

# Investigating the role of dual co-solvents (EG, DMSO) on the performance of PEDOT:PSS/Silicon hybrid solar cells

*A project report Submitted*  
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**Summer Internship**

*by*

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## DECLARATION

I solemnly declare that this summer internship report, titled "Investigating the Role of dual co-solvents (EG, DMSO) on the performance of PEDOT:PSS/Silicon hybrid solar cells" represents my original work and has been conducted solely by me during my internship under the supervision of Dr Sanjay Kumar Srivastava at the CSIR-National Physical Laboratory(NPL), New Delhi.

To the best of my knowledge, it is an original work, both in terms of research content and narrative, and has not been submitted elsewhere, in whole or in parts, for the award of a degree or diploma.

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# Introduction

Photovoltaics is the process of using solar cells to convert sunlight directly into electricity. Solar photovoltaic (PV) is an alternative renewable energy source to fossil fuels, making it an indispensable technology to combat the impending climate crisis. In 2022, solar PV accounted for 4.5% of global electricity production, making it the third largest renewable electricity technology behind hydropower and wind [1]. Over the years, significant advancements and research efforts have been directed towards enhancing the efficiency and practicality of solar cells, aiming to provide a sustainable and renewable energy source to meet the ever-growing global energy demands.

## 1.1 Renewables

Renewable energy is energy derived from natural sources that are replenished at a higher rate than they are consumed[2]. In contrast, conventional energy sources like fossil fuels take hundreds of millions of years to reform and thus are considered non-renewable.

Renewable energy is the cornerstone of sustainable development, representing a crucial shift from finite fossil fuels to cleaner, *more sustainable* power sources. Unlike fossil fuels, renewable energy sources are virtually inexhaustible and do not produce harmful greenhouse gas emissions, making them vital in the fight against *climate change and environmental degradation*.

Some renewable energy sources include:

- **Solar Energy**: Harvested from the sun's rays using photovoltaic cells or solar thermal systems. Photovoltaic cells convert sunlight directly into electricity, while solar thermal systems use the sun's heat to produce electricity or for heating purposes.

Capacity: The rate at which the Earth intercepts solar energy is about 10,000 times greater than the rate at which humanity consumes energy[2,3].

- **Wind Energy**: Wind energy harvesting technology utilizes the kinetic energy of moving air by using large wind turbines located on either land or offshore.

Capacity: The world's technical potential for wind energy exceeds global electricity production[2,4].

- **Hydropower**: Hydropower harnesses the energy of water moving from higher to lower elevations. The hydropower generating stations may be reservoir-based (stored water) or utilize the kinetic energy directly from water moving in rivers. Currently, hydropower is the *largest source of power in the global renewable energy sector*[2,5].

- **Geothermal Energy**: Geothermal energy utilizes the accessible thermal energy from the Earth's interior, leftover from the formative period of the Earth. This source of renewable energy is *extremely reliable*, as it is not dependent on weather conditions like solar or wind power[6].

- **Bioenergy**: Bioenergy is produced from a variety of organic materials, called *biomass*, like charcoal, dung, wood etc., for heating and power production purposes. Biomass is mainly used by poorer populations in developing countries[2].

## 1.2 Solar Energy

### 1.2.1 Why Solar?

Solar Energy stands out as one of the best renewable energy sources for several reasons:

- Abundant and inexhaustible: The sun is an infinite and readily available energy source. Its rays provide abundant solar energy that can be harnessed anywhere on Earth, making it a truly renewable resource.
- Environmentally friendly: Solar energy is clean and emits no greenhouse gases or harmful pollutants during operation. Using solar power and switching away from fossil fuels will significantly reduce our carbon footprint, and *help in the fight against climate change*.
- Low operating costs: Once installed, solar energy systems have minimal operating costs as sunlight is free. This can lead to long-term cost savings on electricity bills and make solar power *economically attractive*, especially as technology advances.
- Scalability and Accessibility: Solar energy systems can be scaled to fit different needs and sizes, from individual homes to large-scale solar farms. Additionally, solar panels can be installed in urban and rural areas, providing access to clean energy where traditional grid infrastructure may be limited.
- Off-the-grid energy: Solar energy is particularly *beneficial for remote and off-grid areas* where traditional electricity grids are not feasible. It offers a sustainable energy solution to improve living conditions and support development in these regions.

### 1.2.2 About solar power

Millennia, before electricity, humans learnt how to utilize solar power in many ways. In addition to lighting, early civilizations used solar energy to regulate the temperatures of buildings and cities. This method is now known as *solar passive heating*—an approach to control the temperature of modern structures through simple devices and architectural design[7].

The roots of modern photovoltaic technology can be traced back to the early 19th century when French physicist Alexandre Edmond Becquerel discovered the **photo-voltaic effect** in 1839. He observed that certain materials produced a small electric current when exposed to light. This seminal discovery laid the foundation for future investigations into photovoltaics.

It was not until the 1950s that significant strides were made in the development of practical solar cells. Distinguished researchers at Bell Laboratories, namely Daryl Chapin, Calvin Fuller, and Gerald Pearson, developed the first functional silicon-based solar cell in 1954. This solar cell had a conversion efficiency of around 6%, marking a crucial milestone in the history of photovoltaics.[8].

### 1.2.3 Evolution of solar cell technology

As research in solar cells progressed, four distinct generations of solar cell technology can be identified, each offering advancements of various kinds:

**First generation**: First-generation solar cells, introduced in the 1950s, utilized crystalline silicon as the semiconductor material. These cells demonstrated moderate to high conversion efficiencies and set the groundwork for modern solar technologies. Despite their reliability, first-generation solar cells are costlier due to the requirement for high-purity silicon in their manufacturing processes.

**Second generation**: This generation includes the progression of the first generation

photovoltaic technology, as well as the development of *thin-film* photovoltaic cell technology from micro-crystalline silicon ( $\mu\text{c-Si}$ ), amorphous silicon (a-Si) and copper indium gallium selenide (CIGS). [9]

While offering *flexibility* and *potential for integration*, their efficiencies lagged behind first-generation cells.

**Third generation:** This generation of solar cells encompassed diverse and innovative technologies. These included multi-junction solar cells, concentrating photovoltaics, dye-sensitized solar cells (DSSCs), organic solar cells, quantum dot technologies, perovskite solar cells, etc.

Research aimed to overcome the limitations of previous generations and achieve higher efficiency, cost-effectiveness, and versatility.

**Fourth generation:** This generation includes the low flexibility or low cost of thin film polymers along with the durability of “innovative inorganic nanostructures such as metal oxides and metal nanoparticles or organic-based nanomaterials such as graphene, carbon nanotubes and graphene derivatives”[9,10].

The focus is on enhancing efficiency and stability and addressing environmental concerns. This generation represents the cutting-edge of solar cell research.

Many *commonly used terms* are repeatedly used to describe and characterize solar cells. Some of them are listed below.

- **Standard Test Conditions (STC):** This refers to a specific set of environmental and operating conditions used to standardize the testing and comparison of solar cells and modules. The STC conditions are defined as follows:

1. Irradiance: 1000 watts per square meter ( $\text{W}/\text{m}^2$ ) of solar radiation.

2. Spectrum: Air Mass 1.5 (AM 1.5) spectrum, which simulates the average sea-level solar spectrum.
3. Cell Temperature: 25 degrees Celsius (77 degrees Fahrenheit).

By testing their solar cells under STC, manufacturers and researchers can easily compare the performance of their samples.

- **Short-circuit current**( $I_{sc}$ ): It is the current which flows through the solar cell when the two terminals are shorted together. This is also the *maximum amount of current* from the cell, and occurs when *voltage across the terminals is zero*[11].

Since it depends on the area of the solar cell, it is more common to use  $J_{sc}$  or short circuit current density to compare two solar cells. These values are typically measured under the *Standard Test Conditions*, mentioned above.

- **Open-circuit voltage**( $V_{oc}$ ): The open-circuit voltage ( $V_{oc}$ ) of a solar cell is the *maximum voltage that the cell can generate* when there is no external load connected to its terminals.

$V_{oc}$  is an important parameter used to evaluate the performance of solar cells. Together with the short-circuit current ( $I_{sc}$ ) and the fill factor (F.F.), it helps determine the overall efficiency of a solar cell.

- **Fill Factor (F.F.)**: The fill factor quantifies how efficiently the solar cell converts sunlight into electrical power. The following formula describes the fill factor:

$$Fill\ Factor(F.F.) = \frac{Maximum\ Power\ Output}{V_{oc} \cdot J_{sc}} \quad (1.1)$$

The maximum power output is the highest power that the solar cell or module can produce under specific operating conditions.  $V_{oc}$  and  $J_{sc}$  have been previ-

ously defined. Solar cells with *higher fill factors are desirable* because they have a greater ability to deliver power under real-world operating conditions.

- **Efficiency ( $\eta$ )**: The efficiency of a solar cell refers to the *percentage of sunlight it can convert into usable electrical energy*. In other words, it measures how effectively a solar cell can harness the energy from sunlight and convert it into electricity. It is described by:

$$Efficiency(\eta) = \frac{Electrical\ Power\ Output}{Solar\ (radiation)\ Power\ Input} \times 100\% \quad (1.2)$$

- **Quantum Efficiency (Q.E.)**: The "quantum efficiency" (Q.E.) is the ratio of the number of carriers collected by the solar cell to the number of photons of a given energy incident on the solar cell. It may be given either as a function of wavelength or of energy[12].

The *External quantum efficiency* includes the effect of reflection and transmission, which are optical losses. However, it is often useful to look at another parameter as well. The *Internal quantum efficiency* refers to the efficiency with which photons which are neither transmitted nor reflected can generate collectable carriers[12].

- **Ideality factor (n)**: The ideality factor (n) is a crucial parameter in solar cell characterization, representing the deviation of a solar cell's behaviour from the ideal diode equation. In an ideal solar cell, n would be exactly 1, implying perfect diode behaviour. However, in real-world solar cells, n typically exceeds one due to recombination and non-ideal effects. A low ideality factor indicates efficient charge carrier collection, reduced recombination, and a device closer to ideal performance. Conversely, a higher ideality factor suggests increased recombination losses and non-ideal behaviour.

### 1.3 Research motivation

As illustrated by the various generations of solar cells, numerous photovoltaic(PV) devices based on advanced technologies and materials have been introduced, but *silicon PV is still dominating* the PV market worldwide. Hybrid-solar cells (HSCs) have often been projected as a viable alternative to the conventional Si-solar cells, which require high-temperature processes for their fabrication, via eliminating the energy consumption up to 35% [13].

In the last few years, a lot of effort has gone into researching solar cells created with various organic semiconductor materials like graphene, P3HT (poly(3-hexylthiophene)), PEDOT:PSS (poly(3,4-ethylene dioxythiophene) polystyrene sulfonate) etc. Among these and other organic semiconductors, PEDOT:PSS is an inspiring and encouraging candidate because of its optical transparency at the visible range, tunable electrical conductivity and work function, high flexibility and stretchability, to name a few[14]. PEDOT: PSS is an excellent candidate for creating *flexible organic solar cells*. PEDOT:PSS/Si Hybrid solar cells have drawn a huge amount of research interest since their first demonstration [15], since in principle, they have the potential to achieve the power conversion efficiency almost to the level of a conventional silicon solar cell [16].

The performance of the HSCs is affected for many reasons; However, the optoelectronic properties are prime among them as it plays a critical role in junction formation[17,18]. But, adding PSS as a *primary dopant* can have an adverse effect on the electrical conductivity properties of PEDOT, which can be further improved by the addition of secondary dopants [19].

Thomas et al. investigated the addition of co-solvents EG (ethylene glycol) and DMSO (dimethyl sulfoxide) separately on the electrical properties of PEDOT:PSS/n-

si HSCs and conclusively found that the addition of EG was more beneficial than the addition of DMSO[20].

### 1.3.1 Variation of EG & DMSO

Thomas et al. also found that a HSC made of 7 wt% EG modified PEDOT:PSS upon planar silicon results in a *higher conductivity* and consequently exhibits an exceptionally high power conversion efficiency ( $>12\%$ ). *This value is greater than with any of the other EG or DMSO amounts.*

Similarly, an optimized amount of 5% DMSO modified PEDOT:PSS (single co-solvent) upon planar silicon results in a high power conversion efficiency.

Therefore, in the study, we aim to investigate how EG & DMSO (dual co-solvents) behave together and how they affect the performance of PEDOT:PSS/silicon hybrid solar cells. In the future, we aim to identify the optimal ratio of EG & DMSO for maximising the performance of the HSCs.

# Experimental details

We used commercial as-cut, CZ(100) Si wafers, thickness= $200\text{ }\mu\text{m}$ . The wafer had a diameter of 4 inches. Because of being as-cut, the surface of the wafer has imperfections because of saw damage.

The wafer was sliced into many squares of dimension  $4 \times 4\text{ cm}^2$ . These were then stored in a covered petri-dish.

## 2.1 Silicon surface micro-engineering

The glassware to be used in the experiment was thoroughly rinsed with DI (de-ionized water). The silicon wafers were placed in a zig using Teflon tweezers and sonicated for 10 minutes.

The sonicator cleans wafers using ultrasonic waves. In addition to DI water, sonication can be done using acetone and IPA (isopropyl alcohol), in that order.

The wafers were placed out to dry. Then, 2% w/v KOH crystals were added into a beaker filled with DI water. A scientific balance was used to weigh the KOH crystals out.

Using a hot plate, the solution was heated until it reached  $70^\circ\text{C}$  when 20% v/v IPA was added. Another beaker containing 200 mL of DI water was kept to heat on the same hot plate. The zig with the wafers was dipped into the solution, and the temperature was kept close to  $75^\circ\text{C}$  for 60 minutes.

5% v/v HCl was dissolved in the second beaker, i.e. 10 mL HCl mixed into 200 mL DI water. After 60 minutes of chemical etching, the zig was dipped into the

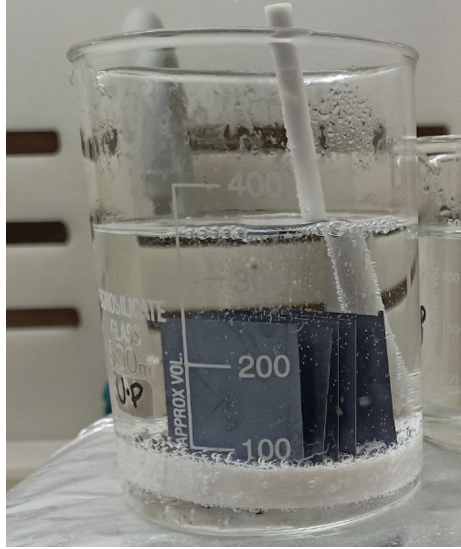


Figure 2.1: Texturing the wafer through chemical etching

second beaker containing dil. HCl solution for 5 minutes. This was done to remove and neutralize any remaining traces of KOH sticking onto the wafer.

The zig was then taken out and washed successively in two beakers containing DI water to wash out the acidic traces clinging to the wafers. Then, the wafers were kept out to dry.

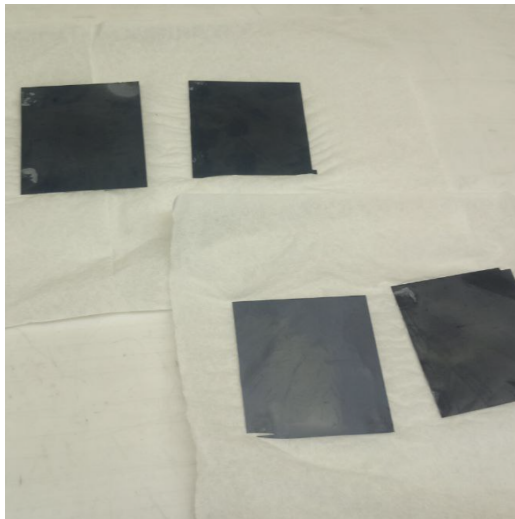


Figure 2.2: Textured wafers

## 2.2 Spin-coating

The micro-textured Si ( $\mu T - Si$ ) wafers were left out for one day to form a silicon oxide layer, as raw silicon is *hydrophobic*. Since our desired outcome was the successful spin coating of PEDOT:PSS upon the Si-wafers, we needed it to be hydrophilic. That is why the  $SiO_2$  layer was created, as it is hydrophilic. All glassware was thoroughly cleaned using DI water. The spin coater was cleaned, and a new Al foil was applied inside the spin coating apparatus to prevent permanent markings due to the liquid splattering.

The ( $\mu T - Si$ ) wafers are cleaned via sonication in 3 solutions: DI water, acetone and IPA. For each solution, sonication was performed for 10 minutes. The various solutions of EG, DMSO & PEDOT:PSS in their respective ratios, given in table 2.1, were prepared. .

| S.No. | Sample                | PEDOT:PSS( $\mu L$ ) | IPA( $\mu L$ ) | EG( $\mu L$ ) | DMSO( $\mu L$ ) |
|-------|-----------------------|----------------------|----------------|---------------|-----------------|
| 1     | Pristine              | 500                  | 500            | 0             | 0               |
| 2     | 7 wt% EG              | 2000                 | 2000           | 140           | 0               |
| 3     | 5 wt% DMSO            | 2000                 | 2000           | 0             | 100             |
| 4     | 1 wt% DMSO + 6 wt% EG | 2000                 | 2000           | 120           | 20              |
| 5     | 2 wt% DMSO + 5 wt% EG | 2000                 | 2000           | 100           | 40              |

Table 2.1: The various samples

Pipettes were used to create the given solutions. All the solutions were kept in the dark to prevent the degradation of PEDOT:PSS. All the solutions were then ultrasonicated for 60 minutes. The wafers were placed upon cleaned glass slides on a hot plate and given a 30-second preheat treatment, as shown in figure ???. This was done to augment the formation of the silicon oxide layer.



Figure 2.3: Preheat treatment of a textured wafer



Figure 2.4: Wafer being spin-coated

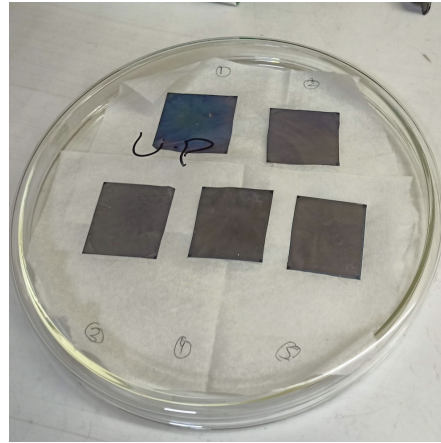


Figure 2.5: Spin-coated wafers

The wafer was then placed on the *chuck* of the spin coater, and the vacuum was turned on. This ensured the sample did not fall off the quickly rotating chuck. Using a pipette,  $350 \mu L$  of solution one was applied across the silicon wafer. This is shown in figure 2.4 and figure 2.5.

The optimized spin-coating programme for PEDOT:PSS is 800 RPM for 240 seconds. After spin coating, the wafers were again subjected to a 30-second heat treatment to remove extra moisture.



Figure 2.6: Masks for thermal deposition

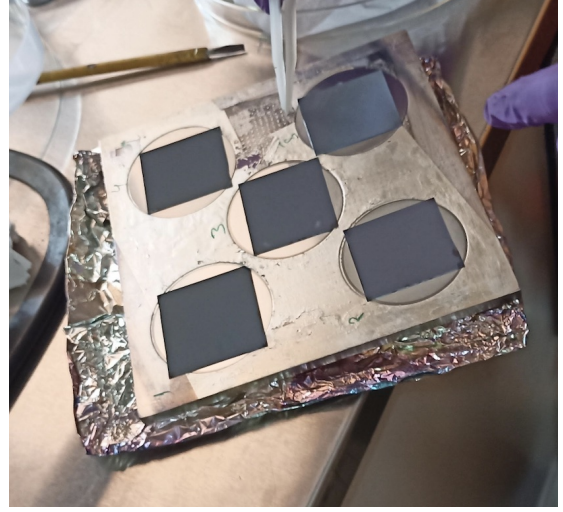


Figure 2.7: Wafers kept on masks

## 2.3 Ag deposition through thermal evaporation

Silver wires (7 cm long) were cut and cleaned in acetone via sonication for 10 minutes. The thermal evaporation apparatus was also cleaned thoroughly using acetone. The wafers were placed upon the metal masks, with the PEDOT:PSS coated side touching the mask.

The thermal evaporation apparatus has two gauges to measure the pressure inside the chamber: the Penning gauge and the Pirani gauge. We used the penning gauge to measure the pressure inside the thermal evaporation chamber. For proper thermal evaporation, we need a near vacuum inside the chamber. Now, this vacuum must be created using two pumps:

- Rotary pump
- Diffusion pump

We need the pressure inside the chamber to be less than  $5 \times 10^{-6}$  torr so that the silver molecules can go straight to the wafer.

First, the rotary pump was switched on. Alone, it takes the pressure to around  $10^{-3}$  torr. The diffusion pump brings it down to  $10^{-5}$  torr. We used liquid nitrogen to cool down the diffusion pump so that it could bring down the pressure by another order of magnitude. The current was turned on, which passed through the boat and vaporised Ag through *resistive heating*.

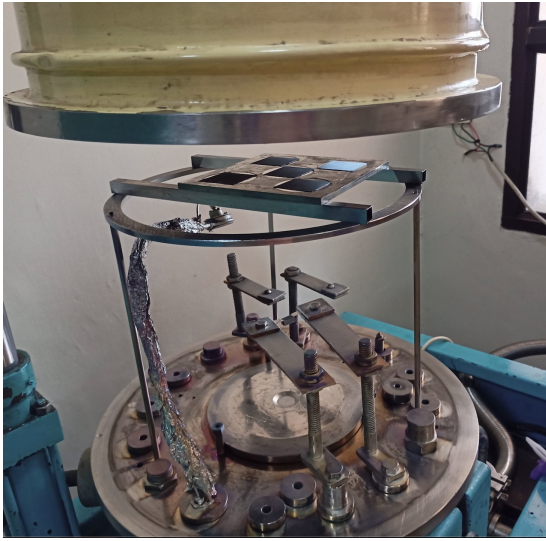


Figure 2.8: Thermal deposition apparatus



Figure 2.9: Thermal deposition

We want deposition of around  $500\text{ nm}$ , i.e.  $5\text{ KÅ}$ . After completing the above process, we let it cool for around 15 minutes. This results in the creation of the anode of the solar cell.

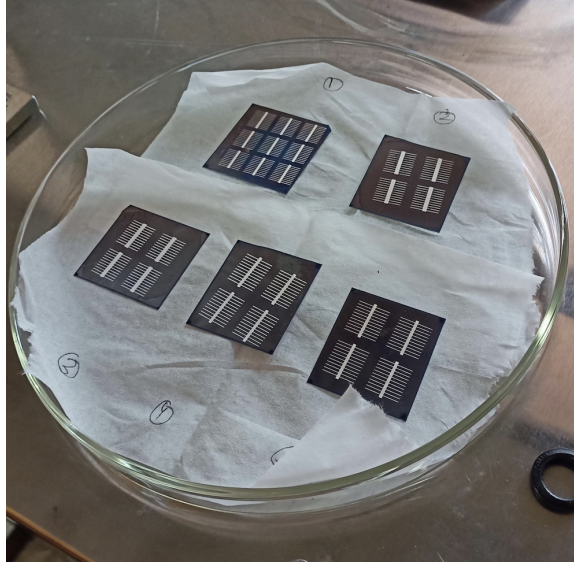


Figure 2.10: Wafers with deposited Ag anode

## 2.4 Making of the cathode

A gallium-indium (Ga-In) liquid alloy was painted on the back side of the silicon wafer to create the cathode. The Ga-In alloy serves as a conductive layer, aiding in the efficient collection and extraction of electrons from the n-side of the solar cell. The wafer was then gently sliced into individual cells for further characterization.

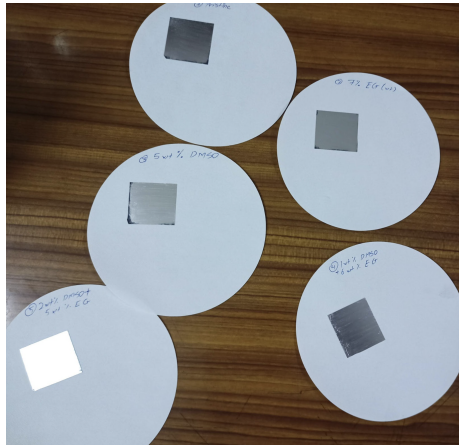


Figure 2.11: Wafers coated using Ga-In alloy

## 2.5 Characterization

The spectral response measurement apparatus measures the short circuit current of a solar cell at selected wavelengths over a broad range of wavelengths. The spectral response is conceptually similar to the quantum efficiency because the EQE gives the number of electrons output by a solar cell compared to the number of incident photons. In contrast, the spectral response is the ratio of the current generated by the solar cell to the power incident on the solar cell.

Five wafers were spin-coated in the experiment with various solutions, as mentioned in Table 2.1. According to the contacts deposited by applying the various masks on each sample's wafer, they were sliced into smaller cells — 8 cells for the pristine sample and four cells each for the other four samples.

Each cell in the group was characterized using the spectral response measurement instrument, and the best-performing cell for each sample was chosen for further analysis, comparison, and EQE measurement.

The photovoltaic characteristics of the different EG-based HSCs were recorded by M/s Bunkoukeiki (Model: CEP-25HS-50). The solar cell performance under illumination was measured at STC condition (25 °C, 100 mW/cm<sup>2</sup>, AM 1.5G).

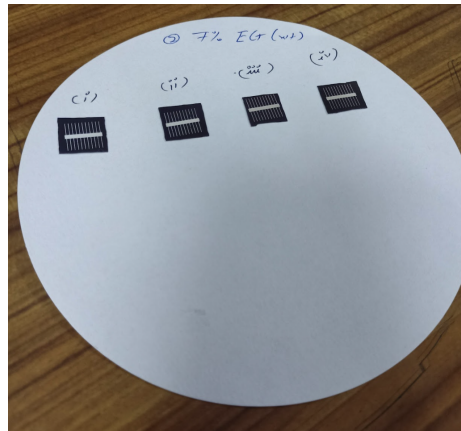


Figure 2.12: Wafers with deposited Ag anode

# Results and Discussion

In the experiment, five distinct samples were created as described by 2.1. Multiple cells were cut out of each sample's wafer and characterized by the spectral response measuring instrument. In this manner, the best-performing cell for each wafer was chosen to represent the sample and used for further measurements and analysis.

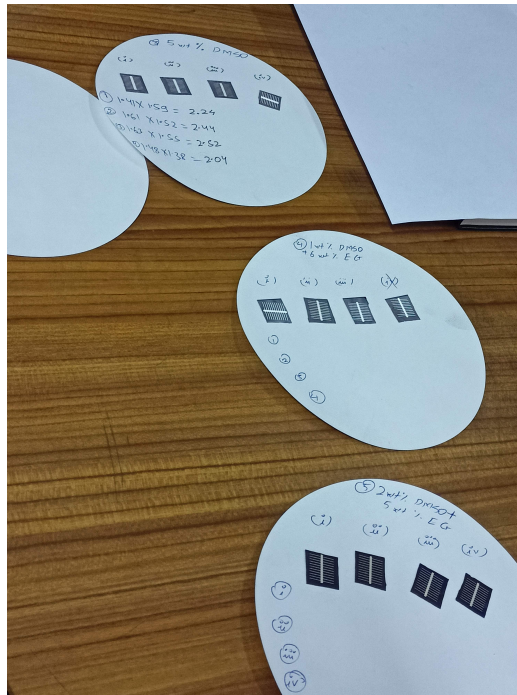


Figure 3.1: Solar cells ready to be characterized

The comparison table of the various cell parameters for the five samples is shown in Table 3.1 on the next page. *The data from the best-performing cell of each sample has been considered.*

| Cell Type        | Cell area ( $cm^2$ ) | Corrected cell area ( $cm^2$ ) | Jsc ( $mA/cm^2$ ) | Voc(mV) | F.F. (%) | Efficiency (%) | Jsc(EQE) ( $mA/cm^2$ ) | n (Ideality factor) | Jo ( $A/cm^2$ ) | $\phi_{bi}$ |
|------------------|----------------------|--------------------------------|-------------------|---------|----------|----------------|------------------------|---------------------|-----------------|-------------|
| <i>Pristine</i>  | 1.520                | 1.321                          | 20.200            | 53.674  | 23.470   | 3.529          | 23.893                 | 2.611               | 2.35E-07        | 0.826       |
| <i>7EG</i>       | 2.340                | 2.045                          | 28.828            | 53.982  | 56.419   | 8.780          | 27.551                 | 2.242               | 2.15E-07        | 0.829       |
| <i>5DMSO</i>     | 2.240                | 1.945                          | 26.533            | 52.544  | 43.412   | 6.052          | -                      | 3.112               | 1.94E-06        | 0.772       |
| <i>6EG+1DMSO</i> | 2.530                | 2.245                          | 24.907            | 52.812  | 55.959   | 7.361          | -                      | 3.077               | 3.51E-06        | 0.757       |
| <i>5EG+2DMSO</i> | 2.610                | 2.325                          | 26.647            | 53.859  | 53.228   | 7.639          | 26.217                 | 2.384               | 2.85E-07        | 0.822       |

Table 3.1: Comparison of cell parameters

### 3.1 Dark characteristics

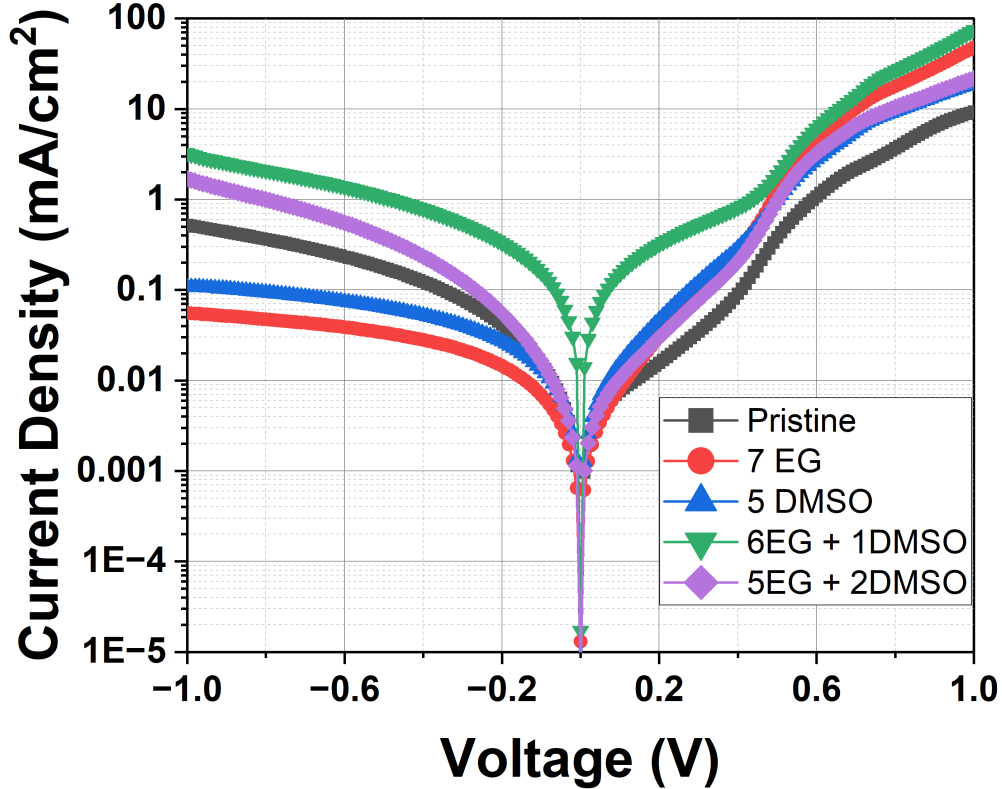


Figure 3.2: Comparison of Dark Characteristics(semi-log graph)

The dark JV characteristics is a good indicator of the quality of diode being formed and hence the solar cell performance. The dark JV curves of the PEDOT:PSS/Silicon HSCs in the present case exhibit typical rectifying characteristics which indicates that all the PEDOT:PSS/Silicon heterojunctions behave like well-defined diodes.

From Table 3.1 and figure 3.2, we can clearly see that the **reverse saturation current  $J_0$  is lowest in the 7 EG sample**, with a value of  $(J_0)_{7EG} = 2.15 \times 10^{-7} \text{ A/cm}^2$ .  $J_0$  characterizes the recombination of charge carriers in the absence of illumination,

and it is one of the parameters used to describe the non-ideal behaviour of a solar cell. For an ideal solar cell, the value of  $J_0$  (reverse saturation current) should be lower. A lower value of  $J_0$  is preferred in an ideal solar cell because it indicates that the device has lower recombination rates and minimal leakage current without light. So, the 7 EG sample is the best in this, with the lowest leakage current.

We can see from the table 3.1 that the **ideality factor( $\eta$ ) is lowest in the 7 EG sample**, with a value of  $\eta_{7EG} = 2.242$ . A solar cell's ideality factor ( $n$ ) provides valuable insights into its electrical behaviour and characteristics. It tells us about the non-ideal aspects of the solar cell's performance and offers information about various recombination mechanisms and other factors affecting its efficiency.

The *ideality factor ( $n$ ) should ideally be close to 1 or lower in a solar cell*. A low ideality factor indicates that the solar cell behaves more closely to the ideal diode equation, which is a *desirable* characteristic for efficient and high-performance solar cells. Therefore, the 7 EG sample also outperforms the other samples in this aspect.

### 3.2 Illuminated characteristics

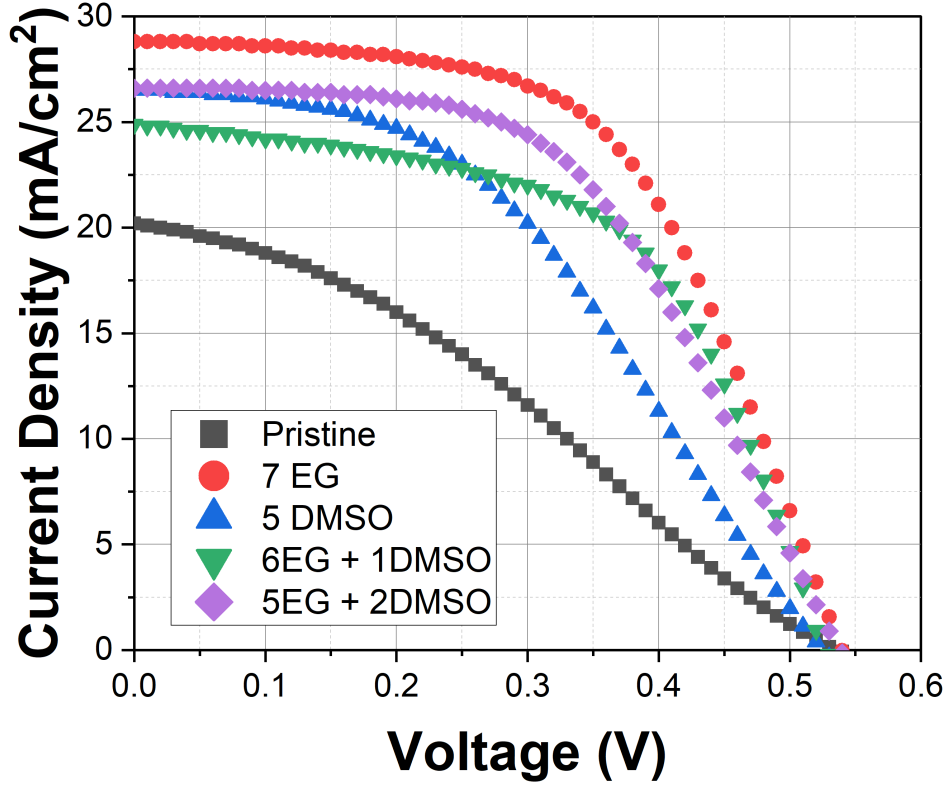


Figure 3.3: Comparison of J-V Characteristics

From the figure 3.3 and the table 3.1, we can see that the value of the short circuit current ( $J_{sc}$ ) in the illuminated condition is the **highest in the 7 EG sample**, with a value of  $J_{sc} = 28.828 \text{ mA/cm}^2$ . Also, the value of open-circuit voltage ( $V_{oc}$ ) in the illuminated condition is also the **highest in the 7 EG sample**, with a value of  $V_{oc} = 53.982 \text{ mV}$ .

We know that the cell with higher  $J_{sc}$  and higher  $V_{oc}$  tends to have better carrier generation and better light absorption capacities. The 7 EG sample is the best in this regard.

Comparing the *fill factor* of all the samples from Table 3.1, we can see that the **7 EG sample has the highest fill factor**, with a value of  $FF_{7EG} = 56.419\%$ . This is followed in the decreasing order by 6EG+1DMSO (FF=55.959%) and 5EG+2DMSO (FF=53.228%). However, we register a sharp drop in the fill factor for the other two samples, i.e. 5DMSO (43.412%) and Pristine (23.470%). Thus, we can see that the **fill factor positively correlates with the wt% of EG** as the secondary dopant, at least up to 7 wt% EG.

For any solar cell, a higher fill factor is desirable because it indicates a more efficient use of available voltage and current, leading to better overall performance and higher power output. It also means that the 7 EG solar cell is operating closer to its maximum power point (MPP), where the product of voltage and current is at its highest value. So, it is the best sample in this aspect, too.

Comparing the values of *efficiency* ( $\eta$ ) of all the samples from Table 3.1, we can again see that the **7 EG sample has the highest efficiency** in comparison to the other samples, with a value of  $\eta_{7EG} = 8.780\%$ .

A higher efficiency means that the solar cell can convert a larger percentage of the incident sunlight into usable electrical power, making it a more effective and valuable renewable energy source. So, the *7 EG cell outperforms the others in this regard as well.*

### 3.3 E.Q.E measurements

In addition to the illuminated JV data, EQE is another important parameter which is used to quantify the efficiency of conversion of incident light to charge carriers as a function of wavelength. Therefore, the  $J_{sc}$  measured from the JV data, and the  $J_{sc}$  estimated from the EQE curve must be properly matching for a stable and good quality solar cell being formed.

In the present study, the EQE measurements were taken for three samples: Pristine, 7EG, (5EG + 2DMSO) samples. The graph EQE v/s wavelength measurements are provided below.

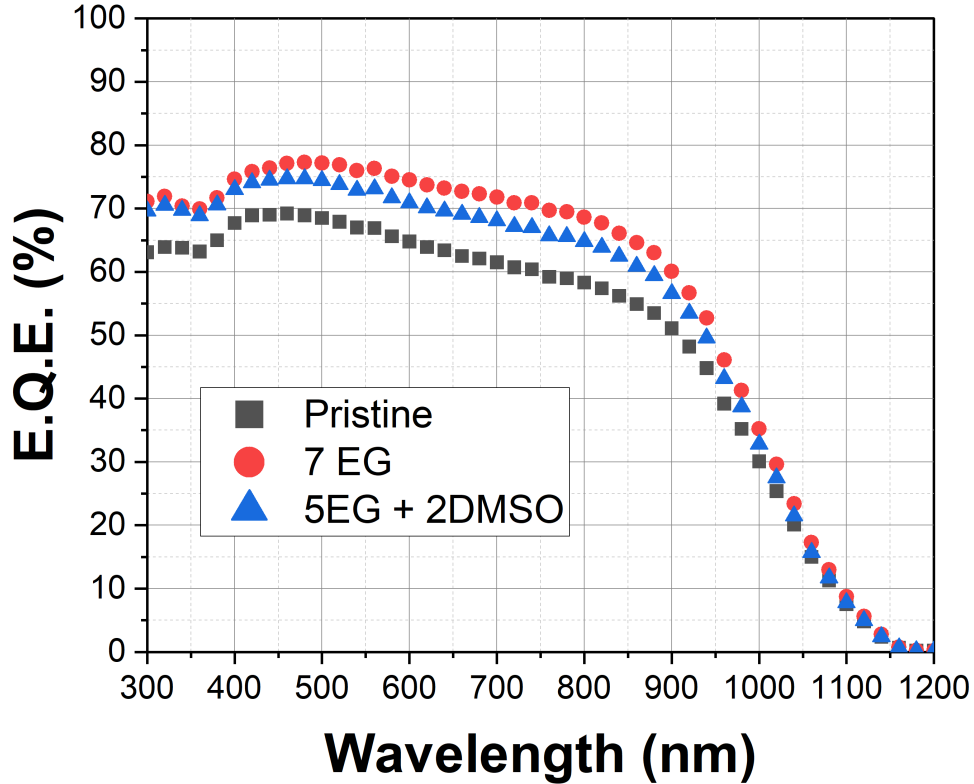


Figure 3.4: Comparison of External Quantum Efficiencies (EQEs)

In the curves for all three samples, we can observe some common properties. The EQE dips down in the short wavelength region ( $<400$  nm) before rising again. Also, the value of the EQE starts falling at longer wavelengths before eventually dropping to zero.

This can be explained based on two effects:

- i The EQE is low at wavelengths  $<400$  nm because these are relatively higher energy photons and hence have a lower absorption depth, i.e. the electron-hole pairs created due to these photons are generated near the surface.

If the solar cell's surface is not adequately passivated, it will possess a high amount of surface recombination. So, some of these carrier pairs recombine, lowering the EQE.

- ii The EQE tapers off at higher wavelengths because longer wavelengths can penetrate the solar cell material more deeply. As a result, some of the incident photons may pass through the semiconductor layer without being absorbed, leading to reduced EQE.

Also, at photon energies lower than the semiconductor's bandgap, they are not absorbed, and the EQE drops to zero.

From the graph 3.4 and the table 3.1, we can see that  $J_{sc}(\text{EQE})$  is highest for the **7 EG cell**, with a value of  $J_{sc}(\text{EQE})_{7EG} = 27.551 \text{ mA/cm}^2$ .

The short-circuit current ( $J_{sc}$ ) represents the maximum current output of the solar cell when it is short-circuited under illumination at a specific wavelength. In the EQE curve,  $J_{sc}$  indicates the efficiency of the solar cell in converting incident photons into electrical current.

A higher  $J_{sc}$  in the EQE curve indicates that the solar cell is more effective at absorbing photons of a particular wavelength and converting them into electron-hole pairs,

leading to higher photocurrent generation. This is a desirable characteristic. So, the *7 EG sample proves to be the best* among the other samples in this aspect as well.

# Conclusion

The internship project involved fabricating and characterizing five distinct solar cell samples. The 7 EG sample demonstrated superior performance across various vital parameters. It exhibited the lowest reverse saturation current ( $J_0$ ) and ideality factor ( $n$ ), indicating reduced recombination and more ideal behaviour.

It also excelled in device efficiency, outperforming others in converting incident sunlight into electrical power. It displayed the highest short-circuit current ( $J_{sc}$ ) and open-circuit voltage ( $V_{oc}$ ), signifying better light absorption and carrier generation capabilities. Additionally, this sample boasted the highest fill factor (FF), showcasing its efficient utilization of available voltage and current. This indicates its operation is closer to its maximum power point, leading to improved performance and higher power output. EQE measurements confirmed the sample's exceptional performance, with the highest short-circuit current ( $J_{sc}$ ) in the EQE curve, highlighting efficient photon absorption and conversion. Overall, *the 7 EG sample emerged as the most promising candidate* out of the samples created in this experiment (table 2.1).

Further scope: The present work leads the way to develop promising HSCs using the low-cost solar grade Si-wafers. The present work may lead to further advancement of the PEDOT:PSS/Si HSCs in the "frontPEDOT" device geometry as the work provides an ample amount of opportunities for improving the performance of these HSCs by incorporating (i) an effective surface passivation layer at the Si/metal interface to minimize recombination losses (ii) an effective anti-reflection coating (ARC) to minimize reflection losses, and (iii) BSF (Back surface field) in the rear side.

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