“Total Junction Metrology”

“... DHE is a powerful method for studying doping and activation processes.”
Micron Technology, Inc.
Agenda

- What is Needed?
- Capabilities and Advantages
- Analysis Procedure
- Data:
  - Comparison with SIMS, SRP and 4PP
- Defect Measure
- Strain Enhancement
Active/Junction Layer Parameters : What is Needed?

**CURRENT ANALYTICAL TECHNIQUES**

- Active Carrier profiles are modeled -
  - Combination of 4PP, SIMS, ThermaWave and Implant/Anneal Schedules
- No mobility data until devices are made
- Incomplete feedback on *Actual* Active Layer Characteristics

**WHAT IS NEEDED**

- Direct Measurements of the key parameters ($\rho$, $\mu$, and $n$)
- *High Resolution* Profile Steps
- Decisions about process lot that is based on *Actual* data
- Need for ALP, Inc. Differential Hall Effect Analytical Technique
ALP Differential Hall Effect (DHE) System

**ALP Unique Capabilities and Advantages:**

- Measurement Resolution ~ 3-5 Angstroms
- Room Temperature Process - No Thermal Steps required
- Clean Procedure - Compatible with Production Sequence
- Fully Automated Measurement Operation - Repeatability
- Direct measurement of $\mu$ and $\rho$ profiles along with $n$ profiles
DHE System - Analytical Process

- Process is divided into 2 parts that alternately steps rapidly through the junction:

- Controlled Step-wise Reduction of Active Layer Thickness

- Measurement is done

- Differential Hall Effect represents a unique analytical method

\[ n(x) = \frac{1}{\mu(x) \rho(x) q_{\text{electron}}} \]

Direct measurements
DHE System: Analytical Process

Each Step Yields: $R_s$ and $\mu$. All Measurements are In-Situ

- Electrical Contacts
- Material Removal
- Electrical Path

Activated Wafer Sample. Size currently ~15mm x 15mm

User Defined
Step-size
3-5 Angstrom +
ALP DHE System: PLAD Carrier Concentration

PLAD $B_2H_6$, 6kV/2e16, Annealed RTP: 995$^\circ$C/20s

SIMS

$B_{SS}: 1.8e20$

DHE

SRP

Native Ox

ALP DHE System: PLAD Mobility

PLAD $B_2H_6$, 6kV/2e16, Annealed RTP: 995°C/20s

DHE Avg. Hole: 1.4e15

DHE: Avg $\mu$: 48.5

Native Ox

$B_{ss}$: 1.8e20

ALP DHE System: PLAD Resistivity

PLAD $\text{B}_2\text{H}_6$, 6kV/2e16
Annealed RTP: 995ºC/20s

DHE Avg. Hole: 1.4e15

DHE Avg $\rho$: 0.0018
## ALP DHE System: 4PP Comparison

<table>
<thead>
<tr>
<th>Sample</th>
<th>4PP (Ω/sq)</th>
<th>DHE Rs (Ω/sq)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1C</td>
<td>128.98</td>
<td>129.33</td>
<td>+0.27 %</td>
</tr>
<tr>
<td>M2C</td>
<td>148.13</td>
<td>145.02</td>
<td>-2.1 %</td>
</tr>
<tr>
<td>M3C</td>
<td>161.52</td>
<td>157.89</td>
<td>-2.24 %</td>
</tr>
<tr>
<td>M5C</td>
<td>143.49</td>
<td>145.60</td>
<td>-1.47 %</td>
</tr>
</tbody>
</table>

- Difference is minimal from accepted 4PP standard
- Minor deviations result from contact variation
Defect Measure

- Measure of deviation of the measure (DHE Drift Mobility) from the ideal (ASTM derived mobility). Presence of lattice damage.

- Matthiessen’s Rule:

\[
\frac{1}{\mu} = \frac{1}{\mu_{\text{impurities}}} + \frac{1}{\mu_{\text{lattice}}} + \frac{1}{\mu_{\text{defects}}} \ldots
\]

Subtracting the ideal (ASTM, defect-free, strain-free),

\[
\frac{1}{\mu_{\text{Measured}}} - \frac{1}{\mu_{\text{Ideal}}} = \frac{1}{\mu_{\text{defects}}}
\]

=0, for Ideal
Defect Measure

Defect Analysis:

\[
\frac{1}{\mu_{\text{Measured}}} - \frac{1}{\mu_{\text{Ideal}}} = 0 \quad \text{IDEAL}
\]

\[
\frac{1}{\mu_{\text{Measured}}} - \frac{1}{\mu_{\text{Ideal}}} > 0 \quad \text{DEFECT DOMINATED}
\]
Defect Measure: Dependencies

- Most specimens indicated significant scatter defect contributions
- Occasionally specimens were found with zero scatter defects
- Factors which affected scatter defect contributions:
  1. Type of Implant (e.g. BL, PLAD, Cluster)
  2. Implant Energy and Dose
  3. Type of Anneal
  4. Anneal Temperature and Time
Defect Measure: Concentration Dependence

Scatter Defects (Beamline, Implant Density)

\[
\frac{1}{\mu_{\text{defects}}} \quad \text{(V-s/cm}^2) \\
\]

- 4E15 B
- 2E15 B
- 1E15 B
- 5E14 B

Depth (Å)

With Dr. Onoda, Nissin Ion
Defect Measure: Implant-Type Dependence

Scatter Defects, Implant type

- HE Beamline B11
- PIII B2H6
- LE Beamline BF2
- Cluster B18H11

\[ \frac{1}{\mu_{\text{defects}}} (\text{V-s/cm}^2) \]

Depth (Å)
Defect Measure: Pre-Implant Dependence

- Effect of a Carbon pre-implant [Excess Scatter Defects] JTG 2011

With Dr. Onoda, Nissin Ion
ALP DHE System: PLAD Vs BeamLine

“ Scatter Defects strongly correlate to the implant ion spece atomic mass unit and energy ”

<table>
<thead>
<tr>
<th>Implant Type</th>
<th>Energy/ Dose [eV/cm²]</th>
<th>RTP/spike</th>
<th>DHE Surface Defect $1/\mu_{DEF}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BL B</td>
<td>500/1E15</td>
<td>1000°C</td>
<td>0.013</td>
</tr>
<tr>
<td>PLAD B2H6</td>
<td>1.2k/5E15</td>
<td>1000°C</td>
<td>0.000</td>
</tr>
<tr>
<td>BL B18H22</td>
<td>10k/5.56E13</td>
<td>1000°C</td>
<td>0.050</td>
</tr>
<tr>
<td>PLAD BF3</td>
<td>1.7k/4E15</td>
<td>1000°C</td>
<td>0.000</td>
</tr>
</tbody>
</table>

$X_j$ Approx. 25nm for all samples

ALP DHE System: Defect Analysis
ALP DHE System: Defect Analysis

- Higher Activation for PLAD Vs Beamline ~17%
- $R_s/\rho$ is ~14% lower for PLAD Vs than Beamline
- PLAD Mobilities are higher near the surface
ALP DHE System: Beamline Vs PLAD Device Data

- Devices were fabricated and tested by Micron Technology, Inc. (W/L=100)

- Higher Transconductance (⇒ higher $I_{DS}$) $\uparrow$ 16% - 30%  
  Lower Scattering Defects + Better Activation

- Lower $V_T$ $\downarrow$ ~3% -16%  
  Better Activation, Lower $\rho$

- Lower $R_s$ $\downarrow$ ~14%  
  Lower $R_{cs}$ $\downarrow$ ~50%  
  Better Surface Film Activation

- Quantitative DHE Analysis CAN be used to get device performance

Defect Measure: Strain-Enhancement

- Strain may be biaxially compressive or tensile
- Generally beneficial
- Modifying Defect Measure,

\[
\frac{1}{\mu_{\text{Measured}}} - \frac{1}{\mu_{\text{Ideal}}} = \frac{1}{\mu_{\text{defects}}} - \frac{1}{\mu_{\text{strain}}}
\]

<table>
<thead>
<tr>
<th>Element</th>
<th>Radius (A)</th>
<th>Element</th>
<th>Radius(A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.77</td>
<td>As</td>
<td>1.21</td>
</tr>
<tr>
<td>B</td>
<td>0.84</td>
<td>Ge</td>
<td>1.22</td>
</tr>
<tr>
<td>P</td>
<td>1.1</td>
<td>Sn</td>
<td>1.4</td>
</tr>
<tr>
<td>Si</td>
<td><strong>1.17</strong></td>
<td>Sb</td>
<td>1.41</td>
</tr>
</tbody>
</table>
Defect Measure

- Defect and Strain-Effect Analysis:

\[
\frac{1}{\mu_{\text{Measured}}} - \frac{1}{\mu_{\text{Ideal}}} = 0 \quad \Rightarrow \quad \text{IDEAL}
\]

\[
\frac{1}{\mu_{\text{Measured}}} - \frac{1}{\mu_{\text{Ideal}}} > 0 \quad \Rightarrow \quad \text{DEFECT DOMINATED}
\]

\[
\frac{1}{\mu_{\text{Measured}}} - \frac{1}{\mu_{\text{Ideal}}} < 0 \quad \Rightarrow \quad \text{MOBILITY ENHANCEMENT}
\]
Strain-Dominated Systems: SiGe

- Combined very-high dose Ge+B plasma implantation + laser anneal
- Structural Data by XRD and XTEM
  - 20% Ge and 55% Ge
  - DHE showed 70% increase in mobility for 20% and 4.3x increase for 55%
  - Data for sample 55% Ge (1E17/cm²) + B (4E16/cm²)
  - 55% concentration peak at ~20 Å

Mobility Data: SiGe Strain

![Graph showing the relationship between Mobility (cm²/V-s) and Depth (Å).](image-url)
Defect Measure: SiGe

Strain Dominated System
Summary

- DHE System *directly* measures key Parameters
- DHE Provides Junction profiles for $n$, $\mu$ and $\rho$
- Selectable step resolution [from 3-5 Angstroms and up]

- Fully Activated Carriers in agreement with SIMS and 4PP
- DHE results published since 2007 in Professional and Technical Journals
- Valuable aid in mobility enhancement studies and defect analysis

- Rapid, Affordable Evaluation of Active Layers
- DHE provides essential data that should be included with every process lot