonator	610
14	566	260	75	Hexagonal	500
15	500	100	2.5	SIR	600
This Work	**400**	**50**	**5**	**SIR**	**520**

CONCLUSION

According to this paper, metamaterial (MTM) absorber based on SIR structure is designed. The analysis and illustration done in this work proves the ability of the design to improve the absorption rate. For this work, the absorption is getting in the range of frequency 470THz to 570THz and peak absorption is at 520THz. The parametric study is done with respect to the variations in dimension and filling material. The geometric parameters plays a major role in the resultant absorption rate. The design is compared with previous works and tabulated in table 2. For the efficient understanding, the electric field and current distribution of the metamaterial absorber is illustrated in fig.6. As a result, this design can be used for higher absorption with efficient solar energy harvesting.

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