Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Département fédéral de l'environnement,
des transports, de l'énergie et de la communication DETEC

Office fédéral de l'énergie OFEN

THIN FILM SILICON SOLAR CELLS: ADVANCED PROCESSING AND CHARACTERIZATION

Final report

Prepared by

Christophe Ballif, IMT, PV-Lab, Université de Neuchâtel
Rue A.L. Breguet 2, 2000 Neuchâtel
ballif@unine.ch, www.unine.ch

Impressum

Date : 23. avril 2008

Sur mandat de l’Office fédéral de l’énergie, programme de recherche photovoltaïque

Mühlestrasse 4, CH - 3063 Ittigen

Adresse postale : CH - 3003 Berne

tél. +41 31 322 56 11, fax +41 31 323 25 00

www.bfe.admin.ch

Responsable du domaine à l’OFEN: Monsieur Stefan Oberholzer, stefan.oberholzer@bfe.admin.ch

Numéro OFEN du projet : 101191 / 151399

Source d’acquisition de cette publication : www.recherche-energetique.ch

Contents

Résumé complet (Français)

Ce projet s'inscrit dans le contexte général d'une recherche de pointe dans le secteur de la fabrication des cellules solaires en couches minces de silicium. Le laboratoire de photovoltaïque de l'IMT (Université de Neuchâtel) détient plusieurs connaissances clé dans un domaine qui a également connu un essor industriel impressionnant ces 3 dernières années. En effet, alors qu'en janvier 2005, au début du projet, la plupart des compagnies vendaient des modules à base de silicium cristallin, plus de 40 compagnies ont annoncé ces trois dernières années qu'elles allaient commencer la production de modules en couches minces de silicium. Ces modules ont l'avantage de la faible utilisation de matière première rare (comme du Si purifié), du bas temps de retour en énergie (~ 1-1.5 ans en Suisse), de la longues durée de vie (> 25 ans). Cette industrialisation dynamique est rendue possible par la venue sur le marché d'équipementiers « high-tech », qui proposent pour la première fois des équipements de production adaptés aux besoins exigeants des couches minces de silicium. Finalement, les capacités de production mondiale pourraient atteindre 4 GW en 2011.

La position de la Suisse est particulière dans ce contexte, puisqu'elle a fortement contribué à dynamiser ce domaines du silicium en couches minces, grâce aux travaux de l'IMT et au soutien continu de l'OFEN. Ainsi l'entreprise VHF technologies a annoncé récemment la création d'une ligne de production de 25 MW de modules flexibles à Yverdon, alors que OC Oerlikon a été la première compagnie à vendre « clé » en main des lignes de production pour modules sur verres à de nombreuses compagnies à travers le monde entier, en utilisant son savoir faire dans les équipements pour la fabrication des écrans plats et en adoptant les procédés mis au points de l'IMT. De fait, il est maintenant probable que, en plus d'une contribution importante au dynamisme économique de la Suisse de par l'industrie « clean-tech » générée, les modules en couches minces sortant de ces différentes usines produiront à terme plusieurs TWh annuels.

Toutes les entreprises actives dans le silicium en couche mince commercialisent des produits basés sur une première génération de concepts et de procédés. Le rôle d'une recherche de pointe reste vital pour que ce secteur puisse s'épanouir sur le long terme, aussi bien face au silicium cristallin et autres technologies concurrentes (CdTe, CIGS), que face aux sources plus conventionnelles d'électricité. Les défis sont toujours les mêmes : il s'agit de fabriquer des dispositifs plus efficaces, plus fiables, de manière moins onéreuse,…. Cela pose de formidable défi car les dispositifs en couches minces sont complexes : dans les cellules micromorphes de l'IMT, il y a près de 12 couches différentes. La chimie et la morphologie d'une couche (= la forme de sa surface) peuvent influencer la couche suivante, et chaque couche peut être fait d'une multitude de manière différente (e.g. en variant les paramètres des procédés plasma), voire même avec des matériaux différents …

Dans ce cadre, les **objectifs principaux** du projet faisant l'objet de ce rapport étaient les suivants :

- **Démontrer la préparation de cellules solaires en couches minces de silicium avec des rendements améliorés** avec comme objectif final des cellules micromorphes à haut rendement. Pour cela il est nécessaire de travailler aussi bien sur les cellules amorphes (absorbant le bleu-vert) et les cellules microcristalline (absorbant le rouge), que sur toutes les couches constituant la cellule. L'accent devait être mis sur les cellules microcristallines et micromorphes fabriquées directement sur un verre recouvert d'oxyde transparent conducteur préparé à l'IMT (LPCVD-ZnO). Pour les cellules sur plastique, l'objectif était la réalisation de dispositifs flexibles à haut rendement, avec un accent sur les cellules amorphes et microcristallines et des procédés compatibles avec un industrialisation.
- **Explorer de nouvelles voies pour fabriquer de manière plus simples les cellules**, ou les fabriquer avec un meilleur rendement. Cela incluait entre autre l'amélioration et l'introduction de nouveaux matériaux dans certains types de cellules.
- En parallèle et en complément, **améliorer les techniques de caractérisation, les procédés de fabrication et les équipement de dépôt**. Un effort devait être fait pour améliorer globalement toute l'infrastructure, c'est-à-dire adapter ou renouveler une partie des équipements de fabrication, et de caractérisation. Au travers de ces aménagements, le but était de mettre en place une infrastructure qui permettent d'augmenter l'efficacité des projets de recherche à l'IMT et de soutenir les partenaires industriels de l'IMT dans des projets plus orientés vers l'application à court-terme (2-5 ans).

Globalement, tous les objectifs principaux du projet ont été atteints. Comparés aux résultats obtenus avant le début du projet, le rendement de pratiquement tous les dispositifs a pu être amélioré de manière significative, aussi bien pour les technologies de dépôt sur plaque de verre, que pour la fabrication sur feuille de plastique flexible (comme du PET ou du PEN). Pour tous les procédés, la reproductibilité a pu être améliorée et l'interaction entre les différentes couches constituant les dispositifs est maintenant beaucoup mieux comprise.

Au niveau des cellules les **résultats suivant ont été obtenus** :

- Sur support en verre, des cellules **microcristallines avec 9.9% de rendement** (contre ~8% au début du projet) on pu être fabriquées sur une nouvelle électrode transparente conductrice améliorée à base de **ZnO-LPCVD**. Ces résultats sont similaires aux meilleurs résultats reportés par d'autres groupes de recherche mais qui travaillent sur des électrodes transparentes différentes.

- Toujours sur verre, **un rendement initial de 12.6% pour des cellules micromorphes** déposées sur une électrode transparent à base de ZnO-LPCVD a été atteint. Ces dispositifs ont un rendement après dégradation de l'ordre de 11.1%. Dans plusieurs configurations de dispositifs différentes (électrodes avec des caractéristiques différentes, autres choix de couches) des rendements initiaux supérieurs à 12% ont été obtenus. Comme aucun revêtement antireflet n'a été utilisé et comme il y a encore un potentiel d'optimisation, il semble maintenant possible de dépasser la barre des 12% stable en configuration micromorphe (reccord officiel à 11.7% par Kankeka sur un autre type d'électrode).

- **Sur les feuilles de plastiques « nanotexturées »**, il a pour la première fois été possible de fabriquer des cellules microcristallines qui dépassaient les 7.5% de rendement, puisque des dispositifs ne présentant aucune dégradation à la lumière avec un rendement **de 8.6% ont été réalisés**. Cela ouvre la voie à l'obtention de cellules micromophes à hauts rendement sur plastique qui seront réalisées dans le cadre d'autres projets.

Ces résultats ont été obtenus grâce à l'amélioration de plusieurs procédés, à l'introduction de nouveaux matériaux dans les cellules et par une meilleure compréhension des mécanismes de croissance des couches :

- Des études de la microstructure des cellules par microscopie électronique on permet de montrer que la forme de la surface initiale pouvait fortement influencer les propriétés électriques des cellules déposées ultérieurement. **Grâce à un nouveau procédé de traitment de surface par plasma**, qui a été breveté, il a été possible de modifier la surface des électrodes transparentes de ZnO et d'obtenir de meilleures dispositifs, sans « micro-fissures » et autres zones défectueuses.

- Un nouveau matériau, **basé sur un oxyde de silicium dopé a pu être fabriqué et incorporé comme « réflecteur intermédiaire »** dans les cellules micromorphes sur verre et plastique. Ce matériau, fabriqué dans la même chambre que les cellules solaires, est inséré entre les cellules amorphes et microcristallines. Il permet de renforcer le courant dans la cellule amorphe par effet optique et d'équilibrer les courants entre les deux cellules qui sont connectées en série. Ce SiOx dopé a été utilisé pour les cellules à haut rendement.

- Une étude systématique des propriétés optique et électriques des couches minces de ZnO-LPCVD utilisées pour l'électrode transparent a permis d'élucider le rôle jouer par les joints de grains (couches polycristalline) et d**'aboutir à la fabrication de couches présentant une très faible absorption optique dans l'infra-rouge**, tout en étant plus efficace pour diffuser la lumière. De telles couches permettent un gain de courant de 5-10% dans les cellules micromorphe.

Finalement, dans le cadre du projet, les infrastructures du laboratoire ont été améliorées de manière significative. Ainsi, de nouveaux systèmes de mesures permettant d'identifier des problèmes de qualités électroniques des matériaux ou de mettre en évidence des courts-circuits localisés ont été mis en service. Plusieurs systèmes de dépôts de couches ont été mis en service et/ou partiellement automatisés dans le cadre du projet. Un nouveau système de dépôt plasma (2 chambres de 50x60 cm2) a été complètement automatisé et en partie réalisé dans le cadre du projet. Globalement ces adaptions d'infrastructures permettent maintenant de gagner en rapidité pour le développement des dispositifs.

Plusieurs des découvertes et innovations apportées dans le cadre de ce projet ont suscité un intérêt industriel et sont (ou seront considérées pour des recherches plus ciblées) dans le cadre de projets CTI ou de mandats directs. Elles permettront de contribuer à une augmentation des rendements où à une diminution des coûts, et donc, à terme, à une production plus efficace d'électricité renouvelable.

Komplete Zusammenfassung (Deutsch)

Dieses Projekt gehört der Spitzenforschung im Bereich der Herstellung von Dünnfilmsolarzellen aus Silizium an. Das Photovoltaiklabor des Instituts für Mikrotechnik (IMT) der Universität Neuenburg besitzt mehrere Schlüsselpositionen in diesem Wissensbereich, der einen eindrücklichen wirtschaftlichen Aufschwung in den letzten drei Jahren erlebt hat. Während zu Beginn des Projektes im Januar 2005 der Markt fast auschliesslich vom kristallinen Silizium beherrscht wurde, sind es jetzt mehr als 40 Firmen, die die Produktion von Dünnfilm-Siliziummodulen angekündigt haben. Die Vorteile dieser Module liegen darin, dass sie wenig Rohstoffe (wie Reinstsilizium) benötigen, eine geringe Energierücklaufzeit aufweisen (Schweiz: 1–1.5 Jahre) und eine lange Lebensdauer besitzen (> 25 Jahre). Diese dynamische Entwicklung wurde möglich durch den Marktauftritt von „high-tech" Firmen, die zum ersten Mal Produktionsanlagen anbieten, welche den hohen Anforderungen des Dünnfilmsiliziums entsprechen. Eine weltweite Produktionskapazität von 4 GW könnte 2011 erreicht werden.

Die Schweiz positioniert sich speziell in diesem Kontext, da sie dank der Arbeit am IMT und der langjährigen Unterstützung des BfE stark zu dieser rasanten Entwicklung im Bereich des Dünnfilmsiliziums beigetragen hat. So hat die Firma VHF Technologies kürzlich den Aufbau einer Produktionslinie von 25 MW für flexible Module in Yverdon angekündigt, während OC Oerlikon die erste Firma war, die schlüsselfertige Produktionslinien für Glasmodule an verschiede Hersteller weltweit verkaufte, basierend auf ihrem know-how für Flachbildschirme und dem am IMT entwickelten Abscheidungsverfahren. Neben der dynamischen wirtschaftlichen Entwicklung in der Schweiz durch die „clean-tech" Industrie ist es jetzt wahrscheinlich, dass die Dünnfilmmodule der verschiedenen Produktionsanlagen mehrere TWh elektrische Energie jährlich erzeugen werden.

Alle aktiven Hersteller von Dünnfilmsilizium verkaufen Produkte, die auf einer ersten Generation von Konzepten und Prozessen basieren. Die Rolle der Spitzforschung bleibt daher vital damit sich dieser Sektor langfristig behaupten kann, sowohl im Bezug auf kristallines Silizium und andere Dünnfilkonkurrenten (CdTe, CIGS) als auch gegenüber der konventionellen Elektrizitätserzeugung. Die Forderungen sind immer die gleichen: Module mit höheren Wirkungsgraden, höherer Zuverlässigkeit bei geringeren Kosten... Dies stellt uns vor eine grosse Herausforderung denn Dünnfilme sind komplex: in einer mikromorphen Solarzelle des IMT hat es gegen 12 verschiedene Schichten. Die Chemie und die Morphologie (Oberflächenstruktur) einer Schicht können die folgende Schicht beeinflussen und jede Schicht kann durch eine Vielfalt von Arten hergestellt werden (z.B. die Variation der Parameter bei der Plasmaabscheidung), oder gar die Wahl verschiedener Materialien...

In diesem Rahmen präsentierten sich die hauptsächlichen Projektziele wiefolgt:

- **Demonstration der Herstellung von Dünnfilmsolarzellen aus Silizium mit verbesserten Wirkungsgraden** für hocheffizienten mikromorphen Solarzellen. Dafür muss die amorphe Zelle (Absorption des blau–grünen Lichtes), die mikrokristalline Zelle (Absorption des roten Lichtes) ebenso wie alle Schichten der Solarzelle verbessert werden. Der Hauptakzent wurde auf die Fabrikation von mikrokristallinen und mikromorphen Zellen gelegt, die direkt auf ein mit einem leitenden transparenten Oxid (LPCVD-ZnO) beschichteten Glass, entwickelt am IMT, abgeschieden sind. Das Ziel für die Zellen auf Plastiksubstraten war die Realisierung von flexiblen Zellen mit hohem Wirkungsgrad, wobei der Akzent auf industrienahe Prozesse für die Fabrikation von amorphen und mikrokristallinen Zellen gelegt wurde.
- **Erforschung von neuen Wegen für eine einfachere Fabrikation von Solarzellen** oder diese bei verbessertem Wirkungsgrad herzustellen. Dies würde unter anderen die Verbesserung und die Einführung neuer Materialien in gewissen Zellentypen umfassen.
- Parallel und in Ergänzung dazu galt es, **die Technik der Characterisation, der Fabrikationsprozesse und der Abscheidungsreaktoren zu verbessern.** Eine Anstrengung für die Verbesserung der allgemeinen Laborinfrastruktur war nötig sowie die Anpassung und Erneuerung eines Teils der Fabrikations- und Charakterisierungsanlagen. Das Ziel dieser Änderungen war die Bereitstellung einer Infrastruktur die erlaubt, die Effizienz der Forschungsprojekte des IMT zu verbessern und die industriellen Partner in den anwendungs-orientierten Projekten kurzfristig zu unterstützen (2-5 Jahre).

Global gesehen wurden alle Hauptziele des Projektes erreicht. Verglichen mit den Resultaten vor dem Projektanfang wurden die Wirkungsgrade praktisch aller Zellen beträchtlich verbessert, sowohl für die Abscheidungstechnologie auf Glas als auch auf flexiblen Plastikfolien (wie PET und PEN). Für alle Verfahren konnte die Reproduzierbarkeit verbessert werden, und die Interaktion zwischen den verschiedenen Schichten der Solarzellen werden nun weit besser verstanden.

Bezüglich der Solarzellen wurden die **folgenden Resultate erreicht**:

- Auf Glassubstraten wurden **mikrokristalline Zellen mit 9.9 % Wirkungsgrad** (gegenüber 8 % am Projektanfang) auf einem verbesserten neuen leitenden transparenten Frontkontakt auf Basis von ZnO-LPCVD abgeschieden. Diese Resultate vergleichen sich mit den besten publizierten Resultaten anderer Forschungsgruppen, mit anderen transparenten Frontkontakten.
- Auf Glas mit transparenten ZnO-LPCVD-Frontkontakten wurden ebenfalls **mikromorphe Solarzellen mit einem Anfangswirkungsgrad von 12.6 %** abgeschieden. Diese Zellen wiesen nach der Degradierung einen Wirkungsgrad um 11.1 % auf. Mit verschiedenen Zellenkonfigurationen (Kontakte mit verschiedenen Charakteristiken, andere Auswahl von Schichten) wurden Anfangswirkungsgrade von mehr als 12 % erreicht. Da bis jetzt noch keine Antireflexschichten aufgebrtacht wurden und noch ein Potential zur weitere Optimierung besteht, scheint es also möglich, die Grenze des stabilisierten Wirkungsgrades von 12 % für mikrokristalline Zellen zu durchbrechen (offizieller Rekord von Kaneka auf einem anderen Frontkontakttyp: 11.7 %).
- Auf **„nanotexturierten" Plastikfolien** konnten erstmals mikrokristalline Solarzellen fabriziert werden, die einen Wirkungsgrad von mehr als 7.5.% erreichten; weiter wurden **Zellen mit 8.6 % Wirkungsgrad** realisiert, die keine lichtinduzierte Degradation zeigten. Dies öffnet den Weg für hocheffiziente mikromorphe Solarzellen auf Plastiksubstraten, welche im Rahmen anderer Projekte realisiert werden.

Diese Resultate wurden erreicht dank der Verbesserung mehrerer Prozesse, der Einführung von neuen Materialien in den Zellen und einem besseren Verständnis der Mechanismen des Schichtenwachstums:

- Das Studium der Mikrostruktur der Zelle durch ein Elektronenmikroskop erlaubt die Form der anfänglichen Oberfläche zu sehen, welche sehr die elektrischen Eigenschaften der später darauf abgeschiedenen Zelle beeinflussen. Dank einem **neuen patentierten Plasmaprozess zur Oberflächenbehandlung** wurde es möglich, die Oberfläche des transparenten Frontkontaktes zu modifizieren und dadurch bessere Zellen ohne „Mikrorisse" und andere defekte Zonen zu erhalten.
- Ein neues Material, **basierend auf einen dotierten Siliziumoxid konnte fabriziert und in die mikromorphe Zelle als „Zwischenreflektor" eingebaut werden**, sowohl für Zellen auf Glas wie auf Plastik. Dieses Material, hergestellt im gleichen Reaktor wie die Solarzellen, wird zwischen der amorphen und der mikrokristallinen Zelle eingebaut. Der Reflektor ermöglicht, den Strom der amorphen Zelle durch einen optischen Effekt zu erhöhen und dadurch den Strom der beiden in Serie geschalteten Zellen ins Gleichgewicht zu bringen. Die dotierte SiOx-Schicht wurde in den Hochleistungszellen eingesetzt.
- Eine systematische Studie der optischen und elektrischen Eigenschaften von dünnen ZnO-LPCVD-Schichten für die transparenten Kontakte hat ermöglicht, die Rolle der Korngrenzen aufzuzeigen, um eine **Schicht mit einer sehr schwachen optischen Infrarot-Absorption** bei gleichzeitiger hoher Lichtstreuung herzustellen. Solche Schichten erlauben einen Stromgewinn von 5-10 % in mikromorphen Zellen.

Schliesslich wurde im Rahmen des Projektes die Laborinfrastruktur beträchtlich verbessert. So wurden neue Messsysteme in Betrieb genommen, welche erlauben, Probleme der elektronischen Materialqualität zu identifizieren oder Kurzschlüsse (shunts) in der Zelle zu lokalisieren. Es wurden auch mehrere Systeme zur Schichtabscheidung in Betrieb genommen und/oder teilweise automatisiert. Ein neues vollständig automatisiertes Plasma-Abscheidungssystem (2 Kammern 50 x 60 cm) wurde zum Teil im Rahmen des Projektes realisiert. Die Anpassungen der Infrastruktur erlauben nun einen beträchtlichen Zeitgewinn bei der Zellenentwicklung.

Mehrere Entdeckungen und Innovationen, welche im Rahmen dieses Projektes erarbeitet wurden, sind auf ein grosses Interesse der Industrie gestossen; sie sind (oder werden) für eine mehr gezielte Forschung im Rahmen von KTI-Projekten oder für direkte Industriemandate relevant. Sie werden erlauben, den Wirkungsgrad zu verbessern oder die Fabrikationskosten zu senken und dadurch zu einer verbesserten zukünftigen Elektrizitätsproduktion aus erneuerbarer Energie beizutragen.

Short abstract (English)

This 3 years project aimed at

- Demonstrating the preparation of thin film silicon based devices with higher efficiency
- Fabricating new high efficiency devices on flexible substrates using low cost processes
- Exploring new routes for improved processing and characterization
- Providing the best infrastructure (process know-how, fabrication and characterization systems) to support industrial partners in the frame of projects funded by other sources

All the major projects goals were achieved. Compared to the status at the beginning of the projects, the efficiency of most devices could be significantly improved, both on glass substrates and on flexible plastic foils. The process reproducibility could be improved and the interactions between the different layers in the device are now better understood.

- Initial efficiency of 12.6% for a 1.2 cm^2 micromorph cells fabricated on in-house transparent conductive oxide has been achieved, without antireflection on the glass. On the same substrate microcrystalline cells with 9.9% efficiency were realized.
- High quality amorphous and micro crystalline silicon solar cells on plastic substrates could be fabricated, with, in particular, stable microcrystalline solar cells with up to 8.6% efficiency on PET/PEN plastic gratings.
- Detailed electrical and microstructural investigations clarified the interaction of the substrate and of the films grown by plasma processes (PECVD). In particular, the presence of cracks and defective areas was analyzed for various solar cells on glass and plastic substrates and their origin understood. Innovative processes to remove such defects were devised an implemented, such as plasma post-treatment of ZnO layers.
- A new material based on doped silicon oxide was developed and could be incorporated for us as intermediate reflector in various solar cells. This layer can be prepared by PECVD and allows an increase in the current of the amorphous top cell and is used in both n-i-p and p-i-n tandem micromorph devices.
- A better physical understanding of the opto-electronic properties of zinc oxide prepared by low pressure chemical vapour deposition was gained. In particular the role of grain boundaries in controlling the mobility has been elucidated and the effect of vapour moisture on the films clarified. A full control of grain size and grain morphology could be realized, allowing for broad scope study of solar cell properties.

In parallel the laboratory infrastructure was improved significantly: several characterization systems were upgraded, new deposition systems were built and taken into operation, systems were partly automated and should allow faster progresses in the next projects.

Several of the findings of this last project year are relevant for industrial implementation at a later stage and are or will be worked out in the frame of CTI projects or direct mandates with industrial partners.

1 Introduction/background

1.1. GENERAL BACKGROUND FOR THIN FILM SI

At the beginning of the project, 1.1.2005, only a few companies were active in the field of thin film silicon based modules. Things have changed dramatically over the last three years, as illustrated in Fig.1. In particular 2007 has been an exciting year for thin film silicon with the announcement of dozens of companies entering mass production for amorphous or micromorph solar module production. With the exception of a few companies developing roll-to-roll process (such as VHF-Technologies, Unisolar or Nuon), most of these companies rely on equipment suppliers such OC Oerlikon, Applied Materials, Leybold Optics, Ulvac. These suppliers base their know-how on their experience in the flat panel display sector and have acquired or are acquiring the competencies for solar cell processing from partnerships, e.g. with research institutions. The first production lines are now in operation (e.g. Oerlikon production reactors at Schott Solar or Ersol, Applied Films at Sontor) and the first micromorph mass production lines should start producing in 2008-2009 in Europe (Sunfilm, Inventux,…). Worldwide announced production capacity for thin film Si by 2011 amounts to more than 4GW and much more announcement will likely be made soon. Most of the products that will be manufactured in the next few years will be "first generation" products. In particular, a strong potential remains for module efficiency improvement and for new, more cost-effective, manufacturing solutions. Indeed there are still a lot of open scientific questions in the field of thin film Si. In this context, the future objective of IMT will be to continue to contribute to a better understanding of such devices, to demonstrate new ways and new ideas to improve the conversion efficiency of amorphous, microcrystalline and micromorph solar cells and to find out new processes that have a chance to be compatible with ultra-low cost industrial module production and hence competitive solar electricity price in the mid-term.

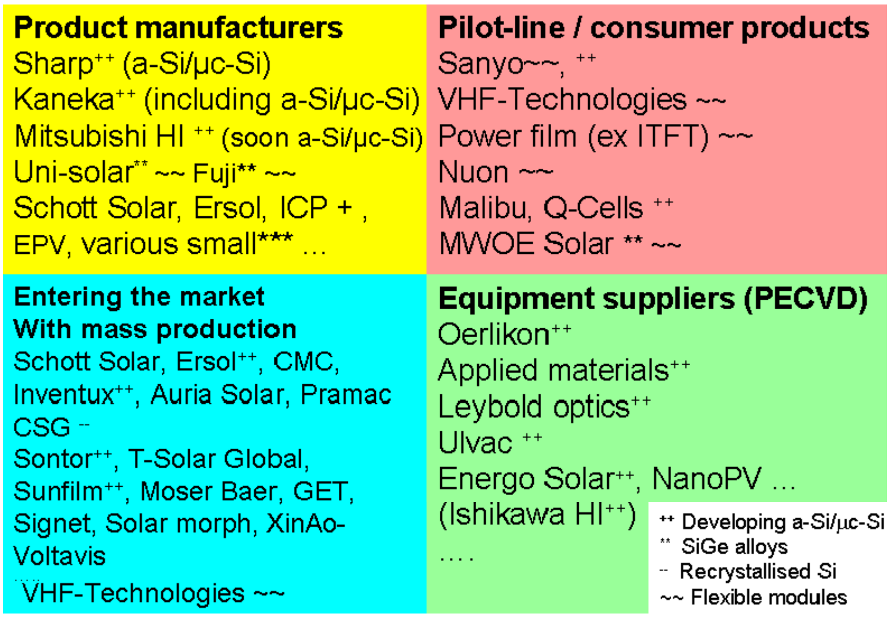


Fig. 1: Summary of the major activities in the field of thin film Si. Note that several producers have announced smaller capacities with equipment of e.g. EPV.

1.2 STARTING POINT FOR THIS PROJECT

Even though IMT had achieved excellent results in the past, with high efficiency cells on glass (record amorphous 9.5% and confirmed micromorph 10.7%), there were critical issues to be solved, including:

- Understanding the problems linked with the fabrication of microcrystalline (μc-Si) on glass where efficiency were limited to 7-8%
- Improving the micromorph cell efficiency to demonstrate further the potential of the technology
- Developing the future generation of devices on plastic, by working on single junction a-Si and μc-Si where cell efficiency was limited at 7%
- Setting-up more stable processes allowing device improvement and mitigating know-how losses in case of personnel changes

- Further deepening our knowledge of these devices, in terms of electronics defects / micro-structure defects
- Providing a serious upgrade and renewable of most of the characterisation systems and deposition systems, if the infrastructure was to remain competitive for high performance research.

2 Project goals and methodology

This three years long research project aimed more specifically at reaching the following goals:

- Introducing new concepts for higher efficiency thin film micromorph devices on glass substrates
- Developing the know-how for device preparation on light-weight unbreakable substrates with industry compatible technology
- Exploring new routes for improved processing and characterization
- Providing the infrastructure that enables the support to industrial partners in the frame of projects funded by other sources than SFOE

To reach these objectives a significant effort was made to:

- Renew, upgrade and automate several systems for the fabrication of thin film solar cells
- Install and run new advanced characterization systems
- Work on process reproducibility by revisiting several fabrication steps, from solar cells patterning and individual layer optimization to the full system optimization on optimized TCO.

3 Results and discussions

3.1 HIGH EFFICIENCY SOLAR CELLS ON GLASS SUBSTRATES

Summary

In 2005 and 2006, the effort was put on improving fabrication process flow (patterning, process control) for the reproducibility of single junction amorphous and microcrystalline silicon solar cells:

- New patterning techniques were developed to avoid shuntings of solar cells and improve results reliability
- For the first time, high efficiency microcrystalline cells could be fabricated directly on LPCVD-ZnO, using TCO's, with different surface morphology. Efficiency up to 9.9% could be achieved and the scientific reasons for the efficiency gain eluded [Bai06]
- New intermediate reflector made out of ZnO [Dom06] were developed and micromorph cells with efficiencies of up to 11.8% could be fabricated.

This work prepared the ground for testing new concepts in micromorph tandem solar cells for higher efficiencies in 2007. In the final part of the project, the focus was set on the following points:

- Intermediate reflectors with a new doped SiOx material, deposited in the same PECVD chamber as the solar cell were successfully prepared [Bue07,Bai07]. It is also a highlight as no one reported such results before. It could indeed facilitate the industrial implementation of the intermediate reflectors in tandem and triple junction solar cells, which has been until now the main drawback of ZnO intermediate reflectors. In several configurations using new intermediate reflectors, initial efficiencies above 12% are now regularly achieved, with up to 12.6% initial efficiency for a 1.2cm^2 micromorph cell, corresponding to a degraded efficiency above 11.1%, without any antireflection on the glass.
- The fabrication of doped TiO_2 antireflection layers, introduced between the TCO and the Si layer. In [Bue07B], the influence of such layers is analysed for different front TCO and a current gain between 1.7% (rougher TCO) and 3.8% is demonstrated.

Patterning of the solar cells

The patterning technique of the solar cells was the first to be adapted in the fabrication process: we changed from a wet etching technique to a lift-off technique. The application of the new lift-off process, described in the reference [Gra05], enabled a dramatic decrease in the spread of the values of the electrical characteristics of the cells. The results in Fig.2 are represented in a box-plot[1] and illustrate

[1] The middle line represents the median of the data. The top of the box represents the upper quartile (it contains 25% of the data higher than the median) and the bottom line the inferior quartile (25% of the data lower than the median). The difference between the top and the bottom of the box can be used as a measure of the spread of the data and is called the interquartile distance. Extreme points are represented with a dash and outliers with an open circle.

the difference between the two patterning techniques. We observe that maximum FF and V_{oc} are the same with both patterning techniques. However, the spread of the data for FF and V_{oc} is strongly reduced when patterning by lift-off rather than by the wet etching technique.

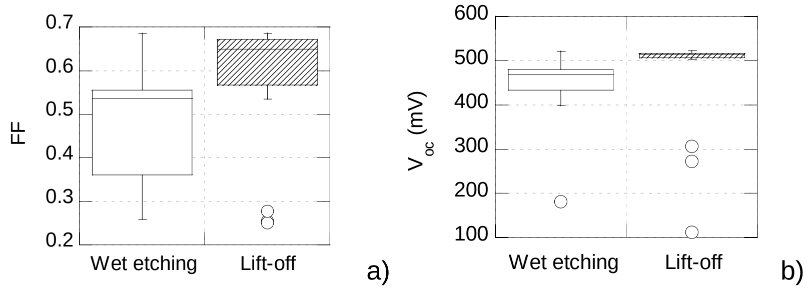


Fig .2: a) fill-factors (FF) and b) open-circuit voltage (V_{oc}) obtained with two different patterning techniques: wet etching (old) and lift-off (new) technique. The measurements were done on 16 single cells in both cases. The outliers (open-circle) are caused by localized shunts.

Reproducibility

The reproducibility of the processes and the homogeneity of the different layers constituting the solar cells enable the continuous improvement of the electrical characteristics of the devices. In Figure 3a are represented the efficiencies of microcrystalline silicon solar cells deposited in 2006. The best solar cell fabricated in 2005 had an efficiency of 9.0%. In 2006, this value was reached or surpassed 10 times, as represented in the histogram in Fig. 3a. Most of the solar cells have their efficiency above 8.5% with a maximum at 9.9%. The scattering in the data is due to the deposition conditions that have been varied for various optimization purposes.
So far pin amorphous silicon solar cells had been developed in the first system built at IMT. To maintain the good results obtained in pin a-Si:H cell, the processes in system C were transferred to the double chamber system B, used until then for microcrystalline silicon solar cells only. Two months only were needed to achieve the transfer and to obtain devices with initial efficiencies above 10%. The homogeneity of the electrical parameters is represented in Fig. 3 b); note the very small scattering of the V_{oc} and FF.

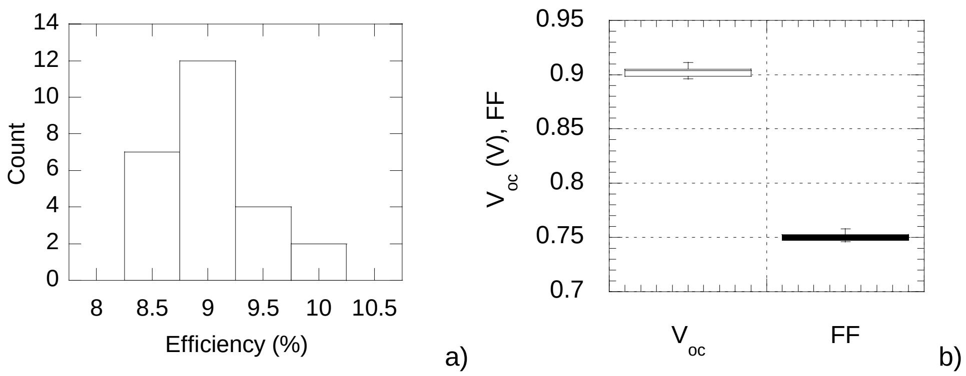


Fig. 3: a) Histogram of the efficiencies of the pin microcrystalline silicon solar cells fabricated in 2006 at IMT. The best efficiency obtained last year (9%) has been attained 10 times so far. b) Box plots of the V_{oc} and FF for 12 amorphous silicon solar cells deposited in the same run using the newly developed processes in system B. The shunted cells (dust), approximately 25% of the cells on this substrate, were removed from this statistics.

Optimization of single junction solar cells

The successful use of LPCVD ZnO in amorphous and partially micromorph cells had not been realised for μc-Si:H single junction solar cells. The best p-i-n cells on LPCVD ZnO only attained efficiencies slightly over 8%, whereas, on sputtered and etched ZnO, several groups managed to produce cells achieving efficiencies over 9%. Hence, we addressed the issue of fabricating single junction μc-Si:H solar cells with efficiencies higher than 9% on LPCVD ZnO. To reach this goal, the front TCO used previously at IMT for a-Si:H and micromorph solar cells was modified for use within single junction μc-Si:H solar cells. The modifications were threefold:

- Reduction of the free carrier absorption (FCA)
- Increase of the light-trapping capability for long wavelengths (700-1000nm)
- Adaptation of the morphology to the growth of μc-Si:H material

The first two modifications to the standard front TCO optimized for a-Si:H solar cells were motivated by the broader absorption spectrum of μc-Si:H. These were easy to implement technologically: (a) by lowering the doping concentration of the LPCVD ZnO film, to reduce the FCA; (b) by increasing the film thickness to increase the surface roughness, as shown in Fig.4b and thereby improve the light trapping at long wavelengths. As both modifications affected the sheet resistance of the TCO layer in opposing ways, it was possible to keep the latter below 10Ω/square [Ste05].

After carrying out these modifications it was, however, no more possible to obtain high values of open-circuit voltage (V_{oc}) and fill-factor (FF). The reasons invoked in ref. [Feit05] was the high roughness and "inappropriate surface morphology" of the front TCO layer. Hence, the third modification to our standard TCO was an adaptation of the surface morphology, which favours a proper growth of μc-Si:H. This last task was challenging as the optimal morphology for the growth of μc-Si:H cells was not known. We introduced a novel surface plasma treatment that renders the surface morphology of LPCVD ZnO fully adapted to subsequent growth of μc-Si:H solar cells. The changes in structure are shown in Fig. 4b and 4c. The time used for the surface treatment, when varied from 0 to 140' leads to dramatic solar cell parameters improvement, as shown in Fig. 5. The efficiency of the μc-Si:H solar cells subsequently grown on these substrates, increased from 3.3 to 9.2% after 40' of surface treatment.

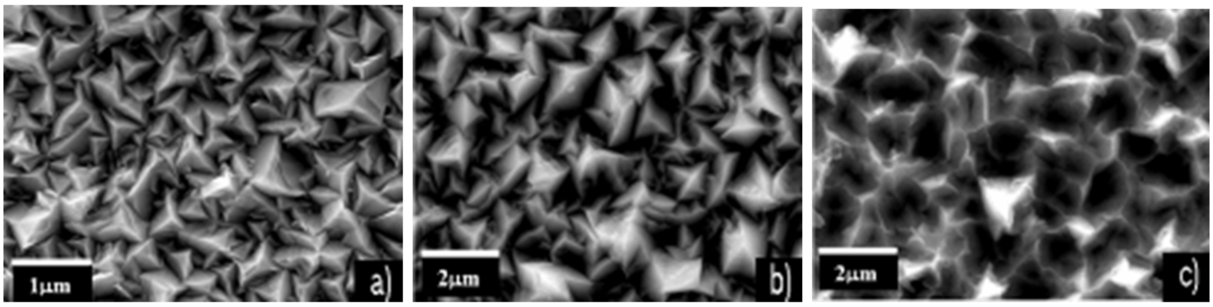


Fig. 4: SEM micrographs of the different 3D nanomorphologies of a) standard LPCVD ZnO, b) new LPCVD ZnO optimized for μc-Si:H before surface treatment and c) same as b), after surface treatment.

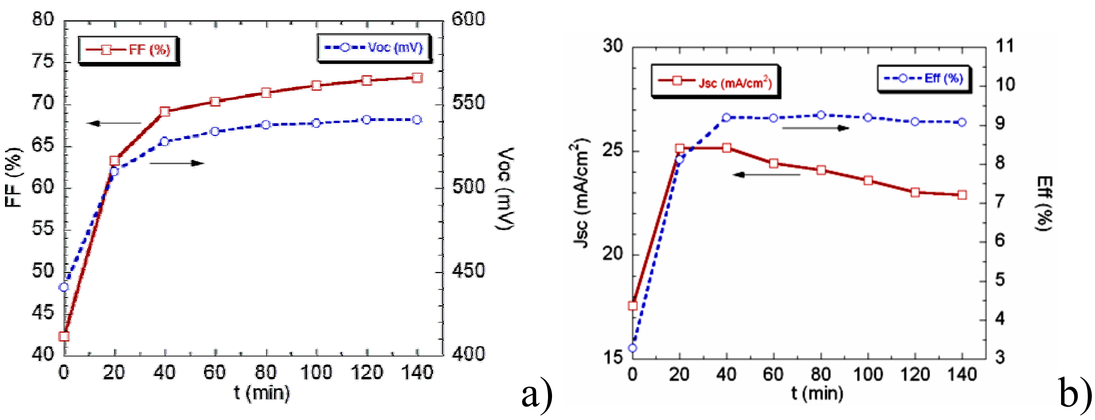


Figure 5: Evolution of the electrical characteristics of the solar cells as a function of the duration of the surface treatment (0 minute stands for no surface treatment): a) V_{oc} and FF, b) I_{sc} and efficiency η.

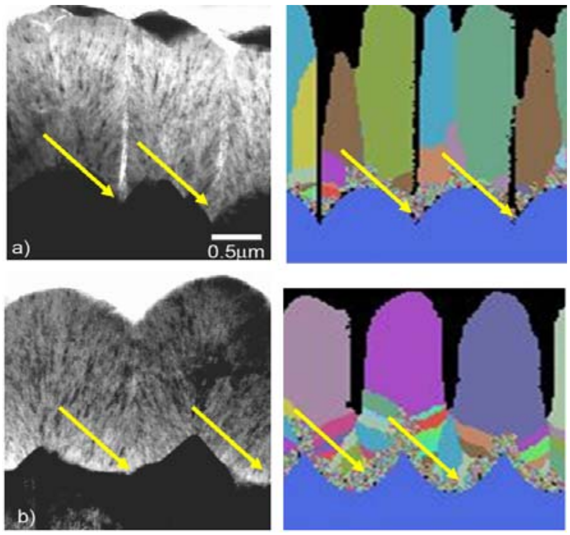


Fig.6. Left) TEM cross-section of µc-Si cells on untreated (top) and treated substrate (bottom). Right) Numerical simulation illustrating the same effects "crack" generation depending on substrate morphology [Pyt07]

This work allowed us to understand which substrate morphology is best suited for the growth of microcrystalline silicon solar cells. It resulted in the filing of a patent in March 2006. Fig. 6 shows transmission electron microscopy images and numerical simulation illustrating the physical effects of the surface treatment : it changes the shape of the TCO from the V to a U shape, leading thereby to a significant decrease in defective areas (voids, cracks) near the zones at the pinch.

After optimization of the microcrystalline silicon solar cells in single junction on this new substrate, the efficiency reached a value of 9.99% [Bai06], which consists in a record on LPCVD ZnO front TCO. The results are shown in Fig.7 and table 1.
Further optimizations focusing at enhancing the current of the bottom cell in the micromorph solar cell also showed that short-circuit current-density as high as 25.7mA/cm^2 are achievable for µc-Si:H cell on LPCVD ZnO, still without any antireflection layer on the front glass (Fig. 8a). This brings the current in the range of the best results reported by the Juelich group for sputtered etch ZnO.

In parallel to the optimisation of the µc-Si cell, all processes for the pin cells were transferred from the system C (single chamber) to system B, double chamber. The pin amorphous solar cells developed in the system B reached initial efficiencies of 10.2% with a relatively thin intrinsic layer of 250nm (Figure 7b, and Table 1). This transferred allowed the realisation of micromorph cells fully done in the same system.

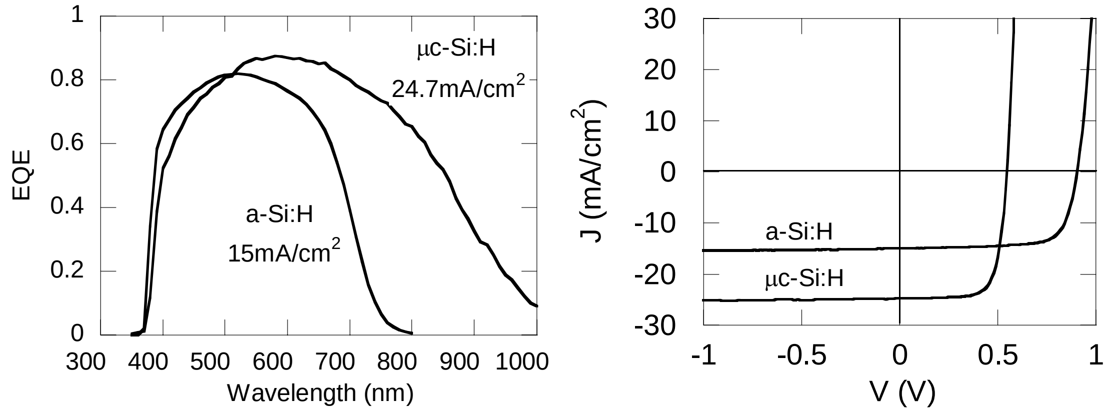
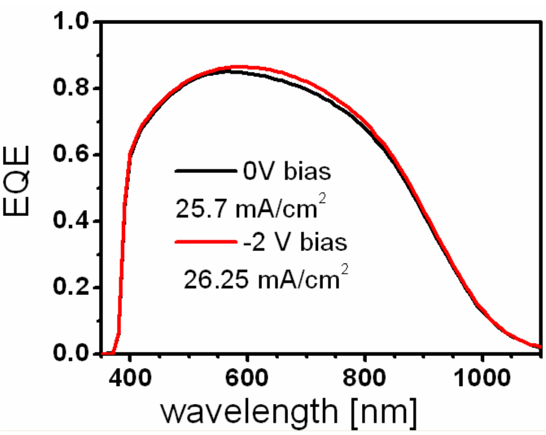


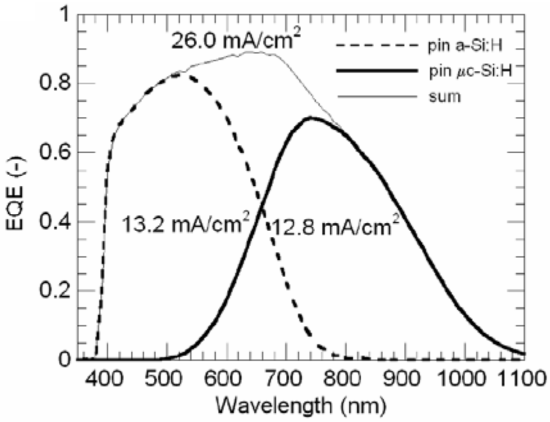
Fig. 7: a) and b) External quantum efficiency and current-density voltage curves of the best amorphous and microcrystalline silicon solar cells fabricated in 2006.

Cell type	V_{oc} (mV)	FF (%)	J_{sc} (mA/cm^2)	Efficiency (%)
a-Si:H (syst.B)	904	75.2	15.0	10.2
µc-Si:H (2006)	545	74.1	24.7	9.99
Micromorph (2006)	1316	70.2	12.8	11.8
Micromorph (2007)	*1380*	*72.2*	*12.7*	*12.6*

Table 1. Summary of the electrical characteristics of the best solar cells made in 2006 (initial efficiencies) and final best efficiency in 2007 (in italic). The thickness of the intrinsic layer of the a-Si:H cell is approximately 250nm; that of the µc-Si:H silicon solar cells is 1.8µm thick. For the micromorph solar cells, with a ZnO intermediate reflector, the thicknesses of the intrinsic layers are 180nm and 1.80µm for the top and bottom cells, respectively.



a)



b)

Fig. 8: a) EQE of a µc-Si cell with thicker (2.5 µm) absorber layer at 0 and -2V. b) EQE curves of a the top and bottom cells of a "high-current" micromorph tandem solar cell with ZnO intermediate reflector optimized on the new front LPCVD.

Micromorph cells with intermediate reflectors based on zinc oxide

The concept of intermediate reflector was introduced in 1996 by Fischer et al. It consists of a reflecting and conducting layer between the top and bottom solar cells in tandem configuration. Its purpose is to increase the current-density in the top amorphous cell without increasing the thickness of its absorber layer which would be detrimental to the light-soaked characteristics of the solar cell.

In a first part of the investigation, a detailed analysis of current gain and losses was done. ZnO intermediate reflectors (ZIR) in tandem cells with 180nm and 1.8um top and bottom solar cells were analysed. Fig. 9a represents the gains in current-density of the top cell ($J_{sc,\ top}$) and the respective loss in the bottom cell ($J_{sc,\ bot}$) as a function of the thickness of the ZIR. The front TCO consists of standard "non treated" ZnO by LPCVD with a root-mean-square (rms-) surface roughness of 80nm. Gains in top cell current density of up to 2.8mA/cm^2 are achieved. In such a configuration, an efficiency of 11.6% is reached with FF=73.2%, V_{oc} 1.315V, J_{sc}=12.1mA/cm^2 with a 70nm thick ZIR [Dom06].

The modified TCO, described in the previous part, is suitable for the fabrication of micromorph devices. Cells with total current of 26 mA/cm^2 (13.2 for the a-Si:H top) using an intermediate reflector can be fabricated, with initial efficiencies of 11.8% [Dom06]. These cells still had limited Voc of 1315 mV and FF (70%), which is attributed to the presence of the intermediate reflector. Cells prepared on the modified TCO without IR reflector show high V_{oc} of 1.41 V, but without current matching. To achieve better micromorph devices, it was hence necessary to combine both advantages (current matching with IR and no Voc losses).

It should be noted, however, that the microcrystalline cell is grown on top of the amorphous cell, which modifies the surface morphology of the TCO. The question remains open if the new TCO morphology is necessary to achieve the highest efficiency micromorph devices, or not.

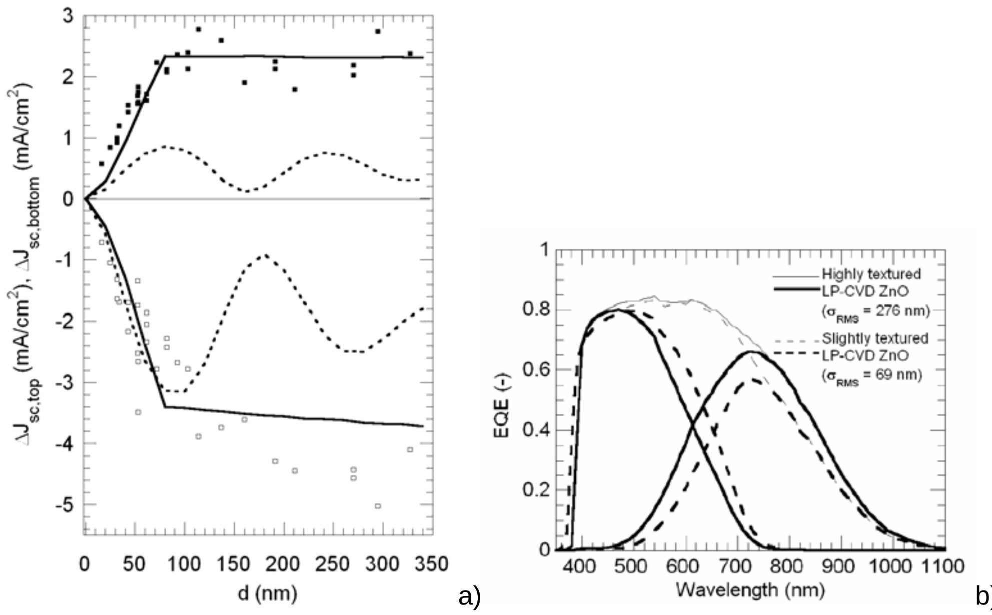
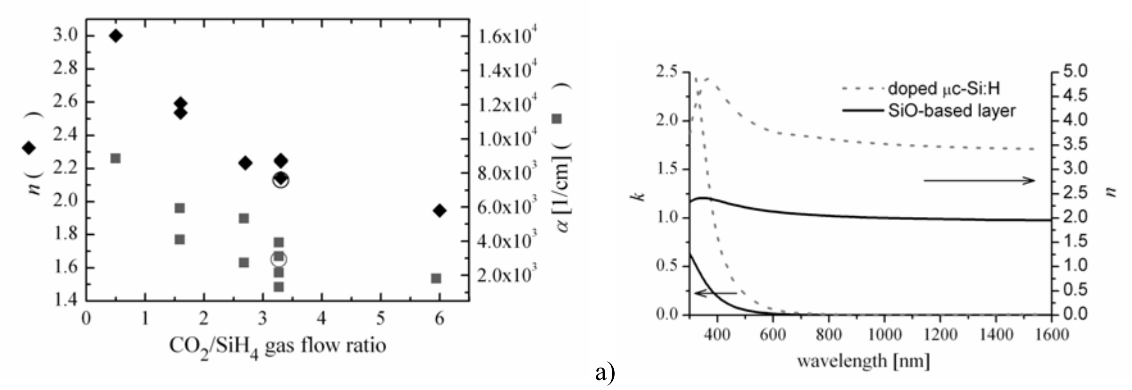


Fig. 9: a) Variation of the current-density in the top and bottom cells ($\Delta J_{sc,\ top}$/ $\Delta J_{sc,\ bottom}$) in micromorph solar cells as a function of the thickness (d) of the ZIR. $\Delta J_{sc,\ top}$ are positive values whether $\Delta J_{sc,\ bottom}$ are negative values. Dots and squares represent experimental values, continuous lines are simulated values for solar cells with rough interfaces and dashed lines represent simulated values for flat interfaces. b) Comparison of EQE curves of a-Si:H top and μc-i:H bottom cells of micromorph tandems with a 90 nm thick ZIR layer and back reflector. The tandems are deposited on two different front TCO layers, with σ_{RMS} values of 69 nm and 276 nm. One finds: $J_{sc,top}$=12.4 mA/cm^2, $J_{sc,bottom}$=9.7 mA/cm^2 for slightly-textured TCO and $J_{sc,top}$=10.7 mA/cm^2, $J_{sc,bottom}$=12.5 mA/cm^2 for highly textured TCO.

Development of doped silicon oxide layers as intermediate reflectors

In 2007 IMT demonstrated silicon doped oxide intermediate reflectors (SOIRs) [Bue07]. Yamamoto et al. from Kaneka Corp. had previously reported on intermediate reflectors without specifying the used material. The advantage of the SOIRs developed here, over ZIRs, is the possibility to deposit the former with the same PECVD equipment as the silicon layers of the solar cells. In opposition to ZIRs, the challenge with SOIRs is to obtain a refractive index as low as possible (typically below 2) and, simultaneously, to keep a sufficient perpendicular conductivity. It is found that a small fraction of crystalline silicon embedded in a a-Si:O:H matrix is necessary to ensure a sufficient perpendicular conductivity through the intermediate reflector.

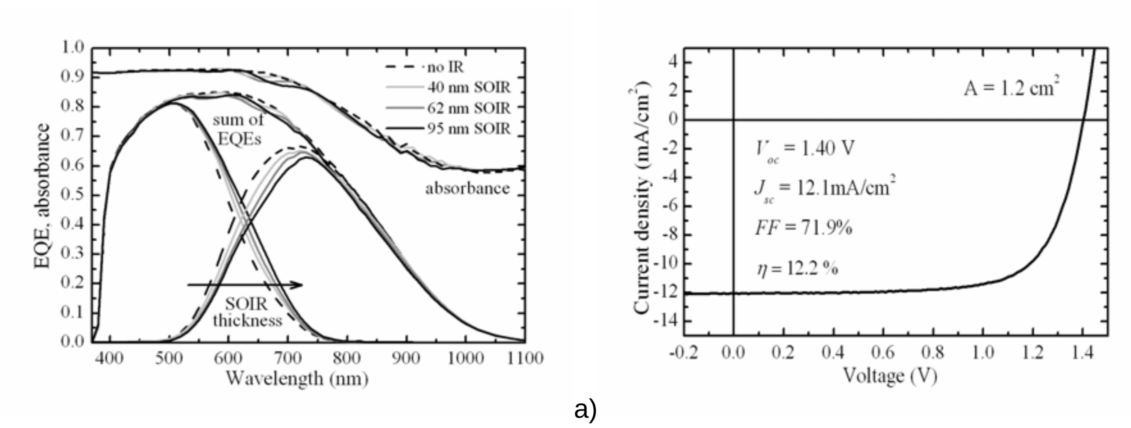
Here, we developed boron-doped silicon oxide layers on glass substrates in the same PECVD chamber where state-of-the-art amorphous and microcrystalline silicon solar cells are produced. The layer is deposited from a mixture of SiH_4, H_2, CO_2 and PH_3. The proportion of the different gases is varied to optimize the electrical and optical properties of the layer. Fig. 10a represents the variation of the index of refraction as a function of the SiH_4 to CO_2 ratio. The lower is the refractive index of the intermediate reflector compared to the one of silicon, the higher is the reflectance of the intermediate mirror. Fig. 10 b shows the dependence of the new materials optical parameter as a function of wavelength. We observe that layers deposited with higher CO_2 /SiH_4 ratios result in better optical properties, i.e. lower refractive indexes and lower absorption coefficient. The electrical conductivity however decreases which, beneath a certain threshold, is detrimental to the serial resistance of the tandem solar cell. To counter this effect, the ratio of doping source gas (PH_3) to SiH_4 is increased to maintain a sufficient conductivity (approximately >10-10S/cm, measured in plane).



a) b)

Fig. 10: a) Refractive index n and absorption coefficient α of doped silicon oxides deposited on glass substrates as a function of the CO2/SiH4 ratio. b) Comparison of optical constants of µc-Si and a typical SiO based layer.

In the first tests made at mid 2007, using doped silicon oxide as intermediate reflector improved the current-density by more than 1mA/cm^2 in the top cell. A series of layers with intermediate reflectors of different thicknesses (Fig. 2a) shows the increase of current in the top amorphous cell. With further optimization of the layer in the micromorph device, an initial efficiency of 12.2% was reached (Fig. 10b). The cell had a thin amorphous i-layer thickness (270 nm), guaranteeing a low degradation, and a microcrystalline i-layer thickness of 1.8 µm [Bue07]. In the series presented here, the gain in J_{sc} obtained in the top cells with SOIR was still lower than those demonstrated with ZIR. The losses can come from the slightly higher index of refraction and higher absorption of the SOIR layer than the ZIR layer. On the other hand, better V_{oc}'s are obtained for the solar cells incorporating SOIRs in place of ZIRs for reasons likely linked to local micro-shunting.



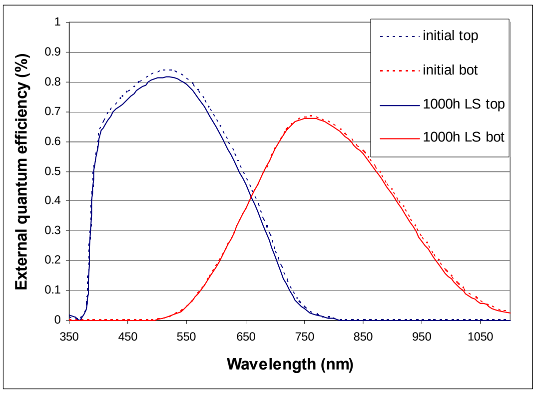
a) b)

Fig. 11 a) EQE and absorbance of micromorph cells deposited in a KAI-S reactor at IMT without IRL (dotted line) and with SOIR layers with different thicknesses: light gray=40 nm, gray=62 nm, and black=95 nm. b) J-V curve of a micromorph solar cell with an intermediate reflector made of doped silicon oxide. The solar cell is limited by the current of the top cell.

Device optimization and best results

A wide range of micromorph solar cells were fabricated on LPCVD-ZnO front TCO using the new SiOx based intermediate reflector. Both for thin (1.8) and thick (3 µm) µc-Si bottom cell, high efficiency could be achieved, with typical values between 12.2 and 12.6%. The results for a cell 12.6% with thin a-Si (300 nm) and thick µc-Si (3 µm) is given in Fig. 12. It shows a remarkable EQE with a total current of 26.6 mA/cm^2 (13.3 mA/cm^2 top cells, 12.7 mA/cm^2 bottom cell). The cell has an initial Voc of 1.38V, higher than with ZnO based IR, and an initial FF of 72.2%. After 1000 hours degradation a reduction of the efficiency to 11.12%, due to a loss of Voc and FF, which can possibly still be mitigated.

All these results are achieved for 1.2 cm^2 cells without any antireflection coating at the glass-air surface, or glass-TCO interface, or even (see next section) at the TCO Si interface. The two first elements are usually used for record solar cells, e.g. by Kaneka which holds a confirmed record at 11.7%. Consequently we think that by adding additional AR elements which should be able to come close and even surpasses such values, by using a device structure completely different than the one of Kaneka (likely on SnO2 with Ag/ZnO back contact).



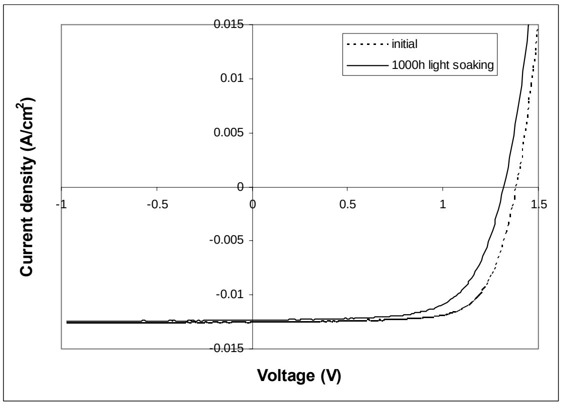


Fig.12. a) EQE of a record 12.6% micromorph cells, in initial and degraded state. b) I-V curves of the same curve in initial and degraded state

Internal antireflection layers [Bue07B].

In a separate experiment, we investigated the effect of a low-resistivity TiO_2-ZnO bi-layer incorporated as an anti-reflection coating between the rough ZnO front transparent conductive oxide (TCO) and the silicon layer, for thin film p-i-n microcrystalline silicon solar cells. The TiO_2 layers are deposited by reactive rf-sputtering from a Ti target with a H_2O/Ar gas mixture. We studied the potential of this coating with respect to TCO surface roughness and morphology and we show that with a TiO_2 layer of 55 nm, having a refractive index of ~2.5 at 550 nm (Fig.13 a) we can decrease the reflectance of typical µc-Si:H solar cell at 550 nm down to 6 %, corresponding to reflectance at the glass interfaces only. Depending on the TCO properties, increases in short-circuit current density ranging from 1.7 to of 3.8 % are obtained, the latter value is obtained for a ZnO layer particularly suitable for the growth of microcrystalline silicon solar cells. The EQE of Fig.13b illustrates the improvement for very rough (short ST) and smoother (long ST) TCOs.

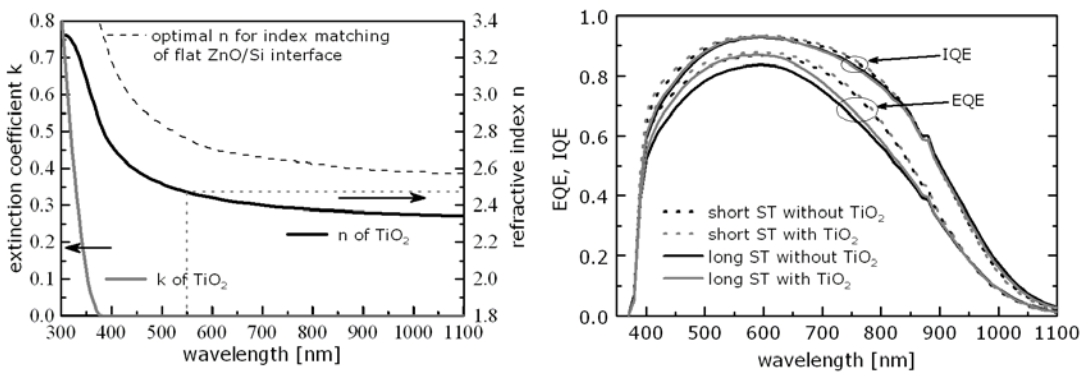


Fig. 13: a) Optical constants of TiO_2 layer determined by spectroscopic ellipsometry measurements. b) EQE and IQE of four cells fabricated in one run deposited on a TCO prepared with a short and a long ST, with and without TiO_2 ARC.

Perspectives and conclusions

The work for high efficiency cell on glass achieved during this year opens new perspectives to reach higher efficiencies both at IMT and in the industry. The results obtained this year are however slightly under the target of 12.6% stable set in this project. At the end of 2006, the main reason for the discrepancy between the target and the results achieved was that the current-density was still too low. In our most recent work, the current of the micromorph cells could be increased up to above 13mA/cm^2 in some cases with matched current, with initial efficiency in the range of 12-12.6% efficiency. The actions that are being taken to further increase the current-density and simultaneous the VocxFF product (open-circuit voltage times Fill Factor) in the solar cells will take place on different levels:

- Anti-reflection coatings at air-glass, glass-ZnO interfaces

- Optimized intermediate reflector
- Optimized recombination junction with an intermediate reflector
- State-of-the-art back-reflectors
- Improved front TCO morphologies.

These improvements will be implemented partly in a next SFOE project and partly in the ATHLET European project. In addition, encapsulated micromorph solar cell will be sent to different calibration centres to compare the current densities of qualified institutes with our set-up, as, because of light scattering in the TCO during the spectral response measurement, we tend to underestimate our current and efficiency values.

Noticeably, there is now a broad parameter space, in terms of current and VocxFF product in which high efficiency micromorph cells can be fabricated. The IMT cells are close to reported world record values of Kaneka, whereas it bases only on full use of in-house technology, especially using our LP-CVD ZnO. Based on the solid background generated in this SFOE project, we see a strong potential for significant further improvement of the micromorph devices.

3.2 LIGHT-WEIGHT UNBREAKABLE SUBSTRATES (CELLS IN NIP CONFIGURATION).

Summary

- In a first phase various reliable "back contacts" were established using a new sputtering tool installed at IMT
- In 2006 and 2007, effects similar to those of the p-i-n microcrystalline cells could be reported for the a-Si nip cells and illustrated the universal nature of the substrate-growing cell interaction
- In 2007, amorphous cells which were much less sensitive to the substrate geometry could be prepared, with initial efficiency of up to 8.8% on PEN foils [Sod07]
- Also microcrystalline cells with stable 8.6% efficiency were deposited on plastic gratings providing strong internal diffraction could be prepared. This is probably the highest reported efficiency for a solar cells deposited directly on a PEN foil [Hau07]
- Even though prepared in the frame of the EU project Flexcellence, it has to be noted that based on the work done in this project, stable micromorph cells with 10.9% initial and over 9% stabilized efficiency on PEN substrate could be fabricated [Sod07, Hau07]

Substrate preparation and cell growth

In a first stage, more homogeneous and more reliable new reflecting substrates [Ter06] were developed in the new sputtering reactor installed in June 2005 at the IMT (Univex System from Leybold) on nano-textured PET substrates. As-grown textured Ag on glass was also developed to have an "easy" reference substrate (Fig. 14). Basically, proper substrate preparation for growth of virtually all devices could be implemented. Fig. 15 shows SEM and TEM cross-sections of micromorph cells grown on plastics substrates, illustrating the quality of the growth (no peeling, no crack) achievable on such substrates.

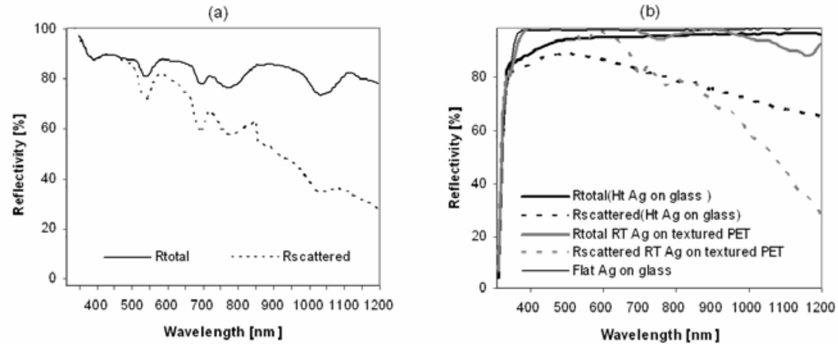


Fig. 14: a) Total and scattered reflectivity of the Al-based back contact currently available at IMT on textured PET substrates. b) Total and scattered reflectivity of the Ag-based back contacts currently available at IMT on glass (as-grown textured Ag deposited at high temperature and flat Ag deposited at room temperature) and on textured PET films.

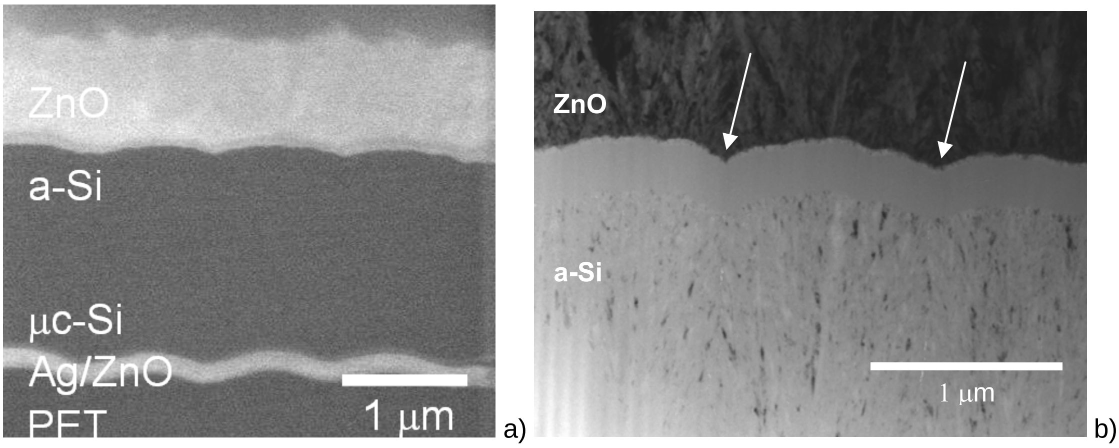


Figure 15: a) SEM view of a FIB cut through a a micromorph tandem solar cell on plastic. b) TEM cross section through the upper part of the cell. In the middle is the amorphous i-layer, the upper dark part represents the ZnO front contact.

Effect of substrate texture

We investigated the effect of the surface morphology on the amorphous nip cell properties, to determine if effects similar to those reported for the p-i-n µc-Si solar cells were to be found . We worked with substrates where we could deliberately change dimension and shape of the surface roughness independently [Sod07]: glass coated with silver and a rough LP-CVD ZnO, followed by a surface treatment. The design of the nip solar cell was kept as simple as possible. The structure was glass/Cr/Ag/LP-CVDZnO/n-µc/a-Si/p-µc/LP-CVD ZnO. The cell thickness was below 300 nm and here the dilution of the i layer was 6. Figure 16a shows the external quantum efficiencies (EQE) at a reverse bias voltage of -1V. Fig. 16 b shows the Voc, and efficiencies of cells with different surface treatment times of the ZnO, and of a flat cell for reference. Effects similar to the case of the µc-Si p-i-n cells are clearly observed. The surface treatments leads to a slight decrease of the current (Fig. 16a) but a strong increase of the Voc and FF ! Hence, a special attention has to be paid also for a-Si n-i-p cells regarding the morphology of the substrate, or processing has to be adapted.

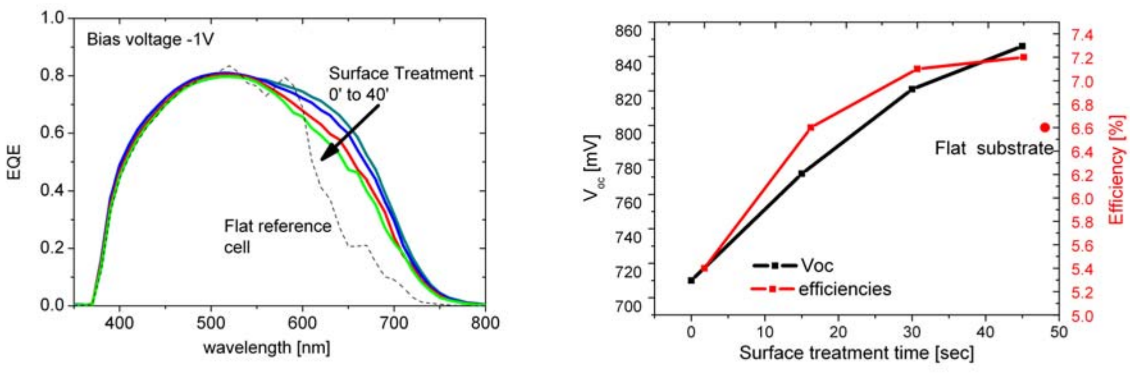


Fig. 16: a) External Quantum Efficiency for different back reflector structures after different time of surface treatment of the LP-CVD ZnO (full lines) and a flat reference (dashed line). b) Corresponding efficiencies.

Device improvements

During 2007, IMT was able to make significant progress in flexible cell development. The work was devoted to the development of robust single cell processes with improved efficiency and keeping in mind their application into micromorph tandem cells.

In amorphous cell we have been able to gain better understanding of the losses that were observed on textured substrates.

We could identify the quality of the microcrystalline n-layer as one of the main reasons. This layer must make a good electrical contact to the back reflector, normally ZnO, and it is also necessary that a high crystalline quality with high doping efficiency is achieved. However, the crystalline quality of this

layer depends on the substrate and its surface morphology. In order to avoid this problem we developed an amorphous n-layer where the constraint of high crystal quality is absent. However, it was necessary to increase the band gap of this new n-layer because absorption in amorphous material is generally higher compared to microcrystalline material. By adding carbon we were able to reach a band gap energy of 2.4 eV which ensures low absorption of the long wavelength light that reaches the back reflector [Sod07].
Fig. 17a) presents open circuit voltages of n-i-p cells on dedicated series of textured ZnO substrates, used at back-reflectors; before cell deposition the back TCO surface morphology has been modified by a plasma treatment that reduces the roughness. The cells with the standard microcrystalline n-layer show a strong variation, ranging from 760 mV on the untreated substrate to 880 mV on the strongly treated substrate. This value compares well to a reference cell on a completely flat back reflector where an open circuit voltage of 890 mV is achieved. In contrast, the series of cells with the amorphous n-layer shows little variation over the whole range, suggesting that this is a very robust layer that yields high performance independent of the substrate morphology.
Applying these findings, we have been able to fabricate flexible amorphous silicon solar cells with initial efficiency of 8.8%. The substrate of this cell consists of flat plastic covered with a flat silver reflector and textured LP-CVD ZnO. On the 2D periodic substrate we obtain efficiencies of 7.2% (initial), but the texture is not ideal for light trapping for a-Si cells.

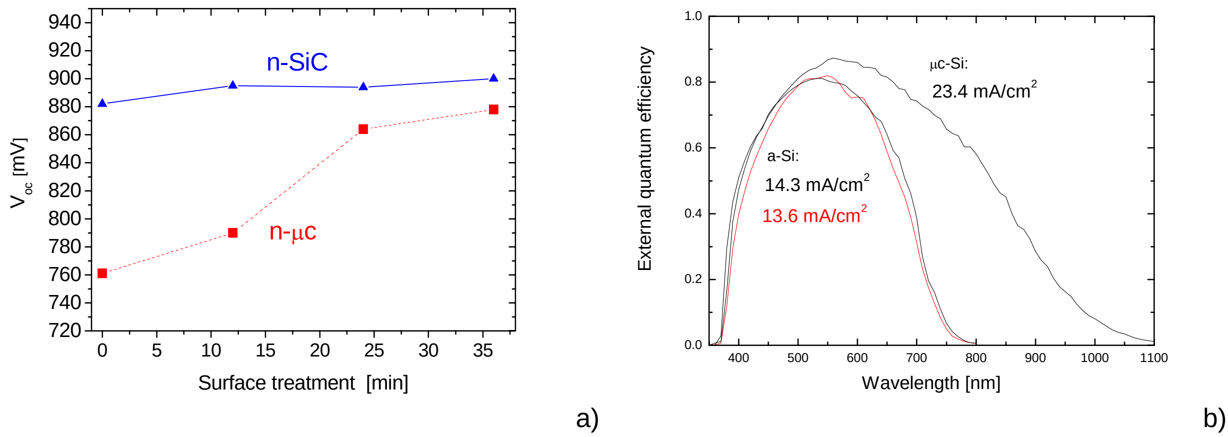


Fig. 17 a) Comparison of the open circuit voltage in cells with microcrystalline and amorphous n-layer with respect to substrate morphology (influenced by time of treatment). A reference cell on flat substrate yields an open circuit voltage of 890 mV. b) External quantum efficiencies of amorphous cells on flexible substrates (random and periodic texture), and of a microcrystalline cell on the periodic texture.

In the area of microcrystalline cells, we were able to further improve the efficiency by introducing dilution grading during the deposition of the i-layer. This procedure compensates the fact that during growth at constant dilution the crystallinity of the layers increases throughout the film. Thus, without grading, an i-layer may be too amorphous in the beginning and too microcrystalline towards the end of the deposition. With dilution grading we obtained a cell efficiency of 8.6% on the flexible plastic substrate with a 2D periodic texture, which is a remarkably high value for a cell deposited on aPET/PEN substrate (to our knowledge the highest value). A current of 23.4 mA/cm2 is found for such a cell and is given in Fig. 17b. Table 2 summarises some of the best results obtained in the project.

	Voc [mV]	**jsc [mA/cm2]**	**FF [%]**	**η [%]**
amorphous (random)	888	14.3	70	8.8 (initial)
amorphous (periodic)	841	13.7	62	7.2 (initial)
microcrystalline	520	23.4	71	8.6 (stable)

Table 2: Solar cell parameters of typical n-i-p single junction amorphous on random and periodic substrate and microcrystalline solar cells on the 2D periodic substrate (initial values for the amorphous cell). All cells are on PET/PEN substrates.

3.3 TRANSPARENT CONDUCTING OXIDES

Introduction

High quality TCO's are required for the fabrication of high efficiency devices. In the one hand, the work has focused on the deposition and optimization of ITO (top TCO for cells on flexible substrates) and ZnO layers (used as front TCO, intermediate reflector or back-reflector) fabricated in the new sputtering system at IMT. The work is not reported here.
On the other hand, the work with Boron doped ZnO layers deposited by Low Pressure Chemical Vapour Deposition (LP-CVD) has been continued. These layers can be used both as front electrode and as back electrode in amorphous, μc-Si and micromorph devices [Fay05]. A special effort was made to achieve a high reproducibility in the fabrication of the layers and control procedures were implemented. This section 3.3. focuses on the work done on the LPCVD ZnO.

Modification of free carrier absorption and increase in haze

The work with LPCVD ZnO focused, in 2005, on the preparation of layers with tailored properties, (e.g. Fig.18) such as surface roughness and light scattering capabilities [Ste05, Fay05B]. In particular, highly diffusive layers with low sheet resistance and reduced free carrier absorption in the IR part of the spectrum could be prepared. The influence of the TCO surface morphology on the current collection of micromorph devices with intermediate reflector was systemically investigated [Dom05] and it could be shown that a high surface roughness, which increases the current collection in the bottom micromorph cell is compatible with the use of thin intermediate reflector. It could also be shown that, without careful process optimization, the fill factor and V_{oc} of p-i-n microcrystalline solar are reduced on substrate with higher roughness [Feit05]. By taking advantage of the flexibility of the LP-CVD ZnO process, and by a careful optimization of the µc-Si:H layers, µc-Si:H solar cell efficiencies of 9% were obtained, as well as micromorph cells with initial efficiency of 11.6%. In the following two years, by improving the surface morphology and adapting further the TCO, remarkably high values for µc-Si cells and micromorph cells could be obtained, as discussed in part 3.1. Finally, the developed TCO could also be implemented for several tests for the n-i-p solar cells both on glass and plastic substrates.

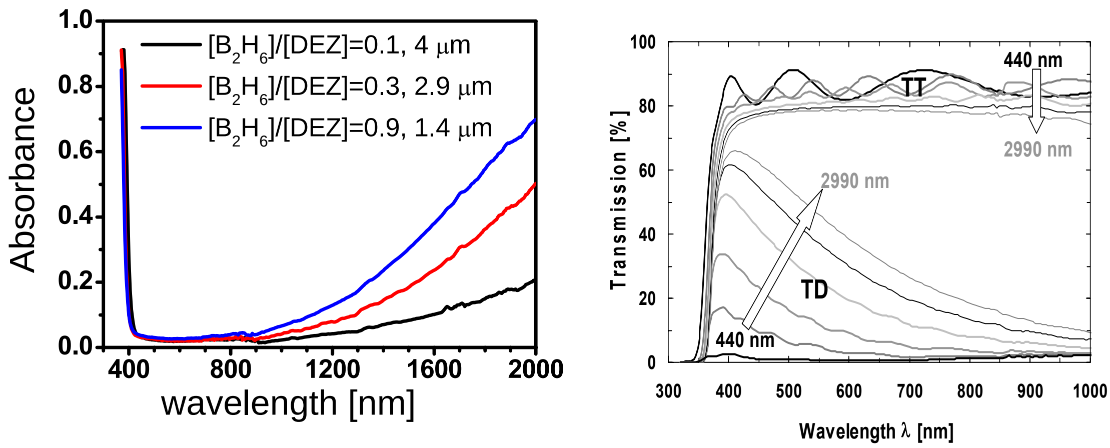


Fig. 18: a) Absorbance curves for LPCVD ZnO series deposited with various doping ratios (i.e. B_2H_6/DEZ ratio). All Layers with10 Ω sq.[Ste05].b) Total and diffuse transmittance as a function of wavelength for different grain sizes of the films.

Process reproducibility

In a second part, the work on LP-CVD ZnO focused on improving the reproducibility of deposition processes of two kinds of front electrode: one for efficient light scattering for amorphous silicon solar cells (up to 800nm), and the other for microcrystalline and micromorph silicon solar cells (up to 1100nm). This improved reproducibility of the LP-CVD deposition process is of prime importance to conduct comparison studies of fabrication processes of solar cells over a wide range of time (several months or years). Furthermore, deposition rates were also drastically improved (with a factor of almost 3), by increasing the vapour flow rates and finely adjusting the substrate temperature during the process in order to stay within the optimal range of deposition conditions that lead to optimized rough TCO films.

Grain boundaries role in LPCVD-ZnO

In parallel to this work of process optimization, a detailed study has been carried out, which focused on the influence of the grain boundaries on the transport mechanisms within the LP-CVD ZnO films. Electron mobility was found to be directly influenced by the size of the grains, and therefore by the scattering that occurs at the grain boundaries (i.e. the larger the grains the higher the electron mobility and hence, the lower the ZnO film resistivity) in the case of slightly doped ZnO films. For strongly doped ZnO films, the electron mobility is rather limited by the scattering within the grains [Ste07, Fay07]. As increasing too much the doping level of the ZnO films will increase the absorption of these films, it is evident now that the resistivity of the ZnO films should be lowered rather by increasing the grain size and keeping the doping level low, than by increasing the carrier concentration with higher doping level.

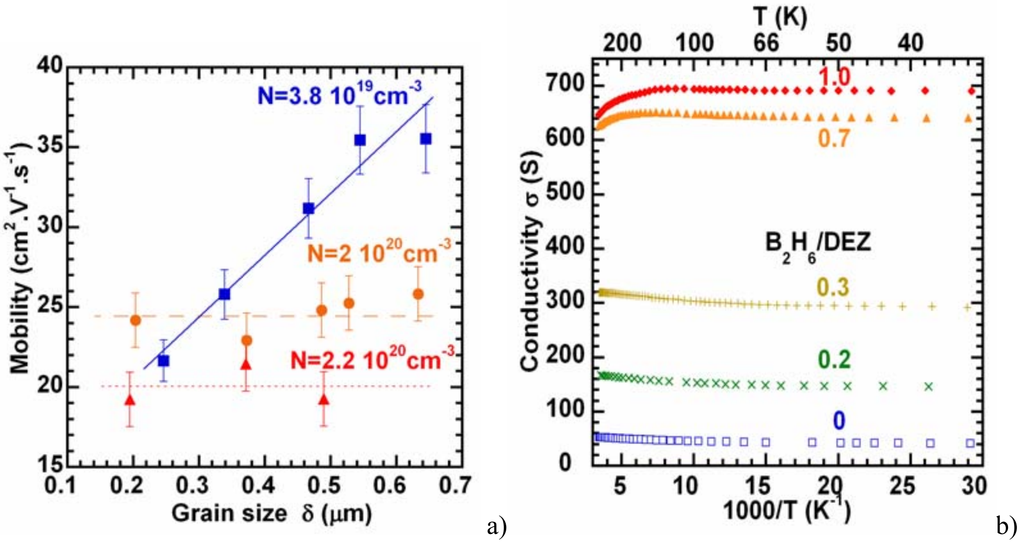


Fig. 19: a)Hall mobility as a function of grain size for LP-CVD ZnO films with carrier concentration (N) of $3.8x10^{19}cm^{-3}$ (full squares), $2x10^{20}cm^{-3}$ (open circles) and $2.2x10^{20}cm^{-3}$ (open squares) [Ste07]. b) Conductivity as a function of temperature for ZnO films with various doping [Myo07] .

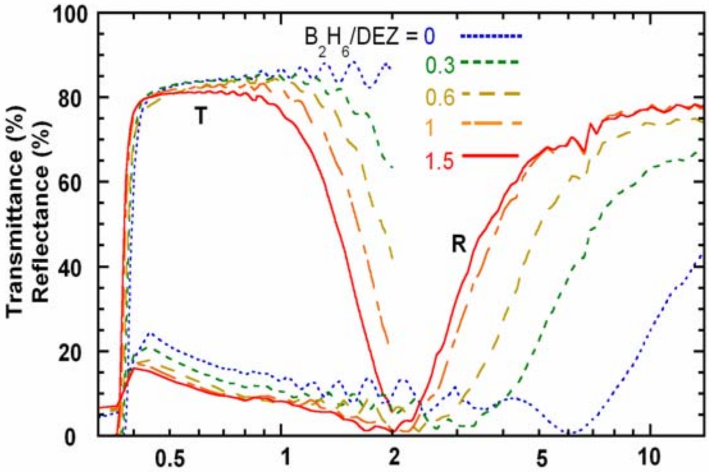


Fig. 20: full transmittance (0.3-2µm) and reflectance spectra (0.3-12 µm) of ZnO films with various doping

Optical reflectance spectra in the Near Infra-Red (NIR) wavelength range of LP-CVD ZnO (fig.20) were fitted with theoretical curves that were based on the Drude model, as shown in Fig. 21a. This fitting allowed us to extract the value of the electron mobility within the large conical grains that compose the ZnO films. This “optical mobility” was then compared with the electron mobility measured by Hall effect, which gives the mobility value of the electron through the whole layer. This comparison allows one to separate the effect of grain boundaries (inter-grain) from the effect of bulk (intra-grain) on the conduction mechanisms within the polycrystalline ZnO films [Ste07A]. In Fig. 21b, the optical and Hall mobility are plotted versus the carrier density N. This graph shows that in lightly doped ZnO films (i.e. $N < 1.10^{20} cm^{-3}$), the electron mobility is limited by grain boundary scattering ($\mu_{opt} \neq \mu_{Hall}$), whereas for heavily doped ZnO films (i.e. $N > 1.10^{20} cm^{-3}$), the electron mobility is limited by scattering within the grains ("bulk" scattering).

We had demonstrated in previous works that TCO with high mobility are mandatory to get materials transparent and conductive enough for microcrystalline and micromorph solar cells. The graph of Fig. 18a indicates that this kind of TCO with high mobility can be obtained at low doping level (i.e. low carrier density) and by increasing the grain size as much as possible. This allows a reduction of the grain boundary density and therefore the detrimental effect of grain boundaries on electron mobility, whereas the intra-grain mobility in the grain remains at a higher level, as there are less scattering centres (e.g. dopants). Finally all the findings, optical and electrical (Fig. 19b) are found compatible with our model and are described in more details in [Ste07].

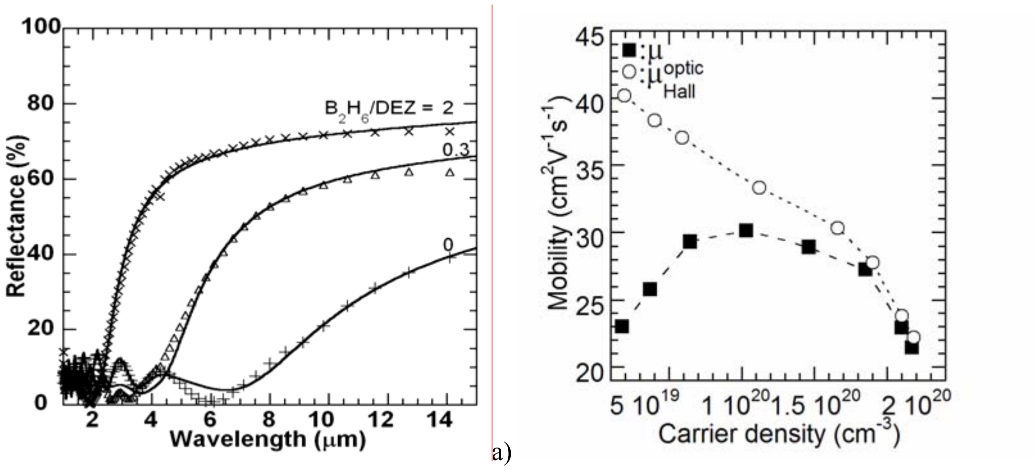


Fig.21: a) Infra-red reflectance spectra as a function of wavelength for ZnO films with various doping. b) Optical and Hall electron mobility as a function of carrier density N in the LP-CVD ZnO films.

Finally, using the same comparison method between μ_{opt} and μ_{Hall}, we were also able to observe that the degradation of the ZnO films submitted to damp-heat treatment occurs mainly at the grain boundaries. Indeed, the optical mobility is not altered during the damp-heat treatment, whereas the Hall mobility is strongly decreased [Ste07C]. We could also show that unprotected strongly doped films have very little degradation in standard damp heat tests. A heavier doping of ZnO layers enhances the tunnelling through potential barrier at grain boundaries and leads to more stable films. In addition, post-deposition treatments also influence the damp heat stability of the film. By applying a suitable treatment, a much slower creation of defects at grain boundaries can be achieved.

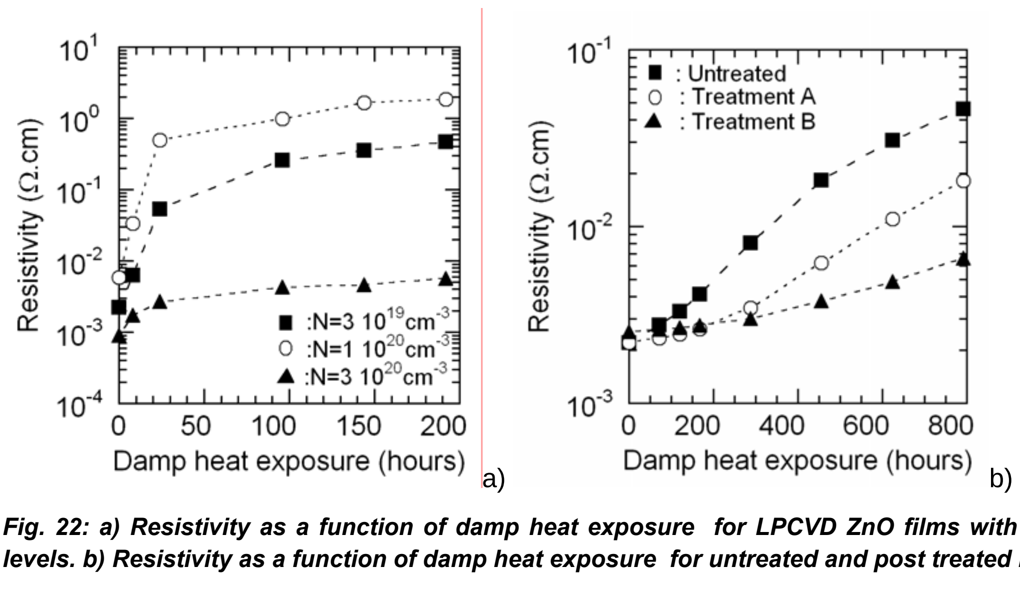


Fig. 22: a) Resistivity as a function of damp heat exposure for LPCVD ZnO films with different doping levels. b) Resistivity as a function of damp heat exposure for untreated and post treated LPCVD ZnO.

Perspectives

In the last three years major improvement in the growth and doping control, in the process reproducibility, and tailoring of the front TCO properties were achieved. The findings could be used both for doing high-efficiency cells on glass, as well as for developing devices on plastic. This work, as well as the work on the ideal morphology for growth of thin film Si have lays the bases for subsequent improvement of the TCO layers and globally of the glass/TCO system. Several innovative ideas will be worked out in the frame of the next project.

3.4 ADVANCED CHARACTERISATION OF SOLAR CELLS

Summary

Even though many of the new tools described in the next sections are used on a daily bases, we shortly report on some specific investigations.

This included the noticeable following results:

- Evidencing for the first time a new defect kinetics in microcrystalline Si cells with different crystalline fraction as detected by the technique entitled Fourier Transform Photocurrent Spectroscopy [Mei05,Mei08].
- Making first quantitative analyses of the role of micro-shunts caused by crack/porosity in microcrystalline cells grown on rough substrates [Pyt07]
- Imaging in an innovative way the electronic properties of μc-Si solar cells, using local probe techniques, and confirming the complex electrical structure of such p-i-n devices [Dom07].

Even though many of the new tools described in the next sections are used on a daily bases, we shortly report on some specific investigtions.

Defects analyses in microcrystalline cells

The FTPS measurement technique allows the measurement in a highly sensitive way (over 6 decades) of the absorption coefficient of the Si-based material incorporated as the active layer of the solar cell. In the sub-bandgap region, this coefficient is in principle directly proportional to the defect density. The influence of light induced degradation on the defect density of the i-layer has been investigated [Mei05a, Mei05b]. It leads to a ~ 5 to 10 fold increase of the defect density in 90% amorphous i-layer whereas the defect density increases by a factor less than two in mixed amorphous-microcrystalline i-layers (deposited within the amorphous/microcrystalline transition).

Dilution series of pin and nip single-junction microcrystalline silicon (μc-Si:H) solar cells were also light-soaked (AM 1.5, 1000h at 50°C) and subsequently annealed at increasing temperatures. The variations of sub-bandgap absorption during light-soaking and thermal annealing were monitored by Fourier Transform Photocurrent Spectroscopy (FTPS). By successive annealing, the light-induced defects are progressively annealed out. Fig. 23a shows clearly that the decreasing absorption coefficient leads to an increasing fill-factor of the solar cell. This observed behaviour clearly indicates that ultimately (e.g. when shunting is not a determinant factor), a high i-layer material quality, with a low defect-related absorption coefficient, is determinant for the FF of the whole solar cell. Note however that in the particular cases of Fig. 23a, some solar cells were not optimized (dilution series) which leads to lower initial values of the Fill factor (~ 55%) and a larger increase of defect density under illumination. High quality microcrystalline silicon solar cells can now routinely be deposited in the laboratory with FF values as high as 72% and a low defect density.

The kinetics of these variations were also shown to follow stretched exponential functions over a long span of time such as 1000 hours. The light-soaking behaviour of microcrystalline silicon is thus very similar to that of amorphous silicon. The effective time constants appearing in the stretched exponential function depend on the crystalline volume fraction as well as on temperature, but they are characterized by a unique value of the activation energy. The defects are thought to be at the surface of the nanocrystals [Mei08].

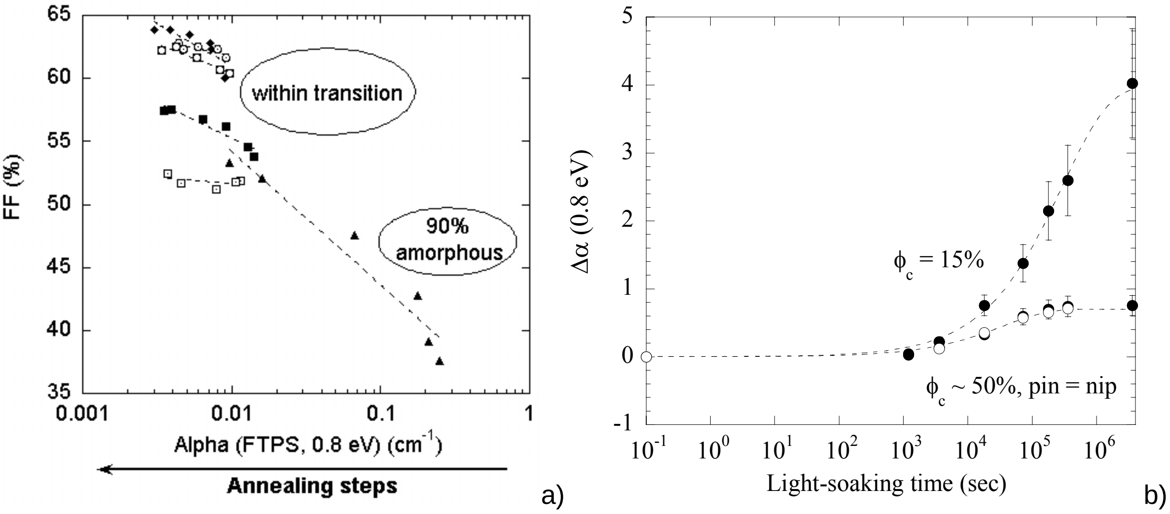


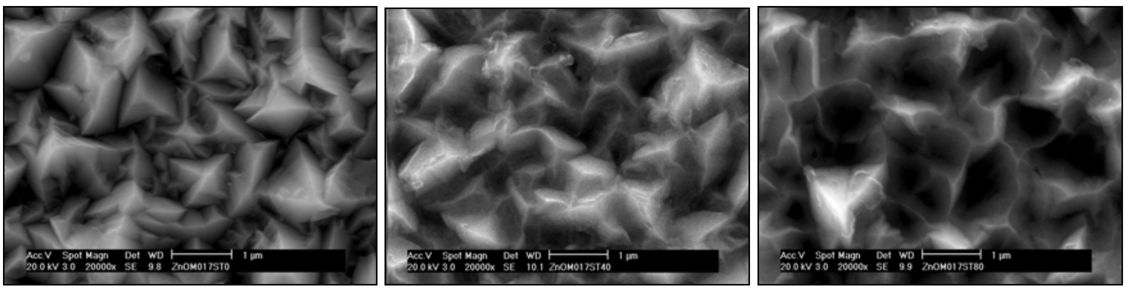
Fig. 23: a) FF of solar cells as a function of defect densities measured by FTPS, for μc-Si solar cells with different crystalline fraction. b) Relative increase of defect-related absorption as a function of light-soaking time for three μc-Si:H solar cells (nip: black dots, pin: empty dots), with i-layer Raman crystallinity factors ϕc = 15% and ϕc ~ 50%. The dotted lines are fits according to Eq. (2).

Microcracks in layers and solar cells

For various amorphous, microcrystalline and micromorph devices on glass and plastics, the influence of the substrate morphology on the solar cell growth and performance was studied in detailed. We give here an example of such a study [Pyt07].

The structural and electrical performances of µc-Si single junction solar cells co-deposited on a series of LP-CVD ZnO substrates having different surface morphologies-varying from V-shaped to U-shaped valleys were analysed (Fig. 24 top). Transmission Electron Microscopy (TEM) was used to quantify the density of cracks within the cells deposited on the various substrates (Fig. 25 bottom). Standard 1-sun, Variable Illumination Measurements (VIM) and Dark J(V) measurements were performed to evaluate the electrical performances of the devices. A marked increase of the reverse saturation current density (J_0) is observed for increasing crack densities. By introducing a novel equivalent circuit taking into account such cracks as non-linear shunts, as illustrated in Fig. 25 a and b, we were able to relate the magnitude of the decrease of V_{oc} and FF to the increasing density of cracks [Pyt07].

The major output of these investigations is that the substrate morphology can to a large extent govern the solar cell properties: it can enhance the light trapping (desirable) but also create parasitic diodes which decrease the efficiency. Our results show that for each kind of solar cells a different optimum geometry must exist, that allows simultaneously light trapping and good electrical properties. Noticeably though, the best substrates geometries have not been fully identified yet, and certainly not fabricated.



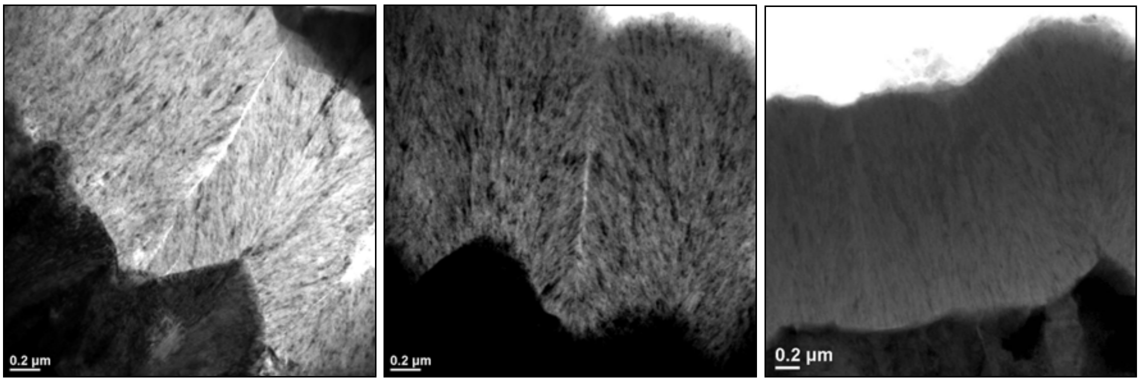


Fig. 24: Top) SEM micrographs of ZnO surface. Bottom) Bright Field TEM cross-section micrographs of µc-Si:H pin on substrates treated with increasing plasma treatment time (Left 0 min // Middle 40 min // Right 80 min). For 40 min of treatment, the cracks do not cross completely through the p-i-n device (compare with sample t=0min), but only begin after the first third of i-layer

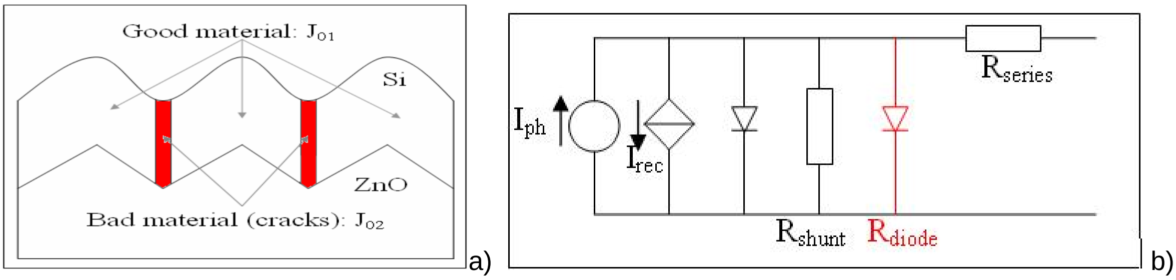


Fig. 25: a) sketch of silicon growth on rough ZnO: cracks are located above the valleys between the substrate's pyramids. b) corresponding equivalent electrical circuit for µc-Si:H solar cells

Local probe investigations of µc-Si solar cells

Advanced studies on the local electrical properties of cross-section of microcrystalline cells have been undertaken, based on Scanning probe Kelvin Microscopy. The work was performed in part at the NREL, in the analytical microscopy group (Direction. M. Al-Jassim). The results confirm the complicated interaction between the substrate and growing PECVD cells.

More specifically, scanning Kelvin probe microscopy (SKPM) was performed on cross-sections of microcrystalline silicon (µc-Si:H) p-i-n solar cells deposited on a surface-textured ZnO layer. Cross-sections were either prepared by a simple fracture procedure or by mechanical polishing. Profiles of the variation in the electric-field induced by different bias voltage (V_{bias}) applied to the cell were deduced from SKPM potential measurements by calculating the first derivative of the modification of the surface potential profiles. The amplitude of the V_{bias}-induced electric-field was found to be heterogeneously distributed over different µc-Si:H clusters, as illustrated in Fig. 25. From these measurements,

we suggest that each cluster behaves as an "isolated nanodiode", the electric-field changes being mainly confined within ~500 nm in the intrinsic µc-Si:H layer either near the p-i or near the i-n interface. This supports the assumption of an important contribution of diffusion-assisted transport along the growth axis of the large crystalline nanograins observed by transmission electron microscopy (TEM) in the µc-Si:H clusters. A comparison of SKPM images with a TEM micrograph demonstrates that cluster boundaries in the intrinsic µc-Si:H layer can be imaged by the SKPM technique. Fig.26 right, shows, after subtraction, the apparition of the clusters, similar to what is observed in the TEM cross section of similar samples (Fig. 26 right top). For more details, the interested reader can refer to [Dom07].

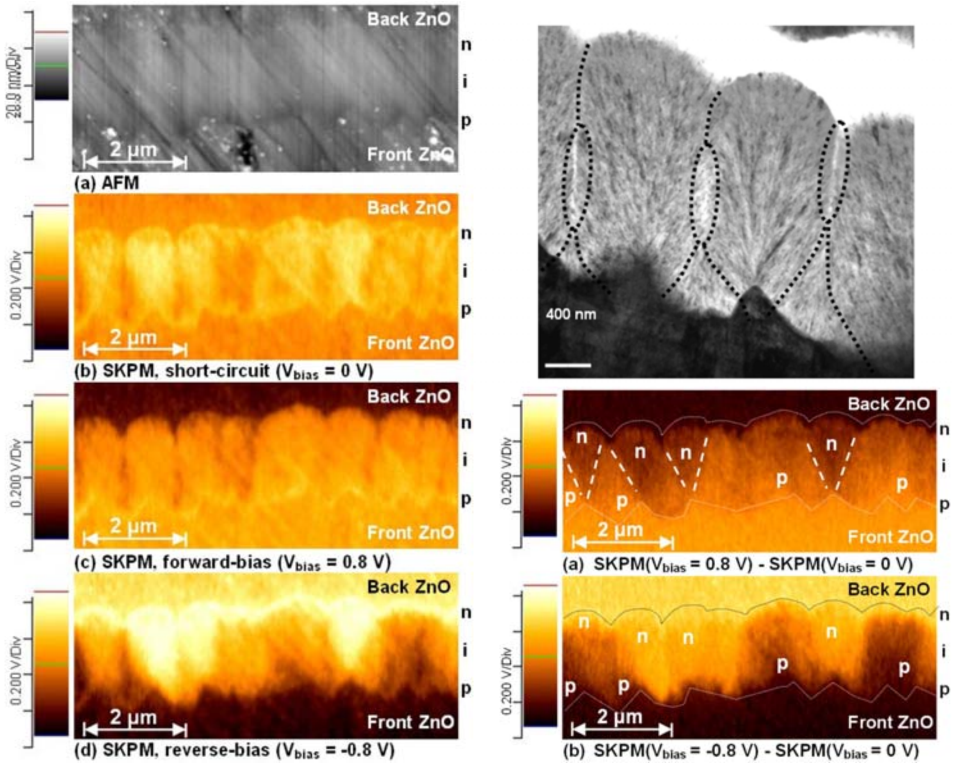


Fig. 26: Left) (a) Atomic force microscopy (AFM) image and the corresponding SKPM images taken under (b) short-circuit, (c) forward-bias, and (d) reverse-bias conditions on a polished cross-section of a µc-Si:H p-i-n solar cell. right) Subtraction of the SKPM image taken under short-circuit condition from the SKPM images taken under (a) forward-bias, and (b) reverse-bias conditions. Top. Bright-field TEM micrograph of a µc-Si:H p-i-n solar cell deposited on a LPCVD ZnO layer.

3.5 NEW CHARACTERIZATION TOOLS

Introduction and summary

Although the objective of the project is to contribute finally to the technological development necessary for lower cost photovoltaic, it is necessary to possess the right investigation tools. These tools should allow the experimentalists to obtain a fast feed back on the quality of the layers, of the devices, and to perform systematic quality controls.

- As planned, IMT made an active use of two techniques installed in 2004: the VIM (variable illumination measurement) technique, which in a simplified form, became a standard measurement, and FTPS (Fourier transform photocurrent spectroscopy) which has been established in the laboratory as a standard tool for measuring the material's quality of the i-layer incorporated into solar cells.
- In addition, an infrared lock-in thermography (IRLIT) -system has been installed. This is a versatile tool that allows the visualisation of short-circuits or the detection of areas with enhanced recombination current. Thermal resolution down to a few tens of micro-Kelvin, and spatial resolution below 50 µm are achievable (Fig.7b).
- Finally several new tools were upgraded, with an attempt to unify the format of data and operating softwares (Labview)

VIM

With the **VIM** technique, one measures the I(V) curves of the thin-film solar cell under very high illumination down to very low illuminations, instead of measuring it only under the standard 1 sun (100 mW/cm^2) illumination. In this way, both parallel and series parasitic resistances can be evaluated. The parallel resistance R_p is typically related to shunts (short-circuits) such as dust particle or structuration issues, whereas the series resistance R_s is related to contacts quality and intrinsic material resistivity. By performing low light intensity measurements (typically at 0.4 mW/cm^2), the parallel resistance plays a pre-eminent role, if its value is too low. In such a case, the Fill-Factor of the I(V) curve of the solar cell drops to very low value. On contrary, in a solar cell with a good R_p, the Fill-factor remains almost constant down to very low illumination intensities. Thus I(V) curves acquired at low illumination are now used systematically to diagnose whether shunting of the device is severe or not.

FTPS

The **FTPS** measurement technique allows the measurement in a highly sensitive way (over 6 decades) of the absorption coefficient of the Si-based material incorporated as the active layer of the solar cell. In the sub-bandgap region, this coefficient is in principle directly proportional to the defect density.

- The influence of light induced degradation on the defect density of the i-layer has been investigated [Mei05A, Mei05B]. The kinetics of defect creation and annealing in µc-Si cells were determined [Mei08] (see previous chapter)
- In the large area Kai reactor, systematic investigations of material quality were performed to determine the process quality [Bug08]..
- The influence of substrate morphology on growth of layers and related FTPS spectra was analysed.

IR-Lock-in thermography

The IR-Lock-in thermography technique allows the lock-in detection of pulsed heat sources. Each pixel of the camera serves as a lock-in, and the thermal resolution of the camera can be decreased from typicall 20 mK to 20 µk. In the frame of the project, a high resolution optical microscope was coupled to the IR-camera, to allow an optical analysis of the defects. In some cases, SEM and subsequent cross-section cutting by focused ion beam (FIB) were performed to further identify further the nature of the defects, such as the types of particles creating the shunts. As shown in Fig. 27b) this technique is extremely powerful and allows the identification at the micrometer scale of virtually all defects.

Hence, this system was used intensively during the project to detect device failures caused by lift-off process, by in-situ or ex-situ particle problems, by laser scribing. Fig. 27 illustrates the different cases.

Other upgrades of equipment

A continuous effort was made for the upgrade or setting-up of several more conventional measurement techniques including:

- An Hall effect setup has been upgraded with new electronics to allow faster and more accurate characterization of the mobility in TCO's
- A set-up was refurbished to allow a measurement of the TCO’s resistance as function of temperature (10-350°K)
- Acquisition software and hardware for spectral response and IV curve measurement have been continuously improved
- A fully functional IV curve measurement system with LABVIEW interface and with measurement set-up for up to 16 cells simultaneously, with automatic measurements at low illumination level.
- A state-of-the-art spectral response system with LABVIEW interface and faster measurement capabilities.
- An improved dark conductivity measurement setup (used e.g. for the development of doped layer) with LABVIEW control, allowing the simultaneous measurement of up to 4 samples and consequently a strong reduction of the measurement time per sample (usually several hours).

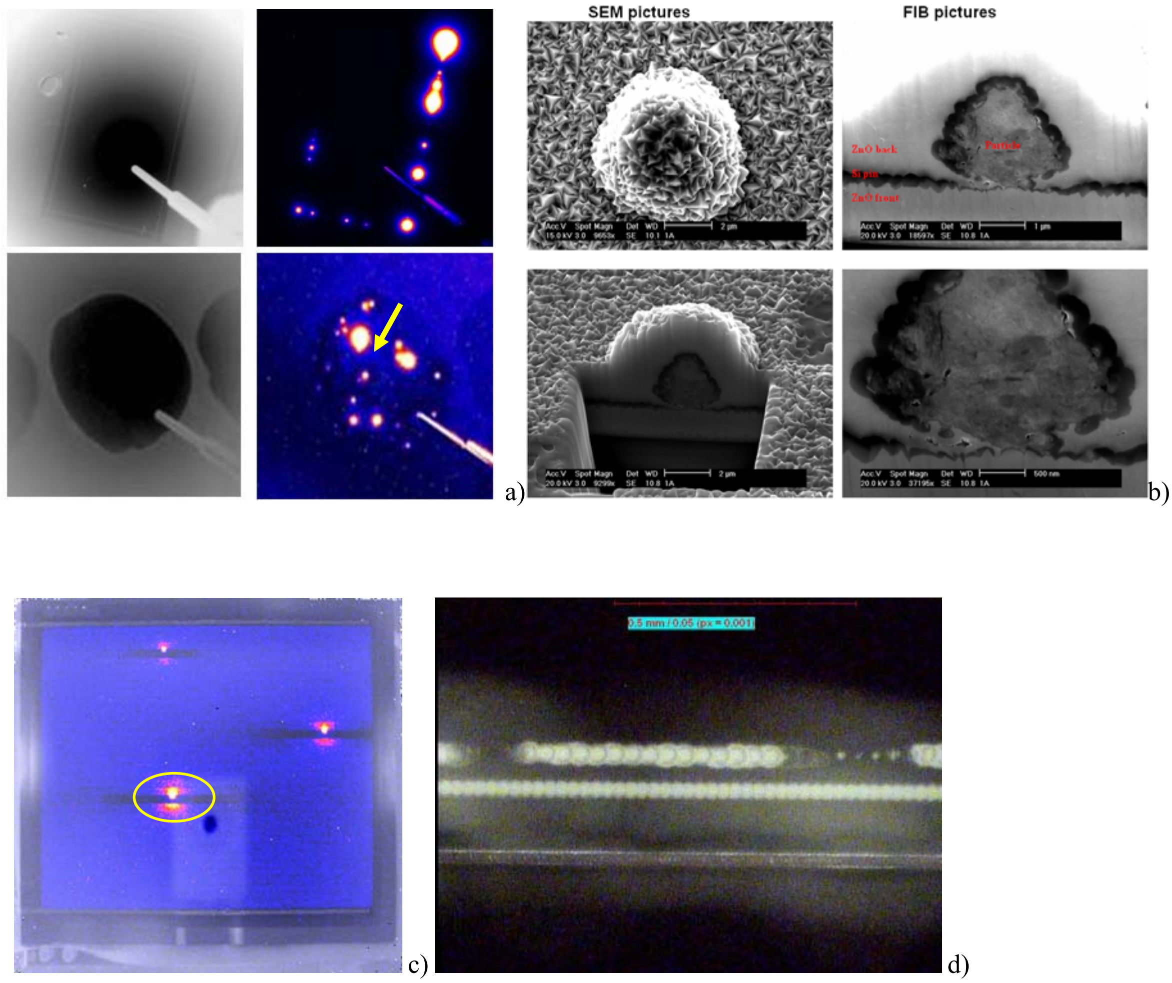


Fig. 27 a) IR and IR-Lock-in images of two types of shunts, one linked to scribing (top) and one linked to particles (bottom). The temperature scale for the IRLIT image is 3 mK. b) Zoom on the defect with the arrow of a), showing a particle covered with ZnO. The particle is cut using a FIB. c) Modules with localised shunts. An optical analysis of shunt A reveals missing laser pulses on the laser scribing line.

3.6 GENERAL LABORATORY INFRASTRUCTURE

Major realisations

An extensive range of fabrication systems are available at the IMT PV lab. Several systems had to be upgraded in order to fill the requirements of a modern research lab.

The goal was to improve process reproducibility and to be able to prepare innovative devices in a more efficient manner (e.g. less time consuming, better control).

The major changes can be summarised as follows

- A new sputtering system for 6" substrates, with three targets, was installed in 2005. The system can be operated in RF or DC mode. All basic process for the fabrication of high quality metal (Ag, Al) and TCO (ITO, ZnO) layers have been established.
- The gas systems and pumping of the two LPCVD ZnO deposition chambers were decoupled, allowing a more effective combination of TCO research and layer supply for the other groups.The two chambers for LPCVD-ZnO fabrication can now be run independently
- The Kai-S large area deposition system (Kai-S) was partly automated and basic process monitoring was introduced.
- A new deposition system by VHF-PECVD for thin film silicon solar cells on large substrates (420x510mm) was constructed with a partial financial support by the SFOE (Project 101417). This system, the conception and assembly of which are completely executed at IMT, is composed of 2 deposition chambers equipped with PLASMABOX® (supplied by OC Oerlikon) and

a central load-lock and transfer chamber, as shown in Fig. 28. A free opening for a third reactor chamber is also available. The system is fully automated to permit the fabrication of multilayer solar cells and the systematic data logging of all important plasma parameters. This system is functional since September 2007 for its first chamber, whereas the second chamber is being installed now.


a)

b)

Fig. 28: View of the new fully automated large-area cluster system at IMT. a) Status end 2006. b) Status September 2007. One chamber is fully operational whereas the second plasma box is being installed at the time of writing this report.

Perspectives for the infrastructure

In 2008, an intense effort is undertaken to continue the modernization of the infrastructure of the PVLAB. Thanks to a special credit of the State of Neuchâtel, two new automated PECVD cluster systems, a new sputtering system, and a new spectral ellipsometer will be installed. The systems will be ramped-up, in large part within the frame of a new project sponsored by the SFOE. These new instruments should boost the research effort (higher throughput, higher reliability, improved process control) and contribute to the competitiveness of the thin film technology. Thanks to the support of the University of Neuchâtel, of the Institutes of Physics and Microtechnology, the PV-Lab was able to secure 255 m^2 additional facilities.

In parallel to project on which we report, IMT launched in 2007 a new activity in the field of module technology, thanks to a support and collaboration with the company 3S. A fully equipped lab with laminator, large area solar simulator, soldering equipment, large area climatic chamber, UV degradation testing, and various other module tests will become operational in the next months. This new laboratory will target R&D in the field of reliability, embedding processes, with emphases on thin films.

3.7 COLLABORATION AND SYNERGIES WITH OTHER PROJECTS/ VARIOUS

National collaboration with industrial and academic project partners was intensive, markedly on the industrial side with OC Oerlikon and VHF-Technologies. Regular academic contacts/scientific and sample exchanges have been maintained throughout the project both with national (CRPP-EPFL, EMPA, HE-Arc,..) and international entities (University of Ljubljana, University of Patras, IPV Juelich, Academy of Science of Prague, ECN….). IMT was one of the instigators of the Swiss thin Film PV project, coordinated now by EMPA (Sponsored by CCEM-CH and Swiss Eletric Research.

IMT continues to be involved into the European projects ATHLET and FLEXCELLENCE. A strong synergy is realized between all these projects and this running SFOE project, with indirect benefits for companies such as OC Oerlikon and VHF-Technologies. A project (1.3.2006-28.2.2008) with the Danish company “Photosolar” financed by Energienet.dk continues to allow synergy for nip devices development.

Starting 2007, IMT organized several “Thin film PV schools” for industries. These schools last 5-9 days and offer an in-depth introduction to the science and technology of thin film silicon. This is a requisite for the fast growing thin film Si industry.

4 Conclusion and outlook

During the project, new key knowledge was generated. It is now useful for all thin film silicon devices, prepared both on glass and plastic. In general, we have now much better tools (receipts, processes, TCO's, backreflector) in hands to fabricate high efficiency devices on a variety of different TCO's or substrates, and this with different device concepts. In particular, micromorph solar cells on glass with initial efficiency significantly above 12% can be routinely prepared and this can be achieved either with devices with a high Voc and FF and limited current or with higher current but limited Voc and FF. The reasons for the difficulty to achieve simultaneously both high V_{OC} x FF and current are now understood. This gives clear guidelines for the next steps. By using additional layers and by device optimisation, record micromorph devices are in sight. Also high quality microcrystalline cells are now mastered on plastic and glass substrates.

In summary, all the major milestones of the project were achieved. All solar cells devices could be improved, a significant gain in understanding the complex interaction between substrate and cell has been realised. New processes, new layers have been successfully integrated into devices. In parallel, a significant upgrade of the lab infrastructure could be realised.

Several findings of this project are now continued either in the form of CTI projects or direct mandates with industrial partners.

Taking into account all the improvement to the laboratory infrastructure realized in 2005-2007 and the full range of new processing equipment to be delivered in 2008, the PV-Lab of IMT, counting now 35 employees, is on its route to become an integrated lab with excellent perspectives for innovation in PV! It will continue its work with the development of high efficiency devices and development of processes which will be relevant for the next generation production lines based on thin film silicon. IMT will continue to provide support to Swiss companies active in PV, thereby contributing in the short-term to job creation and in the medium to long term to the production of multi-gigawatts efficient and low cost PV modules.

Acknowledgements

We thank the PV-Lab personnel for providing all necessary results and documents for this report. Special thanks are addressed to J. Bailat, P. Buelhmann, D. Dominé, S. Faÿ, A. Feltrin, F.J. Haug, M. Python, F. Sculati-Meillaud, T. Söderström J. Steinhauser, and R. Tscharner.

References

Notes: most of these references acknowledge the SFOE support for the project 101191. Preprints of most papers can be downloading from www.unine.ch/pv.

[Bail05] "Recent development of solar cells on low-cost plastic substrates," J. Bailat, V. Terrazzoni-Daudrix, J. Guillet, F. Freitas, X. Niquille, A. Shah, C. Ballif, T. Scharf, R.Morf, A. Hansen, D. Fischer, Y. Ziegler, A. Closset, Proc. of the 20th EU PVSEC, Barcelona, Spain, 2005.

[Bai06] "High-efficiency p-i-n microcrystalline and micromorph thin film silicon solar cells deposited on LPCVD ZnO coated glass substrates", J. Bailat, D. Dominé, R. Schlüchter, J. Steinhauser, S. Faÿ, F. Freitas, C. Bücher, L. Feitknecht, X. Niquille, T. Tscharner, A. Shah, C. Ballif, Proceedings of the 4th WCPEC Conference, Kona Island, Hawaii, USA , pp. 1533-1536, 2006.

[Bai07] "Thin film silicon solar cells: latest developments in Europe", J. Bailat, D. Dominé, P. Buehlmann, T. Söderström, F. J. Haug, V. Daudrix-Terrazzoni, N. Wyrsch, J. Steinhauser, S. Fay and C. Ballif, Technical digest of the 17th PVSEC conference, Fukuoka, JP, 2007.

[Bal06] "Fabrication of High Efficiency Microcrystalline and Micromorph Thin Film Solar Cells on LPCVD Zno Coated Glass Substrates", C.Ballif, J.Bailat, D.Dominé, J.Steinhauser, S.Faÿ, M.Python, L.Feitknecht, p. 1552, Proceedings of the 21th EU PVSEC, Dresden, Germany, 2006.

[Bue07A] "In situ silicon oxide based intermediate reflector for thin-film silicon micromorph solar cells", P. Buehlmann, J. Bailat, D. Dominé, A. Billet, F. Meillaud, A. Feltrin, and C. Ballif , Applied Physics Letters, Vol 91 , 2007.

[Bue07B] "Anti-reflection layer at the TCO/Si interface for high efficiency thin-film solar cells deposited on rough LP-CVD front ZnO", P. Buehlmann, A. Billet, J. Bailat and C. Ballif, Proc. of the 22th EU-PVSC, Milan, It, 2007.

[Bug08] G. Bugnon et al. to be presented at the 33rd IEEE Photovoltaic Specialist Conference, in San Diego, California, USA.

[Dom05] "Effect of ZnO Layer as Intermediate Reflector in Micromorph Solar Cells", D. Dominé, L. Feitknecht, A. Shah, C. Ballif, Proc. of the 20th EU PVSEC, Barcelona, Spain, 2005.

[Dom06] “Micromorph solar cell optimization using a Zno layer as intermediate reflector”, D. Dominé, J. Bailat, J. Steinhauser, A. Shah, C. Ballif, Proceedings of the 4th WCPEC Conference, Kona Island, Hawaii, USA, pp. 1465-1468, 2006.

[Dom07] “Investigation of the electric-field profile in microcrystalline silicon p-i-n solar cells by cross-sectional scanning Kelvin probe microscopy”, D. Dominé, J. Bailat, M. Python, C. Ballif, Proc. of the 22th EU-PVSC, Milan, It, 2007.

[Fay05A] "Low pressure chemical vapour deposition of ZnO layers for thin-film solar cells: Temperature-induced morphological changes", S. Faÿ, U. Kroll, C. Bucher, E. Vallat-Sauvain, A. Shah, Solar Energy Materials and Solar Cells, 2005, Vol. 86, pp. 385–397.

[Fay05B] "ZnO Layers Incorporated into µc-Si :H Solar Cells : Quantum Efficiency (QE) Results and Proposal for a Figure of Merit", S. Faÿ, J. Steinhauser, R. Schlüchter, L. Feitknecht, C. Ballif, A. Shah, Tech. digest, 15th Int. PVSEC, Shanghai, China, 2005.

[Fay07] ”Opto-electronic properties of rough LP-CVD ZnO:B for use as TCO in thin-film silicon solar cells “, S. Faÿ, J. Steinhauser, N. Oliveira, E. Vallat-Sauvain and C. Ballif, Thin Solid Films, 515(2007), pp. 8558-8561.

[Feit05] "Investigations on Fill-Factor drop of microcrystalline silicon p-i-n solar cells deposited onto highly surface-textured ZnO substrates", L. Feitknecht, J. Steinhauser, R. Schlüchter, S. Faÿ, D. Dominé, E. Vallat-Sauvin, F. Meillaud, C. Ballif, A. Shah, Tech. digest, 15th Int. PVSEC, Shanghai, China, 2005.

[Gra05] Urs Graf, Phd. Thesis, University of Neuchâtel 2005.

[Hau07] “Development of Micromorph tandem solar cells on flexible low cost plastic substrates”, F. J. Haug, V. Terrazzoni-Daudrix, T. Söderström, X. Niquille and C. Ballif, ,Technical digest of the 17th PVSEC conference, Fukuoka, JP, 2007.

[Mei05A] "Light-Induced Degradation of Thin-Film Amorphous and Microcrytsalline Silicon Solar Cells", F. Meillaud, E. Vallat-Sauvain, X. Niquille, M.Dubey, J. Bailat, A. Shah, C. Ballif, Proc. of the 31th IEEE Photovoltaic Specialist Conference, Lake Buena Vista, FL, USA, 2005 pp. 1412-1415.

[Mei05B] "Light-Induced Degradation of Thin-Film Microcrystalline Silicon Solar Cells", F. Meillaud, E. Vallat-Sauvain, X. Niquille, M. Dubey, A. Shah, C. Ballif, Proc. of the 20th EU PVSEC, Barcelona, Spain, 2005.

[Mei08] “Kinetics of creation and of thermal annealing of light-induced defects in microcrystalline silicon solar cells“,F. Meillaud et al., Journal of Applied Physics **103** (5) (2008), 054504

[Myo07] “Temperature dependence of the conductivity in large-grained boron-doped ZnO films”, S. Yeop Myong, J Steinhauser, R. Schlüchter, S. Faÿ, E Vallat-Sauvain, A. Shah, A. Rüfenacht, C. Ballif, Solar Energy Materials & Solar Cells 91,(2007), 1269-1274.

[Pyt07] “Relation between Substrate Surface Morphology and Microcrystalline Silicon Solar Cell Performance “, M. Python, E. Vallat-Sauvain, J. Bailat, D. Dominé, A. Shah, and C. Ballif, Accepted for publication in Journal of Non-Crystalline Solids, 2007.

[Sod07] "Open-circuit voltage optimisation of amorphous silicon thin film solar cells for flexible photovoltaics", T. Söderström1, F.-J. Haug, V. Terrazzoni-Daudrix X. Niquille, S. Perregaux, M. Fahland and C. Ballif, Proc. of the 22th EU-PVSC, Milan, It, 2007.

[Sha05] "Microcrystalline and "Micromorph" Solar Cells and Modules: Status and Potential", A. V. Shah, J. Bailat, E. Vallat-Sauvain, M. Vanecek, J. Meier, S. Fay, L. Feitknecht, I. Pola, V. Terrazzoni, C. Ballif, Proc. of the 31th IEEE Photovoltaic Specialist Conference, Lake Buena Vista, FL, USA, 2005 pp. 1353-1358.

[Ste05] "Effect of Rough ZnO Layers in Improving Performances of Microcrystalline Silicon Solar Cell", J. Steinhauser, L. Feitknecht, S. Faÿ, R. Schlüchter, A. Shah, C. Ballif, J. Springer, L. Mullerova-Hodakova, A. Purkrt, A. Poruba, M. Vanecek, Proc. of the 20th EU PVSEC, Barcelona, Spain, 2005.

[Ste07A] “Transition between grain boundary and intragrain scattering transport mechanisms in boron-doped zinc oxide thin films”, J. Steinhauser, S. Faÿ, N. Oliveira, E. Vallat-Sauvain, and C. Ballif, Applied Physics Letters , Vol 90, pp. 142107, 2007.

[Ste07B] “Electrical transport in boron-doped polycrystalline zinc oxide thin films”, J. Steinhauser, S. Faÿ, N. Oliveira, E. Vallat-Sauvain, D. Zimin, U. Kroll, and C. Ballif. Physica status solidi a , Proc. of the E-MRS 2007.

[Ste07C] “Damp heat stability of LPCVD ZnO:B”, J. Steinhauser, S. Faÿ, D. Borrello, U. Kroll and C. Ballif, Technical digest of the 17th PVSEC conference, Fukuoka, JP, 2007.

[Ter06] “Characterisation of rough reflecting substrates incorporated into thin-film silicon solar cells”, V. Terrazzoni Daudrix, J. Guillet, F. Freitas, A. Shah, C. Ballif, P. Winkler, M. Ferreloc, S. Benagli, X. Niquille, D. Fischer, R. Morf, Progress in photovoltaics: Research and application , 2006..

[Val05] "Influence of the substrate's surface morphology and chemical nature on the nucleation and growth of microcrystalline silicon", E. Vallat-Sauvain, , J. Bailat, J. Meier, X. Niquille, U. Kroll, A. Shah, Thin Solid Films, 2005, Vol. 485, p.77-81.