AN INTRODUCTION TO THE TECHNOLOGY OF THIN FILM SILICON PHOTOVOLTAICS

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Key words: thin film silicon, microcrystalline silicon, tandem solar cells

Abstract: Several aspects of the science and technology of thin film silicon for photovoltaic applications will be presented. The potential advantages of this technology over crystalline wafer technology will be discussed. A basic understanding of the material properties of thin film silicon layers enables to assess their potential and limitations when used in photovoltaic devices. A brief review of the production technology for thin films will be given with particular emphasis on amorphous and microcrystalline silicon. As for other photovoltaic technologies, the push for higher efficiency of thin film silicon devices is strong. An appealing feature of these materials is that they can be easily integrated in multi-junction tandem devices. For instance, stacking amorphous and microcrystalline silicon thin films in one tandem cell, the micromorph cell, increases the efficiency well above the characteristic values of single junction cells. The Institute of Microengineering (IMT) has been a pioneer in the research and development of thin film silicon photovoltaics over the last 20 years and several latest developments on are reviewed.

Uvod v tehnologijo tankoplastne silicijeve fotovoltaike

Kjučne besede: tankoplastni silicij, mikrokistalni silicij, tandemske sončne celice

Izvleček: Predstavljeni so številni vidiki znanosti in tehnologije uporabe tankoplastne silicijeve fotovoltaike. Razločene bodo potencialne prednosti omenjene tehnologije glede na kristalno silicijevo tehnologijo. Osnovno razumevanje lastnosti materiala plasti tankoplastnega silicija omogoča podati oceno prednosti in ovir pri uporabi v fotovoltaiki. Podan je kratek pregled tankoplastnih tehnologij s povdarkom na amorfnem in mikrokristalnem siliciju. Kot pri drugih tehnologijah, je tudi tukaj prisotna težnja k povečanju izkoristka sončnih celic. Izstopajoča lastnost teh materialov je njihova enostavna možnost integracije v večspojne strukture. Združevanje amorfnih in mikrokristalnih plasti v tandemsko mikromorfno sončno celic, na primer, povečuje izkoristek precej nad vrednosti enospojnih sončnih celic. predstavljeni so številni razvojni dosežki inštituta IMT (Institute of Microengineering), ki je pionir na področju raziskav in razvoja tankoplastne silicijeve fotovoltaike v zadnjih 20 letih.

1 Introduction

Thin film silicon photovoltaics is one of the emerging technologies to produce electricity from sunlight. Semiconductors like amorphous silicon (a-Si:H) and microcrystalline silicon (μc-Si:H) form the backbone of this technology. The use of a-Si:H as a photovoltaic material can be traced back to publications in the 1970s /1/, whereas microcrystalline silicon solar cells were first made in the mid 1990s at IMT /2/. Since then, this technology has attracted increasing interest in the academic and industrial environment. Despite lower efficiencies than wafer based crystalline photovoltaics, a particularly attractive feature of this technology is the versatility of the deposition techniques. Materials with different optical band gaps are synthesized by changing the silicon phase and by forming compounds with other elements like carbon or germanium /3/. Materials with different optical band gaps can be easily combined to form multiple stacks that exploit a larger part of the solar spectrum increasing the efficiency of the photovoltaic device /4/.

2 Deposition techniques

Crystalline and wafer based photovoltaic technology represents today the biggest market share. This technology uses a top-down approach to prepare solar cells: wafers are obtained by sawing silicon ingots drawn from melted silicon in crucibles. These wafers are processed in multiple steps to obtain solar cells successively assembled in modules. The technology used in thin film silicon is at the opposite. Solar cells are obtained in the so called bottom-up approach: atoms of silicon are stacked one on top of the other on a suitable substrate to form all the layers of a solar cell. Other technologies use this approach as well /5/, however there is a distinctive advantage in doing so in thin film silicon technology. The production technology used to deposit single solar cells is scalable to large surfaces and therefore modules can be prepared on large areas (> 1 m^2) without the need to assemble individual cells. In the following we will briefly describe the two main techniques used at IMT to prepare full solar cells, both scalable to large surfaces and presently employed for industrial production. Additional attractive features of this technology are extremely low material consumptions compared to wafer based technologies and low temperature processing steps (typically below 300°C) in contrast to wafer based technology where processes close to 1000°C are used. This last aspect opens up the possibility to use cheap substrates in thin film silicon technology.

2.1 Low pressure chemical vapor deposition

One of the characteristic components in the design of thin film solar cells are transparent conductive oxide (TCO) layers that have principally three functions: 1-to contact electrically the solar cell; 2- to be transparent to the sunlight; 3- to scatter the incoming sunlight. In the next section of this paper it will be explained how these requirements are intimately related to the material properties of the amorphous and microcrystalline silicon layers. Different techniques are available to deposit these layers. At IMT a modified low pressure chemical vapor deposition (LP-CVD) technique has been developed that allows growing TCO layers with excellent optical and electrical properties that satisfy the three requirements above /6/. Molecular precursors in gaseous form like water vapor, diethylzinc and the dopant diborane are injected at low pressure (< 1mbar) in a chamber and thermodynamically dissociate in the vicinity of a hot plate where substrates are heated up to temperatures between 100°C and 200°C. Depending on the process parameters, different growth modes can be obtained /6/. After optimization of the deposition process layers as shown in Fig. 1 are obtained. They display a characteristic surface roughness due to the presence of pyramidally shaped single ZnO crystals. The rough surface that spontaneously develops during the growth acts as a diffuser for the incoming light /7/. ZnO has excellent transparency in the wavelength range between 400nm and 1000 nm, that is to say in the same range where silicon absorbs light.

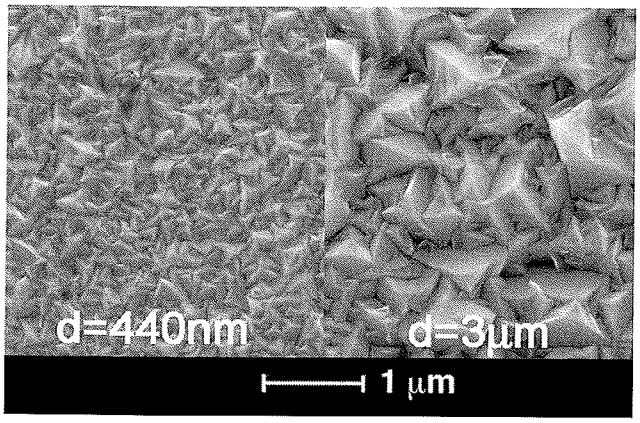

Fig. 1: SEM picture of typical ZnO samples with different thicknesses deposited by LP-CVD technique.

An interesting feature of ZnO deposited by LP-CVD is that by varying process and layer properties different electrical and optical properties can be obtained /8/ and the impact on solar cell performance studied.

2.2 Plasma enhanced chemical vapor deposition

For the deposition of silicon containing layers CVD alone cannot be used, because the dissociation rate of typical precursor gases like silane and hydrogen molecules is extremely low at typical process temperatures around 200°C. Therefore, dissociation has to be provided by another energy source than the hot plate. Electrons oscillating in an electromagnetic field driven at frequencies in the range between 13.56 MHz (RF) and typically 100 MHz can provide the necessary energy to dissociate the gas molecules by electron impact dissociation. In stable discharge conditions a plasma containing electrons and positive ions is obtained and the deposition technique is called plasma enhanced chemical vapor deposition (PE-CVD) /9/. Growth rates between a few Ångströms and a few nanometers per second can be obtained by varying the process parameters and reactor configurations. IMT has been a pioneer in studying the physical and chemical properties of plasmas driven at frequencies higher than 13.56 MHz /10-12/, the so called VHF domain /13-15/. It was shown that in VHF conditions higher deposition rates and smaller ion bombardment energies could be obtained, leading to more favorable conditions for the deposition of silicon layers.

3 Silicon material properties

A quite remarkable feature by of PE-CVD processes is that by varying deposition conditions, typically silane concentration in hydrogen or RF-VHF input power, a transition between the amorphous and microcrystalline phase of silicon can be observed /16/. Therefore, two different phases of this material can be easily deposited using the same technology. In the following of this section we will briefly review a few basic properties of a-Si:H and µc-Si:H.

3.1 Optical properties

The optical absorption spectrum of of a-Si:H and µc-Si:H are displayed in Fig. 2. The two materials are characterized by quite distinct optical band gaps: amorphous silicon has a band gap around 1.7 eV, whereas microcrystalline silicon has a band gap around 1.1 eV. As a result microcrystalline silicon absorbs light in a spectral range where amorphous silicon is already transparent to sunlight. To effectively absorb the sunlight the layer thickness should roughly equal the penetration depth. For amorphous silicon this would mean layer thicknesses of up to 10 µm and for microcrystalline silicon up to 1 mm. With deposition rates of a few Ångströms or even nanometers per second, these thicknesses are prohibitively large. From this simple analysis of the absorption spectrum the need to increase the light path in silicon while keeping an acceptable film thickness emerges as a priority in thin film silicon technology. The light path can effectively be increased in thin layers by scattering processes at rough interfaces that devi-

ate the light path from normal incidence into oblique directions.

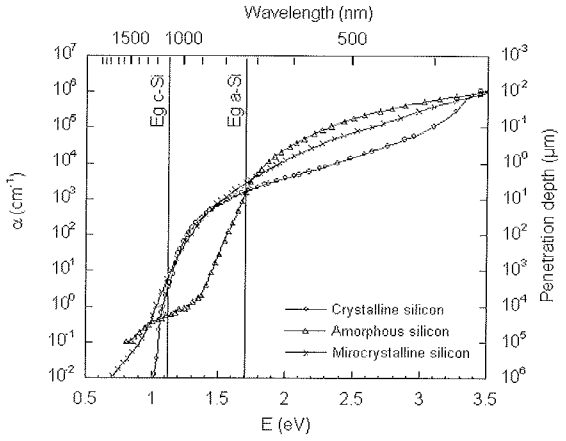

Fig. 2: Absorption spectrum of amorphous and microcrystalline silicon.

The usefulness of rough LP-CVD ZnO and the importance to study light trapping in thin films becomes thus apparent.

3.2 Electronic properties

Amorphous and microcrystalline silicon are primarily characterized by disorder in the atomic lattice /17-18/. As a result, defects play an important role in the electronic and transport properties of these materials. They drastically reduce the carrier diffusion lengths compared to their crystalline (i.e. highly ordered) counterpart by several orders of magnitude. Thin layers and transparent electrodes covering the whole cell surface are therefore needed to efficiently extract the carriers in these materials. In addition, amorphous silicon knowingly suffers from light-induced or Staebler-Wronsky degradation /19/. This process, which is reversible, increases the defect density in amorphous silicon when illuminated and critically depends on the thickness of the layer. Finally, doping n or p type thin film silicon layers further reduces the diffusion length to a few nanometers only.

4 Solar cells

The design of thin film silicon solar cells is basically determined by the electronic properties of amorphous and microcrystalline layers. Since doping drastically reduces diffusion length, doped layers are not photoactive. Therefore their role is to create an electric field in the photoactive intrinsic layer sandwiched between the two doped layers.

4.1 Substrate and superstrate configurations

Depending whether the substrate being used for silicon deposition is transparent or not, two different sequences of layer stacking are used in thin film silicon technology. Fig. 3 shows the two possible configurations. In the first one, called superstrate configuration, the substrate is glass. In the second one, called substrate configuration, the substrate is opaque like a plastic or metal and if the sheet is thin enough, flexible solar cell modules can be obtained.

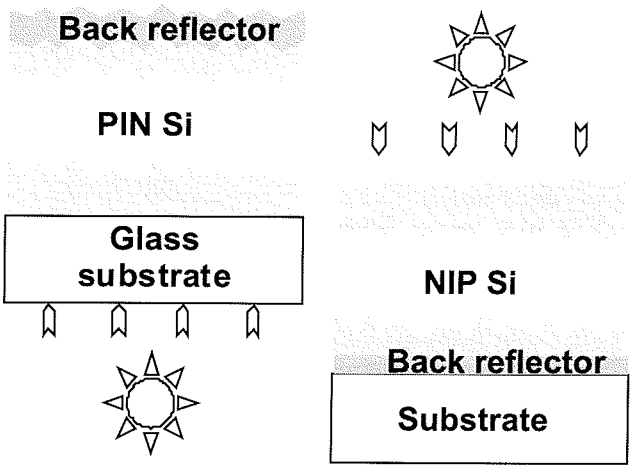

Fig. 3: Sketches of thin film silicon cells in superstrate (left) and substrate (right) configurations.

4.2 Single junction cells

Single junction amorphous and microcrystalline solar cells have been extensively investigated at IMT and high efficiencies of 9.5% after light soaking have been obtained for amorphous single junction cells grown on LP-CVD ZnO /20/.

The growth of μc-Si:H on LP-CVD ZnO has been extensively studied as well. It has been shown that in order to obtain cell efficiencies close to 10%, it was necessary to modify the ZnO surface morphology in order to obtain high open circuit voltages and fill factors. Thus, high efficiencies of 9.9% have been reported at IMT /21/. Plasma process studies have been conducted as well in order to understand the growth of μc-Si:H. Fig. 4 shows the efficiency of microcrystalline single junction solar cells deposited in a large area R&D PE-CVD system at IMT under different process conditions /22/. As can be seen, efficiencies are very sensitive to pressure. It was shown that the improvement in film quality and solar cell efficiency can be related to lower ion energies hitting the growth surface. However, pressure and ion energies are not the only important parameters determining the solar cell efficiencies. Cells deposited at 1.2 mbar, but under high silane depletion conditions show a remarkable improvement as well. Plasma chemistry is likely to be involved in this case, although the exact mechanism remains unclear.

In Fig. 4 some of the cells display deposition rates close to 1 nm/s. These cells have been obtained in plasma conditions where silane depletion is very high and they form the basis process for the development of high rate deposition processes for microcrystalline cells /23/.

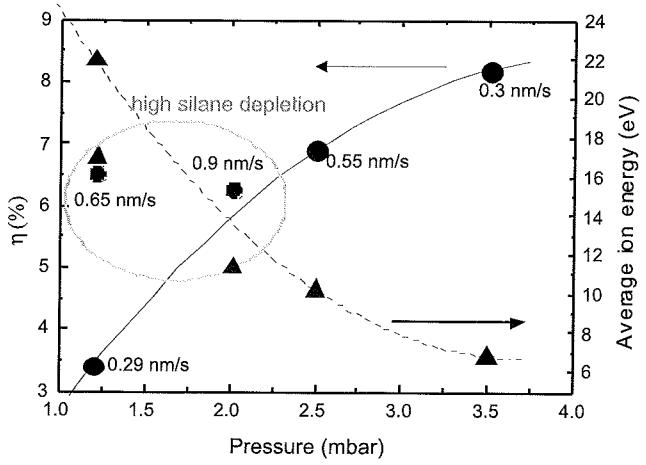

Fig. 4: Efficiency vs pressure of microcrystalline silicon single junction solar cells obtained at IMT.

4.3 Micromorph tandem cells

As mentioned in the introduction, stacking different materials is easily realized in thin film silicon technology because combining materials with different optical band gaps allows exploiting a larger part of the solar spectrum. In particular combining amorphous and microcrystalline silicon thin films in a serially connected tandem cell has first been proposed at IMT in the mid 1990s /4/. Since then, an increasing number of research institutes and companies have adopted this concept.

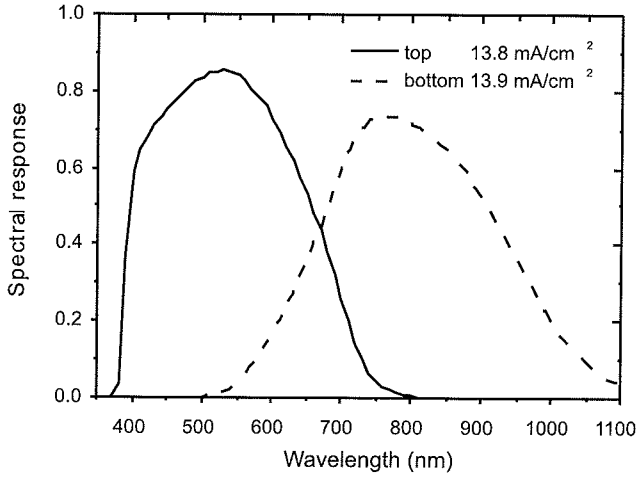

Fig. 5: Spectral response of a 13.3% initial efficiency micromorph tandem cell obtained at IMT.

In Fig. 5 the spectral response of 13.3% efficient micromorph tandem cell is presented. Such high efficiencies and current densities can be obtained only by carefully designing the light trapping in the device. In particular, a high current in the top, or amorphous, cell while keeping the thickness below 300 nm is highly desirable in order to reduce Stabler-Wronski degradation of the amorphous material. This can only be achieved by inserting between the two active layers an intermediate layer that selectively reflects and transmits light in the appropriate wavelength range. Different material options are available for the intermediate layer. At IMT silicon oxide based intermediate reflectors have been investigated for this purpose and current gains around 20% have been observed in the top cell /24/. Additionally, it has been observed that the texture of the front TCO influences the current gain as well /25/.

In substrate configuration the surface roughness of LP-CVD ZnO can be used easily as an intermediate reflector /26/. The device scheme with an AIR is presented in Fig. 6. The μc-Si:H is deposited on hot silver substrate which has morphology with large feature size (about 1 μm) for efficient light scattering for wavelengths between 750 nm and 1100 nm. The shape of the morphology has a moderate roughness in order to provide ideal condition for the growth of μc-Si:H material. The AIR is composed of 1.5 μm of LP-CVD ZnO deposited on the bottom cell. As shown in Fig. 6, it restores a feature size of about 300 nm and morphology needed for the a-Si:H top cell. Therefore, the blue-green light (500 nm - 750 nm) is back scattered at the AIR interface. The light is then trapped between the AIR and the top front contact in the a-Si:H top cell.

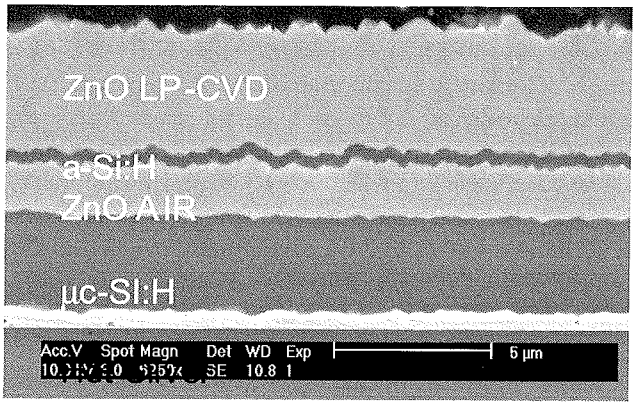

Fig. 6: SEM micrograph of a nip/nip micromorph tandem cell cross-section with a ZnO asymmetric intermediate reflector (AIR) obtained at IMT.

Fig. 7 shows the EQE of our device with thin 1.5 μm μc-Si:H cells. The initial and stabilized electrical parameters of cells without IR and with AIR are also compared. It shows that with the AIR, the top cell can be made as thin as 140 nm and still generates 11.4 mA/cm^2. In tandem cells, the degradation is reduced to 8 % with the AIR compared to 18 % without IR but thicker 300 nm top cell.

4.4 High rate deposition of bottom cell

The absorption coefficient of microcrystalline silicon extends well into the near infrared region compared to amorphous silicon. However, thick layers in the order of several microns are nevertheless necessary in order to achieve high current densities.

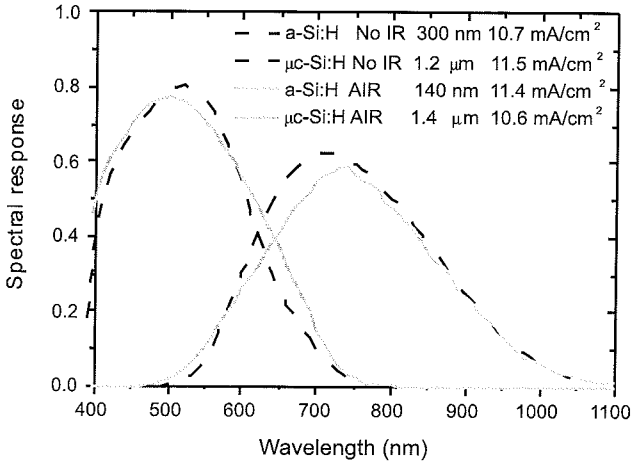

Fig. 7: Initial spectral response of nip/nip micromorph tandem solar cells without IR (300 nm a-Si:H, 1.2 μm μc-Si:H) and with AIR (140 nm a-Si:H, 1.4 μm μc-Si:H) deposited on hot silver coated glass.

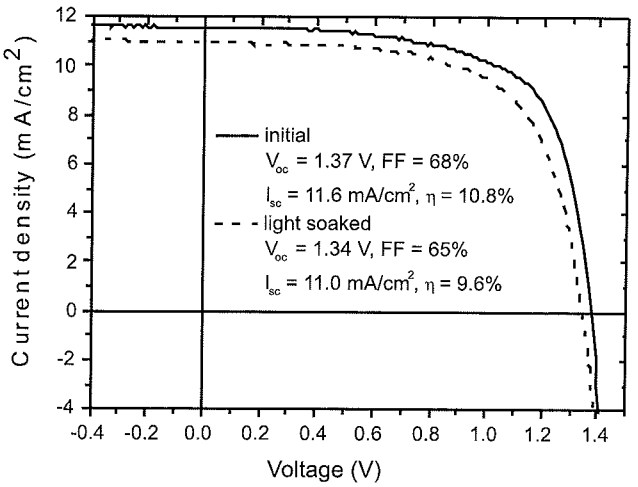

Fig. 8: Current-voltage curve of a micromorph tandem cell in its initial and stabilized state. The bottom cell has been deposited at 1 nm/s.

Therefore, fast deposition of microcrystalline silicon is desirable. In Fig. 8 the current-voltage curves of initial and stable (after 1000 hours light soaking) efficiencies of a micromorph solar cell with the bottom (or microcrystalline) cell deposited at 1 nm/s is shown. In this case the thickness of the top cell is only 230 nm, which limits the light induced degradation to about 12% to a stabilized value of 9.6%. Further improvements in the process conditions of the bottom cell will be necessary in order to lift this efficiency value above the 10% mark.

3 Conclusions

A short review of the main features and challenges in the technology of thin film silicon photovoltaics has been presented. This technology certainly offers great potential in terms of scalability to large surfaces and versatility of the deposition techniques. In addition, materials with different optical band gaps are easily combined in multi-junction structures that can significantly lift the efficiencies above the level of single junction solar cells. In order to achieve high efficiencies it is necessary to properly design all the layers of the stack. The design has to optimize optical and light scattering properties of TCOs and electrical properties of the materials by tailoring PE-CVD conditions, reducing defect densities in intrinsic materials and minimizing absorption in doped layers.

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