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Initiative in Photovoltaic Manufacturing

Final Subcontract Report
2 January 2002 – 15 January 2008

S. Danyluk
Georgia Institute of Technology
Atlanta, Georgia

Subcontract Report
NREL/SR-520-43968
September 2008

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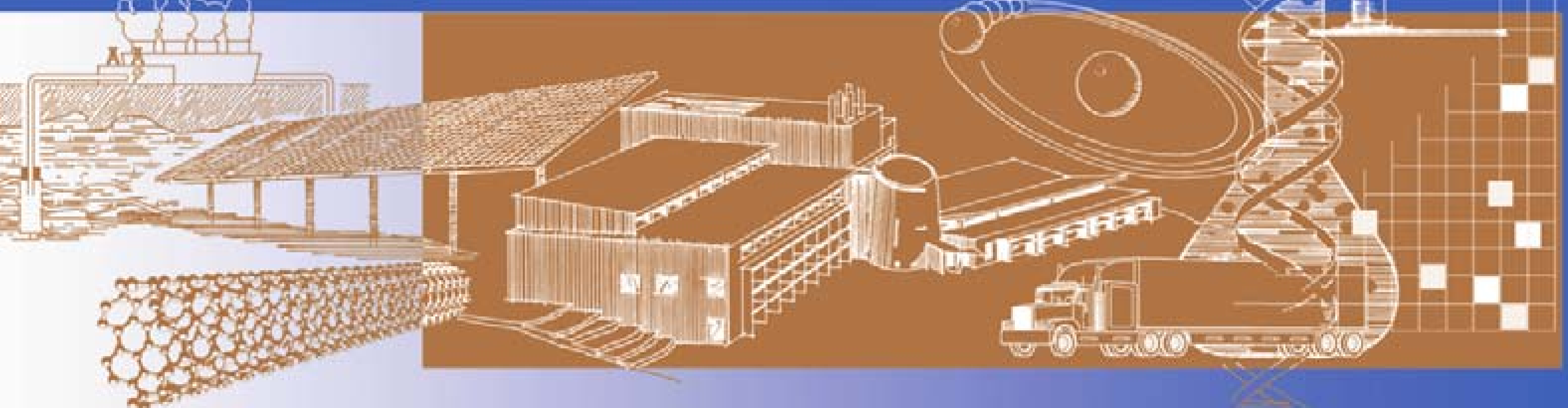

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1. Introduction

The Manufacturing Research Center (MARC) at Georgia Tech has been addressing photovoltaic manufacturing under an NREL grant. The initiative led to the creation of the Photovoltaic Manufacturing Laboratory (PVML) to address fundamental and practical issues related to handling and fracture of thin polycrystalline silicon wafers used in solar cells, measurement of residual and applied stresses in the wafer due to processing and handling, and the development of factory information software tools for real-time monitoring of equipment used in solar cell manufacturing. The lab is researching new and improved manufacturing techniques to enhance solar cell quality and yield, and lower the cost of PV devices. This paper summarizes the major accomplishments of the lab to date in the aforementioned areas.

2. Project Objectives

The major objectives of the photovoltaic manufacturing initiative at Georgia Tech are to research and develop new and improved methods for thin crystalline silicon wafer handling, transport, inspection, and real-time monitoring of equipment used in solar cell/panel manufacturing. The advances made in this research will enhance solar cell yield and quality, and lower the cost of manufacturing silicon-based PV.

3. Technical Approach

Under this grant, the Photovoltaic Manufacturing Laboratory (PVML) was setup at Georgia Tech to address both fundamental and practical issues related to handling and fracture of thin polycrystalline silicon wafers used in solar cells, measurement of residual and applied stresses in wafers due to processing and handling, and the development of factory information software tools for real-time monitoring of equipment used in solar cell manufacturing. Additionally, the project surveyed industry priorities and established research collaborations with PV equipment and cell manufacturers.

This report summarizes the major accomplishments of the project in each of the following three areas: A) Optical inspection of residual stresses in thin silicon wafers, B) Thin wafer handling and breakage, and C) Factory information software development. The report is broken into sub-sections that discuss the aforementioned accomplishments. The appendix contains technical papers containing details pertinent to the sub-sections authored by different members of the project team.

A. Residual Stress Measurement

A1. Introduction

Our group has been working on developing a non-destructive, non-contact optical technique to measure the residual stress in thin silicon sheet. Figure A1 shows a schematic diagram of the polariscope system. Circularly polarized light, which is provided by the first polarizer and quarter waveplate, is used to illuminate the silicon sample. The residual stresses in the sample will change the polarization state of the transmitted light, and the change is extracted by the second waveplate and polarizer. Two partial mirrors are used to increase the sensitivity of the system when the residual stresses are low. A tungsten lamp with an adjustable power up to

250W is used as the light source, and the images are captured by an infrared camera. In the camera, a band-pass infrared filter is used to pick a near infrared wavelength center at 1150nm with a bandwidth of 10nm.

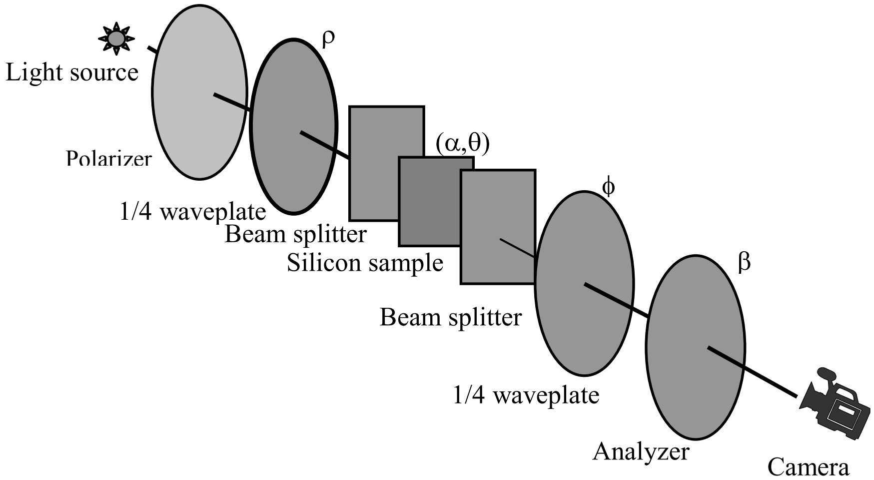

Figure A1: Setup of residual stress polariscope

The stress optic law can be used to obtain the shear stresses in the beam if the stress optic coefficient is known. The stress optic law is shown in equation 1.

$$\sigma_1 - \sigma_2 = \frac{\lambda}{2\pi t C(\theta, \varphi)} \delta \quad (1)$$

Where C is the stress-optic coefficient which is a function of θ (the principle stress orientation) and φ (the crystal grain orientation), t is the thickness of the sample, λ is the wavelength of the light source, and σ1, σ2 are the two principal stresses. δ is the phase retardation which can be measured by the six step phasing method.

A2. Goals and Objectives

- Calibration of anisotropic stress-optic coefficient
- Stress separation
- Finding the relationship between stress and dislocation density
- Analysis of thermal effect on residual stress measurement

A3. Summary of Approach

- Calibration of anisotropic stress-optic coefficient.

The stress optic coefficient, a parameter used for the polariscope, is orientation dependent, as can be seen from equation 1. Back Laue x-ray diffraction system is used to determine the crystallography and find φ. Four-point bending was used to introduce known stresses so as to calibrate the anisotropic stress optic coefficients. The residual stresses in the wafers were assumed to be negligible compared to the applied stresses. Using equation 1, stress optic coefficient could be obtained since stress is known.

- Stress separation

Photoelasticity provides information on the principal shear stress and its orientation in the wafer. To obtain the full state of stress (σ_x, σ_y and τ_{xy}), stress separation must be applied. Four-point-bending together with shear difference technique is proposed to be used for stress separation. Four point bending can tell whether the measured shear stress is positive or negative. Then the shear difference technique is based on the direct integration of the equilibrium equations in the following finite difference format:

$$\sigma_x = \sigma_x(boundary) - \sum \frac{\Delta \tau_{yx}}{\Delta y} \Delta x \quad \text{and/or} \quad \sigma_y = \sigma_y(boundary) - \sum \frac{\Delta \tau_{yx}}{\Delta x} \Delta y \quad (2)$$

By equation (1) and (2) and the basic stress transformation equations of mechanics, full state of stress (σ_x, σ_y and τ_{xy}) can be calculated.

- Finding the relationship between stress and dislocation density

In the case of obtaining the relationship between dislocation density and residual stress, the experiment used an optical microscope and image analysis in addition to the polariscope that measured the residual stresses. EFG wafers were used for the dislocation density experiment since their structure is relatively constant and the surface is smooth for a clear picture of etch pits. A Sopori etch was done to reveal etch pits on the surface of EFG wafers. Etch pit density is taken to be the same as dislocation density. Wafers were also subjected to polariscopy to obtain the residual stress maps, and the results of etch pit density and residual stress were analyzed to find their relationship.

- Analysis of thermal effect on residual stress measurement

This task is designed to address measurement resolution and reliability issues associated with the IR-polariscope. In particular, it is designed to systematically study the role of temperature rise in the silicon wafer due to IR light absorption on the residual stress output by the system. The non-uniform energy profile of the light source can produce a thermal gradient in the Si sample and as a result, a thermal stress may be induced in the wafer, which will increase the system error. A thermal model is built from ANSYS to calculate the temperature in the silicon wafer. Then the temperature profile is input to a structural model to calculate the thermal stress.

A4. Key Findings

- The major preferential orientation in cast wafers is (111) and near (111) but other dominant orientations are (100), (210), (110), (144), (211), (321), and (431). The stress optic coefficients vary with orientation with a magnitude of 2.

- Full components of stresses are obtained for several silicon beams. And the maximum first principle stress is found about 30 MPa for EFG wafers. This is a conclusion based on a small sample size.

- A relationship was found between dislocation density and residual stress. The graph in Figure A2 shows the behavior of residual stress at high values of dislocation density. Equations are shown in the graph to quantify the relationship. There is an uncertainty in which stress relaxation occurs since there are sources of residual stress other than dislocations.

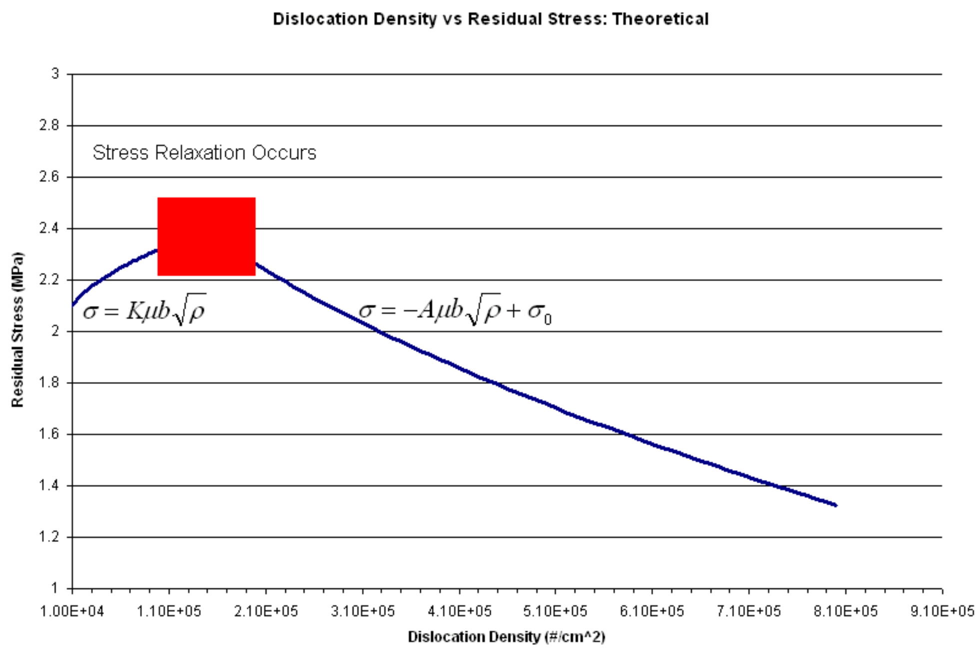

Figure A2. Relationship between dislocation density and residual stress

- Thermal model shows the polariscopy system needs about 1 to 2 minutes to come to steady state.

A5. Conclusions

- The predominant orientations were found for cast wafers.
- The relationship between dislocation density and residual stress is found.
- Full stress components are obtained for several silicon beams.
- Preliminary models are built to calculate thermal effect for the polariscopy system.

B. Thin Wafer Handling and Breakage

B1. Introduction

Shortage of silicon (Si) combined with the need to lower the cost of crystalline silicon based solar cells has contributed to the growing use of thinner and larger wafers. However, studies have shown that the use of thinner wafers can lead to unacceptable yields arising from wafer breakage during handling, transport and/or processing [3]. Consequently, it is critical to understand the causes of wafer breakage [4]. Fundamentally, breakage of Si wafers is due to the propagation of cracks present in the wafer during a processing or handling step in solar cell manufacture. Knowledge of crack locations and sizes is therefore required to predict wafer breakage accurately. A crack will propagate if a sufficiently large in-plane tensile stress is applied orthogonal to it (assuming Mode I fracture). Thus, it is necessary to evaluate the nature, magnitude and distribution of stresses produced in the wafer/cell during manufacture. This includes residual stresses generated in a prior process step and stresses applied to the wafer/cell by the current processing, handling and/or transport method used in manufacture.

B2. Goals and Objectives

The objective of the current work was to analyze the mechanical deformation and stresses produced in sc-Si and mc-Si wafers and the relationship between the handling stresses and possible wafer breakage. In particular, we focused on one of the more commonly-used handling devices in the PV industry, namely the Bernoulli gripper but the approach can be used for any handling device.

B3. Summary of Approach

The experimental setup used to measure the gripper forces and wafer deformation consists of a 4-axis Adept SCARA robot equipped with a Bernoulli gripper used to pick up wafers using high–precision and controlled gripping forces. Wafer deformation profile was measured by a laser displacement sensor (Micro-Epsilon OptoNCDT 1700). The robot moves the wafer that is being handled along a specific path while the laser sensor measures the wafer deformation. The volumetric flow rate is kept constant during the procedure. Once the scanning is complete, the height between the laser and the four rubber pads on the Bernoulli gripper is measured.

In order to predict wafer breakage it is critical to know the stress state of the wafer (applied stresses and residual stresses). Two approaches were developed. First, the total distribution of stresses produced in the silicon wafer due to handling forces exerted by the Bernoulli gripper and the residual stress present in the wafer were obtained by solving finite element models created using the ABAQUS® software using the measured deformation [5, 6]. Second, the combination of analytical fluid dynamics model and a finite element models created using the ABAQUS® allowed predicting the stress level in wafers without using experimental measurement. In this scenario the residual stresses need to be superposed and were not included in the model [7].

B4. Key findings

- The influence of volumetric air flow rate on the maximum wafer deformation was investigated. It is shown that the maximum deformation increases with air flow rate. It also shows that an upper limit of wafer deformation exists for the thin wafers as the flow rate is increased.
- From the investigation of the influence of volumetric air flow rate and wafer type on the wafer deformation contours, identical conclusions were also drawn. In addition, it is found that for all wafer types, there is a preferred orientation of the deformation as the volumetric flow rate is increased. Material anisotropy cannot explain this preferred orientation since it appears to be the more or less the same for all wafer types.
- As shown in Table B1, the critical crack length was calculated assuming that a crack is present at the location of the maximum tensile stress [5]. As expected, irrespective of the

wafer type, an increase in volumetric air flow rate leads to an increase in the tensile stress and a smaller critical crack length for wafer breakage.

Table B1. Max. in-plane principal tensile stress and critical crack length results

	V (L/min)	K_{IC} Mpa.m$^{0.5}$	σ_{max} (Mpa)	σ_{max} Location	l_c (mm)
Cz wafers	30	0.95	5.4	Center	10.037
	35		17.1	Edge	0.984
	40		133.2	Edge	0.016
EFG wafers	30	0.9	42.0	Center	0.146
	35		128.9	Edge	0.016
	40		226.9	Edge	0.005
Cast wafers 125 mm x 125 mm	30	0.75	4.5	Center	8.961
	35		11.1	Center	1.456
	40		118.6	Edge	0.013
Cast wafers 156 mm x 156 mm	30	0.75	8.0	Center	2.784
	35		49.6	Edge	0.073
	40		131.8	Edge	0.010

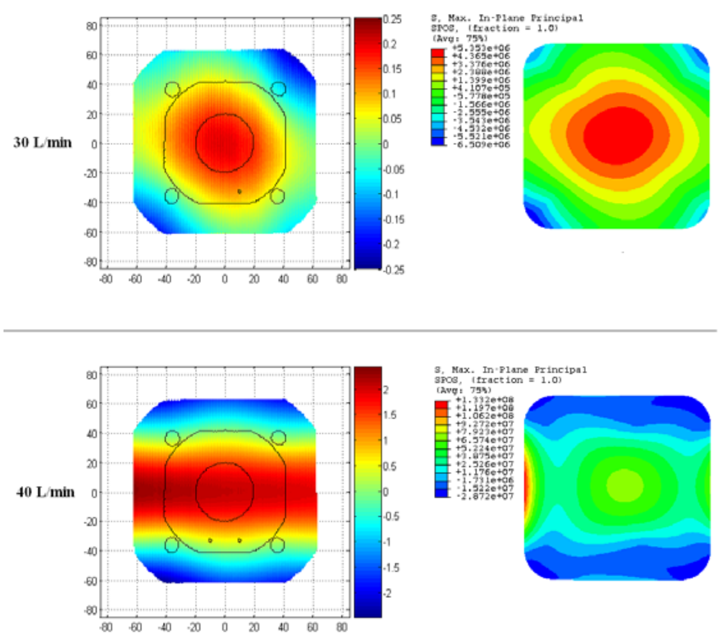

Figure B1. Typical wafer deformation profile (mm) and maximum in-plane principal stress distribution (Pa) for Cz-wafer at both extreme volumetric flow rates (30L/min & 40 L/min)

- Figure B1 shows the typical Cz wafer deformation profiles for the lowest and highest volumetric air flow rates tested. The deformation profile and the corresponding maximum in-plane principal tensile stress distribution are seen to change significantly with increase in the air flow rate. Specifically, the location of maximum tensile principal stress shifts from the center of the wafer to the edge.

- Therefore, for a given wafer type, breakage may initiate either in the center or at the edges depending on the presence, orientation and size of cracks equal to or greater than the critical crack length at the site of the maximum tensile stress. Similarly, if one could guarantee that all cracks present in the wafer are smaller than the critical crack length regardless of their location and orientation, wafer breakage would be avoided.

B5. Conclusions

This section presented the results of an experimental and modeling investigation of deformation and stresses produced in polycrystalline silicon wafers handled by a Bernoulli gripper. The experimental work showed that the air flow rate and wafer thickness have a significant effect on wafer deformation. For all wafer types, results showed a transition in the maximum in-plane principal tensile stress location from the center to the edges as the air flow rate was increased. The relation between the total stress and breakage was analyzed by calculating the critical crack length. Furthermore, with the knowledge of residual stresses, handling stresses (calculated from the FE model) and wafer strength, breakage can be predicted.

C. Factory Information Systems

C1. Introduction

In order to accomplish the Department of Energy (DOE) goals of reducing the levelized cost of energy while scaling-up domestic manufacturing capacity of PV, information technologies must play an every increasing role in the manufacture of such devices. As such, innovative factory information systems were researched, developed and implemented through this effort.

DOE is targeting that the U.S. produce 10 GW of photovoltaic products each year by 2015. This will require the sourcing, manufacture, assembly and installation of billions of parts. As an example, if all domestic production consisted of silicon wafer modules, the number of wafers would wrap the earth more than three times, more than 11,000 modules would have to be produced every hour of every day, which would require 100 factories running 24/7. If domestic PV production is to grow to this level by 2015, then commonality among systems must be defined so that material suppliers, equipment producers, software developers and manufactures can construct factories in a timely basis. A conceptual of a highly automated factory is shown in figure C1.

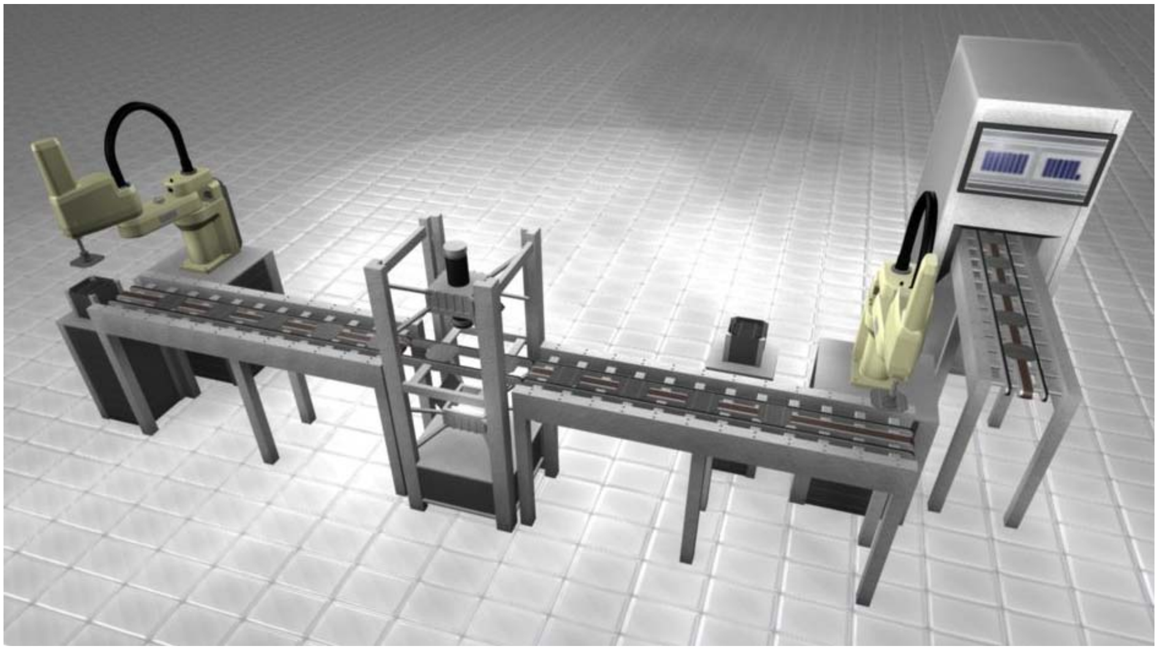
Figure C1. Highly automated photovoltaic factory of the future.

Factory information systems are a major and necessary component of high volume manufacturing. They act as conduits for information flow among equipment, software applications, vendors and the enterprise as a whole. They also aid in decision making from the factory floor to the boardroom. Without correctly architected systems, the ability to build factories that are capable of producing cost effective products is extremely limited.

C2. Goals and Objectives

The goals of this work were to determine if standards used in other industries (specifically electronics assembly) could be applied and extended for use with photovoltaic manufacturing. Specifically, the IPC computer aided manufacturing using XML (CAMX) standards were investigated for use in PV manufacturing. By extending an accepted technology, the cost and risk of implementing a common methodology is greatly reduced. The CAMX infrastructure located in the lab is shown in figure C2.

The use of CAMX standards for collecting, aggregating and presenting experimental photovoltaic data was also investigated by partnering with the National Renewable Energy Laboratory (NREL).

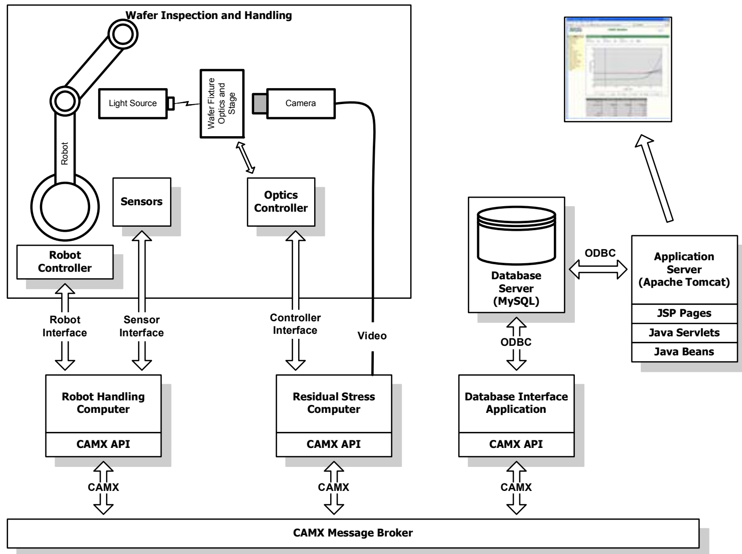

Figure C2. The Photovoltaic CAMX infrastructure developed for the project.

C3. Summary of Approach

In order to determine if the CAMX standards could be used for photovoltaic manufacturing, a CAMX infrastructure was establish in Georgia Tech's Photovoltaic Manufacturing Laboratory. A CAMX message broker that exchanges xml messages based upon predefined schemas was installed. Adapters were written which receive proprietary data structure and translate the information into CAMX standard messages were written. The adapters sent the xml messages to the broker, and the broker sent the messages to a application server and database which compiled the discrete messages into web based charts, graphs and tables for viewing.

NREL J-V experimental data was also streamed over the internet to the CAMX infrastructure located at Georgia Tech. Specific software adapters were developed which were capable of parsing the experimental data and producing aggregated xml messages based upon the IPC-2547 schemas. Specific reports for the CAMX monitor were developed to display the experimental data.

C4. Key Findings

By extending the schemas that were written for electronics assembly, the CAMX standards could easily be used for photovoltaic manufacturing. The IPC-2547 standards were especially useful for encapsulating experimental data. General manufacturing data could be represented through the IPC-2541 and the IPC-2546 standards. The message broker and monitor worked very well for photovoltaic manufacturing.

C5. Conclusions

This work demonstrated that the CAMX standards can be made use of by the photovoltaic industry to improve productivity and reduce cost. The barrier to applying CAMX to photovoltaic manufacturing is low because of the similarity between electronic assembly manufacturing (the industry CAMX was developed for) and photovoltaic manufacturing. The CAMX standards don't fully address photovoltaic manufacturing, but could be extended to do so. It is recommended that a project to extend the CAMX standards be undertaken so photovoltaic manufacturing can receive the full benefits that this technology has demonstrated.

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The major objectives of the photovoltaic manufacturing initiative at Georgia Institute of Technology are to research and develop new and improved methods for thin crystalline silicon wafer handling, transport, inspection, and real-time monitoring of equipment used in solar cell/panel manufacturing. This report summarizes the major accomplishments of the project in each of the following three areas: (1) Optical inspection of residual stresses in thin silicon wafers, (2) Thin wafer handling and breakage, and (3) Factory information software development. The advances made in this research will enhance solar cell yield and quality, and lower the cost of manufacturing silicon-based PV.

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