# Initiative on Photovoltaic Manufacturing DOE Solar Energy Technologies Program Peer Review

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Denver, Colorado

April 17-19, 2007

# Relevance/Objectives

- Research and develop new and improved methods for manufacture, handling, inspection, and real-time process monitoring of thin crystalline silicon wafers and solar cells.
- Enhance *quality* and *yield* of thin crystalline silicon solar cells and thereby lower manufacturing *cost*.
- Build a coalition of PV equipment and solar cell manufacturers to collaboratively address pre-competitive next generation technologies for PV manufacturing.

# Georgia Tech Programs in PV

- University Center of Excellence for Photovoltaics
  - Crystalline-Silicon Processing and Design
    - High Efficiency Cells
    - High Throughput Technologies [RTP/PECVD/SPC]
    - Thin-Layer Growth
    - Novel Furnace Technologies
- **PV Manufacturing Initiative**
  - **Thin-Wafer Manufacture, Handling and Inspection**
    - **Wafer Saw/Cut Technologies**
    - **Residual Stress Measurements**
    - **Physical Handling/transport**
    - **Factory-Floor Communication ……[Software Tools]**
- Center for Organic Photonics and Electronics (COPE)
  - Organic Solar Cell Research
    - Efficiency Issues
    - Pentacene + C60 (Buckyballs)

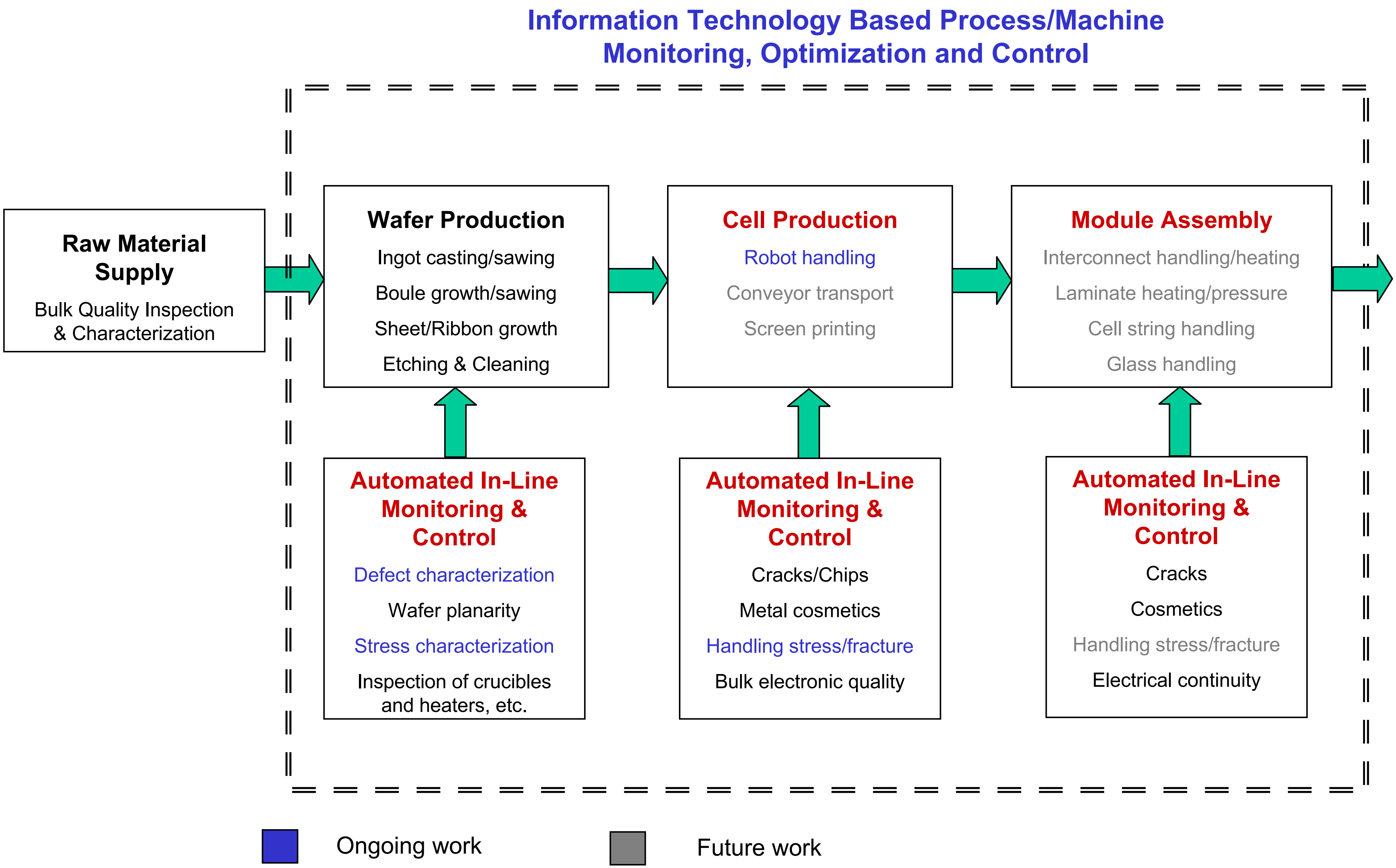
# Participants

- Faculty
  - Steven Danyluk, Professor, George W. Woodruff School of Mechanical Engineering
  - Shreyes Melkote, Professor, George W. Woodruff School of Mechanical Engineering
  - Andrew Dugenske, Research Faculty, Manufacturing Research Center

# Participants

- Graduate students and staff
  - Fang Li, Ph.D. student, Mechanical Engineering
  - Vicky Garcia, M.S. student, Mechanical Engineering
  - Xavier Brun, Ph.D. student, Mechanical Engineering
  - Doug Furbush, Research Engineer, Manufacturing Research Center

# PV Manufacturing Research in MARC



# Overall Activity Summary

- Conducted research on:
  - Thin wafer stress measurement
  - Thin wafer handling and breakage
  - Real-time factory information technology
- Interacted with industry
  - Conducted survey of PV cell/module industry needs
  - Held workshops to prioritize industry needs
  - Developed collaborative research projects with PV equipment and cell manufacturers

# Residual Stress Measurement

- Objectives of Residual Stress Measurement System
  - Developing a method and apparatus to obtain in-plane residual stress in thin single and poly-crystalline silicon
  - Address the crystallographic anisotropy by the use of X-ray diffraction to determine dependence on grain orientation

# Activity Summary: Residual Stress

- Stress Measurements
  - Polariscopy
    - Optimized the light transmission and detection in the polariscope
    - Calibrating the stress-optic. coefficient of the CZ, EFG and CAST wafers
    - Designed the system to measure large wafers.

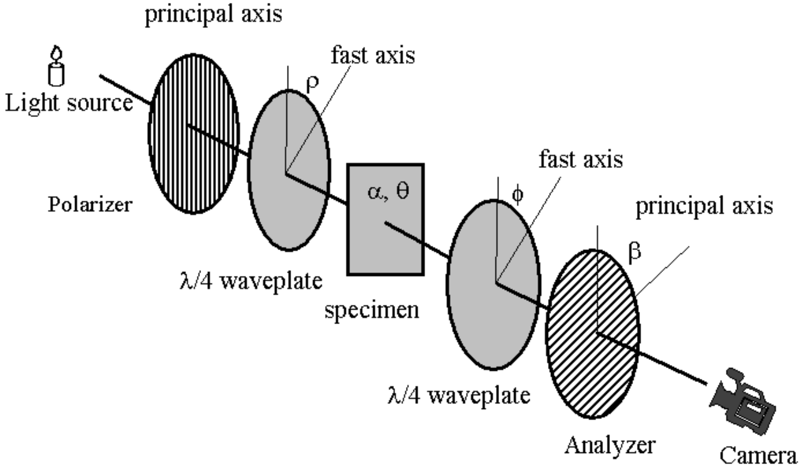
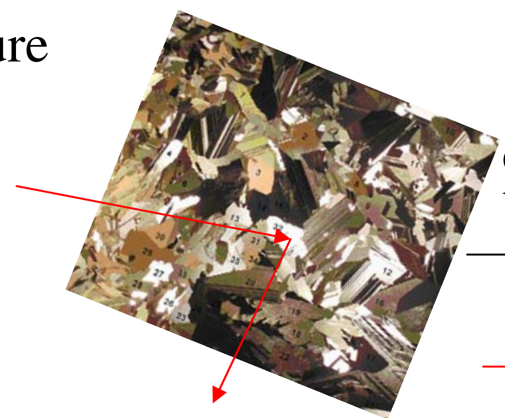
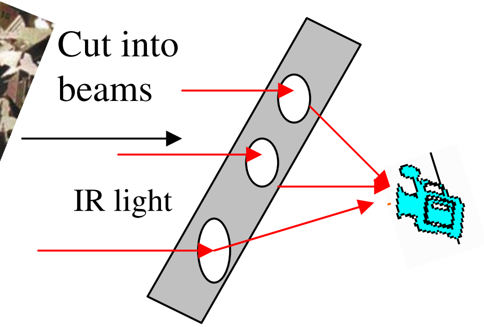



Fig.1: Set up of Polariscope

- X-Ray Diffraction
  - Back Reflection Laue System:
    - determine orientation of large grains in cast wafers



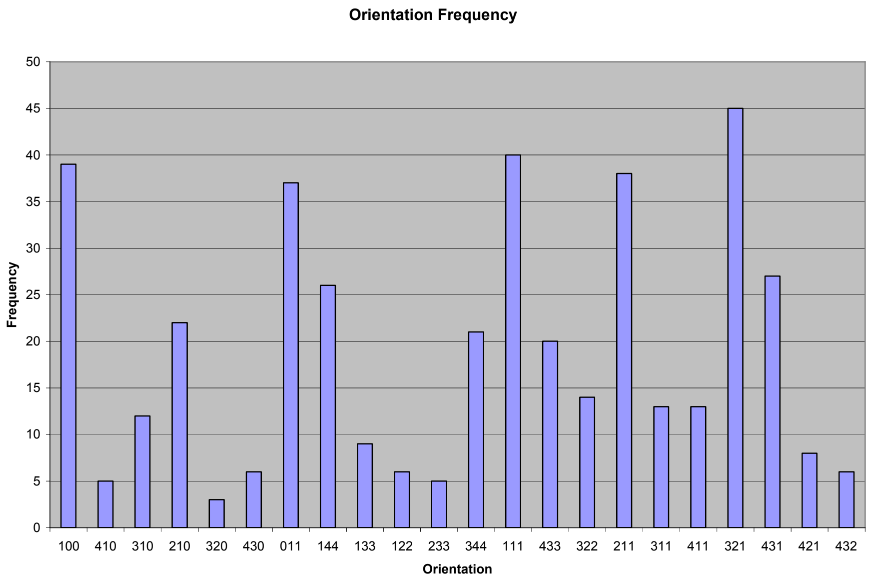
X-ray diffraction



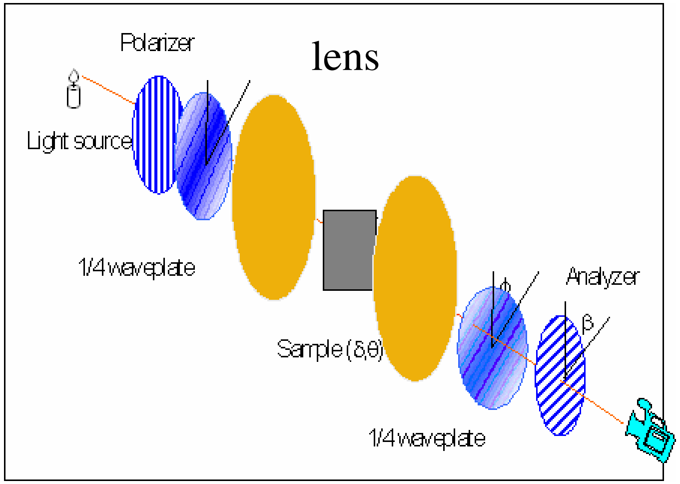

Orientation of grains will influence light transmission

# Accomplishments: Residual Stress

- Residual stresses were obtained for EFG and Cast wafers
  - Overall system errors is 2Mpa
  - A new setup has been developed which can measure wafers as large as 6 inch. Measurement time is around 5s;
  - Stress optics coefficients for Cast, CZ and EFG wafers have been calibrated using 4-point bending assuming the crystal orientation of EFG is predominantly (110), CZ is (111) ;
- Orientations of large grains of cast Si were determined
  - Orientations of the grains are: (100), (210), (110), (144), (344), (111), (433), (211), (211), (321), (431) with respect to the surface of the wafer.

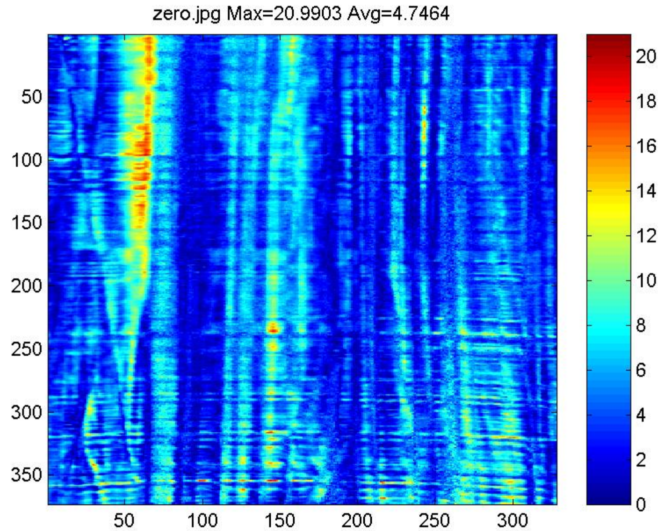



Crystal Orientation frequency in cast wafers

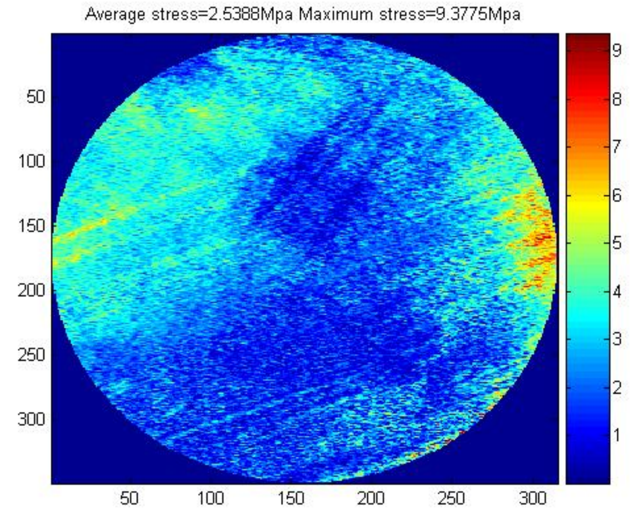



New setup of polariscope

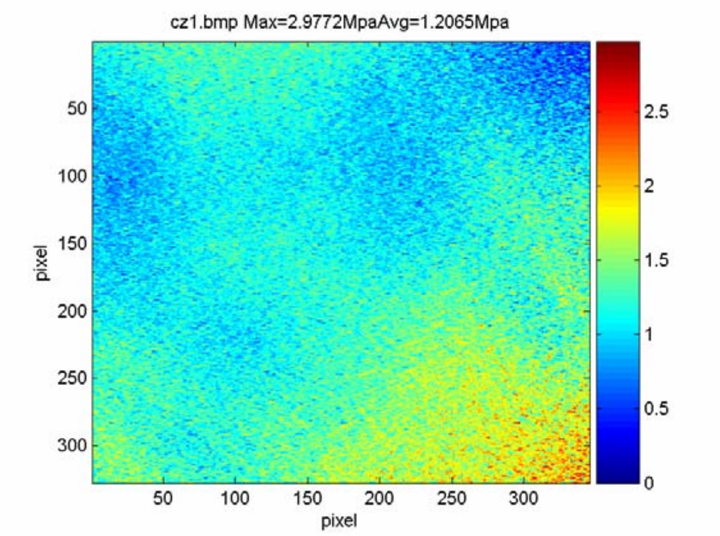
# Accomplishments: Residual Stress




Whole field stress of 4 inch EFG wafer




Cast wafer




CZ wafer

| | Maximum stress (Mpa) | Average stress (Mpa) |
|---|---|---|
| Cast | ~10 | 3 |
| EFG | 20~40 | 4~5 |
| CZ | 3~5 | 2~3 |

# Accomplishments: Residual Stress

## System calibration using 4-point bending

stress-optic coefficient for silicon wafers

Stress-optics law

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

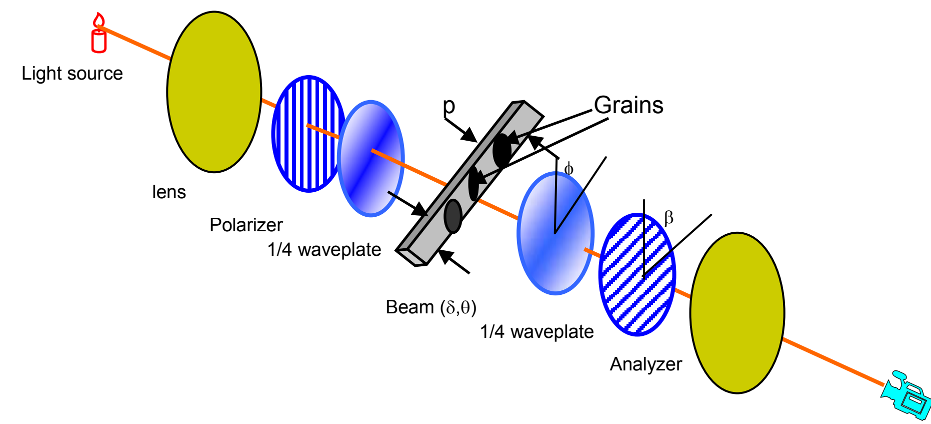
Four point bending stress

Retardation

Crystal orientation efg(110), cast (100) and cz (111)

Experimental Results

Calibration of stress-optic coefficient




4-point bending setup

## Results

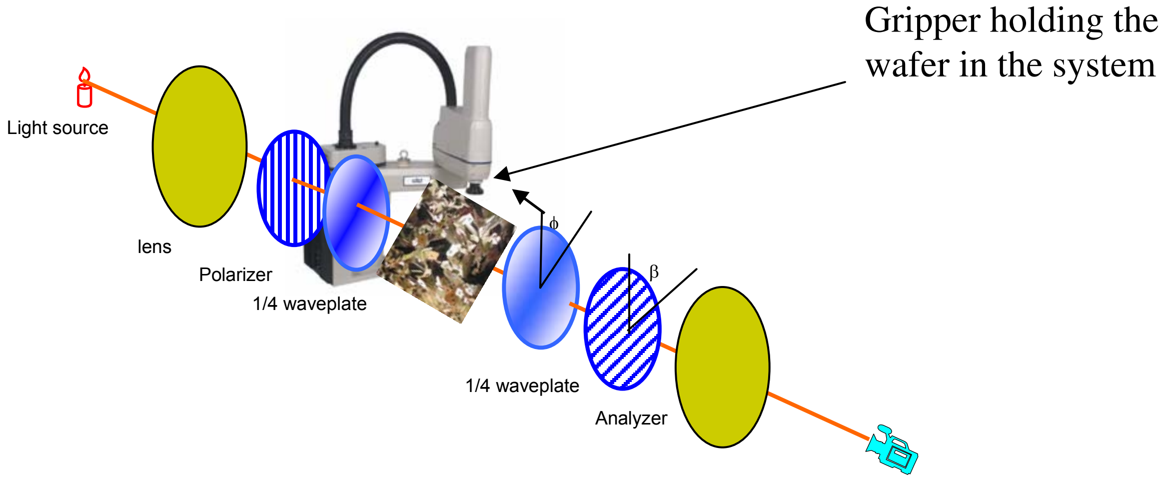
$C_{EFG}=2.52 \times 10^{-11}(Pa^{-1})$

$C_{cz}=1.68\times 10^{-11}(Pa^{-1})$

$C_{cast}=1.73 \times 10^{-11}(Pa^{-1})$

# Future Work: Residual Stress

1. Fully calibrating the set-up for measuring large wafers and develop the light transmission equation for non-collimated beams.
2. System automation. Robot will be used for holding wafers in measuring the stress.



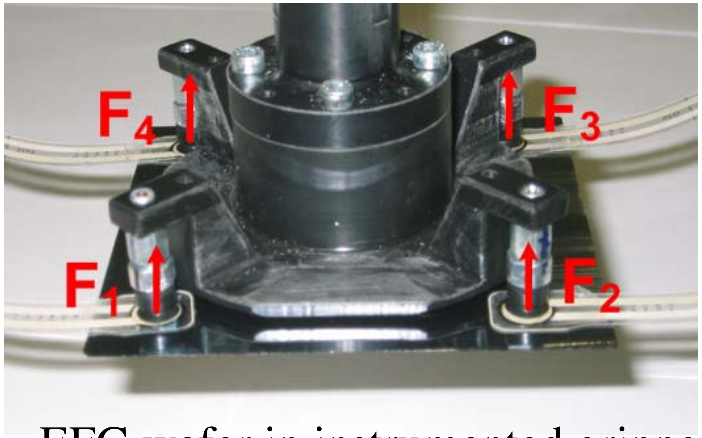
# Thin Wafer Handling

- Research Objectives
  - Develop an experimental test bed for thin wafer handling research.
  - Study influence of gripper variables and Si wafer characteristics on stresses, distortion and breakage. Focus on Bernoulli type grippers.
  - Optimize gripper variables to minimize thin wafer handling stresses and breakage.

# Activity Summary: Handling

- Thin wafer handling
  - Experimental
    - Developed Bernoulli gripper-based robotic wafer handling setup.
    - Instrumentation for measuring wafer gripping forces and deformation.
    - Analyzed effect of gripper variables and wafer thickness on EFG deformation and stresses.
    - Tested new Bernoulli grippers from Manz Automation and OTB Solar.
  - Modeling
    - Modeled pressure distribution on wafer due to Bernoulli effect and resulting deformation and stresses.

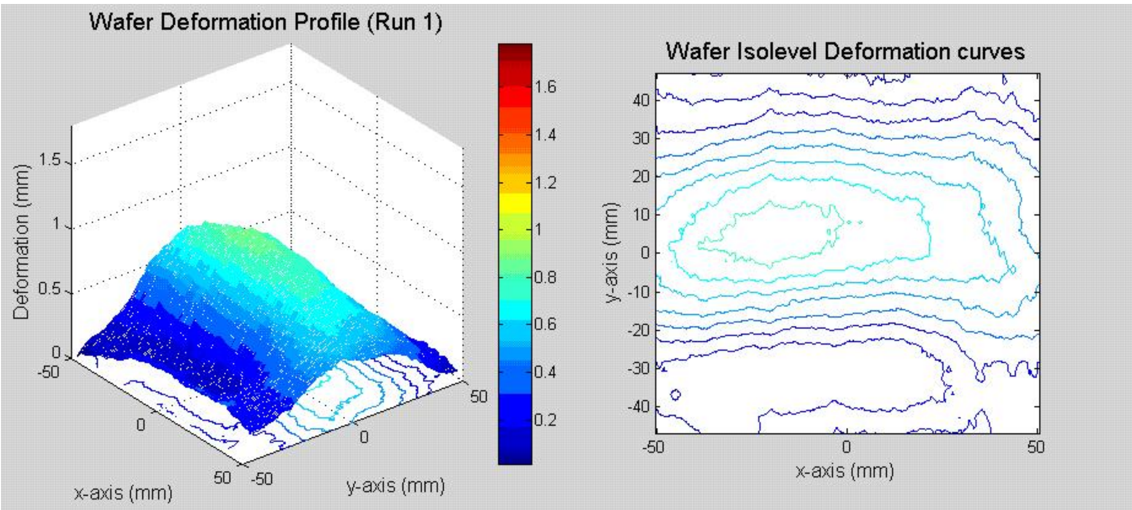
Thin wafer handling test bed




EFG wafer in instrumented gripper

# Accomplishments: Handling

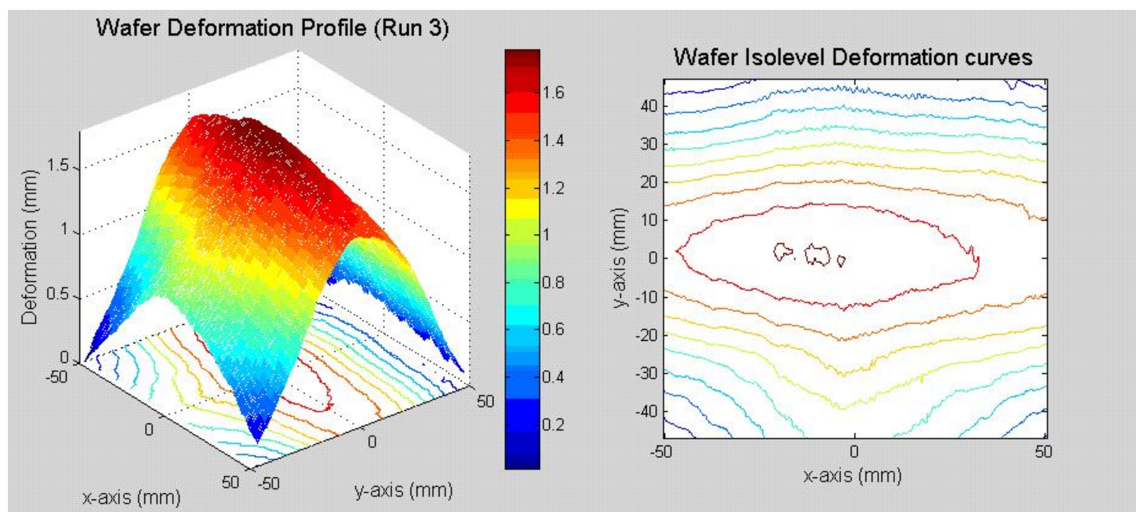
- Effect of wafer thickness and gripper variables - volumetric air flow rate, stand-off distance – on EFG wafer deformation is significant.




20% ↑ in air flow rate

➔ 118% ↑ in deformation

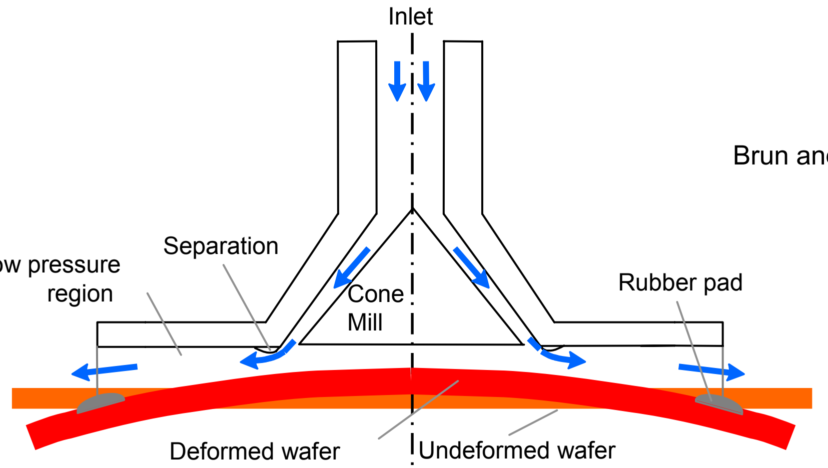
(for T=202 μm & H = '-')



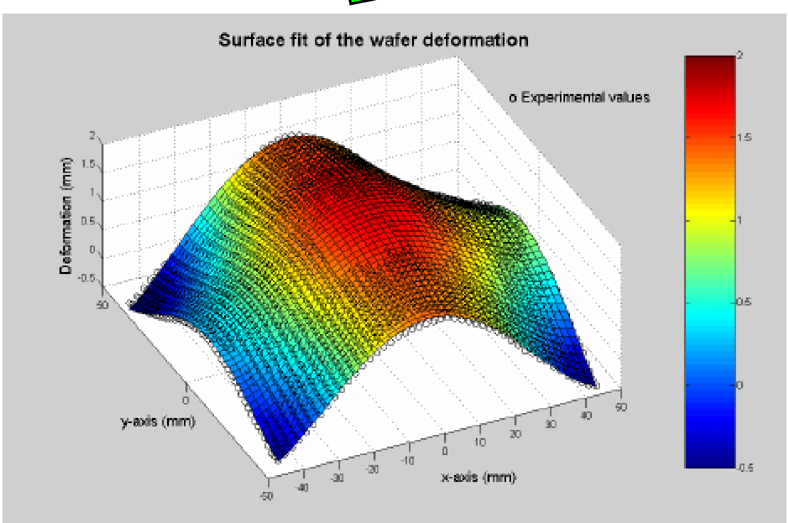

Brun and Melkote, 2006 Int. Symposium on Flexible Automation, Osaka, Japan

# Accomplishments: Handling

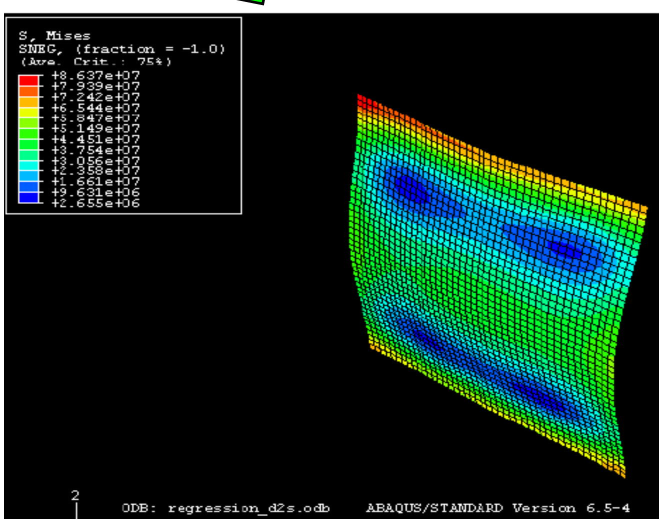
- Developed method to calculate handling stresses from measured wafer deformation and finite element analysis.




Brun and Melkote, 2006 IEEE WCPEC, Hawaii




*Measured EFG Wafer Deformation*




*Calculated Wafer Handling Stresses*

# Accomplishments: Handling

- Developed method to predict wafer deformation and stresses from predicted gripper pressure distribution due to Bernoulli effect.

**-Volumetric flow air**
**-Gripper geometry**

⇩

**Pressure distribution model**

$$p(r) - p_a = \frac{1}{2}\rho\left(v_0{}^2 - v(r)^2\right) + Ef(r)$$

$$dEf(r) = \frac{2\rho f(r) v(r)^2}{de(r)} dr$$

$$\frac{fR}{24} \approx \sqrt{1+\left(\frac{K}{\bar{r}}\right)^2}$$

⇩

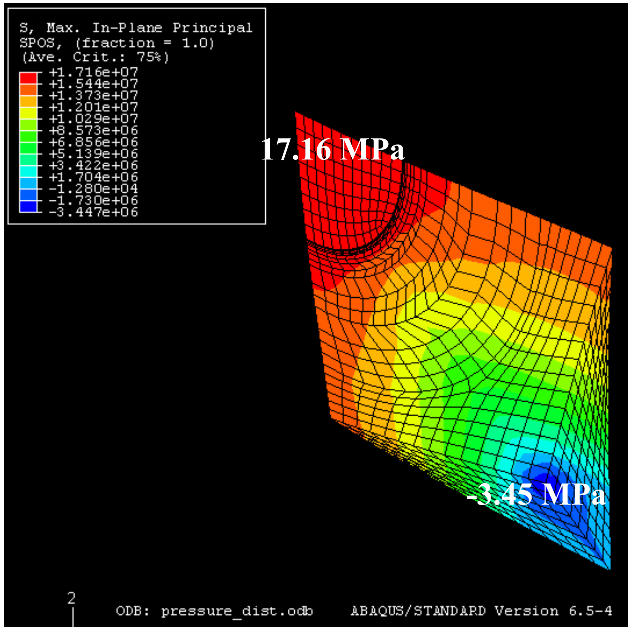
**-Pressure distribution**
**-Wafer characteristics**

⇩

**Finite Element model**

⇩

**-Wafer deformation**
**-Handling stresses**

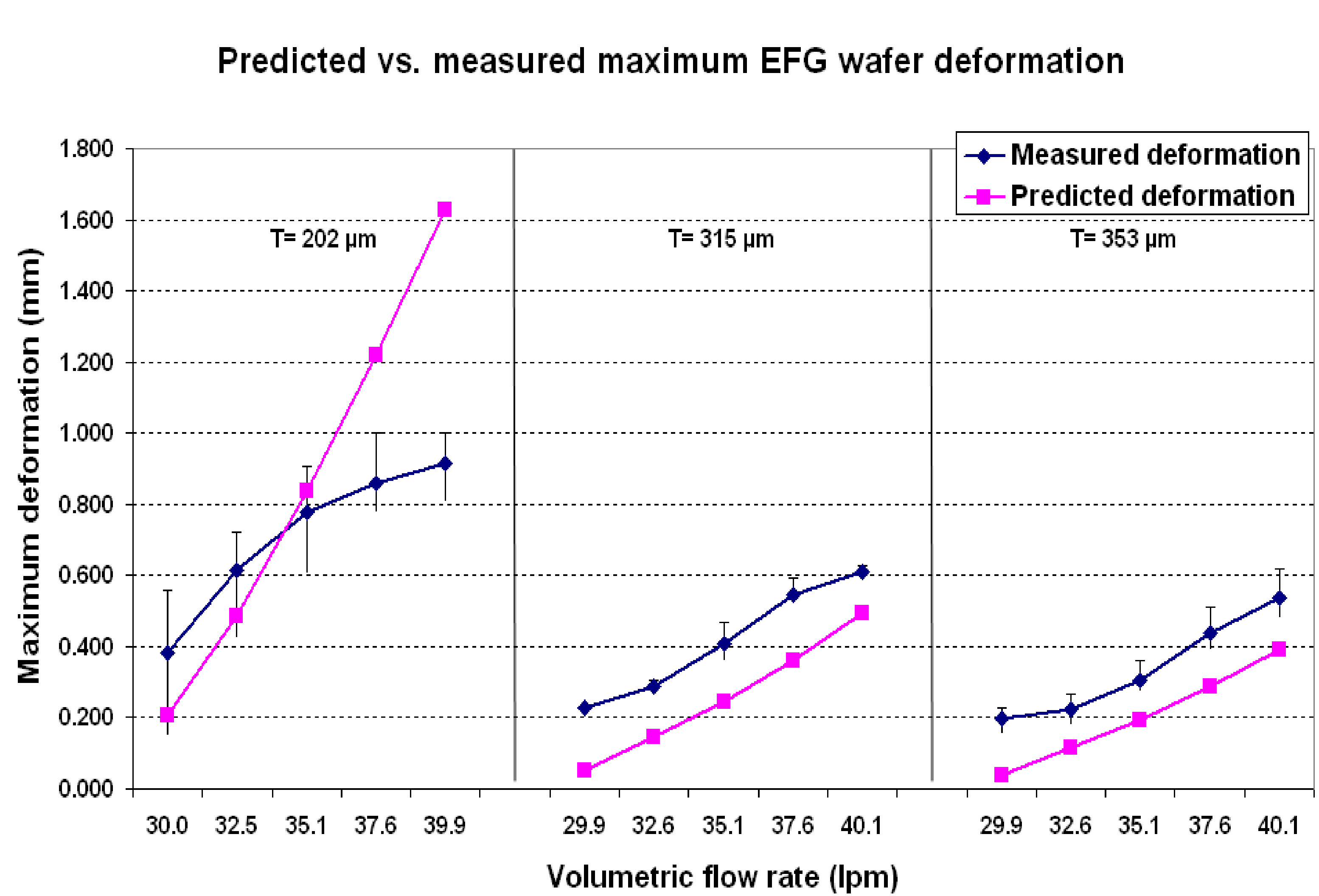



Predicted max. in-plane principal stress in 202 µm EFG wafer @ 35 lpm

Brun and Melkote, 2006 Int. Symposium on Flexible Automation, Osaka, Japan

# Accomplishments: Handling

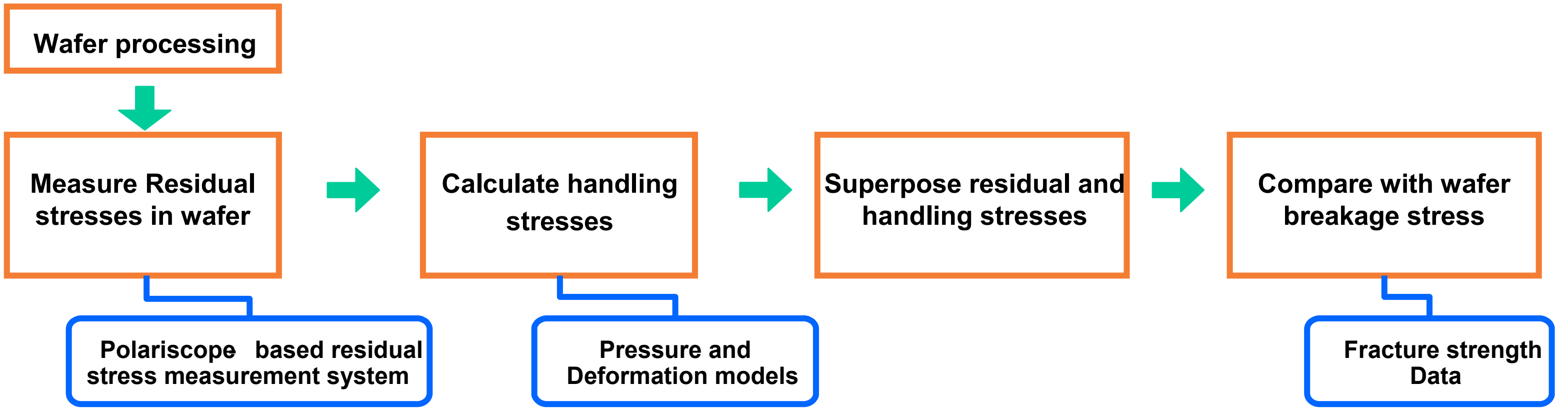
- Experimental validation of predicted wafer deformation due to handling forces.




Brun and Melkote, 2006 Int. Symposium on Flexible Automation, Osaka, Japan

# Future Work: Handling

- Future work will focus on the following:
  - Experimental verification and refinement of wafer pressure distribution model (from Bernoulli effect).
  - Determine fracture strength of mc-Si wafers as a function of thickness.
  - Analyze role of wafer residual stress on fracture due to handling stresses.
  - Work with industry sponsors on their thin wafer handling needs.



# Process Monitoring

- The object of this task is to research, develop and implement a standards-based information technology framework to lower the cost of photovoltaic manufacturing.

## Implementation of CAMX Technologies

- Utilization of CAMX with the Adept robot of equipment status, position, and activity.
- Utilized Microsoft's new Visual Studio 2.0 to accomplish serial communications.
- GT FIS CAMX Monitor illustrated robot Metrics during live demos.

# Summary of Activities: Process Monitoring

## Factory Level Activities

- Enhanced the display of measurements and increased flexibility of the user interface.
- Simulation of a PV line was accomplished.
- GT FIS showed RWE-Schott Solar a live CAMX pilot in process at a facility nearby.

# Summary of Activities: Process Monitoring

## FIS and NREL Exchange

- GT FIS working with NREL to develop a CAMX Industry Standard strategy.
- Weekly FIS and NREL conference calls to facilitate NREL Activities
- Provided NREL with a CAMX API which they demonstrated to various parties.

# Accomplishments: Process Monitoring

- The CAMX (Computer Aided Manufacturing using XML) has been implemented at Georgia Tech's Advanced Photovoltaic Manufacturing Laboratory. CAMX was developed for the electronics manufacturing industry whose needs are similar to PV manufacturers.
- The CAMX framework installed at Georgia Tech is capable of collecting manufacturing data from PV equipment and displaying compiled information through a web based interface.
- The information content definitions of the CAMX framework is being extended to meet the specific needs of the PV industry.

# Future Work: Process Monitoring

- The CAMX framework will be expanded and extended to accommodate the needs of photovoltaic manufacturers. Some of the specifics include the following:
  - New schemas will be developed to define data structures need to transfer information specific to the PV industry.
  - Additional web interfaces will be developed to more clearly display manufacturing information.
  - Methods to reduce costs by application of the framework will be investigated and implemented.
- Additional technology transfer activities will be undertaken with industry. Examples include: proposal submission, joint technology development, factory pilots and embedding technology into manufacturing equipment.

# Summary of Industry Interactions

- Industry current and next-generation manufacturing needs survey (Dec.-Jan. 2006)
  - Participants: AKT/Applied Materials, Spire Solar, Manz Automation, RENA, OTB Solar, Xerox PARC, NPC, GT Equip., BP Solar, Advent, Schott Solar
- PV Equipment Manufacturers workshop held at GT/MARC
  - Participants: AKT/Applied Materials, Spire Solar, Manz Automation, OTB Solar, ATS, GT Equipment
- Industry support received for project activities
  - RWE Schott Solar - \$55K, EFG wafers
  - BP Solar - \$10K, Wafers for stress measurement
  - Manz Automation – \$6.5K, Bernoulli grippers, thin wafers (160 μm)
  - OTB Solar – Low pressure gripper, \$40-50K project under discussion

# Summary

- Project has resulted in new developments in:
  - residual stress measurement in silicon wafers
  - analysis of deformation and stresses in thin wafer handling using Bernoulli grippers
  - CAMX-based process monitoring technology implemented on wafer handling robot in PV lab