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Strength of Si Wafers with Microcracks: A Theoretical Model

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Introduction

- **Production yield losses** resulting from wafer breakage can be as high as 5%–10% in a typical manufacturing facility.

- **Fracture strength becomes even more important** when the new thinner and large-area wafers are manufactured.

- **To successfully reduce silicon usage** and maintain high production yield, one needs to understand the fracture behavior of silicon wafers.

Objective

Develop model for the strength of photovoltaic (PV) wafers.

- Analytical description
- Numerical simulation

Identify the features which limit the wafer strength

- Effect of micro-cracks generated during wafer sawing

Optimize handling and processing to improve production yield

- How to increase wafer strength?
- How to handle fragile wafers?

Classical strength modeling Weibull distribution

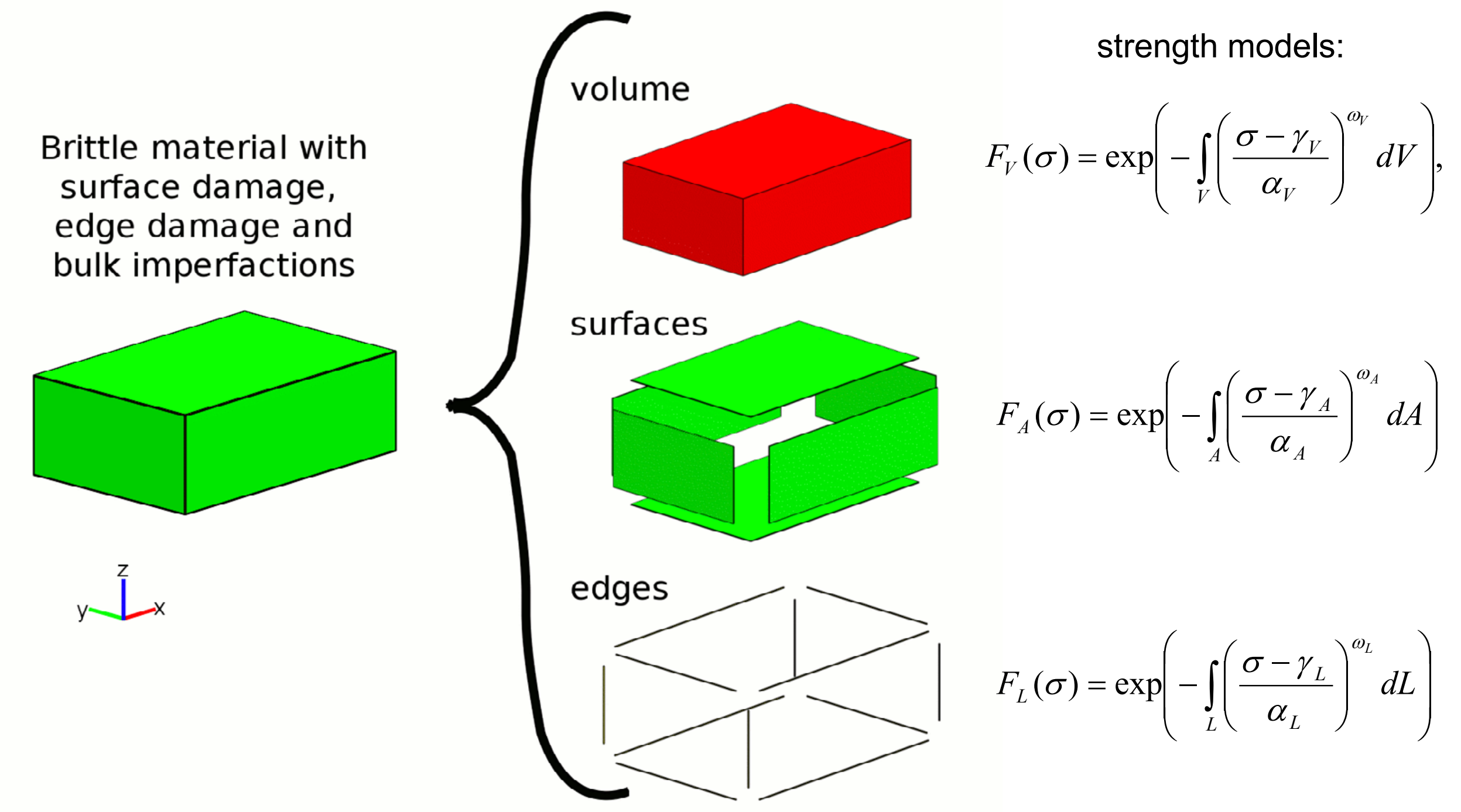
Classical Weibull equation describes the probability $F_V(\sigma)$ that the brittle specimen survives load σ:

$$F_V(\sigma) = \exp\left(-\int_V \left(\frac{\sigma - \gamma_V}{\alpha_V}\right)^{\omega_V} dV\right),$$

where γ_V, α_V, and ω_V are the three parameters of the Weibull distribution.

In the case of the multiaxial stress state, σ represents position-dependent effective stress.

Decomposition into three modes of failure



$$F_V(\sigma) = \exp\left(-\int_V \left(\frac{\sigma - \gamma_V}{\alpha_V}\right)^{\omega_V} dV\right),$$

$$F_A(\sigma) = \exp\left(-\int_A \left(\frac{\sigma - \gamma_A}{\alpha_A}\right)^{\omega_A} dA\right)$$

$$F_L(\sigma) = \exp\left(-\int_L \left(\frac{\sigma - \gamma_L}{\alpha_L}\right)^{\omega_L} dL\right)$$

General strength model

The weakest-link yields the effective probability of survival for the entire brittle specimen with bulk, surface and edge imperfections as:

$$F(\sigma) = F_V(\sigma) \cdot F_A(\sigma) \cdot F_L(\sigma)$$

or:

$$F(\sigma) = \exp\left[-\int_V \left(\frac{\sigma - \gamma_V}{\alpha_V}\right)^{\omega_V} dV - \int_A \left(\frac{\sigma - \gamma_A}{\alpha_A}\right)^{\omega_A} dA - \int_L \left(\frac{\sigma - \gamma_L}{\alpha_L}\right)^{\omega_L} dL\right]$$

How to predict the Weibull parameters?
How to calculate the effective stress?

Cast unpolished PV wafer specific conditions

- Silicon wafers are manufactured by casting of a multicrystalline silicon (mc-Si) ingot followed block cutting, wafer sawing and etching.
- The material removal during sawing can be regarded as a series of micro-indentations that lead to subsurface microcracking.
- The surface of a post-sawn wafer contains deep subsurface damage (micro-cracks 10–70 μm deep).
- Etching does not remove the entire layer with the sawing damage.
- Due to the large surface area and relatively small volume, the volume failure mode can be neglected.
- If blocks are polished before slicing then the edge failure mode can be also neglected.

Monte Carlo simulation for strength of PV wafer

Calculation procedure:

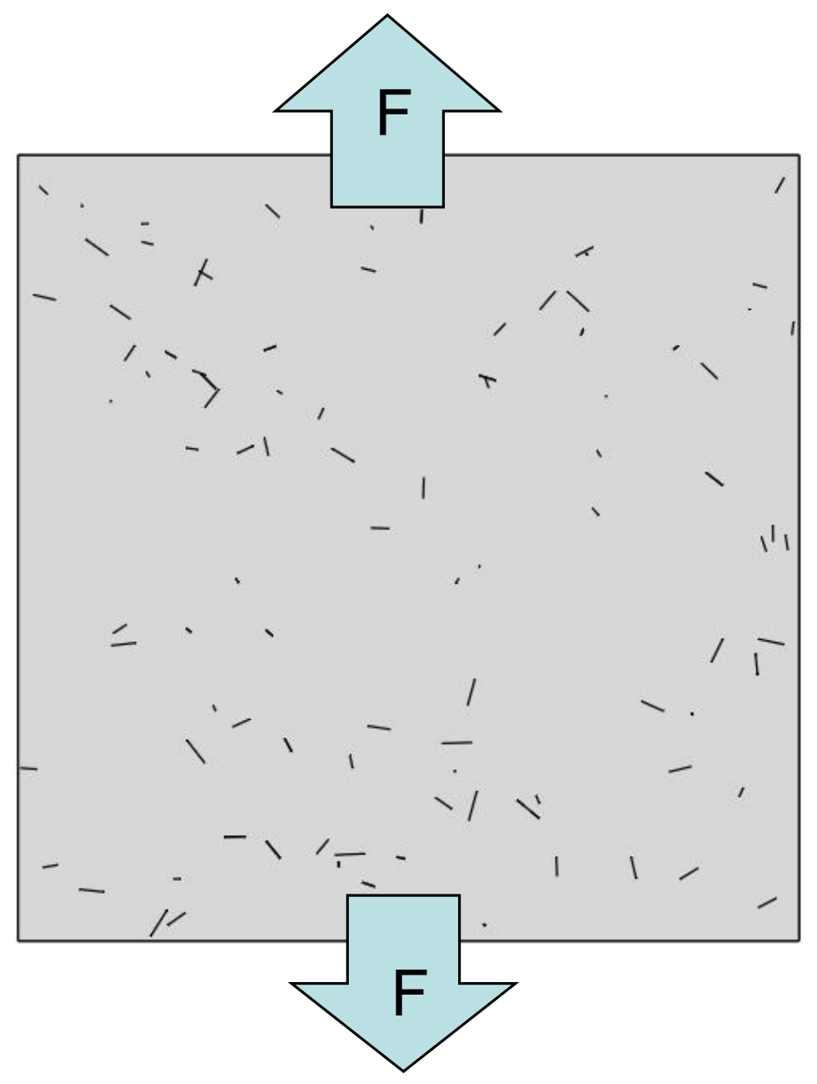
1. We generate a set of 100 virtual wafers. Each wafer contains 100 randomly distributed and oriented surface cracks.
2. The maximum load for each wafer is calculated using the fracture-mechanics methods and the weakest-link principle.
3. Statistical analyses of the results for all 100 wafers are performed to obtain the strength distribution.
4. We determine if the Weibull distribution can accurately fit the obtained results

Monte Carlo simulation assumptions

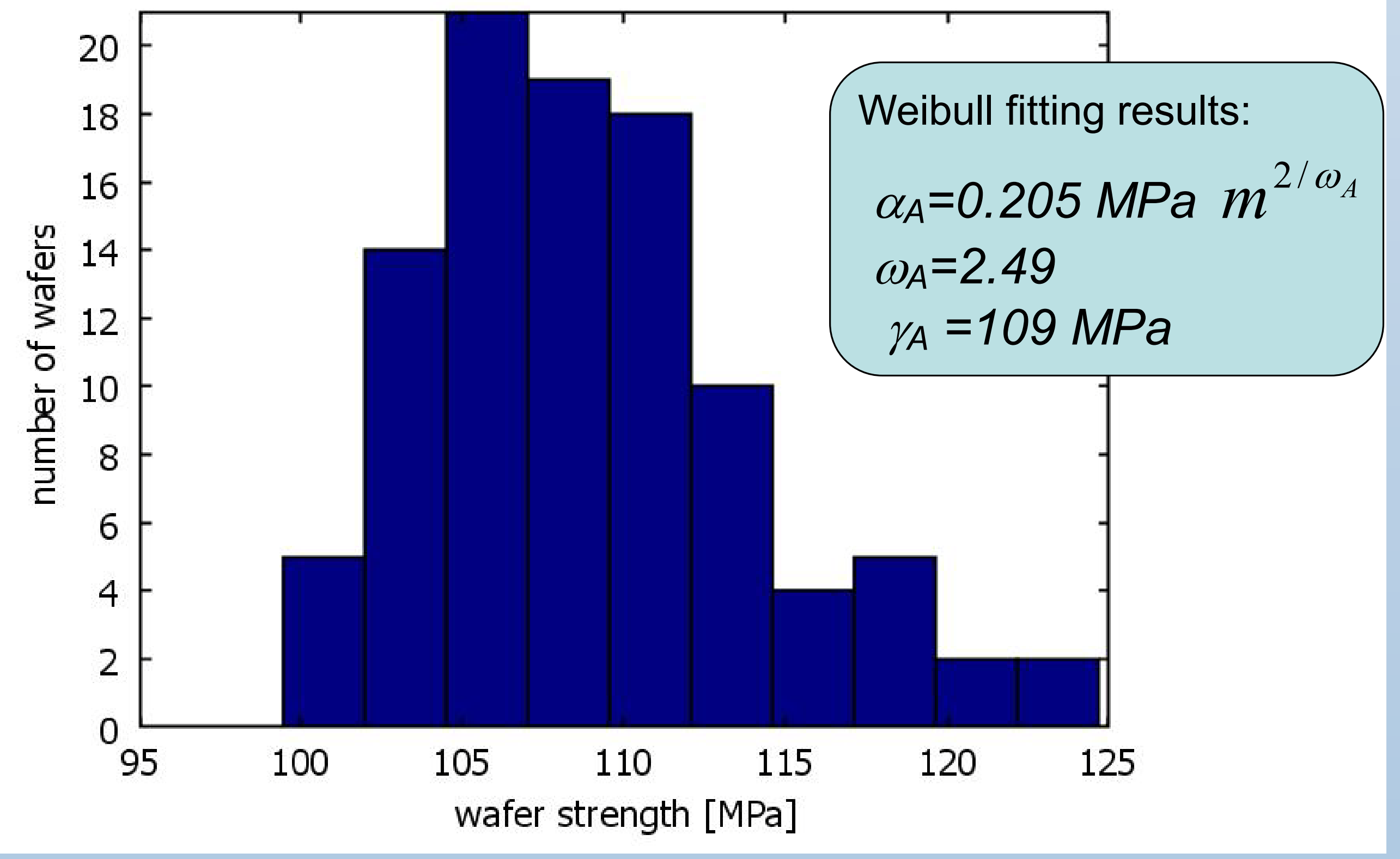
An example of 5" x 5" wafer with surface micro-cracks is shown. For the sake of legibility, the cracks are magnified 20 times in the figure. In our example the wafers were subjected to uni-axial tension.

Assumptions:

a) γ_0 for Si equals 2.47 J/m^2
b) density of cracks is 0.32/cm^2
c) semi-elliptical shape of cracks
d) crack plane is perpendicular to the wafer surface
e) cracks length varies from 0 to 20 μm and the depth up to 200 μm
f) wafer fractures once a single crack starts to propagate
g) cracks do not interact neither with the edge nor with other cracks



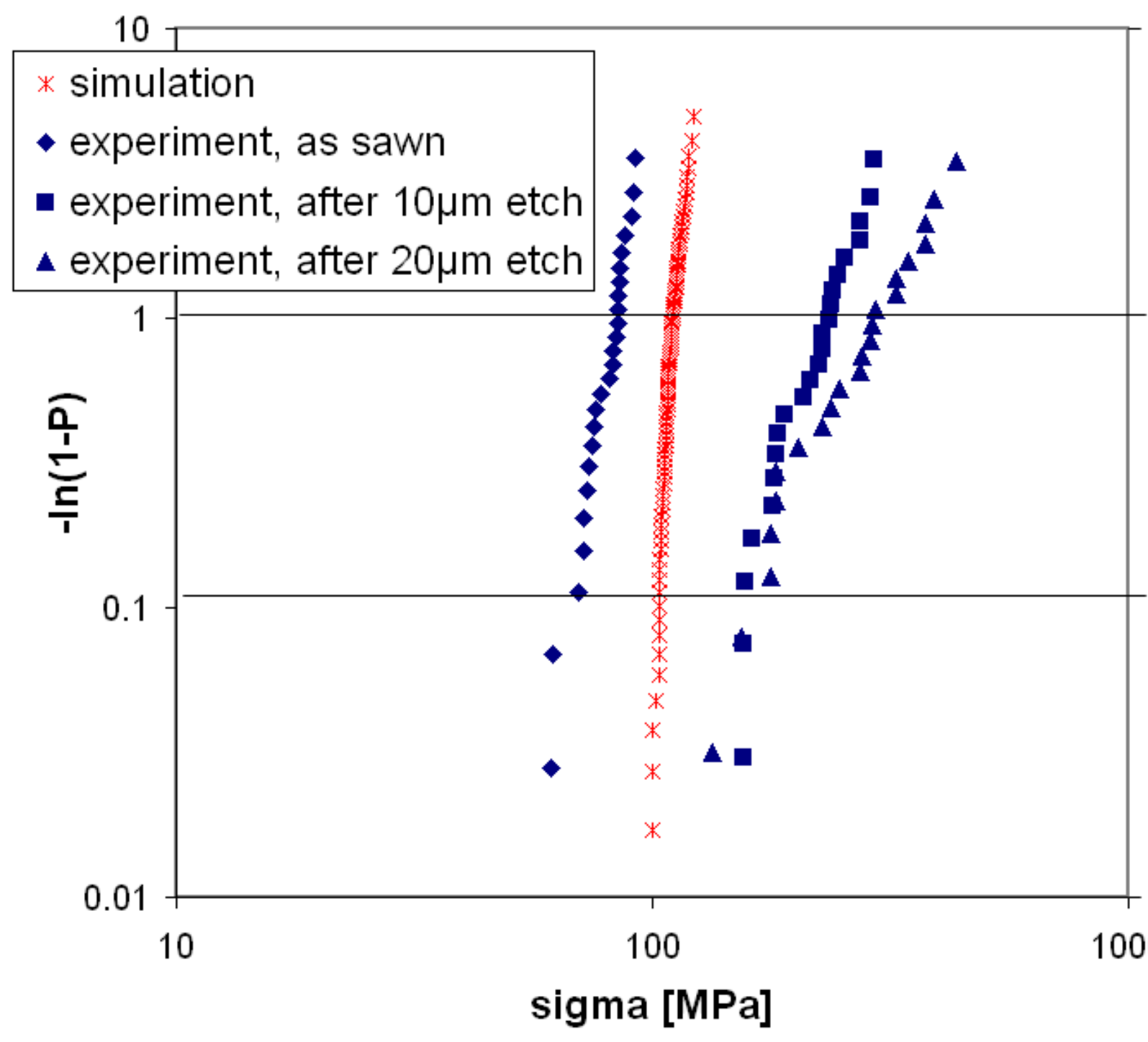
Monte Carlo simulation results



Weibull fitting results:

α_A=0.205 MPa m^{2/ω_A}
ω_A=2.49
γ_A =109 MPa

Comparison with experiment



Experimental data were take from:

[1] C. Funke, E. Kullig, M. Kuna, and H. J. Möller, "Biaxial fracture Test of Silicon Wafers," *Advanced Engineering Materials,* vol. **6**, pp. 594-598, 2004.

[2] H. J. Möller, C. Funke, M. Rinio, and S. Scholz, "Multicrystalline silicon for solar cells," *Thin Solid Films,* vol. **487**, pp. 179-187, 2005.

Discussion

- In our virtual experiment, the strength of wafers varied from 100 to 125 MPa
- The most probable strength value was 106 MPa.
- The obtained distribution can be accurately fitted by the Weibull equation.
- The predicted distribution compares well with the available experimental results from the literature.
- The strength distribution predicted in this study fits between experimental distributions for the as-sawn and 5-μm etched wafers.

Conclusions and Acknowledgments

1) A new analytical expression that takes into account the surface, edge, and bulk properties of a wafer has been proposed to describe the strength of the brittle materials.
2) A new proposed fracture-mechanics numerical simulation successfully predicted the strength of the cast silicon wafers.
3) It has been shown that the predicted wafer strength distribution agrees well with the available experimental results.

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