DOWNLOAD PDF NEW APPROACHES FOR PREPARING THIN FILMS OF AMORPHOUS SILICON FOR PHOTOVOLTAIC APPLICATIONS

Chapter 1 : Third-generation photovoltaic cell - Wikipedia

New approaches for preparing thin films of amorphous silicon for photovoltaic applications By G.T. Hefter, P.J. Jennings and J.C.L. Cornish Publisher: Minerals and Energy Research Institute of Western Australia.

A copper indium gallium selenide solar cell or CIGS cell uses an absorber made of copper, indium, gallium, selenide CIGS , while gallium-free variants of the semiconductor material are abbreviated CIS. It is one of three mainstream thin-film technologies, the other two being cadmium telluride and amorphous silicon , with a lab-efficiency above 20 percent and a share of 2 percent in the overall PV market in Traditional methods of fabrication involve vacuum processes including co-evaporation and sputtering. Amorphous silicon Amorphous silicon a-Si is a non-crystalline, allotropic form of silicon and the most well-developed thin film technology to-date. Thin-film silicon is an alternative to conventional wafer or bulk crystalline silicon. While chalcogenide -based CdTe and CIS thin films cells have been developed in the lab with great success, there is still industry interest in silicon-based thin film cells. Silicon-based devices exhibit fewer problems than their CdTe and CIS counterparts such as toxicity and humidity issues with CdTe cells and low manufacturing yields of CIS due to material complexity. Additionally, due to political resistance to the use non-"green" materials in solar energy production, there is no stigma in the use of standard silicon. This type of thin-film cell is mostly fabricated by a technique called plasma-enhanced chemical vapor deposition. Other methods used to deposit amorphous silicon on a substrate include sputtering and hot wire chemical vapor deposition techniques. It requires a low processing temperature and enables a scalable production upon a flexible, low-cost substrate with little silicon material required. Due to its bandgap of 1. This allows the cell to generate power in the early morning, or late afternoon and on cloudy and rainy days, contrary to crystalline silicon cells, that are significantly less efficient when exposed at diffuse and indirect daylight. This is called the Staebler-Wronski effect SWE â€" a typical loss in electrical output due to changes in photoconductivity and dark conductivity caused by prolonged exposure to sunlight. Its basic electronic structure is the p-i-n junction. The amorphous structure of a-Si implies high inherent disorder and dangling bonds, making it a bad conductor for charge carriers. These dangling bonds act as recombination centers that severely reduce carrier lifetime. A p-i-n structure is usually used, as opposed to an n-i-p structure. This is because the mobility of electrons in a-Si: H is roughly 1 or 2 orders of magnitude larger than that of holes, and thus the collection rate of electrons moving from the n- to p-type contact is better than holes moving from p- to n-type contact. Therefore, the p-type layer should be placed at the top where the light intensity is stronger, so that the majority of the charge carriers crossing the junction are electrons. When only two layers two p-n junctions are combined, it is called a tandem-cell. A new world record PV module based on the micromorph concept with The band gap of a-Si is 1. The c-Si layer can absorb red and infrared light. The best efficiency can be achieved at transition between a-Si and c-Si. As nanocrystalline silicon nc-Si has about the same bandgap as c-Si, nc-Si can replace c-Si. Protocrystalline silicon with a low volume fraction of nanocrystalline silicon is optimal for high open-circuit voltage. Polycrystalline silicon on glass[edit] A new attempt to fuse the advantages of bulk silicon with those of thin-film devices is thin film polycrystalline silicon on glass. These modules are produced by depositing an antireflection coating and doped silicon onto textured glass substrates using plasma-enhanced chemical vapor deposition PECVD. The silicon film is crystallized by an annealing step, temperatures of â€" Celsius, resulting in polycrystalline silicon. Crystalline silicon on glass CSG , where the polycrystalline silicon is 1â€"2 micrometres, is noted for its stability and durability; the use of thin film techniques also contributes to a cost savings over bulk photovoltaics. These modules do not require the presence of a transparent conducting oxide layer. This simplifies the production process twofold; not only can this step be skipped, but the absence of this layer makes the process of constructing a contact scheme much simpler. Both of these simplifications further reduce the cost of production. Despite the numerous advantages over alternative design, production cost estimations on a per unit area basis show that these devices are comparable in cost to single-junction amorphous thin film cells. Although GaAs cells are very expensive, they hold the world record for the highest-efficiency, single-junction solar cell at They are also used in concentrator photovoltaics , an emerging technology best suited for locations that receive much sunlight, using lenses to focus sunlight on a much smaller, thus less expensive GaAs concentrator solar cell. Third-generation photovoltaic cell An experimental silicon based solar cell developed at the Sandia National Laboratories The National Renewable Energy Laboratory NREL classifies a number of thin-film technologies as emerging photovoltaicsâ€"most of them have not yet been commercially applied and are still in the research or development phase. Many use organic materials, often organometallic compounds as well as inorganic substances. Despite the fact that their efficiencies had been low and the stability of the absorber material was often too short for commercial applications, there is a lot of research invested into these technologies as they promise to achieve the goal of producing low-cost, high-efficient solar cells.

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Chapter 2 : Promising pathways for solar photovoltaic power | Kurzweil

The major objectives of this subcontract are (1) to prepare new materials based on hydrogenated amorphous silicon (a-Si:H), (2) to characterize the important defects and impurities in the bulk and at surfaces and interfaces, (3) to identify metastabilities and to determine if the.

The complexity increases from the simplest material, pure silicon single atom, lower left , to the most complex material currently being studied for potential solar cells, quantum dots molecular structure at top right. Materials shown in between include gallium aresenide, perovskite and dye-sensitized solar cells. Worldwide installed capacity has seen sustained growth averaging 43 percent per year since To evaluate the prospects for sustaining such growth, the MIT researchers look at possible constraints on materials availability, and propose a system for evaluating the many competing approaches to improved solar-cell performance. A broader analysis of solar technology, economics, and policy will be incorporated in a forthcoming assessment of the future of solar energy by the MIT Energy Initiative. One useful factor in making meaningful comparisons among new photovoltaic technologies, they conclude, is the complexity of the light-absorbing material. Chart from the MIT report shows the extremely rapid worldwide growth of photovoltaic installations over the last 15 years credit: MIT Technology classes The report divides the many technologies under development into three broad classes: It may be time, he says, to re-examine the traditional classification of these technologies, generally into three areas: In this study, we chose to evaluate all relevant technologies based on their material complexity. Primary absorber layers are labeled in white, and thicknesses are shown to scale. Joel Jean et al. While crystalline silicon is a mature technology with advantages including high efficiency, proven reliability, and no material scarcity constraints, it also has inherent limitations: Silicon is not especially efficient at absorbing light, and solar panels based on silicon cells tend to be rigid and heavy. The authors make clear that their definition of material complexity as a key parameter for comparison does not imply any equivalency with complexity of manufacturing. On the contrary, while silicon is the simplest solar-cell material, silicon wafer and cell production is complex and expensive, requiring extraordinary purity and high temperatures. By contrast, while some complex nanomaterials involve intricate molecular structures, such materials can be deposited quickly and at low temperatures onto flexible substrates. Nanomaterial-based cells could even be transparent to visible light, which could open up new applications and enable seamless integration into windows and other surfaces. The authors caution, however, that the conversion efficiency and long-term stability of these complex emerging technologies is still relatively low. As they write in the paper: The study highlights the need for novel thin-film technologies that are based on Earth-abundant materials. Increasing the power-conversion efficiency of emerging photovoltaic technologies and commercial modules. Reducing the amount of material needed per cell. Thinner, more flexible films and substrates could reduce cell weight and cost, potentially opening the door to new approaches to photovoltaic module design. Reducing the complexity and cost of manufacturing. Here the researchers emphasize the importance of eliminating expensive, high-temperature processing, and encouraging the adoption of roll-to-roll coating processes for rapid, large-scale manufacturing of emerging thin-film technologies. Among solar power technologies, solar photovoltaics PV are the most widely deployed, providing 0. Given the massive scale of deployment needed, this article examines potential limits to PV deployment at the terawatt scale, emphasizing constraints on the use of commodity and PV-critical materials. We propose material complexity as a guiding framework for classifying PV technologies, and we analyze three core themes that focus future research and development:

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Chapter 3 : Photovoltaic Materials and Device Research

Thin-film PV technologies, such as amorphous silicon, hold the promise for low cost.2 Of the thin-film technologies, amorphous silicon is the most mature" Other thinÂ- film technologies have promise, but their manufacturing process yields and costs have not.

Technologies[edit] This article includes a list of references , but its sources remain unclear because it has insufficient inline citations. Please help to improve this article by introducing more precise citations. June Learn how and when to remove this template message Solar cells can be thought of as visible light counterparts to radio receivers. A receiver consists of three basic parts; an antenna that converts the radio waves light into wave-like motions of electrons in the antenna material, an electronic valve that traps the electrons as they pop off the end of the antenna, and a tuner that amplifies electrons of a selected frequency. It is possible to build a solar cell identical to a radio, a system known as an optical rectenna , but to date these have not been practical. The majority of the solar electric market is made up of silicon-based devices. In silicon cells, the silicon acts as both the antenna or electron donor , technically as well as the electron valve. Silicon is widely available, relatively inexpensive and has a bandgap that is ideal for solar collection. On the downside it is energetically and economically expensive to produce silicon in bulk, and great efforts have been made to reduce the amount required. Moreover, it is mechanically fragile, which typically requires a sheet of strong glass to be used as mechanical support and protection from the elements. The glass alone is a significant portion of the cost of a typical solar module. Any photon with more energy than the bandgap can cause photoexcitation, but any energy above the bandgap energy is lost. Consider the solar spectrum; only a small portion of the light reaching the ground is blue, but those photons have three times the energy of red light. If the bandgap is tuned higher, say to blue, that energy is now captured, but only at the cost of rejecting lower energy photons. It is possible to greatly improve on a single-junction cell by stacking thin layers of material with varying bandgaps on top of each other â€" the "tandem cell" or "multi-junction" approach. Traditional silicon preparation methods do not lend themselves to this approach. Most tandem-cell structures are based on higher performance semiconductors, notably gallium arsenide GaAs. Three-layer GaAs cells achieved Such a cell can have a maximum theoretical power conversion efficiency of For a two layer cell, one layer should be tuned to 1. A three-layer cell should be tuned to 1. A theoretical "infinity-layer" cell would have a theoretical efficiency of Use of excess thermal generation caused by UV light to enhance voltages or carrier collection. Use of infrared spectrum to produce electricity at night.

Chapter 4 : New approaches for preparing thin films of amorphous silicon for photovoltaic applications - CO

Amorphous silicon (a-Si) is the non-crystalline form of silicon used for solar cells and thin-film transistors in LCDs.. Used as semiconductor material for a-Si solar cells, or thin-film silicon solar cells, it is deposited in thin films onto a variety of flexible substrates, such as glass, metal and plastic.

Photovoltaic Materials and Device Research VHF plasma reactor MRC scientists and students have established a world-class laboratory for research in photovoltaic solar energy conversion materials and devices. The program focuses on growth of thin film electronic materials suitable for photovoltaic conversion, and on fabricating devices in them. Current materials of interest include amorphous Si and its alloys, and CdTe. H and its alloys A-Si is deposited using a remote, reactive ECR plasma deposition, and after deposition, the films are characterized for their optical and electronic properties. The reactors can be used also to make doped layers and devices in these films. The devices are measured using solar simulators and other electronic measurement techniques, such as capacitance-frequency measurements and quantum efficiency measurements. This is an active research program, supported by National Renewable Energy Laboratory and by industry. ISU is one of the leaders in the world in this field. Activation energy setup Another part of the a-Si program is a theoretical effort to understand the microscopic origins of defects in a-Si, using molecular dynamic simulations to simulate local Si-Si and Si-H bonds in the material, and their statistical distributions. The simulations also try to model the movement of H in these materials in response to energetic inputs, and see how these movements and bond-rearrangements affect the electronic properties. This theoretical effort is complemented by experimental work to measure the diffusion of H and D in a-Si , a- Si,C and a- Si,Ge materials. It is known that diffusion of H plays a critical role in defect creation in these materials, and by using Secondary Ion Mass Spectroscopy, one can determine the diffusion kinetics of H and D, and correlate them with the defect structure in the material. Semiconductor Process research Production cost of solar electric conversion panels is the critical element which determines their commercial success. We work with a local company, Iowa Thin Film technologies, Inc. ITFT deposits these cells on polyimide substrates, in continuous deposition reactors using a roll-to-roll process. ISU scientists work with ITFT to understand the plasma processes that govern deposition, and on development of in-situ sensors for process controls and reliability. MRC scientists and students have developed several new technologies for depositing both amorphous and crystalline Si devices on plastic substrates. Using a rective ECR plasma beam process, we have been able to deposit thin films of crystalline Si directly on a plastic substrate without having to do any laser recrystallization. Recently, we produced a crystalline Si solar cell on polyimide substrates with very good properties. This development is likely to revolutionize semiconductor technology by allowing for multiple-device integration on insulating layers. In addition to crystalline Si films on plastic substrates, we have made thin film transistors TFT in amorphous Si on polyimide substrates. An active area of research in this field is the research on appropriate gate insulators deposited at low temperatures. Several novel approaches such as reactive ECR plasma oxidation are being tried to improve the quality and stability of the gate oxides. Multi frequency capacitance Ames Lab Insider press release A powerpoint presentation on nano-crystalline silicon Nanocrystalline Si: H is a fascinating new electronic material. The H distribution in the material can be estimated using Molecular Dynamic simulations, and is shown in Fig. The simulations clearly show that most of the hydrogen is at the grain boundaries, with nothing inside the nano-grain. The presence of H and a-Si: H tissue at the grain boundaries passivates these boundaries, and allows for efficient transfer of minority and majority carriers across the grain. As a result, hole lifetimes of the order of microsecond can be obtained even in this nanocrystallione material. The hole diffusion lengths can be in excess of 1 micrometer. The nanocrystalline Si material is fundamentally stable, as opposed to amorphous materials. These outstanding properties allow one to make useful devices like solar cells and thin film transistors on plastic substrates in this material. In addition to Si, one can also grow nano Si,Ge: H and nano-

Ge,C: This versatility allows one to visualize many different classes of electo-optic devices in this new material system. The materials are grown using plasma enhanced CVD in a reactive plasma system. Typical Raman spectra of the materials are shown in Fig. Solar cell and TFT devices are being fabricated in these material systems. H modeled using Molecular Dynamic simulations Fig. H solar cells Fig. Spectroscopic gas sensors have greater sensitivity and stability than conventional electrochemical sensors. Spectroscopic sensors of toxic gases rely on the fact that each gas has a unique absorption line in the infrared portion of the spectrum, arising from the molecular stretching or rotational modes. For example CO has a sharp absorption at 4. Spectroscopic infrared gas sensors offer very high sensitivity for conclusive detection of individual species since each gas has unique absorption lines in the infrared spectrum. Spectroscopic sensors are lightweight, battery-powered, low-maintenance and low-cost- essential attributes for counter-terrorism applications. Nanocrystalline Silicon, Amorphous Silicon, Semiconductor Nanowires This has been a long standing project simulating nanocrystalline and amorphous silicon thin films. The objective of the research is to identify, explore, evaluate and model new heterogeneous thin film materials capable of making a breakthrough in the production of low cost electricity from sunlight. This project has been part of the NREL national thin film solar cell team effort. Our approach has been to use molecular dynamics simulations using both classical and tight binding methods to obtain insight into mechanisms of metastability and the structure of nanocrystaline silicon. Metastability The Staebler-Wronski effect or the degradation of thin film silicon solar cells when they are placed in sunlight is a mystery that has plagued the research community for more than 20 years. Intensive studies have established that these changes are due to creating of mid-gap defect states from silicon dangling bonds in the amorphous silicon films. From an annealed defect density of cm-3, the defect density rises to cm-3 after light-soaking. The metastable changes are reversible and can be removed by annealing the material at C. The metastable defects are indistinguishable from native dangling bond defects. We proposed a new mechanism explaining many features of the Staebler-Wronski effect [1,2]. In the first step sunlight creates an excess density of electrons and holes. The electrons recombine with holes on weak silicon bonds in the material. The recombination energy causes the weak silicon bonds to break, generating silicon dangling bond â€” floating bond pairs. Accurate tight-binding molecular dynamics simulations have established the lowering oif energy barriers for bond-breaking when excited e-h pairs are present. During the second step, the floating bonds over-coordinated silicon atoms diffuse away from the dangling bonds and move freely throughout the material since they are a mobile species. In the third step the floating bonds recombine with themselves or with H in the network, and the network is left with primarily dangling bonds. An interesting caveat is that because of charge neutrality charged dangling bond defects are formed in addition to the neutral species. Many features of the Staebler-Wronski are explained well by this model Phys. The model has been featured in news releases Ames Lab Inquiry article , Hindu. Nanocrystalline silicon Nanocrystalline silicon was simulated consisting of nanocrystallites embedded in an amorphous matrix. The presence of the nanocrystallite improves the ordering of the amorphous matrix which may account for the higher stability of nanocrystalline silicon towards light soaking. The nanoscale structure can inhibit the instability and breaking of weak bonds. There is a thin disordered region around the nanocrystal containing an excess density of H where the H density is about twice the background H density. By performing simulations at various temperatures and monitoring the motion of H, we found that the excess grain boundary H is responsible for the anomalous low-temperature H evolution peak that occurs near C in addition to the high temperature H evolution peak at C. Model of nano-crystalline silicon showing crystallization cone surrounded by amorphous tissue. Model of microcrystalline silicon showing crystallization cone surrounded by amorphous tissue. Semiconductor Nanowires Present work is investigating the structure of semiconductor nanowires, including the structure and orientation of crystalline core nanowires. There are many similarities to microcrystalline silicon.

Chapter 5 : Thin-film solar cell - Wikipedia

Preparation and Applications of Amorphous Silicon N2 PH3 E E B2~ SiH4 S a NH3 H2 Figure Vertical, capacitively-coupled system, used at the Dundee laboratory.

 Abstract High surface area titania with crystalline anatase walls has been synthesized using ordered large mesoporous carbon as a template. The pore structure of mesoporous carbon is infiltrated with titanium tetraisopropoxide solution at room temperature and the mixture is subjected to heat treatment at in presence of air to complete removal of the template. The dye-sensitized solar cells performance of this anatase titania material has been tested and energy conversion efficiency of 3. This work reports a new approach for fabrication of nanocrystalline anatase titania by simple hard templating technique for the first time and their applications for dye-sensitized solar cell. Introduction The use of solar cells for energy production by converting sunlight directly into electricity is an avenue to address global energy demand and clean alternative power generation devices. Most commonly used solar cell technologies include crystalline silicon, thin film concentrators, and thermophotovoltaic solar cells. Silicon-based solar cells are large-scale, single-junction devices, and a very high percentage of photovoltaic production comes from these solar cells [1 , 2]. The thin-film solar cells are aimed to decrease the amount of expensive material used in production process without sacrificing efficiency. An alternative approach using multijunction solar cells of dye-sensitized solar cells DSCs and organic solar cells OSCs are also developed to reduce the cost furthermore [5 , 6]. In recent years, DSCs have attracted a great deal of attention due to their simple fabrication and low production cost. In DSCs high internal surface area and wide band gap semiconductor material with adsorbed dye as a photoanode plays an important role. The choice of semiconductor depends on its conduction band, density state that allows efficient electronic coupling with the dye energy level to facilitate charge separation and minimize recombination. Additionally, the semiconductor material must have high internal surface area to maximize light absorption by the dye monolayer with good electrical conductivity to the substrate. Among many other metal oxide semiconductors, nanocrystalline titania is of great scientific and technological interest due to its excellent performance in solar cells [10 , 11], photocatalysis [12], photochromism [13], sensors [14], and so forth. Further, anatase titania nanocrystals are used as best recipient of injected electrons from optically excited dye and provides the conductive pathway to the circuit. However, the preparation of crystalline titania by hard templating technique involves silica, which requires strong acid or base for complete removal of template [15 , 16]. The work in Srinivasu et al. The recent research on templated synthesis of mesoporous carbon using three-dimensional mesoporous silica KIT-6 has attracted a lot of attension for applications in catalysis and adsorption studies [18]. However, three-dimensional mesoporous carbon prepared from KIT-6, has not been used as a hard template for the fabrication of anatase titania in the open literature. Here we report nanocrystalline anatase titania synthesized using three-dimensional mesoporous carbon as a hard template through combustion technique and characterize the prepared material by powder X-ray diffraction, nitrogen adsorption, and electron microscopy techniques. Dye-sensitized solar cell device is constructed with nanocrystalline anatase titania thin film and studied the performance of the material. In a typical synthesis of mesoporous carbon, 1 g of KIT-6 is added to a solution obtained by dissolving 0. In order to obtain fully polymerized and carbonized sucrose inside the pores of silica template, 0. Anatase crystalline titania is prepared by adding 20 mL of titanium tetraisopropoxide 1. The final anatase titania material is used to prepare a film on FTO glass using doctor-blade technique [16] and [17], which is ultrasonically cleaned in ethanol prior to use. N2 adsorption-desorption isotherms are measured at 77 K on a Quantachrome Autosorb 1 volumetric adsorption analyzer. The position of the maximum on pore size distribution is referred to as the pore diameter, which was calculated from adsorption branches by Barret-Joyner-Halenda BJH method. Fabrication of Dye-Sensitized Solar Cell 2. Preparation of Titania Electrode The dye solutions 0. Deoxycholic acid as a coadsorbent was added to the dye solution at a concentration of 20 mM. Preparation of Dye-Sensitized Solar Cell Photovoltaic measurements were performed in a two-electrode sandwich cell configuration. The dye-deposited TiO2 film and a platinum-coated conducting glass were used as the working electrode and the counter electrode, respectively. The electrolyte was composed of 0. Results and Discussion Powder X-ray diffraction pattern is measured for titanium-tetraisopropoxide impregnated mesoporous carbon sample after removal of carbon template through combustion process in presence of air. The well-defined sharp Bragg peaks indicate highly crystalline nature of the material. The Bragg diffraction peaks indexed as , , , , , , , , and are correspond to anatase phase TiO2 with tetragonal arrangement. However, mesoporous ordered structure could not be retained after complete removal of the template due to incomplete filling of pore structure with titanium precursors. The nitrogen adsorption-desorption isotherm for crystalline anatase titanium oxide is shown in Figure 1 b. Figure 2 a shows high resolution TEM images of the nanocrystalline titania particles with particle size in the range of nm. It is very interesting to note the particle size is smaller than commercially available TiO2 P Degussa, average particle size 25â€"30 nm. The circled areas in Figure 2 b , which are in regular pattern, show that all particles are in anatase form. This confirms that material of very small anatase TiO2 particles can be prepared using mesoporous carbon template approach. Figure 3 a shows current-voltage characteristics obtained for the cell with anatase TiO2 thin film. Monochromatic incident photon-to-current conversion efficiency IPCE for the solar cell, plotted as a function of excitation wavelength, was recorded on a CEP system Bunkoh-Keiki Co. The prepared titania thin film is dipped into N dye, and then photocurrent voltage characteristics are measured by irradiating with simulated AM1. The short-circuit current , the open-circuit voltage , and the fill factor FF values obtained for nanocrystalline TiO2 are 6. The anatase nanocrystalline titania thin film showing broad IPCE spectra between and nm indicates higher N dye absorption capacity. These results clearly show dye-sensitized solar cells fabricated with the prepared anatase titania thin film show good solar-to-electricity conversion. Conclusions A nanocrystalline anatase titania with average particle size of 5 nm was successfully synthesized by mesoporous carbon hard template. The synthesized TiO2 particles were fully anatase crystalline form, which was confirmed by various characterization techniques. The novel approach used for the synthesis of nanocrystalline anatase titania using mesoporous carbon as a hard template by combustion process may also be applied to synthesize other metal oxides, such as Cu, Sn, Zr, and so forth. Light-to-electricity conversion yield of 3. View at Google Scholar S. View at Google Scholar M. View at Google Scholar B. View at Google Scholar K.

Chapter 6 : Amorphous silicon - Wikipedia

An analysis has been carried out on the first practical application in Korea of the design and installation of building integrated photovoltaic (BIPV) modules on the windows covering the front side of a building by using transparent thin-film amorphous silicon solar cells.

Applications[edit] While a-Si suffers from lower electronic performance compared to c-Si, it is much more flexible in its applications. For example, a-Si layers can be made thinner than c-Si, which may produce savings on silicon material cost. One further advantage is that a-Si can be deposited at very low temperatures, e. This allows deposition on not only glass, but plastic as well, making it a candidate for a roll-to-roll processing technique. Once deposited, a-Si can be doped in a fashion similar to c-Si, to form p-type or n-type layers and ultimately to form electronic devices. The design of the PECVD system has great impact on the production cost of such panel, therefore most equipment suppliers put their focus on the design of PECVD for higher throughput, that leads to lower manufacturing cost [7] particularly when the silane is recycled. Thin-film solar cell The "Teal Photon" solar-powered calculator produced in the late s Amorphous silicon a-Si has been used as a photovoltaic solar cell material for devices which require very little power, such as pocket calculators , because their lower performance compared to conventional crystalline silicon c-Si solar cells is more than offset by their simplified and lower cost of deposition onto a substrate. The first solar-powered calculators were already available in the late s, such as the Royal Solar 1, Sharp EL, and Teal Photon. More recently, improvements in a-Si construction techniques have made them more attractive for large-area solar cell use as well. Here their lower inherent efficiency is made up, at least partially, by their thinness â€" higher efficiencies can be reached by stacking several thin-film cells on top of each other, each one tuned to work well at a specific frequency of light. This approach is not applicable to c-Si cells, which are thick as a result of its indirect band-gap and are therefore largely opaque, blocking light from reaching other layers in a stack. The source of the low efficiency of amorphous silicon photovoltaics is due largely to the low hole mobility of the material. However, the higher costs of manufacture due to the multi-layer construction have, to date, made a-Si unattractive except in roles where their thinness or flexibility are an advantage. The placement of the p-type layer on top is also due to the lower hole mobility, allowing the holes to traverse a shorter average distance for collection to the top contact. Typical panel structure includes front side glass, TCO , thin-film silicon, back contact, polyvinyl butyral PVB and back side glass. Uni-Solar, a division of Energy Conversion Devices produced a version of flexible backings, used in roll-on roofing products. Nanocrystalline silicon and Micromorph Microcrystalline silicon also called nanocrystalline silicon is amorphous silicon, but also contains small crystals. It absorbs a broader spectrum of light and is flexible. Micromorphous silicon module technology combines two different types of silicon, amorphous and microcrystalline silicon, in a top and a bottom photovoltaic cell. Sharp produces cells using this system in order to more efficiently capture blue light, increasing the efficiency of the cells during the time where there is no direct sunlight falling on them. Protocrystalline silicon is often used to optimize the open circuit voltage of a-Si photovoltaics. These systems combine a solar cell, which converts electromagnetic radiation photons into electricity, with a solar thermal collector , which captures the remaining energy and removes waste heat from the solar PV module. Solar cells suffer from a drop in efficiency with the rise in temperature due to increased resistance. Most such systems can be engineered to carry heat away from the solar cells thereby cooling the cells and thus improving their efficiency by lowering resistance. Recent research showed that a-Si: Thin-film-transistor liquid-crystal display[edit] Main article: Thin-film-transistor liquid-crystal display Amorphous silicon has become the material of choice for the active layer in thin-film transistors TFTs , which are most widely used in large-area electronics applications, mainly for liquid-crystal displays LCDs. Thin-film-transistor liquid-crystal display TFT-LCD show a similar circuit layout process to that of semiconductor products. However, rather than fabricating the transistors from silicon, that is formed into a crystalline silicon wafer , they are made from a thin film of amorphous silicon that is deposited on a glass panel. Polycrystalline silicon is sometimes used in displays requiring higher TFT performance. Examples include small high-resolution displays such as those found in projectors or viewfinders. Amorphous silicon-based TFTs are by far the most common, due to their lower production cost, whereas polycrystalline silicon TFTs are more costly and much more difficult to produce.