STRESS IN SU-8 PHOTORESIST FILMS: DOE APPROACH

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Overview

- Motivation
- Introduction
- Theory - Negative Photoresist
- Deposition Process
- Experimental Design
- Results and Analysis
- Conclusions
- Future Work
SU-8 Photoresist is a common structural material for MEMS devices

**Advantages:** Biocompatibility, structural stability, chemically inert, lithographically patternable, low elastic modulus, hydrophobic

[1] [2]
Cracking or delamination due to the residual stress induced in the PR film material

Might degrade the performance of the fabricated device significantly

A thorough understanding and process optimization is necessary to tackle the problem
Theory- Negative Photo Resist

- Epoxy based, Negative tone PR
- *PAG compound* (triarylsulfoniumhexafluoroantimonate), *EPON SU8 epoxy* (highly functionalized with 8 epoxy groups), *solvent* (*γ*-Butyrolacton)
- Cationic process is induced by *PAG compound* during UV illumination (PEB also accelerates the chemical reaction)
Theory - Residual Stress

- Intrinsic and Extrinsic stress
  
**Intrinsic stress:** mostly generated during crosslinking due to the confinement of the monomers in the polymer matrix.

Evaporation of solvent, loss of mass also result in intrinsic stress.

**Extrinsic stress:** involves the stress induced due to CTE mismatch (Si substrate and SU-8)

\[
\sigma_{th} = (\alpha_{SU8} - \alpha_{Si}) \frac{E_{SU8}}{1 - \nu_{SU8}} (T_{PEB} - T_o)
\]

- \(\alpha\): CTE of the material
- \(\sigma_{th}\): Induced thermal stress
- \(E_{SU8}\): Young’s modulus
- \(T_{PEB}\): PEB Temp
- \(T_o\): Ambient Temp
Theory - Residual Stress

- **Stoney’s Equation**

\[
\sigma = \frac{1}{6} \left( \frac{1}{R_{\text{post}}} - \frac{1}{R_{\text{pre}}} \right) \frac{E}{(1-\nu)} \left( \frac{ts}{tf} \right)^2, \quad \text{Height} = \left[ \frac{(\text{Wafer dia})^2}{2R} \right]
\]

- \(\sigma\): stress in the film, after deposition
- \(R_{\text{pre}}\): substrate radius of curvature before deposition
- \(R_{\text{post}}\): substrate radius of curvature after deposition
- \(E\): Young’s modulus
- \(\nu\): Poisson’s ratio
- \(ts\): substrate thickness
- \(tf\): film thickness

| E = 130 GPa |
| \(\nu = 0.279\) |
| \(ts = 650 \mu m\) |
SU-8 Photoresist Depositon Process

1) Substrate Preparation
   ▶ Clean 6” [100] wafers.
   ▶ No dehydration bake done.

2) Manual Spin Coat
   ▶ Tool: SCS Resist Coater
   ▶ Recipe: Two ramped levels rpm.

3) Post Application Bake (PAB)
   ▶ Tool: Hot Plate
   ▶ Recipe: Constant temperature.

4) Exposure
   ▶ Tool: Karl Suss MA150 Contact Aligner
   ▶ Recipe: Flood exposure with I-line.

5) Post Exposure Bake (PEB)
   ▶ Tool: Hot Plate
   ▶ Recipe: Constant temperature.

6) Development
   ▶ Tool: Wet Chemistry
   ▶ Recipe: PGMEA Puddle,
             IPA rinse,
             DI water rinse.
   Repeat if scrumming is visible.

7) Hard Bake (HB)
   ▶ Tool: Hot Plate
   ▶ Recipe: Constant temperature.

Images Obtained From http://wiki.smfl.rit.edu
Gathering Information

- Need to gain knowledge of the fabrication process.
- Used a set of suggested processing guidelines and ran a test process.
- Test process provides knowledge to help answer:
  - What factors are required?
  - Which factors are controllable?
  - What are the sources of noise?
Factors

<table>
<thead>
<tr>
<th>Factors to Control</th>
<th>Factors to be Fixed</th>
<th>Possible Noise Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>□ RPM of spin coating</td>
<td>□ Quantity of resist</td>
<td>□ Ambient temp. and humidity</td>
</tr>
<tr>
<td>□ PAB time</td>
<td>□ Spin time</td>
<td>□ Hot plate temp. variation</td>
</tr>
<tr>
<td>□ Exposure dose</td>
<td>□ PAB temp.</td>
<td>□ Contamination</td>
</tr>
<tr>
<td>□ PEB temp.</td>
<td>□ Quantity of developer</td>
<td>□ Measurement noise</td>
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<tr>
<td>□ PEB time</td>
<td>□ Development time</td>
<td></td>
</tr>
<tr>
<td>□ Hard Bake (HB) temp.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>□ HB time</td>
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</tbody>
</table>

Possible Noise Factors:

- Ambient temp. and humidity
- Hot plate temp. variation
- Contamination
- Measurement noise
Goal and Objective

Goal

To minimize the residual stress in a film of SU-8 photoresist spin coated onto a bare silicon substrate.

Objective

To test the hypothesis that residual stress in a spin coated film of SU-8 photoresist onto a bare silicon substrate is a function of

- RPM
- PAB Time
- Exposure Dose
- PEB Temp
- PEB Time
- HB Temp
- HB Time
Fractional Factorial Design ($2^{k-p}$)

- Number of Factors $k=7$
- Fraction: $1/8$ $p=3$
- Number of Center Points 3
- Number of Treatment Combinations $n = 19$ (Full Factorial = 131)
- Generators
  - $E \approx ABC$  $F \approx BCD$  $G \approx ACD$
- Defining Contrast
  - $1 \approx ABCE, BCDF, ACDG, ADEF, BDEG, ABFG, CEFG$
- Confounding Pattern
  - $AB \approx CE, FG$  $AF \approx DE, BG$
  - $AC \approx BE, DG$  $AG \approx BF, CD$
  - $AD \approx EF, CG$  $BD \approx CF, EG$
  - $AE \approx DF, BC$

Factor Mapping

- A – HB Temp
- B – PEB Time
- C – Dose
- D – RPM
- E – HB Time
- F – PEB Time
- G – PAB Time

* If A and B are found to not interact: DG, DF, DE, and CD will be free of confounding
**Factor Levels**

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<th>TC Name</th>
<th>Factor</th>
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<th>High Level</th>
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<tr>
<td>A</td>
<td>HB Temp</td>
<td>175 ºC</td>
<td>225 ºC</td>
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<tr>
<td>B</td>
<td>PEB Temp</td>
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<tr>
<td>C</td>
<td>Dose</td>
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<tr>
<td>D</td>
<td>RPM</td>
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<tr>
<td>F</td>
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<td>G</td>
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- 1500 rpm was originally used
  - Thickness of the resist caused poor uniformity (expired material)
  - High spin coat rpm was needed.
## Results

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</table>
Analysis - Stress After Hard Bake

Main and 2-Factor
- Nothing Appears to be Significant.
- Possibly HB Temp

Main Factors Only
- HB Temp is the only significant effect.
Analysis - Stress After Development

**Main and 2-Factor**

- $\alpha = 0.05$
  - Dose
- $\alpha = 0.10$
  - Dose, PEB Temp*Dose, PEB Time
- $\alpha = 0.15$
  - Dose, PEB Temp * Dose, PEB Time, Dose * PEB Time

**Significant Factors**

- $\alpha = 0.05$
  - Dose
  - PEB Time
  - PEB Temp*Dose
  - Dose * PEB Time
Analysis – Model (Development)

- Model is significant and of good fit

<table>
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<tr>
<th>Source</th>
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<th>F Ratio</th>
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<td>4.5118750</td>
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Max R² = 0.7915

- Leverage plot show effects and significance
Confounding in significant effects
- HB Temp * HB Time ≈ RPM * PEB Time, PEB Temp * Dose
- PEB Temp * RPM ≈ Dose * PEB Time, HB Time * PAB Time

No hard bake (Stress After Development)

Based on prior knowledge, exposure and PEB should have an effect on stress due to shrinking caused by cross linking.

Assuming above is true, confounded is resolved as:
- PEB Temp * Dose
- Dose * PEB Time
Analysis – Estimate of Response

Estimate of Stress in design units

\[ \hat{Y} = -6.83 - 0.77 * \text{Dose} - 0.41 * \text{PEB Time} - 0.37 * \text{RPM} * \text{PEB Time} - 0.34 * \text{HB Time} * \text{PAB Time} \]

Optimum Factor Levels (Within high/low bounds)

- *RPM = 2000
- *PAB Time = 2 minutes
- Dose = 110 mJ/cm²
- PEB Temp = 90 °C
- PEB time = 3 minutes
- *HB temp = 175 °C
- *HB time = 10 minutes

\[ \hat{Y} = -4.93 \text{MPa} \]

* Not used in the model equation, values set to minimum for conversation of time and energy.
Conclusion

- Unable to properly model stress after Hard Bake.
  - More knowledge is required on this processing step.
- Model was found for stress after development.
- Not all factors were found to be significant.
  - Dose, PEB Time, PEB Temp*Dose, Dose * PEB Time
  - Deconfounding of 2-factor effects is needed.
- From model and provided bounds
  - Minimum Stress -4.93 MPa
  - Larger bounds could yield lower stresses.
- Goal cannot be accessed without additional wafer to be processed.
- SU-8 is a very thick resist and challenging to work with.
Future Work

- Non-expired resist, wafers from the same batch
- Creating energy based factors i.e. Time*Temperature
- Processing the wafer with an optimum settings and measure the residual stress
- Running additional alpha start points to increase the levels and the range of the effects
- Fabrication of a test structure i.e. microcantilever, guckel rings in order to observe the residual stress effects
References


