Surface texturing effects on the performance of a solar cell

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Abstract

In modern technology, people are becoming more and more dependent on solar energy. For this reason, solar cell is needed to be more improved. Solar cell is basically useful for its cost effectiveness and time saving capabilities. To improve efficiency, reflection of light should be reduced. Surface texturing is used to reduce light reflections and enhance light trapping. In this thesis, surface texturing is used on different layers of a GaAs solar cell. Some basic parameters of textured solar cell are studied here such as short circuit current, open circuit voltage, maximum power, external quantum efficiency, photon absorption rate and fill factor, and we compare them with the results of a non-textured solar cell. ATLAS and DEVEDIT of SILVACO tool are used for the simulation of these parameters. Standard AM 1.5 spectrum is used in this thesis. Maximum power for non-textured solar cell and textured solar cell is 21.08 mW/cm^2 and 24.65 mW/cm^2 respectively. Also, efficiency for non-textured solar cell and textured solar cell is respectively 21.08% and 24.65%. So, it can be shown that textured solar cell has better performance than non-textured solar cell.

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Authorization

We hereby declare that we are the sole author of this thesis. We authorize East West University to lend this thesis to other institutions or individuals for the purpose of scholarly research.

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Chapter 1: Introduction

The demand of electricity is increasing day by day worldwide. To produce electricity, people are dependent over limited means like fossil fuel. It is already a well-known fact that fossil fuel is becoming extinct and quite expensive. To solve this problem, renewable energy is a possible alternative. Renewable energy is the energy that is drawn from natural resources such as wind, sun, water etc. Among these kinds of energies, solar energy is the most widespread renewable energy. The sun emits about 386×10^{24} watts and our earth receives about 174×10^{15} watts power from the sun. The earth gets about 1366 watts per meter square from direct solar radiation. So, if we use 10% of the total energy the sun provides in 0.16% of the total land of the earth we could produce 20 TW of energy and that energy is the double of total consuming energy of the earth. On a sunny day, if an area of 48-meter square gets exposure to sun light for about 6 hours, it will get 288 kilowatts of energy which is nearly 10 times of what the everyday households use in a day. On an overcast day, the amount of power reduces to 28 kilowatts which is also quite sufficient.

The average usable from the sun is 0.4 to 13%. The technology which uses solar energy to produce voltage or electricity is called photovoltaic technology. This happens when a light or photon of certain wavelength hits a semiconductor device which has definite bandgap for that light or photon. This technology was first established by Edmund Becquerel in 1839. He recognized this while he was experimenting on wet cells. When the silver plates were given light, the voltage of the cell was increased. The devices which are used to produce electricity is called solar cells. Solar cell was first invented by Bell Laboratory in 1954. Solar cell is a simple device which has two types of semiconductors, n-type and p-type. When they are connected, an electric field is formed which is called built in electric field. As a result, photo-generated electrons move to the positive p-side and holes move to the negative n-side. When a light of suitable wavelength incidents on the surface, solar cell absorbs that light. Then the energy is transferred to the electrons which will jump to a higher energy state known as conduction band. That creates a hole in the valence band. As a result, the electron-hole pair is created. The absorption of light depends on the bandgap of the material. Light with different wavelengths are absorbed in materials which have certain bandgap only for those wavelengths.

There are three generations of solar cell production. The first-generation solar cells are monocrystalline silicon cell, polycrystalline silicon cell, amorphous silicon cells and hybrid silicon cells. The monocrystalline cells have efficiency around 26.6%. The efficiency of polycrystalline silicon cell is 21.3% which is lower than the previous one but it is cheaper. The next cell is hybrid silicon cells. The efficiency of this device is 13%. The second-generation solar cells are called thin film solar cell because the thickness of the materials is very small compared to the first generation solar cells. These cells consist of cadmium telluride (CdTe), copper indium gallium selenide (CIGS), gallium arsenide (GaAs) silicon cells etc. The highest efficiency of this solar cells is 22.3%. The third-generation solar cells are generally made from variety of new materials besides silicon, nanotubes, silicon wires etc. The efficiency is largely dependent on the kinds of material used. These cells have higher efficiency percentage, for example, a single layer cell which has a bandgap of 1.13 eV, the efficiency is 33.7%. For a double layered cell which has a bandgap of 1.64eV and 0.94eV, the efficiency is 44%.

1.1 Hetero-Structure, Single junction and Texturing:

When we use same type of material to construct a p-n junction, it is called homo-junction. Usually, the materials have same energy bandgaps but the doping is different. Again, we use different kinds of materials to construct p-n junction, it is called hetero structure. The energy bandgaps of the materials are different. We have used homo-structure in our structure. Also, we have used single junction solar cell for this analysis. When there is only one combination of p-region and n-region, this is called single junction. When the photons of sunlight incidents on the cell, some lights are reflected, some are passed through, and some are absorbed by mainly the p-n junction region. The amount of light absorbed depends on the optical path length and the absorption coefficient. Absorbing the light, it produces current by creating electron-hole pair. Here, we have applied texturing on the surfaces of the solar cell. Roughening the surface is called texturing. After texturing the surface it may look like a series of pyramids or inverted pyramids. Texturing can be done by different ways. A single crystalline surface can be etched along the faces of the surface that results in a surface made up of pyramids. The purpose of texturing is to reduce reflection of the light and enhance light trapping. Thus, it increases the efficiency. It also removes the surface damage. When the surface is plane, a certain amount of light is bounced back. If texturing is applied to the surface, chances of reflected light to bounce back will be decreased. If we use surface texturing, we get higher efficiency than the non-textured cell. In 2012, researchers from MIT institution found out that the light absorption using nanoscale inverted pyramids on textured c-Si films is greatly higher than planar c-Si by almost 30 times.

1.2 Objective:

The main objective of this study is to analyze different parameters of a single junction solar cell which has textured surfaces on different regions. The results of single junction solar cell without textured surfaces have been compared with textured solar junction cell. The parameters which are analyzed here are short circuit current, open circuit voltage, maximum power, efficiency, fill factor etc. All of the previously mentioned parameters are analyzed for both plane and textured surfaces of a single junction solar cell. Here, we have used ATLAS device simulator to design model and structure of the cell. Also, DEVEDIT is used to create rough surfaces on the different regions of solar cell. For device simulation, ATLAS is also used. We use MATLAB to plot required curves from the data of ATLAS simulation. Texturing surfaces will enhance light absorption on the surface. Thus, efficiency will also be increased. In our analysis, the non-textured solar cell has the efficiency of 21.08%. If we use texturing on the surfaces of the solar cell, the efficiency increases to 24.65%. We made this study for a single junction GaAs solar cell.

1.3 Literature Review:

Ray and co-authors [1] studied on the performance improvement of GaAs solar cell with anti-reflection coating (ARC) and texturing using PC1D simulator. Mainly they displayed a fundamental optical analysis framework for designing light reflection schemes of thin film SiO_2 and ITO ARC structures for a GaAs solar cell. They suggested that ITO has higher transparency property than a SiO_2 ARC. Also, they reported improvement of external quantum efficiency (EQE) of the GaAs solar cell after deposition of texturing over the surface for both instances of ARCs and declare that the deposition of ARC and texturing on top of the surface are very good for GaAs solar cell.

In their work, Kim et al. [2] presented the improvement of the GaAs solar cells with the nanohole arrays on the InGaP window layer. They prepared anodized aluminum oxide (AAO) masks from an aluminum foil by using a two-step anodization process. They used inductively coupled plasma dry etching to etch and define the nanoarray structures on top of an InGaP window layer of the GaAs solar cells. They also formed inverted-cone-shaped nanoholes on the top surface of the solar cells after the AAO mask removal. Their intention was to investigate photovoltaic and optical characteristics of the GaAs solar cells. They suggested that the reflectance of the AAO nanopatterned samples is lower than that of the planar GaAs solar cell. Moreover, they found that the nanohole arrays fabricated with an AAO technique might be utilized to enhance the light absorption and, thusly, the changed efficiency of the GaAs solar cell.

Kim and his co-authors [3] studied the effect of the surface texturing on the efficiency of crystalline Si (c-Si) solar cells. Their main objectives were to investigate the effect of the texture for solar cells fabricated with various textured surfaces by using conventional anisotropic etching with a mixture of KOH and isopropyl alcohol, reactive ion etching, and Ag-catalyzed etching. They found that the changes in the doping profile improve the cell efficiency for surfaces with various textures.

Abdullah et al. [4] have investigated different models of GaAS solar cell with different texturing surfaces to improve the spectral sensitivity of the photovoltaic by reducing the light reflection and improving the light trapping. They used four models of surface texture: simple structure, V-trench structure, four-sided structure and semi-sphere structure of photovoltaic device. They suggested that the V-trench structure is the best surface texture that has optimum efficiency and short circuit current density for GaAs solar cell than others.

Edwards and co-authors [5] demonstrated the effects of anisotropic texturing on the lifetime and cell performance of heterojunction device structures with a-Si i-layer. They exhibited the preparation of wafer surfaces by NaOH texturing prior to amorphous silicon intrinsic layer deposition. He suggested that with a chemical polish (CP) etch of NaOH texturing or low temperature anneal after texturing, and with correct deposition parameters, effective wafer lifetimes might be achieved which indicate excellent surface passivation. They also suggested that correct preparation of wafer surfaces can lead to excellent heterojunction solar cell efficiencies.

Macdonald and co-authors [6] examined three texturing methods: wet acidic texturing, masked and maskless Reactive Ion Etching (RIE) for commercial multicrystalline silicon solar cells based on reflectance measurements. They found that all three texturing methods significantly reduce reflection losses in solar cells. They suggested that the diminishment in reflection is most noteworthy for masked RIE pyramids, trailed by maskless RIE, and after that acidic texturing. Therefore, the relative distinction between the strategies is significantly diminished after antireflection-coating and encapsulation. Moreover, they mentioned that the cost of execution is significantly less for acidic texturing than for either RIE process, particularly masked RIE.

1.4 Motivation:

For a solar cell, output power and efficiency is the most vital parameters to determine a device's performance. Multiplying both the short circuit current and open circuit voltage results output power. By texturing surfaces of a solar cell, output power can be increased. In this case, both the open circuit voltage and short circuit current increases. Because textured surfaces can reduce reflections of light and enhance light trapping due to their pyramidal structures. Thus, it increases the amount of light to be absorbed by the solar cell resulting to an increase of electron hole pair. So, textured solar cell has more maximum power than the non-textured solar cell. Maximum power can be attained from the peak point of P-V curve. Another important parameter is efficiency. Textured solar cell has greater efficiency than the non-textured solar cell. Textured surfaces of a solar cell can reduce reflection of light. So, the solar cell can take more light into the device so that maximum number of photons can be absorbed by the cell. It increases both current and voltage which leads to a greater efficiency. The prime objective of our thesis is to study the effect of surface texturing on a solar cell. Here, we observe different parameters of textured solar cell and compare the results with non-textured solar cell. In our thesis, we have used SILVACO ATLAS and SILVACO DEVEDIT for the construction of structure and simulation. Also, MATLAB is used to plot the desired curves.

1.5 Thesis outline:

Chapter 1: The introduction of photovoltaic technology as a substitution of renewable energy, its history, advantages and classification are discussed here. Hetero structure of solar cell, literature review and motivation are also discussed here.

Chapter 2: All of the codes used in SILVACO for this thesis is described here. The models used and the syntax of coding in Silvaco are also discussed.

Chapter 3: The characteristics analysis and results of the solar cell from various simulation are shown here such as J-V curve, P-V curve, external quantum efficiency, photon absorption rate curve.

Chapter 4: Conclusion of the complete thesis is given here.

Chapter 2: SILVACO Simulation Setups

SILVACO is an electronic design automation software. In our thesis we use SILVACO atlas and DEVEDIT to design structure. In our solar cell structure we have ARC (antireflection-coating), window layer, emitter, base, BSF (back surface field) layer, and two electrodes. Different surface texturing is used in this thesis to obtain best result. SILVACO atlas and DEVEDIT command are given below,

2.1 Structure

In out thesis we have studied the parameters of a single junction non-textured solar cell and a textured solar cell as shown in figure 2.1 and 2.2. The first layer is ARC (Anti-Reflection Coating) to reduce refection, second layer is window layer to reduce the surface recombination. Third and fourth layers are emitter and base layers that create the p-n junction. Fifth layer is BSF (Back-Surface Field), to reduce the scattering of carriers towards the electrode. We use aluminum as the electrode. We have simulated the texture solar cell structure for different texture angles as shown in figure 2.2, and found that the maximum current can be achieved at an angle of 54°. So we fix this angle for our textured solar cell. For angles other than 54° we get less current. Our device length is 2μm but the ARC ZnO layer has a length of 1.5 μm. In the surface of ZnO layer, we have used 5 pyramid, each pyramid has a height of 0.3 μm and a base of 0.3 μm. The published optimum angle for textured solar cell is 54.7° [1], which is closed to our value used in this work.

Table 2.1 shows the materials used, layer thickness, and doping of the structure.

Layer Name	Material	Thickness (nm)	Doping Type	Doping (cm-3)
ARC	ZnO	500	N/A	N/A
Electrode	Aluminum(top)	500	N/A	N/A
Window	InGaP	500	N	5e19
Emitter	GaAs	500	N	2e18
Base	GaAs	2500	P	1e17
BSF	InGaP	50	P	2e18
Electrode	Aluminum(bottom)	60	N/A	N/A

Table 2.1: Structure parameter of solar cell.

The non-textured and textured structures used in SILVACO for simulation are shown in figure 2.1 and 2.2 respectively.

Figure 2.1: Non-textured single junction solar cell.

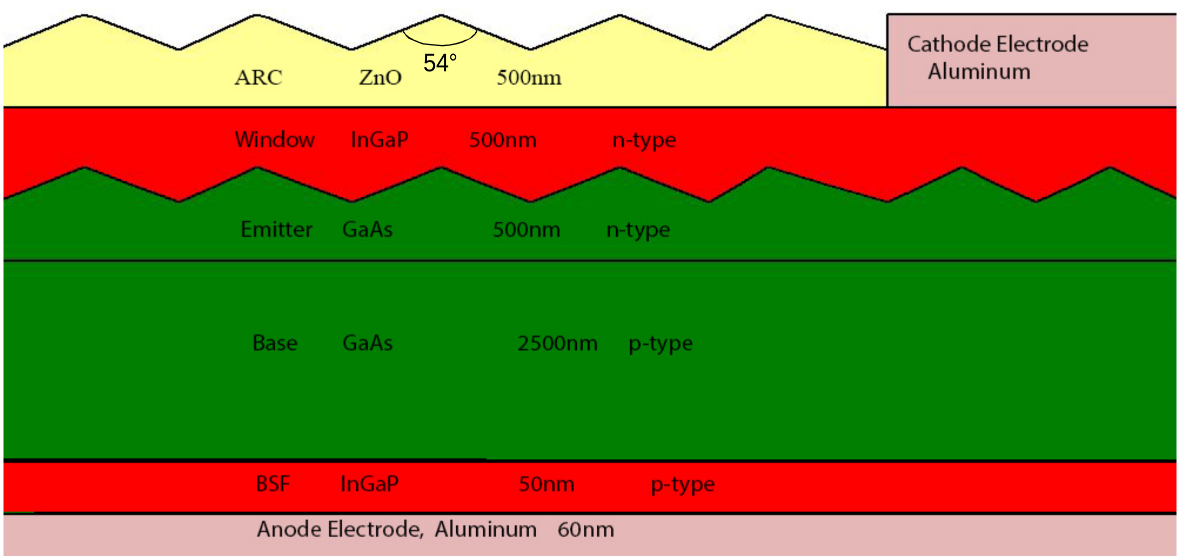

Figure 2.2: Textured single junction solar cell.

Mesh:

Non-textured:

Mesh specifies the grid. It is important for accurate simulation. Mesh divides the device in some small triangles where simulation occurs. Mesh lines divide the full device in much horizontal and vertical part. Simulation time depends on the number of mesh triangles. If the number of triangle increases then the simulation time also increases. Below we show some horizontal mesh,

```
mesh auto
 x.mesh location=0.0       spacing=0.05
 x.mesh location=2.0       spacing=0.05
```

Mesh density can be different in different region based on the significance of any specific region. We use different mesh density for different region in vertical axes.

```
y.mesh loc=0        spacing=0.01 # ARC
 y.mesh loc=0.1      spacing=0.008 # window layer
 y.mesh loc=0.19     spacing=0.008 # Emitter
y.mesh loc=2.7      spacing=0.01
```

mesh auto is used in the structure for auto meshing capability in Atlas.

Textured:

In DEVEDIT for textured structure we use the following meshing commands,

```
constr.mesh region=1 default
```

This statement creates meshes.

To define mesh height and width we use

```
base.mesh height=0.5 width=0.5
```

To define different density mesh we use

```
constr.mesh id=1 x1=0 y1=0.06 x2=100000 y2=0.1 default
max.height=0.2 max.width=0.2
```

Finally we use

```
Mesh Mode=MeshBuild
```

This statement is used to build meshes.

Region:

Non-textured:

Region defines the part of the device area. We use region to put different material in different part of the device and define the range of specific materials. For example,

```
region num=1  material=ZnO y.min=0 y.max=0.06 x.min=0
x.max=1.5
```

Here we define ZnO as region number 1.

Textured:

In DEVEDIT we define the part of the device area with the help of the polygon concept. We make different polygon for different region and fix the range of that region. Here we build textured structure with the help of polygon. Example,

```
region reg=1 mat=ZnO polygon="0,$reg1yb 0.15,$reg1yt \
0.31,$reg1yb  0.44,$reg1yt 0.6,$reg1yb 0.75,$reg1yt \
0.9,$reg1yb 1.05,$reg1yt 1.2,$reg1yb  1.3,$reg1yt 1.5,$reg1yb\
1.5,$reg1yb1 1.3,$reg1yt1 1.2,$reg1yb1 1.05,$reg1yt1 \
0.9,$reg1yb1 0.75,$reg1yt1 0.6,$reg1yb1 \
0.44,$reg1yt1 0.31,$reg1yb1 0.15,$reg1yt1 0,$reg1yb1"
```

Here we define region-1's range and material. $reg1yb is variable name, by using $ sign we can define variable.

Electrodes:

Non-textured:
Electrode statement is used to define electrode, its region and material used. It can be anode or cathode.

```
electrode name=cathode x.min=1.5 x.max=2 y.min=0 y.max=0.06
material=aluminum
```

In the above statement aluminum is defined as cathode electrode.

Textured:
In DEVEDIT the following statement is used to define electrode,

```
region reg=2 name=cathode mat=Aluminum elec.id=1 work.func=0\
color=0xffc8c8 pattern=0x7 polygon="1.5,$reg2Al_b1 \
2,$reg2Al_b2  2,$reg2Al_b3  1.5,$reg2Al_b4”
```

The above statement defines the electrode.

Doping:

Non-textured:
This statement specifies the doping concentration in different region. For example,

```
doping region=2 n.type conc=5e19  uniform
```

Here, region 2 is uniformly n-type doped with a doping density of 5×10^{19} cm^{-3}.

Textured:

The textured structure of the solar cell is made by DEVEDIT. We use the following statement to define doping concentration in ATLAS of that structure.

```
region num=3 modify material=InGaP donor=5e19
```

Here, we have doped region-3 by modifying previous structure which was built by DEVEDIT.

Structure file:

To save the structure in a file we use the following statement,

```
save outf= non_textured.str
```

Here, structure file is saved in “non_textured.str” file.

In DEVEDIT we use following command to save structure file,

```
struct outf=first_devEdit.str
```

Material:

This statement defines the material properties like permittivity, affinity etc. For example,

```
material material=InGaP   affinity=4.08
```

Here, affinity of InGaP is defined.

Sopra database:

We use the sopra database for real and imaginary parts of refractive index of different materials used.

```
material mat=GaAs       sopra=Gaas.nk
```

2.2 Models:

Model statement specifies the physical properties for materials. Different sets of models can be applied for different regions. In SILVACO, typically models can be carrier statistics, mobility, recombination, impact ionization etc. In our thesis we use the following model for non-textured single junction solar cell,

```
Models srh Fermi conmob optr auger bgn
```

We use “srh” model for DEVEDIT textured solar cell structure. By using this command we have enabled Shockley-Read-Hall recombination. In photodetection it is important to model recombination as a computing process that has direct effects on terminal quantum efficiency.

SRH (Shockley-Read-Hall) Recombination:

The Shockley-Read-Hall (SRH) recombination is also called trap-assisted recombination. This theory was established by Shockley, Read and Hall. If any electron trap happens, electron transitions in between forbidden gap of semiconductor material through a new energy state created within the band gap is called localized state. This process also applicable for direct bandgap materials, when very low carrier density present.

CONMOB:

This model is used to define standard concentration dependent mobility (conmob). This command define the doping concentration versus carrier mobility table at temperature 300K.

Fermi-Dirac (FERMI):

We use Fermi-Dirac model for carrier statistics. The probability f(ε) that an available electron state with energy ε is occupied by an electron is:

$$f(\varepsilon) = \frac{1}{1+\exp\left(\frac{\varepsilon - E_F}{KT_L}\right)}$$

Where,

E_f = A spatially independent reference energy known as the Fermi level

k = Boltzmann's constant.

If $\varepsilon - EF >> kT_L$, then the above equation can be express as,

$f(\varepsilon) = \exp(\frac{\varepsilon - E_F}{KT_L})$

Bandgap Narrowing (BGN):

Bandgap narrowing is enabled in ATLAS by specifying the "bgn" command in the model statement. These effects may be described by an analytic expression relating to the variation in bandgap to the doping concentration.

$$\Delta E_g = BGN.E\{ln \frac{N}{BGN.N} + [(ln \frac{N}{BGN.N})^2 + BGN.C]^{1/2}\}$$

where BGN.E, BGN.N, and BGN.C parameters can be specified in the MATERIAL statement. If no value is defined for those parameters then Silvaco will take default values.

Optical Generation/Radiative Recombination (optr):

OPTR model is used for the optical recombination and generation. When radiative recombination occurs an electron loses energy on the order of the band gap and moves from the conduction band to the valence band. For optical generation, an electron gain energy on the order of the band gap and that electron moves from the valence band to the conduction band.

Assuming,

$$C_c^{OPT} = \text{capture rate}$$

$$C_e^{OPT} = \text{emission rate}$$

For recombination,

$$R_{np}^{OPT} = C_c^{OPT}{}_{np}$$

For generation,

$$G_{np}^{OPT} = C_e^{OPT}$$

These rates must be equal in thermal equilibrium so that

$$C_{np}^{OPT} = C_c^{OPT} n^2_{ie}$$

The total band to band generation/recombination is the difference of the partial rates,

$$C_{np}^{OPT} = C_c^{OPT}(np - n_i^2)$$

AUGER Recombination:

In Auger recombination the energy is transferred to another carrier, which is excited to higher energy level but not in any energy band. After this the third carrier again losses the energy by thermal vibration. This process occurs when carrier concentration is high. Auger recombination is modeled by the following equation,

$$R_{Auger} = AUGN\ (pn^2 - nn_{ie}^2) + AUGP\ (np^2 - pn_{ie}^2)$$

Here, AUGN & AUGP defines auger coefficient

Photocurrent:

Photo current is an electric current produced by electromagnetic radiation in the photoelectric effect or photovoltaic effect. Photo current produces when photons are absorbed by the photo sensitive materials and produce electron hole pairs. Photo current depends on photon intensity. Photon intensity reduces as a function of device depth, because some photons are continuously absorbed by device. Photo generation rate can be expressed as follows,

$$G_L = \alpha \frac{P_{op}}{E_{ph}}$$

Here,

α= Photon absorption coefficient.

P_{op} = Photon intensity.

E_{ph} = Photon energy.

2.3 Simulation with beam:

Air Mass (AM) defines the solar spectrum. AM standards are defined for territorial area. The solar spectrum differs throughout the day and with location. Standard reference spectrums are defined by different industries and researchers to research on photovoltaic devices. The standard spectrum were defined in the early 2000's to increase the performance of photovoltaic devices and to stablish the standards worldwide. Solar irradiance under different air mass (AM) conditions are AM0, AM1, AM1.5, and AM2. The spectrum outside the atmosphere is defined by solar irradiance AM0 and it is used in space application. AM0 has a power of 1376mW/m^2. The AM1.5 is called Global spectrum and it is designed for flat plate modules and has power of 1000 W/m^2 (100 mW/cm^2).

Beam:

We use “beam” command to define the light source. In this thesis we use the following command,

```
beam num=1 AM1.5 wavel.start=0.1 wavel.end=2 wavel.num=500
```

In above statement we use light spectrum whose wavelength start with 0.1um and end with 2um.

Log:

When we simulate code, then the results are stored in a log file. The command shows below will create a log file and store output data,

```
log outf=output_file_textured_cell.log
```

This file needs .log extension.

Tonyplot:

We use "Tonyplot" to display all structure and curves in Silvaco atlas. Below is a example of display structure file,

```
tonyplot final_figure_Atlas.str
```

log can be plotted by it, like

```
tonyplot output_file_textured_cell.log
```

Here, "tonyplot" statement is used to plot the log file.

Chapter 3: Results and Analysis

Solar cell is a device that transforms sun light into electricity by absorbing photons from the sun. Power and efficiency of solar cell largely depends on photon absorption. The more photon absorption leads to the production of more electron-hole pair. The more electron-hole pair is produced, the more it generates electricity. To increase the efficiency of solar cell, surface texturing is used. More photons can be absorbed by texturing surfaces. Because it reduces the reflection of light and increases light trapping. The textured solar cells have higher short circuit current and open circuit voltage than non-textured solar cells. Also, it can produce more power. The reason behind the increase of efficiency is that generally when light falls on the surface of the cell, a certain amount of light is bounced back. If the surface is textured, the surface is curved out into little pyramid surface. Here, the incident light is not bounced back to the surrounding air, rather it falls on one side of the pyramid and bounces to the adjacent side of the pyramid. So, more area is utilized to absorb the photons.

In this thesis, we have considered different models of solar cell which have their surfaces textured on different regions to find out which cell has better performance. Here, the combination of texturing different regions of the solar cell is shown in figure 3.1.

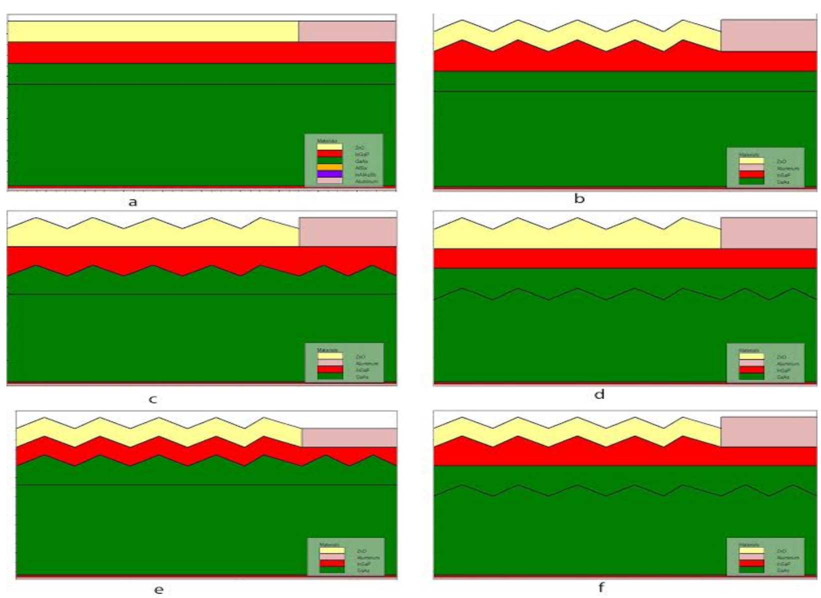

Figure-3.1: Structures of different solar cells having surface texturing on different regions.

In the above figure 3.1, there are actually 5 solar cells each having textured surfaces on different regions including a non-textured cell (a). In (b) solar cell, it has surface textured on ARC and Window layer. In (c) solar cell, the surfaces of ARC and Emitter (GaAs) is textured. In (d) cell, the surfaces of ARC and Base (GaAs) are textured. In (e) cell, ARC, Window layer and Emitter, all of them have their surfaces textured. In (f) solar cell, the surfaces of ARC, Window layer and Base (GaAs) are textured. All of the above solar cells have their surface textured with 5 or more etches. All of them have been analyzed here. The result of Analysis is shown in table 3.1.

Solar cells	Short circuit current, J_{sc} (mA/cm^2)	Open circuit voltage, V_{oc} (V)	Power, Pmax (mW/cm^2)	Efficiency, η (%)
a	27.7	0.91	21.08	21.08
b	30.6	0.944	24.42	24.42
c	30.62	0.95	24.65	24.65
d	29.065	0.94	22.28	22.28
e	30.6	0.93	24.42	24.42
f	29.065	0.938	22.28	22.28

Table 3.1: Comparison of performance parameters among the solar cells having surface texturing on different regions.

From the above analysis, it is observed that the solar cell (c) has the highest short circuit current and the highest power. So, we have chosen the solar cell (c) model for this thesis to do more analysis.

In this thesis, different parameters of textured solar cell have been simulated and compared with the results of non-textured solar cell. Here, GaAs solar cell is used for the analysis on textured and non-textured characteristics.

3.1 J-V curve analysis:

Here, J-V curve represents the anode current density versus anode voltage of the device.

Non-textured Solar Cell:

The structure of non-textured solar cell is given below in figure 3.2.

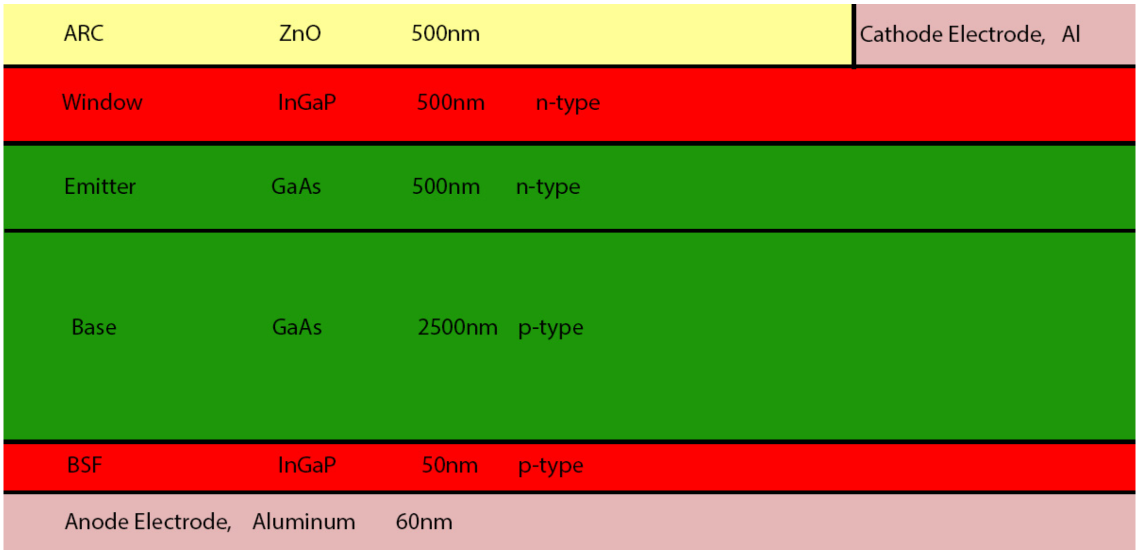

Figure-3.2: Structure of Non-textured solar cell.

At the top of the cell, ZnO is used as Anti Reflection Coating (ARC). The width and the length of ARC are 500 nm and 1.7 µm respectively. Also, aluminum (Al) is used as cathode electrode at the top layer beside ARC with 500 nm width and 0.3 µm length. InGaP is used as window layer with 500 nm width and n-type doping. GaAs is used as Emitter with 500 nm width and n-type doping. Also, GaAs is used as base with 2500nm width and p-type doping. InGaP is also used as back surface field with 50nm width and it is p-type doped. All of them have a length of 2 µm. At the bottom of the cell, aluminum (Al) is used as anode electrode with 60nm width and 2 µm in length.

From the simulation data, the J-V curve of non-textured cell is shown below in figure 3.3.

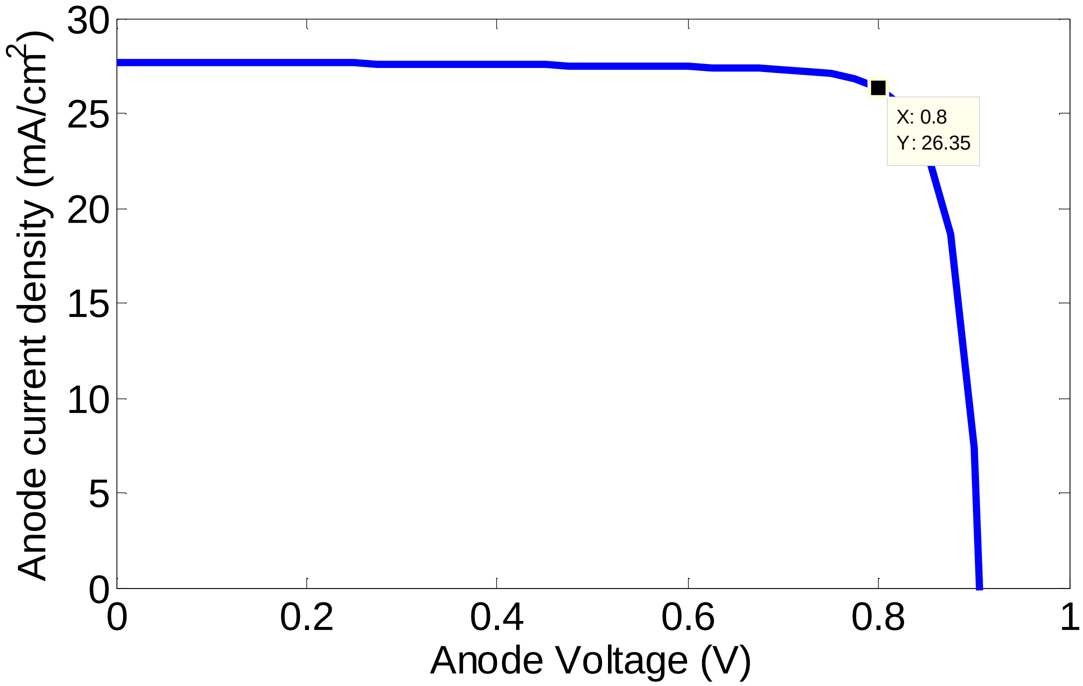

Figure-3.3: Anode current density versus anode voltage characteristics for non-textured solar cell.

According to the J-V curve, the short circuit current density of non-textured cell is 27.70 mA/cm^2. At short circuit condition (V = 0V), maximum current is produced by the solar cell. When both p-type and n-type sides are shorted, short circuit current can be achieved. The open circuit voltage for this cell is 0.91V. At open circuit condition (I = 0A), this cell can produce maximum voltage difference between p-side and n-side. The bandgap of GaAs is 1.43eV.

Textured Solar Cell:

The structure of textured solar cell is given below in figure 3.4.

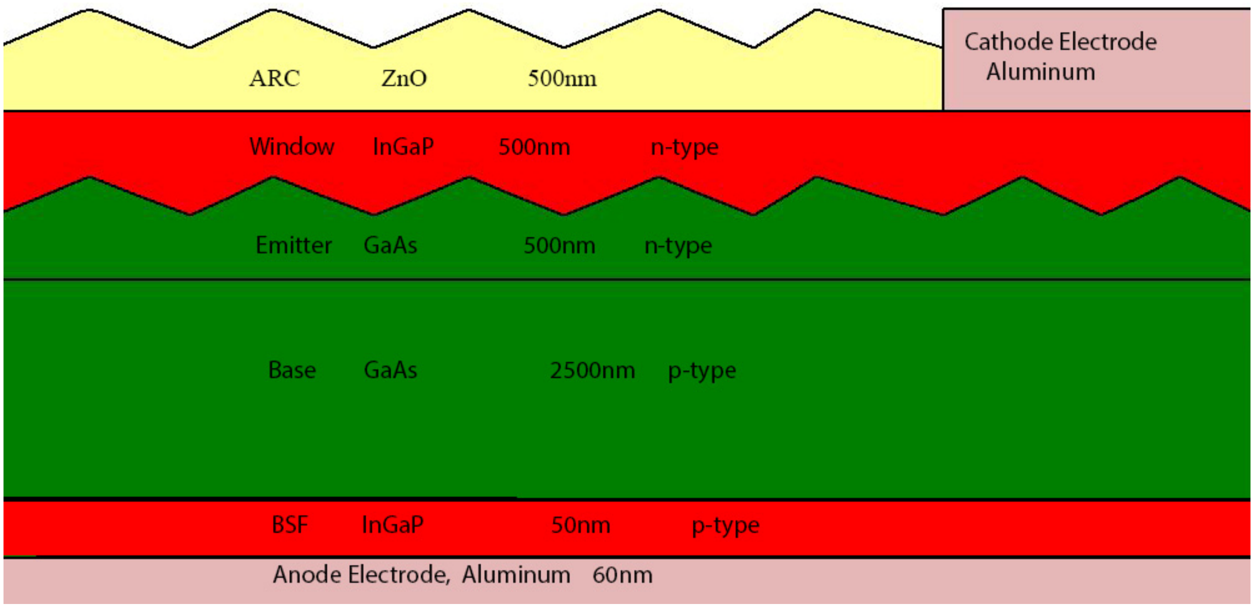

Figure-3.4: Structure of textured solar cell.

In the figure 3.4, the structure and measurement are same as non-textured solar cell. The cell consists of 4 layers which are window, emitter, base and back surface field (BSF). Like non-textured cell, aluminum (Al) is used as cathode and anode situated at top and bottom layer of the cell respectively. The difference between non-textured and textured solar cell is that the surface of region 1 and region 3 are textured with 5 etches. As there is no application of surface texturing in non-textured solar cell, all the three interfaces (ARC, Window and Emitter) cause reflection losses. But in the textured solar cell, primary reflection loss can be minimized as front surface of ARC is textured. So, more light can pass through the ARC. When light incidents on the surface of window layer, some of light are reflected due to plane surface. Also, small amount of light from emitter surface is reflected. But because of back reflection of the reflected light at ARC front texture, these losses can be reduced. The surface of the emitter is textured. So, the incident light on the surface will be scattered into the next region. Thus, it reduces losses of this surface reflection.

From the simulation data, the J-V curve of textured cell is shown below in figure 3.5.

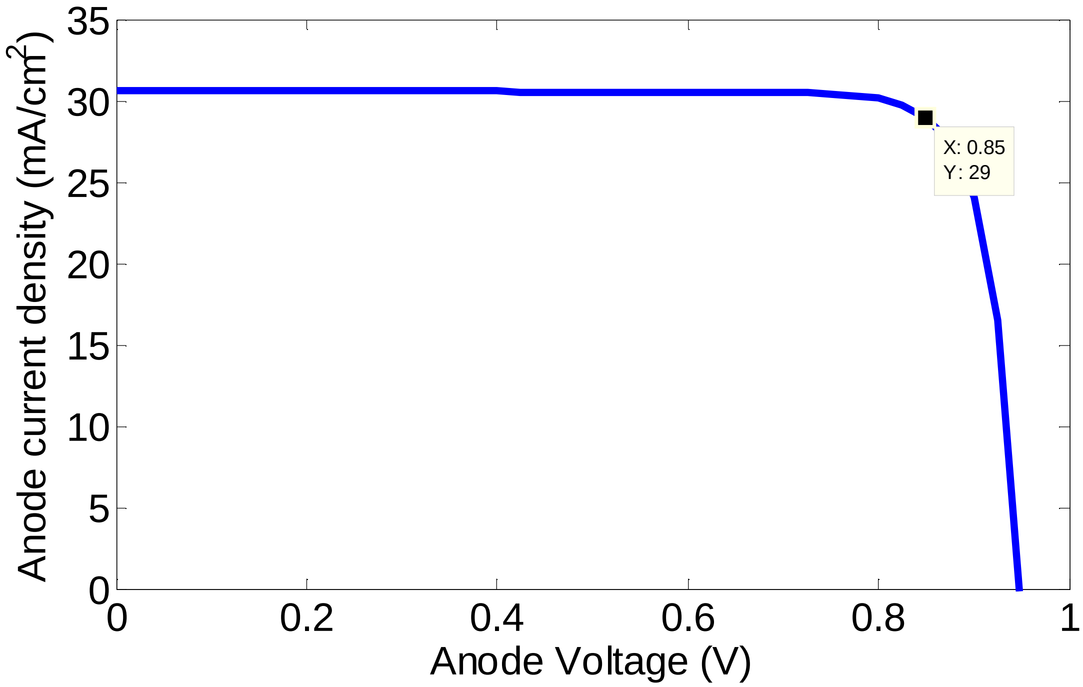

Figure-3.5: Anode current density versus anode voltage characteristics for textured solar cell.

According to the J-V curve, the short circuit current density of textured cell is 30.6 mA/cm^2. At short circuit condition (V = 0V), maximum current is produced by the solar cell. The difference of the short circuit between non-textured and textured solar cell is 2.9 mA/cm^2. The open circuit voltage for this cell is 0.95V. Maximum voltage difference between p-side and n-side can be found at open circuit condition (I = 0A). The voltage difference between these two cells are 0.04V. As GaAs has a bandgap of 1.43eV, the maximum open circuit voltage is 1.43V.

3.2 Power Analysis:

Power is measured by multiplying the output voltage with output current of the solar cell. P-V curve represents the power versus anode voltage of the device.

Non-textured solar cell:

Here, P-V curve for non-textured solar cell is shown in figure 3.6.

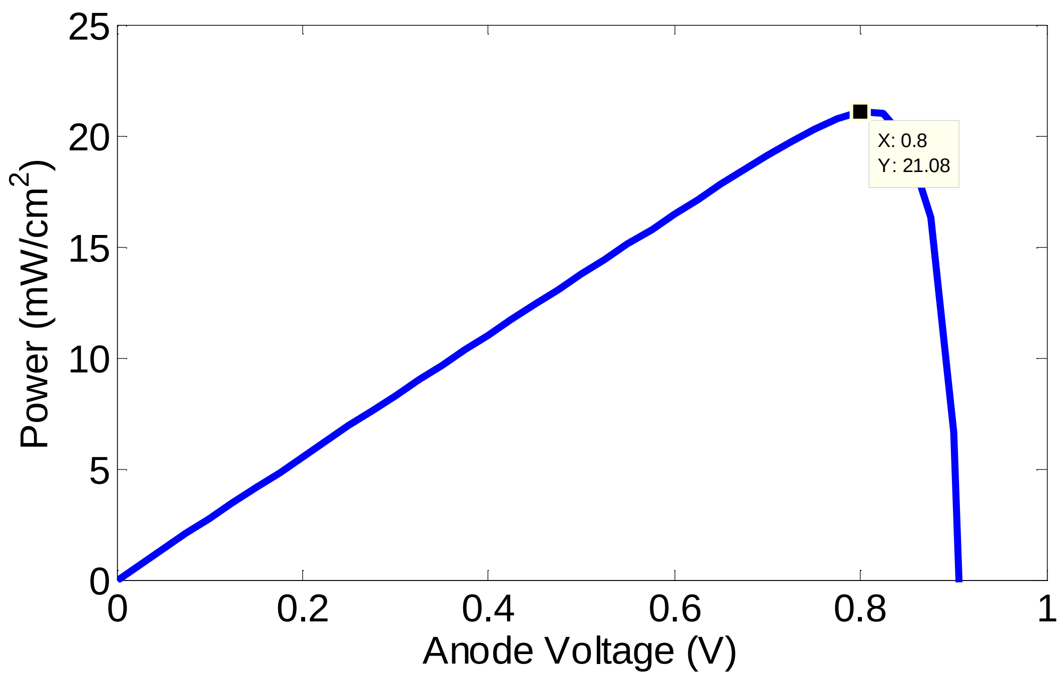

Figure-3.6: Power versus anode voltage of non-textured solar cell.

According to the above curve, the maximum power of non-textured solar cell is 21.08 mW/cm^2. At the time of maximum power, the maximum voltage is 0.8V and the maximum current is 26.35 mA/cm^2. The solar cell is not operating at short circuit condition or open circuit condition. In these cases, the output power is zero. The solar cell is operating at maximum power.

Textured solar cell:

Here, P-V curve for textured solar cell is shown in figure 3.7.

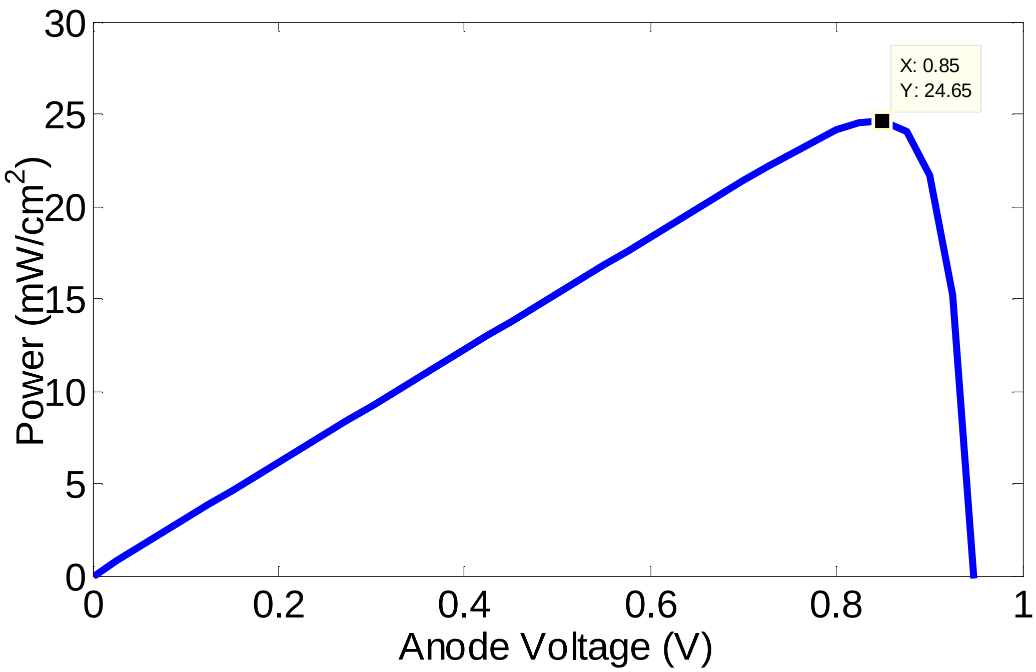

Figure-3.7: Power versus anode voltage of textured solar cell.

From the above curve, the maximum power of textured solar cell is 24.65 mA/cm^2. For this case, the maximum voltage is 0.85V and the maximum current density is 29 mA/cm^2. Also, for this solar cell, the device is operating at maximum power. If it is operating at short circuit or open circuit condition, the maximum power would be zero. From the above observation, the maximum power of the textured solar cell is greater than the maximum power of non-textured cell. It happens because of the increase of voltage and current of textured solar cell than non-textured solar cell.

3.3 Non-textured solar cell VS Textured solar cell:

The J-V comparison between non-textured solar cell and textured solar cell is shown in figure 3.8.

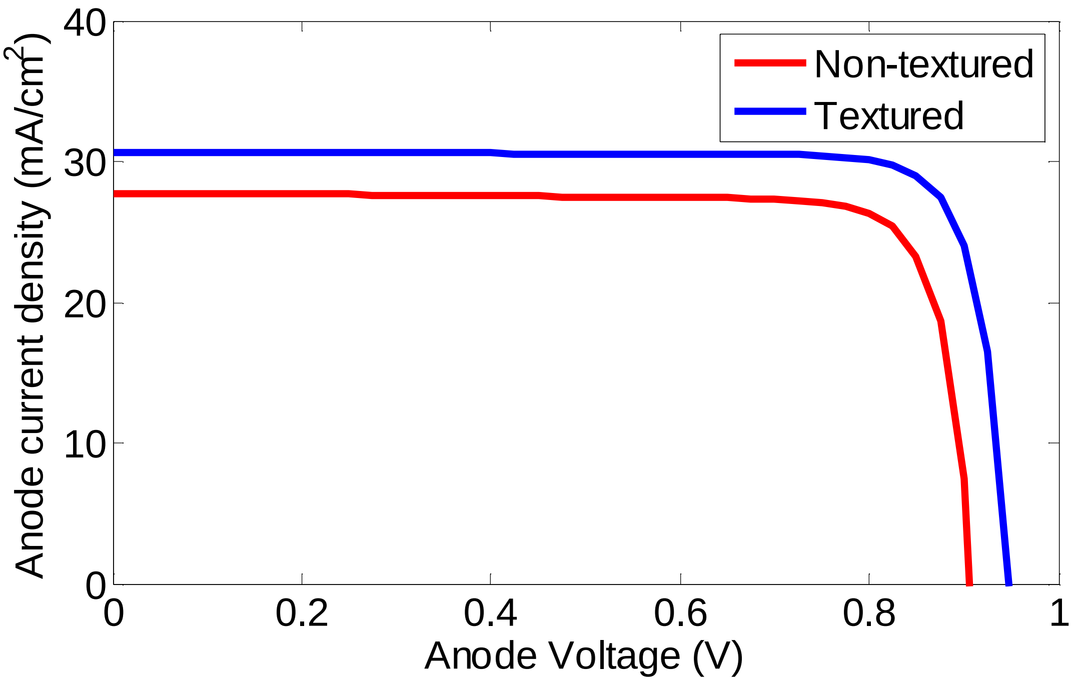

Figure-3.8: Anode current density versus anode voltage characteristics of non-textured solar cell and textured solar cell.

From the above figure 3.8, the textured solar cell is generating more voltage and current density than the non-textured solar cell. This happens because of the application of texturing surfaces in the solar cell. When surface texturing is not applied, a certain part of incident light is reflected to the surrounding air. As surface texturing applied in the solar cell, it reduces light reflection and more light is entering the solar cell. It enhances light trapping and also increases absorption of photons by the depletion layer of the cell. It causes more production of electron-hole pair that leads to increase of the current.

Power comparison curve of non-textured solar cell and textured solar cell is shown in figure 3.9.

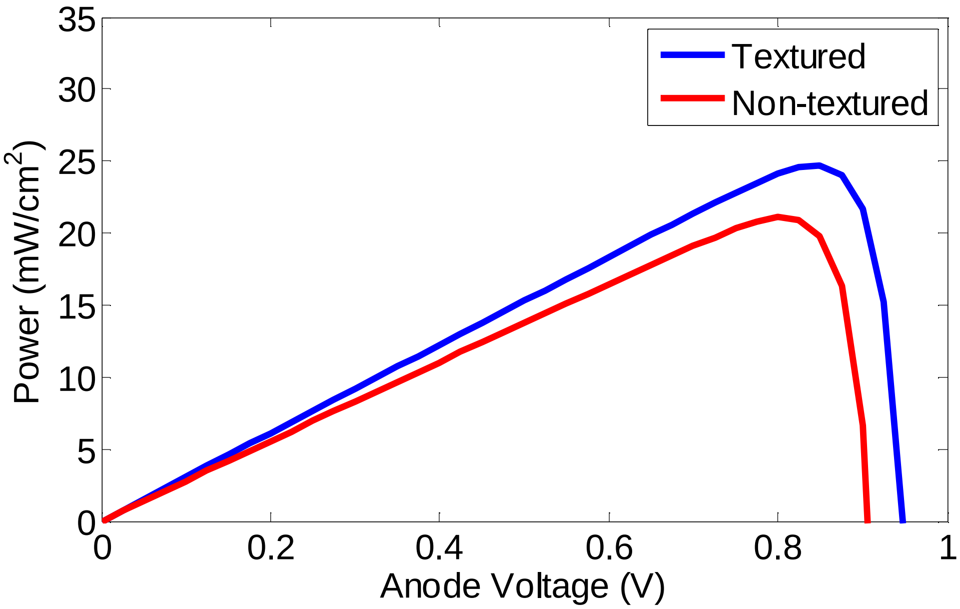

Figure-3.9: Power versus anode voltage of non-textured solar cell and textured solar cell.

According to the above figure 3.9, it is observed that the textured solar cell is producing more power than the non-textured solar cell. For the application of texturing on the surfaces of the cell, the maximum current and maximum voltage is increased. As a result, the power of textured cell is also increased than the non-textured solar cell. Overall comparison between non-textured and textured solar cell is shown in table 3.2.

Parameter	Non-textured solar cell	Textured solar cell
J_{sc}(mA/cm^2)	27.7	30.6
V_{oc} (V)	0.91	0.95
V_m (V)	0.8	0.85
J_m(mA/cm^2)	26.35	29
P_m(mW/cm^2)	21.08	24.65
η (%)	21.08	24.65
Fill factor	0.836	0.848

Table 3.2: Comparison of performance parameters between non-textured and textured solar cell

Short circuit current density (J_{sc}) can be measured when voltage between n-side and p-side becomes zero or at the short circuit condition. Also, open circuit voltage can be measured at open circuit condition or the output current becomes zero. By multiplying output current and voltage, power can be determined. The corresponding voltage is V_m and corresponding current density is J_m can be determined at the maximum power.

The efficiency of solar cell can be calculated by the following equation:

$$\eta = \frac{Maximum\ output\ power\ (P_m)}{100\ (mW/cm^2)} \times 100\%$$

Where, η = The efficiency of solar cell. Also, the input power 100 (mW/cm^2) is used here. We use spectrum AM1.5 in this thesis. The power corresponding to the spectrum AM1.5 is 100 (mW/cm^2).

The Fill Factor is calculated by the following equation:

$$FF = \frac{V_m J_m}{V_{oc} J_{sc}}$$

Where,

FF = Fill Factor

Vm= Voltage at maximum power.

Jm= Current density at maximum power.

Voc= Open circuit voltage.

Jsc = Short circuit current density.

The fill factor value obtained from our calculation is 0.848, which is closed to the published results of 0.82 – 0.84 for GaAs [2] [3].

3.4 Photon Absorption Rate:

Photo absorption is very important parameter for the current production. More photons are absorbed by the materials, more current will produce. When, photons incident on the solar cell, these photons are absorbed by the cell to generate more electron-hole pairs. That causes increase of the net current. Photon absorption rate is measured across device length.

Non-textured Solar Cell:

Here, photon absorption rate of non-textured solar cell is shown in figure 3.10.

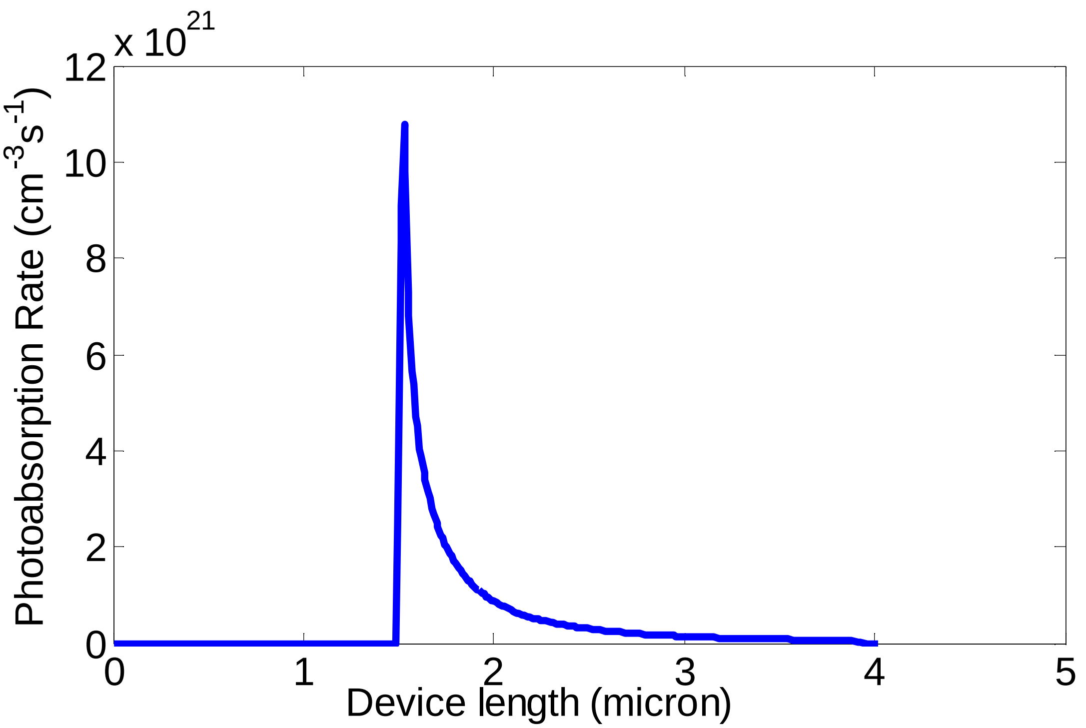

Figure-3.10: photon absorption rate versus device length (micron) of non-textured solar cell

In the non-textured solar cell, the photon absorption starts from 1.48 microns to 4.019 microns. In this period of photo absorption, electron-hole pairs are created. The rate of absorption identifies how much electrons are generated in each of those points of the device. As the length of the device increases, the absorption rate decreases exponentially. Finally, the photon absorption rate becomes constant. At the surface, the device has an absorption rate of

1.08×10^{22} $cm^{-3}s^{-1}$ which means the 1.08×10^{22} electrons are generated at the surface point per second per cm^3.

Textured Solar Cell:

Here, photon absorption rate of textured solar cell is shown in figure 3.11.

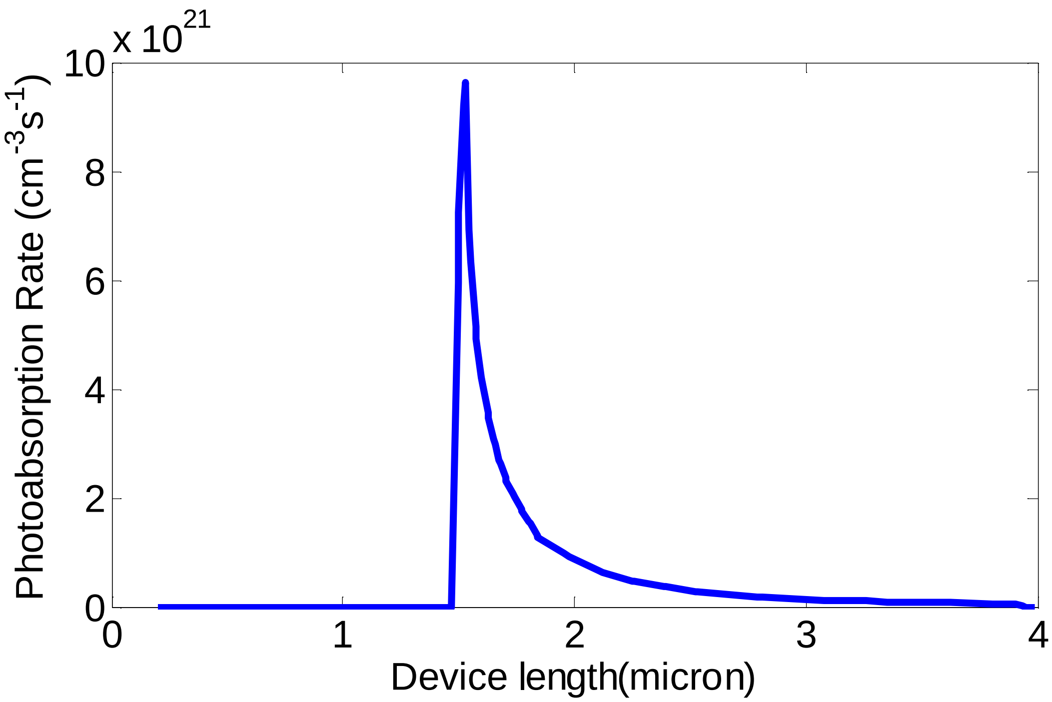

Figure-3.11: photon absorption rate versus device length (micron) of textured solar cell.

In the textured solar cell, the photon absorption occurs from 1.48 microns to 3.991 microns. As like the previous solar cell, this cell is generating electron-hole pairs in this period of length. This rate is also decreasing and finally becomes constant at a certain point. At the surface, the absorption rate is 9.64×10^{21} $cm^{-3}s^{-1}$.

Textured Solar Cell and non-textured solar cell:

The photon absorption rate comparison between non-textured solar cell and textured solar cell is shown in figure 3.12

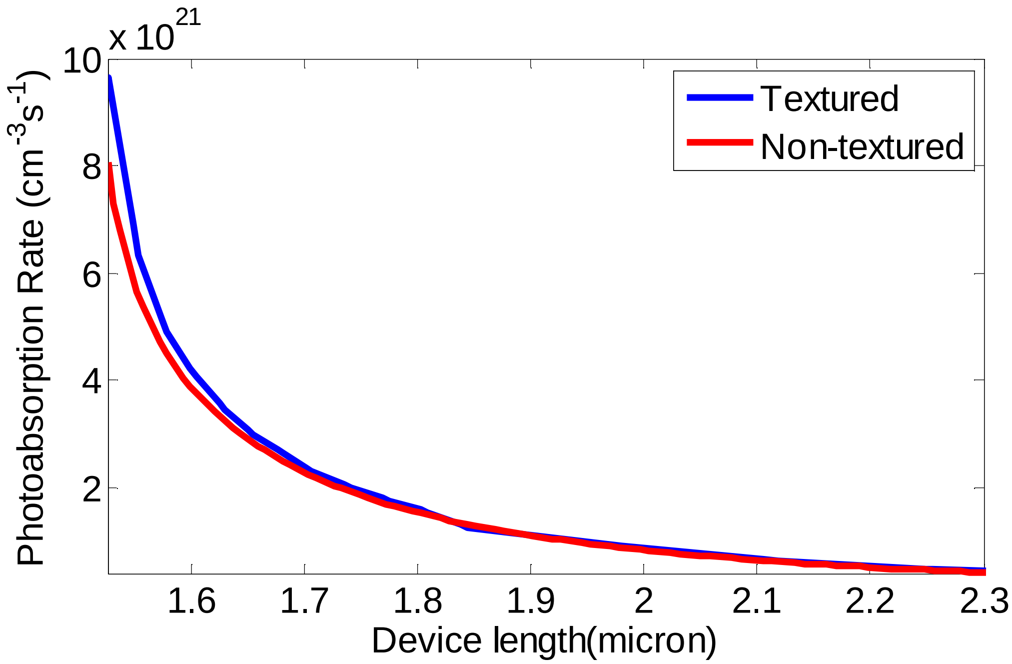

Figure-3.12: photon absorption rate versus device length (micron) of non-textured solar cell and textured solar cell.

In the above figure 3.12, it can be observed that the photo absorption rate of textured solar cell is higher than the non-textured solar cell at the surface point. Here, the absorption rate of both the solar cells keeps decreasing with the device length but the textured solar cell maintains a greater absorption rate than the non-textured solar cell. So, more photons are absorbed for the textured solar cell.

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Chapter 4: Conclusion:

In this thesis, different parameters have been calculated to determine the effect of surface texturing on the solar cells. For this, ATLAS and DEVEDIT tools from SILVACO are used for the structure and simulation. The standard spectrum AM 1.5 is used to simulate the device. After that, all the necessary parameters to measure the performance of the device such as open circuit voltage, short circuit current, output power, efficiency, external quantum efficiency and photon absorption rate have been analyzed. For the structure of the solar cell, ARC of 500 nm, window layer of 500 nm, emitter layer of 500 nm, base layer of 2500 nm are used. Also, Back Surface Field (BSF) is used to reduce surface recombination. Two electrodes are used which are cathode and anode electrodes. Cathode electrode is placed at top and anode electrode is placed at the bottom which has a width of equal of the cell. So, the unused photons cannot pass through the BSF. The photons contacting the anode electrode bounce back to the cell and contribute to generate current. From the analysis, the maximum power of non-textured solar cell is 21.08 mW/cm^2 and that of the textured solar cell is 24.65 mW/cm^2 which is higher than the previous solar cell. So, textured solar cell generates more power. The efficiency of non-textured solar cell is 21.08% and that of textured solar cell is 24.65%. Efficiency is also greater for the textured solar cell. The textured solar cell is absorbing more photons than the non-textured solar cell. It means textured solar cell has a higher photo absorption rate. From all the analysis, it can be proved that the performance of textured solar cell is better than the non-textured solar cell.

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