Recent Advances in Solar Cell Technology

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ABSTRACT - The present technology and further trends of crystalline and amorphous silicon solar cell preparation is described with respect to semiconductor physics. The estimated limit of photovoltaic power conversion based on crystalline silicon due to an illumination density on the surface of the earth of up to 1 kWm^{-3} is about 300 Wm^{-2}. Experimentally crystalline silicon solar cells show conversion efficiencies as high as 75 per cent of the theoretical limit under not concentrated sunlight conditions. Alternate approaches towards less expensive production and photovoltaic devices with improved energy conversion efficiencies are briefly discussed.

1. Introduction

With the beginning of the space exploration in the late fifties of our century the demand for a suitable energy resouce in space was leading to the development of high effient photovoltaic solar cells. In the middle of the seventies the temporary shortcut of oil stimulated research programs on solar cells for terrestrial applications as a competitive energy resource. Although the physics of the photovoltaic conversion of light energy to electrical energy is well understood the technical realization has to deal with a series of circumstances such as availability of the raw material, varying insolation and weather conditions, economical and environmental aspects. Up to present besides a variety of promising materials for photovoltaic solar cells from the science point of view silicon is nearly exclusively used for solar cell array and module fabrication. Due to the continuous development of improved manufacturing technology during the last 20 years a significant reduction of both costs and process energy consumption was achieved. As a result the market for photovoltaic energy converters as a commercially attractive alternative for electrical energy generation is continually growing. The worldwide shipments of photovoltaic modules raised from 47.0 MW in 1990 to 62.5 MW in 1993. Although the advantage of photovoltaic power generators is especially given for applications with missing or poor infrastructure or on isolated sites during the last few years the attempt to integrate solar power plants into an existing electric grid was made.

2. Principles of photovoltaic solar cell operation

The basic function of a photovoltaic device is its ability that incident photons coming from the solar irradiation are absorbed and set carriers free. In silicon which is a group IV element an electron is excited from the valence band where it leaves a hole which can be considered a positively charged carrier to the conduction band by the absorption of a photon which energy, $h\nu$, - h is Planck's constant and ν the frequency of the incident light - is greater than the energy gap, ε_g, between the two band edges. For crystalline silicon ε_g is about 1.1eV - which corresponds to 1.76×10^{-19} Ws - and for amorphous silicon ε_g is about 1.75eV which is equivalent to a wavelength of the incident light of 710 nm which is in the red part of the visible spectrum. In order to prevent the light generated electron hole pairs to recombine it is necessary to seperate them by means of an internal electric field. Beside the appropriate choice of the absorbing material characterized by its band gap which limits both the current output due to the total number of incident photons with energies capable to excite an electron hole pair and the output voltage which depends on the internal electric field and thus on the band gap the optical properties of the solar cell has to engineered. This includes (i) to minimize optical losses due to shadowing and reflection at the front surface of the cell and (ii) to assure that most of the absorbed light contributes to the energy conversion. A schematic presentation of a solar cell is shown in Figure 1.

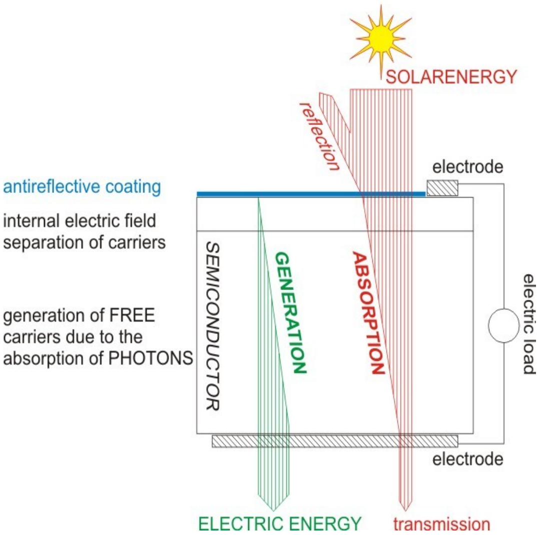

Fig. 1: Schematic presentation of a photovoltaic solar cell

A theoretical calculation of the efficiency limit for crystalline silicon solar cells under non concentrated conditions of incident solar irradiation on earth predict a value of more than 30 per cent [1,2]. Experimentally an efficiency of 23 per cent have recently been reported from the University of New South Wales for a 4 cm^2 large solar cell of monocrystalline silicon [3]. Under not concentrated simulated sunlight conditions this solar cell has a short circuit current density of 40 rnÄcm^{-2} and an open circuit voltage of 0.705 V. Since the typical output voltage of a single photovoltaic device does not match most technical applications a series of solar cells are connected together in series and parallel to arrays with a voltage output adapted to the requirements of the electrical power generator. Due to the difference in current losses within individual photovoltaic devices the inteconnection of several solar cells to an array causes the array efficiency to be lower than the efficiency of a single solar cell. Laboratory type. modules exhibit efficiencies up to 21.6 per cent [4]. Under conditions of Air Mass 1 – AM 1- with a total irradiation density of 1 kWm^{-2} which is defined for direct illumination at the equator under normal incidence an array of 1 m^2 assembled with high efficiency solar cells will produce about 200 W. Or assuming a 1 MW power plant operating under not concentrated AM 1 conditions solar cells with a total area of 5000 m^2 will be necessary. This fact caused by the comparatively low irradiation intensities onto the earth's surface forces the research and development activities towards two major directions: (i) making solar cells as cheap as possible and (ii) trying to obtain a better conversion efficiency for both photovoltaic solar cells and turn key ready electrical power generators. An approach to obtain the same amount of electrical power by the use of less photovoltaic device area is the concentration of sunlight by optical systems. This has two advantages: (i) for properly designed concentrator type solar cells made either from crystalline silicon or from compound semiconductor materials based on gallium and aluminum the conversion efficiency increases with illumination intensity of up to 1000 suns due to the fact that the number of light generated carriers increases proportional to the number of incident photons whereas the internal current losses are nearly independent of the light induced current as can be derived from the power-voltage characteristics shown in Figure 2 and (ii) a significant reduction of the costs of the installed solar cells. However the major disadvantage is that only direct insulation can be reasonably concentrated by optical systems whereas so called flat plate panels of solar cells operating without concentration of the incident light exhibit high conversion efficiencies even under diffuse light conditions and cloudy weather.

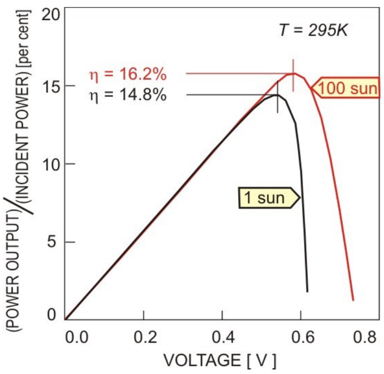

Fig. 2: Power versus voltage characteristics of a crystalline silicon solar cell with low series resistance under air mass 1 irradiation and under 100 times concentrated sunlight conditions which yields a 10 per cent improved collection efficiency.

3. Present state of solar cell technology

Despite several disadvantages the majority of today's commercially available photovoltaic solar power generators is based on single crystal or polycrystalline silicon - c-Si - solar cells. The well established technology of silicon solar cell production as well as their proofen operating reliability are responsible for that fact. Modules of commercial crystalline silicon solar cells have typical conversion efficiencies of 10 per cent to 14 per cent. From the point of physics crystalline silicon is not an effective absorber for the usable part of the incident sunlight spectrum as can be derived from Figure 3. That means that comperatively thick devices are necessary in order not to have significant transmission losses. Moreover the preparation of silicon wafers beginnig with the raw material which is silicon-dioxide in the form of quartzsand consists of a series of energy consuming stages which can not be integrated into a continuous process. In a first step metallurgical grade silicon is earned by the reduction of silicon dioxide in a light arc furnace by the use of a carbon electrode. In order to upgrade the metallurgical grade silicon to solar grade silicon it is dissolved in hydrochloric acid thus forming a series of silanes and chlorosilanes which can be refined, by repeated distillation. From the high purity chlorosilanes polycrystalline silicon rods are produced by a chemical vapor deposition process. The silicon rods are used as starting material for either crystall pulling from the melt or for the directional solidification by pouring the melt into graphite container. In the first case a cylindrically shaped single crystal with a diameter between 6 and 8 inches and a length of about 2 meters is obtained in the latter case bricks with a columnar polycrystalline structure is obtained. However in both cases the silicon wafers have to be prepared by a multiple sawing process thus wasting about one fourth of the ingot before the wafers can be processed to solar cells by the application of a *pn*-junction and the front- and backside metallisation. Finally an antireflective coating is applied onto the front surface and the individual cells are interconnected to arrays and encapsulated into modules with a protective transparent front cover. From the very beginning of the research and development of solar cells for terrestrial applications approaches towards a less energy and captial investment intensive production were made. Up to date however only about 30 per cent of the global production of photovoltaic solar power generators are based on materials others than crystalline silicon [5].

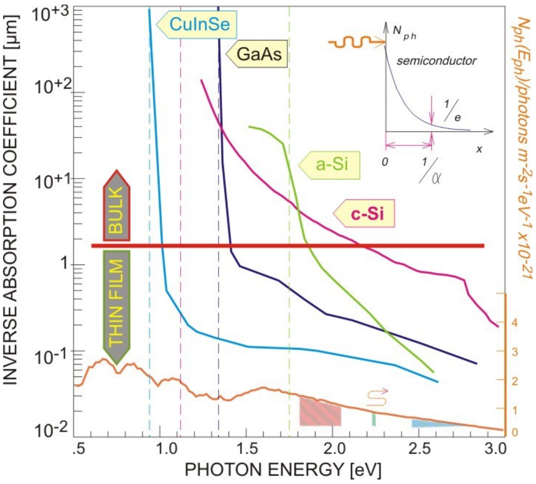

Fig. 3: Inverse absorption coefficient of some semiconductors for potential photovoltaic applications. The minimal thickness of a solar cell can be estimated from these data as shown in the inset. The bottom function displays the distribution of an AM 1 spectra.

4. Progress in the development of low cost solar cells

In order to to significantly reduce production costs of photvoltaic solar cells the following requirements has to be fulfilled: (1) The energy consumption for the 'fabrication must be considerably lower than it is for crystalline silicon solar cells. (2) The process of manufacturing must be capable of large throughput and (3) As many individual production steps as possible shall be done in a continuous way within the same production unit. As mentioned above amorphous silicon - a-Si - attracted attention for photvoltaic applications already 20 years ago. From the physics point of view amorphous silicon is a much better light absorbing material than crystalline silicon as can be seen in Fig.3 however the energy gap of 1.7 eV which limits the useable part of the solar spectrum is less suitable for single junction high efficiency solar cell. The total energy consumption from the raw material to a photvoltaic module however is much lower than for crystalline silicon. This is due to the fact that only process temperatures in the range of 400°C are required for depositing a-Si devices from a chemical vapour whereas the melting temperature of crystalline silicon is 1400°C. The material can be deposited in 1 μm thin sheets which is sufficient to absorbe most of the useable light with an area of 1000 cm^2 directly onto the coverglass of the module and the formation of a *pn* - junction is done during the deposition process from a silane source. Furthermore there is no need for any additional sawing or shaping of the deposited device thus only a negligible fraction of the material is wasted. The principle setup of an amorphous silicon solar cell is shown Figure 4. The material itself and therefore the finally manufactured device however suffers from the lower stability of the more or less random arangement of silicon atoms in the deposited layer compared to the tetrahedral binding of crystalline silicon which is diamond type. A successful approach to stabilize the atomic structure has been made by the incorporation of hydrogen atomsinto the layer [6]. However up to today amorpous silicon solar cells exhibit an ageing at the moment they are exposed to light for the first time [7] thus resulting in a decrease of the conversion efficiency. Modern modules remain stable under normal operating conditions after the first light soaking which structurally rearranges the silicon – hydrogen atoms. Laboratory module efficiencies of up to 10 per cent have been reported [8]. In order to overcome the structural disadventage of amorphous semiconductors much research was elaboured onto the development of thin film crystalline solar cells. These type of cells mainly are made either from cadmium-telluride or copper-indium-diselenide - CIS -. Both materials are attractive by means of their theoretical limit of the conversion efficiency and their absorption coefficent as well as their ability to be processed to a thin large area device which remains stable during outdoor operation due to the crystalline binding of atoms. Although solar cells made from both types of material have demonstrated efficiencies as high as 16 per cent on a laboratory scale the processing of large area modules is still under development due to the high technical requirements of the equipment [9]. The latest trend in the development of low cost solar cells is based on microcrystalline or nanocrystalline silicon - μc-Si or nc-Si - and silicon carbide -μc-SiC, nc-SiC - which can be made with a process technology similar to amorphous silicon. In contrast to conventional polycrstalline silicon which has grains of single crystals with diameters between 0.1 mm to 10 mm microcrystalline silicon consists of grains with diameters from several nanometers up to 1 μm. Since the electronic properties of this material is governed by quantum size effects it appears to be extremely attractive for a new photovoltaic cell design and to match the requirement of a long time stable device. However up to present only fundamental research on the characteristics of the material is reported [10,11].

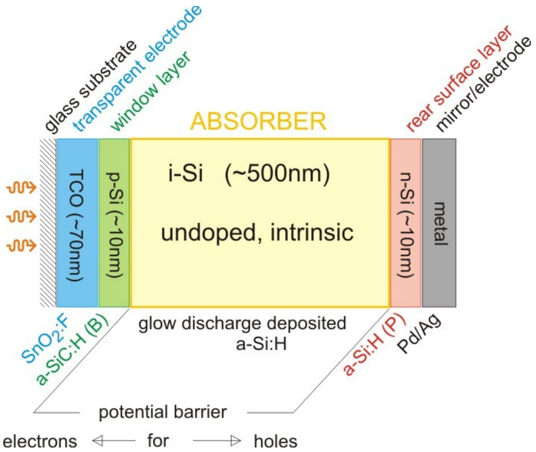

Fig. 4: Cross sectional view of a typical a-Si solar cell. The incident light is coming from the left side. The sequence of deposition of the different layers is from left to right starting with th TCO front side electrode onto the cover glass.

5. Progress in the development of high efficiency solar cells

Despite the less attractive electrical and optical properties of crystalline silicon for the preparation of high efficiency solar cells compared with other kinds of semiconductors a conversion efficiency well above 18 per cent for cells with areas of 50 cm^2 has been repeatedly demonstrated with a cell design called buried contact solar cell - BCSC - [12]. This is mainly due to the well established technology for the production of highly integrated silicon devices which allows a cell design in three dimensions compared to a conventionally processed solar cell which is typically composed by two dimensional layers as shown in Fig.l. The design discussed in reference 12 consists of a textured front surface in order to completely avoid reflection losses, a buried metal grid at the top side of the solar cell which minimizes shadowed areas and a structured back side in order to totally reflect the light which is not absorbed during a single path through the cell. The rear contact is formed in a similar manner like the front contact that means the backside is not fully metallised like it is in a conventional silicon solar cell thus reducing internal current losses caused by surface recombination of light generated carriers at the metal semiconductor interface. An even more complex device layout was recently proposed which shall be capable to process a high performance cell by the use of low-cost, thin-film polycrystalline silicon [13].

New methods for the preparation of thin solid crystals of an almost free selectable composition - Molecular beam epitaxy, MBE, and metallorganic chemical vapor deposition, MOCVD - are widely used for the attempt to make high efficiency solar cells with optimally tailored semiconductor materials. The most promising approach is based on a combination of group III and group V elements - gallium, aluminum, indium and phosphorus or arsenic -. Amultilayer structure as described by K.A. Bertness exhibits an efficiency of 29.5 per cent [14]. Since these type of photovoltaic solar cells are still under laboratory evaluation and the choice of material is still under discusssion no large scale manufacturing line has yet been established. Especially the latter devices are suitable to arrange several solar cells on top of each other in order that light which is transmitted through the top cell can be absorbed by one of the following cells. This approach to increase the conversion efficiency per cell area presently is often used for the evaluation of stacked amorphous solar cells based on compounds of silicon, germanium and carbon. However the processing of so called two terminal tandem solar cells usually is leading to a significant increase of internal current losses thus partly compensating the potential gain in conversion efficiency. Another approach which allows to use any pair of suitable photovoltaic solar cells is the electrically seperated arrangement of the top cell and the bottom cell. Some experience has been made with the combination of an a-Si solar cell as the top device and a CIS cell as the bottom one. dowever there are two major disadvantages. Two types of cells have to be manufactured seperately thus doubling the cell production costs whereas the gain in conversion efficiency is only 30 to 50 per cent and the resulting module has four electric terminals with two individual load characteristics.

6. Conclusions

For the near future most of the commercially available photovoltaic power generators will consist of solar cells either made from crystalline or amorphous silicon with expected module efficiencies of 15 to 16 per cent in the first case and 8 to 9 per cent in the latter. There exist still a great potential in both improving the conversion efficiency and reducing the production costs of silicon solar cell modules. Currently great efforts are made in (i) fundamental research for a basically better understanding of the influence of defects on the solar cell's output which is particularely essential for improving a-Si solar cells (ii) in the development of improved processing and design of solar cells and modules on a laboratory scale and (iii) in incorporating processes into large scale production which have lead to improved solar cell performance in the laboratory and upscaling of equipment for commercial production units.

Solar cells based on new materials which are potentially more attractive than silicon still suffer from the implementation into a large throughput process and from little outdoor experience including environmental and economic aspects. However due to the predicted and partly already demonstrated higher conversion efficiencies they may become important for photovoltaic energy conversion in the future especially when operated under concentrated sunlight conditions.

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