Chapter One
Introduction

1.1 Introduction

Renewable resources are clean or green energy sources that give much lower environmental impact than conventional energy sources. Renewable resources are attractive so that they come from nature such as sun, air, etc. which means that they will stay forever.

Silicon is the most commonly used semiconductor in optoelectronic devices and Silicon photodiodes are extensively used in industrial applications as reliable devices for light to electricity conversion. Solar cells use the sun, a free and inexhaustible source of fuel, to produce emission-free electricity. In (2006), global cell production grew by 41% to 2520 MW. The crystalline silicon is the most important material in the photovoltaic today. According to predictions it will remain an important and dominant material in photovoltaic over the next 10-30 years; owing to its will recognized properties and its established production technology crystalline silicon solar cells operate by absorbing light and using the discrete energy from the received photons to pump electrons to their exited state. The excited electrons migrate through the material's layers and produce an electrical current, there is no doubt that due to low production costs multicrystalline silicon is attractive substrate for solar cells.

Cell efficiency depends on the silicon dopant, light density and wavelength, optical thickness and surface texture.

Surface texturing, either in combination with an anti-reflection coating or by itself, can also be used to minimize reflection. Any "roughening" of the surface reduces reflection by increasing the chances of reflected light bouncing back onto the surface, rather than out to the surrounding air (Predication, 2015).

Laser processing is a very good technique for texturing silicon structures due to the contactless treatment. Moreover, textures of different patterns can easily be implemented on the treated surface without any additional masking. We have developed a method of laser texturing as a possible solution to the problem of surface textured silicon. Surface texture ensures that incident light meets the cell surface at least twice; transmission of light into the cell is thus considerably increased, the surface texture has many properties simultaneously, including very low reflectance at all incidence angles, and good light trapping that increases the optical path length inside the solar cell

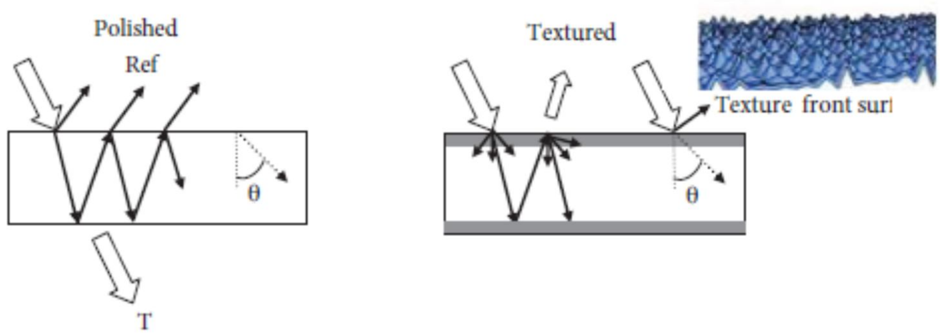

Fig (1.1): Texturing Surface of Solar cell.

1.2 Research Problem

Solar cell efficiencies vary from 6% for amorphous silicon-based solar cells to 44.0% with multiple-junction production cells and 44.4% with multiple dies assembled into a hybrid package. (https://en.wikipedia.org/wiki/Solar_cell_efficiency, 2017) Solar cell energy conversion efficiencies for commercially available multi crystalline Si solar cells are around 14-19% (Schultz,2007); this work focus in develop laser surface modification and applying magnetic field method to enhance solar cell efficiency.

1.3 Literature review

Dobrzański & A. Drygała in 2008elaborated a laser method of texturization multicrystalline silicon. The main reason for taking up the research is that most conventional methods used for texturization of monocrystalline silicon are ineffective when applied for texturing multicrystalline silicon. This is related to random distribution of grains of different crystallographic orientations on the surface of multicrystalline silicon.

In their work the topography of laser textured surfaces was investigated using ZEISS SUPRA 25 and PHILIPS XL 30 scanning electron microscopes and LSM 5 Pascal ZEISS confocal laser scanning microscope. The reflectance of produced textures was measured by Perkin-Elmer Lambda spectrophotometer with an integrating sphere. Electrical parameters of manufactured solar cells were characterized by measurements of I-V illuminated characteristics under standard AM 1.5 radiation. They found that a method of texturing of multicrystalline silicon surface using ND: YAG laser appeared to be much more independent on grains crystallographic orientation compared to conventional texturing methods. Laser texturing makes it possible to increase absorption of the incident solar radiation. (Dobrzański & A. Drygała, 2008).

Taleb et al2011 investigated and demonstrated the experimental evidence of the effect of femtosecond laser pulses on the spectral response of a silicon photovoltaic cell. The observed enhancement is related to the appearing of Nano-structured grooves in the 700-900 nm range. The responsivity and the conversion efficiency of the photovoltaic cell are enhanced by this technique. Ultrashort laser pulses should be still economically reasonable in the large scale production. (Taleb et al 2011).

Kais A. Alnaimee in 2011, utilized fast laser texturing technique to produce Micro/Nano surface textures in Silicon by means of UV femtosecond laser. He had prepared good absorber surface for photovoltaic cells. The textured Silicon surface absorbs the incident light greater than the non-textured surface. His results show a photovoltaic current increased about 21.3% in two dimensions' laser textured area. (Kais A. Alnaimee, 2011).

Jostein Thorstensen and Sean Erik Foss 2011 in conference contribution, a process was developed for production of inverted pyramids and patch textures on (100) - oriented monocrystalline silicon for light-trapping. These textures have a high potential for light-trapping, but are normally produced by photolithography. The process described in this paper is based on the use of a laser to create openings through an etch barrier, after which KOH etching of the underlying silicon develops a pattern consisting of (111) crystal orientations. The geometrical accuracy of the laser system is good, and the structures develop as intended, resulting in a texture with up to estimated 94 % area coverage.

D.A. Zuev et al in 2012 they performed experiments on the "black" mc-Si surface fabrication by the nanosecond pulses of the YAG laser second harmonic and on application of the introduced laser texturing method for the mc-Si solar cells efficiency improvement are represented. The developed version of laser texturing permits producing a low-reflection mc-Si surface with the reflectance of ~3% in the spectral range of 0.3-1 µm. The application of the introduced laser texturing method in mc-Si solar cells fabrication makes it possible to increase the short circuit current density and quantum efficiency. (**D.A**. Zuev et al, 2012).

Antanas VINČIŪNAS et al in 2013, they presented results of laser texturing of Poly-Si solar cells surface by direct laser writing and novel Laser Beam Interference Ablation techniques. Texturing of the surface can increase the solar energy coupling within an active medium. Solar cells with laser-modified surface were characterized by optical and Raman spectroscopy as well as photo-electrically. After laser texturing of polycrystalline silicon solar cells, reflection from their surface was reduced by up to 14%. Structural defects induced by laser irradiation and ablation decreased the lifetime of photo-generated charge carriers and they could not reach the p-n junction. Laser texturing of silicon substrate can be done using direct ablation by interfering laser beams. A reduction in the structure period was demonstrated by up to 3 times by sub-period shift of the work piece between exposures. (Antanas VINČIŪNAS, 2013).

Jostein Thorstensen and Sean Erik Foss 2013in this paper, the light-trapping properties of the patch texture developed in paper I was investigated. Jo Gjessing (IFE) was of great assistance during the optical measurements. Optical absorption measurements on a patch textured silicon wafer are performed and these measurements are compared with ray-tracing simulations. This enables us to extract information about the quality of the texture. From these simulations, the current-generating potential of the textures is extracted. It is found that the created texture gives an increase in I_{sc} of up to 0.5 mA/cm^2 compared to the random pyramids texture and as such, it is concluded that it is possible to generate high quality textures with laser based methods. The process would be interesting for application on (100)-oriented monocrystalline silicon. It is recognized that the process must be simplified in order to justify the added process complexity. **(**Jostein Thorstensen and Sean Erik Foss ,2013).

Marouf et al 2014 utilized a fast laser texturing technique to produce micro/nano surface textures in silicon by mean of UV femtosecond laser pulses. They demonstrated and investigated the experimental evidence of effect of femtosecond laser pulses on the spectral response of a silicon photovoltaic cell. And found that the use of this method leads to improve the responsivity and the conversion efficiency of the photovoltaic cell. The irradiation process leads to the formation of micro-Nano meter periodic structure on substrates with a large area using single or double exposition. This technique is much cheaper and simpler than the electron beam lithography. (Marouf et al, 2014).

1.4 Research Objectives

This research aimed mainly to:

- Firstly, study the effect of magnetic field on the solar cell.
- Secondly modify the surface of silicon solar cells using pulsed CO_2 laser.
- Both investigations the effect of magnetic field and textured technique on the IV-characteristics curve and electrical properties of silicon solar cell.

1.5 Methodology

The method used to investigate the subjects that are focus on this research is experimentally in Vito modify solar cell surface and experimentally set up to operate solar cell and measurement.

1.6 Layout

This research consists of four chapters: chapter one contains a brief introduction of renewable energy, surface texturing and previous studies. The second chapter concern about the basics concepts and detailed theoretical background, which contain the basics of the semiconductor solar cells, interaction of laser with silicon, application of laser in semiconductor material, and mechanism of laser surface texturing, also concept of the magnetic field and its application, experimental part is fully described and presented in chapter three, a setup used to study the IV characteristic of the solar cell, also defines some material which used and each component with it is specifications. Then the results have been presented, analyzed and discussed in chapter four and finally conclusions of this research and recommendations were presented for future works followed by list of reference.

Chapter Two
Basic Concepts

2.1 Solar Cells

A solar cell, or photovoltaic cell, is an electrical device that converts the energy of light directly into electricity by the photovoltaic effect, which is a physical and chemical phenomenon (chemistry explained ,2015).

It is defined as a device whose electrical characteristics, such as current, voltage, or resistance, vary when exposed to light. Solar cells are the building blocks of photovoltaic modules, otherwise known as solar panels.

Solar cells are described as being photovoltaic irrespective of whether the source is sunlight or an artificial light. They are used as a photo detector (for example infrared detectors), detecting light or other electromagnetic radiation near the visible range, or measuring light intensity. Figure (2.1) shows a conventional crystalline silicon solar cell. Electrical contacts made from bus bars (the larger strips) and fingers (the smaller ones) are printed on the silicon wafer (Wikipedia 2015).

Fig (2.1): A conventional crystalline silicon solar cell Electrical.

2.1.1 Solar Cell Construction and Theory

The primary type solar cell is constructed from a single crystal of silicon semiconductor. Silicon, chemical symbol (Si) is an abundant material on Earth. The Earth's crust is comprised of 25.7% silicon in its various forms. Silicon is may be found in sand, clay, granite, quartz, glass, cement and ceramics. It is the second most abundant element found on earth, after oxygen. Silicon must be highly purified (99.9999 %). Pure silicon does not conduct electricity; in fact, it's an insulator. Each silicon atom has four electrons in its outer shell.

What makes silicon so useful in electronics is that by adding a small amount of impurities to the silicon while it is being manufactured alters its electrical properties in a very useful way. The impurities are called dopants in the industry, and the process of adding the impurities is called doping. One dopant material used is phosphorus. Phosphorus has five electrons in its outer shell. The free electron is a negative charge carrier and renders the silicon crystal electrically conductive and is called N-type silicon. Boron is another dopant. This element has only three electrons in its outer shell. The holes do render the silicon crystal conductive. The electron deficient silicon is called P-type silicon. When P-type and N-type silicon are placed in contact with one another it forms a PN junction. A basic PN junction creates a diode that allows electricity to flow in one direction but not the other. Near the PN junction the electrons diffuse into the vacant holes in the P material causing a depletion zone. This depletion zone acts like an insulator preventing other free electrons in the N-type silicon and holes in the P-type silicon from combining. In the next diagram (Fig 2.2) connected an external power source; a battery with a light and current meter that indicate current flow. The negative terminal of the battery is connected to the N-type silicon. So the free electrons are pushed toward the PN junction. Similarly, the holes are repelled by the positive terminal of the battery toward the PN junction. If the voltage pushing the electrons and holes has sufficient strength to overcome the depletion zone (approximately 0.7 V for typical silicon diode) the electrons and holes combine at the junction and current passes through the diode. When a diode is arranged this way with a power supply it is said to be forward-biased. When the battery was connected to the diode so that the negative terminal of the battery connects to the P-type silicon and the positive terminal of the battery connects to the N-type silicon. The negative terminal attracts the positive holes in the P-type silicon and the positive terminal of the battery attracts the free electrons in the N-type silicon. All the charge carriers are pulled away from the PN junction which essentially creates a larger depletion region and no current flows. When a diode is arranged this way with a power supply it is said to be reverse-biased.

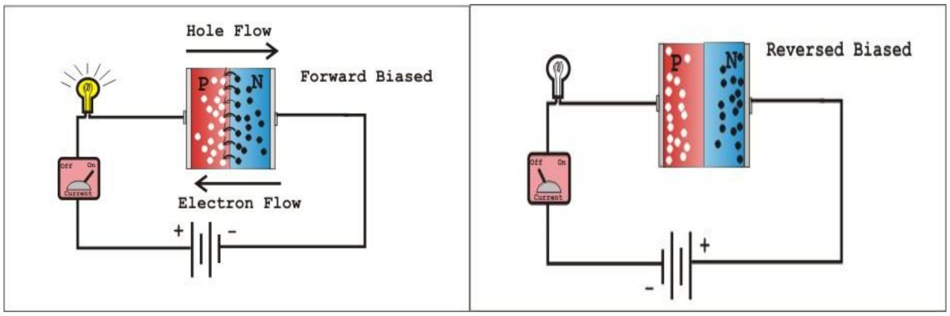

Fig (2.2): forward biased & reversed biased in diode.

A solar cell is essential a PN junction with a large surface area. The N-type material is kept thin to allow light to pass through to the PN junction.

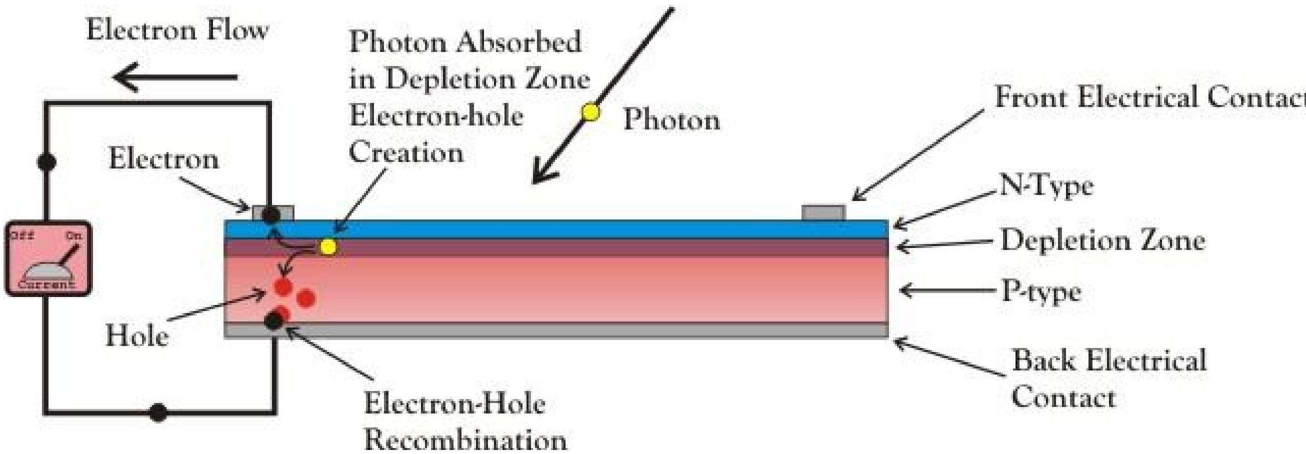

Fig (2.3): Solar Cell Theory.

Light travels in packets of energy called photons. The generation of electric current happens inside the depletion zone of the PN junction. The depletion region as explained previously with the diode is the area around the PN junction where the electrons from the N-type silicon, have diffused into the holes of the P-type material. When a photon of light is absorbed by one of these atoms in the N-Type silicon it will dislodge an electron, creating a free electron and a hole. The free electron and hole has sufficient energy to jump out of the depletion zone. If a wire is connected from the cathode (N-type silicon) to the anode (P-type silicon) electrons will flow through the wire. The electron is attracted to the positive charge of the P-type material and travels through the external load (meter) creating a flow of electric current. The hole created by the dislodged electron is attracted to the negative charge of N-type material and migrates to the back electrical contact. As the electron enters the P-type silicon from the back electrical contact it combines with the hole restoring the electrical neutrality as showed in (figure 2.3) (Pveducation, 2015).

2.1.2 Optical properties of semiconductors

Photon absorption in semiconductor material strongly depends on the interaction between the incident photon flux and the electronic and lattice structures of the semiconductor. As the most important semiconductor material, silicon (Si) is a good example to illustrate the variations of optical properties of semiconductors in crystalline, polycrystalline, amorphous, and liquid forms (Costas p. Grigoropoulos, 2009).

Solar cells can be classified into first, second and third generation cells. The first generation cells also called conventional, traditional or wafer-based cells are made of crystalline silicon, which made of c-Si from wafers between 160 to 240 micrometers thick. The commercially predominant PV technology, that includes materials such as polysilicon and monocrystalline silicon which are made from cast square ingots large blocks of molten silicon carefully cooled and solidified. Second generation cells are thin film solar cells, that include amorphous silicon, CdTe and CIGS cells and are commercially significant in utility-scale photovoltaic power stations, building integrated photovoltaics' or in small stand-alone power system. The third generation of solar cells includes a number of thin-film technologies often described as emerging photovoltaics' most of them have not yet been commercially applied and are still in the research or development phase. Many use organic materials, often organometallic compounds as well as inorganic substances Organic and polymer solar cells are built from thin films (typically 100 nm) of organic semiconductors including polymers, such as polyphenylene vinylene and small-molecule compounds like copper phthalocyanine (a blue or green organic pigment) and carbon fullerenes. Energy conversion efficiencies achieved to date using conductive polymers are very low compared to inorganic materials.

Despite the fact that their efficiencies had been low and the stability of the absorber material was often too short for commercial applications, there is a lot of research invested into these technologies as they promise to achieve the goal of producing low-cost, high-efficiency solar cells.

2.1.3 Photovoltaic Effect

When the solar cell (p-n junction) is illuminated, electron–hole pairs are generated, and acted upon by the internal electric fields, resulting in a photocurrent (I_L). The generated photocurrent flows in a direction opposite to the forward dark current. Even in the absence of an external applied voltage, this photocurrent continues to flow, and is measured as the short-circuit current (I_{sc}). This current depends linearly on the light intensity, because absorption of more light results in additional electrons to flow in the internal electric field force. The overall cell current (I) is determined by subtracting the light induced current (I_L) from the diode dark current I_D.

Then;

$$I = I_D - I_L \qquad (2.1)$$

$$I = I_0\left[\exp\left(\frac{eV}{kT}\right) - 1\right] - I_L \qquad (2.2)$$

This phenomenon is called the photovoltaic effect (Tiwari G. N. and Mishra R. K . ,2012).

2.1.4 Basic Parameters of Solar Cell

2.1.4.1 Overall Current (I)

This is determined by subtracting the light-induced current from the diode dark current and can be expressed as:

Overall current (I) = Diode dark current (I_D) - light induced current (I_L)

2.1.4.2 Short-Circuit Current (I_{sc})

This is the light generated current or photocurrent, I_L. It is the current in the circuit when the load is zero in the circuit. It can be achieved by connecting the positive and negative terminals by a copper wire.

2.1.4.3 Open-Circuit Voltage (V_{oc})

It is obtained by setting I=0 in expression for overall current, i.e. I=0 when $V=V_{oc}$. The open-circuit voltage is the voltage for maximum load in the circuit.

2.1.4.4 I–V Characteristics

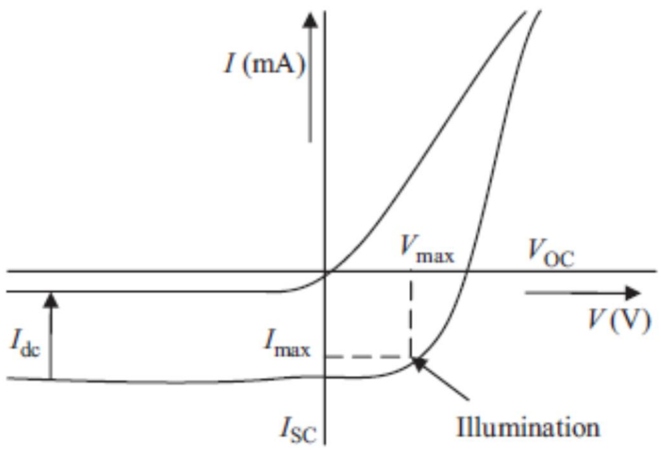

Fig (2.4): I–V characteristics of a solar cell with and without illumination.

The current equation for a solar cell is given by,

$$I = I_0\left[\exp\frac{e(V - IR_S}{kT} - 1\right] \qquad (2.3)$$

And is shown in Figure (2.4) For a good solar cell, the series resistance, R_s, should be very small and the shunt (parallel) resistance, R_p, should be very large. For commercial solar cells, R_p is much greater than the forward resistance of a diode so that it can be neglected and only R_s is of interest. The optimum load resistance R_L (P_{max})=R_{Pmax} is connected, if the PV generator is able to deliver maximum power.

$$P_{max} = V_{pmax}\ I_{pmax} \tag{2.4}$$

And

$$R_{pmax} = V_{pmax} / I_{pmax} \tag{2.5}$$

The efficiency is defined as,

$$\eta = P/\Phi \tag{2.6}$$

Where,

$P=V\times I$, is the power delivered by the PV generator.

$\Phi=I_T\times A$, is the solar radiation falling on the PV generator.

I_T is the solar intensity and A is the surface area irradiated.

2.1.4.5 Fill Factor (FF)

Another defining term in the overall behavior of a solar cell is the fill factor (FF). This is the available power at the maximum power point (P_m) divided by the open circuit voltage (V_{OC}) and the short circuit current (I_{SC}):

$$FF=\frac{P_m}{V_{oc}\times I_{sc}}=\frac{\eta\times A_c\times E}{V_{oc}\times I_{sc}} \tag{2.7}$$

The fill factor, also known as the curve factor (Figure 2.5), is a measure of the sharpness of the kneein the I–V curve. It indicates how well a junction was made in the cell and how low the series resistance has been made. It can be lowered by the presence of series resistance and tends to be higher whenever the open-circuit voltage is high. The maximum value of fill factor is one, which is not possible. Its maximum value in Si is 0.88. (Tiwari G. N. and Mishra R. K, 2012).

$$FF = \frac{P_m}{V_{oc} \times I_{sc}} = \frac{I_{max} \times V_{max}}{V_{oc} \times I_{sc}} \quad (2.8)$$

Cells with a high fill factor have a low equivalent series resistance and a high equivalent shunt resistance, so less of the current produced by the cell is dissipated in internal losses.

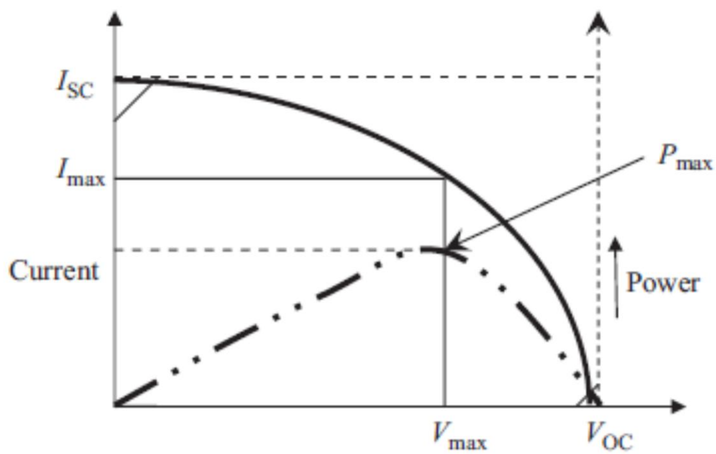

Fig (2.5): Characteristic and power curve for determining the fill factor (FF).

2.1.4.6 Maximum Power (P_{max})

No power is generated under short or open circuit. The power output is defined as,

$$P_{out} = V_{out} x\ I_{out} \quad (2.9)$$

The maximum power P_{max} provided by the device is achieved at a point on the characteristics, where the product IV is maximum. Thus,

$$P_{max} = I_{max} x\ V_{max} \quad (2.10)$$

The maximum possible output can also be given as,

$$P_{max} = V_{oc}\ x\ I_{sc}\ x\ FF \quad (2.11)$$

Where, FF is the fill factor given by Eq (2.8)

2.1.4.7 Solar Cell Efficiency (η_{ec})

It is the ratio of the electrical output of a solar cell to the incident energy in the form of sunlight. This is calculated by dividing a cell's power output (in watts) at its maximum power point (P_m) by the irradiance (input light), (I), in W/m^2 and the surface area of the solar cell (A_c in m^2).A solar cell has a voltage dependent efficiency curve, temperature coefficients, and allowable shadow angles.(Wikipedia 2015).

The solar cell power conversion efficiency can be given as;

$$\eta_{ec} = \frac{p_{max}}{P_{in}} = \frac{I_{max} \times V_{max}}{incidentso\ larradiati\ on \times Areaofsola\ rcell} = \frac{V_{oc} \times I_{sc} \times FF}{I_{(t)} \times A_c} \quad (2.12)$$

Where, I_{max} and V_{max} are the current and voltage for maximum power, corresponding to solar intensity (I (t)).Due to the difficulty in measuring these parameters directly, other parameters are substituted: thermodynamic efficiency, quantum efficiency (refers to the percentage of photons that are converted to electric current. Quantum efficiency is most usefully expressed as a spectral measurement (that is, as a function of photon wavelength or energy). Since some wavelengths are absorbed more effectively than others, spectral measurements of quantum efficiency can yield valuable information about the quality of the semiconductor bulk and surfaces), integrated quantum efficiency, V_{OC} ratio, and fill factor. Reflectance losses are a portion of quantum efficiency under "external quantum efficiency". Recombination losses make up another portion of quantum efficiency, V_{OC}

ratio, and fill factor. Resistive losses are predominantly categorized under fill factor (Tiwari G. N. and Mishra R. K, 2012).

2.2 Interaction between Lasers and Matter

When light strikes the surface of a material, a portion will be reflected from the interface due to the discontinuity in the real index of refraction and the rest will be transmitted into the material. The fraction of the incident power that is reflected from the surface (R) depends on the polarization and angle of incidence (θ_i) of the light as well as the index of refraction of the atmosphere (n_1) and the material (n_2). The reflection coefficients (R) are related to the transmission coefficients through T= 1- R, for the case of normally incident light on a flat surface.

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2 \tag{2.13}$$

The reflectivity of a given material will depend on the frequency of the light source through the dispersion relation of its index of refraction. Also depend on the temperature of the material through changes in the permittivity, band structure, plasma oscillations, or material phase.

Once inside the material, absorption causes the intensity of the light to decay with depth at a rate determined by the material's absorption coefficient (α). In general, (α) is a function of wavelength and temperature, but for constant (α), intensity (I) decays exponentially with depth (z) according to the Beer–Lambert law.

$$I(z) = I_0 e^{-\alpha z} \tag{2.14}$$

Where; I_0 is the intensity just inside the surface after considering reflection loss.

It is convenient to define the optical penetration or absorption depth, $\delta = 1/\alpha$ which is the depth at which the intensity of the transmitted light drops to (1/e) of its initial value at the interface. Absorption depths are short relative to bulk material dimensions.

When dealing with CW or nanosecond duration laser pulses, it is typically assumed that most of the absorption is due to single photon interactions. However, for picoseconds (PS) and femtosecond (fs) lasers, the extremely high instantaneous intensity enables phenomena such as optical breakdown and multiphoton absorption which can significantly decrease absorption depths.

2.2.1 Relation Between Reflectance, Transmission and Absorption

In general, reflection, transmission and absorption depend on the wavelength of the affected radiation. Thus, these three processes can either be quantified for monochromatic radiation. In addition, reflectance, transmittance and absorbance might also depend on polarization and geometric distribution of the incident radiation, which therefore also has to be specified. The reflectance(R) is defined by the ratio of reflected radiant power to incident radiant power. The transmittance (T) of a medium is defined by the ratio of transmitted radiant power to incident radiant power. The absorbance (A) of a medium is defined by the ratio of absorbed radiant power to incident radiant power. Being defined as ratios of radiant power values.

By Kirchhoff's radiation law, the flux emitted by a hot object must be equal to the amount absorbed by it; therefore, the emittance of an object must be equal to

$$A + R + T = 1 \tag{2.15}$$

As all light that is neither reflected nor transmitted must be absorbed the difference (1-R-T) is equal to the absorption (A). In a rough approximation we could now calculate the absorption coefficient (α) according to the equation:

$$R + T = e^{-\alpha d} \tag{2.16}$$

Where (d) is the thickness of the sample (Grolik Benno, Kopp Joachim 2003).

angle at which the incident Reflectance, transmittance and absorbance are dimensionless. The optical properties of materials are not a constant since they are dependent on many parameter such as:

- Thickness of the sample.
- Surface conditions.
- Angle of incidence.
- Temperature (Gigahertz-opitks, 2015).

There are several key characteristics of the incident solar energy which are critical in determining how the incident sunlight interacts with a photovoltaic converter or any other object. The important characteristics of the incident solar energy are:

- The spectral content of the incident light.
- The radiant power density from the sun.
- The solar radiation strikes a photovoltaic module.

The radiant energy from the sun throughout a year or day for a particular surface (Pveducation ,2015).

2.2.2 Energy Absorption Mechanisms

The specific mechanisms by which the absorption occurs will depend on the type of material. In insulators and semiconductors, the absorption of laser light predominantly occurs through resonant excitations such as transitions of valence band electrons to the conduction band (interband transitions) or within bands (intersubband transitions). These excited electronic states can then transfer energy to lattice phonons. Photons with energy below the material's band gap will not be absorbed (unless there are other impurity or defect states to couple to or if there is multiphoton absorption). Such energies typically correspond to light frequencies below vacuum ultraviolet for insulators and below the visible to infrared spectrum for semiconductors.

The time it takes for the excited electronic states to transfer energy to phonons and thermalize depends on the specific material and the specific mechanisms within the materials. For most metals, this thermalization time is on the order of 10^{-12}–10^{-10} s.

The spread in energy during the laser pulse combined with the spread in energy after the pulse can lead to changes in the material properties. The region over which these changes occur is denoted the heat affected zone (HAZ).

2.2.3 Material Response

Material responses is that can occur in a material due to laser irradiation. These responses typically result in permanent changes to the material's surface chemistry, composition, crystal structure, and morphology. By choosing the appropriate laser parameters, precise control of the final material properties can be achieved.

2.2.4 Interaction between Laser and Silicon

After the absorption of short laser pulses of high peak intensities silicon is heated up so that the surface is partially molten. If the absorbed energy is sufficiently high some of the material is explosively evaporated from the molten layer. The recoil pressure of evaporated material and the plasma plume formed in this process ejects a part of molten layer. As a result of this violent expulsion of the material the deposition of solidified silicon droplets, both inside and outside of the groove can be observed Bottom and sidewalls of laser scribed grooves are covered with molten, not evaporated and resolidified material. Solar cells manufactured from laser textured wafers that were not etched shown very low conversion efficiency. It was a result of detrimental influence of laser induced defects on the operation of solar cells. Therefore, post laser processing etching was performed to remove laser damaged layer. With the increase of thickness of removed layer positive ridges were etched off and textured surface was smoothened away. Furthermore, the angle between sidewalls increased resulting in formation of so-called V-grooves. In the bottom of the grooves may be observed regions of regular shape dependent on crystallographic orientation of substrate. As a result of laser processing and subsequent etching texture of uniform structure were obtained Solar cells manufactured from laser textured wafer that were not etched demonstrating extremely low efficiency. This is the result of damages introduced into the top layer of the material during laser texturing. These damages have detrimental influence on the operation of solar cell and reduce its performance mainly through increased recombination and/or junction shunting. Fortunately, it appears that detrimental influence of laser induced damage on the solar cells performance may be successively mitigated by post laser processing etch procedure. Applied etching step enable to remove layer of laser induced defects from the textured surface. Many trials have been performed to adjust etch concentration and thickness of removed layer. It can be observed that with the increase of thickness of removed layer efficiency of solar cell grows but at the same time the effective reflectance increase as well. Consequently, post-laser texturing etching improves electrical properties of textured material but deteriorates its optical properties. That is why the proper adjustment of thickness of removed layer must be a trade of balancing these properties of solar cells. (Dobrzański & A. Drygała, 2008).

2.3 Laser Surface Modification

Lasers provide the ability to accurately deliver large amounts of energy into confined regions of a material in order to achieve a desired response. For opaque materials, this energy is absorbed near the surface, modifying surface chemistry, crystal structure, and/or

Multiscale morphology without altering the bulk. Modification of surface properties over multiple length scales plays an important role in optimizing a material's performance for a given application. For instance, the cosmetic appearance of a surface and its absorption properties can be controlled by altering its texture and presence of chemical impurities in the surface. Confinement of deposited energy to desired regions on a material's surface can be achieved by controlling the laser's spatial intensity profile. The predominant methods for control include beam steering by fixed or galvanometric scanning mirrors, beam focusing through telescoping or converging optics, and beam shaping with homogenizers, amplitude masks, refractive elements, and diffractive optical elements (DOE) (Matthew S. Brown and Craig B. Arnold ,2010).

2.3.1 Surface Texturing for Enhanced Optical Properties

Surface Texturing for Enhanced Optical properties use to decrease reflections and increase absorption for enhanced device performance without altering bulk properties.

One of the method for the reduction of reflections are to texture the existing semiconductor surface. Because no additional material is added, these textured surfaces are inherently more stable and do not suffer from material compatibility issues that plague thin films such as weak adhesion, thermal expansion mismatch, and interdiffusion. Multiscale texturing of a surface can cause significant deviations in how light is reflected and scattered, leading to enhanced absorption over that of a flat smooth surface. For surface features with dimensions greater than several wavelengths of light, this enhancement can most easily be described using the principles of ray optics. A portion from a ray of light will specularly reflect from a flat surface, and have no further interaction with the material. On the other hand, protruding features can reflect and scatter light back onto the surface; Light can effectively become trapped in crevices and holes where multiple reflections enhance the coupling into the material. Once inside these protruded structures, multiple internal reflections can guide the light into the bulk.

Refraction at the surface of these structures also leads to transmission at oblique angles, effectively increasing the optical path length, enhancing absorption. The degree of enhancement depends on the particular geometry and dimension of the surface features. The creation of features at or near the surface with dimensions on the order of a wavelength (e.g., cracks, voids, and surface roughness) can also affect the surface reflectivity by scattering light in the material and increasing the optical path length, leading to enhanced absorption. This is especially important for enhancing absorption in thin-film devices where the thickness of the film is on the order of the optical wavelength. Light trapping is usually achieved by changing the angle at which light travels in the solar cell by having it be incident on an angled surface. A textured surface will not only reduce reflection. Also couple light obliquely into the silicon like (figure 2.6) thus giving a longer optical path length than the physical device thickness. The angle at which light is refracted into the semiconductor material is, according to Snell's Law, as follows:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \qquad (2.17)$$

Where; θ_1 and θ_2 are the angles for the light incident on the interface relative to the normal plane of the interface within the mediums with refractive indices n_1 and n_2 respectively. θ_1 and θ_2

By rearranging Snell's law above, the angle at which light enters the solar cell (the angle of refracted light) can be calculated:

$$\theta_2 = \sin^{-1}(n_2 n_1 \sin\theta_1) \qquad (2.18)$$

In a textured single crystalline solar cell, the presence of crystallographic planes makes the angle θ_1 equal to 36°.

The amount of light reflected at an interface is calculated from the Fresnel reflection formula. For light polarized in the parallel to the surface the amount of reflected light is:

$$R\| = \tan^2(\theta_1 - \theta_2)\ \tan^2(\theta_1 + \theta_2) \quad (2.19)$$

Using total internal reflection, light can be trapped inside the cell and make multiple passes through the cell, thus allowing even a thin solar cell to maintain a high optical path length.

While the reduction of reflection is an essential part of achieving a high efficiency solar cell, it is also essential to absorb all the light in the silicon solar cell.

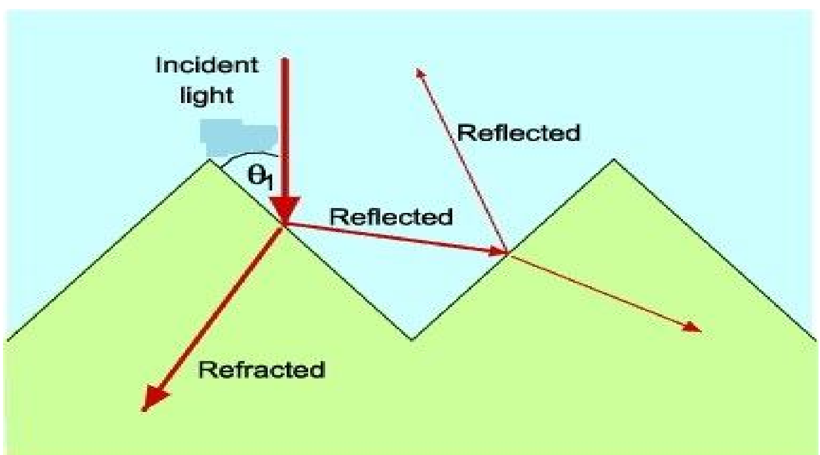

Fig (2.6): Reflection and transmission of light for a textured silicon solar cell.

The amount of light absorbed depends on the optical path length and the absorption coefficient (Bunea G,et al, 2006).

2.3.2 Laser Direct-Write Processing

Direct-write techniques enable computer controlled two and three dimensional Pattern formation in a serial fashion.

Among these techniques, the versatility offered by laser based direct-write methods is unique, given their ability to add, remove, and modify different types of materials without physical contact between a tool or nozzle and the material of interest. Laser pulses used to generate the patterns can be manipulated to control the composition, structure, and even properties of individual three-dimensional volumes of materials across length scales spanning six orders of magnitude, from nanometers to millimeters. Such resolution, combined with the ability to process complex or delicate material systems, enables laser direct-write tools to fabricate structures that are not possible to generate using other serial or parallel fabrication techniques.

In general, direct-write processing refers to any technique that is able to create a pattern on a surface or volume in a serial or "spot-by-spot" fashion. This is in contrast to lithography, stamping, directed self-assembly, or other patterning approaches that require masks or preexisting patterns.

The key elements of any LDW system can be divided into three subsystems:

Laser source, (2) beam delivery system, and (3) substrate/target mounting system. (Figure 2.7) shows a Schematic illustration of a laser direct-write system. The basic components of an LDW system are (left to right) a substrate mounting system, a beam delivery system, and a laser source. Motion control of either the beam delivery system or the substrate mounting system is typically accomplished using computer-assisted design and manufacturing (CAD/CAM) integrated with the laser source.

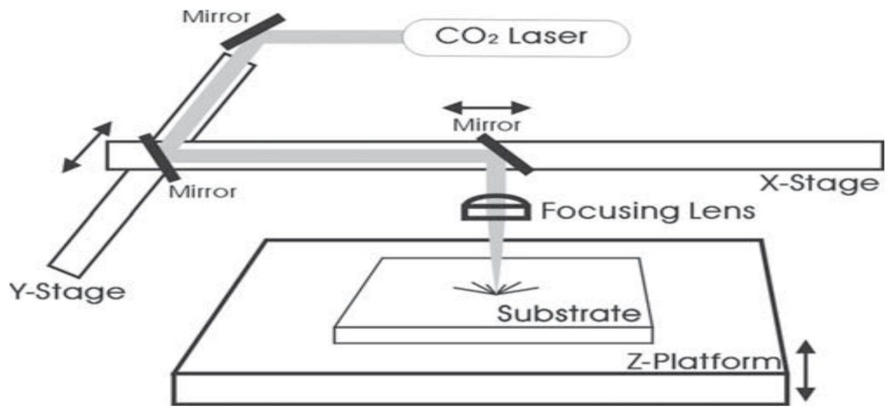

Fig (2.)7: Schematic illustration of a laser direct-write system.

2.4 Effect of Temperature

Like all other semiconductor devices, solar cells are sensitive to temperature. Increases in temperature reduce the band gap of a semiconductor, thereby effecting most of the semiconductor material parameters. The decrease in the band gap of a semiconductor with increasing temperature can be viewed as increasing the energy of the electrons in the material. Lower energy is therefore needed to break the bond. In the bond model of a semiconductor band gap, reduction in the bond energy also reduces the band gap. Therefore, increasing the temperature reduces the band gap.

2.5 Magnetic Fields

All charged particles create electric fields, and these fields can be detected by other charged particles resulting in electric force. However, a completely different field, both qualitatively and quantitatively, is created when charged particles move. This is the magnetic field. All moving charged particles create magnetic fields, and all moving charged particles can detect magnetic fields resulting in magnetic force. This is in addition to the electric field that is always present surrounding charged particles .The term is used for two distinct but closely related fields denoted by the symbols **B** and **H**, where **H** is measured in units of amperes per meter (symbol: $A \cdot m^{-1}$ or A/m) in the SI. **B** is measured in tesla (symbol: T) and Newton per meter per ampere (symbol: N.m−1.A−1 or N/(m.A)) in the SI. B is most commonly defined in terms of the Lorentz force it exerts on moving electric charges (Wikipedia, the free encyclopedia, 2017).

2.5.1 Measurement

Devices used to measure the local magnetic field are called magnetometers. Important classes of magnetometers include using a rotating coil, Hall effect magnetometers, NMR magnetometers, SQUID magnetometers, and fluxgate magnetometers. The magnetic fields of distant astronomical objects are measured through their effects on local charged particles. For instance, electrons spiraling around a field line produce synchrotron radiation that is detectable in radio waves.

2.5.2 Relation between H and B

The formulas derived for the magnetic field above are correct when dealing with the entire current. A magnetic material placed inside a magnetic field, though, generates its own bound current, which can be a challenge to calculate. (This bound current is due to the sum of atomic sized current loops and the spin of the subatomic particles such as electrons that make up the material).The H-field as defined above helps factor out this bound current; but to see how, it helps to introduce the concept of magnetization first.

2.5.3 Applications of the Magnetic field

- Dynamo theory – a proposed mechanism for the creation of the Earth's magnetic field
- Helmholtz coil – a device for producing a region of nearly uniform magnetic field

- Magnetic field viewing film – Film used to view the magnetic field of an area
- Maxwell coil – a device for producing a large volume of an almost constant magnetic field.
- Stellar magnetic field – a discussion of the magnetic field of stars
- Teltron tube – device used to display an electron beam and demonstrates effect of electric and magnetic fields on moving charges.

2.6 Hall Effect

The Hall Effect is the production of a voltage different (the Hall voltage) across an electrical conductor, transverse to an electric current in the conductor and magnetic field perpendicular to the current.

The Hall coefficient is defined as the ratio of the induced electric field to the product of the current density and the applied magnetic field. It is a characteristic of the material from which the conductor is made, since its value depends on the type, number, and properties of the charge carriers that constitute the current (Wikipedia).

The Hall Effect is often used to measure the magnitude of a magnetic field. It is used as well to find the sign of the dominant charge carriers in materials such as semiconductors (negative electrons or positive holes).

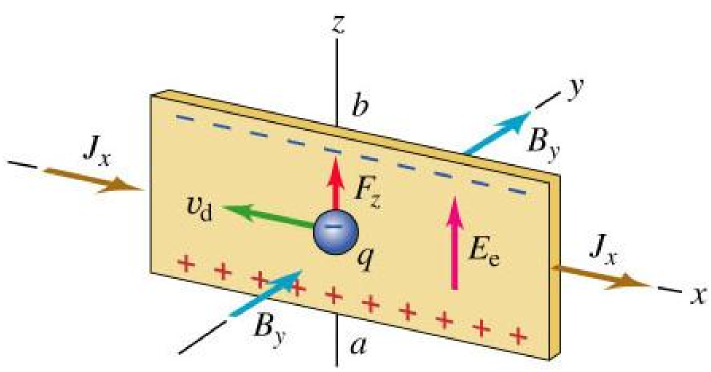

Fig (2.8): Hall Effect

2.6.1 Hall effect in semiconductors

When a current-carrying semiconductor is kept in a magnetic field, the charge carriers of the semiconductor experience a force in a direction perpendicular to both the magnetic field and the current. At equilibrium, a voltage appears at the semiconductor edges.

The simple formula for the Hall coefficient given above becomes more complex in semiconductors where the carriers are generally both electrons and holes which may be present in different concentrations and have different mobility's (*Kasap, Safa, 2008).*

2.6.2 Applications

- Hall probes are often used as magnetometers, i.e. to measure magnetic fields, or inspect materials (such as tubing or pipelines) using the principles of magnetic flux leakage.
- Hall Effect devices produce a very low signal level and thus require amplification. While suitable for laboratory instruments, the tube amplifiers available in the first half of the 20th century were too expensive, power consuming, and unreliable for everyday applications. It was only with the development of the low cost integrated circuit that the Hall Effect sensor became suitable for mass application.
  - Many devices now sold as Hall Effect sensors in fact contain both the sensor as described above plus a high gain integrated circuit (IC) amplifier in a single package. Recent advances have further added into one package an analog-to-digital converter and I^2C (Inter-integrated circuit communication protocol) IC for direct connection to a microcontroller's I/O port.

Chapter Three

Experimental Part

This chapter presents the experimental part of this work, setup arrangement and experimental procedure:

3.1 Material

The materials used to complete this work, and their specifications are given here

3.1.1 Silicon Solar Cell

There are four solar cells used in this work were assembled by San Fu Chemical Company, Chung Shan, and Taipei, Taiwan with specifications listed in table (3.1). And Figure (3.1) below shows the cell (austinsolartech,2015).

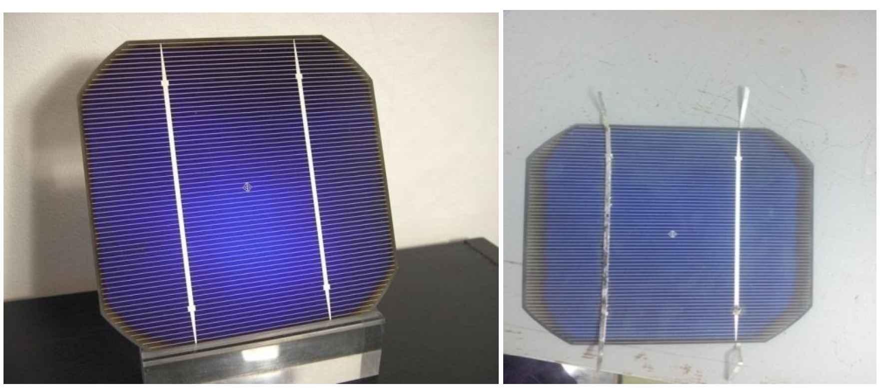

Fig (3.1): 125x125 mono-crystalline solar cells

Table (3.1): Solar cells samples specifications

Properties	Value
Size	125*125mm ±1mm (5 inch)
Efficiency	17.2%
Thickness (Si)	240 µm +/- 40 µm
Busbar quantity	2
Color	nice uniformity blue color
Front	Blue silicon nitride anit-reflection coated.1.5mm silver busbar
Max power	2.505~2.535 Watt
Diagonal:	150 mm± 1.0 mm (round chamfers)
Based Material	P-type mono-crystalline silicon wafer doped with boron
Back	Surface Aluminum back surface field. 3mm wide segment soldering pads (Silver).
I_{mpp} (A)	4.824
I_{sc} (A)	5.163
V_{pm} (V)	0.525
V_{oc} (V)	0.628

3.1.2 Light Source (Lamp)

Fig (3.2): halogen lamp.

Table (3.2) Lamp commercial & electric's specifications:

Properties	Value
Intensity of irradiation on a distance 40cm	407 W/M^2
Lamp Wattage	10 W
Voltage	220 V
Lamp Current	2.5 A

3.1.3 laser Machine

Fig (3.3): Technique of deliver laser beam to working area by mirrors.

Table (3.3) Show the Properties of the machineCO_2LaserUsed to Textured Solar Cell

Properties	Value
Max power	130W
Velocity	400 mm/s

3.1.4 Magnetic Field Source

Fig (3.4): Helmholtz coils used to generate magnetic field.

Table (3.4): show the properties of Helm holtz coils.

Properties	**Value**
Number of turns (N)	320
Max current	2 A
Radius	6.7 cm

Fig (3.5): coils used to generate magnetic field.

Table (3.5): show the properties of coils used to generate magnetic field.

Properties	**Value**
Number of turns (N)	480 9
Max current (I)	10A
Resistance (R)	1.1 Ω

Also used variable rheostat (40Ω) three terminals, DT-700D digital multimeter as Ammeter and Voltmeter and CO_2 (130W) laser.

3.2 Experimental setup

3.2.1 IV Characteristics Measurements of Solar Cell of as Obtained

Measured the open circuit voltage (V_{oc}) and short circuit current (I_{sc}) between the terminals of solar cell.

Fig (3.6): setup arrangement to measure I-V characteristics of solar cell.

3.2.2 IV Characteristics Measurements of Solar Cell in Vertical Magnetic Field

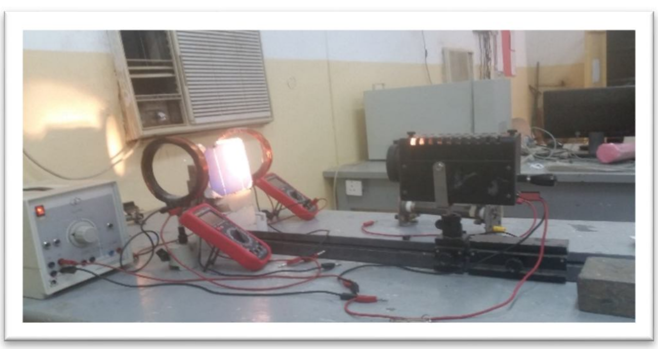

Fig (3.7): setup arrangement to measure I-V characteristic of solar cell in vertical magnetic field.

3.2.3 IV Characteristics Measurements of Solar Cell in Horizontal Magnetic Field

Fig (3.8): **setup arrangement to measure I-V characteristics of solar cell in magnetic field.**

3.2.4 IV Characteristics Measurements of Solar Cell after texturing

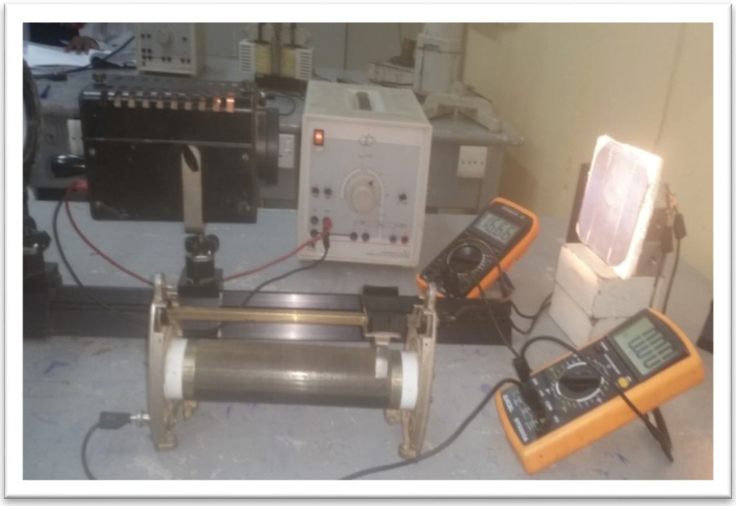

Fig (3.9): **setup arrangement to measure I-V characteristics of textured solar cell.**

3.2.5 IV Characteristics Measurements of textured Solar Cell and in magnetic field

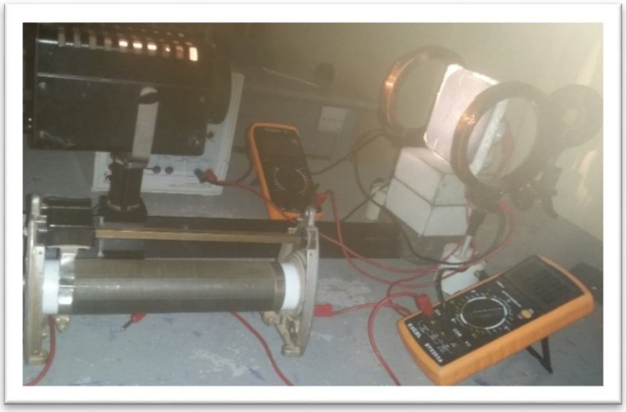

Fig (3.10): **setup arrangement to measure I-V characteristics of textured solar cell in magnetic field.**

3.3 Experimental procedure

The apparatus was connected as shown in Fig (3.6), the distance (D) from the lamp to the solar cell was carefully measured and control during all measurements= 40cm, one solar cell without laser irradiation was used firstly and read its voltage and current which controlled by rheostat, the obtained results were tabulated and plotted. Solar cell fill factor were calculated according to: $FF = \frac{I_m V_m}{I_{sc} V_{oc}}$, and the efficiency calculated by divided the output power from the cell over input power to it. All this steps repeated in existing of solar cell in a vertical and horizontal magnetic field as shown in fig (3.7) and fig (3.8) respectively, after that textured the cell by used CO_2 laser (130W) and CNC table which shows in figure (3.9) above. Parameters of laser treatment were adjusted and assumed to take the following values: output power (P = 65W), speed of laser beam $\upsilon = 400$ mm/sand the textured area is 3x3 cm^2. The texture consisting of parallel points of molten silicon with spacing of 40μm was produced, and finally putted it in magnetic field as shown in fig (3.10).

*All treatments and measurements have been done at room temperature.

Chapter Four

Result and Discussions

4-1 Result and Discussions

4-1-1Results of I-V Characteristics of as Obtained Solar Cell$_1$

Figure (4.1) shows the plot between voltage and current density values for sample of as obtained cell. The X axis represents the voltage by unit (volt) whish changes with variation of resistance value. The Y axis represents the values of current density by unit (ampere) and power by unit (watt) which changes according to voltage changes.

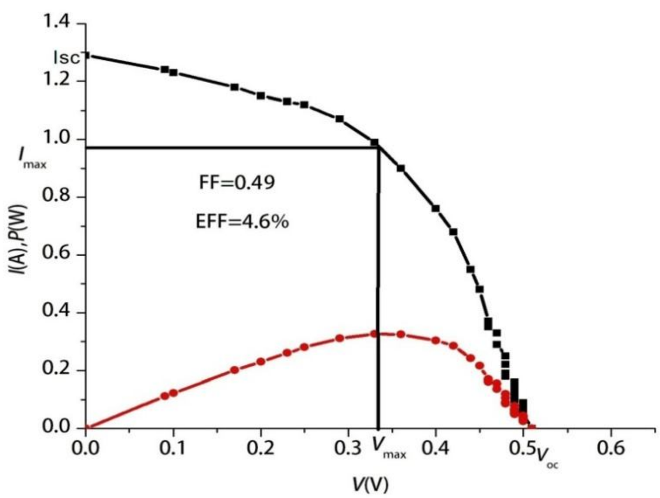

Fig (4.1) plot of the I-V characteristics curve of as obtained solar cell$_1$.

4.1.2 Results of I-V Characteristics of Solar Cell in Vertical Magnetic Field

Figure (4.2) shows the plot between voltage and current density values for the same sample solar cell when putted in vertical magnetic field.

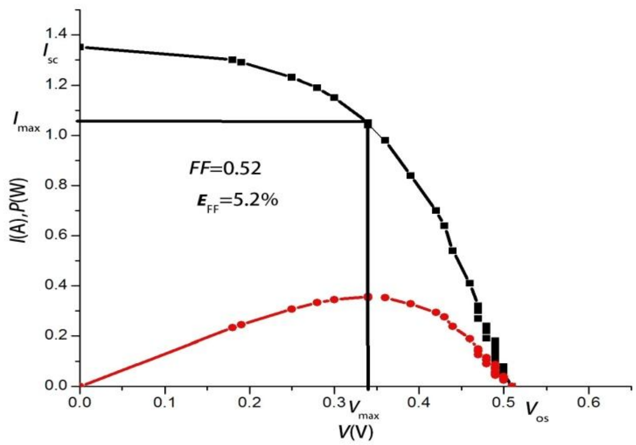

Fig (4.2): plot of the I-V characteristics curve of solar cell$_1$ in vertical magnetic field.

4.1.3 Irradiation with 10.6µm

When take look on laser textured wafers revealed that grooves are irregular in shape with positive ridges at both rims. This is the result of interaction of laser beam with the treated surface. Fig (4.3) shows the textured area on the cell which appeared darker than un textured area.

Fig (4.3): textured area on the cell$_1$ in one dimension.

4-1-4 Results of I-V Characteristics of solar cell after Irradiation by laser

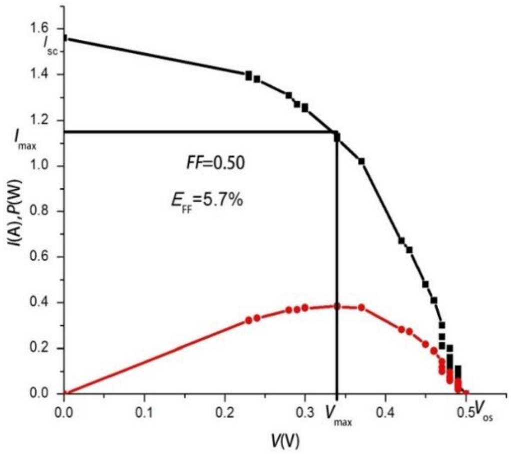

Fig (4.4) plot of the I-V Characteristics curve of the textured solar $cell_1$ in one dimension.

By take the $V_{oc,}$ I_{SC}, I_{max} and V_{max} from each graph, I calculated fill factor and then efficiency. The value of light intensity from distance equal to 40 cm was 407Watt/m^2 and the cell area equal to 0.0169 m^2.

Table (4.1) shows the electrical properties for solar $cell_1$ before and after texturing and in vertical, magnetic field.

Type of solar cell	V_{oc} (V)	I_{sc} (A)	V_{max} (V)	I_{max} (A)	FF	E_{ff} %
Solar $cell_1$ of as obtained	0.50	1.29	0.33	0.97	0.49	4.6%
Solar $Cell_1$in vertical magnetic field	0.50	1.35	0.34	1.05	0.52	5.2%
$Cell_1$after textured	0.50	1.56	0.34	1.15	0.50	5.7%

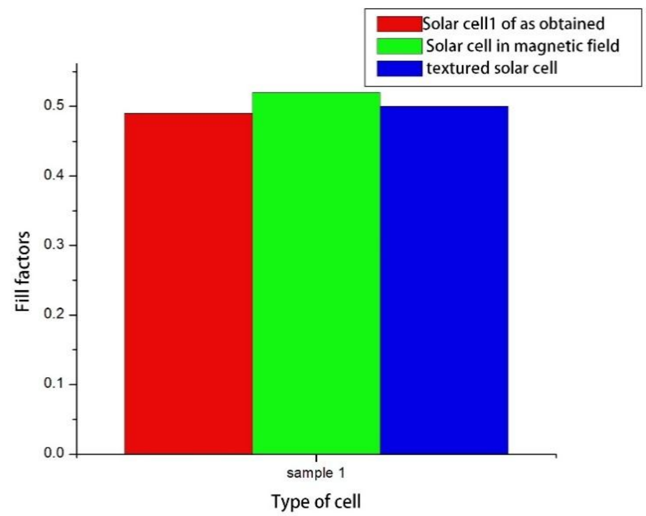

Fig (4.5) chart shows the changes of fill factors for cell$_1$ of as obtained and after operated in vertical magnetic field and finally textured.

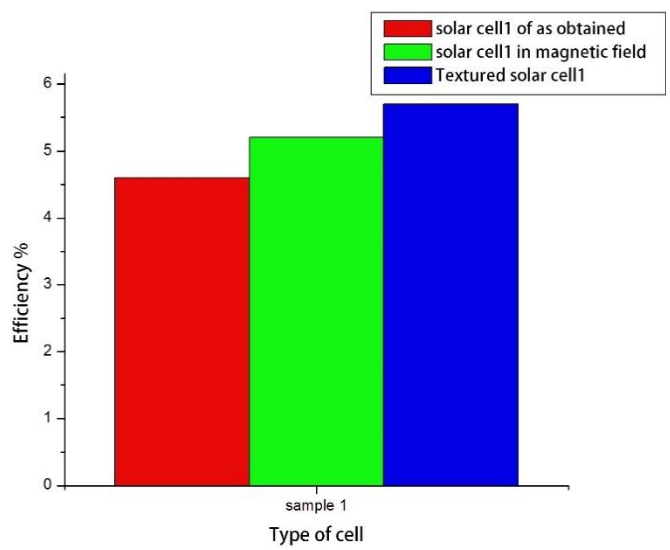

Fig (4.6) chart shows the changes of efficiency for cell$_1$ of as obtained and after putted in vertical magnetic field and finally textured.

- When applying vertical magnetic field to the cell$_1$resulted in an increase of its efficiency by 0.6% and fill factor by 0.03.

- Irradiation the $cell_1$ with CO_2 laser (1.06µm) resulted in an increase in Short Circuit Current (I_{sc}) magnitude, efficiency by 1.1% and fill factor (see the charts above).

4.1.5 Results of I-V Characteristics of Solar $cell_2$of as obtained

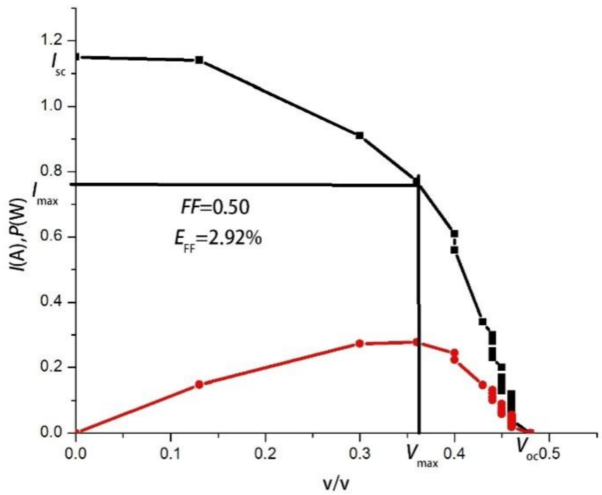

Fig (4.7) plot of the IV Curve characteristics of as obtained solar $cell_2$.

4.1.6 Results of I-V Characteristics of Solar $cell_2$in horizontal magnetic field

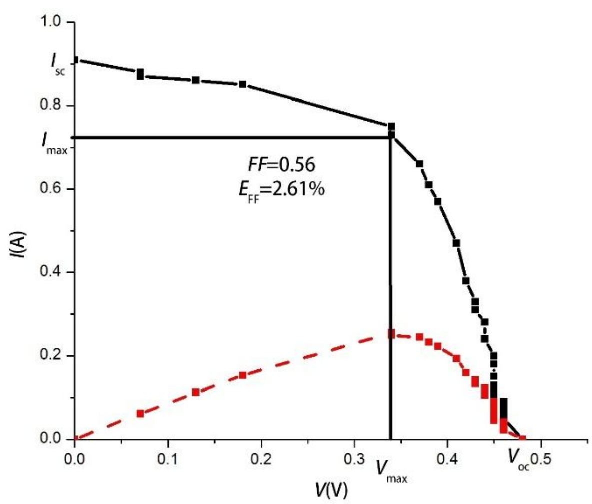

Fig (4.8) shows the I-V Curve Characteristics of solar $cell_2$in horizontal magnetic field.

Table (4.2) shows the electrical properties for solar $cell_2$ before and after applying magnetic field horizontally to it.

Type of solar cell	V_{oc} (V)	I_{sc} (A)	V_{max} (V)	I_{max} (A)	FF	E_{ff} %
Solar $cell_2$ of as obtained	0.48	1.15	0.36	0.76	0.50	2.92
Solar $cell_2$ in horizontal magnetic field	0.48	0.91	0.34	0.72	0.56	2.61

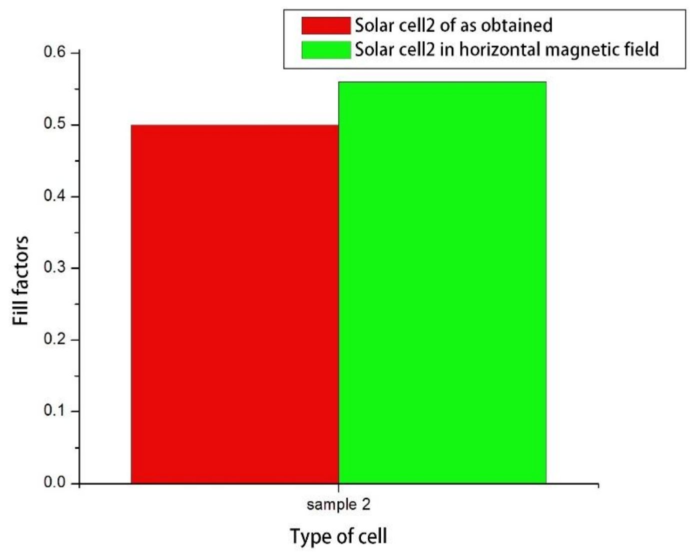

Fig (4.9) chart shows the changes of fill factors for $cell_1$ of as obtained and after operate in horizontal magnetic field.

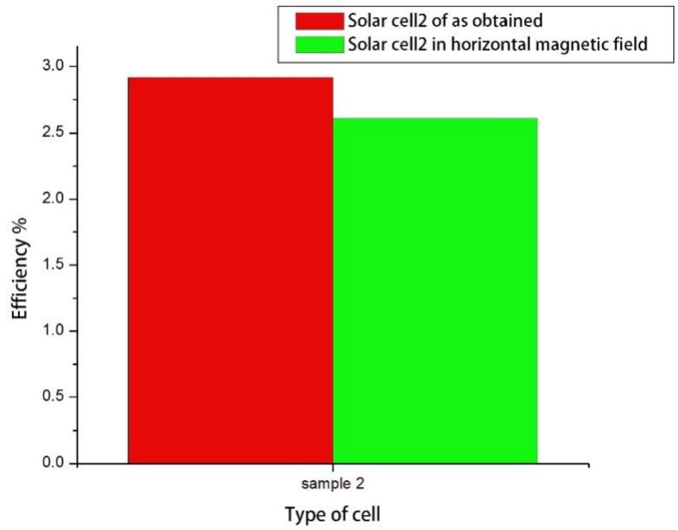

Fig (4.10) chart shows the changes of efficiency for cell$_1$ of as obtained and after operated in horizontal magnetic field.

- When applying magnetic field horizontally to the cell$_2$ it increases fill factor by 0.06 and the same time it decreases short circuit current and its efficiency.

4.1.7 Results of I-V Characteristics of already textured solar cell$_3$in one dimension

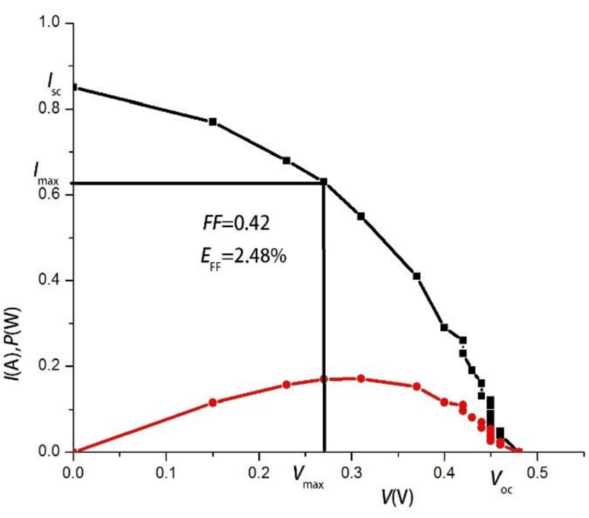

Fig (4.11): plot of the I-V Curve characteristics of the textured solar cell$_3$ in one dimension.

4.1.8 Results of I-V Characteristics of already textured solar cell$_3$ and putted in magnetic field

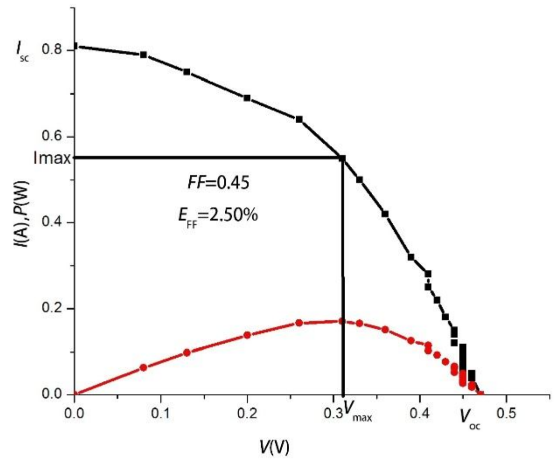

Fig (4.12): shows the I-V curve characteristics of the textured solar cell$_3$in magnetic field.

Table (4.3) shows the electrical properties for already textured solar cell$_3$ and in the magnetic field

Type of solar cell	V_{oc} (V)	I_{sc} (A)	V_{max} (V)	I_{max} (A)	FF	E_{ff} %
Texturedsolarcell$_2$in one dimension	0.48	0.85	0.27	0.63	0.42	2.47%
Textured solarcell$_2$ in one dimension and in the magnetic field	0.47	0.81	0.31	0.55	0.45	2.50%

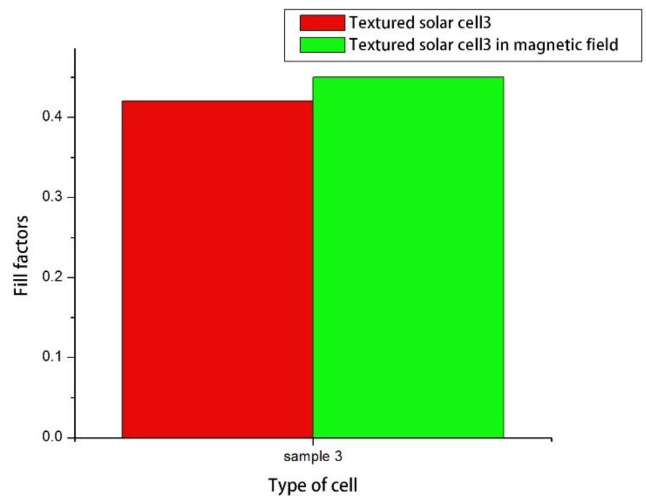

Fig (4.13): chart shows the changes of fill factors for texturedcell$_3$and after operated in magnetic field.

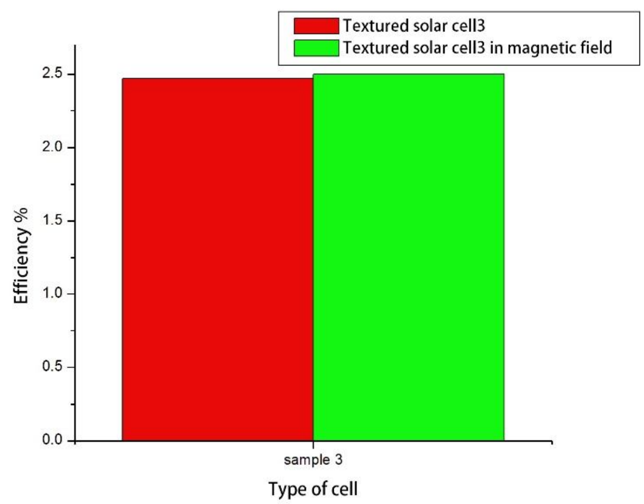

Fig (4.14): chart shows the changes of efficiency for texturedcell$_3$and after operated in magnetic field.

❖ When applying vertical magnetic field to the already textured cell$_3$in one dimension it increases efficiency by 0.03% and fill factor by 0.03.

4.1.9 Results of I-V Characteristics of already textured solar cell$_4$in two dimensions

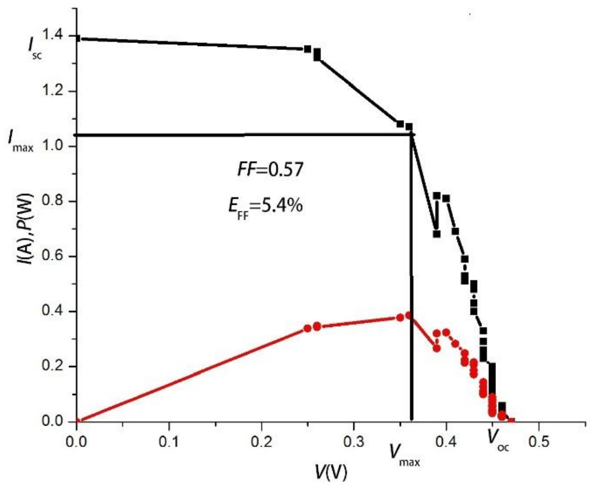

Fig (4.15): shows the I-V curve characteristics of the textured solar cell$_4$ in two dimensions.

4.1.10 Results of I-V Characteristics of already textured solar cell$_3$ in two dimension and putted it in magnetic field

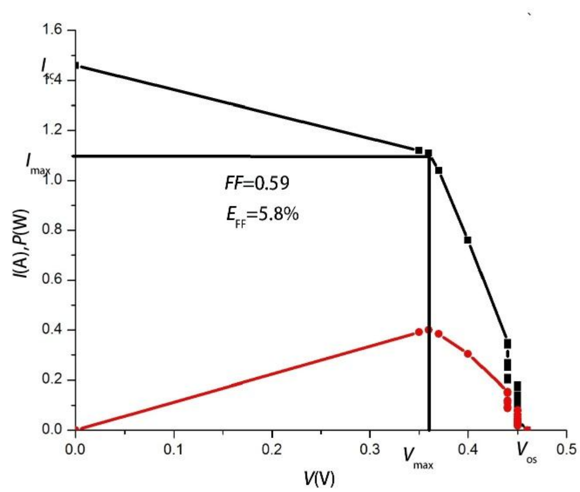

Fig (4.16): shows the I-V curve characteristics of the textured solar cell$_3$in magnetic field.

Table (4.4) shows the electrical properties for already textured solar cell₃ and when applying vertical magnetic field

Type of solar cell	V_{oc} (V)	I_{sc} (A)	V_{max} (V)	I_{max} (A)	FF	E_{ff} %
Texturedsolarcell$_3$ in two dimension	0.47	1.39	0.36	1.042	0.57	5.4%
Texturedsolarcell$_3$ in two dimension and magnetic field	0.46	1.46	0.36	1.095	0.59	5.8%

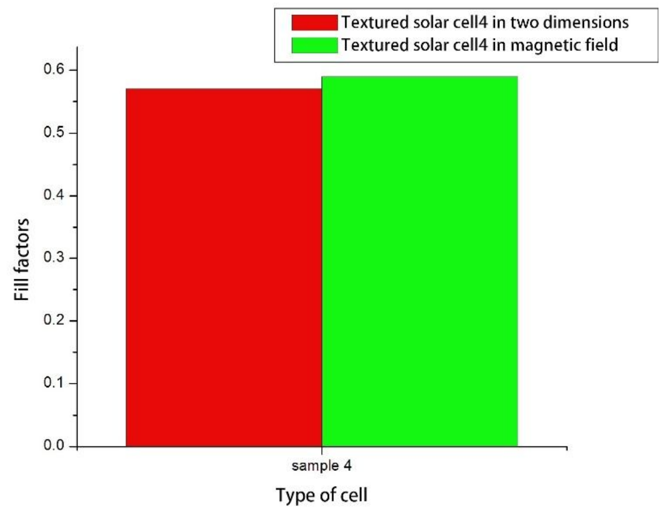

Fig (4.17): chart shows the changes of fill factors for texturedcell$_4$and after operated in magnetic field.

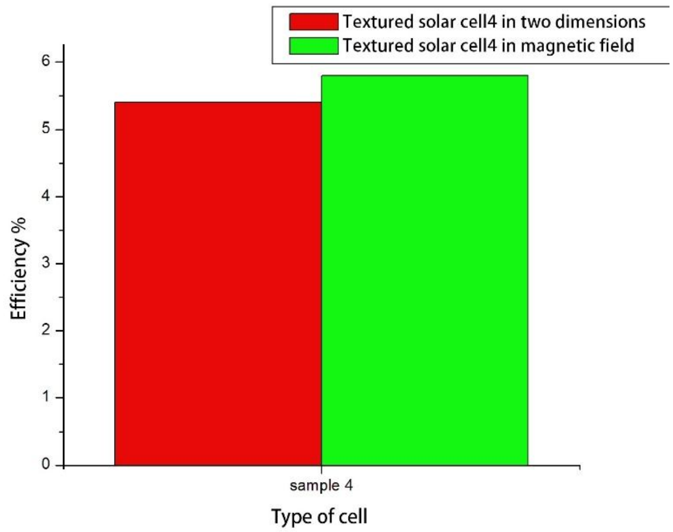

Fig (4.18): chart shows the changes of efficiency for textured $cell_4$ and after operated in magnetic field.

- ❖ Finally applying vertical magnetic field to the already textured $cell_4$ in two dimensions it increases efficiency by 0.4% and fill factor by 0.02.

4.2 Conclusions

In this study; some of the versatile capabilities of laser processing to modify the surface properties of materials were done; In order to enhance their performance for variety of application. Textured surface was obtained on conventional monosilicon photovoltaics' cell by carbon dioxide laser (10.6μm).

Images show a semi periodic structure known as ripples in the micrometer ranges.

The results in this work showed that the use of laser is good method to enhance the efficiency of solar cell by allow trapping more light inside it.

Laser surface treatment introduces defects into the top layer of processed material that deteriorate performance of the solar cell. Fortunately, applied post-laser texturing etching step makes it possible to remove distorted layer and improve efficiency of corresponding solar cells.

The magnetic field also increased the efficiency and fill factor of the cell either textured or not, and both The magnetic field and The texturing of solar cell increased from the efficiency and fill factor of this cell.

4.3 Recommendations

The following can be recommended for future research:

- Usage of CO_2 laser with a different power and different repetition rate to increase the efficiency, or another type of laser source.
- Change the type of cell by poly silicon type instead of mono silicon.
- Take different values of intensity magnetic field with fixed distance to study its effect to the cell efficiency.
- Further studies can be done by investigate another optical or electric phenomena.

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