EFFECTS OF ENCAPSULATION ON PEROVSKITE THIN FILMS AND SOLAR CELLS

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ABSTRACT

EFFECTS OF ENCAPSULATION ON PEROVSKITE THIN FILMS AND SOLAR CELLS

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Perovskite materials have attracted considerable interest due to their potential as viable options for a range of optoelectronic applications. Among them, their potential as active materials in solar cells has drawn considerable interest. Perovskite materials possess exceptional properties that make them well-suited for the efficient conversion of sunlight into electricity, thereby boosting solar cell performance. However, a significant challenge lies in their susceptibility to degradation when exposed to external environmental conditions, which hampers their ability to perform. This thesis focuses on addressing the issue of perovskite thin film and solar cell degradation by exploring encapsulation techniques. Encapsulation involves the development of protective barriers to shield perovskite materials from harmful environmental factors. By effectively encapsulating solar cells, it is possible to extend their operational lifespan. The process of encapsulation has the utmost importance in perovskite solar cell technology because of the stability and large-area manufacturing problems that are still not solved for large-scale industrial production. Exposure to environmental factors such as oxygen and water vapor leads to irreversible degradation in the performance of perovskite solar cells. A good encapsulation should offer effective

environmental insulation, preventing the ingress of harmful substances, while also being transparent and electrically non-interfering with the functioning of the solar cell. In this work, various encapsulation materials such as Surlyn-based Meltonix sheet, EVA, and Enlight were studied. The effect of vi the encapsulation material and production conditions on the electrical and optical properties of the solar cell and perovskite thin film were studied for these three encapsulation materials. The solar cell parameters were found to be less affected by Surlyn-based Meltonix and Enlight encapsulation. In the case of Enlight encapsulation, the efficiency dropped slightly after the lamination and remained stable after a limited time of testing. In the last study, Enlight and Meltonix materials were applied as a double-layer encapsulation format on perovskite solar cells, and they underwent aging tests involving heat and humidity exposure. However, the duration of the aging experiment is not sufficient to draw conclusions about the longterm stability of the investigated perovskite solar cells and films. Additionally, it was observed that the electrical properties of the perovskite solar cells were not affected by the double-layer encapsulation using Enlight and Surlyn-based Meltonix, along with the PIB edge seal. This result indicates that the materials and processes employed in this study did not cause any significant changes in the material properties of the perovskite layer.

Keywords: Photovoltaics, Perovskite Solar Cells, Perovskite Thin Films, Encapsulation

ÖZ

ENKAPSÜLASYONUN PEROVSKİT İNCE FİLMLERİ VE GÜNEŞ HÜCRELERİ ÜZERİNDEKİ ETKİLERİ

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Perovskit malzemeleri, çeşitli optoelektronik uygulamalar için önemli bir potansiyele sahip olduğundan büyük ilgi çekmektedir. Özellikle güneş hücrelerinde aktif malzeme olarak kullanıldığında, perovskitler güneş enerjisini verimli bir şekilde elektriğe dönüştürme kabiliyetleri sayesinde ön plana çıkmaktadır. Ancak, bu malzemelerin dış etkenlere maruz kaldıklarında bozulma eğilimleri çevresel faktörlerin etkisi altında performanslarını olumsuz yönde etkilemektedir. Bu tez, perovskit ince filmler ve güneş hücrelerinin bozulmasını ele alarak, bu soruna çözüm bulmayı hedeflemektedir. Bu amaçla, perovskit malzemelerini zararlı çevresel faktörlerden korumak için bariyer geliştirme süreci olan enkapsülayon teknikleri çalışılmıştır. Perovskit ince filmleri ve güneş hücrelerini etkili bir şekilde kapsülleyerek, çalışma ömürlerini uzatmak mümkün olmaktadır. Enkapsülasyon işlemi, büyük ölçekli endüstriyel üretim için hala çözülmemiş olan kararlılık ve geniş alanlı imalat sorunları nedeniyle perovskit güneş hücresi teknolojisinde en büyük öneme sahiptir. Oksijen ve su buharı gibi çevresel faktörlere maruz kalma, perovskit güneş hücrelerinin performansında geri dönüşü olmayan bozulmaya neden olmaktadır. İyi bir enkapsülasyon, çevreden sıkı bir yalıtım sağlamalı ve viii herhangi bir zararlı maddenin güneş hücresine girmesini önlemesine ek olarak şeffaf olmalı ve elektriksel olarak güneş hücresinin çalışmasına müdahale etmemelidir. Bu çalışmada Surlyn bazlı Meltonix, EVA ve Enlight gibi çeşitli

malzemeler incelenmiştir. Enkapsülasyon malzemesinin ve üretim koşullarının perovskit güneş hücresinin ve ince filmin elektriksel ve optik özelliklerine etkisi bu üç malzeme için incelenmiştir. Güneş hücresi parametrelerinin Surlyn bazlı Meltonix ve Enlight malzemesinden daha az etkilendiği bulunmuştur. Enlight ile enkapsülasyon durumunda, verimlilik laminasyondan sonra biraz düşüş göstermiş ve sınırlı bir test süresinden sonra sabit kalmıştır. Bu durum üzerine son çalışmada Enlight ve Meltonix malzemeleri perovskite güneş hücresi üzerine çift katmanlı enkapsülasyon şeklinde uygulanmış, ısı ve nem ile yaşlandırma testine tutulmuştur. Bununla birlikte, yaşlandırma deneyinin süresi, incelediğimiz perovskit güneş hücrelerinin ve filmlerin uzun vadeli kararlılığı hakkında bir sonuca varmak için yeterli değildir. Son olarak, Enlight ve Surlyn bazlı Meltonix ile birlikte PIB kenar dolgusu kullanılarak gerçekleştirilen çift katmanlı enkapsülasyonun, perovskit güneş hücrelerinin elektriksel özelliklerini etkilemediği gözlemlenmiştir. Bu sonuç, bu çalışmada malzemelerin ve işlemlerinin, perovskit filmlerin malzeme özelliklerinde herhangi bir büyük değişikliğe neden olmadığını göstermektedir.

Anahtar Kelimeler: Fotovoltaik, Perovskite Güneş Hücreleri, Perovskite İnce Filmler, Enkapsülasyon

To my lovely family and friends

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LIST OF ABBREVIATIONS

ABBREVIATIONS	
Ba	Barium
Br	Bromide
Ca	Calcium
CIGS	Copper Indium Gallium Selenide
Cl	Chlorine
Cu	Copper
Cs	Cesium
EVA	Ethylene-Vinyl Acetate
ETL	Electron Transport Layer
FF	Fill Factor
FWHM	Full Width at Half Maximum
Ge	Germanium
HI	Hydrogen Iodide
HOIP	Hybrid Organic and Inorganic Perovskites
HTL	Hole Transport Layer
I	Iodine
J_{sc}	Short-Circuit Current Density
J_{mp}	Current Density at Maximum Power Point
J_0	Saturation Current Density
Li	Lithium
MA	Methylammonium

MAPbI	Methylammonium Lead Iodide
MPP	Maximum Power Point
N	Newton
Na	Sodium
O	Oxygen
OTR	Oxygen Transmission Rate
Pb	Lead
PCE	Power Conversion Efficiency
P_{in}	Incident Power
PIB	Polyisobutylene
PL	Photoluminescence
P_{max}	Maximum Generated Power
PSC	Perovskite Solar Cell
PV	Photovoltaics
RH	Relative Humidity
UV	Ultraviolet
WVTR	Water Vapor Transmission Rate

LIST OF SYMBOLS

SYMBOLS

C_s	Concentration of Surface Saturating Agents
D	Diffusivity
E_c	Conduction Band Energy
E_g	Band Gap Energy
E_v	Valence Band Energy
G	Generation Rate
J	Current density
k	Boltzmann Constant
l	Thickness
L_n	Electron Diffusion Length
L_p	Hole Diffusion Length
n	Intrinsic Carrier Concentration
P	Power
q	Charge of Electron
R	Ionic Radii
T	Temperature
t	Passage of Time
t	Tolerance Factor
η	Efficiency

V	Voltage
λ	Wavelength

CHAPTER 1

INTRODUCTION

Photovoltaic solar cells offer us the chance to generate electricity from solar radiation in a cleanand sustainable way. With the recent development in Si-based solar cell industrial production,the cost of electricity has dropped to very favorable levels concerning other available sources of electricity generation. Extensive research and development effort high volume production worldwide has resulted in an increase in the efficiency of solar cells while decreasing the cost of manufacturing. Research and development activities are going on with the aim of even further increasing conversion efficiency and lowering the cost. This is needed for the ultimate victory of solar energy over other resources.

Perovskite solar cells (PSCs) have proven to have great potential in terms of conversion efficiency, and their efficiency records have been demonstrated with great success. However, the perovskite materials suffer from stability problems. They are sensitive to external agents like oxygen and water vapor leading to irreversible degradation of the device's performance. To solve this problem, they must be isolated in a good way so that oxygen and water vapor donot reach the device structure. This requires an effective encapsulation process. In this thesis, we have studied several encapsulation materials and processes to understand their effect and to search for a reliable encapsulation route for perovskite solar cells.

1.1 Energy Supply

Energy is a crucial element for national economies and one of the most significant indicators of a nation's social and economic development potential. The energy used in every aspect of everyday life—chemical, nuclear, mechanical, thermal, geothermal, hydraulic, solar, wind, and electrical—can be found in various forms and converted to one another by the right methods. Energy sources are called and classed in various ways, depending on how profitable they are. Renewable and non-renewable energy sources are classified according to their use. Energy thathas not undergone any modification or alteration is referred to as primary energy. Primary energy sources take many forms, including nuclear energy, fossil energy like oil, coal, and natural gas, and renewable sources like wind, solar, geothermal, and hydropower [1].

Nonrenewable energy sources are expected to be depleted in the not-too-distant future. Renewable energy sources are endless in the future and can be counted as renewable resources.Today primary energy sources provide most of the world's energy needs. According to 2021 data, the world’s total energy supply by source was oil, with a value of 29 %. Afterward, with a value of 26,4% coal, 23,4% natural gas, 3,8% traditional biomass, 9,3% geothermal, solar, wind, heat, and other sources, and 2.6% hydro [2].

The International Energy Agency (IEA) forecasts a 28% decline in world oil supply and a 23%decline in gas supply by 2030 in its "Net Zero Emissions by 2050 Scenario". Oil and gas shortages will intensify, energy prices will rise even higher, and the market will grow more unpredictable as long as the world continues to rely on fossil fuels [3]. As an example of the threats posed by the traditional energy use sector on the world, the following can be given; Theworldwide energy industry is responsible for around two-thirds of greenhouse gas emissions, and overheating can happen if the global average surface temperature exceeds 1.5°C from the pre-industrial era. In addition, nuclear power is problematic since the poisonous waste it produces lasts for thousands of years, and it is also an expensive choice.

Furthermore, the usage of fossil fuels leads to environmental devastation. Global warming and environmental devastation are unavoidable consequences of burnt fuel emitted into the atmosphere. Toxic chemicals fill the atmosphere, causing a greenhouse effect and reflecting thesun's rays back into space. Carbon emissions' greatest damaging impacts are the greenhouse effect and acid rain. When combustible hydrogen and carbon components react with oxygen, energy is released from the bonds that link them. The greenhouse effect is just one of the disadvantages of using traditional energy sources.

The most important disadvantage of fossil-based resources found in nature is their scarcity. They are not a long-term solution as an energy source. As a result of this dilemma, humankindis compelled to look for new sources of energy. Studies have shown that natural energy sourceslike water, wind, sun, geothermal, hydrogen, and biomass are reliable energy sources. These renewable resources have practically no negative environmental effects. The type of energy thatneeds to be used in the world to expand should be energy sources that can be recycled and reused. The use of fossil and nuclear fuels, including oil, natural gas, and coal, among non- recyclable energy sources, usually known as non-renewable energy sources, has been delimitedin recent years.

Looking at the changes in global energy production across various energy sources, it is worth noting that renewable energy sources had the largest annual average increase from 1971 to 2018. Other than hydropower and biofuels, the amount of energy produced from renewable sources worldwide rose by an average of 9.4% throughout this time. Only 1% of the average yearly gain in energy production over the same period was due to oil. It is more common to produce electricity using renewable resources like wind and solar. The increase in the renewableenergy output of 11.2 percent between 2017 and 2018 demonstrates that this trend has continued [4].

Renewable energy sources are inexhaustible resources that remain at the same degree the nextday, thanks to nature's evolution. Renewable energy is described as energy sources that can regenerate far more quickly than

they can be used up. These resources are used in natural processes to produce energy. Renewable energy sources are less threatened by depletion than nonrenewable energy sources. Natural resources that can be regenerated without humaninterference are what the International Energy Agency refers to as renewable resources [5]. The primary distinction between renewable energy sources and fossil fuels is that fossil fuels cannot be transformed again once utilized. On the other hand, renewable energy sources are almost limitless that can be reused and turned back into energy. These sources are seen to be the answerto today's quest for alternative energy sources. The main premise is that renewable technologyshould be widely used, and costs should be decreased as technology advances. In the long run, traditional energy sources are anticipated to be replaced by renewable energy sources.

Renewable energy is a low-cost energy source, with a few exceptions. It is a form of energy that is good for the environment. It has an environmentally acceptable and non-polluting structure during the energy generation phase, even though it does relatively little environmentalharm during the construction and installation stages. It's crucial in the fight against the greenhouse effect by lowering emissions. Much of the technology required to create energy from renewable sources is now available in today's world. If sufficient investments are made inindustries, costs will decrease, and energy production from renewable sources will become a more preferred source. Solar energy systems have advanced to the point that they may successfully compete with traditional energy sources in recent years.

1.2 Photovoltaic Solar Cells as an Alternative Energy Generation

The words "photovoltaic" and "volt" are both derived from the Greek words "phos," which means "light," and "volt," which denotes a unit of electromotive force. French physicist Alexandre-Edmond Becquerel (1820-1891) made the first formal description of the photovoltaic phenomenon. In 1839, while conducting laboratory research, he developed

the first photovoltaic cell by using silver chloride in an acidic solution. He identified the first solar cell by observing the voltage output while illuminating the platinum electrodes.

Willoughby Smith, a British electrical engineer, was the first to define and publicize selenium'sphotosensitivity in 1873. According to two English scientists, Richard Evans Day and WilliamGrylls Adams (1836–1915), light reflecting on selenium rods generated an electric charge. Charles Fritts (1850–1903) made the first functional solar cell. Soon later, he produced the first solar cell panel in 1883. He made selenium light-transparent by covering it with an incredibly thin layer of gold and attained an energy conversion efficiency of 1 to 2% [6]. Despite their modest efficiency, these devices marked the start of one of engineering's most rapidly evolvingfields. In addition, Charles Fritts pioneered the use of solar panels. In the mid-1880s, he set upa test array on a Manhattan rooftop [7]. These pioneers and their contemporaries lacked a deeper grasp of this impact, so they could not further improve solar cells. When Michael Faraday discovered the action of electromagnetic induction in 1831, the photovoltaic phenomenabecame apparent.

An American engineer, Russell Shoemaker Ohl (1898-1987), was the first to patent thecontemporary junction semiconductor solar cell, invented in 1946. The first repeatable p-type and n-type silicon production was carried out by Russell Shoemaker Ohl and his Bell Laboratories colleagues. In fact, he used this technique to make the first p-n junction in silicon.Ohl used an ohmmeter to evaluate a silicon crystal sample with a crack on the center of the silicon crystal sample in 1940. When the sample's electrical resistance was measured and recorded, it was known that the current through the sample changed when exposed to light. However, after the crack, it was observed that there was a noticeable jump on both sides. When exposed to light, semiconductors like selenium generate a little current. The break on the molten silicon is marked, as Ohl demonstrated to his colleagues at Bell Labs. Different impurities andcontaminants in silicon were separated by various methods at the time. As a result of the observation, in silicon atoms, it was noticed that there were extra electrons

on one side of the crack in the region, and, on the contrary, there was electron deficiency. The two regions were designated P and N, P for the positive type and N for the negative [8].

Daryl Chapin and Bell Telephone Laboratories colleagues Calvin Fuller and Gerald Pearson atBerkeley Heights, NJ produced the first functional photovoltaic solar cell, which turns sunlightinto useful electrical power with a conversion efficiency of roughly 6%. They presented a cell that is based on diffused silicon P-N junctions. It was initially released on April 25, 1954, and led to the creation of photovoltaic solar panels, which were first used to power practically all spacecraft in March 1958, and later to power many of today's photovoltaic solar cell power systems. This invention was based on existing solar cells as a prototype [9].

Following that, solar cell conversion efficiency gradually improved, reaching 11% in 1958 and 14% in 1960, although at a high cost. Researchers first found other photovoltaic materials in the 1960s, such as gallium arsenide (GaAs). Despite being more expensive, these materials could withstand temperatures higher than silicon. One of the first important uses for GaAs technology was space exploration [10].

The first applications were in isolated terrestrial locations without access to electrical infrastructure. Photovoltaic energy has steadily become the dominant source of electrical energy for remote applications since the mid-1980s. The cost of solar cells has steadily decreased as technology has progressed. With the studies and research carried out in the following years, solar cells started to have high efficiencies over the years. Solar cell efficiencies, which have improved because of research over the years, are graphed in Figure 1.1on a year-by-year basis. Scientific research reports are reflected in the values.

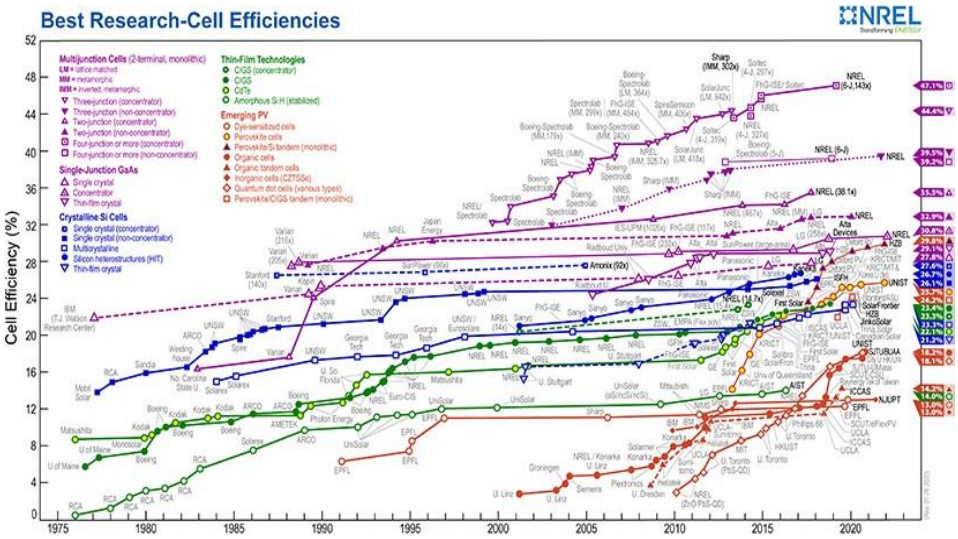


Figure 1.1 Best Research-Cell Efficiency Chart, NREL [11]

So far, the most effective technology appears to be tandem solar cells, also called multi-junctionsolar cells. Each layer is deliberately doped in tandem cells to take advantage of a certain wavelength, allowing them to convert a wider spectrum of solar energy than most solar cells, which typically only use visible light to generate power. Multiple layers of various semiconductor materials make up multi-junction cells. They can be created by monolithically developing each semiconductor layer on top of the other in a single piece or mechanically stacking independently generated layers. They are made up of stacked single-junction cells.

The primary factor distinguishing solar energy from other renewable energy sources is that solarpanels only depend on the sun to produce photovoltaic electricity. The high radiation values and climatic circumstances create an ideal setting to assess this potential with solar energy system applications. Only the sun is used to generate photovoltaic electricity. It produces no hazardous gas emissions and actively works to reduce global warming. A solar module has a 30-year lifespan. It is also known to drop to only 80% of its original output value after 25 years,and this technology has proven excellent efficiency performance and long-term durability. Furthermore, reliable items are supplied to investors because of the high-quality

standards established in European Union rules. The amount of electricity produced by solar energy systems developed with proper planning and engineering studies can be calculated at the planning stage with data that is close to 100% accurate. They can be erected far faster than traditional energy generation systems and begin producing in hours.

Solar energy is a type of power produced in the sun's core by the fusion of hydrogen and helium.Large amounts of radiant energy are released during this process, and this energy can be used to create electricity. Technological advancements have increased the efficiency and economics of solar energy systems. Compared to the energy people utilize today, only a small portion of solar energy penetrating the Earth is significantly more potent. It has established itself as an environmentally clean energy source.

Perovskite solar cells have recently become more popular among the literature on organic solarcells that are still being studied. It has been noted that after manufacturing, the chemical structures of PSCs become unstable. However, the chance of becoming a commercial solar cellin the future is quite high due to its high efficiency and the abundance of perovskite material innature. Light-harvesting metal-halide perovskite materials have shown reduced exciton bindingenergy, high optical cross-section, tunable band gaps, and low-cost production, making PSCs viable for new photovoltaics technology [12]. For application in large-scale production alongside conventional solar cells, the highest PCE of PSCs, over 25.8 percent, has shown promising future potential [13]. On the other hand, PSCs are not yet widely used in commercialapplications due to their lack of stability. The key external elements that contribute to the degradation of PSC are oxygen, heat, and moisture. Careful interface engineering, such as encapsulation, can be used to control all the potential internal processes for degradation in PSCs. The cathode interface and active layer can be protected from chemical and physical damage by preventing oxygen and moisture from diffusing through the encapsulating material. The encapsulating material layer structure is crucial to solve these difficulties and improve device stability because the oxygen and moisture barriers of encapsulation materials should bevery high. In addition, to reduce the

deterioration in PSCs, it is also necessary for the electricalconnection and contact materials to be of suitable design and quality.

For the commercialization of perovskite solar modules, module designs need to be developed. This work focuses on the development of encapsulation and electrical coupling techniques necessary to prevent chemical degradation and physical damage of perovskite solar modules in outdoor conditions. The PCE of perovskite solar cells can be increased using module designs, but since the chemical stability of these solar cells is poor under outdoor conditions, the required level of cell efficiency cannot be maintained. To overcome this stability problem, encapsulationmethods need to be developed.

1.3 Fundamentals of Photovoltaic Solar Cells

Solar cells that directly convert sunlight into electricity are called photovoltaic (PV) solar cells.Because of their unique ability to absorb light energy and produce an electric current, they are composed of semiconductor materials. The photovoltaic effect—the phenomenon of a substance producing a voltage or current upon exposure to light—underlies the operation of a PV solar cell.

When light energy reaches a semiconductor material's surface, the extra energy may drive electrons loose from their atoms, resulting in free electrons and holes as well as the creation ofan electric field. The built-in electric field divides the free electrons and holes, causing the freeelectrons to flow toward the negative side of the cell and the free holes to flow toward the positive side, producing a current.

The performance of a PV solar cell can be characterized by several key parameters, including the open-circuit voltage (V_{oc}), short-circuit current density (J_{sc}), fill factor (FF), maximum power point (MPP), and efficiency.

The maximum voltage a solar cell can produce when no load is attached across its terminals isknown as the open-circuit voltage. It is a crucial factor since it establishes the highest voltage a solar cell can produce. Setting the net current in the solar cell equation to zero yields an equation for V_{oc},

$$V_{oc} = \frac{nkT}{q} \ln \left(\frac{J_{sc}}{J_o} + 1\right) \qquad (1.1)$$

Where n is intrinsic carrier concentration, $\frac{kT}{q}$ is the thermal voltage, J_{sc} is the short circuit current density, and J_o is the saturation current density.

The short-circuit current is the highest current generated from a solar cell while the voltage across its terminals is zero. It is a crucial variable since it establishes the maximum current density that may be generated from a solar cell given as,

$$J_{sc} = qG(L_n + L_p) \qquad (1.2)$$

Where G is the generation rate, L_n is the electron diffusion length, and L_p is the hole diffusionlength.

The fill factor measures the solar cell's ability to convert available energy into electrical energy. It offers details on the solar cell's effectiveness in practical settings. The fill factor is computed by multiplying the solar cell's maximum output by the sum of its open-circuit voltage and short-circuit current density,

$$FF = \frac{J_{mp}V_{mp}}{J_{sc}V_{oc}} \qquad (1.3)$$

Where J_{sc} is the short circuit current density, V_{oc} is the open circuit voltage, J_{mp} and V_{mp} is the current density and voltage at the maximum power point on the J-V curve.

The maximum power point (MPP) is the location on the solar cell's current-voltage (J-V) curve where the product of current density and voltage is at its

highest. The solar cell is now operating at its highest efficiency and producing the most power. MPP is a crucial variable since it affects the solar cell's power output.

Efficiency is defined as the solar cell's electrical power output to incident light power ratio,

$$\eta = \frac{J_{mp}V_{mp}}{P_{in}} = \frac{P_{max}}{P_{in}} \qquad (1.4)$$

Where P_{max} is the maximum generated power, and P_{in} is the incident power.

It evaluates how effectively the solar cell transforms the light that strikes it into electrical energy. The characteristics of the semiconductor material, the caliber of the junction, and the solar cell's design are some of the variables that affect a solar cell's efficiency.

An essential tool for describing the performance of photovoltaic (PV) solar cells is the J-V curve. The open-circuit voltage (V_{oc}), short-circuit current density (J_{sc}), fill factor (FF), and maximum power point (MPP) of a solar cell can all be determined by graphing the output current density versus the output voltage under a variety of different load circumstances. Any problems or inefficiencies in the solar cell's performance can be found by examining the J-V curve's shape. For instance, a low V_{oc} could point to an issue with the p-n junction's quality, but a low J_{sc} could point to an issue with the solar cell's capacity to absorb light. A low FF could mean the solar cell is not efficiently converting the available energy into electrical power. In contrast, a non-optimal MPP could mean that there is a problem with the solar cell's construction or operation. J-V curves can be used to compare the performance of various solar cells, determine the impact of various operating conditions on the performance of a single solar cell, and provide details on the essential solar cell parameters. It is feasible to determine the solar cell's ideal working parameters and create plans for enhancing its performance by examining the J-V curve's shape under various circumstances. A photovoltaic solar cell's ideal current density-voltage curve should show a linear increase in output current when the input voltage is increased up to a certain point, followed by a sharp decrease in output current density as the input voltage is increased further.

A solar cell's ideal J-V curve ought to show a variety of traits that point to high performance and efficiency. Zero voltage and zero current should be present at the curve's origin and rise linearly until it reaches a specified point, known as the curve's knee. The voltage should rise steadily while the current density decreases rapidly, signaling that the solar cell has reached saturation, as shown in Figure 1.2.

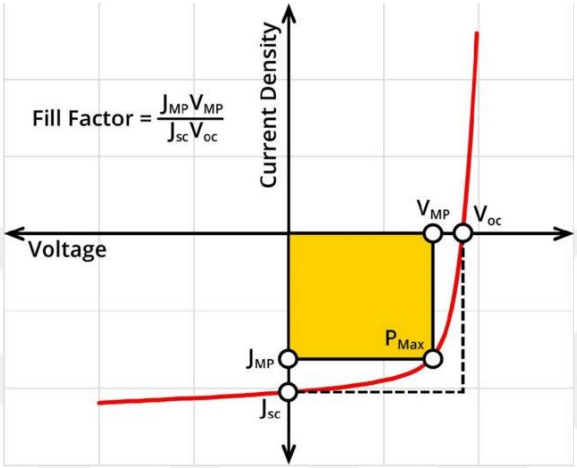


Figure 1.2 Typical J-V characteristics curve of a PV cell [14]

The two most crucial factors affecting a solar cell's efficiency are the open-circuit voltage (V_{oc}) and short-circuit current density (J_{sc}). The solar cell's output is measured in terms of voltage while no load is attached to its terminals and current when those terminals are shorted. A high V_{oc} and a high J_{sc} on an ideal J-V curve show that the solar cell can provide a high output voltage and current density. An ideal J-V curve should also have a high fill factor (FF), high maximum power point (MPP), and a high V_{oc} and J_{sc}. The MPP is the point on the J-V curve where the solar cell runs at its highest efficiency and generates the maximum power. In contrast, the FF measures how successfully the solar cell transforms the available power into electrical power.

The solar cell should be able to generate a high output voltage and current density and convert a significant amount of the incident light into electrical power, according to an ideal J-V curve.

1.4 Perovskite as a Solar Cell Material

1.4.1 The Scientific History of Perovskite Solar Cells

Silicon-based PV devices are reaching the theoretical maximum efficiency limits, and the search for new PV technologies expected to exceed this limit has begun. Recent developments in academia and business have focused a lot of interest on organometal halide perovskite absorbers through their potential for high PCE and low-cost production methods.

Since the initial realization of efficient PSCs with a PCE of 3.9 percent in 2009, hybrid organic and inorganic perovskites (HOIP) have made significant progress; in 2018, the PCE achieveda new high of 23.3 percent, and Perovskite solar cells' efficiency rose to 25.7% in 2020 [15]. The next technology is anticipated to develop scale-up methods for transforming small-area tolarge-area modules. Perovskite materials are among the most promising in modern PV because they offer superior optoelectronic characteristics like high absorption coefficient, long carrier diffusion length, high carrier lifetime, and low exciton binding energy.

In 1839, a German researcher named Gustav Rose found a calcium titanate-based mineral in the Ural Mountains and named it "perovskite" in honor of the Russian mineralogist Lev von Perovski. A perovskite is any material having the crystal structure ABX_3, which was first foundas the mineral perovskite, which is made up of calcium titanium oxide ($CaTiO_3$). “A” and “B”are two ions with different sizes, and “X” is an ion that forms a bond with both. Typically, atoms beginning with the letter “A” are bigger than atoms beginning with the letter “B”. In theideal cubic configuration, encircled by an octahedron of anions, the B cation is in 6-fold coordination, whereas the “A” cation is in 12-fold cuboctahedral coordination [16]. One of themost widespread structural families, perovskites, can be found in various compounds with various characteristics, uses, and significance. There has been a lot of interest in and research into perovskite materials since the 2009 discovery of PCSs [17].

Due to their potential to replace conventional silicon-based solar cells with a low-cost, highly effective alternative, PCSs, a relatively new type of solar cell, have recently attracted much attention. The material utilized in these cells has the same crystal structure as the mineral perovskite, referred to as "perovskite" in this context.

Perovskite solar cells' great efficiency in converting sunlight into electricity is one of their mainbenefits. Compared to or even better than conventional silicon-based solar cells, they have attained conversion efficiencies of over 25%. PSCs may also be more affordable than conventional solar cells since they can be produced from ingredients that are inexpensive and widely accessible.

The design and application flexibility of PSCs is another benefit. They are easily integrated into various surfaces, including building facades and windows, by being fashioned into thin, lightweight, and flexible panels. PCSs are not without their difficulties, though. One of the mainissues is that they don't last very long because they degrade quickly when exposed to environmental variables. By creating more stable perovskite materials and encapsulatingtechniques, scientists are attempting to solve this problem. Perovskite solar cells are a crucial topic of study in renewable energy despite these difficulties due to their potential advantages.

Perovskite solar cells were first developed in 2009, it was found that specific kinds of perovskitematerials may be used to make effective solar cells. Although the initial PSCs had poor efficiencies of only 3.8%, scientists rapidly recognized their promise and started working to enhance their efficiency [17]. Perovskite solar cells did not initially garner much interest due totheir weak stability and efficiency, but that changed after studies revealed an efficiency of over9% and stability of over 500 hours.

The efficiency of PSCs was significantly increased over the following few years by researchers.Researchers obtained an efficiency of 15.4% in 2013, while those at the Swiss Federal Institute of Technology in Lausanne (EPFL) achieved a 12.3% efficiency in 2012. These efficiency gainswere made possible by combining material advancements with device

architectural optimization [18]. Perovskite solar cells have since become more effective, with the most recent record efficiency being 25.8 %, accomplished in 2023 [11]. The efficient development of perovskite solar cells is shown in Figure 1.3.

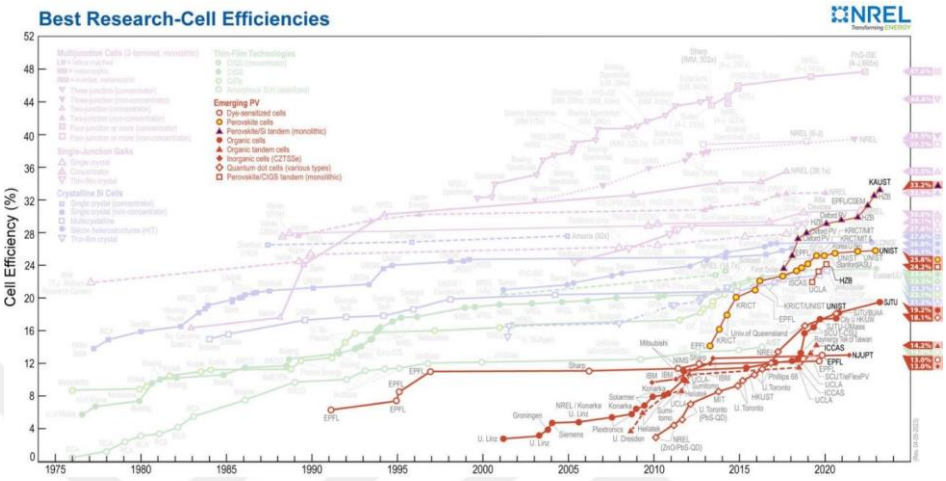


Figure 1.3 The efficient development of perovskite solar cells [11]

Perovskite materials are generally inexpensive and simple to produce, which makes them an appealing choice for widespread deployment. Though still in their infancy, PSCs face several obstacles that must be overcome before they can be extensively used.

1.4.2 Structure of Perovskite Solar Cells

Perovskite minerals are plentiful and exist in a variety of forms in the mantle layer of our planet. Perovskites' lattice structures are cubic in nature. Inorganic ABX3 denotes the general form of perovskites with a crystalline structure. The A cation (A = Ca, Sr, Ba, Pb) is shared with 12 “X”anions in this structure. This component forms the cubic octahedral crystal structure. The smaller “B” cation is an octahedral crystal shared by 6 “X” anions. The side makes up the structure.

In the Perovskite structure “ABX3”, "X" stands for salt elements, "A" for

organic/inorganic cation group (typically methylammonium, formamidinium or cesium), and "B" for metal cation group (Sn^{2+}, Ge^{2+}, Pb^{2+}). While organic cations such as CH_3NH_3+, $CH(NH_2)_2$ +, and inorganic cations such as Cs+, Rb+ share the “A” position in a cubic perovskite structure, the smaller “B” position is generally occupied by the Pb_2+ or Sn_2+ cation. I-, Br- or Cl- salts all occupy the “X” position (figure 1.3). Perovskite has a high absorption coefficient and is a direct band material. Unlike silicon solar cells, it is possible to absorb many photons with a much thinner layer because of this characteristic. The octahedral " BX_6" shape is created by the " ABX_3" structure, where "A" and "B" stand for the center of the octahedron and "X" stands for the corners. The ratio between "A" and "B" and "X" is 1:2:1. “A” indicates a large metal cation centered in the hole created by eight “BX_6” octahedra.

“X” is a halogen from group 7A of the periodic table (I-, Cl-, Br -) in inorganic-organic perovskite compounds, A is an organic cation (CH_3NH_3 +), and “B” is Pb or Sn. Solar cells mostly use perovskites that are either single halide or mixed halide. Methylammonium lead iodide ($CH_3NH_3PbI_3$ or $MAPbI_3$) and methylammonium lead bromide are two common single halide perovskites ($CH_3NH_3PbBr_3$ or $MAPbBr_3$) [19]. Studies on methylammonium lead bromide ($MAPbI_3$) were attempted in this thesis work.

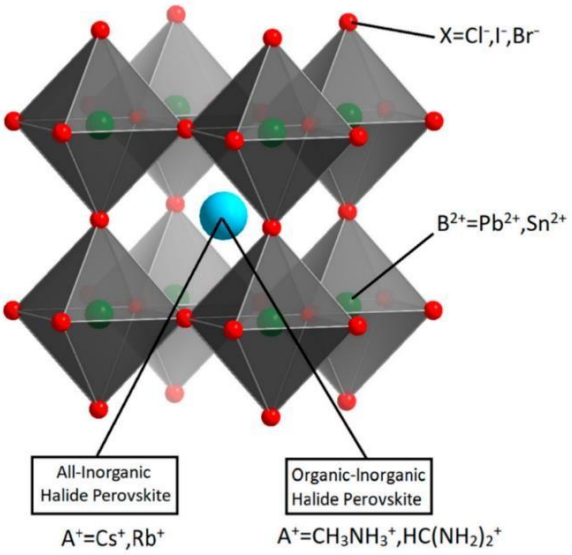


Figure 1.4 Structural diagram of ABX3 perovskite crystal [19].

Cation-anion pairs do not produce the stable three-dimensional structure needed to form the octahedral framework. The B and X ion dimensions set the parameters for the A cation's potential dimensions. Anions and cations that produce a perovskite structure are chosen using two empirical parameters. The first parameter (*t*), defined by the equation below, is the geometrical tolerance factor, Ra, Rb, and Rx. are used to denote the ionic radii of the A, B, and X sites, respectively.

$$t = \frac{R_a + R_x}{\sqrt{2}(Rb + Rx)} \qquad (1.5)$$

Perovskite geometry only appears when the A ion's radius is noticeably larger than the ion's radius when the tolerance factor is near or equal to 1. A specific critical transition occurs whenthe tolerance factor is between 0.89 and 1. Values of "t" above one lead to unstable structure formations [19].

In the construction of a perovskite solar cell, the active layer is positioned between two remarkably thin carrier transport materials, specifically an electron transport layer (ETL) and a hole transport layer (HTL). The alignment of their bands is influenced by factors such as energy levels,

electron affinity, and ionization potential. Ultra-thin layers with low electron affinities and ionization potentials play a vital role in transporting holes, while layers with high electronaffinities and ionization potentials facilitate the transport of electrons. To ensure effective holetransport, the HTL incorporates electron-blocking materials, which prevent the release of holestowards the front electrode. The HTL facilitates the transfer of holes from the perovskite activelayer to the back electrode. Conversely, the ETL aids in the movement of injected electrons from the active layer to the front electrode and functions as a barrier, impeding the escape of holes to the front electrode. This intricate arrangement allows for efficient charge transport andcollection within the perovskite solar cell structure.

The anode plays a crucial role in the collection and generation of carriers within the structure of a PSC. Its importance stems from several advantageous properties, including low reflectivity, high transmissivity, and strong electrical conductivity. Additionally, the anode possesses a high work function, which contributes to efficient carrier collection. Moreover, the anode allows forstraightforward patterning, enhancing the fabrication process of the PSC. On the other hand, the cathode, which can be either transparent or non-transparent depending on the specific type of PSC, predominantly collects the holes generated in the absorption layer. When a current flows through the device, the cathode serves as the recipient of these holes.

When photons possess sufficient energy, $E > E_g$, to be absorbed, they can induce the movementof electrons and holes in distinct directions. Electrons migrate to the conduction band, while holes relocate to the valence band within the perovskite material. In PSCs, excitons, which are bound electron-hole pairs, have the ability to interact and undergo various processes. They caneither generate new excitons or separate them into free carriers, free electrons, and holes, whichcontribute to the production of electrical current. This behavior arises due to the diverse bindingenergies of excitons in perovskite materials.

Within the field region of the solar cell, electron-hole pairs are generated, and the presence of an electric field causes their subsequent separation. As

a result, holes are driven toward the p- side, while electrons are propelled toward the n-side of the cell. At the boundaries of the field region, the accumulation of some electrons and holes occurs, leading to the neutralization of certain particles. Notably, when the excitation energy of absorbed photons surpasses a certain threshold, electrons and holes can effectively transition to their respective energy bands. Consequently, the bandgap of the absorbing layer in the solar cell can be determined using thisprinciple.

Overall, these processes within the perovskite solar cell allow for the efficient utilization of photons' excitation energy to create electron-hole pairs and facilitate the generation of electricalcurrent.

The bandgap of a material can be defined as the energy difference between the conduction band (E_c) and the valence band (E_v), expressed by the equation $E_g = E_c - E_v$. When electrons are promoted to the conduction band, holes are simultaneously created in the valence band, and their movement occurs in opposite directions.

In the context of a p-n junction in a PSC, the carriers generated near this junction can reach the space charge region without undergoing recombination. An accumulation of excess electrons and holes near the p-n junction creates an electric field, depicted in Figure 1.5, which acts in the opposite direction to the potential energy barrier. This internal electric field facilitates the migration of electrons into the n-type region and the diffusion of holes into the p-type region.

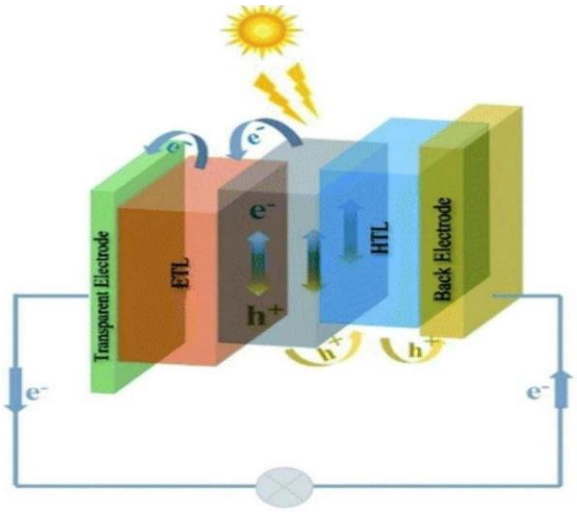


Figure 1.5 Structure and working principle of PSCs

However, a complication arises when there is an excess of holes present in the p-type region. This surplus of holes disrupts the balance of electrons in the n-type region, posing a challenge for their mobility and overall device performance.

Currently, the focus is on developing highly efficient perovskite solar cell devices with enhanced output parameters, such as efficiency. However, existing literature highlights several factors that limit the device's performance. These factors include the incorrect selection of perovskite materials, subpar power conversion efficiency, the toxicity of lead in the active layers, and reduced device lifetime. These constraints significantly decrease the overall efficiency and effectiveness of the PSC.

In response to these challenges, researchers have been exploring various solutions to address the issue of efficiency. Efforts are being made to improve the selection and optimization of perovskite materials, enhance the power conversion efficiency through innovative device architectures, seek alternative non-toxic materials to replace lead-based perovskites, and extend the lifetime of PSCs through improved stability and durability measures. These aim to overcome the barriers and achieve higher performance and reliability in PSC devices.

1.5 Design Challenges of Perovskite Solar Modules

Years after their first manufacture, the efficiency of perovskite solar cells increased significantly. PSCs have progressed to the point where they can compete with other solar cell types. Although PSCs are a promising renewable energy technology, they must overcome several obstacles to gain widespread adoption. The greatest difficulty is stability. Perovskite solar cells' lifetime and dependability are constrained since they are less stable than conventional silicon solar cells and can quickly deteriorate when exposed to moisture or heat. Water vapor, oxygen, electric field, and light degrade PSCs immediately after manufacture. Despite the high PCE potential of perovskite solar cells, their commercialization is constrained due to their fragility in harsh environmental conditions. Due to the perovskite crystal structure's inherent instability, which can readily be broken or decomposed under specific circumstances, PSCs are unstable. Moisture poses a particular risk since it might interact with the perovskite structure and cause it to disintegrate, which would reduce electrical performance. Researchers are attempting to solve these stability problems with several different approaches. Encasing the perovskite solar cells is one method for shielding them from moisture and other external elements. Encapsulation entails applying a thin film to the solar cells that serve as a barrier, keeping moisture and other pollutants from getting to the perovskite layer. Encapsulation can be difficult because the films must be light-transmissive and robust enough to offer protection.

Overall, stability is a major problem for perovskite solar cells, and researchers are working hard to create solutions. According to the study, 10 minutes after the PSCs were produced, efficiency dropped by 80% [20]. Long-term stability experiments were conducted for the $CH_3NH_3PbI_3$ PSCs kept in the air at ambient temperature without encasing for more than 500 hours when exposed to one sun illumination [21] and 1000 hours under full sunlight [22]. This indicated that light soaking is not the only factor contributing to the instability. It has also been found that encapsulated PSCs have long-term stability for 500 hours at 45 ℃ [23], under continual illumination of around 100 mW/cm^2 and 1000 hours at 40 ℃ [24], with continuous exposure and operating under simulated full spectrum sunlight.

1.5.1 Degradation of Perovskite Solar Cells

Perovskite solar cell deterioration is associated with several problems, including device and interface instability. These issues must be resolved to obtain high conversion efficiencies, superior repeatability, and long PSC lifetimes.

PSCs can degrade due to intrinsic and extrinsic stability factors, such as perovskite material's vulnerability to environmental factors like oxygen and humidity. Other parts of the device structure can also degrade, such as the interface's electron transport layer (ETL) when exposed to light or the hole-transport material's instability. External variables such as ambient conditions make PCSs degrade. The lack of stability of perovskite solar cells under outdoor operating circumstances, particularly for long-term usage, has hampered their commercialization. Various ways to overcome degradation have been tried, but commercial PSCs have yet to emerge; they comprise the perovskite substance's deterioration when exposed to light, moisture, or a higher temperature. In most stability studies, tests were reported after the perovskite devices were kept in ambient or dark storage with regular intervals to observe performance evaluations. Before looking at the remedies for degradation, it's crucial to understand the degradation mechanisms. Understanding the stability aspects of PSCs and investigating the degradation mechanisms is critical, and knowledge of the degradation mechanisms is crucial for finding cures for the factors that cause deterioration.

1.5.1.1 Oxidation and Humidity

Oxidation occurs inside the solar cell when oxygen and humidity levels rise above a specific point. In turn, the ensuing deterioration modifies the chemical composition of perovskite solar cells. The issue with perovskite material deterioration is a chemical reaction in which moisture serves as a catalyst. When the bonds between the "A" site cations are broken by the extremely polar H_2O , then instability, and subsequent irreversible degradation result. The perovskite, $CH_3NH_3PbI_3$, $MAPbI_3$, decomposes into HI, MA, and PbI_2 in the presence of water, O_2, and UV radiation (equation 1.2). The procedure is not likely to be completely reversible because phase separation and crystallization of PbI_2 are anticipated.

$$MAPbI_3 \overset{H_2O}{\longleftrightarrow} PbI_2(s) + CH_3NH_2I\ (aq) \qquad (1.6)$$

Water dissolving these products can affect the performance of solar devices and cause irreversible degradation reactions. Perovskites' inferior phase shift from the black polymorph phase to the yellow polymorph phase can also be accelerated by water. The organic cation MA^+ is dissolved by moisture to produce PbI_2 and HI, which aids in the breakdown of the perovskite layer, because of this subsequent breakdown of hydroiodic acid (HI) caused by UV light and oxygen, which results of the production of H_2O , hydrogen (H_2), and iodine (I_2) gases as byproducts given as equation 1.3 and 1.4.

$$CH_3NH_2I\ (aq) \leftrightarrow CH_3NH_2(aq) + HI(aq) \qquad (1.7)$$

$$4HI\ (aq) + O_2(g) \leftrightarrow 2I_2(s) + 2H_2O(l) \qquad (1.8)$$

The rapid decomposition of the perovskite material at a low relative humidity of 40% and the weakening of the bonds between the cations due to the strong hydrogen bonds that form between water molecules and organic cations in perovskite crystals were both reported to study the degradation of $MAPbI_3$ material exposed to heat or an electric field [25].

It has been discovered that metal halide perovskites can degrade very quickly in the presence of oxygen and light. Studies have revealed that photo-induced generation of exceptionally reactive superoxide radicals occurs concurrently with fast oxygen penetration into the $MAPbI_3$ films. The creation of superoxide species, which occurs when oxygen transforms into oxygen two, is a crucial stage in the degradation process. O_2^-, which is formed when oxygen becomes O_2 (equation 1.5), then reacts with a photo-oxidized $MAPbI_3$ to create PbI_2, I_2, H_2O, and CH_3NH_2 (equation 1.6) [26].

$$O_2 \leftrightarrow e^- + O_2^- \qquad (1.9)$$

$$CH_3NH_3PbI_3 + O_2^- \leftrightarrow 4PbI_2 + 2I_2 + 2H_2O + 4CH_3NH_2 \qquad (1.10)$$

According to the study, oxygen diffuses through iodide vacancies both at the surface and within the bulk of the crystal volume, beginning immediately after exposure and completing within an hour for $MAPbI_3$ film. According to predictions, iodide vacancies have high intrinsic densities and can be produced quickly under photoexcitation [27].

1.5.1.2 Illumination and Heat

When organic molecules are present, UV radiation can trigger the diffusion of oxygen molecules, and superoxide or hydrogen peroxide can be formed, which can assault and damage the active layer. A common first step in determining whether the selected active material is appropriate for solar systems is to confirm that the material does not degrade when exposed to continuous light. Numerous studies have demonstrated that PSCs can be fully maintained their current generation even after being exposed to light for hundreds of hours [28][29][30]. However, other investigations have also found that important modifications, including halide segregation, ion migration, and compositional deterioration, occur in perovskite films due to light [31][32]. Some varieties of PSCs are less stable than others due to the varying photostability of the charge transport layers utilized in these devices. According to one of these studies, species of I^- moved away from the lighted area as photoluminescence intensities increased. This research offered some of the first concrete physical proof of iodide migration in perovskite layers. It is connected to the ionic species' slow diffusion throughout the perovskite layer [32].

Additionally, when heated, perovskite materials have a propensity to release volatile gases, which promotes the thermal breakdown reaction. Additionally, thermal and photo-degradation are frequently coupled to affect PSCs. According to the findings of one study, the considerable transformation of $MAPbI_3$ to PbI_2 happened when it was heated at 100 °C for 20 minutes under vacuum circumstances. This study examined the independent effects of high temperature on $MAPbI_3$ in this situation [33]. Another study also showed that the photodecomposition and thermal decomposition reactions took place in low-heating circumstances, whether light or dark, which was compatible with the photovoltaic operation, and this degradation is irreversible.

Due to the combination of impacts like many stressing elements on the active layer in PSCs, the degradation processes could generally be highly complicated.

1.6 Outline of This Theses

To significantly reduce carbon emissions, research in renewable energy focuses on clean technology, and emerging new-generation photovoltaic technologies are a key component of this area. Researchers used the "wonder material" perovskite about ten years ago to create commercially viable, ultra-efficient solar cells. With an efficiency of 3.81 percent, it was first described as a sensitized perovskite solar cell in 2009 [34]. After that, research on perovskite photovoltaics has expanded in an exceptional and exponential manner since the initial announcement of a perovskite solar cell with a PCE of 9.7 percent and 500 hours of stability in 2012 [35]. Recently, a PCE of 25.8 percent has been observed, and both the overall number of publications and articles on PSCs have grown rapidly since 2012 [36]. In parallel, research is being done on several designs to improve the performance of PCSs.

Numerous other solar cell types, such as silicon (Si), copper indium gallium selenide (CIGS), narrow band gap PSCs, and dye-sensitized, organic, and quantum dot solar cells, can be combined with PSCs with high PCEs. However, despite rapid improvement, the stability problem of PSCs remains one of the primary challenges for perovskite devices replacing commercial Si-based and thin-film solar cells lies in the efficiency's rapid development. The primary barrier to commercialization is the ease with which perovskites and PSCs degrade. However, the various perovskite cell degradation rates can impact the overall degradation of a solar module. Both perovskite and PSCs are susceptible to outside influences and environmental conditions. While several methods combat degradation, commercial PSCs are still not achieved. Laboratory-scale technology is constantly improving more quickly than PSC stability advancements. The rate of deterioration of perovskite cells has a significant impact on the lifetime energy yield and commercial viability of PSCs. The protective encapsulation that won't contribute to deterioration and designs that are necessary for PSCs have been studied in this thesis to address the stability problem, with an emphasis on the perovskite cell to enhance their performance. Using various perovskite cell packing, an investigation of the long-term energy yield of PSCs is described in this research.

By proving the quantitative impact of perovskite cell degradation on long-term performance, this thesis study will aid in the eventual commercialization of Perovskite solar modules.

The PSC stack consists of many layers with different coefficients of thermal expansion. Consequently, the chosen encapsulation method should reduce the heat stress on the perovskite stack. Low-temperature processable polymers with suitable optical properties have been applied to encapsulate solar cells to minimize internal reflections. The encapsulation experiments in this thesis aim to test the candidate encapsulation materials on PSCs after the literature search required to find encapsulation materials suitable for the chemical and physical structures of PCSs.

Within the scope of this thesis, candidate encapsulation materials were applied on PSCs with two different tools, vacuum lamination, and pressure lamination devices. Efficiency, open-circuit voltage (V_{OC}), fill factor (FF) , and maximum power point (MPP) values of PSCs whose encapsulation trials were completed were measured using “PICO G2V Solar Simulator” and “LabVIEW” program. The measured values were compared with the values before encapsulation at the first stage. The encapsulated perovskite solar cells were left in outdoor conditions and the hourly measurements were repeated. As a result of repeated measurements, productivity reductions were calculated as percent, and the encapsulation material that provided the lowest efficiency reduction to the most suitable encapsulation method was evaluated as suitable for commercialization.

CHAPTER 2

ENCAPSULATION OF PEROVSKITE SOLAR CELLS

2.1 Encapsulation

Encapsulation has an important role in extending the lifespan of perovskite devices by blockingthe entry of oxygen and moisture. As a result, it is also seen as a viable strategy for avoiding instability problems with PSCs. Encapsulation materials can act as barrier layers, limiting the diffusion of oxygen and moisture, preventing the penetration of UV light, reducing the sensitivity to abrupt thermal fluctuations, and inhibiting the irreversible escape of volatile decomposition products that may form from the perovskite solar cell materials, protecting the electrode interface and the active layer of the device. To enable the commercialization of PCSs,it is critically important to develop suitable encapsulation strategies to shield perovskite from outside stimuli. The best method to speed up the commercialization of these devices seems to be to encapsulate the entire device because degradation in PSCs is still a difficult problem to comprehend and handle.

2.1.1 Encapsulation Requirements

The layers of the PSC device should be held in place by the encapsulant material, which must also possess strong insulating properties, high light transmittance, and the ability to keep oxygen and water out of the PSC device and should be chemically compatible with the solar cell's layers. Therefore, they must be carefully selected while considering the more complex and specialized degradation types that take place in the device. Along with strong chemical inertness, good processability, and high barrier performance for oxygen and moisture, ideal encapsulation materials must have moderately low water and oxygen permeability [37].

Oxygen and Water Vapor Transmission Rate

To extend the lifespan of perovskite solar cells, moisture entry must be avoided. High resistanceto oxygen and water penetration is anticipated as perovskite material features. The stability ratesat which oxygen and water vapor gas can penetrate a film are measured using the metrics oxygen transmission rate (OTR) and water vapor transmission rate (WVTR). By measuring theamount of oxygen that passed through the cathode steadily over a predetermined period and bymonitoring the temporal rate of variation of the cathode electrical conductance, the OTR and WVTR were calculated. Knowing the values of OTR and WVTR makes it feasible to assess how well the enclosed materials safeguard perovskite devices from degradation over their lifetime and performance. The OTR and WVTR values must be between the boundaries of $10^{-3} - 10^{-5} cm^3 m^{-2} d^{-1}.atm^{-1}$ and $10^{-4} - 10^{-6} g\ m^{-2} d^{-1}$, respectively to provide a protective effect against environmental factors [38][39]. Given that oxygen and water vapor diffusivity follow Fick's law, the following generic formula is used to calculate transmission rate:

$$WVTR = \frac{DCs}{l}\left[1 + 2\sum_{n=0}^{n}(-1)^n\, e^{\left[\frac{-Dn^2\pi t}{t^2}\right]}\right] \qquad (2.1)$$

In the above formula, D is the diffusivity, t is the passage of time, C_s is the concentration of surface saturating agents, and l is the thickness of the film [40]. Temperature raises transmission rates, and high transmission rates at high temperatures, in particular, lead to rapid mass transport processes.

Mechanical and Electrical Requirements

Encapsulants are necessary to counteract the mechanical stress that the thermal cycling processcauses to build up over time in the solar cell. It is frequently essential to anneal PSCs at higher temperatures, >80 °C, to produce an appropriate perovskite film, which creates mechanical tension between the layers of the device. The mechanical stress that cooling imparts on the perovskite

layers creates some tensile stress between the layers, which produces delamination, moisture ingress, and cracking that impairs the material's performance. The layers' tension mustbe reduced by using elastic encapsulant materials. Additionally, a strong creep resistance shouldbe a property of the encapsulant material. Compared to non-cross-linked polymers, cross-linked polymers often exhibit superior creep resistance. Cross-linking aids in keeping the layers together and slows the ingress of oxygen and moisture into the device [41].

The encapsulation material should also be an electrical insulator to minimize leakage current. Volume resistivity, which measures a material's capacity to obstruct current flow, is crucial forthe stability of a solar cell.

Chemical Requirements

The chemical criteria include substrate adhesion, water absorption, chemical inertness at highertemperatures, and easy lamination processes. Encapsulant material should not react with any chemicals, and to determine whether an encapsulant is suitable and meets this requirement, immersion tests with chemicals are typically performed on copper (Cu) wires covered in encapsulant material. According to a study, the encapsulant is considered chemically stable if no reaction occurs on the Cu at 90 ℃ [42].

Additionally, the encapsulant material should not react with other layers since this could resultin an unwanted chemical reaction and have a negative impact on the solar cell's performance and lifespan. The melting point of the encapsulant material must be lower than 140 °C, becausehigh-temperature processes can degrade the chemical structure of perovskite and other layers in the cell. Furthermore, at a suitable lamination temperature, the viscosity should be at its ideallevel. In addition, the encapsulant must have extremely little shrinkage, which is less than 1%,both during and after cooling; otherwise, cracking and delamination problems may arise.

2.1.2 Encapsulation with Different Materials and Strategies

Different encapsulation solutions are developed considering the differences in various encapsulant materials and application circumstances to suit the fundamental needs of protectingthe device's performance. Glass-to-glass encapsulation, polymer encapsulation, and thin-film encapsulation are the fundamental encapsulation techniques used on solar cells [43]. Commercial silicon solar cells have traditionally been encapsulated with glass-glass structure. Still, due to the encapsulation process' significant adverse effects on the thermosensitive perovskite, care should be taken when choosing encapsulating materials to prevent temperature- related device performance damage. In this respect, alternative encapsulating techniques based on different polymer encapsulation materials have recently been produced. Polymer materials are suitable contenders for the encapsulation of PSCs due to their wide range of polymeric material options and excellent compatibility with roll-to-roll processes. Therefore, it is necessary to develop suitable polymeric materials that can serve as an effective protection layer from oxygen and moisture to increase the reliability of polymer encapsulation. In this thesis, different polymer-based encapsulation materials were studied on PSCs. As candidate encapsulation materials Surlyn™ based Meltonix, Polyolefin ENLIGHT™ 4015 PL and EVA(ethylene-vinyl acetate) materials were tested on PSCs during the studies.

Surlyn based Meltonix

The chemical structure of Surlyn™, an ionomer thermoplastic resin, is an ethylene methacrylicacid copolymer containing zinc (Zn), sodium (Na), lithium (Li), or other metal ions [44]. Theseresins are made to provide superior end-use performance or processing properties in several specific industrial applications. Surlyn™ ionomers in various packaging are used worldwide for the following reasons; low sealing temperature, hot tack strength, oil resistance, very goodadhesion, puncture and scratch resistance

[45].

Surlyn-based Meltonix encapsulation films are specially produced by Solaronix company for solar cells. These films are in polymer structures specially adapted to insulate the electrodes. These materials are based on Surlyn™ and show chemical compatibility with other componentsof PSCs. After the lamination process with these films, it ensures the confinement of the internalmaterials of the devices. The lamination process of Meltonix encapsulation films can be performed at different pressures and temperatures. It has a high transparency feature so that thesolar cells can receive the sun's rays, showing high stickiness on glass surfaces. In addition to not leaking the chemical components of the solar cell, it also prevents moisture and air from entering. Within the scope of the work, sheet types with 25, 45, and 60 μm (micrometer) thickness from Meltonix encapsulation films were used. Meltonix film ranges from Metlonix 1170-25 (25 μm thick thermoplastic film made from Surlyn®), Metlonix 1170-60 (60 μm thickthermoplastic film made from Surlyn®), and Metlonix 1161-60 (45 μm thick thermoplastic filmmade from Bynel®).

Polyolefin ENLIGHT

Polyolefin-based ENLIGHT™ films are produced as an encapsulation material for photovoltaicmodules by The Dow Chemical Company. It has been introduced to the market to increase efficiency in photovoltaic module production and have a lower cost. The films offer increasedmodule stability and improved electrical performance compared to conventional encapsulants.

The ENLIGHT™ encapsulant is designed to protect solar panels from environmental factors such as moisture, temperature, and UV light. It is made of a non-crosslinking, thermoplastic material that can be processed at lower temperatures than traditional encapsulants. ENLIGHT™encapsulant offers high mechanical strength, excellent adhesion to both glass and solar cells, and superior light transmission. It is also resistant to degradation from

weathering and UV light,ensuring solar panels' long-term reliability and performance. Additionally, ENLIGHT™ encapsulant has a low refractive index, which helps reduce light reflection and increase poweroutput from the solar panel. It is also free from halogens, which can be harmful to the environment.

ENLIGHT™ is a type of encapsulant material made mainly of polyolefin copolymers. Polyolefins are polymers derived from olefin monomers like ethylene and propylene, known for their stability and low environmental impact. The specific chemical composition of ENLIGHT™ may vary depending on its manufacturing process but typically includes a mixtureof monomers such as ethylene, propylene, butylene, or other alpha-olefins, along with additives and stabilizers to enhance its performance and durability.

ENLIGHT™ polyolefin encapsulation film is chosen as a suitable candidate material to be tested on perovskite cells in this thesis due to its low water vapor transmission value (3.3 g/m²/day), more than 90% optical transmittance, high adhesion (> 7.2 kN/m), high resistivity, low lamination temperature (90 ℃ − 100 ℃) and high UV stability [46]. In 2018, ENLIGHT™polyolefin was aged at 85 ℃ in the ambient atmosphere on mixed cesium and formamidinium (FA) cation perovskite with a composition of $Cs_{0.17}FA_{0.83}(Br_{0.17} - I_{0.83})_3$ with indium tin oxide (ITO) as a transparent electrode. PSCs enclosed in ENLIGHT™ polyolefin were kept inthe ITO-protected area after 1000 hours. The initial performance following the lamination of all encapsulated PSCs dropped by less than 5%. Glass-glass encapsulation ($ITO/\ ENLIGHT™\ /PSC/\ ENLIGHT™\ /ITO$) improved thermal stability at 85 ℃ in an inert atmosphere, allowingthem to preserve. 97% of their initial PCE was protected in 1000 hours. ENLIGHT™ encapsulated PSCs aged for 1000 hours in an 85℃-85% RH damp heat test by the IEC 61646 standard to hasten the degradation caused by heat and moisture, and it was reported that efficiencies were maintained in 99% of these encapsulated PSCs [47][48].

EVA (ethylene-vinyl acetate)

EVA (ethylene vinyl acetate) is a copolymer of ethylene and vinyl acetate. It is a highly versatile material used in various industries due to its properties. EVA is a soft, flexible, and lightweight material with good toughness and elasticity. It is resistant to many chemicals and weather conditions and has good electrical insulating properties. Ethylene-vinyl acetate (EVA) is commonly used as an encapsulant material in photovoltaic (PV) modules. It acts as a protectivelayer between the solar cells and the environment, helping to prevent moisture, dust, and other contaminants from entering the module and reducing its efficiency.

EVA is chosen as an encapsulant for its optical and mechanical properties. It is transparent, allowing maximum transmission of solar radiation to the solar cells. Additionally, EVA has excellent adhesion properties, which ensures strong bonding between the encapsulant and the solar cells, providing long-term stability and durability. EVA encapsulation has become a widely adopted technology due to its proven reliability and cost-effectiveness. However, research is ongoing to develop new encapsulation materials that can provide even higher efficiency and durability for solar PV modules.

In EVA, the ethylene and vinyl acetate monomers are linked by covalent bonds, resulting in a linear polymer chain. The vinyl acetate monomer contains an ester functional group, giving EVA unique properties, including good adhesion and flexibility. EVA is a thermoplastic material, meaning it can be melted and reshaped multiple times without undergoing any chemical change. It is also easily processed using various techniques, such as extrusion, injection molding, and blow molding.

Due to its optical properties and low cost, EVA has been studied as a potential encapsulant forPSCs. It has been shown to provide good adhesion to the perovskite layer, which helps to prevent moisture and oxygen from entering the device. Additionally, EVA has a low glass transition temperature, which means it can be processed at lower temperatures, reducing the risk of thermal damage to the perovskite layer. However, there

are some reports in the literatureof EVA causing changes in the perovskite morphology or causing a slight decrease in the photovoltaic performance of the device. These effects may depend on factors such as the EVA formulation, the processing conditions, and the specific perovskite composition and structure.

A study found that applying EVA to PSCs at temperatures of 135, 145, and 155°C significantlydecreased cell performance. After storage for six days under normal room conditions in the dark, the cells' performance dropped by more than 50%. The study concluded that EVA is unsuitable for use in PSCs under these conditions. Another study found that the perovskite absorber in EVA-encapsulated cells turned yellow when the temperature was raised to 120°C. This observation was consistent with previous findings on planar PSCs based on $FAPbI_3$ and is attributed to acetic acid released by EVA. Due to the performance loss caused by the encapsulation process and the yellowing of the perovskite absorber, the study concluded that EVA films are ineffective for PSCs.

Due to the reports of a decrease in perovskite cell performance with EVA encapsulant in the literature, EVA encapsulant was tested on perovskite solar cells with the additional use of different encapsulant materials as a second layer in this thesis.

Polyisobutylene (PIB) as an Edge Sealant Material

While encapsulant can provide effective protection for the solar cell's top surface, the device's edges are still vulnerable to degradation. Edge sealant is a material that is for protection of theedges of the perovskite solar cell, providing an additional layer. In addition to providing enhanced protection against moisture and oxygen, edge sealant can also improve the adhesion of the encapsulant to the solar cell. Poor adhesion can lead to delamination, where the encapsulant separates from the solar cell, exposing it to environmental factors. Edge sealant can help prevent delamination by increasing the bond strength between the encapsulant and the solar cell.

Furthermore, edge sealant can help to prevent mechanical stress, such as bending ortwisting, which can cause damage to the solar cell. Finally, in some cases, edge sealant can also improve the performance of the perovskite solar cell by reducing the loss of charge carriers at the edges of the device and help to reduce by acting as a barrier against charge carrier recombination. In summary, adding edge sealant to perovskite solar cells is an important step in ensuring their long-term stability, durability, and performance. By providing an additional layer of protection against moisture and oxygen, improving adhesion, preventing mechanical stress, and reducing charge carrier loss, edge sealant can help to make perovskite solar cells more suitable for commercial applications. In this thesis, polyisobutylene (PIB) materials as edge sealants were studied on PSCs [49].

Synthetic elastomer polyisobutylene (PIB), which is typically colorless, has excellent oxygen barrier characteristics. The homopolymer of isobutylene, known as polyisobutylene, serves as the foundation for butyl rubber. Different kinds of adhesives and sealants have been modified with polyisobutylene.

Polyisobutylene (PIB) has been studied as a promising edge sealant encapsulation material for PSCs due to its barrier properties and low reactivity with other chemicals. PIB-based edge sealants can be used as hot-melt adhesives that can be applied to the edges of PSCs to create aseal, which helps protect the cells from moisture and oxygen. Several studies have investigated using PIB as an edge sealant encapsulation material for perovskite solar cells. These studies have shown that PIB-based edge sealants exhibit excellent barrier properties and can effectivelyprotect the PSCs from environmental factors such as moisture and oxygen. It has also been shown to maintain their properties under harsh environmental conditions. Overall, PIB is a promising material for edge sealant encapsulation in PSCs due to its excellent barrier properties and low reactivity with other chemicals, it is a very adaptable, non-toxic, water-

white viscous liquid [50]. In addition, the PIB has WVTR values of $1x10^{-2}$ to $1x10^{-3}$ g/m^2day, which is the very low value required for solar cells to remain chemically stable. In 2017, PIB edge- sealant and encapsulation were applied to PSCs under low temperatures (90 °C). As a result ofthe research, it was revealed that PSCs kept their stability in the 200-day self-life test, 540 hoursof damp heat (85 °C, 85% RH), and 200 thermal cycles test [51].

CHAPTER 3

EXPERIMENTAL DETAILS

3.1 Research Frameworks

The purpose of this study is to look at how different encapsulation methods affect the performance of solar cells and the material properties of perovskite solar cells. The power output and stability of PSC can be greatly enhanced by applying encapsulation. The present study made use of a variety of materials to accomplish this purpose. Materials made of perovskite were created and processed in accordance with accepted practices. Different processes, such as vacuum and hot press lamination methods, were used to apply encapsulationtechniques. Numerous methods, such as spectrophotometry as reflection measurements, current density-voltage measurement, and photoluminescence (PL) spectroscopy before and after the stability testing, were used to evaluate the performance of the produced solar cells.

Table 3.1 Water Vapor Transmission Rate (WVTR), Application Temperature, and Optical Transmittance Values of Encapsulation Materials

Encapsulants	**WVTR ($g/m^2/day$)**	**Minimum Application Temperature (°C)**	**Optical Transmittance**
Surlyn based Meltonix	0.66	100 °C	>88 %
Enlight	3.3	110 °C	>90 %
EVA	2.61	110-150 °C	>93 %
PIB	$1x10^{-2}$	90 °C	>85 %

3.2 Encapsulation and Testing Procedures

In this study, three encapsulation materials, ionomer copolymer substances, Surlyn™, EVA and polyolefin ENLIGHT™ and edge sealant material polyisobutylene (PIB) were used on perovskite solar cells. The selection of the encapsulation materials was made based on their transparency, electrical conductivity, mechanical strength, and capacity to keep moisture and other impurities from penetrating the solar cell [52][53][54].

The hot press lamination technique coats the solar cells with encapsulation materials. The DYESOL laminator (Figure 3.1) was used as a hot press laminator. The solar cell and the encapsulation material are placed in the lamination device and brought to the desired temperature; the device ensures that the material is laminated without leaving an air gap on thecell with the help of applied pressure. This laminator is suitable for small and medium-sized solar cells and modules.

Figure 3.1 DYESOLE Hot Press Solar Cell Laminator

Pico™ G2V Solar Simulator and the LabVIEW program were employed to test the efficiency of solar cells. Pico™ G2V is a solar simulator with variable illumination intensity managed bysoftware. Photovoltaic cells are positioned in a light source in the Pico™ G2V Solar Simulator,and the power output of the cells is monitored. This light source imitates the sun's rays to monitor the performance of cells in a manner comparable to how actual sun rays would do. Thus, it is possible to forecast how cells behave under actual circumstances. There is a light source and a control system in the Pico™ G2V Solar Simulator in Figure 3.2. The lamp and spectrally selective filter that make up the light source are intended to generate light with a spectrum that closely resembles the solar spectrum. The control system enables adjustments tothe light source's spectrum and intensity, as well as the recording and analysis of solar cell andmodule performance under various environmental factors [55].

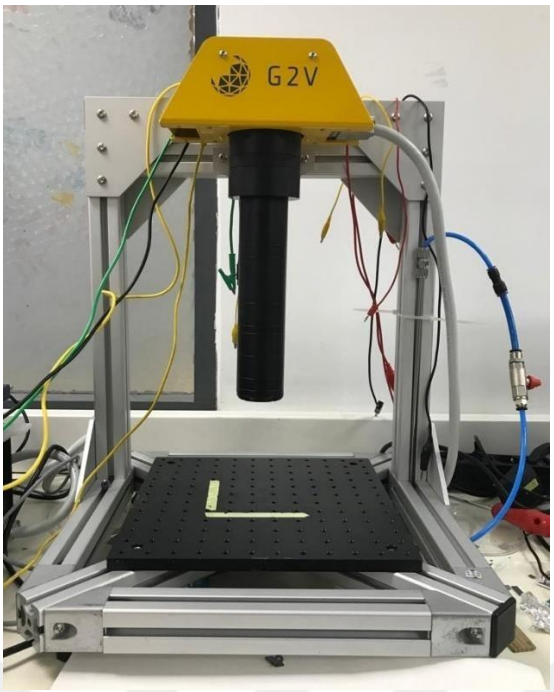


Figure 3.2 Pico™ G2V Sun Simulator

A software platform called LabVIEW (Laboratory Virtual Instrument Engineering Workbench)controls the microcontroller to perform specific tasks, such as testing solar cells and collectingdata which is used for further analysis. A power source provides the current and/or voltage application, and a current measurement tool is used to generate the J-V data of the solar cell.

The solution prepared with potassium bromide and distilled water provides 85 degrees of heat and 85% humidity. The solution and PSCs were placed on the hot plate in the heat-humidity tests, as in Figure 3.3.

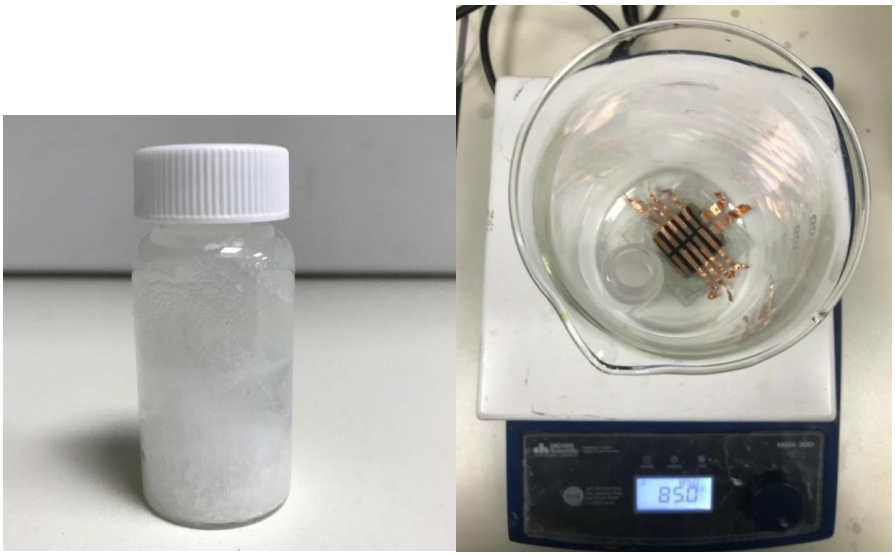


Figure 3.3 Heat-humidity test solution and process structure

Current density-voltage measurements were performed with a Keithley 2401 Series Sourcemeter, an instrument that can both source and measure electrical signals controlled by the LabVIEW™ platform.

In this study, OceanView software is used to measure the Photoluminescence (PL) of perovskite thin films. The experimental setup included a laser as the excitation source, a spectrometer with a wavelength range of 400-900 nm, and a custom-made sample holder to position the sample properly. The laser was positioned at a perpendicular angle to the sample,and the spectrometer was positioned to collect the emitted light at a right angle to the excitation source. The PL measurements resulting data were analyzed to determine the peak emission wavelength and full-width at half maximum (FWHM) of the spectrum. Using the OceanView program and optimizing our experimental parameters obtained accurate and valuable insights into the optical properties of perovskite thin films in the study.

3.3 Optical Properties of Encapsulation Materials

This section investigates the optical properties of the preferred candidate materials for encapsulation. Optical property analysis was evaluated by taking reflection vs. wavelength graphs for each candidate material separately. The amount of light reflected by these materials as a function of the wavelength of the light is depicted in reflection graphs, which helps better understand how these materials act in this regard.

A spectrophotometer is used to measure the intensity of light reflected at various wavelengths to create graphs. Regarding how much light the substance reflects or absorbs, these graphs offer useful information. To determine the material's capacity to reflect light of various wavelengths,we plot this graph by determining the intensity of the reflected light at various wavelengths. It comprehended the optical behavior of the five different materials, three types of Surlyn™ based Meltonix, Polyolefin ENLIGHT™ 4015 PL and EVA (ethylene-vinyl acetate)**,** and howit might affect the performance of perovskite solar cells by analyzing graphs in Figure 3.4.

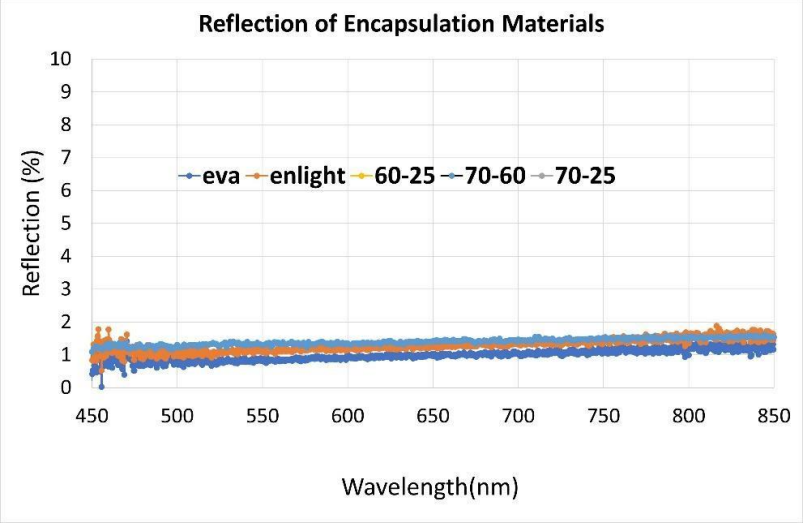


Figure 3.4 Reflection percentiles of encapsulation materials

It has been observed that the reflectance rates of all five materials are below 2%, in case the materials are applied, they will allow sufficient light to pass through the solar cell.

3.4 Effects of Encapsulation on the Optical Properties of Perovskite Thin Films

In this section, candidate encapsulants were examined by laminating them onto Perovskite thinfilms to determine the most suitable encapsulation structures before conducting encapsulation trials on PSCs. The optical properties, including photoluminescence spectroscopy, were investigated both before and after encapsulation. This method entails measuring the light that solar cells emit after being activated by an outside light source. The photoluminescence spectrum of perovskite thin films can reveal important details regarding the absorption and emission characteristics of their constituent materials as well as the effectiveness of their internal energy transfer mechanisms. It is a non-contact, non-destructive method for examiningmaterials' optical properties before and after any operation on PSCs. Light is applied onto a material where it is absorbed, and photoexcitation can occur. It is possible to observe material defects and impurities by measuring the PL spectrum. Photoluminescence spectra were acquired using a spectrophotometer in the present work to assess the effect of the encapsulationprocedures on the optical properties of the perovskite thin films. The stability of the layers wascompared by taking PL measurements of the perovskite layers before and after encapsulation by observing Intensity (counts) vs. Wavelength data. The results are presented below.

3.4.1 Encapsulation with Surlyn-based Meltonix

Before the electrical test, encapsulated perovskite thin films are inspected visually and optically with the interpretation of PL measurements. The perovskite thin films coated on glass were encapsulated with Surlyn™ based on Meltonix encapsulation films.

Three different types of Meltonix films, 1170-25 (25 μm thick thermoplastic sheet made of Surlyn™), Metlonix 1170-60 (60 μm thick thermoplastic sheet made of Surlyn™), and Metlonix 1162-60 (45 μm thick thermoplastic sheet made of Bynel) were applied to perovskitethin films. The lamination process was carried out using DYESOLAR hot press lamination device at a temperature of 110 ° C, and 100 Newton pressure for a period of 200 seconds. In Figure 3.5, it is seen the uniform perovskite thin films on glass before encapsulation.

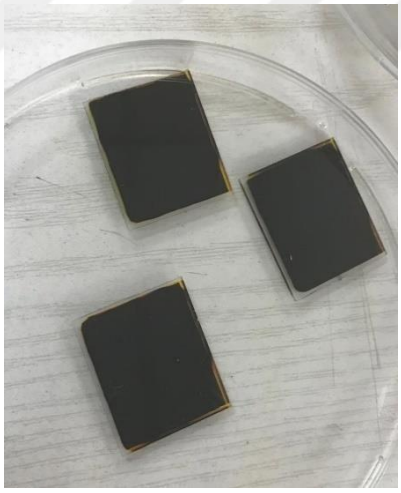


Figure 3.5 Perovskite layers coated on glass

However, after the encapsulation process, air gaps remained between the perovskite thin filmsand the encapsulation materials, so it was thought that these materials were not suitable for encapsulation as a single-layer encapsulant and could be used in two-layer encapsulation designs in addition to other encapsulation materials.

Figure 3.6 Perovskite thin films after encapsulation with Meltonix film types (1170-60,1162-60 and 1170-25)

In addition, due to the air bubbles formed in the encapsulated perovskite thin films, these threetypes of films could not be compared visually. Thereupon, the most suitable film was selectedby looking at the reflections and PL measurements of each film for comparison.

PL measurements were taken before and after the encapsulation of perovskite thin films with these three different materials, and they are given in Figure 3.7.

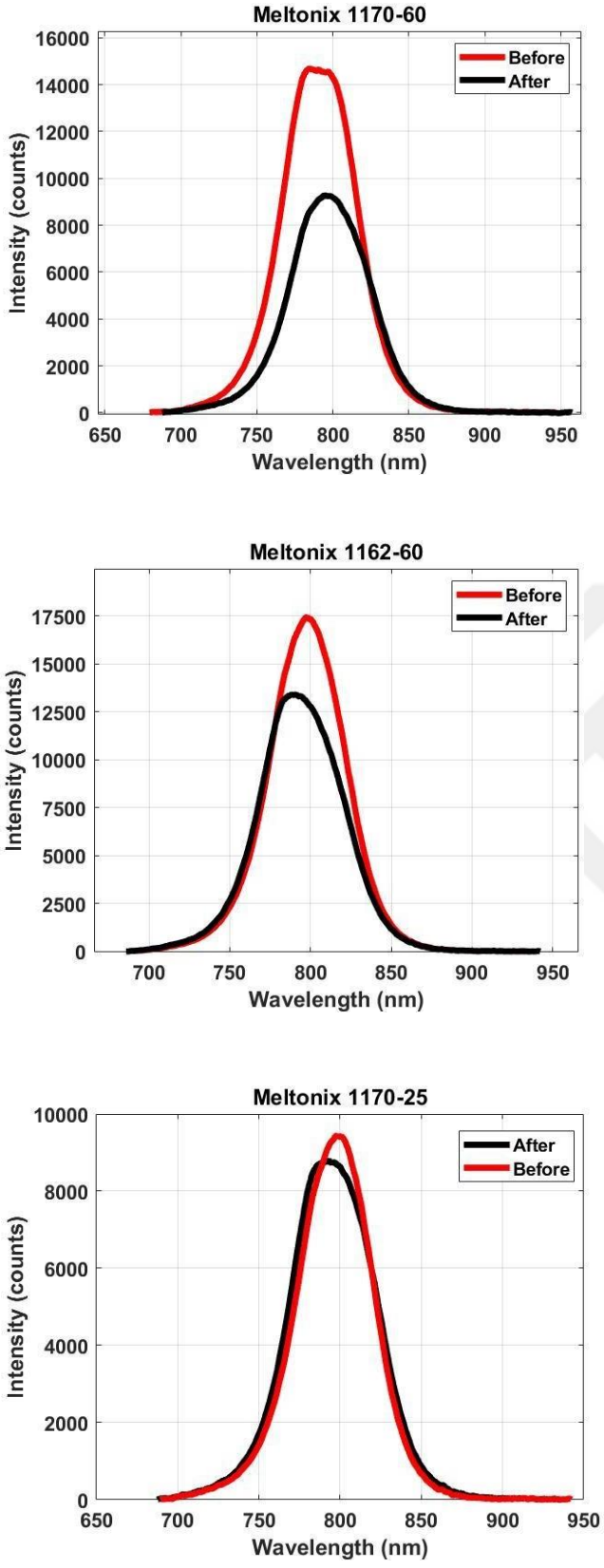


Figure 3.7 PL measurements before and after encapsulation of perovskite thin films (Meltonix 1162-60, 1170-60, 1170-25)

Table 3.2. PL peak position and PL intensity values of perovskite thin films before and after encapsulation

Film Type	PL Peak Position Before	PL Peak Position After	PL Intensity Before	PL Intensity After
Meltonix 1170-25	756 nm	796 nm	14656	9260
Meltonix 1162-60	798 nm	790 nm	17410	13379
Meltonix 1170-25	799 nm	793 nm	9413	8757

The decrease in PL intensity after encapsulation of perovskite thin films is due to changes inthe structural properties of the perovskite film during the lamination process. These changesmay be caused by factors such as chemical reactions or structural deformations occurring at the surface or interfaces of the films. These changes may affect the optical properties of the perovskite film, resulting in a decrease in PL intensity.

Table 3.3. Percent decrease of PL intensity values of Perovskite thin films after encapsulation with Meltonix film types

Film Type	Percent decrease in PL intensity
Meltonix 1170-25	37%
Meltonix 1162-60	23%
Meltonix 1170-25	%7

Considering the reductions in PL density values, Meltonix 1170-25 material was chosen as themost suitable material with the lowest decrease

percentage of 7% in PL intensity. Afterward, the perovskite layer with Meltonix 1170-25 is kept in an environment of 85 °C and 30% humidity for 48 hours. PL measurements are taken again after 48 hours, as shown in Figure 3.8.

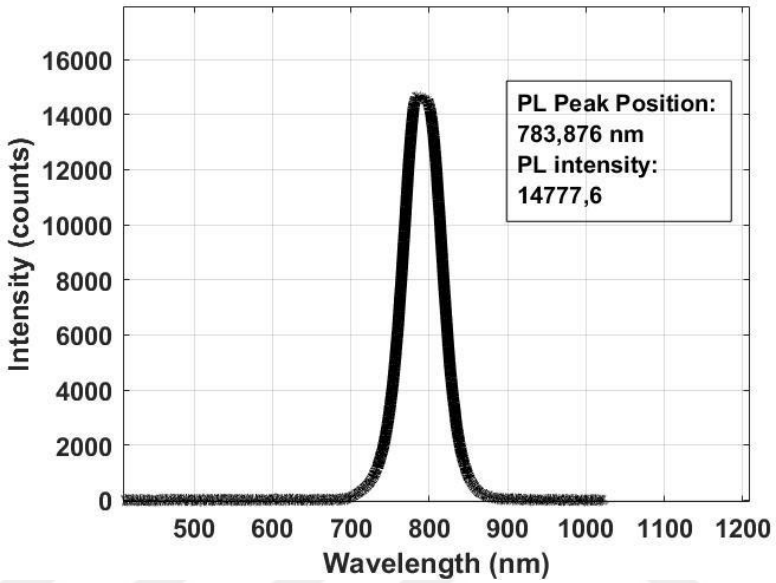


Figure 3.8 PL measurement of Perovskite thin layer encapsulated with Meltonix 1170-25after 48 hours heat-humidity test

There was a 57% increase in the PL intensity count, 9413 to 14778, of the encapsulated perovskite thin film kept in a 48-hour heat-humidity environment, which was attributed to theannealing of the perovskite thin film with high temperature during lamination. Heating perovskite thin films can result in an increase in their photoluminescence intensity due to various reasons. Firstly, heating promotes the enhancement of the crystal structure by minimizing defects and imperfections within the film, leading to improved interaction and higher PL intensity. Secondly, it facilitates ion diffusion within the film, enabling ions to be more orderly placed and enhancing energy transfer, thereby contributing to higher PL intensity.

Lastly, heating can passivate surface defects on the film, enhancing surface reactivity and light-emission efficiency. Consequently, thermal treatments tend to cause an elevation in the PL intensity of perovskite thin films.

3.4.2 Encapsulation with EVA (Ethylene-vinyl acetate)

In this part, the perovskite thin film is encapsulated with EVA for 180 seconds at 110 ℃ and 100 newtons pressure in a hot press laminator. After the encapsulation process, it is not observed any yellowing on the perovskite layer after encapsulation as shown in Figure 3.9.

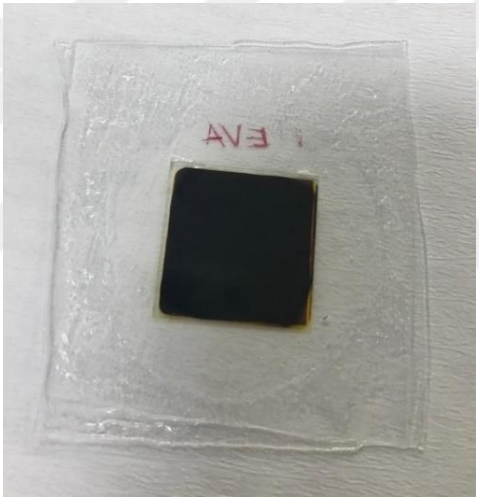


Figure 3.9 Perovskite layer after encapsulation with EVA

PL measurement of perovskite thin film with EVA encapsulation is taken before and after encapsulation, as shown in Figure 3.10.

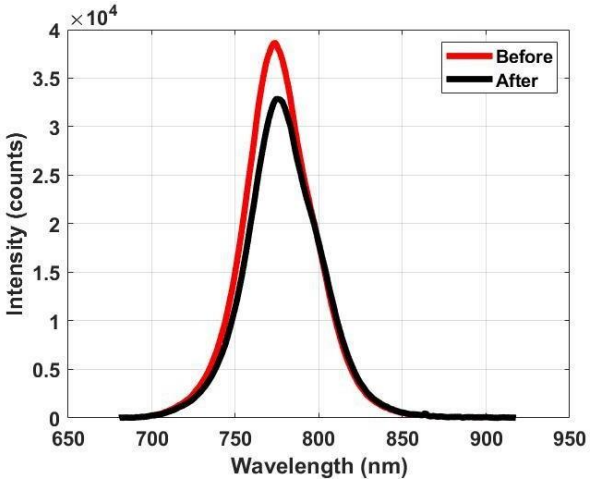


Figure 3.10 PL measurement before and after encapsulation with EVA

PL peak position and PL intensity values before and after encapsulation are given in Table3.4.

Table 3.4. PL peak position and PL intensity values before and after encapsulation with EVA

Film Type	PL Peak Position Before	PL Peak Position After	PL Intensity Before	PL Intensity After
EVA	773 nm	775 nm	38626	32885

It also applied a stability test to the EVA-encapsulated sample in an environmental test chamber. A high level of yellowing was observed, as shown in Figure 3.11, after the sample was kept in an environment of 85 ℃ and 80% humidity for 48 hours. For this reason, PL measurement was not taken again, it is observed that direct contact of the EVA material with the perovskite surface caused degradation in the thin film. Even if the EVA material provides protection of perovskite thin films in direct contact with

the external environment, it has been interpreted that it interacts with perovskite chemically, it has been interpreted that using it as asingle layer in the encapsulation of PSCs may not be effective.

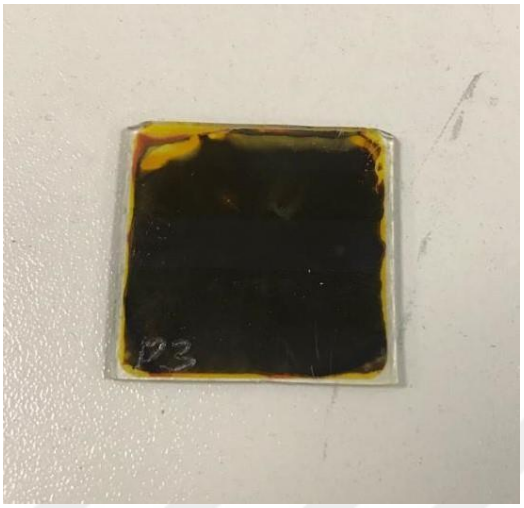


Figure 3.11 Perovskite thin film encapsulated with EVA after 48 hours of heat-humidity test

3.4.3 Encapsulation with ENLIGHT™ 4015 PL

In this part, the perovskite thin film is encapsulated with ENLIGHT™ for 220 seconds at 110 ℃ and 100 newtons, Figure 3.12.

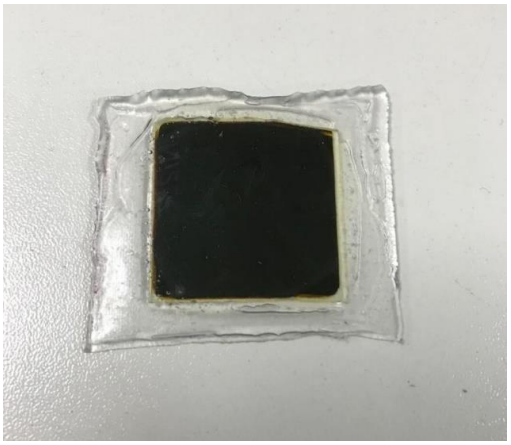


Figure 3.12 Perovskite thin film after encapsulated with ENLIGHT™

PL measurement of perovskite thin film with ENLIGHT™ encapsulation is taken before andafter encapsulation, as shown in Figure 3.13.

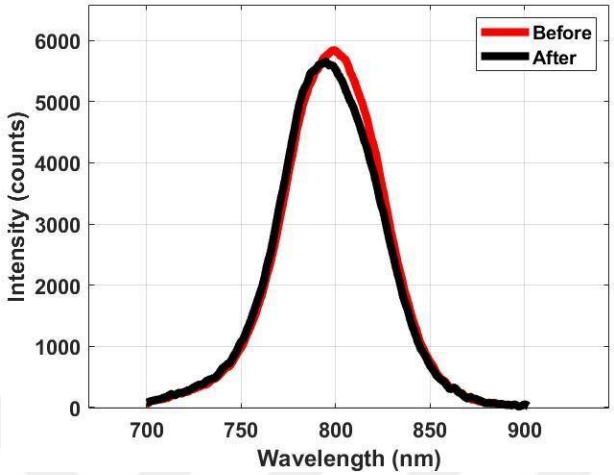


Figure 3.13 PL measurement before and after encapsulation with ENLIGHT™

PL peak position and PL intensity values before and after encapsulation are given in Table3.5.

Table 3.5. PL peak position and PL intensity values before and after encapsulation withENLIGHT™

Film Type	PL Peak Position Before	PL Peak Position After	PL Intensity Before	PL Intensity After
Enlight	799 nm	795 nm	5840	5654

After encapsulation, there was a 3.2% decrease in perovskite thin films' PL intensity countcompared to before encapsulation.

Afterward, the perovskite thin film with ENLIGHT™ is kept in an

environment of 85 °C and 85% humidity for 48 hours. PL measurements are taken again after 48 hours, as shown in Figure3.14.

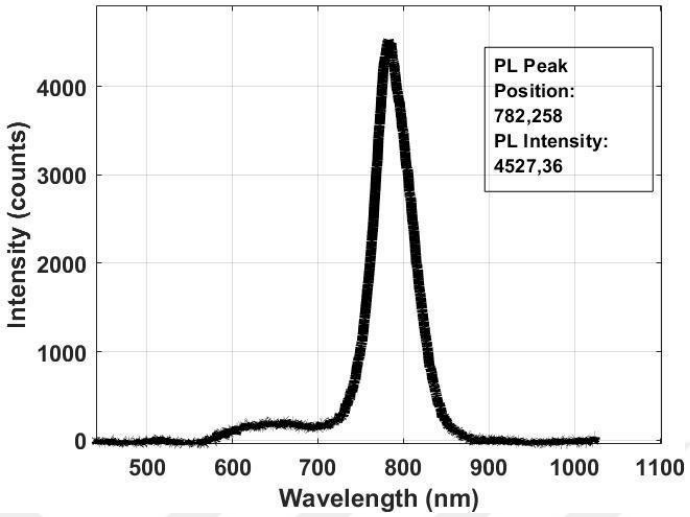


Figure 3.14 PL measurement of Perovskite thin film encapsulated with ENLIGHT™ after48 hours of heat-humidity test

After 48 hours of the heat-humidity test, there was a 19.9% decrease in perovskite thin films'PL intensity count compared to before the test.

CHAPTER 4

RESULTS AND DISCUSSIONS

This part results in the effects of different encapsulation materials on the electrical performanceof perovskite solar cells. Solar cell performances are given for two materials, namely, EVA andENLIGHT™ 4015 PL, and for a combined encapsulation structure with ENLIGHT™, Meltonix 1170-25, and PIB. Then efficiency and fill factor values are interpreted over J-V curves. The effects of these materials on the electrical performance of perovskite solar cells are presented on the J-V graphs of each sample.

4.1 Effect of encapsulation on perovskite solar cell performance

The effects of encapsulation materials on perovskite solar cells with the structure of Glass/ITO/NiOx/Perovskite/C60/BCP/Cu, Figure 4.1, were interpreted on J-V curves before and after encapsulation. On the other hand, over the encapsulation combination, which creates a minimal decrease in the efficiency and Fill Factor values after encapsulation, a heat-humiditytest with 85°C and 85% humidity, lasting 192 hours, was applied, and J-V measurements weretaken, and electrical performance drops were examined in 24 hours cycles.

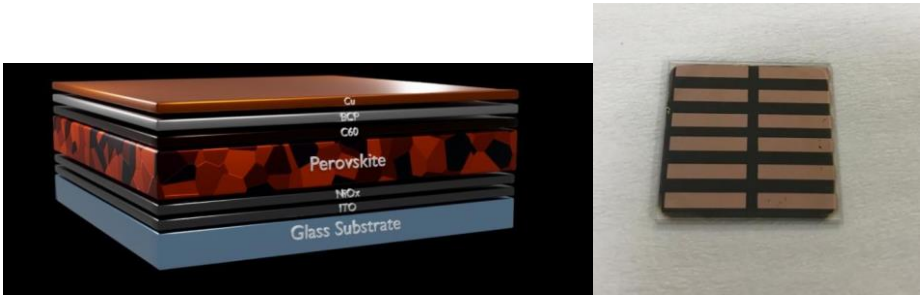


Figure 4.1 Perovskite solar cell structure and a sample used in encapsulation tests

4.1.1 Encapsulation with EVA

The perovskite solar cell is encapsulated with EVA material with a lamination process lasting 300 seconds under 110 ℃ temperature and 100 N pressure. Copper conductor wires were attached to the contact point for J-V measurement. Figure 4.2 shows the J-V curves before and after encapsulation.

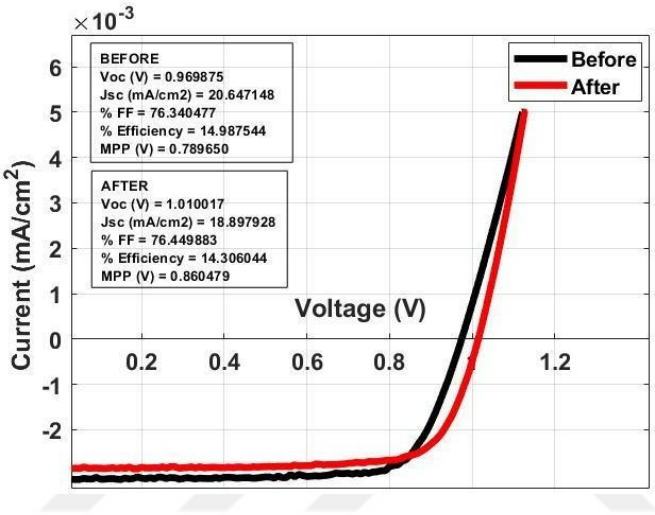


Figure 4.2 J-V curves of Perovskite solar cell before and after encapsulation with EVA

A stability test is applied to the EVA-encapsulated PSC in an environmental test chamber. A high level of yellowing was observed, as shown in Figure 4.3, after the sample was kept in anenvironment of 85 ℃ and 80% humidity for 24 hours. Because of this reason, J-V measurement was not taken again. It is observed again that direct contact of the EVA materialwith the perovskite surface caused degradation.

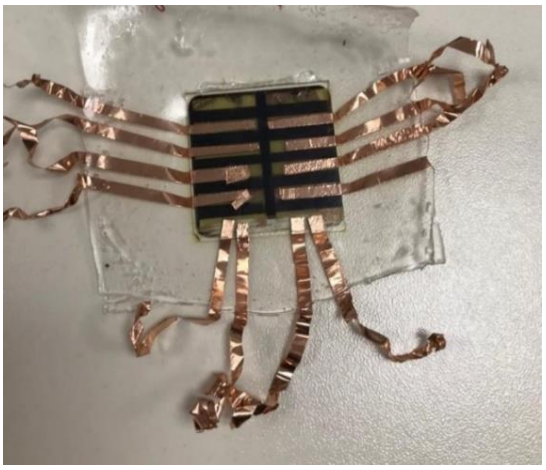


Figure 4.3 PSC with EVA encapsulated after 24 hours of heat-humidity test

4.1.2 Encapsulation with ENLIGHT™

Perovskite solar cell is encapsulated with a Polyolefin structure, ENLIGHT™ 4015 PL. The lamination process was done by keeping the device in a hot press lamination device at 110 ℃ and 100 N pressure for 200 seconds. Copper conductor wires were attached to the contact pointfor J-V measurements. Figure 4.4 shows the J-V curves before and after encapsulation.

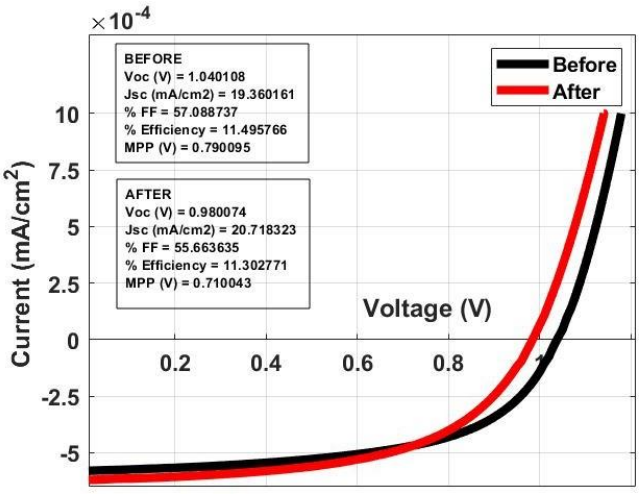


Figure 4.4 J-V curves of Perovskite solar cell before and after encapsulation with Enlight

No yellowing was observed in the PSC, which was left to the 24-hours heat-humidity test, andthe J-V measurement was taken again, as in Figure 4.5.

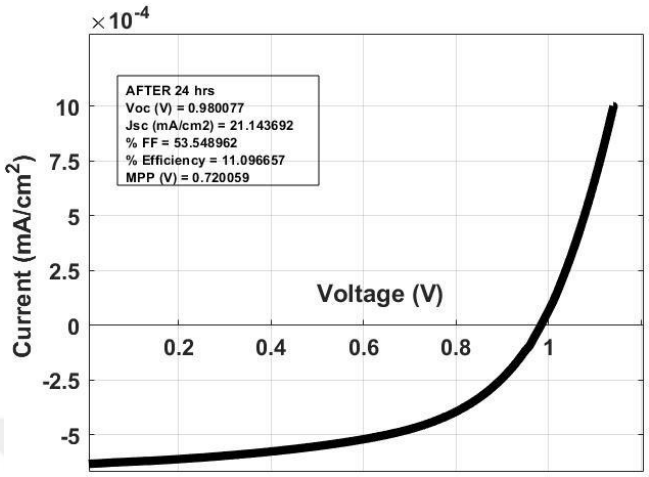


Figure 4.5 J-V curve of PSC encapsulated with ENLIGHT™ after 24 hours of heat-humidity test

The decrease in the efficiency of PSCs encapsulated with ENLIGHT™ can be seen asinsignificant, and it can be concluded that ENLIGHT™ material is a promising material for perovskite solar cell encapsulation. It is clear that more extended measurements with longer aging duration are needed to test the performance degradation of this material.

4.1.3 Encapsulation of Perovskite Solar Cells with a Combination of EVA, Meltonix, and PIB

Due to yellowing observed after direct contact with PSC with EVA, an additional encapsulationmaterial, Meltonix 1170-25, was added between the EVA material and the PSC to prevent chemical reactions by cutting off the direct contact of the EVA and PSC. PIB was also added as an edge sealant to minimize exposure to air and create a more strong encapsulation

design. A conductive silver band with a lower resistivity value was placed instead of the copper band to perform the J-V measurements, and encapsulation was done between glasses as a glass-glass encapsulation structure. The lamination process was done by keeping the device in a hot presslamination device at 110 ℃ and 100 N pressure for 300 seconds. Figure 4.6 shows the J-V curves before and after encapsulation.

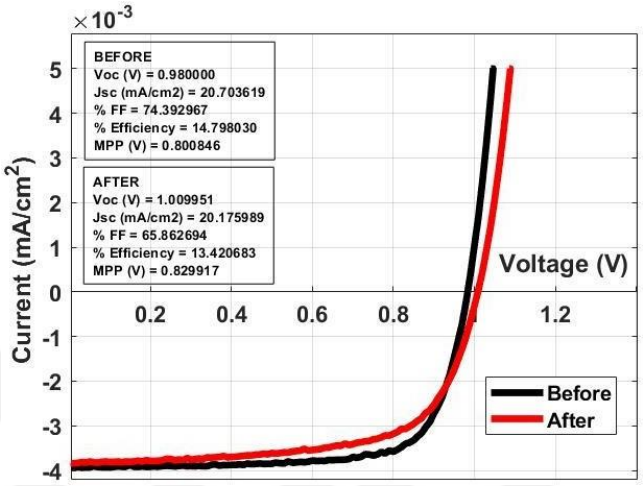


Figure 4.6 J-V curves of PSC before and after encapsulation with EVA, Meltonix 1170-25,and PIB

After encapsulation, the PSC was placed in an environment of 85 ℃ and 85% humidity, andJ-V measurements were taken at the 24th and 48th hours, as seen in Figure 4.7.

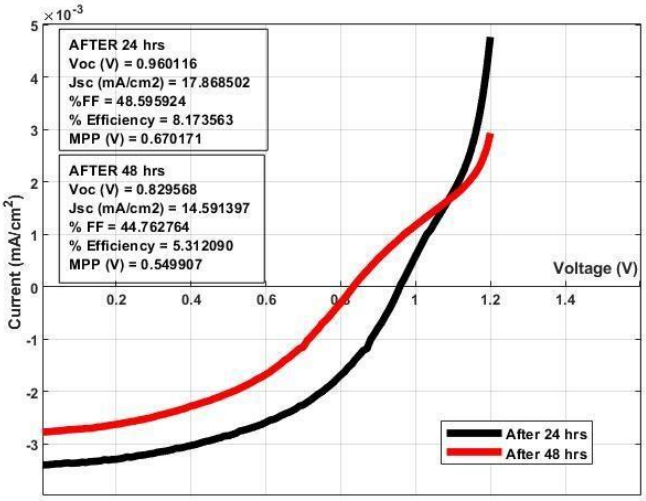


Figure 4.7 J-V curves of PSC 24 and 48 hours after humidity test

As a result of the heat-humidity test, a rapid decrease in electrical performance and high-levelyellowing was observed in Figure 4.8. After 48 hours, distortion of the J-V curve was observed in the S-shape. This can be attributed to several factors associated with the EVA encapsulation process. Firstly, the EVA material itself may introduce optical effects such as increased light reflection or scattering, resulting in a reduced amount of light reaching the solar cell. As a consequence, the current generated by the cell decreases, leading to the S- shaped J-V curve. Secondly, the EVA encapsulation process involves the application of heat and pressure, which can induce additional resistive losses at the interconnections and contact areas within the solar cell. These resistive losses contribute to the modification of the J-V curve. Lastly, the EVA layer can affect the charge transfer efficiency and carrier transport properties within the solar cell, altering the overall shape of the J-V curve. Thus, when a solarcell is encapsulated with EVA, it can result in the transformation of the J-V curve into an S- shape due to the combined influence of optical effects, resistive losses, and charge transport mechanisms associated with the encapsulation process. This situation was interpreted as encapsulation with EVA was unsuitable, and the heat-humidity test was not continued.

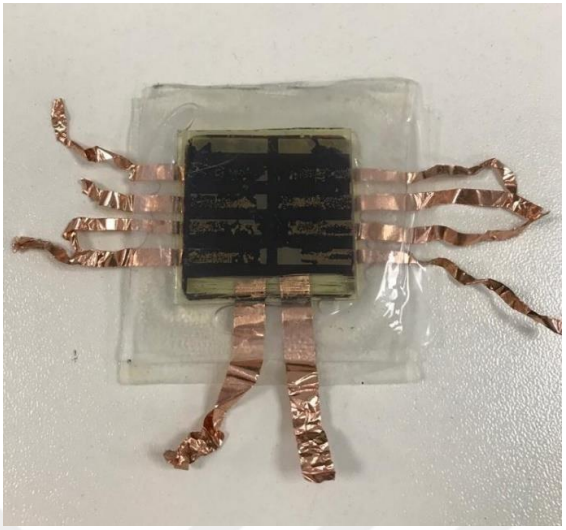


Figure 4.8 PSC encapsulated with EVA, Meltonix 1170-25, and PIB after 48 hours of a heat-humidity test

4.1.4 Encapsulation of Perovkite Solar Cells with Combination of Enlight, Meltonix and PIB

To minimize the PSC's contact with the external environment, Meltonix 1170-25 is used as a second layer in addition to the ENLIGHT™, and PIB is added as an edge sealant. The lamination process was done by keeping the device in a hot press lamination device at 110 ℃ and 100 N pressure for 300 seconds. Figure 4.9 shows the J-V curves before and after encapsulation.

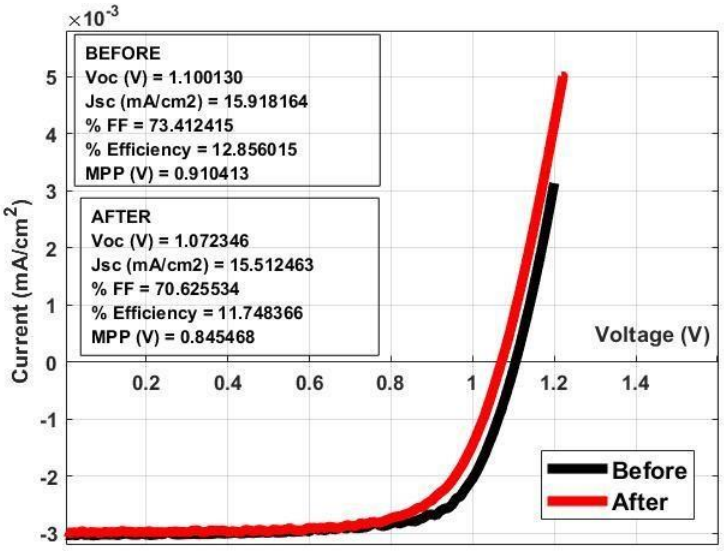
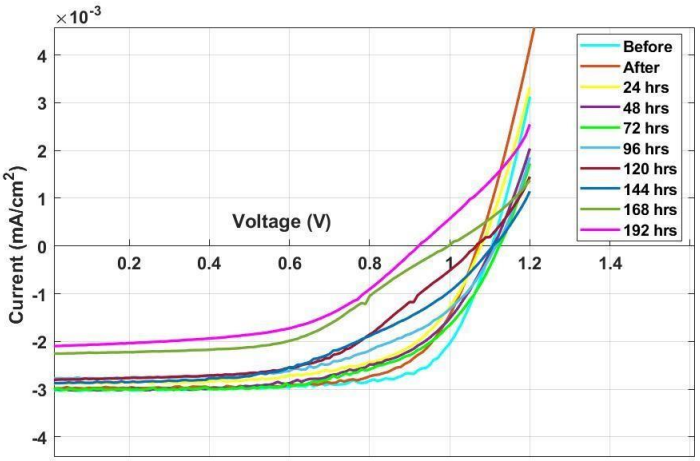


Figure 4.9 J-V curves of PSC before and after encapsulation with ENLIGHT™, Meltonix1170-25, and PIB

After encapsulation, the PSC was placed in an environment of 85 ℃ and 85% humidity for 192 hours, and J-V measurements were taken at each 24-hour cycle, as shown in Figure 4.10.



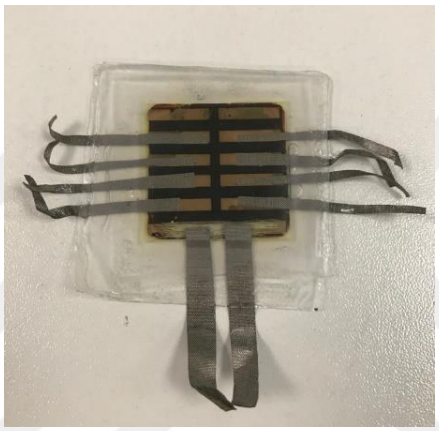


Figure 4.10 J-V curves of PSC taken at each 24-hour cycle and PSC after 192 hours

Table 4.1. Electrical performance of the PSC every 24 hours cycle

Hours	Jsc (mA/cm2)	Voc (V)	Fill Factor (%)	Efficiency (%)	MPP(W)
Before	15.9	1.10	73.4	12.9	0.047
After	15.5	1.07	70.6	11.7	0.042
24	15.2	1.08	63.4	10.4	0.038
48	15.9	1.10	60.5	10.7	0.039
72	15.9	1.12	61.6	10.9	0.04
96	14.6	1.12	56.6	9.3	0.033
120	14.8	1.07	54.7	8.7	0.031
144	15.1	1.10	49.7	8.4	0.030
168	11.9	0.99	53.4	6.2	0.023
192	11.1	0.91	54.1	5.4	0.02

Figure 4.11 shows the Fill Factor and Efficiency decrease of the PSC every 24 hours in the192 hours 85 ℃ and 85% heat-humidity test.

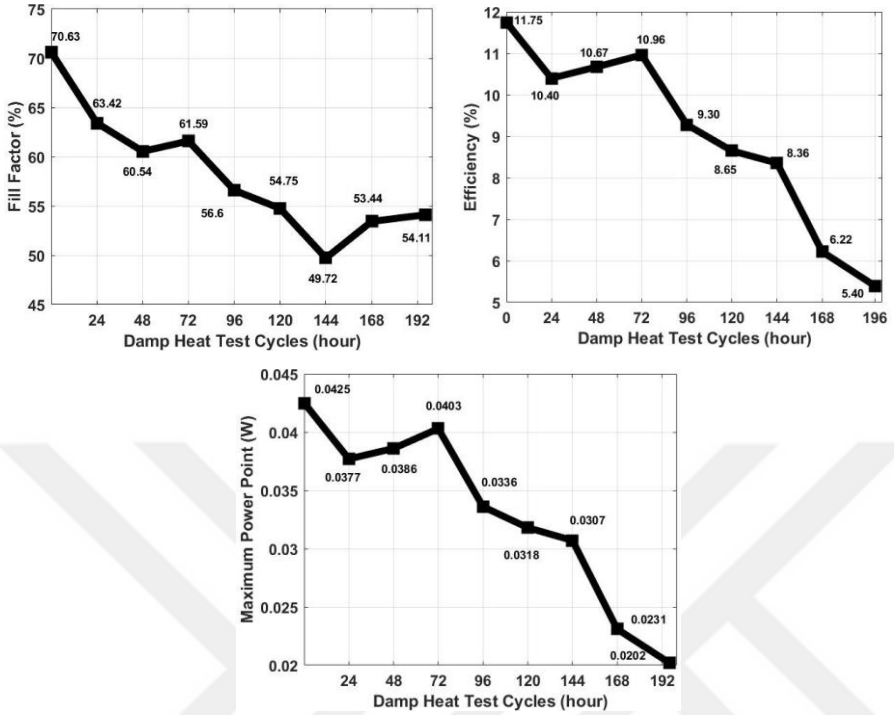


Figure 4.11 Fill Factor, Efficiency, and MPP decrease of PSC in 192 hours heat-humidity test

The average daily decrease in fill factor values was 2.6%, and the total decrease from the firstday to the last day was 23.4%. The average daily decrease in efficiency values was 6%, and the total decrease from the first day to the last day was 53.9%. An average decrease of 5% has been observed in MPP values every 24 hours.

CHAPTER 5

CONCLUSIOS AND FUTURE LOOK

In this thesis, the encapsulation of perovskite thin films and perovskite solar cells was studied.Various encapsulation materials have been applied to perovskite solar cells and perovskite thinfilms. As a new competitive research area, most of the material information is not available in the open literature. The number of known material types is quite limited. In this work, we havetested three different materials that are available to us: 1. Surlyn-based Meltonix film types, 2.Enlight, and 3. EVA. In addition, PIB has also been used to improve edge encapsulation. With technical difficulties in solar cell fabrication and technical problems, some tests have been carried out on fewer electrical and optical measurements.

All encapsulated perovskite thin film samples were inspected visually and optically just after the lamination process. In encapsulation with Surlyn-based Meltonix sheet types on perovskite thin films, air bubbles were observed, which indicates that the process is not well optimized forthis material system as a single-layer encapsulation design. Further studies are needed for this purpose. However, in encapsulation with EVA and Enlight on perovskite thin films, quite a uniform coating was obtained.

The effect of the encapsulation process and materials on the optical properties of the perovskite thin films and photoluminescence measurements were performed before and after the encapsulation. In general, the PL spectrum of the perovskite film is not much affected by the encapsulation process with Enlight and EVA materials. Subsequently, the EVA material subjected to the heat and humidity test (85 ℃ - 85% RH)

exhibited a high level of yellowing, leading to the decision not to repeat the PL measurement. In the context of encapsulation usingEnlight on the perovskite thin film, a notable reduction in PL intensity values was not observedbetween the before and after encapsulation measurements. This observation implies that the material exhibits favorable chemical compatibility with the perovskite thin film. However, afterthe application of Surlyn-based Meltonix 1170-25 type encapsulation material onto the perovskite thin film, a 57% increase in PL intensity count was observed following the heat andhumidity test. This increase is attributed to the high-temperature annealing of the perovskite thin film during the heat and humidity test.

No significant changes were observed in PL peak positions in PL measurements before and after the encapsulation of perovskite thin films. Photoluminescence (PL) peak positions in perovskite materials serve as indicators of crystal structure stability. Perovskite materials havea unique crystalline lattice arrangement that directly influences their optoelectronic properties.

Changes in the crystal structure can lead to variations in the PL peak positions. Moreover, PL peak positions also provide insights into the energy band structure of perovskite materials. Theenergy band structure determines the absorption and emission properties of the material. If the encapsulation process is successful, the PL peak positions in the emission spectrum of perovskite thin films should remain consistent. This indicates that the crystal structure remains stable, ensuring the material's optoelectronic properties are maintained. Consistent PL peak positions also suggest that the energy band structure, responsible for light absorption and chargegeneration, remains unchanged. However, it is clear that more tests with longer duration and more extreme conditions are needed to draw a certain conclusion.

Subsequently, these encapsulation materials were implemented onto PSCs, both as a single layer and second-layer structures. The perovskite solar cells were subjected to electricalmeasurements while exposed to a heat-

humidity environment. This experimental setup aimed to evaluate the performance and stability of the solar cells under such conditions. In Table 5.1,the effect of encapsulation on the efficiency of the PSCs is summarized below.

Table 5.1 Efficiency changes of PSCs with encapsulation strategies

Encapsulation	Efficiency before encapsulation (%)	Efficiency after encapsulation (%)	Aging time (hours)	Efficiency after aging
EVA	15	14,3	24	~1
Enlight	11,5	11,3	24	11
EVA+Meltonix 1170-25+PIB	14,8	13,4	48	5,3
Enlight+Meltonix 1170-25+PIB	12,9	11,8	192	5,4

In the encapsulation experiment with EVA, there was no significant decrease in the efficiencyof PSC before and immediately after, which showed that lamination parameters such as heat, time, and pressure were appropriate. However, as a result of the 24-hour heat and humidity test,the PSC was completely degraded, and it was observed that EVA caused deterioration in the chemical structures of PSCs and was not suitable for encapsulation. In another experiment, a second layer of Meltonix 1170-25 sheet was put in between to prevent direct contact between EVA and PSC, and lamination was made; again, no high-efficiency decrease was observed before and after. However, due to the 48-hour heat and humidity test, the efficiency decreasedby more than 50%, and it was concluded that this structure was unsuitable for encapsulation.

In the encapsulation experiment performed on PSC with Enlight material, the decrease in efficiency is negligibly minimal, showing the suitability of lamination parameters and chemicalcompatibility. However, the efficiency

of the PSC, which was subjected to the 24-hour heat andhumidity test with Enlight used alone, decreased by more than 50%, and it was observed that the Enlight material alone was not suitable for encapsulation. A minimal decrease was observedin the efficiency of PSC before and immediately after the encapsulation structure strengthenedwith Enlight, Meltonix 1170-25, and PIB edge sealant. Afterward, it was subjected to 192 hoursof heat-humidity test, and a decrease of approximately 6% was observed every 24 hours in theproductivity measurements taken every 24 hours. However, the decrease in MPP values was below 5% on average for every 24 hours. To determine whether this encapsulation structure complies with the heat and humidity test standards, it should be tested on more PSCs, and these samples should be subjected to the Damp-heat test, known as the 85 ℃ and 85% heat-humiditytest for 1000 hours, to observe whether they meet the IEC 61215 standards.

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