PROGRESS IN UP-SCALING OF THIN FILM SILICON SOLAR CELLS BY LARGE-AREA PECVD KAI SYSTEMS

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ABSTRACT

UNAXIS KAI PECVD reactors developed for AM LCD technology have been demonstrated to possess a high potential for thin film silicon solar cells based on amorphous and microcrystalline silicon. For the next generation of thin film modules with highly effective light-trapping LP-CVD ZnO large-area deposition is developed at Unaxis as well, in combination with a very simple but effective back reflector concept. A first prototype module of 0.447 m\(^2\) active area with 7.1 % initial efficiency has been achieved for amorphous silicon. Micromorph mini-modules were prepared with 9.3 % initial aperture efficiency. All important module fabrication steps are under development at Unaxis for a complete line concept.

INTRODUCTION

Large area thin film silicon technology: In order to bring thin film solar cells to market, synergies with other types of mass production technologies have to be considered. In case of amorphous silicon based solar cells a high synergy exists to the flat panel displays. In this industry segment the development of large high-throughput deposition systems for the fabrication of flat panel screens based on the amorphous silicon thin film transistor (TFT) is driven by the market. Due to the coming market of flat panel TV screens larger mother glasses are required and, therefore, large production equipments.

The comparison of both markets is interesting; Today's worldwide produced thin film PV modules and even the total volume of all types of solar cells represent only a fraction of the yearly fabricated display area volume [1]. In consequence production equipment of the flat panel industry is more developed than that of thin film solar cells, and, hence, should be used as driving force for the development of new thin film silicon solar cell production tool equipment. Therefore, the compatibility of UNAXIS KAI PECVD systems for thin film solar cells combined with demonstrated performance of efficient high volume, high yield manufacturing can potentially bridge the gap of up-scaling of laboratory research results to large-area mass products of high performance.

Unaxis displays is a major manufacturer of production equipment for the deposition of amorphous silicon TFT's on glass for flat panel displays. To react on the fast growing display market over the last ten years, different generations of large-area KAI production equipment have been developed. These KAI manufacturing systems as schematically shown in Fig. 1 are well approved in display production, they run 24h a day, 360 days a year at a high uptime.

Unaxis has investigated the potential of the KAI PECVD reactors for the thin film silicon solar cell concepts as developed at IMT Neuchâtel. In 2003 Unaxis decided to enter into the field of solar, in order to develop and adapt the present KAI PECVD technology for the fabrication of thin film silicon solar cells. Hereby, end of 2003 a R&D laboratory was implemented in Neuchâtel, whereas in Trübbach large-area developments have started. The goal of our business is not to produce thin film solar modules, our intention is to build manufacturing equipment for the thin film silicon PV industry. Highly automated KAI production systems developed for display technology once adapted for solar will have a significant impact on the cost reduction of PV modules.
EXPERIMENTAL

PECVD KAI reactor: The heart of the KAI system is the plasma box® PECVD reactor [2]. The plasma box® combines isothermal heating in the reactor with differential pumping, which minimizes process contamination and makes it fully compatible with fluorine-based self-cleaning processes, a necessity for high yield, low maintenance manufacturing. In order to improve the deposition rate we adapted our reactors to an excitation frequency of 40.68 MHz. Our developments run in three R&D reactors, one in a KAI-1200 (substrate size 1250x1100 mm), one in a KAI-S (350x450 mm) and one in a KAI-M (520x410 mm). Homogeneous depositions can be achieved in all systems.

Modified LP-CVD ZnO process: In order to render the full efficiency potential of thin film silicon solar cells management of light is fundamental. It has been shown by the work of IMT that low-pressure chemical vapor deposition (LP-CVD) of ZnO has excellent light-trapping properties in amorphous and microcrystalline silicon solar cells [3-5]. IMT has developed a “modified LP-CVD process” for the fabrication of ZnO. We, at Unaxis, have already achieved ZnO layers with good homogeneity (haze) and conductivity over 1.4 m². Further results to film properties and up scaling will be presented at the 20th EPVSE conference in Barcelona (June 2005).

Light management has to be optimized on both sides of the thin film silicon cell absorber, i.e. on the front and on the back. Whereas in laboratory research most groups apply for highly reflective silver back contacts, mass production of a-Si:H based modules uses aluminum reflectors [6, 7]. Reasons for that are reduced costs and better properties of aluminum in removing shunts. Thanks to the simple, “cheap” and low temperature ZnO LP-CVD process one can apply ZnO as well as back contact. Hereby, the back ZnO is chosen in the way that it acts additionally fully as electrical contact. The reflective properties of a standard metallic Ag or Al reflector are substituted by a high reflective and resistive dielectric, e.g. a white paint. This concept is shown in Fig. 2, and has been applied on our different types of cells and on all our modules. In case of amorphous silicon solar cells the former Siemens group has applied a similar alternative, more than 10 years ago [8].

Fig. 2: Concept of the white back reflector in combination with LP-CVD ZnO as back contact in comparison with conventional ZnO/Ag or Al or ITO/Ag or Al contacts.

Laser-scribing: One of the main advantages of thin film solar technology is the concept of monolithic series interconnection of the cell segments to large area modules by laser scribing. Unaxis has developed laser patterning on substrate areas of up to 1250x1100 mm [1]. In order reduce the dead area scribe losses special attention was given to a high positioning accuracy of all three scribes and throughput. Modules of different type and dimension have been fabricated at high scribe speeds.

RESULTS AND DISCUSSION

White back reflector concept

Our back reflectors have been optically characterized and compared with conventional contacts used in amorphous silicon cells. There is a significant difference in the reflectance properties of the white reflector and sputtered ITO/Al(or Ag) or ZnO/Al(or Ag) contacts. Considering the diffused part of the reflectance LP-CVD ZnO/white paint reflectors show a much higher diffuse contribution than flat conventional back contacts. Fig. 4 shows the fundamental difference of the diffuse reflectance of the different reflectors in function of the wavelength. Each reflector was deposited on an AF45 Schott glass and characterized by the UV/Vis spectrometer from the glass side. The sputtered ITO/Al or ZnO/Ag contacts are developed for amorphous silicon solar cells, e.g. the thickness of the sputtered ITO or ZnO is about 80 nm.

The different reflector properties were analyzed by the quantum efficiencies (QE) measurements of an a-Si:H p-i-n solar cell (0.3 μm) deposited on AFG SnO₂ coated glass substrates. The impact is given in Fig. 5, where, in agreement to the reflectance measurements the white reflector leads to a considerable improved light-trapping in the longer wavelength region.

An additional advantage of this concept in mass production lays in the reduced sensitivity to shunts within the cell segments of the module as ZnO has a lower specific conductivity than metallic films. Due to the simplicity of this white reflector combined with the modified LP-CVD ZnO technology and the stated advantages of this solution we consider this reflector concept very attractive for all next generations of thin film silicon modules. Moreover, from the view of manufacturing and investment costs the white reflector is certainly a very attractive option.
Fig. 4: Diffuse reflectance of a white reflector in comparison with standard sputtered ZnO or ITO / metallic contacts deposited on AF 45 Schott glass.

Fig. 5: Relative QE’s of an a-Si:H single-junction cell with different back reflectors applied. Note, the concept of the ZnO / white paint reflector leads to a remarkable improvement of the photocurrent compared to industrially applied aluminum back reflectors or even silver contacts.

Microcrystalline silicon growth in KAI reactors

Microcrystalline silicon growth is investigated in all our three KAI systems. Whereas the main focus in the KAI-M was the improvement of the device performance, in the KAI-S the possibility of high rate growth and in the KAI-1200 first large-area tests. The microcrystalline films were characterized by Raman spectroscopy (514 nm). Fig. 6 reflects the sofar-achieved results in our KAI-S reactor: Homogeneous and high crystallinity of μc-Si:H over the substrate area could be observed at a high rate of over 14 A/sec. The feasibility of a homogenous μc-Si:H deposition at such a high rate in KAI reactors is an important result.

The result of the microcrystalline growth in the large-area KAI-1200 (110x125 cm2 substrate area) is represented by the Raman spectra of Fig. 7. We observe as in case of KAI-S a quite homogeneous deposition of μc-Si:H even at the transition zone to amorphous silicon. It has to be noted that just close to this transition region best microcrystalline cells are deposited and additionally just in this region small deposition parameter changes provoke strong variations in material properties. Further studies will be done with respect to rate and device performance.

Fig. 6: Microcrystalline Si growth by Raman (514 nm) within the substrate area (center to edge). The film has a thickness in the center of 0.96 μm.

Fig. 7: Raman study (λ = 514 nm) of microcrystalline silicon growth in a KAI-1200 reactor. Homogeneous deposition rates of around 2 A/sec could be obtained at the transition border to amorphous silicon.

Cells and modules

Amorphous silicon single-junction p-i-n test cells have been successfully transferred in the KAI-reactors. Further details can be found in references [9, 10, 1]. In the KAI-M reactor initial cell efficiencies of around 10 % could be achieved for both type of front TCO’s (LPCVD ZnO and Asahi SnO2) for a cell thickness of 0.3 μm [10]. In the 1.4 m2 large-area reactor high FF in the range of 70 to 72 % could be obtained at a deposition rate of around 3 A/sec. In the past microcrystalline silicon single-junction and micromorph tandem test cells have been prepared in our KAI-M reactor leading to efficiencies of above 9 % in case of the tandems [1].

Modules have been fabricated by laser-scribing system at Unaxis on different substrates and cell type structures. The appearance of amorphous p-i-n junctions with different front TCO are given in Fig. 8. Compared to commercially available AFG front TCO (right hand side) the LP-CVD ZnO front TCO (left side) leads to a more attractive darker and more homogeneous appearance of amorphous Si modules thanks to the improved light-trapping.

Figure 9 shows the I-V characteristics of an amorphous single-junction module deposited on AFG front TCO and fully fabricated at Unaxis.

In case of micromorph tandem modules first results of 10-segmented mini modules (63 cm2) are shown in Fig. 10. The performance is improved to initial aperture efficiency 9.3 %. We are confident that further
optimization with respect to higher values of $V_{oc}$ and $J_{sc}$ of both component cells and the interfaces will soon lead to stable module efficiencies of 10%.

Fig. 8: Amorphous silicon modules prepared at Unaxis: On the right hand a 1250x1100 mm KAI 1200 module on SnO$_2$ (AFG), on the left a 900x 550 mm module based on LPCVD grown ZnO as front TCO. Note the dark appearance of ZnO due to better light-trapping [3].

Fig. 9: First large-area a-Si:H module fully fabricated at Unaxis (under outdoor conditions). AFG SnO$_2$ substrates were used, the series interconnection by laser scribing has a width and quality as shown in Fig. 3.

Fig. 10: I-V characteristics under AM1.5 of a micromorph tandem mini-module prepared on Asahi SnO$_2$ substrate.

CONCLUSIONS

The KAI single-chamber reactors could demonstrate already high performance cells and reasonable modules. The high productivity of UNAXIS KAI PECVD machines has the strength to minimize cost and risk of a thin film production line. In order to improve light-trapping the concept of LP-CVD ZnO as conductive back contact in combination with a white resistive back reflector has been successfully applied on all our modules. Unaxis proves to manage all process steps for industrial solar module fabrication. This includes glass cleaning, coating of front TCO, thin film Si, back TCO coating and laser-scribing for monolithic series connection.

A very critical aspect will be the process yield because of its big impact on direct cost. Moreover, high yield is important from a logistical point of view in production planning. In AM-LCD yield levels of above 95% are commonly reached and the remaining yield loss is mainly due to process particles, causing defects of individual TFT’s. The impact of this type of yield loss will be far less severe in thin film silicon solar cell production and it can be assumed that yield levels of above 95% are attainable for the PECVD deposition alone using the KAI production technology.

Material cost estimation for the thin film device (TCO, Si absorber and back contact) alone is promisingly low. They amount to roughly 1/3 €/W$_p$ and can be reduced further with process optimizations and increased production volumes. Larger production volumes combined with larger module sizes and cell efficiency optimizations will allow additional cost reductions.

As soon as high module performance at high throughput is demonstrated on a production level as well, Unaxis KAI PECVD systems will have a pronounced impact on cost reduction of future PV modules. In conclusion, direct manufacturing costs of complete modules including encapsulation etc. of close to 1 €/W$_p$ should be achievable using KAI production systems in near future. Therefore, thin film silicon technology can pave the path to economical large-scale application of PV.

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