ELECTRA-CLAD

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Contractor

ICP Solar Technologies UK Ltd

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SUMMARY

The Building integrated Photo-Voltaics (BiPV) market is now accepted as one of the most promising Photovoltaic (PV) applications, particularly in Northern Europe. Curtain walling elements, based on toughened glass have been developed, and are becoming widely used. This has generated a demand from the building products industry for further lower cost cladding materials incorporating PV. In particular there is increasing interest in the potential for sheet metal cladding elements to be available with a thin film PV surface.

The Electra-Clad project sought to utilise existing steel based building cladding materials as a substrate for direct fabrication of a fully integrated solar PV panel of equivalent design to the ICP standard glass based panel. This would represent a major step forward in BiPV panel manufacture if achieved and open up the substantial BiPV cladding market for later exploitation of the technology. It was planned that this would be achieved by the further development and productionisation of the Electra Clad technology, working in partnership with cladding manufacturers to develop a facility capable of producing at least 20MWp p.a. The time scales to achieve this were expected to be less than 5 years and no more than 10 years.

The nominal 3 year programme was progressed from January 2002 to August 2005, though with a 1 year suspension due to the liquidation in December 2002 of the Lead Contractor, Intersolar / British Photovoltaics Limited (BPL). The work was progressed under 5 interrelated Activities as follows:

A). Inverted Cell Deposition Development to develop the required inverted cell process on the a-Si deposition system based at Plasma Quest Limited (PQL).

B). Laser Patterning / Cell Isolation Development to develop laser patterning schemes that were able to meet the demands of the inverted structure.

C). Contact and ‘Barrier’ Layer Materials Development to identify and deposit materials for the substrate barrier layer and cell electrical contacts that were fully compatible with the inverted a-Si process.

D). Integration Studies to develop a monolithically integrated solar PV panel.

E). Bussbar and Encapsulation Studies to develop the basis for the techniques that would be required to ensure that integration into new and existing buildings could be readily achieved.

The project was successful in achieving most of the Activity objectives. Each of the process elements required for the Electra-Clad product has been developed and proven; these include the initially high risk steps of laser patterning, commercially viable inverted cell deposition, a low temperature front contact deposition process and electrical integration techniques. All have also been shown to be potentially consistent with production of a low cost commercial product.

Overall therefore the project has successfully demonstrated that the underlying principles of the panel design are sound and achievable. However, a wide range of trials and substantial development activity in the last 6 months of the project have failed to deliver a commercially realistic solar PV performance from the demonstrator product.

The main problem is evidenced by loss of solar conversion efficiency as the active area of the panel is increased in size. To date, only small ($1cm^2$) cells have shown the solar PV conversion efficiency that is required to make the Electra-Clad product commercially viable (i.e. above 3%).

The problem is assessed as resulting from the coatings used on the steel cladding substrates. We have now run trails using the full range of products in widespread building use, without success. It is clear that a new coating will need to be developed for the PV application; this work lies outside the scope of the project.

Subject to this being resolved, the required Electra-Clad elements are proven and in place. We have developed the required processes for good efficiency inverted a-Si based solar cells, compatible processes for the deposition of the contact layers, including a low temperature process for the TCO, the laser patterning required for cell isolation and monolithic integration, and the essential final electrical connection and encapsulation techniques.

Accordingly, further studies into identified alternate steel cladding and coating technologies are recommended to be pursued post project, as very rapid achievement of the required Electra-Clad commercial demonstrator could result once a successful coating is found.

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1. INTRODUCTION

The Building integrated Photo-Voltaics (BiPV) market is now accepted as one of the most promising Photovoltaic (PV) applications, particularly in Northern Europe. Curtain walling elements, based on toughened glass have been developed, and are becoming widely used. This has generated a demand from the building products industry for further lower cost cladding materials incorporating PV. In particular there is increasing interest in the potential for sheet metal cladding elements to be available with a thin film PV surface.

The market potential for this product is extremely large. At the time of project inception, the largest steel cladding sector, that of the industrial roof market, annually installed over 9.5 million square meters of material in the UK. The proportion of this available for PV installation was estimated to be in the region of 30% for existing buildings with low pitch roofs. The European market was approximately 10 times larger than for the UK alone (Information provided by Corus market research).

For a typical thin film PV panel output of 50Wp/sq.m, this equated to a potential annual demand of about 150MWp p.a. in the UK. Currently, this is an order of magnitude greater than planned ICP production by 2008.

Although coating of thin PV cells onto steel had already been accomplished by ECD (Canon), these were coated onto thin, almost foil type, substrates with a limited width and needed to be laminated onto cladding material. These were single cell devices and required a post fabrication interconnection process to link the cells together. Work had also been undertaken by IOWA Thin Films, with Swansea University, EETS and British Steel. Their product was not coated onto steel but a flexible substrate material, again a roll to roll process with a limited width. The major drawback with both of these processes was the need to laminate them onto a cladding material, which itself added cost and introduced further interfaces and interconnection costs.

ICP Solar already fabricated monolithically integrated amorphous silicon (a-Si) based thin film solar cells directly onto glass, providing a pre-connected multi-cell PV large area solar panel. It was believed that in principle this technique could be adapted to production onto a metal substrate. However, initial studies confirmed that it would be necessary to invert the total cell structure. This would require the deposition of a NIP[1] a-Si layer structure rather than the standard PIN structure; in addition, the obviously required reversal of the transparent and opaque contact layers, transparent conducting oxide (TCO) and aluminium metal

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[1] Note: in the report the following convention is used for the doped a-Si layers making up the cell: N= n doped material, P = p doped material and I = undoped (or 'intrinsic') material. Where appropriate the superscript + or – is used to indicate highly or low doped material respectively, e.g. N^+.

respectively, would introduce new constraints and challenges for the film deposition and patterning steps.

The Electra-Clad project sought to address these issues and thereby to utilise existing steel based cladding materials as a substrate for direct fabrication of a fully integrated solar PV panel of equivalent design to the glass based panel. This would represent a major step forward in BiPV panel manufacture if achieved and open up the substantial BiPV cladding market for later exploitation of the technology. It was planned that this would be achieved by the further development and productionisation of the Electra Clad technology, working in partnership with cladding manufacturers to develop a facility capable of producing at least 20MWp p.a. The time scales to achieve this were expected to be less than 5 years and no more than 10 years.

The Electra-Clad project was initiated with the overall objective of developing the technology to allow the direct deposition of multi-cell thin film amorphous silicon (a-Si) based solar PV structures onto metallic substrates, with the aim of integrating solar panel technologies onto existing typical building cladding products.

This project was started in January 2002 by Intersolar Group and its collaborators – Plasma Quest Limited (PQL) and Exitech Limited.

PQL bought specialist expertise in plasma deposition technology, specifically relating to ‘thin film’ silicon deposition using Plasma Enhanced Chemical Vapour Deposition (PECVD) and contact deposition using sputtering technology, to the project. Exitech, the UK’s leading laser technology company, had produced laser systems for the thin film solar and Thin Film Display industries and were ideally placed to develop the laser patterning processes required by the new cell structure.

Following the liquidation of the Intersolar Group in December 2002, the project was put on hold, pending reappraisal and replanning of the project by the new owners of the Intersolar Bridgend production plant, ICP. After nearly a one year delay, the project was approved to continue in October 2003 under the direction of ICP Solar UK Ltd, and using the same group of collaborators, with a revised completion date of July 2005. This allowed slightly less than the originally planned 3 years for the work.

(It should be noted in the following that where ICP is referenced, this should be read as ICP and / or Intersolar – a majority of the staff and facilities transferred from Intersolar to ICP Solar UK, maintaining project continuity.)

2. TECHNICAL BACKGROUND

The primary challenge of the Electra-Clad concept was that of integrating a number of established processes onto an unusual substrate. These elements gave rise to the following issues.

Inverted thin film a-Si PV cells had been developed and proven by other researchers, and were used in the commercial production of stainless steel based solar PV product. However, this was a ‘single cell’ product that required mechanical subdivision and interconnecting to achieve a multi-cell panel as planned for Electra Clad. In order to permit the required monolithic integration required by the Electra-Clad product, the a-Si cell would need to be deposited onto a substrate containing an additional electrically insulating layer between the cell and stainless steel plate. In addition, the project would need to develop the inverted cell process. Whilst the consortium had produced inverted cells in past R&D activity and therefore had experience of the issues involved, there had been no prior application of this to the equipment in use.

The monolithic integration process had been developed and proven and was used in widespread commercial production of large area a-Si based solar panels; ICP already used laser patterning systems to achieve high yield with such products. However, this was glass based solar panel based on the ‘usual’ TCO - a-Si cell – rear metal contact sequential deposition and patterning scheme. The inversion of this scheme coupled with the surface coating required on the steel substrate plate mandated by the Electra-Clad product posed new challenges for laser patterning.

The materials commonly used for a-Si based solar panels were also well established, but again primarily for glass panel based product. Thus the TCO, being deposited first, had no especial process constraints; the rear contact, typically aluminium, similarly did not have to withstand further deposition steps. Both these raised potential difficulties for the inverted Electra-Clad product; most critically, it was known that aluminium could not be used for the first contact layer due to incompatibility with the later a-Si deposition step. A low temperature process (sub 200 degrees C) would also be required to deposit the transparent top contact.

Finally, a critical basis for the commercial attraction of the Electra-Clad product was that it would be readily and easily integrated into standard building technology, ideally as a straightforward replacement for existing steel cladding. This required the essential wiring interconnect schemes to be defined and proven; it was considered unlikely that the processes developed for the standard laminated glass products would suffice.

The project plans defined the following approximately sequential tasks to be addressed by the project (exception – task h laser scribing was run concurrently with tasks e, f and g).

Task a). Assess the requirements for metallic surfaces coated with thin film solar cells.
Task b). Research the deposition of solar cells onto metal substrates.
Task c). Metallic substrate surface preparation requirements.
Task d). Electrical isolation material selection and development.
Task e). Rear contact material selection and development.
Task f). Development of NIP structure.
Task g). Develop transparent front contact layer.
Task h). Laser scribing trials.
Task i). Buss bar material selection and development.
Task j). Optimisation of full cell (monolithically integrated solar PV panel).
Task k). Protection coating.

Five interrelated work activities were planned to address these tasks, allowing parallel development of solutions. These were to essentially address tasks a) to h) over years one and two, with final integration to achieve full Electra-Clad demonstrators in year 3. The activities were:

Activity A). Inverted Cell Deposition Development: this would initially develop the required inverted cell process on the a-Si deposition system based at PQL, the Trials Deposition Unit (TDU). Once successful, work would then progress to investigating coated steel substrate – cell process options and defining a compatible combination. It was anticipated that this would be the most difficult element of the project.

Activity B). Laser Patterning / Cell Isolation Development: the second major challenge was to develop laser patterning schemes that were able to meet the demands of the inverted structure. This work could initially be conducted using 'standard' a-Si cells, as the inversion of the a-Si itself was not a critical aspect from the point of view of patterning, allowing work to proceed in parallel with cell deposition development.

Activity C). Contact and 'Barrier' Layer Materials Development: work was required to identify and deposit materials for the cell electrical contacts that were fully compatible with the inverted a-Si process. The low temperature requirement for the transparent front contact was anticipated to be particularly challenging. In addition, contingency plans required that barrier materials – primarily electrically insulating coatings – be identified in case the existing building cladding coating proved totally unsuited to the later high temperature a-Si deposition process.

Activity D). Integration Studies: with Activities 1 to 3 complete, work on the development of a monolithically integrated solar PV panel would be possible. In practice, it was anticipated that much of this would have been attempted as part of previous studies e.g. to check that the laser patterning was not damaging the a-Si cell. However, this phase of the work would focus on the achievement and optimisation of solar PV output from a demonstrator solar panel of at least 10x10cm.

Activity E). Bussbar and Encapsulation Studies: a final - but key - element of the Electra-Clad product was that integration into new and existing buildings should be readily achieved. The thin film PV cell was expected to be electrically ‘terminated’ in 200nm thick sputtered aluminium pads and therefore the panel needed to ‘convert’ from these fragile thin film electrical connections to mechanically robust and reliable external panel wiring points for use by fitters. The connect technique also had to allow for the overall panel encapsulation that would be required, most likely a transparent plastic or similar thin coating (rather than glass as used in standard ICP product).

The subsequent report is structured to match the above Activity breakdown. It is derived from more detailed reports issues throughout the project, though process details and some key elements of the results have been ‘sanitised’ to protect the project Intellectual Property. Those seeking further detail should contact ICP or the relevant collaborator(s).

3. EXPERIMENTAL WORK

Initially the project activity focussed on defining the critical requirements for the proposed Electra Clad component materials, layers and fabrication processes. This Requirements Specification phase of the work was critical to understanding and defining the interdependencies between the various elements, and allowed the 'building block' elements of Activities A to C to be conducted in parallel.

As the Requirement Specification was so essential in defining the work performed under each Activity, the relevant elements from this are summarised at the start of each section following.

Activity A). Inverted Cell Deposition Development.

The difficulties arising from inverting the cell layer deposition sequence in PECVD based a-Si deposition are well known and widely reported in the open literature[2]. The key requirement for achieving good performance from an inverted (NIP) a-Si solar cell is the minimisation of residual n type doping gas in the undoped layer deposition.

The nature of the deposition process and equipment makes it difficult to totally eliminate prior process gases from subsequent layers. There are many potential 'voids' and poorly pumped locations within a large area parallel plate PECVD system within which residual gases will reside, and the impact of any residual n dopant is magnified by the high efficiency with which it dopes the a-Si[3]. Thus for the Electra-Clad project, the performance impact of the layer order change first needed to be quantified and the means for minimising or eliminating the deleterious effects then needed to be defined.

The most common means for reducing prior process residual gases is to use a repeated vacuum pump / next layer process gas purge cycle. To be effective this requires a combination of an appropriate high vacuum pump system and a well designed PECVD chamber and internal fittings to maximise the vacuum pumping speed of internal voids and components.

The latter was judged to be the major challenge for the TDU to be used in this work; the unit was designed for PIN cell deposition and had many large area glass sheets placed in close but loose contact to equally large area sheet metal electrodes. These were all contained within an enclosed

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[2] Essentially, any residual n layer dopant gas in the PECVD system during the I layer deposition adds to the tendency towards n type material that this layer naturally exhibits. The resultant internal electric field profile (effectively N^+ - N^- - P) fails to collect photogenerated carriers as efficiently as the intended NIP cell, resulting in a poor cell fill factor (FF) and thereby low PV response. In contrast, residual p type dopant gas incorporated into the I layer (in a conventionally deposited PIN cell) counteracts the natural n type tendency, with beneficial effects (in moderation).

[3] As compared to the much poorer p doping processes – another reason that PIN a-Si cell PECVD is easier.

‘plate carrier’ module connected to the process gas and vacuum feeds within the chamber. This resulted in large, variable, inter-sheet gas volumes with very limited pumping ‘apertures’ to the vacuum systems, coupled with a chamber volume (outside of the plate carrier) that was only pumped via the seams and small apertures of the plate carrier itself. Initial pumping speed tests with and without the plate carrier and using a number of ‘dummy loads’ had confirmed that the TDU vacuum design was intrinsically unsound for the NIP work.

Thus the following modifications were identified as being required:
1. The design and installation of new gas supply pipework, control valves and isolation valves in order to provide a capability to fully purge and ‘clean’ residual gas from the process gas mixing manifold and supply lines.
2. Major redesign and modification of the plate carrier and it’s interfacing to the deposition system in order to greatly increase pumping speed to the inter-sheet spaces and surrounding chamber volume, without compromising plasma confinement and deposition uniformity.
3. Increased control software capability to permit an improved ‘clean-up’ cycle to be incorporated between the N and I layer depositions.
4. Addition of a high vacuum pumping unit to improve the vacuum level achievable during the intended clean-up cycles.
5. Control and safety software modifications to permit automated and safe use of the high vacuum pump within the normal PECVD process.

The modifications work was conducted in two phases, items 1 to 3 being implemented and proven before moving on the fitting and integrating the high vacuum system. Proving trials were conducted by deliberately omitting the normal clean up / gas purge cycles and depositing PIN cells by an established process recipe, but without P-I layer deposition ‘breaks’. This ensured that p dopant gases were incorporated into the I layer, with expected deleterious effects on cell PV response. A comparison of cell PV characteristics prior to and after the modifications provided a very sensitive and direct assessment of the impact of the change on pumping speed.

Following achievement of an adequate baseline pumping performance, work moved on to the development of an optimum NIP cell, initially using ‘standard’ substrates and contacts (i.e. glass – TCO – NIP – Al metal configuration), later the coated steel substrates and appropriate contact materials. This work is discussed further in the Results section.

Activity B). Laser Patterning / Cell Isolation Development

The project Requirements Study identified the laser patterning activity as one of the highest technical risks to achieving the Electra-Clad product. This was primarily the result of concerns regarding the inability to process layers from both sides of the substrate, a technique used to advantage with glass based panel. This was amplified by concerns regarding a possible lack of selectivity of the proposed laser processes to some of the expected Electra-Clad layer combinations, particularly the use of previously untested paint and other protective coatings for the steel substrates.

Figure 1 shows a typical monolithic integration scheme used for standard glass based a-Si solar panel manufacture. In principle, replacing the glass substrate with a coated steel substrate (and changing the contact and cell materials) provided the required Electra-Clad product. In summary, the three key steps required were:

1. Laser scribing to define a series of isolated rear (metal) contact pads on the coated metallic substrate. Metal contact thickness ~100-300nm. This step was allowed to partially ablate the coating material, so long as no lifting or damage to the metal rear contact results and the resulting topographical step was compatible with further deposition and layer processing.

2. Laser cutting of apertures (‘vias’) into the subsequently deposited a-Si based solar cell layers. These apertures had to fully remove the a-Si without appreciable removal of or damage to the underlying metal. a-Si layer thickness ~ 300-500nm. The subsequent front contact material was required to deposit down these apertures and provide electrical connection between the front and rear contacts of adjacent cells, thus via edge delamination (a-Si to metal) had to be minimised.

3. Laser scribing of the transparent front contact material, Indium Tin Oxide (ITO) to define a series of electrically isolated front contact pads. The ITO layer was expected to be ~500nm thick. Damage to and/or removal of the a-Si layer below the ITO was permissible as long as this did not extend to the lower contact layer, or detrimentally affect a-Si cell performance.

In addition, the laser patterning had to have a reproducibility of width and linearity compatible with the tolerances required for an 11mm cell pitch. In practice, this required the patterned line to fall within a 0.2mm wide zone. Isolation lines also needed to be of sufficient width to provide full electrical isolation between adjacent cell contact pads, yet as thin as possible to minimise the unusable cell interconnect region - ideally not exceeding 0.1mm. This required reliable and thorough removal of the contact materials. Spacing of the 3 patterned ‘lines’ also needed to be minimised, ideally to 0.2mm or less.

Development of the laser processes and techniques to achieve each of the above steps individually progressed without difficulty as the materials became available or changed during the project. In preparation for the later integration activity, additional multiple patterning trials were also run to check for potential interference problems, e.g. the impact of very close spacing of the laser patterning steps. Again, no significant difficulties were experienced.

The final trials required to support the Integration Activity used the materials combinations derived elsewhere in the project to provide the layers to be patterned. Laser processing used the processes previously derived for the individual patterning steps, with minor adjustment as required to accommodate layer thickness or properties changes.

As reported later, the initial integrated cells showed very poor solar PV conversion efficiency. Although most likely an a-Si deposition issue, it was decided to address all possible causes in parallel to achieve a prompt resolution of the problem. For the laser patterning this required an examination of any patterning induced sources of performance loss. The following candidates were considered (in order of probability):

a) Failure to achieve good electrical contact between adjacent front and rear contacts due to residual a-Si in the apertures provided by laser process step 2.
b) Contact 'step coverage' issues due to lifting or delamination of materials following laser patterning. This could apply to all of the patterning steps.
c) Laser induced damage of the a-Si layers adjacent to the patterning resulting from laser processing at steps 2 and 3.

Although discounted as a likely cause of low efficiency, it was also decided to re-check the inter-cell isolation achieved at steps 1 and 3 for completeness.

In order to separate out any issues due to cell deposition, trials aimed at testing the above also used structures in which the a-Si NIP was replaced by an a-Si I layer. This provided a semi-insulating layer in place of the electrically active solar cell and allowed any a-Si damage to be more readily assessed.

The trials used a combination of electrical testing and physical examination including surface profiling and optical and electron microscopy. As expected, this work demonstrated that the laser patterning was effective, concluding development on this work activity. Subsequent patterning was however continued as a 'fixed' process to support further integration studies as reported later.

Activity C). Contact and 'Barrier' Layer Materials Development

This activity encompassed three distinct panel components: the substrate and overlying insulating coating; the back (metal) contact; and the front (ITO) contact. These are dealt with separately in this section.

i) Coated Substrate

Substrate material compatibility with later processing was determined to be a critical issue in the Requirements Study. A number of materials – even with 'barrier' coatings – were likely to be unsuitable due to innate incompatibility with the a-Si PECVD process. Surface morphology and topography of the substrate was also important. The thin film layers used in the fabrication of the required PV device could all be produced by techniques that allowed a good degree of conformal coverage; however the scale of any abrupt surface irregularity needed careful consideration.

Most critically, in order for the PV device patterning to be effective (in producing series electrically connected cells), an electrically insulating coating was required on the metal substrate. The project proposed to use, as a priority, already established coated steel building cladding products to provide this insulation. However, the acceptable coatings were constrained both by the need to provide an essentially low roughness finish (as above) and to be compatible with later deposition stages, in particular the 200 deg.C –Si PECVD process. A large range of normal industrial finishes would therefore be unsuitable, e.g. paints, plastics and lacquers having a high porosity and / or a chemistry that was likely to release contaminants into the vacuum deposition processes. Additionally, 'pinhole' defects in most industrial finishes tended to be on too large a scale and at too high a density to be appropriate for the required level of electrical isolation.

Initial discussion and review of options with Corus ColorSteels identified that a wide range of coated substrate options still existed within the above constraints. Whilst other metal could be considered, stainless steel was the best candidate, being known to be intrinsically compatible with subsequent deposition steps. Corus ColorSteels were also able to supply this with a large range of coatings, all either in use or potentially acceptable to the building cladding industry. Following a review of the coating options, it was determined that their powder coat material provided the best potential solution to the substrate requirements, particularly in terms of microscopic smoothness (the typical 'orange peel' texture was macroscopic and potentially useful in improving cell PV response). Initial compatibility tests indicated that this substrate option appeared acceptable and work progressed using powder coated steel as the substrate for the Electra-Clad trials.

A further two substrate and coating reviews were carried out within the project, in order to resolve problems that later came to light (reported later). The first of these identified an alternate coated steel product that became the project 'standard' substrate. The second looked at the broader option of providing the steel coating by a separate process. The two most prospective technologies identified were that of thick (1 to 10μm) dielectric coating or the use of a new coating material, 'Parylene', that was in use for electrically insulating and environmentally encapsulating military and other high specification electrical circuits. Secondary trials were conducted using both of these materials, but were ultimately limited in effectiveness due to supplier difficulties as later reported.

ii) Back Contact
The Requirements Study judged this to be a low risk element of the project, as there was a great deal of relevant prior R&D reported in the open literature, and the consortium had first hand experience of the issues.

The back contact layer was required to have good electrical conductivity in thin film form, good optical reflection to enhance light absorption in the finished structure and excellent adhesion to and compatibility with the underlying substrate. The film had also to adequately cover the 'rough' texture that the ColorSteels substrates possessed in order to maintain electrical continuity. The layer needed to be compatible with the subsequent a-Si:H and TCO layer deposition processes – i.e. stable in vacuum at elevated temperatures (250 deg.C), unreactive with the a-Si deposition gases and deposited layers (both in process and subsequently over many years of operation) and capable of forming a good electronic contact to the first doped a-Si layer. In addition, the material needed to be able to be readily deposited over very large areas by high volume production processes (probably sputter deposition) and be of low intrinsic cost.

Despite these constraints, there were a number of potential material choices which could be used within the project. Following a literature review of prior art, coupled with prior experience within the project on the use of candidate materials in both PV and non-PV applications and consideration of facilities availability, the following metal layers were short-listed for test:

Chromium (later nickel-chromium in addition)
Nickel
Tungsten
Tantalum
Molybdenum

Facilities were already in place at PQL to permit these materials to be deposited, primarily by electron beam evaporation, though sputter deposition facilities were also potentially available and were used initially for nickel deposition and, later in the project, for chromium as well. PQL facilities for large area sputter deposition of stainless steel also became available in the last 6 months of the project and later work therefore focussed on the use of this and sputter deposited chromium as the preferred back contact materials.

iii) Front Contact

The selection of the top contact material was limited by the critical requirements for this final layer. It was required to be transparent, electrically conducting and unreactive with the underlying a-Si:H layers, both during its deposition and in the long term. Additionally, the deposition process had to keep the substrate temperature below about 180 deg.C, in order to avoid degradation of the a-Si:H and hence PV device electronic properties. As with the metal layer, the material had also to be readily deposited over very large areas by high volume production processes and be of low intrinsic cost. Facilities availability was also a consideration.

The Requirements Study concluded that the front contact needed to match the characteristics provided by the glass - TCO substrate in the conventional glass based scheme as closely as possible. The key requirements were:
Optical transmission (integrated over visible spectrum): 85%
Electrical sheet resistance: <25 ohms / square.

It was critical that the substrate temperature did not exceed about 180 degrees C during deposition and processing of the contact, preferably less than 120 degrees C. The deposition process and front contact material had also to be able to form good electrical contact through 'vias' (holes) laser patterned through the a-Si cell in order to provide the electrical interconnection of adjacent front and rear contacts required by the monolithic integration scheme. This implied a 'clean' process (to avoid interfacial layers) and good step coverage.

A review of the front contact requirements against available technologies, both in-house and routinely available, concluded that ITO sputtered by advanced high density plasma processes provided the most appropriate material for the trials. In addition, PQL staff had substantial experience of this material for production coating (including as a contact for solar cells) and had briefly trialled the relevant sputter systems and proven that a very low temperature process was feasible.

Accordingly, a PQL 'HiTUS' R&D system was dedicated to developing a suitable process for the Electra-Clad trials. This work is detailed in the Annex to this report.

Subsequent work during the integration studies phase of the project was planned to be directed at improving this contact through relaxation of the maximum process temperature requirement or the addition of a water cooled substrate stage to permit more plasma treatment of the depositing ITO thin film. Due to integration issues reported later, this work was not required.

Activity D). Integration Studies

The aim of this work was to integrate the materials and processes developed in the previous activities to build a monolithically integrated multi-cell BiPV solar panel as a final 'proof of concept' demonstrator. Although identified as a discrete work element for the final year of the project, in practice a substantial amount of more limited integration studies had formed part of the prior activities, e.g. NIP deposition onto metal back contacts, coated steel substrates.

Initial trials used all previously developed processes and materials to form the cell structures, i.e.:

Substrate: 'ColorSteels' powder coated steel substrate
Rear contact: thin film metals – chromium, nickel-chromium, tantalum and molybdenum.
Cell: amorphous silicon NIP.
Front contact: Indium Tin Oxide (ITO) deposited by PQL low temperature process.
Laser patterning: standard scribe / via / scribe (as reported above).

In addition, other samples were included in each deposition run to provide 'standard' test pieces to assist with the identification of the causes of any performance or fabrication deficiencies. These were:

Reference sample type A: TCO coated glass substrate based samples, with aluminium front contact, i.e. standard ICP cell structure with the exception of the inversion of the cell to NIP configuration (i.e. for comparison with earlier NIP results).

Reference sample type B: identical to the coated steel based structure, but with the front contact replaced by thin, semitransparent aluminium. This was to eliminate concerns regarding the possible impact of the ITO deposition process.

Minor changes to processes were made during this phase of the work in response to results obtained. Key amongst these was a reduction of a-Si deposition process temperature in response to concerns that poor integrated cell performance was resulting from contamination due to the release of absorbed gases or chemicals from the steel coating materials.

Following investigation and assessment of the origin of performance shortfalls in the integrated structures, a second phase of the work was conducted using alternate substrates. Discussions with ColorSteels had resulted in an alternate range of coated steel substrates being identified that might meet the Electra Clad needs and resolve the performance shortfalls. The earlier trials were repeated using the two most promising candidate materials. In addition, facilities became available at PQL for the deposition of stainless steel as the back contact and this was also incorporated into the trials.

In all cases, a mixture of contact sizes and structures were used to aid assessment of the samples. These ranged from millimetre diameter 'dots' and 1cm^2 'pads' for the front contact, to full integrated solar small scale solar panels comprising 5 monolithically interconnected cells of 13.5cm by 1cm size (see figure 2).

Activity E). Bussbar and Encapsulation Studies

This work was started with a study and definition of the requirements that would need to be met by the Bussbar technique. It was determined that there were two major requirements to be met; electrical connectivity between the microscopically thin PV cell layers and the macroscopic sized building wiring looms; and mechanical integration (and possibly fixture) of the steel plates to the building or structure to which the plates are to be attached.

The latter required expertise outside of the project and was likely to be application dependent; it was not therefore suitable for explicit consideration within the project, although the bussbar technique was required to incorporate adequate scope for change to allow for the likely manner of mechanical fix – i.e. it had to be a versatile and adaptable solution.

Thus the project requirements for this Activity were focussed primarily on the means of providing a suitable electrical interconnect. The following requirements were defined:

1. The PV cell was expected to be electrically 'terminated' in 200nm thick sputtered aluminium pads – it was to these that the bussbar needed to electrically connect.

2. The connection to these pads had to be readily and cheaply made, reliable and robust. It was permissible to consider schemes that required thicker material layers to be laid over these pads (e.g. screen printed metals), but the cost implications of this had to be borne in mind – i.e. it had to be a necessary step.

3. The connect technique had to allow for the overall panel encapsulation that would be required. This was likely to be a transparent plastic or similar thin coating (rather than glass) and it would be acceptable for this to be done prior to the bussbar connect, with the inner regions – not edges – of the contact pads left exposed for connection and later additional encapsulation.

4. The interconnect had to ultimately end in an electrical connection point that would be manageable to those installing the PV wiring looms – i.e. it had to allow for rapid and reliable fitting and replacement. It was

permissible for the interconnect to have several ‘transition’ stages to get to this end point (e.g. pad – aluminium tape – connection post).

5. The technique had to allow for the possible need to provide an electrical connection to the underlying steel plate (as a safety earth or Radio Frequency Interference shield).

6. The technique had to allow for final encapsulation and environmental sealing compatible with the requirement for long life of the product – probably decades.

7. The bussbar – panel assembly had to be highly robust once finished, i.e. suitable for use in the building industry.

8. The bussbar technique had to be an inherently low cost process, ideally of low technical complexity.

Test modules were prepared by sputter depositing 200nm thick aluminium pads directly to the coated steel substrates in use on the other Electra-Clad activities. In the final Electra-Clad panels these would connect to the thin TCO layer deposited on the NIP structure. However, as these were planned to lead to the edges of the panels (i.e. they will not be underlain with other thin film depositions), multiple thick aluminium strips sputtered direct to appropriate coated steel substrates provided a simple and realistic test module for these trials.

The standard technique used for ICP glass based PV panel was to ultrasonically bond thin aluminium strip to the panel end cell aluminium top contacts, then lead these tapes out of the later encapsulated product to either a terminal block, or to solder standard tinned copper wires to these using tin/zinc solder. In both cases, the termination was then environmentally sealed using either hot melt type glue or cyanoacrylate adhesive. This provided a start point for the Electra-Clad work.

Initial work focused on the ability to bond our current aluminium tape to the substrate material. This simple process used an ‘ultrasonic weld’ to bond the thin aluminium tape to the thin aluminium evaporated rear contact. Very few trials were carried out on this process as no indications of a successful bond were achieved. This was largely as expected and studies of previously identified alternate techniques were therefore started.

The first processes explored were the use of current soldering techniques in use at the ICP manufacturing plant to terminate large area modules and smaller Original Equipment Manufacturer (OEM) cut plate cells. Four current types of solder and one ‘epoxy’ type conductive adhesive were tested for electrical and mechanical bonding to the aluminium ‘Buss bar’ strip. As reported later, none of these proved successful.

Further research was therefore made into alternate products that would enable us to achieve the required bond. One method was to further explore the option of an adhesive paste, as one of the epoxy materials used in the previous work had been the most successful of the options trialled. The paste was required to have electrical and properties close to that of solder but not damage or remove the aluminium bussbar.

A specialist company (Emerson and Cumming) were supplied with Electra-Clad samples and they conducted trials using a selection of their products. They were able to source two conductive adhesives which closely matched our requirement.

Both were easily dispensed, could be heat cured at a relatively low temperature (important as high temperatures can damage the cell structure and the substrate) and had good electrical and mechanical properties.

Further trials were conducted at ICP using the preferred conductive epoxy indicated by the testing. This set of trials used a more advanced test substrate having a defined layout of cell structures, one bussbar pad connected to the rear contact and the other to the front contact material. Two wires were attached to the aluminium pads using the preferred epoxy resin and cured in a conventional oven for the times stated in the report. This tested all potential future Electra-Clad layout schemes under consideration at that time.

4. RESULTS

Results - Activity A). Inverted Cell Deposition Development.
The first phase of this work tested the essential engineering changes to the gas supply system and modifications to the plate carrier. This demonstrated a dramatic reduction in layer cross-contamination. A standard TDU panel process (PIN) was modified to eliminate all 'clean-up' process steps, thereby maximising cross contamination effects. The process was run in the TDU immediately prior to the engineering modifications; figure 3 shows the solar PV performance of the resultant panel. The detrimental impact of the cross contamination is readily apparent, with the performance parameters all falling in a manner consistent with the theoretical impact of a heavily contaminated I layer and yielding a very poor peak wattage (3W, c.f. c.12W for the standard TDU 'T' panel at this time).

This trial was then repeated following the improvements to the gas supply system and plate carrier; figure 4 shows the solar PV performance of this panel. The dramatic reduction in cross contamination impact is readily apparent, with PV performance (peak wattage in excess of 10W) now close to that of a cell structure fabricated using the full standard TDU process (i.e. incorporating clean up / gas purge cycles). Separate quantitative assessment of the overall system pump / clean-up speed indicates an improvement by more than a factor of ten.

The initial N-I-P depositions showed only a need to adjust the doped layer parameters somewhat to improve electrical contact between the amorphous silicon and the metal and TCO layers comprising the cell to achieve reasonable performance. Figure 5 shows a PV performance characteristic for an initial example N-I-P structure.

In conjunction with the installation of the high vacuum pumping system, a number of other unplanned improvements had been made to the plate carrier unit outside of the project, primarily to improve deposition uniformity. Testing showed that these also had the benefit of improving overall system vacuum pumping speed so far as elimination of residual contamination from prior process steps was concerned. In conjunction with NIP cell process optimisation, including the establishment of an adequate and commercially realistic 'clean up / gas purge' cycle, this was shown to resolve the performance deficiencies apparent in the first NIP solar cells. Figure 6 shows the current-voltage responses of a NIP cell made at this time.

With the achievement of a good baseline NIP cell process, further cell development and optimisation was subsumed into the integration activity.

Results - Activity B). Laser Patterning / Cell Isolation Development

A wide range of process trials has shown that current commercial laser systems will be able to provide the required patterning capability for the proposed Electra-Clad products. All requirements defined by the Electra-Clad Requirements Study have been met or exceeded.

The laser patterning steps met all physical requirements for line width, spacing, linearity and reproducibility needed for the Electra-Clad product.

A process for laser patterning of the lower metal contact was developed to provide perfect pad to pad electrical isolation and no observed edge lifting / delamination, thermal degradation, distortion or removal of the underlying steel substrate coating. This applied to all the coatings used during the course of the project. An example of the laser 'scribe' line patterned onto an early coated steel substrate is shown in figure 7. Note that this substrate type was rejected for further use due to the excessively 'rough' topography; nevertheless, the laser patterning was able to accommodate this surface and produce the required patterning.

A process for laser patterning of the 'via' interconnect holes in the a-Si layers was achieved to provide full a-Si removal without underlying metal contact damage or removal, again for all metals used for this layer. Electrical measurements confirmed that the required ohmic electrical interconnect of top and bottom contact layers could be achieved. Tests on reference substrates using only a semi-insulating a-Si layer confirmed that there was no measurable loss of electronic performance in the a-Si layer. An example micrograph of the laser 'vias' is shown in figure 8. Note that as with the prior example, the coated steel substrate shows excessive topographical variation, yet the laser patterning process is able to accommodate this. Note also the removal of the thin metal layer in the absence of the a-Si NIP layers; this confirms the earlier concerns regarding low selectivity of process and the resultant need to control laser process parameters tightly to avoid unwanted metal removal.

A process for laser patterning of the front (ITO) contact has been developed to provide the required electrical isolation between cells. As with the 'via' testing, no measurable deterioration of the a-Si material adjacent to the scribe was found, despite the localised visual damage. An example micrograph of the laser 'scribe' for this layer is shown in figure 9.

The above patterning proved possible to achieve over a reasonable range of process parameters, confirming commercial suitability of the process schemes. Typical final processes were as follows (as used in final integration work).

Rear metal (stainless steel) scribe
Fundamental mode (1064nm) Nd:YAG laser, Q switched, 7ns pulse
0.5 J/cm2
1 shot per area, flat profile
100µm square apertures at c. 90µm repeat distance to provide a continuous scribed line

a-Si aperture ('via') formation
Frequency doubled (532nm) Nd:YAG laser, Q switched, 7ns pulse
0.5 J/cm2
1 shot per area, flat profile
100µm square apertures at c. 200µm repeat distance

Front (ITO) contact scribe
Frequency tripled 355nm Nd:YAG laser, Q switched, 7ns pulse
0.5 J.cm2
1 shot per area, quasi-Gaussian profile
20µm circular apertures at c. 15µm repeat distance to form a continuous scribed line.

In each case the laser pulses were synchronised to the workpiece movement, allowing accurate pulse placement for processing at rates up to 5kHz. (The limitation on repetition rate is a trials system limitation and scanner/stage based synchronised scanning systems could process at up to 25kHz depending on spot size used in commercial systems).

Results - Activity C). Contact and 'Barrier' Layer Materials Development

i) Coated Substrate

The initial ColorSteels powder coat steel substrates in all cases met the requirement for electrical isolation of the steel substrate from the PV cell layers, for all process conditions used in the cell and panel fabrication. There were no problems with delamination or degradation of the selected coatings at any time. However, as reported under Activity D, these coatings ultimately failed to provide an acceptable surface for the production of a large area solar PV panel. The later 'high temperature coating' steel samples acquired from ColorSteels similarly met all isolation requirements and greatly improved the cell performance. Again however, they proved unsuited to the development of the required large area solar PV panel.

The 'contingency' options of dielectric coating and 'Parylene' coating were also unsuccessful insofar as we were able to trial. Steel substrates coated with an insulating film of alumina produced cell structures that were electrically shorted to the underlying steel and were heavily shunted. SEM analysis of the samples indicated that the steel surface topography was unsuited to thin film deposition, due to very deep inter-grain boundaries that could not be readily coated by the various thin film deposition processes in use (figure 10).

Trial samples of Parylene coated glass obtained from the supplier and run through the back contact metallization and amorphous silicon deposition steps were unsuccessful, with the material crazing and delaminating from the glass. After further discussion with the manufacturer, a new, high temperature Parylene coating was provided (on very small glass samples, c. 1cm^2). These samples were tested and shown to be stable for the required Electra-Clad process steps, though the small size of the samples precluded realistic cell fabrication. However, no further trials of this promising material were able to be conducted due to supplier difficulties.

ii). Back Contact
As anticipated, there were no major difficulties in using a range of metals to provide a back contact meeting the requirements. Of the metals originally rested, tungsten and molybdenum were eliminated due to process difficulties arising from the use of the electron beam evaporation technique. For the remainder of the project, sputter deposited chrome, nickel- chromium and, latterly, stainless steel were all used to provide fully effective back contacts. Early problems experienced with reliable adhesion of the metal films to the coated steel substrates proved to originate from the use of the electron beam technique; all later films deposited by PQL sputter processes showed excellent adhesion and materials compatibility, coupled with near ideal electrical and optical reflectance properties.

iii). Front Contact
Thin ITO films of good electrical conductivity and optical transparency were deposited whilst maintaining a very low substrate temperatures and low plasma damage.

For ITO films of thickness 50nm, a value of 90% integrated optical transmission over the visible spectrum of interest for amorphous silicon PV cells was achieved, with a corresponding sheet resistance of 100 ohms / square. Whilst this fell somewhat short of the total objective, it was clear that this was primarily limited by the need to restrict the plasma energy to avoid substrate heating during deposition.

Subsequent to these trials, the heating requirement was relaxed to determine whether the other requirements could be independently met. ITO films of resistivity 3x10-4 ohm.cm and transmission better than 85% for a 120nm thick film were achieved – yielding a sheet resistance of 25 ohms / square. Trial samples also indicated that, despite the temperature relaxation, PV performance was not degraded by the process, thereby delivering the required layer properties for the integration phase of the work.

Results - Activity D). Integration Studies
The initial trials of monolithically integrated panels showed that the PV cells were heavily shunted, therefore yielding little or no PV response. The reference samples indicated that this was due to the NIP deposition not providing good PV devices on the coated steel substrates (i.e. only the glass based reference sample type A was functioning correctly).

The most probable candidates for this failure were assessed to be contamination of the amorphous silicon by materials released from the powder coating during deposition at the elevated temperatures used (220 degrees C), or microscopically rough surface morphology. A series of further deposition trials was run to test this, primarily aimed at reducing the deposition temperature, both through reduction of the overall deposition chamber set point and through elimination or reduction of some high energy plasma treatment steps.

Despite the deposition process changes, no improvement was observed in any samples and the reference sample type A showed decreasing efficiency in all cases, precluding further temperature reductions. Following further microscopic analysis and testing, it was decided that the substrate in use was unsuitable for the Electra Clad devices, despite earlier promising results.

The cause appeared to be that, despite remaining undamaged by the plasma processes, the powder coating did in fact soften sufficiently during deposition to allow the stresses in the deposited amorphous thin films to 'buckle' the surface, leading to localised 'pinhole' shorting at the resultant ridges, possibly due to high localised electrical field strengths. Thus although film adhesion was excellent, the amorphous silicon topography was too rough after deposition to allow working thin film cells to be fabricated – probably as a result of the very thin P and N layers required.

The second trials phase, using steel substrates with the new 'high temperature' coating was more successful. The new coated steel substrates eliminated the shunting seen in the earlier work, allowing the successful deposition of NIP cells and the achievement of a first PV response from an integrated cell. Examination of the post deposition surface topography confirmed that the previously observed 'buckling' was no longer present and that the back contact and amorphous silicon thin films were providing the expected conformal coverage.

However, PV conversion efficiency was less than 1%, due primarily to a large series resistance in the structures and resultant low photogenerated current output (less than 1mA/cm2) and poor fill factor (circa 0.3); cell open circuit voltage was reasonable at 0.7V. The current limitation was seen only on the coated steel substrates and was assessed to be most likely associated with a need to remove a surface oxide film from the back contact metal – especially from the stainless steel, that was in use at that time as it was the preferred material from a production viewpoint. Work therefore focussed on interface and overall cell improvement

Despite trialling a wide range of process conditions, interfacial treatment options and, in some cases, additional coatings, no further significant improvements in cell performance were achieved. Furthermore, it became clear that the fundamental problem was one of performance loss as the active area was scaled up; some of the smaller area devices (1cm^2) were shown to perform reasonably, whilst very small area units (mm diameter' dots') were significantly better. Larger areas, including the full panel cells, failed completely, whether laser patterned or not.

Studies have shown that this is not an integration issue. The laser patterning, and inter-cell isolation and inter-layer connections perform as required in separate test pieces that accompanied the layer deposition steps used in the cell improvement studies. Assessment of the glass based reference samples has also eliminated the possibility that the substrates are a source of gross a-Si deposition process contamination, as reasonable PV results are achieved on these, even when these are placed alongside the coated steel samples during deposition.

The latter stages of the project therefore focussed on identification of the source of failure, using a combination of deposition trials, electrical assessment and microscopy studies, including high magnification SEM. The results of these point strongly to a topographical problem – i.e. the 'smooth' surface finish that the steel coatings provide is inadequate at the microscopic level of the thin film depositions required.

Results - Activity E). Bussbar and Encapsulation Studies

As reported earlier, all trials using standard ICP production bonding techniques failed to achieve the required interconnect. Equally, the use of current ICP soldering techniques in use at the ICP manufacturing plant, including one 'epoxy' type conductive adhesive, also failed to achieve the required interconnect integrity.

However, the trials by Emerson and Cumming using one of their heat curable conductive epoxy resins were successful. These trial results are included as an appendix to this report.

Further trials using this material at ICP confirmed their results; wires attached to the aluminium pads using the epoxy resin (XCE 80212-3i) and cured as specified resulted in good ohmic electrical contacts between the thick wires and microscopically thin aluminium pads, with good mechanical adhesion (limited only by thin film layer adhesion). Figure 11 shows the resultant electrically bonded wires and thin film pads.

Although the bond was clearly electrically sound and had passed humidity stability testing, the need to make a more mechanically reliable required to be ‘potted’ with a protective material as the wire, if pulled excessively, would remove the aluminium bussbar away from the cell. ICP currently use a cyanoacrylate adhesive to seal our standard connections on glass based panel. This seal provides mechanical strength and proven environmental sealing. Figure 12 shows the wire terminations successfully sealed in this manner.

5. DISCUSSION

It is clear that, despite having met most of its sub-objectives, the project has failed to deliver the required Electra-Clad demonstrator within the available time and resources. However, it is also clear that the problem is solvable and that, the project has been successful in demonstrating that the Electra-Clad concept is sound.

Overall, each of the process elements required for the Electra-Clad product has been developed and proven; these include the initially high risk steps of laser patterning, commercially viable NIP deposition, a low temperature ITO deposition process and bussbar integration techniques. All have also been shown to be potentially consistent with production of a low cost commercial product.

Identifying the cause of failure is therefore critical in assessing the future potential of the Electra-Clad scheme. The evidence strongly points to the substrate and coating as the cause. We believe that our trials have eliminated film contamination as the problem as extended degassing of samples under vacuum at temperatures exceeding those present during a-Si deposition has failed to yield any improvement in performance (coating integrity has been confirmed post process). We therefore assess the problem as topographically induced.

This appears to be a limitation inherent in existing building cladding materials. Our analysis of a wide range of samples supplied shows that the coatings that provide microscopically ‘smooth’ surfaces are incompatible with later process (i.e. they soften and outgas above about 100 – 150 degrees C). In addition, these coatings still show some major topographical ‘inclusions’ that disrupt the thin film coatings due to distortion during the a-Si deposition process. Higher temperature coatings, whilst unchanged by the a-Si deposition process, have an initially higher surface roughness which has proven inherently incompatible with the thin layers required in the solar cell itself.

As a contingency, we had intended to coat a suitable dielectric onto uncoated steel cladding. This has also proved ineffective due to the microscopically ‘rough’ steel surface topography. Effective coverage of this with an electrically insulating dielectric will be a significant challenge needing very thick, stress free films. Such work is currently beyond the capacity of the project collaborators, though PQL expect to have a suitable system operational within the next 6 months. Given our assessment that this might resolve the Electra-Clad problems, it is unfortunate that a commercial supplier of a newly announced dielectric coated steel panel did not deliver the trial products expected during the last year of the project.

Future work clearly needs to address this coating issue. Three possibilities have been identified to provide the required surface finish.

The first is to use the new PQL facility to coat thick dielectric onto the cladding products, coated and uncoated, as discussed above (or obtain other dielectric coated steel product). The second is to obtain samples of steel building cladding, coated and uncoated, and add a further coating of high temperature Parylene. It had been hoped to do this within the project timescales, but the supplier has been unable to provide these coatings to date. Nevertheless, the characteristics of this material – especially as it may provide a suitable encapsulation product as well – appear well suited to the Electra-Clad product and are worthy of further investigation when the product becomes available (post project).

Given the good results obtained on metal on glass based NIP test samples in some trials late in the project, it seems likely that either of the above will resolve the remaining difficulties in the integration and permit the Electra-Clad demonstrator product to be achieved.

In addition to this overall outcome, the individual work activities have also raised some valuable new insights and knowledge.

The NIP deposition work has given some significant and unexpected results regarding the criticality or otherwise of vacuum pumping capability for the PECVD process. In particular, the initial TDU engineering changes – prior to installation of the high vacuum pumping system - coupled with the later plate carrier modifications appeared to largely eliminate the N layer cross-contamination issue. The improvement in cell response evident between figures 5 and 6 resulted primarily from process optimisation and there was little or no evidence that the high vacuum pump contributed to the improved cell response. We do not believe that this will necessarily remain the case; there are a number of reasons to explain the apparent lack of effectiveness.

1. Release of 'adsorbed' contaminants from chamber walls at I layer plasma start up. The material released at the start of the I layer may be substantially greater than the residual contaminant in the gas phase. Elimination of this contaminant source is primarily determined by the nature of the surface and adsorbed species, the temperature, and the time allowed for desorption; the vacuum base pressure has little or no effect (at the levels considered here). A recent external publication has demonstrated the value of specific process treatments to eliminate or stabilise this source of contamination in PIN cells. Their conclusions are likely to be of equal or greater validity for the NIP structure.

2. Current 'over-pumping' of the system by the process pump. The TDU was equipped with a process dry pump unit that was sized for a much larger volume and plate capacity chamber required for another

project. In conjunction with the improvements made to the gas feed pipework and plate carrier to reduce or eliminate 'trapped volumes' – i.e. regions with poor vacuum conductance to the main chamber - the TDU was very rapidly pumped to near ultimate base pressure for that pump unit. In conjunction with 1 above, this limited the effectiveness of the further improvements to base pressure and high vacuum pumping speed resulting from installation of the high vacuum pump.

3. Process 'tolerance'. The current NIP cells are unlikely be fully optimised in terms of process throughput as the deposition process still includes long interlayer vacuum pump cycles for residual gas 'clean up'. The project necessarily focused on cell and panel performance issues in the final year, rather than throughput optimisation. The high vacuum pump may prove to be critical to achieving a realistic deposition time in a commercial system.

It remains possible that, ultimately, the high vacuum pump will be proven to be unnecessary in a well designed system and process – i.e. conventional wisdom dictates its use only as a means of compensating other design defects. In view of the capital and operational costs associated with the high vacuum capability, this would be an important result from the project.

The laser patterning activities progressed extremely well, despite initial concerns regarding the ability to successfully limit underlying material removal in some cases. In part, this was a result of the very significant advances that have taken place in Exitech over the last 5 years in both the laser systems themselves and the focussing / profiling optics and translation systems required to achieve uniform large area patterning. This has been largely driven by the flat panel display market, where tolerance and uniformity demands are far higher than the solar industry. As a result of this, new laser patterning systems are now available commercially that will fully meet the Electra-Clad requirements, both for patterning effectiveness and commercially viable throughput.

Finally, the latest advances in heat curable conductive pastes simplified the interconnection activity. The conductive paste tested provided a good solution to the problem of connecting external wiring to the thin aluminium contact pads of the thin film Electra-Clad panel. It has good electrical properties as shown by Emerson and Cumming's testing and can be easily dispensed using 'of the shelf' equipment. The cost for the material is not known at this stage as the products tested were only recently introduced by the company. However, it is unlikely to substantially impact panel cost compared to the standard process, as costs other than bonding materials dominate in the current interconnection process.

Although not explicitly addressed within the project (due to the timescales required for testing), in further development of the Electra-Clad panel the front of the device will need to be environmentally sealed to protect the a-Si and very thin layers of TCO (transparent conductive oxide) from the elements. The ICP standard process can be modified to coat the surface with a clear lacquer which can be cured by UV light; this will be fully compatible with the materials to be used. Alternatively Corus ColorSteels has developed a heat curable clear paint lacquer which can be applied to the surface. The curing process is relatively low temperature and basic tests carried out show that it does not attenuate the intensity of light passing through (i.e. would not effect the performance of the solar cell). Areas could be ‘masked’ to allow the conductive adhesive to be bonded to the bussbar and this more limited remaining exposed area can be sealed post wire bonding using the standard ICP cyanoacrylate adhesive.

6. LESSONS LEARNED

Despite the technical work failing to achieve it's final goal, a review of the project plans and activities shows that the root cause of this – the coated steel substrate - was always a recognised risk to the project and was accordingly given appropriate attention and resources throughout. The two prospective solutions that exist to address this were part of early contingency planning, and have as yet only been unable to be addressed due to supplier issues beyond the scope of the project.

The major problem lies with the substantial impact that the liquidation of the initial Lead Contractor, Intersolar, had on the project, most critically a reduction in actual project work duration due to the one year suspension of activity whilst the contract was re-planned with ICP.

Thus the primary lesson learned from this project is the need for contingency planning to deal with major commercial changes, in this case the impact of losing the Prime Contractor through a totally unexpected forced liquidation.

Though with hindsight it is difficult to understand why the creditor responsible for this chose to force Intersolar into liquidation, this should be taken as an indication of the unpredictability of commercial change that can occur in a 3 year project and needs consideration in future projects.

The major problem was that contingency plans were in place only to deal with the loss of a collaborator, not the Prime Contractor. A 'succession' policy could have been prepared and, with DTI approval, rapidly implemented with a consequent reduced delay to the project. This would have probably required a reduction in the project scope (to match the reduced resources), but could nevertheless have allowed project continuation whilst a new collaborator or partner was found. In the event, this would have been ICP, and the project team would probably have had the full 3 years of the project to complete the work. This might well have allowed the contingency substrate coating options to have been addressed, with a consequently successful Electra-Clad demonstrator being produced.

7. CONCLUSIONS

The Electra-Clad project has successfully demonstrated that the underlying principles of the panel design are sound and achievable. All steps required to fabricate the Electra-Clad product have been demonstrated. However, a wide range of trials and substantial development activity in the last 6 months of the project have failed to deliver a commercially realistic solar PV performance from the demonstrator product.

The main problem is evidenced by loss of solar conversion efficiency as the active area of the panel is increased in size. To date, only small ($1cm^2$) cells have shown the solar PV conversion efficiency that is required to make the Electra-Clad product commercially viable (i.e. above 3%).

The problem is assessed as resulting from the coatings used on the steel cladding substrates. We have now run trails using the full range of products in widespread building use, without success. It is clear that a new coating will need to be developed for the PV application; this work lies outside the scope of the project.

Subject to this being resolved, the required Electra-Clad elements are proven and in place. We have developed the required processes for good efficiency inverted (NIP) a-Si based solar cells, compatible processes for the deposition of the contact layers, including a low temperature process for the TCO, the laser patterning required for cell isolation and monolithic integration, and the essential final electrical connection and encapsulation techniques. Accordingly, very rapid achievement of the required Electra-Clad commercial demonstrator could result once a successful coating is found.

8. RECOMMENDATIONS

With all other elements of the required demonstrator established, the clear need is to conduct further trials using the alternate steel cladding coating technologies identified in this report, and to supplement this with a more widespread options study. Therefore recommendations for immediate follow up work are:

1. Produce or obtain thick (10µm or more) dielectric coated steel substrates and trial these as a basis for the Electra-Clad demonstrator.

2. Obtain steel samples, coated or uncoated, and have these coated with high temperature Parylene by the supplier, and trial these as a basis for the Electra-Clad demonstrator.

3. Further review options for providing a barrier layer between the thin film PV panel elements and the steel substrate. These should include the lamination of high temperature plastic films onto the steel surface prior to PV layer deposition and processing.

Subject to one or more of these achieving the required solution, work will need to proceed with an initial optimisation study with a target of achieving at least 3% solar PV efficiency, preferably 5%. In addition to the usual a-Si layer optimisation process, this should include back contact pre-deposition treatment and front contact ITO deposition optimisation, using a cooled substrate holder for the latter work.

This work will provide the basis for the commercialisation cost and risk studies that will be required before committing to further prototype development.

Finally, it should be borne in mind that, as presently envisaged, the Electra-Clad product will make use of the same facilities that are intended for ICP expansion of standard glass plate production. It is therefore recommended that the possibility of fabricating both glass and steel based PV panel within a single facility be considered in future production scale up studies.

9. ACKNOWLEDGEMENTS

ICP and their collaborators would like to acknowledge the financial support provided to this project by the DTI.

We would also like to acknowledge the help and support of the various project Officers and staff of FES (originally ETSU) who assisted in the definition of the project changes that ultimately enabled us to restart the project following the loss of the original Prime Contractor.

Figure 1

Schematic of Monolithic Integration for a Thin Film Solar Cell Panel

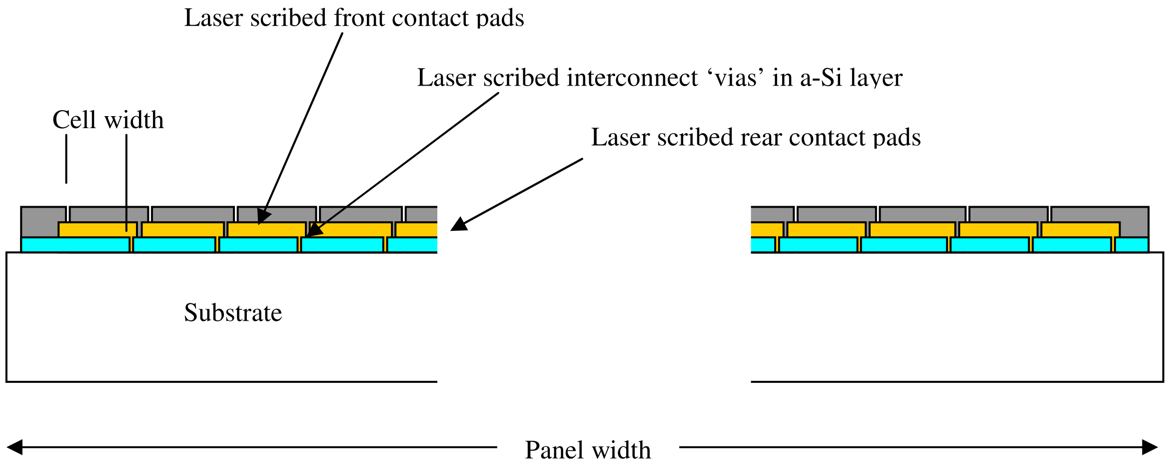


Figure 2

Example Electra-Clad Thin Film Solar Cell Panel

(edge markings result from holder clips used in metal coating stage)

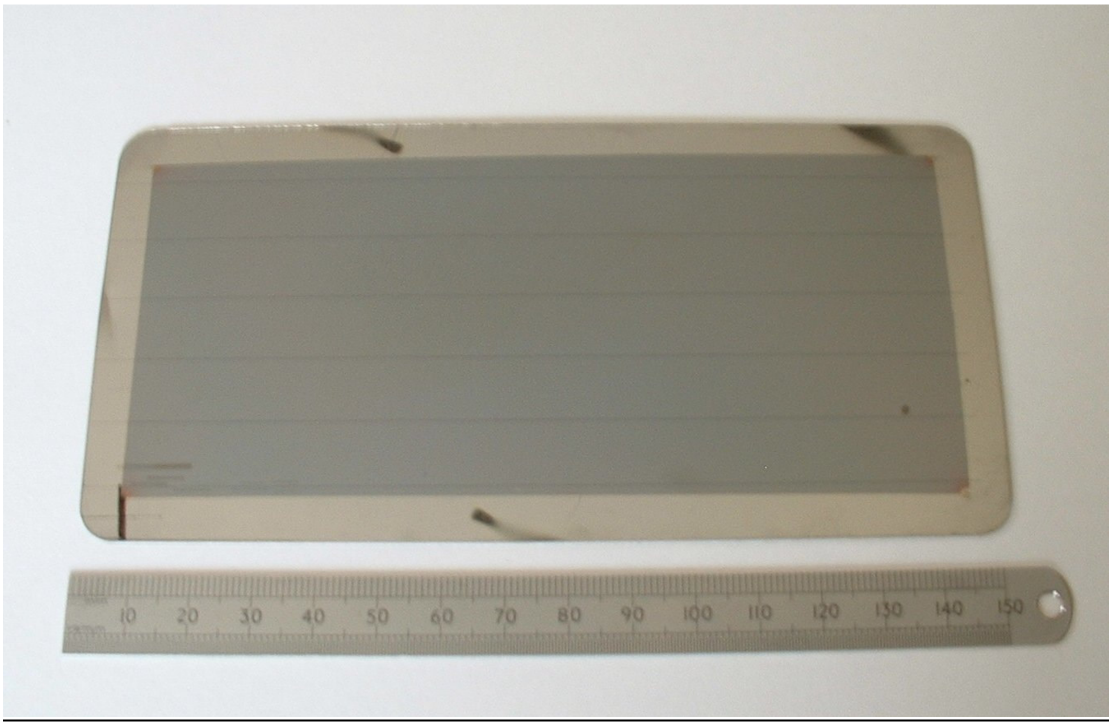


Figure 3
PV performance of standard ICP 'T' panel with clean up cycles omitted (original TDU configuration)

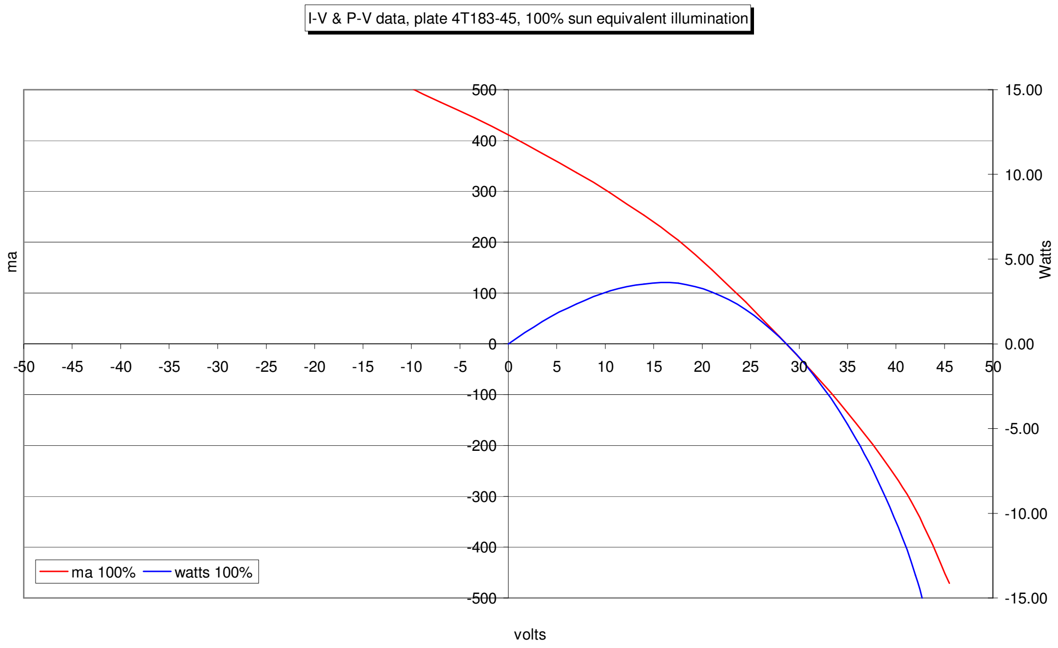


Figure 4
PV performance of standard ICP 'T' panel with clean up cycles omitted (modified TDU configuration)

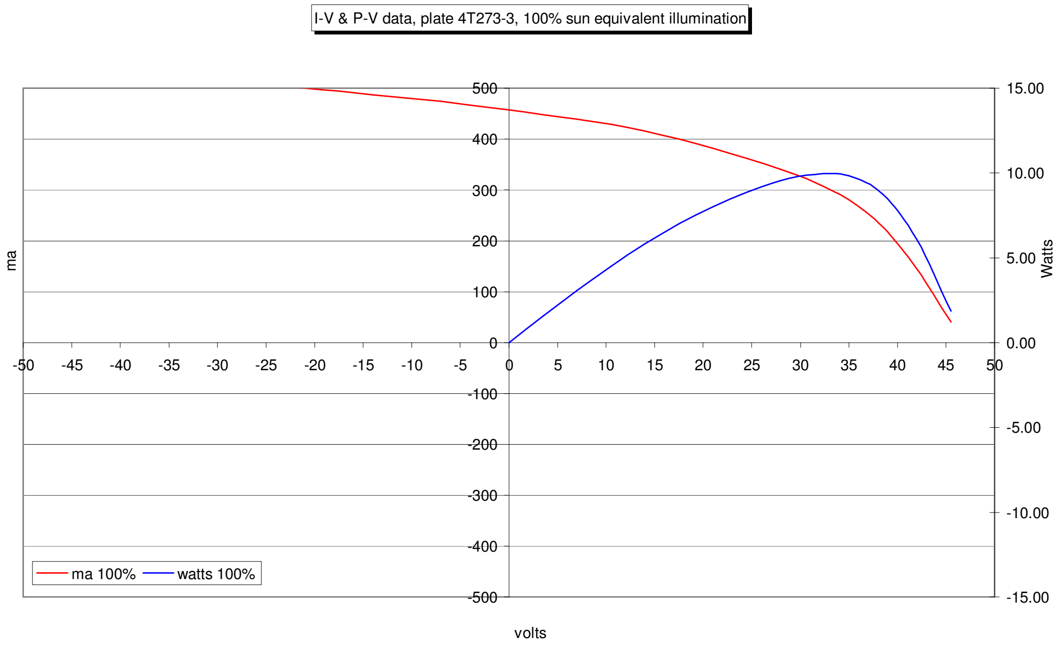


Figure 5

PV performance of initially developed NIP solar cell

(1cm^2 cell area, 85% sun equivalent illumination)

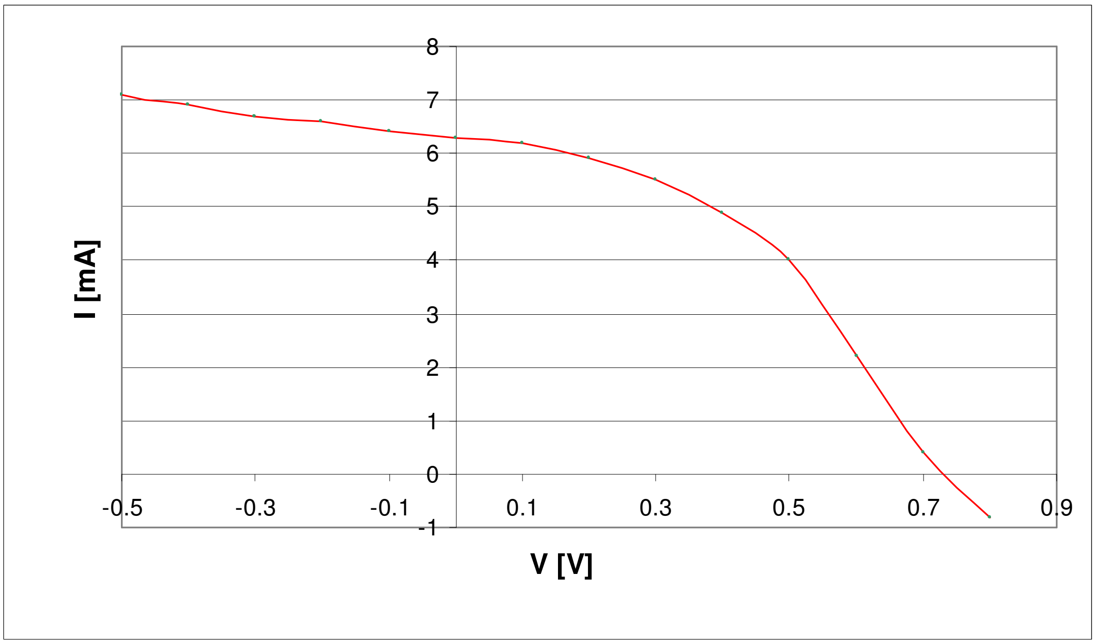


Figure 6

PV performance of optimised NIP solar cell, June 2004

(1cm^2 cell area, 75% sun equivalent illumination)

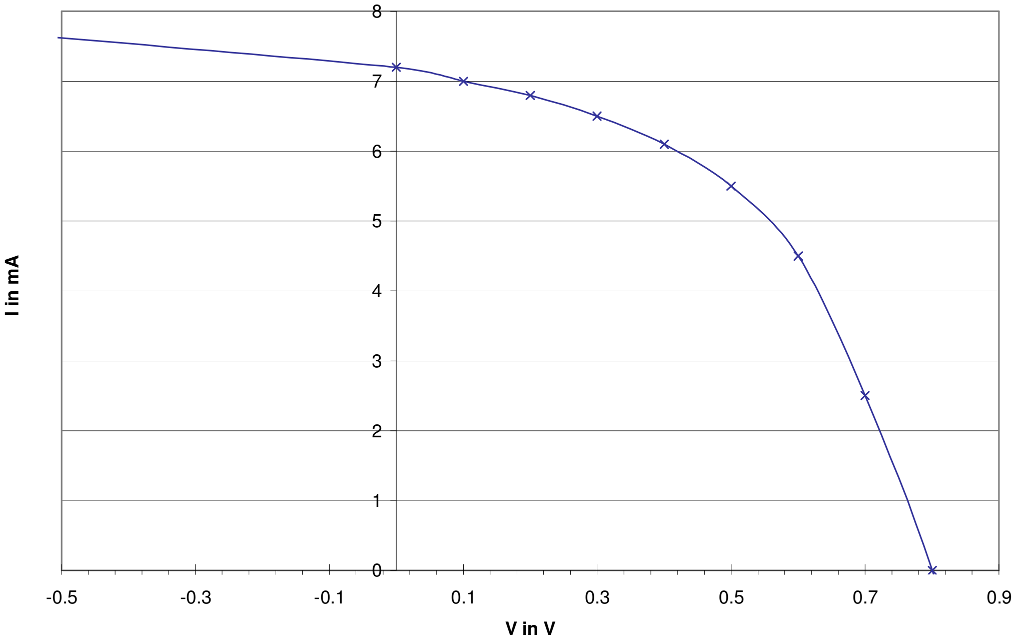


Figure 7
Micrograph of an Example Laser Patterned Back Contact Scribe

200nm thick chromium film on coated steel substrate (early test sample)

Scribe width is c. 0.17mm

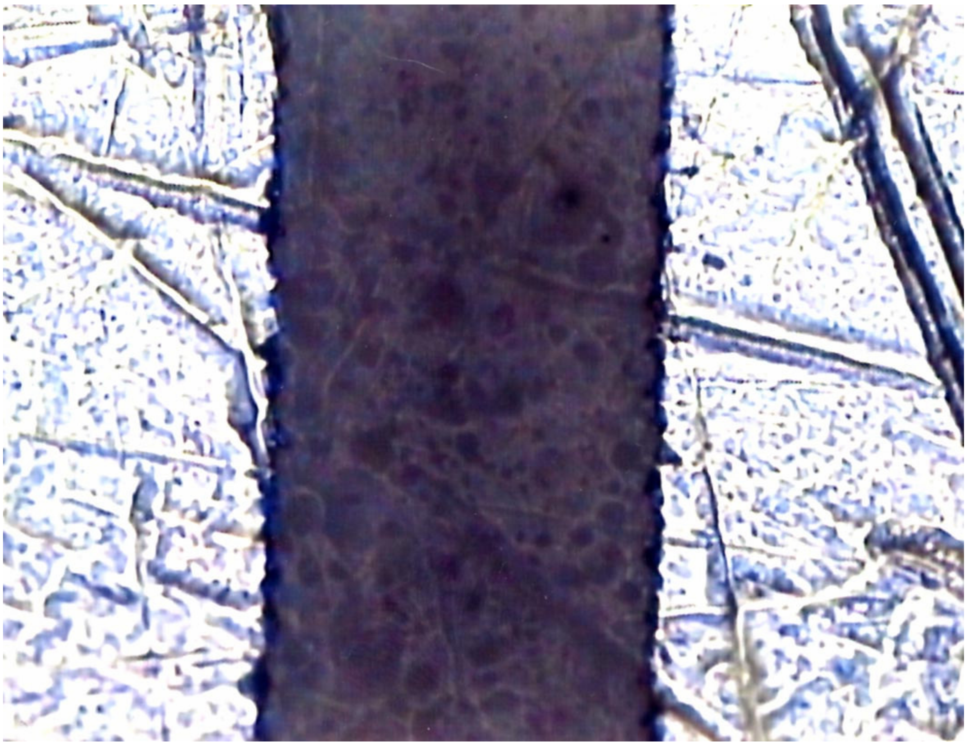
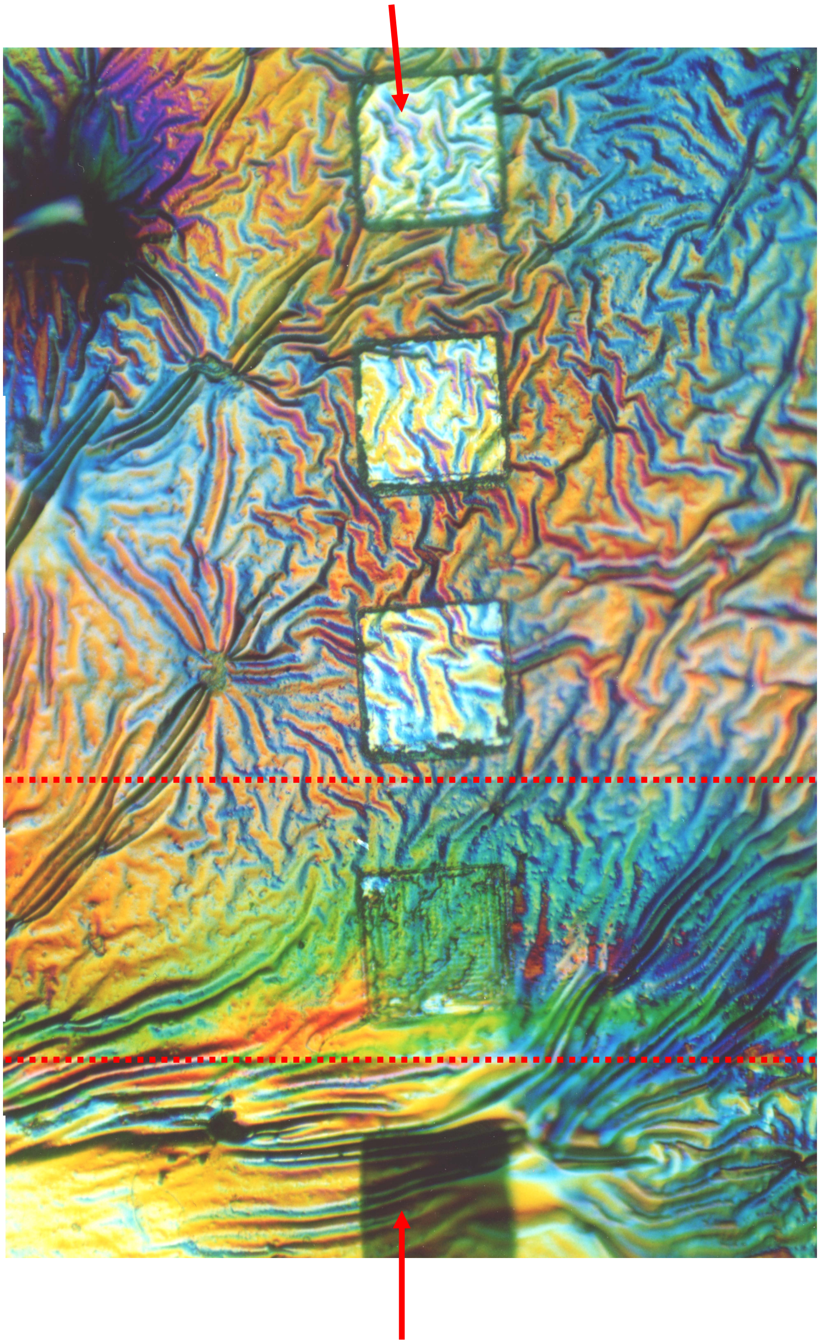


Figure 8
Micrograph of Example Laser Patterned a-Si Layer ‘Vias’



NIP thin film removed, exposing metal thin film

NIP film on top of metal thin film on coated steel substrate

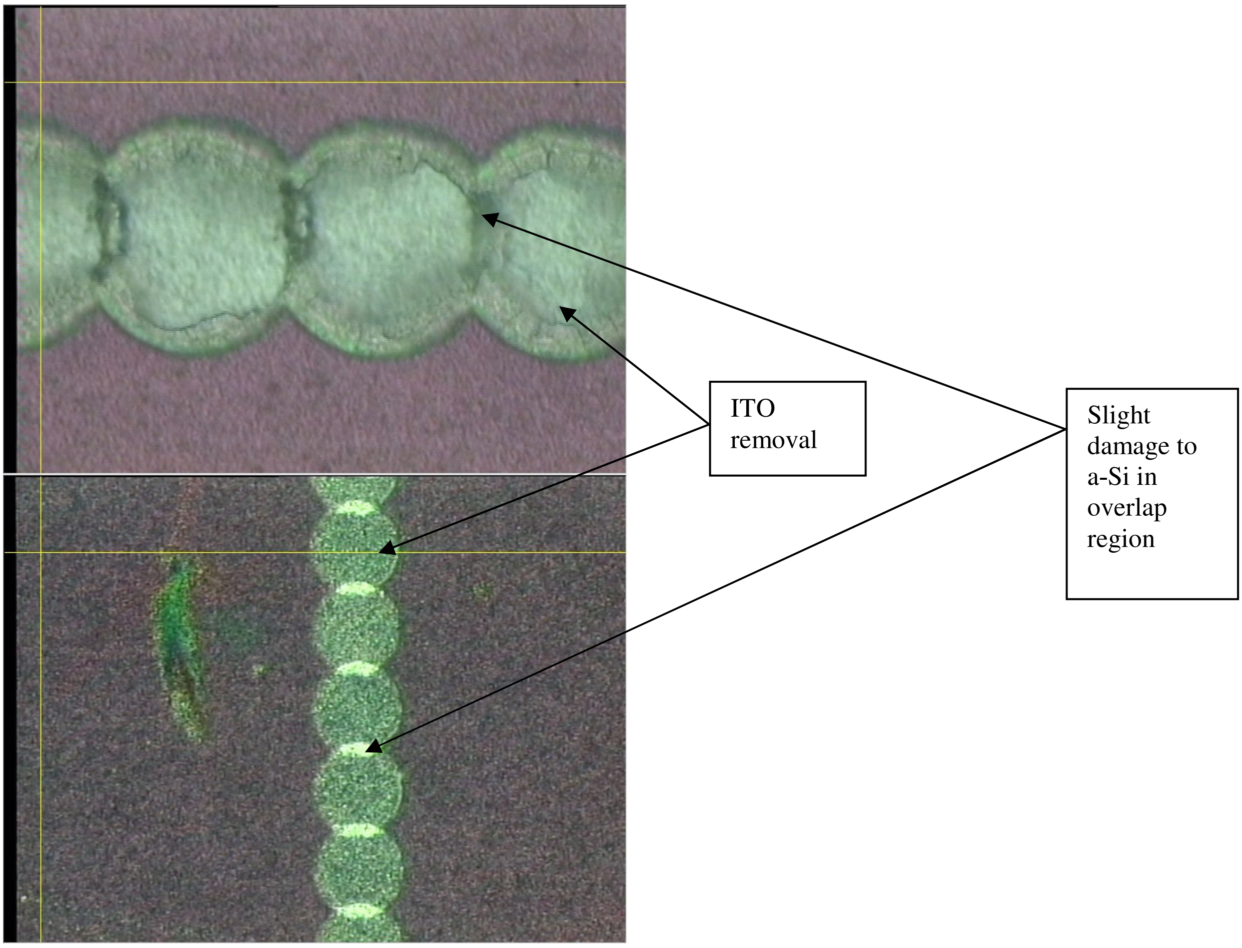
NIP coating transition region: full thickness NIP on metal above region, metal only below region

Metal thin film only on coated steel

Metal thin film removed, exposing substrate

Figure 9
Micrograph of Example Laser Patterned ITO Layer Scribes

Sample Type 1: ITO on a-Si on TCO on Glass.



Sample Type 2: ITO on a-Si on TCO on Steel.

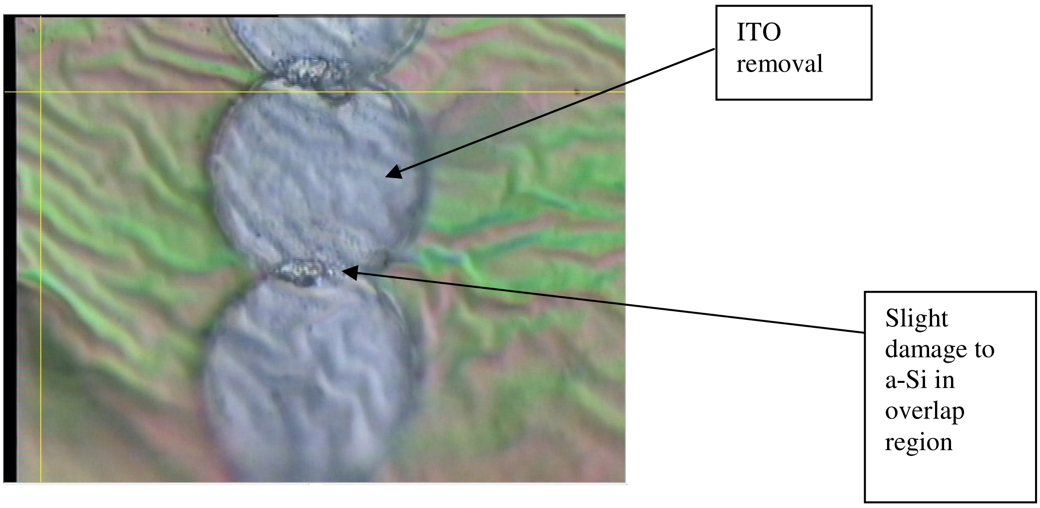


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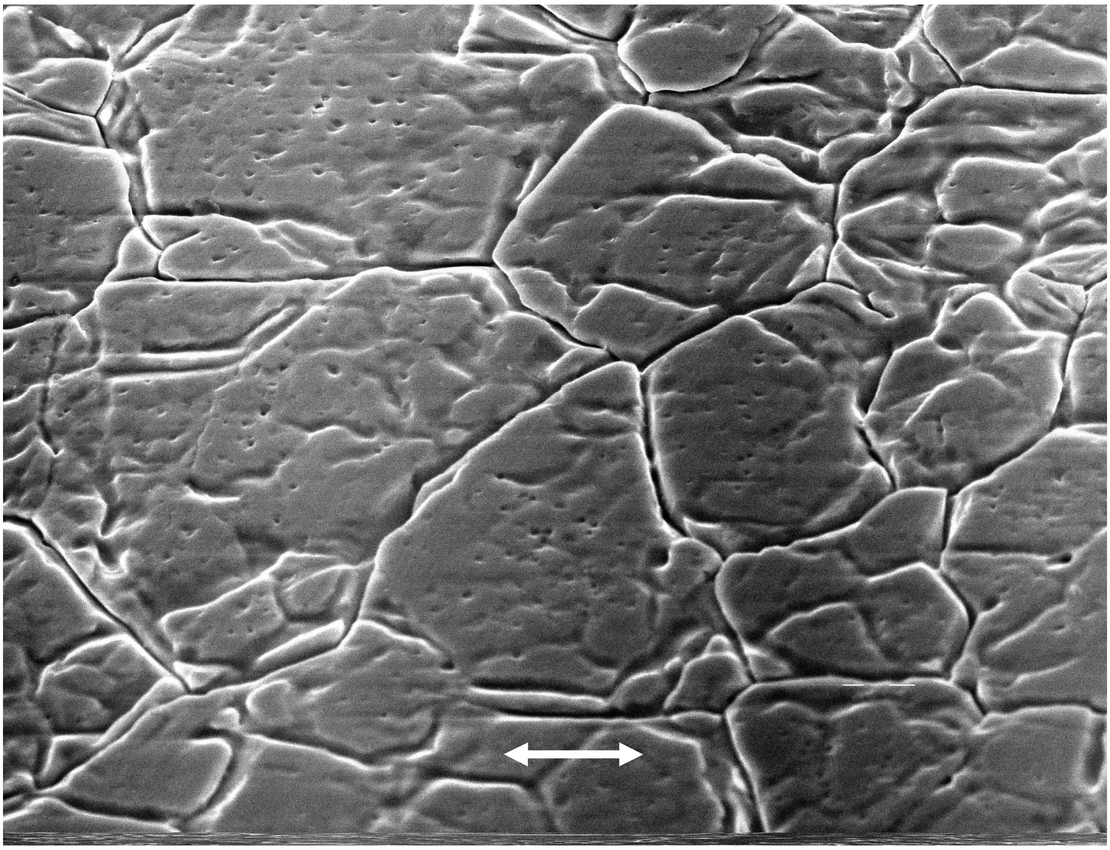
Figure 10

SEM Image of Uncoated Building Cladding 'Polished' Stainless Steel Surface

(Note that inter grain boundaries are substantially deeper than the thin PV cell film layers in many locations)



(Marker indicates c.2 µm)

Figure 11

Example of Wire Bonding to Electra-Clad Test Piece using Electrically Conductive Adhesive

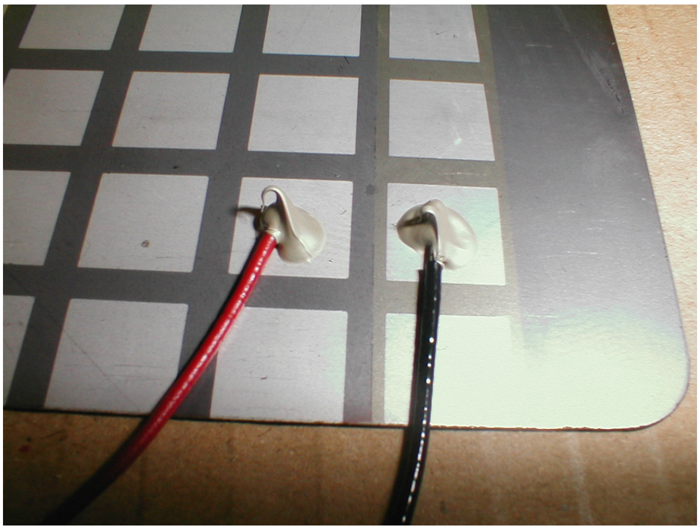
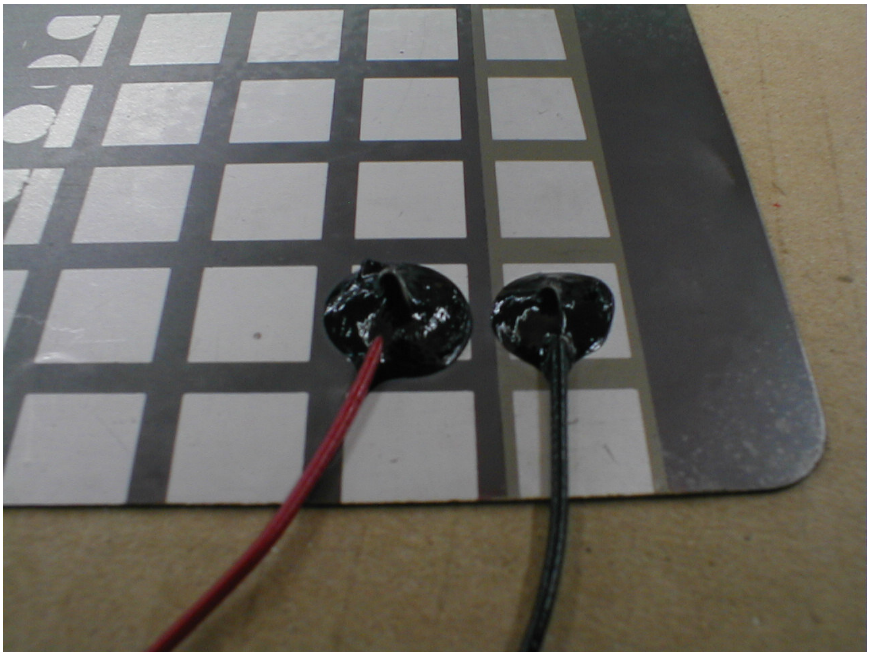


Figure 12

Example of Encapsulated Wire Bond



APPENDIX

Customer Report

Bonding Copper Wire to Aluminium Backing of Solar Panel Using Electrically Conductive Adhesive

05-330

Tania Fassbender

20 June 2005

1. Objective

Bonding Copper wire to the 0.004 mil (100 micron) thick aluminium backing of a solar panel using electrically conductive adhesive.

Determine joint stability after humidity test (85°C/85% RH).

2. Results and discussion

Materials tested:

- CE 3103 batch 61390 Cure: 5 minutes @ 150°C
- XCE 80212-3i batch 5503 Cure: 5 minutes @ 150°C

The adhesives were manually dispensed on the Aluminium pads. The copper wire (red one on one side, black one on the opposite side) was pushed into the adhesive and held in place using some polyimide tape during cure. The green strength of the adhesives was sufficient to hold the end of wire securely. All wires used were cut to the same length.

After cure, resistance was measured from the Aluminium pad to the end of the wire. Parts were put in humidity tests (85°C/85%RH) and re-measured.

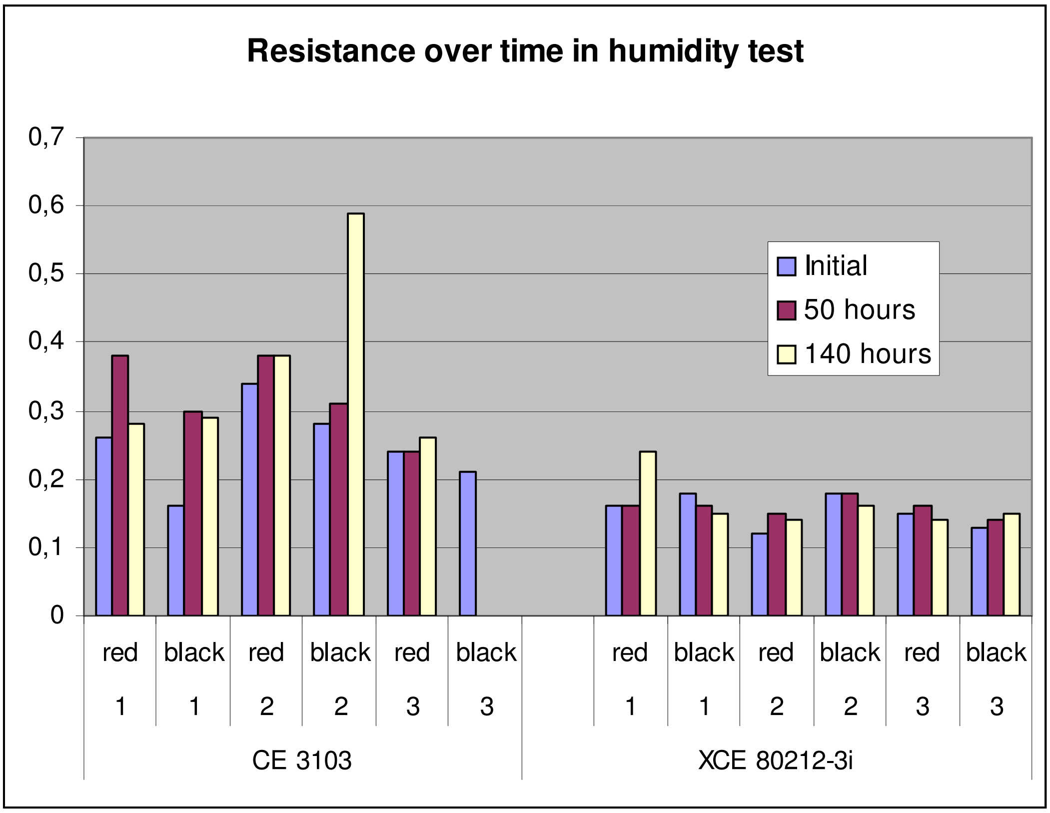
Results:

	Initial	**50 hours**	**140 hours**
CE 3103			
1 Red/black	0.26/0.16 Ω	0.38/0.30 Ω	0.28/0.29 Ω
2 Red/black	0.34/0.28 Ω	0.38/0.31 Ω	0.38/0.59 Ω
3 Red/black	0.24/0.21	0.24/- Ω	0.26/- Ω

	Ω		
XCE 80212-3i			
1 Red/black	0.16/0.18 Ω	0.16/0.16 Ω	0.24/0.15 Ω
2 Red/black	0.12/0.18 Ω	0.15/0.18 Ω	0.14/0.16 Ω
3 Red/black	0.15/0.13 Ω	0.16/0.14 Ω	0.14/0.15 Ω

Note: The failure mode on the black wire of sample n°3 was the adhesive to solar panel.

Graphic results:



3. Conclusions

- In both cases we observe low contact resistance.
- These resistance values are constant during humidity testing.

However, XCE 80212-3i has lower and more constant contact resistance after humidity tests compared to CE 3103.

ANNEX

Low Temperature Deposition of Indium-Tin Oxide using the PQL HiTUS Sputter Deposition System

September 2004

J Anguita and P Hockley, PQL

Aim:

The Electra-Clad Project requires low temperature deposition of a high transparency, electrically conducting Indium-Tin Oxide (ITO) film as part of a front contact scheme.

Trials targets:

- Substrate temperature must remain below 100°C, ideally 70°C.
- Optical transmission of ITO film >85% over visible spectrum (400-800nm nominal)
- Electrical sheet resistivity of ITO film <25 ohm/square.
- Film thickness circa 50-150nm, as required to achieve above.

Sputter System Configuration:

The PQL HiTUS R&D system (LTW) was used in normal configuration for process development and trial depositions. The following detail changes were made to minimise substrate temperature:

Working distance of 12 inches.

Used two shutters above the substrate: Top shutter gets hot during target pre-clean. Lower shutter used as a thermal shield from the plasma. Lower shutter remains cooler, minimising radiative heat transfer from plasma to substrate.

Argon gas inlet directed straight at substrate to cool surface layer and to increase pressure locally, thereby reducing the energy of in-coming particles and therefore heating of substrate.

Substrate table (large aluminium table) raised 1cm from turbo pump baffle plate using very thin stainless steel (substrate table effectively thermally floating). In a short run, the substrate table does not have enough time to heat up and will keep glass substrate cold. (The turbo baffle plate gets hot hence reason for isolation).

Process argon pressure set high compared to normal, around 50×10^{-4} mbar.

A 4-inch target of 90-10 In:Sn was used in reactive deposition mode (with oxygen) to provide a high rate process.

The oxygen flow controller (100sccm) was replaced late in the trials with a 20 sccm unit for greater control accuracy for the intended low rate process.

Summary of Trials and Results:

Process Parameters investigated:

Position of gas inlet (Ar and O_2), argon pressure, rf power, target voltage, steering magnet current, and use of top hat to further maximise working distance.

Initial process development observations:

Best results are obtained when the oxygen gas is introduced from the side arm (better transparency), and the argon is introduced into the chamber (target current about twice that when introducing argon through side-arm).

Best conditions are achieved at the lower target voltage values. However, the resistivity becomes more sensitive to changes in oxygen flow and base pressure at the lower target voltages. Around 200 Volts seems to be best condition.

Reducing the electromagnet steering current and increasing the plasma sidearm rf power (to maintain target current) gives best film properties (optically and electrically), but also causes more substrate heating. A balance needs to be struck between performance of ITO and damage to substrate. For the trials reported here, the minimum damage settings were chosen.

Maintaining the target current above about 200mA is needed to maintain a metallic target surface, otherwise target partially oxidises. Results in this report use a target current of about 500mA.

With these conditions, it is easy to control the transparency to values > 80%. Control of material resistivity is more difficult, being very sensitive to small variations in oxygen flow or process base pressure.

Use of the “top hat” extension piece to increase the exposure of the sputtered material to the plasma and reaction time did not result in an obvious improvement in film quality. The decrease in deposition rate made this arrangement unfavourable.

Results for optimised process:

Substrate temperature:

In all the runs, the chamber was vented immediately after finishing the deposition, and the sample removed. In all cases, the substrate table and glass could be removed with the bare hand, indicating the temperature had not exceeded the required 70°C.

In a separate trial, a temperature strip was placed on a glass slide, and a 10 minute run (200 Volts, 750W rf, 0.5 Amps) was made. The strip indicated a 54°C substrate temperature (therefore 60°C maximum possible), consistent with the above general observation.

In addition to glass substrates, thin plastic film ('Cling Film') was applied to glass and used as a substrate. By experience, this film is especially sensitive to plasma damage and localised surface heating from energetic particles, thereby providing a demanding test for development of a low energy process. No damage or change of physical properties was apparent to the film.

ITO performance:
ITO film resistivity was measured using a multimeter, (sheet resistance values were outside the measurement range of the 4-point probe system). The transmittance was measured using an amorphous silicon solar cell detector and 85% 'solar' light source, in order to obtain an appropriate integrated transmission value for the wavelength range of interest.

ITO films grown on glass substrates gave best results at the lower target voltage values. Figure 1 shows the resistivity as a function of oxygen flow for two target voltage values. Figure 2 shows the transparency of the samples. Note that more than one parameter is being changed in the runs at 209V, so the graph only gives an indication of the trends.

The samples grown on cling film showed similar resistive properties to those grown on glass substrates.

Conclusions

Thin ITO films of good electrical conductivity and optical transparency have been deposited by a low energy PQL sputter process, thereby maintaining low substrate temperatures and low plasma damage.

For ITO films of thickness 50nm, a value of 90% integrated optical transmission over the visible spectrum of interest for amorphous silicon PV cells can be achieved. Corresponding sheet resistance is 100 ohms / square.

Whilst this does not fully meet the ITO properties requirement, it is judged that the Electra-Clad samples themselves will be capable of supporting a more energetic deposition process. Increasing the plasma power has been shown to produce films of half the best resistivity reported here, and with slightly improved optical transmission, though at the cost of an increase in substrate heating. The steel based Electra-

Clad substrates should be able to be cooled to offset this; it is calculated that a 100nm film will then achieve the targets of 85% transmission sheet resistance of 25 ohms / square.

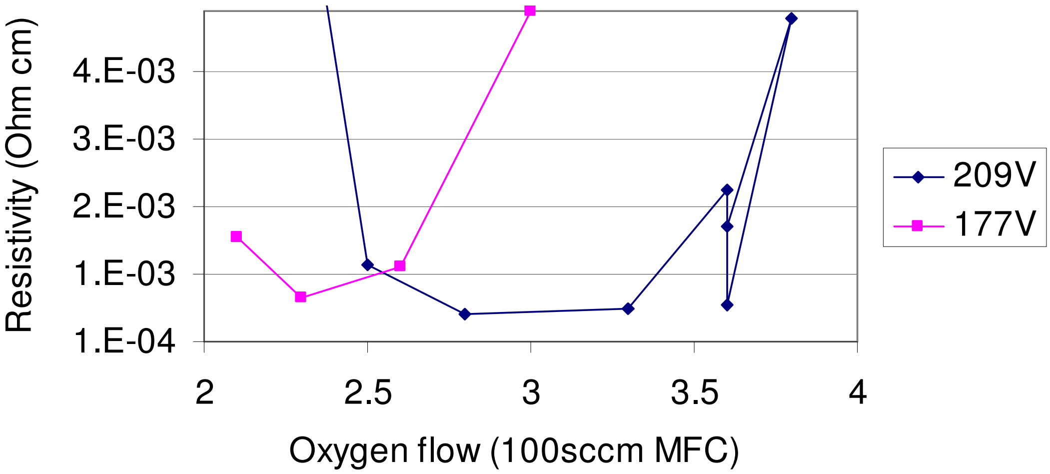


Figure 1: Resistivity Vs oxygen flow, for films grown on glass substrates

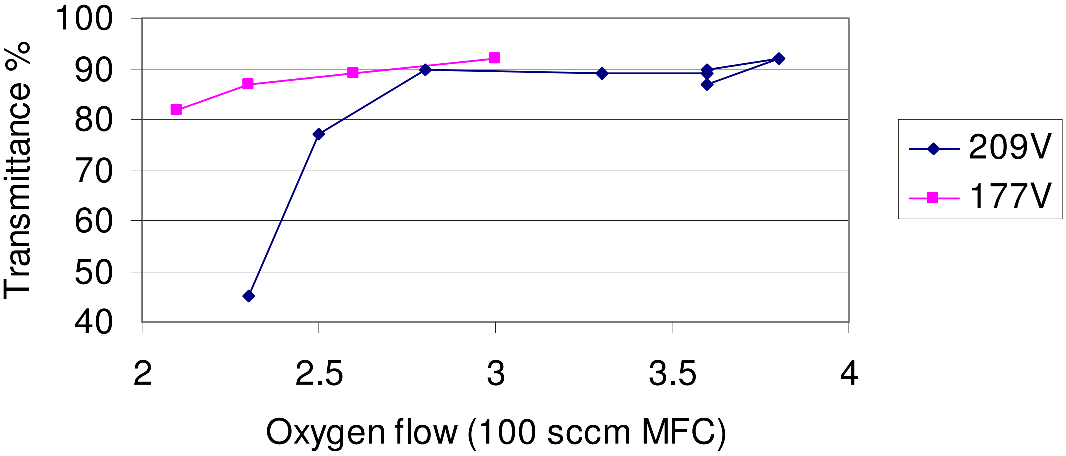


Figure 2: Transmittance Vs oxygen flow for the films in Figure 1