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## Technical Progress and Performance Enhancement of Solar Energy Systems

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**ABSTRACT:** We need effective techniques to turn photons into electricity, fuel, and heat if solar energy would be to substitute for fossil fuels as a viable source of energy. Much recent advancement in physics, materials, and particularly nanoscience are motivated by the demand for better conversion technologies. We examine the technological advancements achieved in the field of photovoltaic (PV) technologies during the last few years. One of the finest solutions for the world's future sustainable energy needs is PV electricity. The PV market is now expanding quickly at a rate of 35–40% annually, with PV production being around 10.66 GW in 2009. Monocrystalline solar cells made of Si and GaAs have efficiencies that are extremely close to their theoretically expected maximum levels. Wafer, both mono- and polycrystalline Si solar cells, with module production costing about \$1.50 per peak watt, continue to be the most popular PV technology. In order to significantly lower the cost of solar cells, thin-film photovoltaic technology was created. In recent years, this field has seen remarkable advancements. Thin-film solar cells made of CdTe and Cu(In,Ga)Se<sub>2</sub> showed record efficiencies of 16.5% and nearly 20%, respectively. The highest values yet obtained for thin-film solar cells are these ones. CdTe thin-film modules currently cost \$0.76 per peak watt to produce.

**KEYWORDS:** photovoltaic (PV) technologies, GaAs, Wafer, thin-film, Cu (In,Ga)Se<sub>2</sub>

### I. INTRODUCTION

Future global energy output will be greatly impacted by the ability to directly harvest solar energy utilising photovoltaic (PV) technology or concentrating solar power (solar thermal energy conversion). The need for new ecologically friendly energy sources, particularly renewable energy sources, is being sparked by the depletion of fossil fuel reserves and the awareness of the harmful long-term impacts of atmospheric emissions of CO<sub>2</sub> and other greenhouse gases. The growing global concern about energy security and price stability is another motivating factor. The overall energy balance would be drastically altered if even a small portion of the 162,000 terawatts (TW) that reach the globe were captured. Additionally, PV systems are lightweight and well suited for distributed applications. Photovoltaics manufacturing on a large scale is becoming more and more feasible economically. With little negative effects on the environment, concentrated solar power (CSP) systems and the rapid expansion of PV component manufacturing capacity have the potential to meet 10% of our energy needs without the use of storage. Furthermore, it is evident that these technologies will eventually replace the microelectronics, telecommunications, and display industries as one of the primary high-technology economic drivers. It will need cost reductions that are motivated by materials science, rather than just small-scale economies of scale, to actually accomplish this goal. According to data from the U.S. Department of Energy, the average annual global power consumption in 2004 was 15 TW (1.5 10<sup>13</sup> W), with 86.5% of the energy coming from the combustion of fossil fuels. 13.1 quads of net electrical energy were produced by power plants for public consumption after conversion losses. 1 This much electricity might be generated

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by solar panels with a 15% power conversion efficiency covering a 100 km by 100 km area with high sun insolation, like the desert in Rajasthan's northwest. These modules would need to be produced at a cost of \$50/m<sup>2</sup> or less in order to fulfil the Ministry of New and Renewable Energy's (MNRE) cost objective of \$0.33/W or \$0.05-0.06/kWh for utility-scale production.<sup>2</sup> The objectives for solar thermal power are similar. Even though module costs are declining significantly, achieving these goals with current technology will necessitate major advancements in cell performance as well as other parts that make up the balance of solar systems. The cost per watt may also be considerably decreased by a number of novel technologies, including thin films, thin silicon, organic photovoltaics, multi junction concentrator methods, and next-generation nanostructured devices. The past few years have seen a sharp increase in global production levels of terrestrial solar cell modules as the enormous potential of photovoltaic technology has come to light. Crystalline silicon modules, which account for 94% of the market and include both large-grain polycrystalline and single-crystalline materials, are the main product in use today.<sup>3</sup> Single- or polycrystalline silicon wafer-based devices are referred to be "first-generation" photovoltaic devices. The maximum possible power conversion efficiency of these relatively straightforward single-junction devices (diodes) is 31% under direct AM1.5 sunlight due to thermodynamic constraints. Standard test conditions (STC), which correspond to 1 kW/m<sup>2</sup> (100 mW/cm<sup>2</sup>) direct perpendicular irradiance under a global AM 1.5 spectrum at 25°C cell temperature, are typically used to describe solar cells and modules according to the IEC norm<sup>3</sup> for solar cells and modules.<sup>4</sup> Sanyo's high-efficiency Si heterojunction with intrinsic thin layer (HIT) solar cell, which has an efficiency of up to 22.3%, is shown in Figure 1. 4

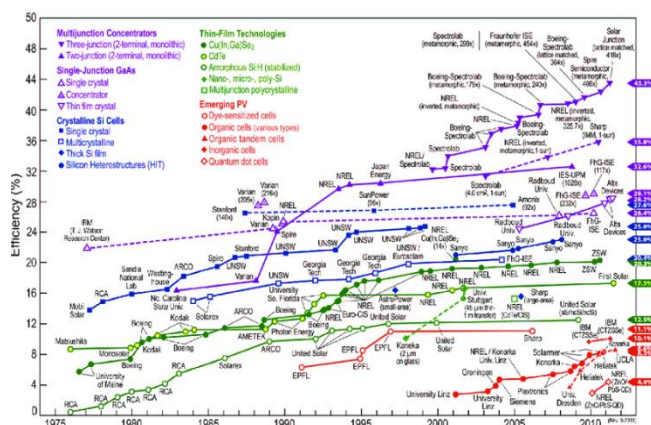


Figure 1: Global solar PV Production and capacity

Achieving significant cost reductions for the production of these complex structures is necessary because some existing cells are really pushing towards the theoretical limit for the bandgap of Si. Figure 3 depicts the development in research-scale photovoltaic devices' efficiency over the course of several decades. A better understanding of the characteristics of materials and devices has led to a consistent rise in efficiency across almost all technologies. Si is extremely close to its theoretical limit, as was already mentioned. Contrarily, the theoretical maxima of thin films like amorphous Si (a-Si), Cu(In,Ga)Se<sub>2</sub> (CIGS), and CdTe are all much below what they could be, and research efficiencies are not always easily transferable to production efficiencies. Dye cells, organic photovoltaics, and third-generation concepts are examples of recent technologies that still have a long way to go in terms of materials and development. These findings are clear from the compilation of greatest confirmed cell and module efficiencies for numerous PV technologies that is cited.<sup>5</sup> Any photovoltaic technology's progress depends in part on economies of scale-related cost

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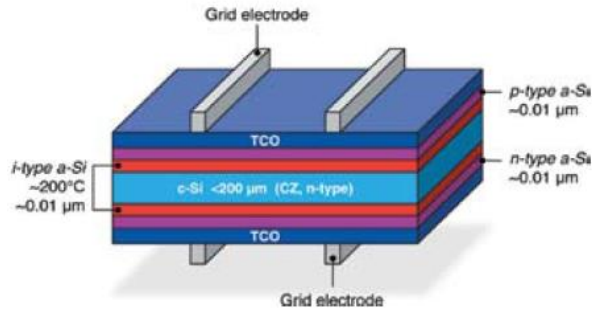


Figure 2:A Sanyo high-efficiency Si heterojunction with intrinsic thin layer (HIT) solar cell

reduction. This has become particularly clear in the case of photovoltaics made of crystalline silicon (c-Si). The development of any photovoltaic technology is the cost reduction associated with economies of scale.

Figure 4 illustrates the decrease in the cost of crystalline silicon photovoltaic modules as the production rate has increased as well as predicted future costs for both wafer-based c-Si and the emerging technologies to be discussed. The cost per watt peak is currently around \$4, which is still too expensive to have a substantial impact on the markets for energy production.<sup>6</sup>

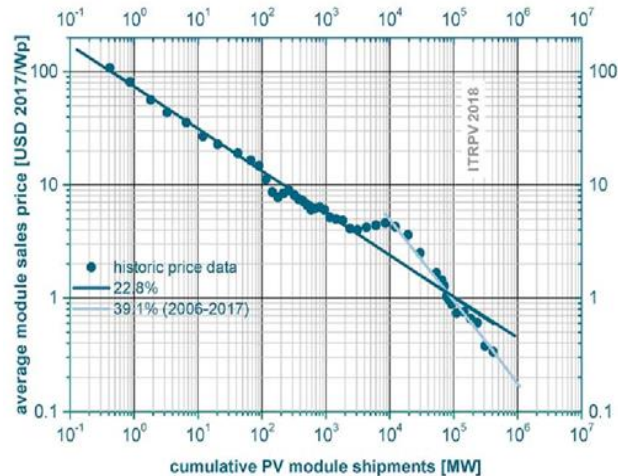


Figure 3: Cost reduction potential, including improving efficiencies

Although precise predictions are impossible to make, best estimates indicate that wafer-based Si panel costs will significantly exceed the aim of \$0.33/Wp in the next ten years, levelling off in the \$1–1.50/Wp region. As a result, during the past ten years, tremendous effort has been put into developing thin-film, "second-generation" technologies that do not need silicon wafer substrates and can therefore be produced at a significantly lower cost. Figure 3 shows steady advancements in laboratory efficiencies for devices based on Cd S/Cd Te, Cu(In, Ga)Se<sub>2</sub> (CIGS), and amorphous Si. Sputtering, physical vapour deposition, and hot-wire chemical vapour deposition are some of the fabrication methods used to create these devices.<sup>7</sup> Due to their ability to be manufactured at a cheap cost and be

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Vol. 4, Issue 3, March 2015

incorporated into electronics and roofing materials, multi junction cells based on amorphous Si and amorphous Si Ge alloys have been the most commercially successful second-generation technology to date.

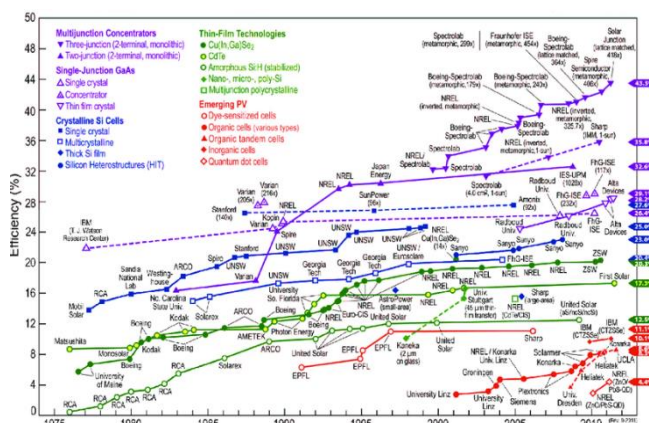


Figure 4: Progress in the efficiency of photovoltaic devices

These cells make up 6% of the non-silicon market along with other single junction amorphous Si devices. Second-generation technologies may be able to replace silicon; however this is unclear unless they can show considerable cost savings. With a convincingly low manufacturing cost in the order of \$1.25/Wp, CdTe from First Solar<sup>8</sup> just emerged as the lone counterexample. However, certain ongoing worries about the effects of Cd on the environment have prompted First Solar to implement a "cradle-to-grave" strategy, starting with acquiring Cd from mining by products and continuing with the recovery and recycling of Cd from worn solar cells. Despite not being based on thin films, concentrating solar applications that use solar thermal collectors or photovoltaic cells which are typically high-efficiency but expensive groups III-V multi junction devices take advantage of the relatively low cost of concentrating optics to make up for expensive converters. These methods are economically competitive with the majority of thin-film technologies. The Grätzel cell, organic photovoltaic cells, and several third-generation concepts, such as intermediate-band devices (i.e., devices that use an impurity level in the semiconductor's bandgap to essentially split the gap to absorb more solar radiation), quantum dot solar cells, and multiple exciton devices, are additional emerging devices that use organic- or dye-based absorbers/acceptors. Some of these devices, such as the polymer-based bulk heterojunction devices and the Grätzel cell, have shown initially appealing efficiencies of over 10% and over 5%, respectively.<sup>8</sup> The fabrication of many of these devices can be accomplished using low-cost, solution-based, low-temperature, atmospheric-pressure processing techniques like inkjet printing or spray painting. Figure 1's rising solar cell production capacity and the unpredictability of fossil fuel energy sources are undoubtedly important drivers for the development of contemporary photovoltaic technology. The amount to which the costs of present technologies may be decreased will eventually hit a ceiling. True cost and efficiency parity may need innovations in even stalwart technology.<sup>9,10</sup> Here, the emphasis is primarily on methods for converting solar energy that aim to achieve extremely high efficiencies by utilising procedures with lower losses than a diode-based method, such as hot-carrier collection, multiple electron-hole pair creation, and thermo photonics, where the theoretical maximum efficiencies are greater than the 31% Shockley-Queisser limit for a single-junction device. The permitted cost of the cell may be higher in this situation. The development of gadgets with intermediate efficiency (15%) at incredibly low cost is an alternative. This is where printable organic solar cell technology and other methods that don't require a lot of resources or energy can be crucial. True cost and efficiency parity may need innovations in even stalwart technology. Over the next 20 years,

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considerable advances in basic and applied science will be needed in a number of technologies to reach the target of \$0.30 per watt.<sup>9</sup> The advancement of Si, thin-film, and concentrator technologies in the near future, as well as the creation of third generation technologies over the course of the following 20 to 30 years, all depend critically on materials science. Although the emphasis in this article is on materials science at the level of cells and devices, it's crucial to bear in mind the wide range of material considerations needed for solar conversion systems that are both efficient and affordable. For instance, solar systems must have up to 25-year warranties and projected installation lives. All of the system's components must be durable, low-maintenance, and stable to achieve this goal. In order to do this, solar cell packaging, contacting (bus structures), and support structures must be stable in a range of climatic conditions including variations in wind speed, humidity, and temperature, for instance. These difficulties have been overcome by stabilising amorphous Si as well as crystalline Si. The capacity to undertake accelerated ageing on modules to anticipate stability is a crucial developing area of solar science because the other thin-film technologies have not yet been commercially available for long enough to evaluate their lives. The eventual development of low-cost energy storage options is intimately related to the improvement of cost-effective photovoltaics. PV modules include precious components that need to be recycled, much like all other technologies. Some solar companies (like the aforementioned First Solar) are becoming interested in cradle-to-grave or lifecycle techniques, whereby they install, eventually remove, and recycle their equipment. As the solar energy industry develops, it is also crucial to take into account the demands on natural resources environmental concerns with diverse technologies, and effects of recycling on the effectiveness of technologies that utilise rare or hazardous materials.

### First-Generation Technologies

Crystalline Si (including large-grain poly- and single-crystalline) materials are predominantly used in first-generation technologies. **Figure 5** shows a 600 MW installed at the Solar Park.



Figure 5:600 MW Solar Plant, Gujarat

The cost of existing technology is rising quickly to \$1–2/Wp (see Figure 4). The availability of Si feedstock, the costs associated with manufacturing silicon wafers, and the development of low-cost, high-throughput processing are major concerns.<sup>10</sup> In order to do this, some businesses are investigating the use of ribbon-based technologies, in which crystalline Si is produced as a thin sheet straight from molten Si. This prevents the kerf loss (materials lost by sawing) that occurs while cutting boules of single-crystal silicon or polycrystalline silicon into wafers. Although ribbon-based materials haven't yet generated materials with the same efficiencies as wafer-based single-crystal materials, their efficiencies are still sufficient for commercial viability. Thinner cells are a goal of both the ribbon and boule technologies. The cost of materials would be greatly reduced for a cell that is roughly 30 microns (m) thick and has efficiency comparable to that of present cells (which are 100-200 m thick). Such a cell would require novel techniques for handling, processing, and contacting such thin materials. For instance, inkjet noncontact printing might be used to contact instead of the existing screen-print method.

# International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 3, March 2015

## Second-generation technologies

Second-generation technologies are ones without a sizable market share at the moment but have shown real-world conversion efficiency and may have lower costs per watt than crystalline silicon. These methods are often in the early manufacturing phase when they are commercialised. This group includes a variety of new technologies that fall between second- and third-generation technologies, such as thin-film photovoltaics, solar concentrators, solar thermal conversion, and organic photovoltaics. With a stated production cost of \$1.25/Wp for CdTe solar cells, First Solar recently proved the potential for producing power at a significantly reduced cost.<sup>11</sup> The continuous development of these multijunction cells is a materials challenge that is testing the still-unknown boundaries of material synthesis and processing. Since the bandgap of amorphous silicon is quasidirect, it has a higher absorption coefficient than crystalline silicon, smaller absorbent layers, and lower material costs. Si does not absorb light as effectively as a-Si, which has a very fast absorption turn-on, at its band edge (indirect gap) (direct gap). Figure 6 illustrates how alloying with Ge enables absorbance to be tuned across a practical range of the solar spectrum at a reported manufacturing cost of \$1.25/Wp.<sup>12</sup> The Staebler-Wronski effect, a light-induced instability, causes the cell efficiency of amorphous silicon to gradually deteriorate. The level of the degradation may often be decreased to between 10% and 20% of the efficiency as-manufactured (not aged), even if the effect cannot yet be completely eradicated. One of the major materials science difficulties this technology faces is maintaining the initial efficiency of a-Si controlling the hydrogen concentration and shape of the film during growth is the majority of the effort put out to prevent this deterioration. If the hydrogen concentration and deposition temperatures are altered, for instance, the same growth procedures used to deposit amorphous silicon can also be used to produce films made of nano- or microcrystalline silicon, either with or without an accompanying amorphous matrix.<sup>13</sup> These materials often develop at elevated process temperatures and exhibit crystalline, regularly organised areas on a tiny length scale. The film starts to resemble polycrystalline silicon (also known as polysilicon) more as the grain size increases, with the energy gap being more indirect, thicker layers being necessary for full absorption, and passivation becoming more significant. Polycrystalline silicon thin films with large grains are now being researched and developed (CSG Solar). To further lower costs for large-area production, combinations of polysilicon, amorphous silicon, and microcrystalline silicon are being investigated. These combinations could result in low-cost thin-film silicon solar cells atop glass.

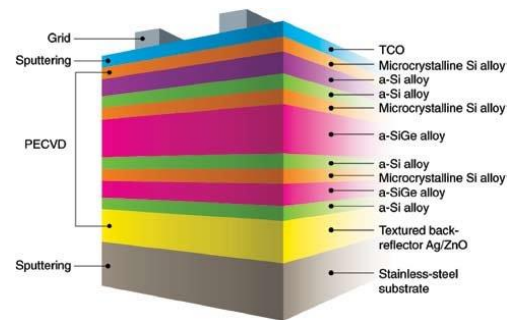


Figure 6: Triple-junction spectrum-splitting amorphous (Si/Ge and Si) and microcrystalline silicon solar cell structure

## High-Efficiency Concentrators

Multijunction solar cells made of GaAs and related III-V materials have the greatest known efficiencies. Here, a multilayer device like the triple-junction cell shown in Figure 7 is grown using extremely complex molecular beam epitaxy or metal-organic chemical vapour deposition (MOCVD) processes. For large-area applications, these cells are prohibitively expensive; nonetheless, they are typically utilised at the focal point of mirrors or lenses that increase the solar light's concentration by a factor of 50–1,000. The optic collection system's mechanical complexity is increased by the requirement to track the sun for maximum efficiency. However, the cost of the cell can be significantly decreased so that the cost of the optics takes centre stage by focusing the solar energy up to 500 times. As a result, the technique can be very competitive with thin-film technologies if low-cost optics and trackers are produced. This presents a considerable material challenge on its own. Transmission losses of photons with energy below the bandgap and thermal relaxation of carriers produced by photons with energies above the bandgap are what limit the efficiency of a single junction device. A multi-junction device's objective is to maximise solar spectrum collection while minimising thermalization losses. Light is automatically filtered as it passes through the stack when cells are stacked in order of their bandgaps, with the cell with the widest bandgap at the top. This ensures that the light is absorbed in the cell that is most effectively able to convert it. If bandgaps are chosen properly, all of the cells in the stack will create near to the same current, allowing the cells to be simply connected in series. This is another smart simplification. Figure 7

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Vol. 4, Issue 3, March 2015

demonstrates how a three-junction solar cell divides the sun spectrum, resulting in a potential efficiency of 52% of the incoming energy transferred to usable electricity for this specific set of components. Above 60% is the theoretical upper bound for multi-junction devices where the number of junctions is limitless. According to a recent report for Spectrolabonmultijunction cells with solar concentration, the best efficiencies to date have been over 40%.

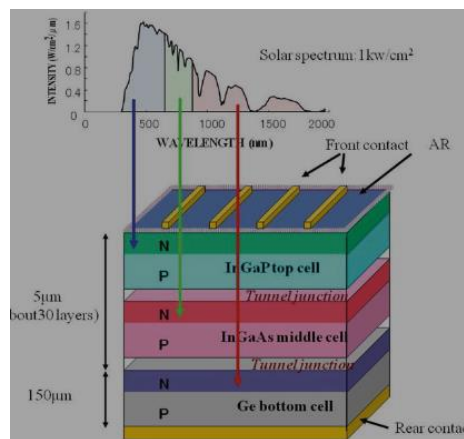


Figure 7: Schematic of a possible configuration for a three- (triple-) junction

## Solar Thermal Conversion

For home hot water or heating, flat-plate systems have historically been the most common application for solar thermal systems. According to a research from Environment California, this is currently the greatest use of solar energy in the world, with estimates of up to 88 gigawatts (GW) annually. These systems come in passive and active varieties. Figure 8 illustrates how a passive system relies on gravity feed and normally does not utilise any pumps. These programmes stand for a significant energy-saving innovation that can be used practically anywhere. Large-area solar thermal systems have become a promising alternative more recently. These systems employ solar radiation concentrators to heat a



Figure 8: Passive solar hot water system on a residential roof top

working fluid to a high temperature, which may then be conveniently stored and used later to create steam, which turns a turbine to produce electricity. Parabolic dish systems and parabolic trough systems are additional methods for generating central solar thermal energy. The ideal operating temperature for all of the systems is 400 °C or above. This makes it possible to store steam on-site and produce it instantly. The creation of working fluids for solar collectors that are stable across the wide temperature range

experienced, have high heat capacities (amount of heat stored per molecule), and are yet inexpensive are key materials problems. Polysilicon's, nanostructured fluids, and molten salts are examples

of new working fluids. The creation of high-efficiency optical coatings for mirrors and solar energy absorption is the other important area. By 2015, generation of solar thermal electricity is predicted to reach 7 GW.

## High-Efficiency Thin Films

Typical cross sections of CdTe and polycrystalline Cu(InGa)Se<sub>2</sub> (CIGS or CIS without Ga) solar cells are shown in Figure 9. Laboratory efficiencies for the former are getting close to 20% (Figure 3),<sup>14, 15</sup> and several businesses are working to create a range of production techniques that will result in low-cost, high-yield, large-area devices while maintaining laboratory efficiencies. Each layer of these devices faces material problems, as do the interactions between layers; the first of these is the pursuit of better transparent conducting

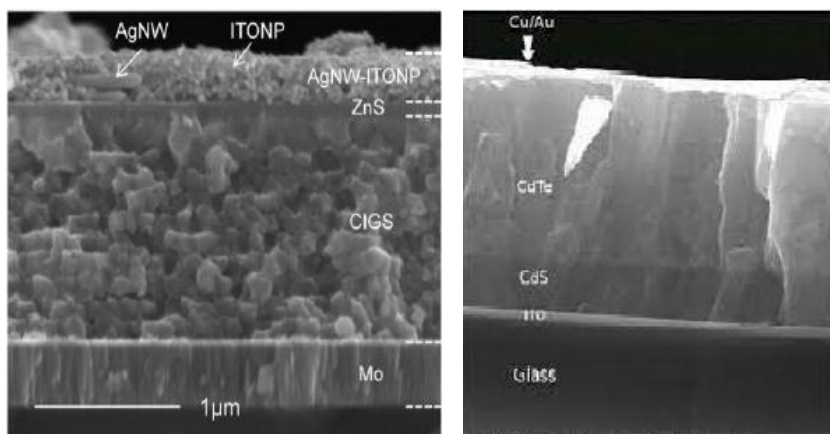


Figure 9: Cross-sectional scanning electron microscopy images of a Cu(InGa)Se<sub>2</sub> (CIGS) solar cell (left) and a CdTe cell (right)

oxide (TCO) connections. These contacts must be produced from inexpensive, abundant materials, exhibit high conductivities and visible spectrum transparency, and make it simple to electrically isolate devices. Another illustration is the tiny CdS contact layer that serves as a window for solar radiation in both devices.<sup>16</sup> This layer must be thin because CdS absorbs in the blue wavelength band. Pinholes between the TCO contact and the absorber layer, on the other hand, cause short circuits when the layer is too thin. This is particularly problematic for CdTe cells because during post-growth annealing, sulphur diffuses into the CdTe layer,

further reducing the thickness of the CdS layer. Efficiency is increased by adding thin buffer layers, such as a highly resistive transparent oxide, between the TCO and the CdS.

It is crucial to optimise this interface since it is unclear exactly what the buffer layer does—whether it only adds resistance to short circuits or alters the energetics of the interface. As demonstrated in Figure 9, Even though the optimal thickness of the absorbing CIGS and CdTe films are 1 µm and 5 µm, respectively, the grain size for effective devices is a significant portion of the thickness. This huge grain size in CdTe is attained through a post-deposition annealing in the presence of oxygen and CdCl<sub>2</sub>, which encourages low-temperature grain development. Research and development are currently being done to find predictable and manufacture-friendly ways to perform this annealing treatment or, even better, to include it right into the growing process. The most effective CIGS films are made by physical vapour deposition, and during growth, a complicated evolution from Cu-rich to In- and Ga-rich phases defines the grain microstructure.<sup>17</sup> It is quite difficult to replicate this growth course using other, more attainable deposition techniques. It's crucial to incorporate Na<sup>+</sup> ions, which naturally exist as a component of growth on soda lime glass substrates, in order to maximise the effectiveness of the CIGS device. Na is thought to decrease the film's resistivity and perhaps grow the grain size, while there is no clear explanation for its advantageous effects.<sup>18</sup> It is thought that the defect structures at the grain boundaries in CIGS and CdTe, which are still poorly understood, dominate minority carrier lifespan and carrier collection. The need to reduce growth and processing temperatures, which now approach 500°C for the highest efficiency films, and the desire to employ thinner films without sacrificing absorption are other absorber layer materials and processing concerns that have an impact on cell costs. The latter objective necessitates strategies for lengthening the optical path using back reflection, texturing, or light trapping. Understanding and enhancing the electrical and structural properties of these layers in both CIGS and CdTe devices present important problems for the back contact. For instance, delamination concerns in CIGS cells are frequently linked to troubles with the molybdenum back contact layer. Finally, we point out that moisture sensitivity exists in both CIGS and CdTe technologies despite their good operational lifetimes. Currently, they are shielded by being enclosed between glass plates. A big advancement might be a thin-film encapsulation technique that offers a moisture barrier without sacrificing effectiveness. Beyond the straightforward thin-film cells shown in Figure 9, it is possible to combine thin-film materials, such as Si, a-Si, CIS, and CdTe, to create tandem cells that catch more of the solar spectrum, similar to the multijunction concentrator structures mentioned earlier. Such a strategy would impose even stricter constraints on comprehending and managing the interactions between various materials.

### Organic Photovoltaic Cells

A fast developing device technology with the potential for low-cost, non-vacuum-processed devices is organic photovoltaics (OPV). According to data from the National Renewable Energy Laboratory, OPV devices have rapidly



## International Journal of Innovative Research in Science, Engineering and Technology

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Vol. 4, Issue 3, March 2015

improved from having very low efficiencies to ones of 5.4% and 5.2%, respectively, obtained by Plextronics and onarka (NREL)<sup>19</sup>. The key is that these devices construct an exciton-based structure by combining polymers, tiny molecules, and inorganic nanostructures. An exciton solar cell first experiences an excited bound electron-hole state, which is followed by a decomposition at an interface that produces charge carriers (which can do work in an external circuit). The charge carriers are then normally collected. Although the exciton mechanism is distinct from the traditional PV mechanism, it still has a theoretical efficiency comparable to that of traditional semiconductor devices and a cost structure resembling that of plastics processing, which opens the door to the possibility of significant per-watt cost reductions. The advent of an organic electronics sector based on displays (organic light-emitting devices, or OLEDs) and transistors is leveraging the development of materials for OPV systems.<sup>20, 21</sup> The investigational organic small-molecule and polymer materials' intrinsic low cost is a significant feature of OPV technology. Extremely thin films can be used to produce these materials because they often have very high optical absorption coefficients, are compatible with plastic substrates, and can be made using roll-to-roll methods with cheap start-up costs.<sup>22</sup> Therefore, there may be strong financial justifications in favour of OPV devices if their efficiencies are on par with or even slightly below those of incumbent technologies. The adaptability of organic materials is another significant feature. The synthesis of basic molecules in organics is remarkably flexible, allowing for changes in a variety of properties, such as molecular weight, bandgap, molecular orbital energy levels, wetting properties, structural properties (such as rigidity, conjugation length, and molecule-to-molecule interactions), and doping.

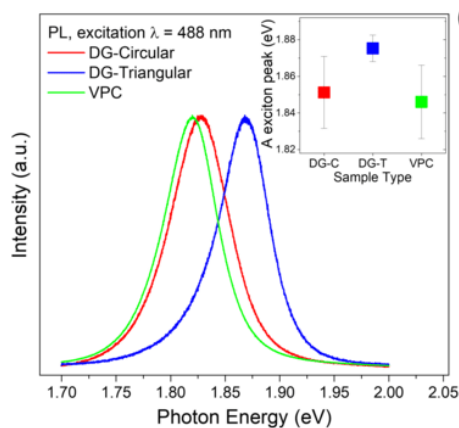


Figure 10: Silicon quantum dots in an oxide material

Designing and synthesising molecules, then incorporating them into organic-organic and inorganic-organic composites, offers a special route for creating new materials for electronics. Additionally, OPV cells can be incorporated into current building structures and new commercial products in ways that conventional technologies cannot due to the device's ability to be coloured differently, to be manufactured on flexible substrates, and possibly to be printed in any pattern. For the OPV technology to be successful in the long run, a number of major problems must be resolved. One is the creation of red-absorbing compounds that allow for more solar spectrum utilisation without sacrificing open-circuit potential. Additionally, it is essential to create nanoscale-optimized interfaces that enable exciton breakdown, charge transfer, and modification of the morphology of the organic component. The stability of the organic materials is another important material issue that the organic electronics community as a whole deals with. It is encouraging that organic light-emitting screens are displaying acceptable lifetimes under high injection currents and that automobile paints include chromophores that are comparable to chemicals frequently utilised in OPV devices. Instead of solely chemical disintegration, device degradation pathways are mostly driven by changes in shape, loss of interfacial adhesion, and interdiffusion of components. Consequently, careful design, wise materials engineering, and enhanced encapsulation should significantly lengthen device lifetimes. Encapsulation is a problem that affects all PV systems, and research in

## International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 3, March 2015

this field is becoming more and more active. It is extremely difficult to create encapsulates that are durable for 10–25 years without yellowing or water or oxygen penetration, have minimal beginning costs, and are simple to produce. Researchers are increasingly thinking about using sealants made of nanomaterial/polymer composites that scavenge impurities and slow diffusion for OPV devices. Additionally, attempts are being made to create novel polymers with less photosensitivity or diffusion for the top and bottom layers of flexible PV systems. The "ultimate" thin-film solar cell technology is what gave rise to the name "third-generation photovoltaics." High efficiency (resulting from operating principles that avoided the performance limitations of single-junction cells) and the utilisation of plentiful, nontoxic, and robust materials were among the features listed. However, in common usage, the phrase has been used to refer to any modern photovoltaic technology, including organic cells to multijunction concentrator cells with three junctions. The multijunction strategy mentioned earlier is one of the most well-known and extensively researched strategies for enhancing the performance of single-junction cells. Efficiency should only be constrained by the number of cells connected in series; nevertheless, due to practical concerns, devices are typically limited to three to five junctions. The best cells have drawbacks that are less significant in solar concentrating systems, despite the fact that they do not fit the original criteria of third-generation technology because they are not thin films and require poisonous and scarce ingredients.<sup>23</sup> Although the photovoltaic conversion unit is simpler, such concentrating systems closely resemble solar thermal electric systems, particularly dish-Stirling and power tower designs is potentially more reliable, and now has higher conversion efficiencies. Additionally, the multi-junction cell strategy is being used to significantly less expensive and more experimental material systems. The method may offer similar efficiency benefits in other solar cell types, such as organic and dye-sensitized solar cells, however in this instance the challenge is locating a stable, low-bandgap cell that makes use of comparable/compatible components. It has been successful to combine these materials with inorganic cells that have a lower absorption threshold; however such devices go against the fundamental rule that the best cells must be placed on top in a stacked cell design. Another multi junction technique investigates the use of quantum confinement to widen the bandgap of silicon and so enable the realisation of a "all-silicon" tandem cell at higher temperatures. <sup>24</sup> An enhanced optical bandgap has been shown by embedding Si quantum dots in a matrix of silicon oxide, nitride, or carbide (Figure 10). Dot density affects how photo-generated carriers are transported because carriers can tunnel more easily between dots that are closer together. <sup>25</sup> It has been suggested to stack one or two of these quantum dot cells on top of a thin-film Si bottom cell, with the effective bandgap of each cell being dictated by the size of the individual dots. Although the limit for conversion methods that are time-symmetric is slightly lower at 68%, the thermodynamic limit for the terrestrial conversion of sunlight to electricity is approximately 74%. Theoretically, a multi-junction cell with many cells in the stack can reach this limit, with the limiting efficiency continuously declining with the number of cells in the stack, bottoming out at 31% for a single cell. (The most effective single Si or GaAs laboratory cells are capable of achieving roughly 80% of this limiting efficiency.) The performance potential of hot-carrier cells is likewise very near to its theoretical maximum. The operational criteria for hot-carrier cells are stringent, even though they could be constructed as "simple" two-terminal devices and would almost definitely be quite small.<sup>26</sup> A hot-carrier cell must be built so that the carriers are collected before the photoexcited carriers thermalize with the atomic lattice of the cell, which happens in ordinary cells. This provides methods for minimising the interaction between the carriers and the host lattice as well as short transport distances. There may be some prospects here due to developments in nano structural engineering targeted at manipulating lattice vibrational characteristics. The need to pay close attention to the hot carriers' interface with the outside world makes the job even more difficult. Again, practical difficulties arise since transfer should ideally take place only across a small range of energy to prevent cooling of the heated carriers. One method for fulfilling this need has been proposed: resonance tunnelling through quantum dots. This limiting efficiency increases to 85% for direct sunlight conversion, as in the concentrating solar power systems previously addressed (but this value applies to only the fraction of the available light that is direct). Practical efficiencies in this scenario are only a small portion of this figure due to the several processes running in series and temperature restrictions. Once more, nanostructures are being studied as a way to introduce several ranges of readily available energy within a material to enable two-step excitations. The limiting efficiency is the same as that which might be achieved with optical up converters, which could be installed at the back of a cell. In this instance, the up converter can perform a two-step excitation to combine two low-energy photons that cannot separately excite the cell with one higher energy photon that the cell can employ. Utilizing down-conversion, in which one high-energy photon generates two (or more) lower-energy photons before the light reaches the cell, has some advantages as

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(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 3, March 2015

well. In PbS, PbSe, PbTe, CdSe, and InAs quantum dots, as well as more recently in Si quantum dots, there is proof that a single photon can produce up to eight excitons. Now, a method for transforming these many excitons into electrons capable of performing useful work is required. It is obvious that contemporary third-generation research activities are directly related to novel materials, particularly nanomaterials. Even the trickier of these methods might eventually be put into practise due to the flexibility provided by nanoparticles in the engineering of crucial material properties.

Summary: The solar energy sector, including both PV and thermal technologies, has been reviewed here and is expected to play an increasingly important role in future global energy supplies. Although Si presently dominates the market, Si may ultimately be unable to satisfy long-term cost objectives, making thin films and solar thermal conversion more attractive. These technologies face significant material problems as well, although the recent increase in Cd-Te production shows that they are getting closer to being mass produced. Multi-junction and organic-based devices are two examples of new, high-efficiency or low-cost technologies that are developing quickly and could have second- and third-generation embodiments. The possibility to create devices that can convert considerably wider areas of the solar spectrum lies in the development of new, extremely high-efficiency methods for converting solar energy. To meet demand, nearly all of these strategies will need to be researched simultaneously given the predicted market growth. The descriptions of various solar technologies had to be condensed due to the article's length, and not all of the distinguished scientists who have made contributions to this field could be adequately acknowledged.

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