Materials Characterization for Stress Management

Ehrenfried Zschech, Fraunhofer IZFP Dresden, Germany

Workshop on Stress Management for 3D ICs using TSVs

San Francisco/CA, July 13, 2010
Outline

- Stress management in complex systems: The need of multi-scale materials characterization
- Materials parameters database
- Device strain measurements for model validation / calibration
- Interaction modeling / simulation – multi-scale materials data
Outline

- Stress management in complex systems: The need of multi-scale materials characterization
- Materials parameters database
- Device strain measurements for model validation / calibration
- Interaction modeling / simulation – multi-scale materials data
Materials data, techniques and validation

Questions to be answered:

- Which DATA is needed, what needs to be measured?
- Which CHARACTERIZATION TECHNIQUES are needed?
- Which VALIDATION is needed?
Stress engineering for 3D TSV-based technology *

Chip Performance

- FET stress engineering vs. 3D IC integration impact (wafer thinning to some 10 μm, metal TSV, metal micro-bumps, ...)
- Effect of package-induced stress on transistor-to-transistor performance variation through variation in carrier mobility and threshold voltage (effect on device characteristics)
- Stress effect on leakage and power

Reliability

- 3D thermal and stress effects in electromigration and stress migration
- ILD/IMD cracking, delamination, etc.

* Particular integration scheme: “via-middle” (particularly sensitive to mechanical stress)
Potential EM and Reliability Issues With 3D Integration

Very thin active Si layer (10 – 140 nm for SOI wafer, 1-10 μm for bulk Si wafer)

Device reliability in the bonded and thinned active Si layer due to thermal-mechanical stress

Device degradation during 3D process

Via yielding and reliability due to thermal, mechanical, electrical stress

Wafer bond reliability

Via contact reliability

Yet to be explored!

- TSV electrical-magnetic performance
- Inter-strata electrical-magnetic, thermal-mechanical interferences

lui@rpi.edu
Multi-scale materials characterization

- Stress management in complex systems (packaged dies, 3D integration, etc.) requires multi-scale modeling and MULTI-SCALE CHARACTERIZATION.

- Local materials modifications require MULTI-SCALE CHARACTERIZATION.

  Example: Low-k/ultra low-k dielectrics
  1) E in IMD in dense OSG
  2) E in UV-cured porous OSG

- Analytical TECHNIQUES with different spatial resolution are needed.
Multi-scale materials mechanical characterization

**Scale**

10 mm | 1 mm | 1 µm | 1 nm
---|---|---|---

**Macro**
- Tensile tester
- Bending tester

**Micro**
- Micro-shear tester
- DMA
- 4P bending

**Nano**
- Nanoindenter
- AFAM
- Ultrasonic microscopy

- $E(T,t)$, CTE(T), Poisson(T), (visco)-plasticity, viscoelasticity
- geometry and microstructure dependency
Outline

- Stress management in complex systems: The need of multi-scale materials characterization
- Materials parameters database
- Device strain measurements for model validation / calibration
- Interaction modeling / simulation – multi-scale materials data
Materials parameters database

Materials parameters database is needed
  o as input for modeling / simulation
  o For each technology node (characterized by geometry, materials, strain, ...)

Multi-scale materials parameters are needed
  o for wafer-level materials
  o for packaging materials
## Materials for assembly and packaging

<table>
<thead>
<tr>
<th>Materials</th>
<th>Functionality</th>
<th>Chemical Compositions</th>
<th>Materials properties</th>
<th>Measurement techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interposer (organic PCB)</td>
<td>Chip carrier and electr. redistribution</td>
<td>Composit of epoxy polymer and glass fibers</td>
<td>E=f(T,t), CTE=f(T), Poisson=f(T)</td>
<td>DMA, bending test</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TMA, image correlation</td>
</tr>
<tr>
<td>Molding compound</td>
<td>Chip encapsulation, protector</td>
<td>Ceramics-filled epoxy polymer</td>
<td>E=f(T,t), K=(T,t), CTE=f(T), Poisson=f(T)</td>
<td>DMA, tensile tests, compression test</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TMA, image correlation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ultra sonic transmission microscopy</td>
</tr>
<tr>
<td>Solder balls</td>
<td>Electrical and mechanical connection</td>
<td>Sn-rich alloy (SnAg3.5, SnAgCuA_yB_z)</td>
<td>E=f(T), visco-plasticity CTE=f(T), Poisson=f(T)</td>
<td>Nanoindentation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>microstructure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>micro shear tester, tensile tester,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>image correlation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ultra sonic transmission microscopy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FIB-SEM, EBSD</td>
</tr>
<tr>
<td>Cu pillars</td>
<td>Electrical and mechanical connection</td>
<td>Electroplated Cu</td>
<td>E=f(T), Plasticity CTE=f(T), Poisson=f(T)</td>
<td>nanoindentation, tensile tests</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Image correlation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ultra sonic transmission microscopy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FIB/SEM, EBSD</td>
</tr>
<tr>
<td>Underfiller</td>
<td>Mechanical stabilization of joints</td>
<td>Epoxy resin (filled &amp; unfilled)</td>
<td>E=f(T,t), K=(T,t), CTE=f(T)</td>
<td>DMA, tensile tests, compression test</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TMA, image correlation</td>
</tr>
</tbody>
</table>
## Materials for wafer-level process

<table>
<thead>
<tr>
<th>Materials</th>
<th>Functionality</th>
<th>Chemical Compositions</th>
<th>Materials properties</th>
<th>Measurement techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungsten, Copper</td>
<td>Electrical wiring</td>
<td>W, Cu, Cu alloy</td>
<td>E, v CTE strain grain size, texture</td>
<td>Nanoindentation, AFAM X-ray reflectometry X-Ray diffraction Blanket films: XRD, Patterned structures: OIM (SEM, TEM)</td>
</tr>
<tr>
<td>ILD: SiO₂, low-k, ULK</td>
<td>Insulation</td>
<td>SiO₂-based, FSG, low-k, ULK (SiCOH)</td>
<td>E, v CTE adhesion</td>
<td>Nanoindentation, scratch test AFAM/FM-AFM, UFM X-ray reflectometry 4-point bending, DCB Ellipsometry, TEM-EELS</td>
</tr>
<tr>
<td>Silicide</td>
<td>Contact</td>
<td>NiSiₓ, NiSiₓAᵧ</td>
<td>E, v CTE</td>
<td>Nanoindentation, AFAM/FM-AFM X-ray reflectometry Ultra sonic transmission microscopy</td>
</tr>
<tr>
<td>Stress liner</td>
<td>Stress in channel</td>
<td>SiNₓ</td>
<td>E, v CTE strain</td>
<td>Nanoindentation X-ray reflectometry Blanket films: Wafer curvature</td>
</tr>
<tr>
<td>Passivation</td>
<td>Adhesion, etch stop, barrier</td>
<td>SiNₓCᵧ, SiNₓ</td>
<td>E, v CTE</td>
<td>Nanoindentation X-ray reflectometry</td>
</tr>
<tr>
<td>Si channel</td>
<td>FET channel</td>
<td>Si (in future Ge, III-V ?)</td>
<td>strain</td>
<td>TEM (NBED, DFEH), NanoRaman</td>
</tr>
</tbody>
</table>
Outline

- Stress management in complex systems: The need of multi-scale materials characterization
- Materials parameters database
- Device strain measurements for model validation/calibration
- Interaction modeling/simulation – multi-scale materials data
Validation/Calibration

- Electrical measurements: $I_{on}$, $V_t$, etc.
  - Fast & accurate measurements
  - Specially designed test-chip is needed
    - expensive & time consuming
  - Stress variation is not responsible for total variation in electrical characteristics.

Other sources of variability should be accounted:
- sub-wavelength lithography
- random dopant fluctuation
- temperature fluctuation, etc.

- Strain measurements inside transistor channel
  - Direct but time consuming measurements
  - No need in test chip
MOSFET cross-sections

NMOS

- NiSi
- Stress Memory
- electrons ➔ tensile

PMOS

- SiGe
- holes ➔ compressive
Strain analysis in Silicon

Wafer curvature: Stress = Force / Area (Stoney equation)

X-ray diffraction: Strain via lattice parameter changes (Bragg equation)

**TEM analysis:** Strain via lattice parameter changes (HRTEM, CBED, NBED, HoloDark)

Photoluminescence: Strain via band gap changes

Raman spectroscopy: Strain via lattice vibrations
High-Resolution TEM (HR-TEM)

Difficulties:
- Thin-film relaxation
- Insufficient precession due to missing unstrained reference
Dark-Field Electron Holography (DFEH)

Dark-Field Electron Holography (DFEH)

Bright-field TEM image

Dark-field hologram

Phase image

$\varepsilon_{xx}$ component of strain tensor

Experiment

Modeling

Electron Diffraction Techniques

Parallel Beam

Convergent Beam

SAD

C2 Aperture

Sample

Objective Plane

Back Focal Plane

CBED

High convergence

Nano Beam Electron Diffraction

[110]

high convergence

Small convergence 0.4 - 1.2 mrad
Beam size: 6-10nm

almost parallel

© Fraunhofer IZFP-D
Convergent Beam Electron Diffraction (CBED)

Line scan along z direction

<table>
<thead>
<tr>
<th>z (nm)</th>
<th>a (Å)</th>
<th>c (Å)</th>
<th>α (deg)</th>
<th>γ (deg)</th>
<th>ε_{xx} (%)</th>
<th>ε_{zz} (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-55</td>
<td>5.4271</td>
<td>5.4267</td>
<td>90.00</td>
<td>89.91</td>
<td>-0.15</td>
<td>-0.08</td>
</tr>
<tr>
<td>-40</td>
<td>5.4221</td>
<td>5.4279</td>
<td>90.00</td>
<td>89.83</td>
<td>-0.31</td>
<td>-0.06</td>
</tr>
<tr>
<td>-25</td>
<td>5.4155</td>
<td>5.4345</td>
<td>89.89</td>
<td>89.66</td>
<td>-0.58</td>
<td>+0.06</td>
</tr>
</tbody>
</table>

Nano Beam Electron Diffraction (NBED)

\[ \Delta x[880] \Rightarrow d[880] = \frac{1}{\Delta x[880]} \]

\[ \Delta x[008] \Rightarrow d[008] = \frac{1}{\Delta x[008]} \]

Lorentz fit of data
⇒ strain:

\[ \varepsilon[hkl] = \frac{d_{\text{strained}[hkl]} - d_{\text{unstrained}[hkl]}}{d_{\text{unstrained}[hkl]}} \]
Good reproducibility: strain values within ~ ±0.15 %

NBED results agree well with Raman results

Transistor channel region shows clearly compressive strain
## Characterization of various strain analysis techniques

<table>
<thead>
<tr>
<th>TEM Method</th>
<th>TEM Mode</th>
<th>Accuracy</th>
<th>Spatial Resolution</th>
<th>Field of View</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CBED</strong></td>
<td>Diffraction / Probe</td>
<td>2*10^-4</td>
<td>5 nm</td>
<td>n.a.</td>
</tr>
<tr>
<td><strong>NBED</strong></td>
<td>Diffraction / Probe</td>
<td>1*10^-3</td>
<td>10 nm</td>
<td>n.a.</td>
</tr>
<tr>
<td><strong>HRTEM</strong></td>
<td>Image</td>
<td>1*10^-3</td>
<td>2 nm</td>
<td>150 x 150 nm²</td>
</tr>
<tr>
<td><strong>DFEH</strong></td>
<td>Image</td>
<td>2*10^-4</td>
<td>4 nm</td>
<td>1500 x 400 nm²</td>
</tr>
</tbody>
</table>

Hýtch et al., IEDM (2009).
<table>
<thead>
<tr>
<th>TEM Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CBED</strong></td>
<td>High accuracy</td>
<td>Strong influence of sample bending</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strain mapping time consuming</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Modeling to assess strain relaxation</td>
</tr>
<tr>
<td><strong>NBED</strong></td>
<td>Suitable for Si bulk &amp; SOI substrates</td>
<td>Spatial resolution (improvement with probe Cs-corrector possible)</td>
</tr>
<tr>
<td></td>
<td>Applicable for thick lamellae (no stress relaxation)</td>
<td></td>
</tr>
<tr>
<td><strong>HRTEM</strong></td>
<td>High spatial resolution</td>
<td>Stress relaxation due to thin specimens</td>
</tr>
<tr>
<td></td>
<td>Continuous strain mapping</td>
<td>Limited application for SOI substrates</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Limited field of view</td>
</tr>
<tr>
<td><strong>DFEH (HoloDark)</strong></td>
<td>High accuracy</td>
<td>Modeling to assess strain relaxation</td>
</tr>
<tr>
<td></td>
<td>Large field of view</td>
<td>Limited application for SOI substrates</td>
</tr>
<tr>
<td></td>
<td>Continuous strain mapping</td>
<td>Highly advanced TEM setup (Holography + image Cs-corrector)</td>
</tr>
</tbody>
</table>
Model calibration / validation

Status for high-resolution techniques
... to determine strain in devices

- Only TEM techniques are able to characterize strain in silicon channels of devices (~ 10 nm dimension)
  - Nano Beam Electron Diffraction (NBED)
  - HoloDark (DFEH) technique (not for SOI !)

- NanoRaman spectroscopy is currently limited to 80…100nm spatial resolution
Outline

- Stress management in complex systems: The need of multi-scale materials characterization
- Materials parameters database
- Device strain measurements for model validation / calibration
- Interaction modeling / simulation – multi-scale materials data
Multi-scale modeling, characterization, materials data

Multi-scale modeling needs multi-scale materials data (sub-μm materials-data are dimension-dependent!)

Multi-scale materials data need analytical techniques with different levels of resolution (macro ➔ micro ➔ nano)