NBSIR 79-1778

A Perspective of a Workshop on Stability of (Thin Film) Solar Cells and Materials

H. A. Schafft and D. E. Sawyer

Electron Devices Division
Center for Electronics and
Electrical Engineering
National Engineering Laboratory
National Bureau of Standards
Washington, DC 20234

June 1979

Issued July 1979

Prepared for
Advanced Materials R&D Branch
Division of Distributed Solar Technology
Department of Energy
Washington, DC 20545

NBSIR 79-1778

A PERSPECTIVE OF A WORKSHOP ON STABILITY OF (THIN FILM) SOLAR CELLS AND MATERIALS

H. A. Schafft and D. E. Sawyer

Electron Devices Division
Center for Electronics and
Electrical Engineering
National Engineering Laboratory
National Bureau of Standards
Washington, DC 20234

June 1979

Issued July 1979

Prepared for
Advanced Materials R&D Branch
Division of Distributed Solar Technology
Department of Energy
Washington, DC 20545

A Perspective of a Workshop on Stability of (Thin Film) Solar Cells and Materials

Harry A. Schafft
and
David E. Sawyer

Abstract

The results of a workshop on the Stability of (Thin Film) Solar Cells and Materials are reviewed from a measurements perspective. Solar cells of the following three material groupings were considered at the workshop: (1) Cu_2S/[CdZn]S, Cu-ternaries/CdS, InP/CdS, and amorphous Si; (2) polycrystalline, MIS, and conducting-oxide Si; and, (3) polycrystalline and AMOS GaAs. Considering the relative state of immaturity of these developing cells and the goal for high reliability and stability, two general areas of work are recommended. One is to develop an improved understanding of cell operation and of component structures of these cells. The other is to develop an improved measurements base. Specific needs and recommendations are provided.

Key Words: Accelerated tests; failure mechanisms; failure modes; photovoltaics; reliability; semiconductors; solar cells; stability; testing; thin films.

1. Introduction

A workshop on the Stability of (Thin Film) Solar Cells and Materials was conducted by the National Bureau of Standards at its Gaithersburg, Maryland, site on May 1 to 3, 1978, for the Department of Energy's Advanced Materials Research and Development Branch.[1] Three groups of exploratory materials and device concepts for solar cells were considered: (1) Cu_2S/[CdZn]S, Cu-ternaries/CdS, InP/CdS, and amorphous Si, (2) polycrystalline, metal-insulator-semiconductor (MIS), and conducting-oxide Si, and (3) polycrystalline and antireflection-coated metal-oxide-semiconductor (AMOS) GaAs.

The basic questions asked of the workshop participants were: (1) what are the obstacles to achieving the necessary stability and reliability of thin-film solar cells and (2) what needs to be done to overcome these obstacles? They responded by relating their experiences with the many new and developing thin film cells, by reviewing the status of the knowledge of cell operation and cell degradation, and by identifying the many gaps in the applicable device, processing, and measurement technologies.

This report supplements the formal report of the workshop.[2] It considers the results of the workshop from the perspective of measurement requirements related to the achievement of cell stability and reliability and integrates the recommendations made and needs identified by the participants of the workshop in the context of this perspective. The highlights from the workshop report are reprinted here as an appendix for reference by the reader.

2. Implications of High Reliability and Stability Goals

With their papers and discussions, the workshop participants revealed how convoluted is the task of achieving the high reliability and stability goals for thin film solar cells. Given the status of the technology, a coordinated effort on a number of fronts is required. Consider why this is so.

---

[1]In support of the Department's Photovoltaic Program.

[2]Sawyer, D. E., and Schafft, H. A., *Semiconductor Measurement Technology*: NBS/DOE Workshop, Stability of (Thin Film) Solar Cells and Materials, NBS Special Publication 400-58 (August 1979).

To achieve these goals requires the use of accelerated tests to measure reliability and stability and therefrom to measure improvements of these performance attributes as a result of changes in materials, design and manufacture. The workshop participants accepted this observation as a given. What are the implications of such a reliance on accelerated tests? It was pointed out that there are two underlying assumptions to the meaningful use of accelerated tests which are often overlooked and in the present case are not adequately satisfied.

One assumption is that information exists about what stresses to impose in these tests. Knowing what stresses to impose comes from a knowledge of which degradation mechanisms operate in these solar cells and under what conditions. To learn which of these mechanisms are active requires both a thorough understanding of the principles of cell operation, an understanding of component materials, and the existence of a data base on cell use.

The other assumption is that the cells to be tested have been fabricated under conditions where the materials and processes are under sufficient control that reproducible cells are being produced. To be able to do this requires an understanding of the principles of cell operation and an understanding of how variations in material characteristics and fabrication processes can affect cell performance.

Implicit to the requirements needed to satisfy the above assumptions is the existence of an adequate measurements base. This base provides the measurement tools to characterize and learn about cell materials, fabrication, and operation; it provides the tools and procedures to develop a history of cell experience that can be used to compare and evaluate different cells and fabrication processes; it provides the measurement tools to study and understand cell degradation from which an intelligent selection of stresses can be made for use in accelerated tests; and it provides the test procedure for accelerated tests to achieve the measurement precision needed to predict reliability and stability with sufficient accuracy.

The workshop participants considered these assumptions which underlie meaningful accelerated tests and found them wanting. They reported that many degradation mechanisms are not understood in sufficient detail to be able to design adequate accelerated tests; the structure and principle of operation are not adequately understood for many cells; and the effects of material characteristics and cell processing steps on cell performance are also not sufficiently understood. In addition, standard measurement methods and procedures to characterize materials and cell components and minimum standards for reporting characterization and accelerated test data are all either inadequate or nonexistent.

3. An Integration of Needs

Two major areas of work emerge as ones that require serious attention and support. This conclusion follows after an examination of the participants' statements about (1) the requirements for realizing the goals for cell stability and realibility, (2) how well the thin film cell technology is able to match these requirements, and (3) what tasks need to be undertaken to make possible the goals of this thin film program.

One general area of work is to develop an improved understanding of cells and their structures. This is understandable from the relative state of immaturity of these developing cells and materials. The second general area of work is to develop an improved measurements base. It should be recognized that no research and development program, certainly not one with as many elements and participants as the thin film program, can expect to be executed efficiently and effectively without such a supporting measurement base. Without this base, there is no way to measure and evaluate progress with confidence and be assured that past successes can be reproduced. It is also important to recognize that both areas of work must be pursued together because progress in one depends and feeds on the advances in the other.

The following two sections list important tasks in the two major areas of work which were identified by the participants of the workshop.

4. An Improved Understanding of Cells and Their Structures

In their presentations and discussion groups, the workshop participants identified many tasks to achieve the necessary understanding of cells and their structures. They stated that such work is needed to understand better the operating principles of the new and developing thin film cells, and of the material, processing, and assembling factors that can affect cell performance and stability.

The need to understand better the operating principles of thin film cells in general was discussed. Polycrystalline Si, MIS, and conducting oxide on Si cell types were specifically mentioned. To this was added the need to clarify what cell and material parameters are most relevant to cell efficiency. Certainly, the perception of these needs is an indication of the relative immaturity of these and other developmental thin film types. It can also be interpreted to mean that a more equitable balance needs to be struck between efforts to understand the physics of these cells and the urgent work underway to increase cell efficiency as rapidly as possible. Achieving such a balance by giving greater attention to the former can aid in achieving the goal of the latter.

The need to understand better the effect of material factors such as grain boundaries, polycrystalline silicon charcteristics, and various MIS and conducting oxide material systems on cell performance was cited. Participants also recommended that a better understanding was needed of the various Schottky barrier GaAs systems so that those with the greatest potential for high reliability could be identified. This would avoid wasting time in trying to develop systems which would eventually prove to be unsuitable.

There are a number of parts of the cell structure which need to be better understood and improved: low-cost substrates for GaAs AMOS devices, interfacial oxides, metal oxide windows, barrier metal alloys, and encapsulations. However, by far the most often repeated interest and concern expressed was in regard to diffusion, interdiffusion, and surface reaction phenomena affecting virtually every interface of the various thin film cells. Mentioned were diffusion of metals from grid contacts into GaAs and Cu-ternaries; diffusion of electrically active defects through Cu-ternaries; general compatibility problems of Cu-ternaries with adjacent cell components; growth of interfacial layers due to oxygen diffusion through and from conducting oxides and through Cu_2S overlayers; effects of grain boundaries on diffusion coefficients; effect on Cu nucleation of the structural quality of Cu_2S; and generalized interactions of window materials with adjacent materials.

Deficient knowledge of the component materials and their interactions is reflected in concerns expressed about the need to understand better how various processing and assembling procedures can affect cell performance. How and why does cell performance depend on, for example, the method of deposition, growth, and treatment of Cu-ternaries, and on the method of application of oxides and metallizations in MIS cells?

Three aspects related to the assembly of thin film cells were highlighted which bear directly on the ability to achieve the 20-year life goals of the thin film solar cell program. They are hermeticity, encapsulation, and contacts. Ways need to be found to define and improve the quality of hermetic protection of these cells. There are questions about encapsulations and their ability to sustain long term exposure and to maintain good bonds to the device structure. Some of these questions may be answered by experience gained in the low cost solar array program. Finally, there is concern about not only assuring that good electrical contacts can be maintained for metallization grids but about how to make good electrical contacts to thin films without degrading device performance.

5. An Improved Measurements Base

The participants cited many tasks that will need to be completed before a satisfactory measurement standards base for thin film cells can be established.

There are a number of problems that need to be solved if accelerated tests are to be used in a meaningful way. One is the need to develop clear functional relationships between test stresses and degradation mechanisms. Another is the necessity to incorporate the synergistic effects that different stresses may have on cells. To be able to do this requires detailed knowledge about the degradation mechanisms. This can evolve out of work described in the previous section. Added to these is the observation made that adequate measurement precision in accelerated testing is very important. This is because of the necessity to predict from small parameter changes, during the time of the accelerated test, the period of useful life.

Specific material characteristics were identified for which test standards and test development are needed. In particular, standards for various polycrystalline silicon characteristics such as resistivity, mobility, lifetime, and diffusion length were identified, as well as standards for measuring grain size and orientation, void space between grains, and impurity within grains and at grain boundaries. Methods need to be developed to measure and characterize interfacial layers in MIS cells for thickness (with time), pin holes, defects, impurities, stoichiometry variations, and for the density and energy of charge states.

Finally, the need to establish guidelines for reporting results was emphasized. To serve as a starting point, one discussion group developed a list of test conditions that need to be specified (i.e., insolation, thermal, stress, electrical loading, and ambient).

6. In Conclusion

As progress is made in the cell characterization work outlined in section 4, a natural outcome will be a better understanding of (1) the degradation mechanisms of these cells and (2) the requirements for achieving the degree of control over cell processing and assembling steps needed to obtain greater cell performance uniformity. Armed with this knowledge and control and the improved measurements base that can be developed from the other area of work outlined in section 5, it will be possible to make more meaningful estimates of the long term stability of these cells and to make more knowledgeable decisions about material, device, and process design improvements to achieve the performance goals for efficiency and long term stability of the thin-film solar cell program.

APPENDIX

HIGHLIGHTS OF WORKSHOP SESSIONS

The workshop was divided into three sessions. In the first, researchers reviewed modes and mechanisms for degradation and failure and the status of present reliability testing pertinent to the three groupings. In the second session, speakers from related device technologies discussed measurement and test approaches that they have used for achieving high reliability in their device areas. Three discussion groups were formed for the third session, one for each of the three cell and material classifications. The task of these groups was to identify what means are available and what is to be done to satisfy needs in achieving goals for long term stability of advanced-technology solar cells. Reports of these working groups were presented by the group chairmen at the final session of the workshop. Highlights of the presentations and discussion groups follow. The title and author(s) of each presentation are located in the margin adjacent to the highlight.

Session I: Status of Present Reliability Testing, Failure Modes, Failure Mechanisms, and Data for Thin Film Solar Cells and Materials

The Stability and Reliability of CdS/Cu_2S Solar Cells, J. D. Meakin and J. E. Phillips, Univ. of Delaware

The primary degradation mechanisms of the Cu_2S/CdS heterojunction cell are the oxidation of Cu_2S, diffusion of Cu into CdS, electrolytic decomposition of Cu_2S to nucleate copper, and loss of structural integrity of electrical contacts and device/encapsulant interfaces due to thermal expansion mismatch and UV-induced bond strength degradation, respectively.

None of these degradation mechanisms preclude 10- to 20-year life, but the measurement of the rate of degradation of these cells and hence the prediction of life is a problem. To use accelerated test procedures to predict life requires a detailed knowledge of the mechanisms being accelerated. For thin film solar cells in general and for Cu_2S/CdS cells in particular, this information is not available. Meaningful accelerated testing will not be possible until accelerated tests are matched to specific degradation mechanisms in a knowledgeable way.

The following four major research needs for Cu_2S/CdS solar cells were identified: (1) Work is needed to improve and define the quality of the cell's hermetic protection, because these cells will degrade rapidly if exposed to air. This effort should also include the development of a quantitative understanding of the oxidation of the Cu_2S layer and the resultant structural and electronic changes. (2) The interdiffusion mechanisms which reduce cell performance need to be identified. (3) The relation of various structurally related degradation modes, such as encapsulation delamination and loss of grid contact, to use-conditions needs to be identified. And, (4) the relationship between copper nodule formation (due to electrolytic decomposition of Cu_2S) and the structural quality of the CdS layer needs to be identified in detail so that the level of Cu_2S quality required for 10- to 20-year life can be established.

Stability and Ternary Chalcopyrite Photovoltaic Devices, L. L. Kazmerski, Solar Energy Research Institute

Work on the copper ternaries ($CuInS_2$, $CuInSe_2$, and $CuInTe_2$) with CdS for photovoltaic devices is in its infancy. Relatively little is known about the compatibility of these materials in a device context and much materials work needs to be done. More work is also needed to understand how methods of deposition, growth, and treatment of ternary films critically affect the cell's structural and electrical characteristics and their relevancy to cell stability.

Major causes for Cu-ternary/CdS device degradation are various impurity diffusion and interdiffusion reactions, which are aggravated by grain boundaries in the polycrystalline films. The high diffusion coefficients reported for Cd and other elements in Cu-ternary/CdS heterostructures, because of the number of vacancies in the ternary, pose potential reliability problems. Fast diffusion of metals into the ternaries can undermine contact stability. Diffusion of oxygen from the ambient during annealing can cause an unwanted oxide layer to form at the interface between CdS and the Cu-ternary. And, rapid diffusion of electrically active defects can cause a rapid increase in electrical conductivity of the ternary.

Stability of Thin Film Polycrystalline Silicon Solar Cells, T. L. Chu, S. S. Chu, and E. D. Stokes, Southern Methodist University

Preliminary results of the stability of thin film polycrystalline silicon solar cells prepared on metallurgical silicon substrates were described.

The temperature coefficients of the cell parameters are similar to those for single crystal silicon solar cells. Exposure to 115°C for up to 160 h, temperature cycles from -40°C to 100°C, and high humidity resulted in no significant change in cell parameters. Exposure to an irradiance of 1.2 W/cm^2 at 150°C under load for 150 h showed some degradation due presumably to a deterioration of grid contacts.

Reliability Studies on MIS and Transparent Oxide-Si Solar Cells, W. A. Anderson and J. K. Kim, Rutgers University

The results of preliminary studies of the stability and degradation of MIS (silicon) and metal-oxide-on-silicon heterojunction* solar cells was described. The few previously reported results of degradation studies of MIS cells using silicon were reviewed, recent environmental stress and Auger analysis data on Cr/oxide/Si systems were reported, and some degradation results obtained by R. L. Anderson of the conducting metal oxide materials SnO_2, In_2O_3, and $In_2O_3:SnO_2$ (indium-tin oxide) on silicon cells were mentioned.

The degradation of tin-oxide-on-silicon heterojunction solar cells is attributed to field assisted transport of O_2^- from the metal oxide to the silicon to form a SiO_2 layer at the interface and adversely affect the series resistance, fill factor, and V_{oc} of these cells. Aluminum contact degradation has also been observed.

The major degradation problem in MIS cells is the alteration of the oxide interfacial layer due to exposure to air and moisture. Examples of the growth of layer thickness beyond optimum thickness were shown for Au on *n*-type Si and for Al on *p*-type Si where moisture trapped in the oxide during formation led to the growth of an aluminum oxide.

Some general observations were made: Hermetic sealing of MIS cells is needed to prevent air and moisture from degrading the oxide interfacial layer and also from degrading the conductance of thin metal films and contacts to these films. Encapsulants are needed which do not discolor or soil during extensive outdoor use. Also, encapsulants need to be studied for their long term performance.

*The metal oxide forms a junction with the semiconductor and also acts as a low resistance, transparent contact.

Extensive results of the degradation of conducting oxides on silicon cells were described. Both heterojunction and heteroface (oxide serves as window only) cells were considered.

Stability of Conducting Oxide/Si Heterostructure Solar Cells, S. L. Franz, M. L. Andren, and R. L. Anderson, Syracuse University

The prominant degradation mechanism for SnO_2 on Si heterojunction cells is the formation of a high resistance SiO_2 layer at the SnO_2-Si interface at room temperature. In_2O_3-Si interfaces also degrade in this way but only at elevated temperatures. For both conducting metal oxides, the degradation proceeds more rapidly for polycrystalline silicon than for single crystal cells. Degradation of the In_2O_3:SnO_2-Si interface for both heterojunction and heteroface cells does not occur at temperatures below 470°C. This high threshold temperature allows the annealing of process-induced defects in the silicon and makes promising the use of this conducting oxide for both *n*- and *p*-type Si heteroface cells.

Degradation of aluminum electrical contacts to the conducting metal oxides can be prevented by using a chromium barrier.

While the MIS solar cell design holds promise for use with polycrystalline and amorphous semiconductors, there are a number of problems whose importance is affected by the material system selected and fabrication process used. These problems are related to chemical and electronic effects at the insulator-semiconductor interface and film structure effects.

Unique Problem Areas in M-I-S Solar Cell Structures, S. J. Fonash, G. Fishkorn, and T. E. Sullivan, Pennsylvania State University

The electronic nature of the semiconductor surface can undergo considerable changes as an oxide is grown or an insulator is deposited. These changes can be desirable or undesirable depending on the material system used. The problems encountered with a Pd-oxide-*n*-type Si system were described.

The performance of an MIS cell can be strongly affected by the rate, method, and material of the metal film deposition as well as the surface condition of the semiconductor. A case in point is that while Ag films of good quality can be deposited on Si, Ag deposited on Si having 20 to 30 nm of oxide can lead to a porous film. Such a film leads to high sheet resistance and provides openings for covering materials and the ambient to reach and degrade the junction.

The selection of the semiconductor can also be important: while considerable slow trapping of charge induced by current and causing hysteresis effects has been observed in GaAs, it has not for Si-based systems.

A polycrystalline GaAs/Ge/steel AMOS solar cell system now under development at JPL was described. Two areas under exploration are the passivation of the Ge/steel interface and various combinations of barrier metals and interfacial oxides. Life testing with several metal-oxide combinations has only recently been initiated using 100°C laboratory air environments. Examples were given of cases where the choice of barrier metals such as Ag, Ni, and Cu can be important not only for cell reliability but for efficiency as well. The choice of oxides such as native oxide, MoO_3, and Sb_2O_3 can have marked effects on the cell V_{oc}, fill factor, and stability. Additional experiments are needed (1) to study other deposited oxides with Ga-saturated metals, particularly with reproducible stoichiometric oxides, and (2) to identify metal-oxide-GaAs systems with potential high reliability.

Reliability Testing of GaAs AMOS Solar Cells, R. J. Stirn, Jet Propulsion Laboratory

Stability of Thin Film Polycrystalline Silicon Solar Cells, T. L. Chu, S. S. Chu, and E. D. Stokes, Southern Methodist University

Preliminary measurement results of the temperature dependence and stability of polycrystalline GaAs solar cells were reported. The change with temperature of V_{oc} and conversion efficiency of gold barrier MIS polycrystalline GaAs cells were found to be similar to those of single crystal GaAs *p-n* junction cells, while silver barrier cells were found to have higher temperature coefficients. Storage at 60°C for 24 h left the I-V characteristics of gold-barrier cells essentially unchanged but left those of the silver-barrier cells with evidence of increased series resistance. Gold barrier cells were operated under an irradiance stress of ∿325 mW/cm^2 at a temperature between 50 and 55°C for more than 48 h. While some degradation of room temperature cell performance was noted immediately after stress, complete recovery was noted after a few hours.

Stability Studies of Amorphous Silicon Solar Cells, D. E. Carlson, RCA Laboratories

Hydrogenated amorphous silicon solar cells should be stable under normal operating conditions. The results of a number of experiments to explore the stability of amorphous silicon were described. The evolution of hydrogen (applicable at temperatures above about 350°C) will not be a problem at 100°C. The diffusion of dopants such as P and B will not be a problem even at deposition temperatures as high as 300 to 350°C. Electrode materials such as Cr, Mo, Nb, and Ta exhibit little evidence of diffusion, even at temperatures of 400°C. The use of Al and Fe, however, will require care. Iron silicides may form at a fabrication temperature of 400°C to create a large series resistance, while at 300°C the diffusion coefficient is low enough to prevent this formation. Aluminum interdiffuses at 300°C and has been reported to induce crystallization of amorphous silicon at 335°C. The presence of an oxide layer on Al inhibits this interdiffusion, but it also creates a large series resistance.

Good stability of devices made with Schottky barriers and of *p-i-n* cells using other than native oxides was reported. MIS devices utilizing the native oxide as a thin insulating layer exhibit degradation when exposed to air, but this can be reversed by heat treatment.

Session II: Measurements and Tests Used to Define Stability in Related Technologies

Silicon Cell Space Program Experience, P. A. Iles, Optical Coating Laboratory, Inc.

The experience of the silicon cell space program and its implications for thin film cells were presented. Most of the methods used to ensure stable space cells are ruled out for terrestrial application because of the costs involved. On the other hand, efforts made in the space cell program to develop a spirit of cooperation between cell makers and users and to select realistic tests will be even more important in the thin film cell program.

The wide range of possible materials and processes for thin film cells will make difficult the early utilization of automated production (which will probably be needed to achieve low-cost goals). It will also make complex the task of developing tests to measure the stability of these many cell types.

The use of thin film materials can present major problems in attempting to achieve long cell life. For all thin film cells, the contacts will pose a major problem due to initial requirements (low cost and good conductivity) and stability needs (freedom from corrosion and failure under temperature cycling). Also, problems should be expected from interlayer movements of material during cell life, with their adverse effects on cell properties.

Effective methods of encapsulation will need to be developed to reduce the degradation effects of the atmosphere on cells. Also, the search for metallurgically stable systems must be continued.

Reliability Concerns and Life Test Procedures for Concentrator Solar Cells, W. V. McLevige, Sandia Laboratories

Reliability concerns and life test approaches for concentrator solar cells were described. Reviewed were the many stressful operating and environmental conditions that concentrator cells must sustain which hold the possibility of many causes for degradation. Just how serious these stressful conditions may be remains to be seen because only limited life test data are presently available.

The three most basic accelerated tests used and ones that were recommended for consideration are those involving constant temperatures, temperature-humidity cycling, and temperature-illumination stresses. Some preliminary results were described of recent accelerated tests on Si and AlGaAs/GaAs concentrator solar cells. These examples were provided for their tutorial value in demonstrating the kind of information that can be obtained from such tests.

Some Reliability Problems in Integrated Circuits - Their Detection, Definition, and Remedy, J. W. Adolphson, NASA/Goddard Space Flight Center

Some of the reliability problems encountered in integrated circuits were reviewed to alert the photovoltaic community of potential pitfalls and to advise it of ways to view the reliability problems to help achieve solar cell stability.

Proper device design and fabrication are not only necessary to achieve the desired functional performance but also the desired reliability. The need to assure that reliability is built in the device has led to, for example, the use of the scanning electron microscope to check the quality of metallization interconnections. The introduction of such a sophisticated instrument on a manufacturing processing line was revolutionary at the time, but its use is now an accepted fact. The ability to detect problems with this instrument early in the manufacturing process led to production cost savings and to process changes that have resulted in inherently more reliable devices.

In summary, the importance of user involvement was emphasized. Involvement means a heightened awareness of device design, processing, manufacturing, testing, and device specification. Additionally, it means the development of capabilities to perform product evaluations and failure analyses. And, it implies coordination and cooperation not only with other users but with manufacturers themselves to promote product reliability and standardization.

Tests for Instabilities in Silicon Integrated Circuits, C. W. Green, Bell Telephone Laboratories

The major degradation and drift phenomena of integrated circuits and the tests which can be used to uncover them were reviewed. While these tests can reveal problems, sophisticated analytical techniques are necessary to thoroughly understand and to control the processing and material parameters which lead to instabilities and degradation.

Most of the instabilities encountered in integrated circuits are functions of electrical bias, humidity, or temperature and can be accelerated by subjecting the devices to the application of extraordinary levels of these stresses. Tables were reviewed which summarize the types of tests expected to be useful in identifying devices afflicted by the various drift and degradation mechanisms.

Because of the complexity of integrated circuits, it is impractical to subject all sensitive components to stressful conditions of accelerated life tests to predict long field service. Insight into device quality and reliability is acquired from a combination of using selected stress tests, thorough analysis of the component materials and processes, and assurances that the quality of materials and the processes and devices remain controlled.

Real-Time Controls for Reliability Assurance, S. Kukunaris, RCA

An approach to device stability analysis which can be accomplished quickly and with few samples was described; this approach has been used with transistors and CMOS devices. It is called real-time control testing, and its basis is the use of accelerated testing where the level of stress is selected to maximize the acceleration of degradation mechanisms active during device life. The stress level is selected to be as high as possible without activating failure mechanisms not active during the operational life of the devices tested. This stress level can be selected with assurance only when an information bank is available which consists of the results of extensive traditional efforts in life testing, stress testing, failure analysis, and field use.

Interdiffusion and Interface Problems Relating to Thin Film Photovoltaic Devices, L. L. Kazmerski, Solar Energy Research Institute

Interdiffusion and interface problems were reviewed which are related to thin film polycrystalline photovoltaic device performance and stability. These problems are aggravated by enhanced interactions at grain boundaries. It was cautioned that while the diffusion processes have been much studied by a variety of techniques, these studies have sometimes been conducted with mixed success and skill. The relatively recent development of surface analysis techniques and the use of two in particular, Auger electron spectroscopy and secondary ion mass spectroscopy, have highlighted interdiffusion investigations, however.

The three major interface problem areas were considered: the grid contact to the semiconductor, the semiconductor to semiconductor junction, and the semiconductor to back contact region. Representative problems were cited for a number of material systems: InP/CdS, GaAs, amorphous Si, Cu_2O, Cu_2S/CdS, Cu-ternaries, and SnO_x/Si. With these examples, it was concluded that much work needs to be done in controlling interdiffusion mechanisms in thin film polycrystalline solar cells so that these degradation processes can be minimized.

Corrosion and Its Control, R. P. Frankenthal, Bell Laboratories

The conditions for which electrolytic, galvanic, and stress corrosion can develop were reviewed. Many corrosion problems can be avoided by the proper choice of materials and device design, and by rigorous efforts to avoid moisture and ionic contamination. Moisture can reach the device surfaces either as a result of exposure of parts to moisture prior to or during device processing, by diffusion through encapsulants (most encapsulants used are permeable to water), or by ingress through faulty seals. Only minute amounts of ionic contaminant residues on surfaces, due to inadequate cleaning procedures, can greatly increase the rate of corrosion where moisture exists.

Corrosion failure modes mentioned are increased resistance of conductor stripes, short circuits due to dendritic formations, and increased leakage currents due to the spreading of corrosion products between conductors.

Two other noteworthy observations were made. No metal is immune from corrosion, given the right conditions; and many instances of corrosion can be attributed to dust particles from the atmosphere.

Experiences in the Low-Cost Solar Array Project with silicon flat-plate solar cell modules were described. Six key failure modes have been identified from field experience. They are: electrical interconnect breakage, metallization deterioration, electrical insulation breakdown, solar cell cracking, encapsulation cracking and delamination, and optical surface soiling. It is probable that they will be important in thin film arrays also. Problems with the first three have been substantially solved, while considerable progress has been made with the others.

Terrestrial Silicon Array Field and Test Experience, R. G. Ross, Jr., Jet Propulsion Laboratory

Qualification tests have been used to evaluate design solutions to address various failure modes. Some of the problems in the selection of meaningful environmental test stresses were discussed, and the relative value of the environmental tests used were reviewed. Thermal cycle, humidity, and structural tests have proved to be of great value, while ultraviolet stress tests have been difficult to interpret. Research on ultraviolet-humidity, bias-humidity, and module soiling tests is under way.

Recently proposed concepts and methodology for designing accelerated tests for silicon solar cells were highlighted. The basic approach is equally valid for the accelerated testing of thin film cells, although accelerated tests for thin film cells will likely have to be designed to be specific to each of the different cell types. Among the aspects of this design approach is the requirement of using only "mature" devices made by well-controlled fabrication processes, the availability of a broad range of data on device experience, engineering judgments based on these data to assess the relative severity of various combinations of stresses that need to be considered, an approach for uncoupling different failure mechanisms, a suggested time-acceleration factor of ten, and the use of at least five stress levels for each type of stress.

Methodology for Designing Accelerated Aging Tests for Predicting Life of Photovoltaic Arrays, R. E. Thomas and G. B. Gaines, Battelle-Columbus Laboratories

Session III: Discussion Group Sessions to Identify Tests and Measurement Procedures That Can be Used to Enhance the Prediction of Material and Device Stability

Several general aspects of measuring and reporting cell and material characteristics and stability were discussed. As a guide to what to expect of the types of cells under discussion, the following five classes of degradation mechanisms were developed and discussed: interdiffusion (implies mass transfer), chemical (oxidation, corrosion, or other chemical state change), electrolytic (decomposition due to field-induced ion motion), mechanical (such as grid lift-off, delamination, etc.), and photochemical (which encompasses any cell change which is directly induced by photons).

Discussion Group I on Cu_2S/[CdZn]S and Amorphous Si, L. L. Kazmerski, Solar Energy Research Institute, and J. D. Meakin, Univ. of Delaware

To allow for the development of a meaningful data base on which to assess test results of others and to evaluate cell stability, substantial agreement was reached in defining what conditions should be reported and the circumstances under which it is necessary to specify the test method details. Some of the general test conditions identified are insolation, temperature, stress, electrical loading, and ambient. Also cited was the importance of providing complete information about the experimental design and the characteristics of the cells before the initiation of the tests. The group also felt that to intercompare the performance of cells from different organizations and production periods, it would be better to establish a set of test procedures to which all would adhere than to establish a central test facility, as has been suggested by some.

A number of aspects and considerations regarding accelerated tests were discussed. To be able to project long term performance of cells, it will be necessary to establish functional relationships between test stresses and the degradation mechanisms to be accentuated. Also, the synergistic effects of different stresses to a given degradation mechanism cannot be ignored. Furthermore, the need to extrapolate long term cell stability from small changes in characteristics resulting from stress tests over a relatively short testing time places considerable importance on the precision of the test methods used to measure these changes. The paper presented in Session II on the methodology for designing accelerated aging tests for degradation mechanisms stimulated considerable discussion about its application to thin film cells. While the potential value of this approach was appreciated, some members of the group felt that the use of five stress levels, which was recommended, would require an excessive amount of testing.

Discussion Group II on Polycrystalline Si, MIS, and Conducting Oxide/Si, J. Schewchum, McMaster University, and R. L. Anderson, Syracuse University

An extensive and far-reaching set of research needs was developed which reflects both the breadth of cell designs and the immaturity of the material, cell, and measurement technologies involved. What is needed, basically, is a better understanding of and an improved measurement capability for virtually every aspect of these cells.

The material parameters of the various classes of polycrystalline silicon pertinent to solar cell performance need to be identified. Measurement standards of polycrystalline silicon are needed to allow for more meaningful assessment of data being reported. In particular, methods to measure the following were cited: resistivity, mobility, lifetime, diffusion length, grain size and orientation, void space between grains, and impurity content within grains and at grain boundaries.

Guidelines are needed to measure the various aspects of interfacial layers such as interfacial resistance, variation of thickness with time, pinholes, impurity composition, and density and energy of charge states.

A better understanding is needed of the various reactions at interfaces; of the influence of grain boundaries on the mechanical and electrical properties of materials and cells; of the effects of built-in and applied electric fields; of the compatibility of the various material combinations; of interdiffusion phenomena at interfacial layers, window interfaces, and grain boundaries; of conducting window materials; and of the encapsulants used.

Indicative of the relative immaturity of the technology for these cells, the need to understand better the operation of these cells and to understand their degradation mechanisms was emphasized. As a consequence, there is a need to identify which parameters affect most the energy conversion efficiency of these cells. Also, ways are needed to predict the potential conversion efficiency of various material systems to determine which are worth developing.

Regarding the matter of long term stability, it was felt that all mechanisms encountered in single crystal homojunction solar cells must be considered. To these must be added degradation mechanisms related to any possible incompatibilities of the various materials used, including encapsulant materials. The classes of degradation mechanisms identified by the group are essentially identical to those identified by Discussion Group I. Because of the great differences in the material systems, it will not be possible to have accelerated test standards applicable to all cell types. Initial approaches in developing these standards should, however, be based on those for single crystal silicon cells. To accelerate the development of a data base, laboratory and use tests should be conducted concurrently. Tests on unprotected cells, insofar as that is possible, should be made to assist in discovering intrinsic degradation mechanisms.

Discussion Group III on Thin Film GaAs, R. J. Stirn, Jet Propulsion Laboratory

Thin film GaAs solar cell technology was considered to be sufficiently immature to require the discussions to be oriented more to understanding the various mechanisms at play in these cells than to address the question of predicting cell lifetime. Three broad topic areas were examined: classes of degradation, test strategies to uncover degradation problems, and areas where more research is recommended.

Regarding degradation, three major classes of phenomena were identified and discussed: interdiffusion, chemical, and mechanical.

Under interdiffusion phenomena are a plethora of effects, for example: degradation of the contacts between the GaAs and the substrate and the front metallization; reactions involving the barrier metal, interfacial oxide, and bulk GaAs; degradation of conducting oxide layers; and reactions at grain boundaries. Under the category of chemical effects were mentioned front contact corrosion and interfacial oxide modification problems. Under mechanical effects were potential problems with the strength and integrity of the front contacts and interconnects, especially in Schottky barrier-type cells where bonds to a thin metal film are required.

A number of screen, operating, and accelerated tests were suggested to reveal some of the above degradation modes. They involved the use of I-V characteristics, as a function of temperature, and the use of changes in spectral response to reveal cell degradation, in the process of subjecting cells to temperature cycling and high temperature storage stresses. High humidity is added to accentuate those stresses.

Four general areas of research were called out as requiring extra attention to promote the development of viable cells. The most crucial area is in the selection of the low cost substrate and its treatment. Research is also needed to better understand the interfacial oxide layer and barrier metal alloys of these cells, to investigate more cost-effective means of manufacturing GaAs, and to study the making of electrical contacts to thin films with adequate bond strength and low contact resistance that do not lead to shorted junctions or degraded Schottky barriers.

NBS-114A (REV. 9-78)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. NBSIR 79-1778	2. Gov't. Accession No.	3. Recipient's Accession No.

4. TITLE AND SUBTITLE

A Perspective of a Workshop on Stability of (Thin Film) Solar Cells and Materials

5. Publication Date

June 1979

6. Performing Organization Code

7. AUTHOR(S)

Harry A. Schafft and David E. Sawyer

8. Performing Organ. Report No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, DC 20234

10. Project/Task/Work Unit No.

11. Contract/Grant No.

Task Order A054-SE

12. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)*

Advanced Materials R&D Branch
Division of Distributed Solar Technology
Department of Energy
20 Massachusetts Avenue, N.W., Washington, DC 20545

13. Type of Report & Period Covered

Final

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The results of a workshop on the Stability of (Thin Film) Solar Cells and Materials are reviewed from a measurements perspective. Solar cells of the following three material groupings were considered at the workshop: (1) Cu_2S/[CdZn]S, Cu-ternaries/CdS, InP/CdS, and amorphous Si; (2) polycrystalline, MIS, and conducting-oxide Si; and, (3) polycrystalline and AMOS GaAs. Considering the relative state of immaturity of these developing cells and the goal for high reliability and stability, two general areas of work are recommended. One is to develop an improved understanding of cell operation and of component structures of these cells. The other is to develop an improved measurements base. Specific needs and recommendations are provided.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Accelerated tests; failure mechanisms; failure modes; photovoltaics; reliability; semiconductors; solar cells; stability; testing; thin films.

18. AVAILABILITY ☒ Unlimited

☐ For Official Distribution. Do Not Release to NTIS

☐ Order From Sup. of Doc., U.S. Government Printing Office, Washington, DC 20402, SD Stock No. SN003-003-

☒ Order From National Technical Information Service (NTIS), Springfield, VA. 22161

19. SECURITY CLASS (THIS REPORT)	21. NO. OF PRINTED PAGES
UNCLASSIFIED	15
20. SECURITY CLASS (THIS PAGE)	**22. Price**
UNCLASSIFIED	$4.00

USCOMM-DC