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Book of Abstracts

Fourth Workshop

Role of Point Defects/Defect Complexes in Silicon Device Processing

June 27-29, 1994
Beaver Creek, Colorado

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
Operated by Midwest Research Institute
for the U.S. Department of Energy
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REPRESENTATIVE

WORKSHOP CHAIRMAN
BHUSHAN L. SOPORI

WORKSHOP THEME

TOWARDS 18% COMMERCIAL Si SOLAR CELLS:
RESEARCH ISSUES AND APPROACH

MONDAY, JUNE 27, 1994

Towards 18% Commercial Si Solar Cells: Research Issues and Approach

Bhushan L. Sopori
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Commercial Si solar cells based on low-cost multicrystalline or single-crystal wafers or ribbons typically yield cell efficiencies in the range of 12% - 14%. Further improvements in the cell efficiencies are needed to meet the cost goals that can make photovoltaic energy delivered by these cells cost competitive. It is now known that the cell efficiencies are limited by the material quality and that further improvements in the efficiency can be brought about by incorporating defect engineering approaches such as impurity gettering and impurity/defect passivation. The current DOE/NREL program on Crystalline Silicon Materials Research has led to many advances in the understanding of the mechanisms involved in these processes as well as development of new processing approaches. These processes have recently been applied in the laboratory on small-area cells with considerable success. Although these laboratory results have contributed a significant understanding of the various gettering and passivation processes, their commercial applications demands further understanding of many critical issues. The major issues are related to:

- Uniformity of gettering and passivation over the entire wafer/cell
- Development of method(s) for gettering and passivation that can be compatible with low-cost cell fabrication
- Development of technologies for thinner cells to take advantage of light trapping and low bulk recombination
- Development of low-cost cell fabrication techniques and new processes that can reduce the number of process steps, and lower the cell cost.

In addition to pursuing the current approaches for high-efficiency cell fabrication, it is apparent that thin-film silicon cells, using the quality of the material currently available, can achieve this goal. However, again in this situation, many problems need to be solved both in the thin silicon film growth and cell fabrication areas. This paper will discuss the basic issues that must be addressed and solved by the research community before these processes can be applied commercially to fabricate low-cost cells with efficiencies reaching 18%.

SESSION 1:

IMPURITIES AND DEFECTS IN COMMERCIAL SUBSTRATES: THEIR SOURCES, EFFECTS ON MATERIAL YIELD, AND MATERIAL QUALITY

MONDAY, JUNE 27, 1994

DEFECTS AND DEFECT ENGINEERING IN SPHERAL SILICON™ SOLAR CELLS

John K. Arch
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Sphere processing is the first level of fabrication required to make Spheral Silicon™ Solar Cells [1]. Sphere processing involves upgrading irregularly shaped silicon particles into single-crystal silicon spheres, as well as formation of the p-n junction required to turn every sphere into a miniature photovoltaic cell. Defects can degrade the electrical performance of these spheral cells; therefore, it is important to understand the types of defects that reside within the silicon spheres and how the various sphere processing steps influence the creation and number of these defects. An oxygen denuding process is employed to create a denuded zone around the surface of the sphere; in this zone, the oxygen concentration is reduced to a level where little or no oxygen precipitation or associated defect formation occurs. After phosphorus diffusion and a post-diffusion anneal, TEM micrographs reveal defects very near the surface; it is believed that these defects are dislocation loops and are associated with phosphorus gettering in the device [2]. Because this near-surface region is later removed by chemical thinning, these surface defects should not influence electrical performance; however, the gettering associated with the formation of these defects may be responsible for increases in electrical performance that are only realized if this post-diffusion anneal is used.

[1] Jules D. Levine, Gregory B. Hotchkiss, and Milfred D. Hammerbacher, *Proc. 22nd IEEE PVSC* (IEEE, Las Vegas, 1991), p. 1045.

[2] John K. Arch, Jeffrey S. Reynolds, Milfred D. Hammerbacher, Richard K. Ahrenkiel, Sally Asher, Kim Jones, and Mohafak Al-Jassim, submitted to the *First World Conference on Photovoltaic Energy Conversion* December 5-9, 1994, Hawaii.

OPTIMIZATION OF HEM SILICON PRODUCED IN A REUSABLE CRUCIBLE

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M. Cudzinovic, M. Symko, and B. L. Sopori
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Golden, CO

A reusable crucible[1] was developed for directional solidification of multicrystalline silicon ingots by the Heat Exchanger Method (HEM). Sixteen 40 kg ingots were solidified in a 33 cm x 33 cm cross-section crucible; the ingot size has been scaled up to 65 kg, 44 cm x 44 cm cross-section. High efficiency solar cells with good uniformity have been fabricated.

The conditions in the HEM processing cycle have been varied to optimize the quality of silicon ingots. Data will be presented to correlate formation of particles in silicon, degradation of the coating, and segregation of impurities with the processing cycle. Mechanisms to minimize degradation of silicon near the top surface of the ingot will be analyzed. This data will be compared with silicon grown in a silica crucible.

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[1]C. P. Khattak et.al., Proc. 23rd IEEE PVSC (IEEE, N.Y. 1993) p. 73

Kim Mitchell

Unavailable at Time of Printing

IDENTIFICATION AND PASSIVATION OF THE PRIMARY LIFETIME-LIMITING DEFECT IN DENDRITIC WEB SILICON SOLAR CELLS

Daniel L. Meier
EBARA Solar, Inc.

The primary defect that limits the minority carrier lifetime in dendritic web silicon solar cells is a dislocation decorated with SiO_x precipitates. This has been established by comparing cells having a relatively high conversion efficiency (15%) with cells having a relatively low conversion efficiency (10%). The comparison included a correlation of the structural defects observed by cross-sectional transmission electron microscopy (XTEM) with the electrical properties of the cell, primarily efficiency and minority carrier diffusion length. Dislocations in the bulk silicon at a density of $\approx 10^6$ cm^{-2} were found by XTEM for the low efficiency cells but were seldom observed (10^4 cm^{-2} detection limit of XTEM) for the high efficiency cells. Mass spectroscopy in conjunction with atom probe field ion microscopy (APFIM) revealed the precipitate composition to be silicon and oxygen. The source of the oxygen is the quartz crucible which slowly dissolves during web growth. No evidence from APFIM or from deep level transient spectroscopy measurements was found for metallic contamination or for other point defects or complexes in web cells. Multiple twin planes, which run parallel to the external web surfaces and are located near the center of all web crystals, were shown to be electrically benign by cross-sectional electron beam induced current measurements and by laser beam induced current measurements on beveled samples. Dislocation density in the heavily-twinned region was generally a factor of 100 times as great as that in the bulk, or $\approx$ 10^8 cm^{-2} for the low-efficiency cells. Atomic hydrogen, introduced by low energy ion implantation, passivated the dislocation/oxide precipitate defect through the entire thickness (120 m) of the web cell. Analysis of an assumed distribution of defect levels throughout the silicon bandgap using the Shockley-Read-Hall recombination formalism has indicated that a reasonable immunity to the dislocation/oxide precipitate defect could be realized by using high resistivity (> 10-cm) web crystals. With such crystals, prototype cells (1 cm^2 area) have been fabricated with efficiencies up to 16.7% and diffusion lengths (from internal quantum efficiency measurements) up to 333 m. Dislocations are introduced into web crystals from thermal stresses during growth and an effort has been initiated to reduce their density to a minimal level. Modifications of the growth furnace to achieve the desired reduction will be guided by finite-element modeling based on temperature measurements made during web growth.

FORMATION AND ELIMINATION OF GROWTH DEFECTS IN LIQUID PHASE EPITAXY OF SILICON

Tihu Wang and Ted Ciszek

Various types of defects can form during liquid phase epitaxial growth of silicon layers on multicrystalline and single-crystal silicon substrates, including solvent inclusions, facets, stacking faults, dislocations, solvent trapping in grain boundaries and discontinuous layer growth. These defects are closely related to the substrates, solvent and growth conditions used. While some of the defects may be tolerated for thin layer solar cells, others are critical for decent cell performances. Their formation mechanisms and measures to eliminate them will be discussed.

NEW METHODOLOGIES FOR DEFECT ANALYSIS IN SILCON SOLAR CELL

L. C. Kimerling
Massachusetts Institute of Technology

Recent work on the analysis of TI Spheral Solar™ and Mobil Solar EFG silicon will be described. Correlation between trapped density and metal contamination with cell performance have been made. Progress in components for a global simulator for materials handling and metal contamination will be reviewed.

Dick Ahrenkiel

Unavailable at Time of Printing

EFFECT OF ULTRASOUND TREATMENT ON DIFFUSION LENGTH IN SI: NEW APPROACH IN DEFECT ENGINEERING

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Ultrasound vibrations applied to a semiconductor stimulate the change of properties controlled by point and extended defects. This had been refered to as the process of ultrasound treatment (UST) and was previously observed in II-VI and III-V (compounds). The following physical mechanisms were identified as the background for UST effect: (1) dissociation of complex centers stimulated by ultrasound; (2) ultrasound enhanced gettering of point defects by dislocations, grain boundaries and precipitates. We present the results of UST applied to monocrystalline and polycrystalline silicon wafers which demonstrate that ultrasound vibrations cause the variation of minority carrier diffusion length in Si.

Non-contact and non-destructive techniques of the diffusion length, L, mapping - laser/microwave photoconductive decay and surface photovoltage were used to monitor the influence of ultrasound on the value of L in Si wafers. Complimentary, these methods give an access to a quantitative measurement of Fe concentration, typical heavy metal contamination in silicon, and iron distribution in samples by using method of FeB-pairs optical dissociation combined with L mapping. The main results of UST study in silicon are the following:

1) Ultrasound vibrations can provide the gradual increase of L value versus number of subsequent treatment. It means that UST effect on diffusion length can be accumulated in a crystal. The value of relative change, L/L, depends upon parameters of ultrasound (temperature, holding time and amplitude). In particular, it is activated with temperature and proportional to the density of ultrasound power. 2) Increase of diffusion length is stable versus post-UST holding time (72h at room temperature or 1h at 100°C). 3) The maximum value of L/L is 50% in Cz-Si and reaches 170% in polycrystalline Si. 4) Besides positive change of L we observed the negative variation of diffusion length due to UST in p-Si doped with Fe at 10^{11} - $10^{14}cm^{-3}$. The "negative" UST effect is characterized by relaxation behavior versus post-UST holding time, which provides the identification of this process as Fe and B association kinetics.

Based on temperature dependence, kinetics and correlation with FeB pair distribution across the wafer the following two-step mechanism account for UST effect in Si. In the first step, ultrasound vibrations force the break of FeB pairs and release of Fe_i . In the second step, released interstitial iron, being unstable in p-Si at room temperature, can be either repaired with boron demonstrating relaxation of L/L value, or captured by sinks to form Fe precipitates (Fe gettering) showing the stable UST effect.

The observed change of diffusion length by UST in Si wafers can provide an effective mean to improve recombination properties of poly-Si solar cell material, where the interaction of point and extended defects is enhanced by ultrasound waves.

Fe AND Cr INTERACTIONS WITH DOPANTS IN POLYCRYSTALLINE SILICON AND INFLUENCE ON CELL DEGRADATION*

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We report on the study of Fe and Cr pairing reactions with dopants in p-type polycrystalline silicon grown by the Edge-defined Film-fed Growth (EFG) technique. Pairing behavior of Fe and Cr in association with B, Al and other defects is followed using diffusion length (L) mapping by the Surface Photovoltage (SPV) technique and by monitoring pair concentrations by Deep Level Transient Spectroscopy (DLTS). Dissociation of pairs is accomplished either by annealing, for times of the order of 10-20 minutes at temperatures of 210-225 C, or by optical excitation. Mapping of variations in L and impurity levels over extended areas of 10 cm x 10 cm area EFG wafers is used to obtain information on contributions of Fe and Cr to quality degradation and to distinguish pairing effects on L from those associated with other defects. The time dependence of the reformation kinetics of FeB and CrB are also obtained.

We find that Fe and Cr behavior in polycrystalline B-doped silicon parallels in most respects that observed in single crystal material. The pairing studies in the Al-doped silicon are still in the preliminary stages at this time. The deep levels associated with Fe and Cr provide recombination which leads to diffusion length degradation in polycrystalline silicon that is dopant concentration dependent. Modeling of the deep level behavior with PC-1D confirms that the fall off in solar cell efficiency observed with dopant concentration can be accounted for by pair recombination.

*This work was supported in part by DOE/NREL through subcontract No. XD-2-11004-5.

DLTS OF TRACE IMPURITY CONTAMINATION IN EFG SOLAR CELLS

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The conversion efficiency of EFG solar cells is strongly influenced by trace contaminants present in as-grown material or introduced during cell processing. The use of Deep Level Transient Spectroscopy to identify impurities in EFG material is reviewed, with emphasis placed on the lifetime-killing slow diffusers Mo, Ti and V. Recent results on process-induced defects generated during rapid thermal processing and high-temperature annealing of EFG material are presented. These processes are shown to introduce transition metals which sharply reduce the bulk diffusion length, and in many cases, the impurities responsible for the degradation are directly identified. Historically, the most critical requirements for high-purity processing are in the crystal growth area, in particular, the purity of graphite furnace components. In this work, a combination of diffusion length mapping and DLTS is used to locate the spatial distribution of recombination sites and identify the contaminants. This technique has now been deployed as an on-line quality control tool for EFG material which has virtually eliminated the occurrence of poor quality crystal growth runs in the production line.

CHARGE STATE DEPENDENT IRON DIFFUSION IN SILICON BELOW 200°C

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The long-range diffusion of both neutral and positively charged iron in boron-doped silicon in the 80 to 135°C range has been investigated by DLTS and C-V measurements. Both diffusivities were obtained on the same samples taking advantage of samples with non-uniform iron distribution in the near-surface region. The iron charge state was controlled by using a reverse biased Schottky diode. The migration enthalpies for Fe_i^o and Fe_i^+ were determined to be of 0.56 eV and 0.92 eV, respectively, revealing the impact of the charge state on Fe diffusion at low temperatures. Implications for low temperature gettering will be discussed.

EFFICIENCY-LIMITING DEFECTS IN POLYCRYSTALLINE SILICON

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The top efficiency of solar cells made from polycrystalline silicon materials lags well below peak efficiencies of single crystal cells. This fact is generally attributed to a greater density of crystallographic defects and transition metals present in polycrystalline material compared to single-crystal silicon, although a detailed accounting of the predominant carrier recombination processes is often unattainable in low-efficiency materials. By measuring the low-temperature precipitation rate of intentionally-added iron in a variety of silicon photovoltaic materials, it has been possible to show that intragranular structural defects exist in greatest abundance in materials with the lowest as-grown diffusion length, including Edge-defined, Film-fed Growth (EFG) silicon. Materials for high-efficiency cells-float-zone and magnetic Czochralski silicon-exhibit the lowest rates of both carrier recombination and iron precipitation. A consistent relation is found among all materials. Only the regions of EFG material with the highest as-grown diffusion length are found to contain dissolved iron after growth, indicating retarded iron precipitation during cooling after growth in these regions. Phosphorus diffusion gettering has been performed on some materials after identical transition metal contamination, and it is found that EFG silicon in particular is more resistant to diffusion length increase than single crystal Czochralski material. A model is proposed in which the predominant diffusion-length limiting factors in low diffusion length material are not residual dissolved transition metals but structural defects, whose recombination activity depends upon their density and degree of transition metal decoration.

SDMS-A TOOL FOR CHARACTERIZING COMMERCIAL PV SI MATERIALS AND CELLS

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Characterization of silicon substrates and solar cells requires identification of the sources of material nonuniformities as well as changes in the photoresponse associated with them. Crystal defects such as dislocations and grain boundaries are believed to be a primary source of such nonuniformities. Recently, a Scanning Defect Mapping System (SDMS) was developed to rapidly map dislocations and grain boundaries in commercial solar cell substrates. The operation of SDMS uses optical scattering from a defect-etched surface to separate dislocations and grain boundaries, and dislocation density is measured by statistical counting. This instrument is now being commercially developed by Labsphere and will be available in the near future. Further, improvements in this system will extend the applications of this instrument to analyses of crystal growth processes and solar cells. Typical time to generate a set of maps for a 10-cm x 10-cm wafer or a cell is about 1 hour. This processing time is expected to be reduced to 15 min in the commercial model.

FLOAT-ZONE SILICON CRYSTAL GROWTH AS A TOOL TO STUDY THE INFLUENCE OF DEFECTS AND IMPURITIES ON MINORITY CARRIER LIFETIME AND PV DEVICE PERFORMANCE

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Float-zone (FZ) silicon crystal growth is a useful, high-purity baseline growth process which can be perturbed in a controlled manner to study a variety of silicon defects. When coupled with photoconductive decay (PCD) bulk minority charge carrier lifetime () measurements and diagnostic PV device fabrication, the effects of various defects on and solar cell efficiency can be quantified. Examples of these effects for grain boundaries, dislocations, point defects, and selected impurities will be discussed.

CAST POLYCRYSTALLINE SILICON RESPONSE TO HIGH TEMPERATURE PROCESSING

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The buried contact solar cell process developed at the University of New south Wales contains several high temperature processing steps. The efficiency of cells made with float zone, Czochralski, HEM, and Solarex cast polycrystalline wafers vary considerably with this process. High temperature processing steps above 900°C degrade silicon with high oxygen concentrations. This effect is worse for Solarex cast polycrystalline than Cz silicon indicating that other impurities may play a role. Process modifications to reduce these effects are discussed.

SESSION 2:

NEW APPROACHES TO CELL PROCESSING: SHORT PRESENTATIONS + DISCUSSION

MONDAY, JUNE 27, 1994

R&D ISSUES FOR HIGH EFFICIENCY SCREEN-PRINTED SILICON SOLAR CELLS

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The baseline silicon solar cell fabrication technology of IMEC is a simple semi-continuous process, based on conventional screen-printing for the emitter and electrode formation. Using 420 m thick standard 10 cm x 10 cm quasi-square Cz material, this process yields embedded average efficiencies of 15.1% with a standard deviation of 0.14. The process combines the use of both conventional and IR firing belt furnaces. Additional options to this baseline process are an aluminum treatment using a screen-printed aluminum paste at the backside and a TiO_2 APCVD anti-reflection coating. The average embedded efficiency increased from 15.1% ($\sigma = 0.14$) for the baseline process to 15.9% ($\sigma = 0.14$) by adding the aluminum treatment and to 16.3% ($\sigma = 0.2$) by adding both the aluminum treatment and the antireflection coating.

The efficiency of this process should be increased without having a strong effect on the cell fabrication cost and taking into account that future wafers will be considerably thinner (≤200 m). Cost related and efficiency related R&D issues can therefore not be separated. Important cost related issues are:

- The development of a continuous process with a minimum of manual handling and a high mechanical yield (→ continuous processes).
- The reduction of the use of chemicals (e.g. cleaning).
- Low thermal budget processes with high throughput.
- Manufacturing science.

Efficiency related R&D issues include:

- A more optimal back side processing.
- A better top contract formation: fine line printing (<< 100 pm) with good aspect ratio. Interesting possibilities are screen-printing using novel metal screens and off-set printing.
- An optimized emitter formation both for homogeneous and selective emitters. The cost-effective implementation of a selective emitter in a cell with screen-printed electrodes requires high quality low temperature oxides.

It can be concluded that commercial Cz screen-printed silicon cells with efficiencies into 18% range are a realistic goal.

POINT DEFECT INJECTION INTO GRAIN BOUNDARIES FOR GRAIN ENHANCEMENT

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Grain boundaries in poly-crystalline Si are comprised of grain boundary dislocations. Theory shows that these grain boundary dislocations have smaller Burger vectors than lattice dislocations. For these dislocations to glide, both their Burger vectors and their line direction must be contained in the {111} plane.

The atomic mobility of grain boundaries in small grain (e.g. CVD) poly-Si can be substantially enhanced by injecting Si selfinterstitials through, for example, oxidation, implantation of Si, or diffusion. The injected interstitials migrate to and anneal out at grain boundaries. The absorption of these point defects permits the grain boundary dislocations to move non-conservatively into any direction. The enhanced atomic mobility leads to both grain growth and reconstruction of the grain boundary into a low energy configuration.

High resolution transmission electron microscopy shows that this reconstruction frequently leads to a dissociation of the grain boundary into symmetric, twin related, subboundaries. The spacing of these two subboundaries may be as small as 10Å . Electrical measurements using IGFETs show that the dopant diffusion, on average, slows down along such reconstructed grain boundaries. Concomitantly, one measures a reduced density of electronic gapstates. Both observations are in agreement with results on macroscopic, twin related boundaries which show, e.g., the absence of grain boundary diffusion and electrical activity at first and second order symmetric twin boundaries.

In highly stressed, semicrystalline materials, the injection of interstitials will promote the non-conservative motion of dislocations in the grain interior as well. TEM shows the polygonization of dislocations into low angle grain boundaries as well as dislocation multiplication. A comparison between solar cells fabricated with deposited emitters and reference specimens made with diffused emitters shows that the latter tend to have lower base lifetimes. The observation is in agreement with the argument that in semicrystalline material with grain sizes large compared to the diffusion length, improvement of grain boundaries will have relatively little influence and therefore will not be able to compensate the Si self-interstitial triggered increase in intra-grain defects.

HIGH-EFFICIENCY SEMICRYSTALLINE SILICON SOLAR CELLS WITH LOW-COST PRODUCTION TECHNOLOGY

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[1]Netherlands Energy Research Foundation ECN,
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THE NETHERLANDS

A low-cost processing technology for multicrystalline silicon solar cells has been developed. The average encapsulated cell efficiency is 14.7% with a standard deviation of 0.3%, both on Wacker SILSO and Bayer material. The process sequence consists of 9 distinctive steps, including a combined Al- and P-gettering and a hydrogen-passivation step. A further increase in efficiency is foreseen by the implementation of etched-back (selective) emitters with passivated front surfaces. Investigation of the process parameters has been performed in an industrial pilot-line with experiments of typically 1000 wafers.

The paper describes a number of experiments illustrating the influence of various process-parameters on the effect of gettering and H-passivation on the solar-cell performance. Although it is shown that both gettering and H-passivation enhance the solar-cell efficiency, the underlying mechanisms are not well understood yet.

The effectiveness of surface passivation with silicon-oxides and -nitrides largely depends on the condition of the surface just before the passivation step. As an example, the compatibility of H-passivation using a plasma and surface passivation with a PECVD nitride and/or oxide will be discussed.

SOLAR CELL CONTACT FORMATION BY OPTICAL PROCESSING

Michael Cudzinovic, Xiaojun Deng, Craig Marshall, and Bhushan Sopori
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Optical Processing (OP) is a new approach for semiconductor device fabrication that takes advantages of photon-assisted interface reactions produced by illuminating a S-M interface with near-bandgap energy. This processing approach is particularly suitable for fabricating contacts to solar cells because it offers control of the interface characteristics to produce low-resistivity contacts that can simultaneously offer such features as high optical reflectance and light-trapping capabilities. Due to the photo-induced nature, the interface reactions can be induced only in the selected interfaces while masking the regions in which the interface reactions need to be suppressed. This feature can be applied to form the front and the back contacts of a solar cell in a one-step process, thus reducing the number of process steps required for cell fabrication. Optical Processing has other advantages. It operates at lower temperatures, is rapid, uses significantly less energy than other conventional processes, and is very tolerant to impurity indiffusion. The photon-assisted nature of the process and preferential dissipation of the optical energy at the interface make this process suitable for producing contacts on hydrogenated cells, as well as improving cells that may have existing contact problems. This paper will discuss the principles of OP and how this technique can be applied to fabricate higher efficiency devices at a significantly lower cost.

SESSION 3:

IMPURITY GETTERING IN SILICON

TUESDAY, JUNE 28, 1994

PHOSPHORUS AND ALUMINUM GETTERING IN SILICON: SIMULATION AND OPTIMIZATION CONSIDERATIONS

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Via the use of the *diffusion-segregation equation*, which has been derived recently by the present authors, modeling and simulations of gettering Au away from the Si bulk have been performed for the first time. Au is a substitutional-interstitial species in Si, and in the Au gettering processes Si point defects are involved. Three *external* gettering schemes have been considered: wafer frontside P indiffusion gettering, wafer backside Al deposition gettering, and a combination of the two processes. Under otherwise the same processing conditions, it has been shown that P indiffusion gettering is faster than Al gettering, but P gettering has a lower gettering capacity and is less stable than Al in long gettering time cases. The combined P and Al gettering process is as fast as P gettering in reaching an optimum gettered state, and possesses the capacity and stability of the Al gettering process. A most outstanding feature of these external gettering processes is that an impurity dynamic concentration value below its thermal equilibrium solubility can be obtained in the gettered Si region. The Al gettering process has been also shown to be highly effective for gettering the more mobile metallic impurities interstitially dissolved in Si.

GETTERING OF FE IN CZ AND MCZ SILICON

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The gettering of Fe in p-type silicon using polycrystalline films was studied by determining the minority carrier lifetime using the SPV method. The samples doped with Fe were annealed at temperatures ranging from 400°C to 700°C. A novel approach to study the internal and external gettering of Fe in CZ-silicon has been presented. Finally, the gettering behavior of Fe in CZ and MCA silicon is compared and contrasted.

EFFECT OF CI, P AND AI/RTP NON-EQUILIBRIUM GETTERING ON INHOMOGENEITIES OF LIFETIME IN PV POLY-CRYSTALLINE SILICON

L. Jastrzebski, G. Nowak, W. Henley, D. Schielieu and J. Lagowski
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Tampa, FL

The results of chlorine (Cl) and phosphorous (P) gettering of pv poly-crystalline silicon are presented together with a novel technique, non-equilibrium AI/RTA gettering. Using surface photovoltage (SPV) diffusion length measurements, it has been established that pv poly-silicon is very inhomogeneous and P, and Cl gettering only improves diffusion length values in regions in which the diffusion length is relatively high and a large amount of non-precipitated Fe and Cr is present. In regions with low diffusion lengths, non-precipitated Fe and Cr were not detected in as-grown poly-silicon and gettering did not result in any substantial improvement in diffusion length values. It is conceivable that recombination in these regions is controlled by grown-in defects. On the other hand, Al/RTA gettering substantially improves diffusion length values even in low diffusion length regions (up to five times). The results of isochronal and isothermal annealing (700°C to 900°C, 30 to 300 seconds) will be presented. Although at present the mechanism is not fully understood, it appears to be different than that of classical Al furnace gettering.

ENHANCEMENT PROCESSES FOR THE AP-225 SILICON-FILM™ SOLAR CELL

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Solar cell fabrication processes for the gettering and passivation of defects are under development for the AP-225 Silicon-Film™ solar cell at AstroPower. Specifically, hydrogenation, gettering diffusion and forming gas annealing are being developed for use as manufacturing processes. Results and analysis of this development effort will be presented.

EFFECTS OF PECVD AND Al TREATMENTS ON THE SILICON SOLAR CELL EFFICIENCY

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A detailed investigation of quality enhancement techniques, such as PECVD SiO_2 /SiN deposition and forming gas anneal (FGA) for defect passivation, and Al treatment for defect and impurity gettering, was conducted on several promising multicrystalline Si materials. The PECVD SiO_2 /SiN coating followed by photo-anneal increased the bulk lifetime by a factor of 1.3 to 1.7, and decreased the surface recombination by a factor of 5 - 22, depending upon the multicrystalline material. Besides bulk and surface defect passivation, PECVD coatings were also found to be very effective in passivating phosphorus diffused emitters. The OTC multicrystalline cell parameters showed 59% increase in J_{sc} 24 mv in V_{oc} and 60.5% in cell efficiency due to the PECVD coatings. These improvements result from the combination of two layer AR coating and bulk and surface passivation effects. Al gettering in multicrystalline Si showed a significant improvement in bulk lifetime and Light Beam Induced Current (LBIC) response. Solar cells fabricated on EFG sheet Si showed an efficiency improvement of 2.6% from FGA alone, 1.5% due to Al gettering alone, and 1.2% from Al diffusion and FGA interaction. Finally, cells fabricated on cast Si from OTC, using optimized gettering and passivation techniques, gave record high multicrystalline Si efficiency of 17.8%.

SESSION 4:

IMPURITY/DEFECT PASSIVATION: PRESENTATIONS + DISCUSSION

TUESDAY, JUNE 28, 1994

DIXSI: DEFECTS IN CRYSTALLINE SILICON FOR SOLAR CELLS A COOPERATIVE GERMAN RESEARCH PROJECT

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Fraunhofer Insitut fur Solare Energiesysteme (FhG-ISE)
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Multicrystalline silicon (mc-Si) from cast ingots and monocrystalline silicon grown by the Czochralski technique (Cz-Si) are still by far the dominating materials for solar cell fabrication. Compared to Cz-Si mc-Si offers some cost advantages but shows lower solar cell efficiencies due to the large number of crystal defects originating from the solidification process. Detrimental defects are grain boundaries and dislocations especially when decorated by impurities.

The aim of this combined project is to understand the origin of these defects, their dynamics during solar cell processing and their influence on the solar cell performance and on the other hand to elaborate techniques to reduce their influence. The project was set up in 1990 in collaboration with the German PV industry and is financed by the German Minister for Research and Technology.

The cooperating research organizations and their respective project leaders are:

Fraunhofer Institut fur Solare Energiesysteme, Freiburg	A. Eyer, Coordinator
Max-Planck-Institut fur Mikrostrukturphysik, Halle	O. Breitenstein
II. Physikalisches Institut, Universitat Koln	H. Gottschalk
Institut fur Halbleiterphysik, Frankfurt/Oder	M. Kittler
Institut fur Experimentelle Physik, TU Bergakademie, Freiberg	H.J. Moller
IV. Physikalisches Institut, Universitat Gottingen	W. Schroter
Institut fur Angewandte Physik, Universitat Erlangen-Number	M. Schulz
Inst. fur Wekstoffwissenschaften, Universtitat Erlangen-Nurnberg	H.P. Strunk
Institut fur Kristallzuchtung (IKZ), Berlin	E. Wolf

The industrial partners (Bayer AG, Deutsche Aerospace AG, Freiberger Elektronikwerkstoffe, Nukem, Siemens Solar, Wacker-Chemitronic) provide their respective silicon materials and their different solar cell processes.

The research institutes and universities offer their diagnostic techniques and their experiences in the field of defects in silicon. Although the influence of the defects is very complex, there are already some significant results which led to a better understanding of mc-Si solar cells and which will be introduced into the solar cell processes in order to improve the quality and/or to reduce the cost.

DAMAGE-FREE HYDROGENATION SYSTEM

Edward M. Nadgorny, Dept. of Physics
Michigan Technological University,
Houghton, MI

A new **damage-free hydrogenation** system with a new source of atomic hydrogen are to be built for studying its properties and effects on passivation of semiconductor materials and devices. The system will be attached to MTU Reference Cell to employ the crossed beam concept (CBC) which allows one to produce the beams of atomic hydrogen without any ionic components.

The neutral hydrogen atoms are produced when a supersonic beam of molecular hydrogen is passing through a magnetically confined hydrogen plasma of, for instance, one of the ECR sources. Hydrogen molecules dissociate and produce both hydrogen atoms (free radicals) and ions. The ions remain in plasma held by the magnetic field, and the neutral (atomic) species keep moving crossing the plasma space.

The absence of charged component in the hydrogen flow is the basic advantage of the CBC. It helps to avoid deleterious effects related to strong plasma interaction with the surface of a sample during either plasma etching, reactive ion etching or sputtering. The CBC-based hydrogen systems could be used for the hydrogenation of not only photovoltaic silicon and GaAs materials but also of such surface-decomposable compounds as InP, InGaAsP, InSb, and even the entire devices. In particular, promising performance gains have been observed after making use of a CBC-based hydrogen system for passivation of polycrystalline silicon solar cells (the increase in the efficiency from 8.5 to 12.5%), InSb and InP MIS-capacitors, and GaAs and InP Schottky diodes.

POSITRON ANNIHILATION SPECTROSCOPY OF VACANCY-TYPE DEFECTS IN SILICON

Suresh C. Sharma
Center for Positron Studies, Department of Physics
The University of Texas at Arlington, Arlington, TX

Positron Annihilation Spectroscopy (PAS) has been used to study vacancy-type defects in silicon samples. We present results from two different types of measurements made on Czochralski-grown silicon wafers: 1) positron lifetime measurements by using positrons with an energy distribution characteristic of the beta-decay of the ^{22}N a radioisotope and 2) Doppler broadening measurements in the annihilation gamma ray energy by implanting monoenergetic positrons at different depths from surface down to about 1 µm. The positron annihilation characteristics are known to be sensitive to the presence of lattice defects in the sample. Negatively charged vacancy-type defects trap positrons. Upon trapping, the positron lifetime increases and the Doppler broadening in the annihilation gamma energy decreases. These changes result from a diminishment in the electron density and core electrons within the trap, respectively. The positron lifetime measurements (the so-called bulk measurements), provide information averaged over implantation depths ranging from the surface down to about 100 µm. From these measurements, we identify monovacancies and divacancies in the Czochralski-grown silicon wafers. The variable energy positron beam measurements, on the other hand, are used to obtain the depth profile of defects in the top m of the wafer. In addition to results from a Cz-grown silicon wafer, we also present results from the positron lifetime measurements on FZ silicon and silicon ribbons.

A BRIEF REVIEW OF HYDROGEN PASSIVATION IN SOLAR CELLS

Jack I. Hanoka
Mobil Solar Energy Corporation
Billerica, MA

A number of somewhat disparate results will be presented. The method to study hydrogen passivation in solar cells used here has been EBIC both at 300°K and at 77°K. An attempt to integrate these results into a coherent picture will be made. Remaining issues will be discussed.

HYDROGEN PASSIVATION OF DANGLING BONDS IN SILICON

Stefan K. Estreicher-- Texas University

The passivation of defects that limit the lifetime of charge carriers is of particular importance in photovoltaic devices made of rapidly grown silicon material, such as polycrystalline silicon. The dominant defects involving dangling bonds (from isolated vacancies to grain boundaries or dislocations) can in principle be pssivated with hydrogen. The passivation process itself is fairly easily understood. However, the problem of getting hydrogen to the dangling bond in an inexpensive and efficient way has yet to be fully solved. Theoretical studies at or near the *ab-initio* level suggest that many interactions need to be taken into account. In this talk, I will summarize the results of our calculations involving vacancies, hydrogen-vacancy complexes, and vacancy-hydrogen pair diffusion. Some consequences of our results will be discussed.

HYDROGEN IN SINGLE-CRYSTAL AND POLYCRYSTALLINE SILICON

Noble Johnson
Xerox Palo Alto Research Center
Palo Alto, CA

Several recent studies have revealed new properties of hydrogen in polycrystalline and single-crystal silicon. In thin films of polycrystalline silicon, hydrogenation introduces the following metastabilities: (1) the light-induced creation of paramagnetic defects (Si dangling orbitals) [1] and (2) a cooling-rate dependent metastable change in the dark dc conductivity [2]. While such phenomena have long been known in hydrogenated amorphous silicon (a-Si:H), they display dissimilar features in the two materials which yield new insights. For example, in poly-Si:H it is evident that hydrogen directly contributes to the light-induced metastability (a conclusion still debated in a-Si:H) and the quenching metastability is not due to the activation and passivation of dopant impurities (unlike in a-Si:H). In single-crystal silicon it has now been experimentally demonstrated that monatomic interstitial hydrogen has a large negative effective correlation energy, with the donor level situated ~0.20 eV below the conduction band and the acceptor level coincidentally located essentially at midgap [3].

[1] N. H. Nickel, W. B. Jackson, and N. M. Johnson, Phys. Rev. Lett. 71, 2733 (1993).
[2] N. H. Nickel, N. M. Johnson, and C. G. Van de Walle, Phys. Rev., Lett. 72, 3393 (1994).
[3] N. M. Johnson, C. Herring, and C. G. Van de Walle, Phys. Rev. Lett., in press.

RECENT RESULTS FROM IMEC ON HYDROGEN PASSIVATION

H. E. Elgamel, J. Nijs and R. Mertens
IMEC, Leuven, BELGIUM

This paper describes recent results from IMEC on hydrogen passivation of multicrystalline silicon solar cells.

A first set of interesting results concerns the use of a microwave induced remote (MIR) hydrogen plasma to passivate multicrystalline silicon. This technique causes almost no plasma induced damage since most charged species recombine before reaching the sample. It is also characterized by a higher dissociation yield of molecular hydrogen into atomic hydrogen. Therefore, this technique can be efficiently used after oxide surface passivation which is advantageous when fabricating high efficiency cells. A fabrication process including thermal oxide growth, an rf plasma from the backside and an MIR plasma from the front side yields the following results for 2 cm x 2 cm multicrystalline cells.

Material	J_{SC}	V_{OC}	FF	EFF.
DS	34.5	615	78.3	16.7
EMC	35.2	610	77.0	16.0

The second part of the paper deals with hydrogen passivation by deposition of a thin layer of PECVD silicon nitride. It has been reported in the literature that the deposition of such layers at low temperatures (350°C-400°C) on both sides, followed by a high temperature step at 700°C results in a very efficient hydrogen passivation of multicrystalline silicon. Recent results at IMEC indicate that, although a substantial efficiency improvement is found, this is not due a bulk hydrogen passivation effect since the PECVD Si_3N_4 layer does not provide a cap for outdiffusion of hydrogen at high temperatures (≥600°C). This conclusion has been triple checked using lifetime, FIR and temperature effusion spectroscopy measurements.

Finally, the third part of the paper describes recent results, confirming the influence of the oxygen concentration on the efficiency of hydrogen passivation. Epitaxial layers (having a very low oxygen content) of 10 m thickness were grown on Cz silicon material with high oxygen content. The material has then exposed to a deuterium rf plasma. SIMS measurements of deuterium were performed before and after the plasma. These measurements clearly indicate that the deuterium concentration in the epi layer is at least two orders of magnitude larger than in the substrate. This confirms the blocking effect of oxygen on hydrogen and indicates the potential of hydrogen passivation of thin film crystalline Si solare cells.

EXPERIMENTAL RESULTS IN SUPPORT OF HYDROGEN DIFFUSION VIA A H-V MECHANISM

Xiaojun Deng and Bhushan Sopori
National Renewable Energy Laboratory
Golden, CO

Diffusion of hydrogen via a vacancy mechanism was first proposed by Corbett to explain kinks in the hydrogen and deuterium diffusion profiles in silicon[1]. More recently, our group independently concluded that the observed enhanced diffusivity of hydrogen in some solar cell silicon was related to H-V diffusion mechanism[2,3]. A theoretical analysis showing the possibility of this mechanism has been performed by Estreicher using ab-initio calculations [4]. This paper presents further experimental results that support occurrence of the H-V diffusion mechanism. Because a direct observation of the presence of vacancies and/or H-V complex is difficult, we have used a two-fold approach to study this problem. In one case we studied hydrogen diffusion in silicon substrates containing different concentrations of nonequilibrium vacancies. These samples consisted of solar cell substrates grown at different rates and with different oxygen and carbon concentrations. It is known that rapidly grown substrates can have high concentrations of quenched-in vacancies and that the vacancy concentration increases with the growth speed. It is also believed that high concentrations of carbon can encourage vacancy generation while a high concentration of oxygen reduces the propensity for vacancy formation. The hydrogen (or deuterium) profiles were fitted with **erfc** profiles to determine the bulk diffusivity and the solubility of hydrogen. In the second case, substrates were first hydrogenated by low-energy implantation to produce a hydrogen-rich surface region. The samples were then injected with vacancies and the changes in the hydrogen profile analyzed. The results of these experiments may be summarized as follows:

- The diffusivity of hydrogen is higher in the substrate having an existing high non-equilibrium concentration of vacancies. Consequently, materials grown at high speeds, such as ribbons, will exhibit higher diffusivity. (Results from Positron Annihilation Spectroscopy have confirmed this behavior). Likewise, a material having high concentration of carbon exhibit higher diffusivity.

- Hydrogen diffusion is slower in an oxygen-rich material. This property also explains why the diffusivity of hydrogen is lower in CZ than in the FZ wafers.

- The solubility of hydrogen at the surface of a typical cast solar cell substrate is $1x10^{17}/cm^3$, (at 250°C), and can greatly increase with surface damage.

- Injection of vacancies following a hydrogenation results in a remarkable change in the hydrogen profile can enhance the hydrogen diffusion.

We will discuss implications of these results towards development of a low-cost, commercially compatible technique for hydrogen passivation.

References:

1. J. W. Corbett. J. L. Lindstrom, and S. J. Pearton, MRS Proc. **104,** 229 (1988).
2. B. L. Sopori, MRS Proc. **262,** 407(1992).
3. B. L. Sopori, K. Jones, and X. J. Deng, Appl. Phys. Lett. **61**, 2560 (1992).
4. M. A. Roberson and S. Estreicher, to be published.

SESSION 5:

NEW CONCEPTS IN SILICON GROWTH: IMPROVED INITIAL QUALITY AND THIN FILMS

WEDNESDAY, JUNE 29, 1994

NEW CONCEPT IN SOLID-PHASE GROWTH FOR THIN FILM SILICON

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Silicon solid phase crystal growth processes are of potentially great interest to photovoltaic devices and systems because of the low process temperatures employed relative to competing technologies, such as solidification. Thus, low-cost glass substrates with low softening temperatures may be employed, and the total energy input in cell fabrication may be reduced.

In the last decade, enormous effort has been directed to investigations of various solid state processes for synthesis of single-crystal silicon on amorphous substrates, driven by interest at various times in three-dimensional integration of silicon integrated circuits, silicon-on-insulator circuits, and thin film transistors for flat display applications. Several interesting new processes have emerged in the course of this work. However, these solid phase processes have not yet been exploited and tested specifically for use in photovoltaic applications.

This talk will be a critical assessment of the role of various solid phase processes in thin film silicon photovoltaics, and will discuss various processes for selective nucleation and control of nucleation in crystal-amorphous and vapor-crystal growth processes, as well as recently developed methods for transfer of single-crystal silicon films to other substrates.

THIN FILM SILICON GROWTH BY ZONE MELT RECRYSTALLIZATION

Cameron A. Moore
University of Denver, Denver CO

Zone melt recrystallization (ZMR) has been used to produce thin (0.5 - 2μm) films of single crystal silicon on various crystalline and amorphous substrates, primarily for use in submicron microelectronics. However, ZMR-prepared films for this application have been supplanted by those fabricated using SIMOX and bonded-wafer techniques. This shift in focus, and concomitant reduction in interest in liquid recrystallization technologies, has impeded extension of ZMR methods to thick (10's of μm) films for photovoltaic applications. The possible routes to a thick film ZMR process will be presented, including a review of the fundamental growth kinetics of thin film ZMR growth, the requirements of a low-defect density ZMR process, and prior work where thick films were recrystallized. Finally, possible alternative or modified approaches to future ZMR of thick silicon films will be discussed.

MATERIALS AND SOLAR CELL RESEARCH AT Fh G-ISE

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Freiburgh, GERMANY

The photovoltaic departments of the institute are working on different aspects of preparation and evaluation of silicon materials for solar cells and on the development of solar cells. One main direction of materials research is the improvement of ingot casting in collaboration with the German industry. Based on such multicrystalline material, a cooperative project between 9 universities and research institutes was started in 1990 and continued in 1993. It is coordinated by the institute. It is focused on the origin and dynamics of defects in crystalline silicon and their influence on the solar cell performance. The associated industrial partners provide their materials and their solar cell processes.

A second but minor research activity is dealing with growth and characterization of silicon sheet/ribbon materials partially together with the industry.

A third direction of research is focused on crystalline thin film solar cells on low cast silicon or foreign substrates. The thin film is prepared by optically heated CVD and recrystallization processes.

For the development of solar cells of high efficiency from single crystalline silicon a clean room laboratory has been established, various measuring stations for the characterization of processes and solar cells have been set up, and a processing sequence for the manufacturing of cells has been developed.

For FZ-silicon, the highest efficiency (AM1.5) obtained up to now is 22.1% for a 2x2 cm^2 cell and 21.4% for a 6x3.5 cm^2 cell. Applying this processing sequence with some changes to Cz-silicon has resulted in 20.7% efficiency for a 2x2 cm^2 cell. Using this process for mc-silicon has given 16.2% efficiency for a 2x2 cm^2 cell.

Momentarily, we investigate the influence of simplifications of processes and of cell design on the efficiency.

For mc-silicon we have established a very simplified process, resulting in η= 15.8% for a cell 2x2 cm^2. Here, in the future the emphasis will be on rapid thermal processing (RTP). All activities are supported by German and European projects.

UNSW APPROACH FOR THIN-FILM CRYSTALLINE-SILICON CELLS

Prepared by: Paul A. Basore Presented by: James M. Gee
Sandia National Laboratories, Albuquerque, NM

Last month, Martin Green and Stuart Wenham held a press conference at the University of New South Wales to publicly announce their new concept for thin-film silicon modules. As with most press conferences, the reports were filled with optimism, claiming that "This new approach should in 10 years cut the cost of solar electricity to under $1/watt, which is less than the cost of most modern coal-fired power stations," and "The cost of producing solar electricity can now be slashed by at least 80% - making solar energy as cost effective as fossil fuels."

The UNSW concept, which was first published in the April issue of *Progress in Photovoltaics* and presented at the EC-PVSEC last month in Europe, involves a stack of as many as 10 very thin alternating-polarity layers of silicon, for a total thickness of 20-30 m. Laser grooves doped either n-type or p-type provide a method for connecting the different layers in parallel. This is a very interesting thin-silicon concept because it has the potential to produce efficiencies approaching 15% from material with a diffusion length as short as 2 m, which is what might be obtainable in material deposited by chemical-vapor deposition onto a low-cost substrate. Although the concept is very promising and can reasonably be projected to produce modules approaching $1/watt if it works, there is a lot of work left to be done before it is a proven technology. UNSW claims that the key pieces (CVD deposition, laser grooving, multijunction structures) have been demonstrated separately using polycrystalline silicon, and that they only have to integrate them together. Still, Martin Green estimates that the concept needs at least $20M and 10 years of development before it is commercially viable. This is a reasonable estimate provided there are no insurmountable technical hurdles along the way. The probability of commercial success for this concept seems at least as high as for other thin-film materials currently being developed.

The UNSW approach obtains high current despite poor diffusion length and small grains by locating a collecting junction with 1.5 m of any point in the cell. The total current is still somewhat limited by the total absorption thickness of 20-30 m, so some form of light trapping would be beneficial. Because such low diffusion lengths are tolerable, the doping level in the layers can be increased by an order of magnitude or moving the collected current to the nearest buried contact. It also reduces the volume of the depletion regions in the cell to a value comparable to a conventional cell, despite having a much larger junction area. This should keep space-charge-region recombination under control, but this critical issue still needs to be resolved. Another potential problem is obtaining adequate grain size in the deposited layers. One option is to recrystallize the first layer, then use this as a template for the subsequent layers, but this requires a substrate compatible with high temperature.

The method proposed to dope the grooves cut by the laser has not been revealed in any detail by UNSW. Normal thermal diffusion is probably unacceptable, because it would redistribute dopants between the layers, especially along grain boundaries. But there are other options, including deposition of doped silicon into the groove, or in-situ doping of the groove during the laser-cutting process. By double-cutting the grooves with a slight offset, it is possible to obtain grooves where one wall may be p-type and the other side n-type. Metal plated in the groove would then make a series connection between adjacent cells, so that monolithic module fabrication is feasible, much as is done with amorphous silicon today.

Sandia has supported work at UNSW since 1986 using DOE funds, with current funding of $50K/year. The thin-silicon work was not explicitly included in any of these contracts, but the laser grooving and multiple junctions that they propose to use in the thin-silicon module are related to tasks in our current contract. In addition, Paul Basore was a Visiting Academic Fellow at the Centre for Photovoltaic Devices and Systems at UNSW for three weeks earlier this year. The presentation will elaborate on the merits and potential problems with the new concept.

Prepared by Sandia National Laboratories for the US Department of Energy under Contract DE-AC04-94AL85000.

Enrique Grunbaum

Unavailable at Time of Printing

LIGHT TRAPPING IN THIN-FILM CELLS

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National Renewable Energy Laboratory
Golden, CO

Thin silicon solar cells offer the promise of producing high-efficiency devices on a low-cost material whose minority-carrier diffusion length is comparable to the cell thickness. This advantage arises primarily from a reduced bulk recombination and, in some cases, may be accompanied by a reduced material cost. However, in order to harness these advantages, the cell design must include the following two features: (i) an efficient means of light trapping to greatly enhance the absorption of light, and (ii) minimize the interface recombination to offset the effect of the close proximity of interfaces to the carrier generation regions. A quantitative design of a thin cell must include a detailed analysis of light trapping that can determine the distribution of photon absorption as well as changes in the device operation due to light trapping effects.

We have developed a ray-optics approach to carry out optical modeling of a typical thin silicon solar cell (thickness $\geq$ 3-5 μm) of any surface texture. This analysis gives the following parameters:

- Photon absorption distribution in the textured region(s) and the bulk of the cell
- Maximum achievable current in any given cell structure
- Optimum design of antireflection coating

This paper will describe the major results of our ray optical analysis and discuss the effect of different texture morphology on the cell operation. We will be show that light trapping increases demands on the interface passivation due to increased carrier generation at the interfaces. This model can also be applied to perform the optical analysis of the cell in the module. We will also present some preliminary results of a wave theory that is applicable to all thicknesses of the cell.

SESSION 6:

SILICON SOLAR CELL DESIGN OPPORTUNITIES

WEDNESDAY, JUNE 29, 1994

OPPORTUNITIES FOR PROCESS SIMPLIFICATION FOR CRYSTALLINE-SILICON SOLAR CELL FABRICATION

James M. Gee
Photovoltaic System Components Dept.
Sandia National Laboratories
Albuquerque, NM

The journal *Progress in Photovoltaics* recently sponsored a special issue on the future of crystalline-silicon (c-Si) photovoltaic (PV), technology [1]. The authors in this issue were uniformly upbeat about the prospects of c-Si PV technology, and project c-Si module costs below $\$2/W_p$ and considered c-Si PV capable of meeting the PV community's ultimate goal of providing a significant fraction of the world's electrical energy supply. As pointed out by Mitchell, reaching $\$2/W_p$ requires careful consideration of the starting material, of the manufacturing process, and of the cell and module design [2]. In this presentation, we review cell and module concepts for improving performance and reducing cost of c-Si commercial PV modules. The objective of the presentation will be to identify opportunities for improvements in manufacturing and possible topics for future research.

References

1. *Progress in Photovoltaics*, volume 2, number 2, April 1994.
2. K. W. Mitchell, *ibid.*, pg. 115.

Prepared by Sandia National Laboratories for the US Department of Energy under Contract DE-AC04-94AL85000.

PRACTICAL CELLS WITH EFFICIENCY ABOVE 18%

Antonio Luque and Adriano Moehlecke
Insituto de Energia Solar
Universidad Politecnica de Madrid

After several years of research, the efficiency limiting processes of silicon solar cells that has included the achievement of cells with efficiency up to 23.5%, it seems that there are several ways to produce commercial cells with efficiencies in the range of 18%. Such cells must contend in cost with the well established screen printing process, that can lead to 15% cells. The MONOCHESS Project, funded by the European Union and integrated by some European laboratories and industries, is devoted, in part, to this research.

One way, already industrialized, of reaching this goal is the well known LGBG cell process. Other procedures, less revolutionary, but maybe equally effective are in development in our Institute, and are being considered by some companies in the MONOCHESS consortium. They refer in all cases to cells fabricated with single crystalline silicon.

All of them must have, in our opinion, a common characteristic: they must possess an effective gettering step that voids very stringent requirements in the manufacturing process and plant, and in particular the need of a clean room environment.

Among these it is the deep emitter P/Al process. In this process a P predeposition is made followed of an Al depositon. Then a drive-in is performed producing simultaneously deep n^+ and p^+ regions in both faces, lowly doped in surface (10^{19} cm^{-3}).

Due to the low surface doping, we think that the screen printing technology is not applicable for the grid contacting because of the high contact resistance. However, contact mask metal grids may be deposited, or better an electroless/electrolytic grid can be formed. This may imply one photolithographic step without mask alignment, and vacuum deposition steps, but these are performed in other industries at very low costs, so we believe they may be cost competitive.

One positive aspect of such processing is the effective gettering caused by the Al drive-in process.

Maybe the most negative aspect of such process is the poor reflectivity of the alloyed Al back layer that reduces the effectiveness on light confinement, and therefore this reduces the efficiency of thin wafers, other of the keys of future reductions in cost.

To prevent this drawback, another process is being developed based on P/B predeposition and drive-in. In this process the gettering is based on the P gettering, and to achieve it a relatively high surface concentration (10^{20} cm^{-3}) must be obtained. There are, however, methods to reduce the high recombination in such a highly doped region.

An interesting conclusion is that locally diffused emitters or BSF's, in general, do not allow for the needed gettering and therefore are probably not cost effective for commercialization of non concentrating cells.

SESSION 7:

PANEL DISCUSSION:
WHAT WILL IT TAKE TO MAKE 18% CELLS/
WHAT RESEARCH ISSUES NEED TO BE ADDRESSED?

CHAIRMAN: DICK SWANSON

WEDNESDAY, JUNE 29, 1994

SESSION 8:

PANEL DISCUSSION: WRAP-UP/FUTURE DIRECTIONS

JOHN BENNER, JAMES GEE, CHANDRA KHATTAK, LUBEK JASTRZEBSKI

WEDNESDAY, JUNE 29, 1994