• Optimization of DOFZ for manufacturing process
• Cost effectiveness, how much [O] is enough?
• <111> vs. <100>, influence on surface properties
• Hidden parameters affecting radiation hardness
  (example: HCl vs. TCA)
• Czochralski silicon, a possible alternative?

Material: FZ: Wacker, Cz: Sumitomo

Processing: CiS Erfurt, process very similar to ATLAS wedge
  Test diodes multi g.r.(HH) + test fields(Dortmund)

Material characterization:
  IR: ITME Warsaw, B. Surma
  SIMS: SIMS Lab Warsaw, A. Barcz
  4-point probe and management: ITME, E. Nossarzewska
  DLTS, C/V + I/V: Uni-HH

Radiation damage studies (Uni-HH):
  Irradiations with p (PS-CERN), n (TRIGA-Ljubljana),
  Co-60 Gamma (BNL, collab. with Z. Li, E. Verbitskaja)
  Tools: DLTS + Laplace-DLTS, TSC, TCT, C/V + I/V-
  annealing, Simulation-studies

Project started: November 2000
  First irradiations: p (July + Sept. 01), n (Oct. 01), γ (Sept. 01)
Resistivity profiles on 4" CiS wafers
Wacker <111> and Topsil <100>
measured from depletion voltage on diodes

Wacker <111>

Standard process

$\langle \rho \rangle = 3.71 \, \text{k}\Omega\text{cm} \pm 4\%$

Topsil <100>

Standard process

$\langle \rho \rangle = 1.12 \, \text{k}\Omega\text{cm} \pm 16\%$

Wacker <111> exhibits less radial dispersion than
Topsil <100>
Resistivity profiles on 4" SINTEF wafers
Wacker <111> and Topsil <100>
measured from depletion voltage on diodes

Wacker <111>
DOFZ 72h/1150C
\(<\rho> = 3.02 \text{k}\Omega\text{cm} \pm 3\%\)

Topsil <100>
DOFZ 72h/1150C
\(<\rho> = 3.85 \text{k}\Omega\text{cm} \pm 9\%\)

Also for SINTEF process and after DOFZ:
- Wacker <111>
- exhibits less radial dispersion than
- Topsil <100>
1. A first survey:

- SIMS profiles reliable, symmetric wrt 140 μm!
- Theory predictions excellent
- [O] in Cz extremely homogeneous as expected

2. The final choice:

- Depth profiles of Oxygen concentration
  DOFZ: 8 – 72 h at 1150°C
  measured with improved SIMS on bevelled samples

- All experimental profiles normalised to theoretical curves wrt integrals between 50-100 μm
  \[ F_{\text{theor/exp}} = 1.03 \pm 10\% \]

- Cz as grown, \( <O> = 8.14 \times 10^{17} \text{ O/cm}^3 \), \( <C> = 1.7 \times 10^{15} \text{ C/cm}^3 \)
- FZ 72h/1150°C, \( <O> = 1.14 \times 10^{17} \text{ O/cm}^3 \), \( <C> = 2.9 \times 10^{15} \text{ C/cm}^3 \)
- FZ 48h/1150°C, \( <O> = 9.86 \times 10^{16} \text{ O/cm}^3 \), \( <C> = 5.8 \times 10^{15} \text{ C/cm}^3 \)
- FZ 24h/1150°C, \( <O> = 5.68 \times 10^{16} \text{ O/cm}^3 \), \( <C> = 3.3 \times 10^{15} \text{ C/cm}^3 \)
Depth profiles of Oxygen concentration
DOFZ: 8 – 72 h at 1150°C
Integrated SIMS compared to IR absorption results

Examples of IR absorption spectra

IR and SIMS results in comparison:

<table>
<thead>
<tr>
<th>Sample#</th>
<th>t_{diffusion} [h]</th>
<th>[O]_{SIMS} [1/cm³]</th>
<th>[O]_{IR} [1/cm³]</th>
<th>IR/SIMS</th>
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</thead>
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<tr>
<td>1</td>
<td>None, (Cz)</td>
<td>8.13e17</td>
<td>8.55e17</td>
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<td>5</td>
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<td>6.97e16</td>
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<td>6</td>
<td>24</td>
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<tr>
<td>7</td>
<td>48</td>
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<td>1.04e17</td>
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<tr>
<td>8</td>
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<td>1.30e17</td>
<td>1.140</td>
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<tr>
<td>9</td>
<td>72</td>
<td>1.13e17</td>
<td>1.34e17</td>
<td>1.186</td>
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</tbody>
</table>

SIMS results: integrated average between d= 0 and 140 µm
IR results: averages of 4 measured samples in each case

$<|O|_{IR}/|O|_{SIMS}| = 1.10 \pm 10\%$

Agreement between SIMS and IR excellent
Resistivity profiles on 4" wafers
Change due to oxidation?
measured with 4-point probe

Wacker <111> $\rho = 2 – 5 \, k\Omega \text{cm}$, ■ before, ◆ after oxidation

Wacker <100> $\rho = 1 – 6 \, k\Omega \text{cm}$, ■ before, ◆ after oxidation

➢ Little change in resistivity after oxidation
➢ slight improvement of radial dispersion
Resistivity profiles on 4\" Cz-wafers
Influence of thermal donors
\( \rho \) measured with 4-point probe

**Cz Sumitomo \(<100>\), \( \rho \geq 600 \, \Omega \text{cm} \)**

Before oxidation:
\[
<\rho> = 590 \, \Omega \text{cm} \\
\pm 11\%
\]

After oxidation:
\[
<\rho> = 355 \, \Omega \text{cm} \\
\pm 11\%
\]

Comparison:

After oxidation and TD kill:
\[
<\rho> = 820 \, \Omega \text{cm} \\
\pm 12\%
\]

- Thermal donor kill essential for final process
- 1h/800\°C + 1min ramp to RT sufficient (?)
- final \( \rho \) larger than on as grown wafer
Resistivity of Cz-wafers
Influence of thermal donors
Results from DLTS

Cz Sumitomo <100>, $\rho \geq 600 \, \Omega cm$

**DLTS and $N_{\text{eff}}$ by $V_{\text{dep}}$ on test diodes:**

**Diode #12:**
$N_{\text{eff}} = 6.88 \times 10^{12} \, \text{cm}^{-3} \Rightarrow 625 \, \Omega cm$
$N_{thD}= 1.32 \times 10^{12} \, \text{cm}^{-3}$ (double charged!), measd. by DLTS
Effective concentration: $2.64 \times 10^{12} \, \text{cm}^{-3}$
Net doping conc.: $(6.88-2.64) \times 10^{12} \, \text{cm}^{-3} = N_{\text{eff,corr}}=4.24 \times 10^{12} \, \text{cm}^{-3} \Rightarrow 1014 \, \Omega cm$

**Diode #35:**
$N_{\text{eff}} = 9.10 \times 10^{12} \, \text{cm}^{-3} \Rightarrow 472 \, \Omega cm$
$N_{thD}= 2.16 \times 10^{12} \, \text{cm}^{-3}$ (double charged!), measd. by DLTS
Effective concentration: $4.32 \times 10^{12} \, \text{cm}^{-3}$
Net doping conc.: $(9.10-4.32) \times 10^{12} \, \text{cm}^{-3} = N_{\text{eff,corr}}=4.78 \times 10^{12} \, \text{cm}^{-3} \Rightarrow 900 \, \Omega cm$

After thermal donor correction: $960 \, \Omega cm \pm 6\%$

**4-point probe measurements:**
(on different wafer!)
$\rho$ after oxidation: $360 \, \Omega cm \pm 11\%$
$\rho$ after oxidation and TD kill: $820 \, \Omega cm \pm 11\%$

➢ TD-concentration measured by DLTS can fully explain the change of resistivity
➢ proper TD killing needed in process
Resistivity profiles on 4" CiS-Cz-wafers
ρ measured from depletion voltage
on processed diodes

Cz Sumitomo <100>, ρ ≥ 600 Ωcm

After processing including TD kill:

<ρ> = 1.34 kΩcm
± 6%

Comparison:

Before processing
But after oxidation
+ TD kill
(4-point probe)

<ρ> = 0.82 kΩcm
± 12%

Final process including TD kill is working!
homogeneity of ρ excellent
difference in V_{dep} and 4-point probe not understood
Bistable effect both appreciable for n- and p-irradiation
24 h/RT relaxation after each 80°C step necessary ($\tau_{\text{relax}} = 8\text{h} @ \text{RT}$)

Resulting annealing curves can only be fitted with 1st order
Large differences in $N_Y$ between prompt/2nd order and relaxed/1st order

Gunnar Lindström, CiS report, CERN 29-Nov-01
Proton Irradiation of Test Diodes from CiS ATLAS Wedge Wafers, $E_p = 24\text{GeV}/c$

- Annealing Results at 80°C -

- Test Diodes with Identical Mask Design and Process as ATLAS Wedge Strip Detectors, Manufactured on Same Wafer

- For Reliable Analysis Relaxation of Bistable Effect Important (24h RT after Each HT Annealing Step)

- Annealing Functions only to be fitted by 1st order fits
ROSE results are reproduced in ATLAS wedge for similar material (Wacker <111>) & oxygenation

DOFZ process => saturation of \( N_Y \) for \( \Phi_p > 10^{15} \) p/cm\(^2\)
change in \( V_{\text{dep}} < 1000V \) independent of \( \Phi_p \) and annealing
CiS – SRD test diodes
Wacker <111> and <100> standard process
CERN scenario for $\Phi_p = 2 \cdot 10^{13} - 1 \cdot 10^{15}$ p/cm$^2$

➢ Model description only possible for low $\Phi$ range
   Total donor removal, $\beta$ compatible with ROSE results

➢ Change of $N_{\text{eff}}$ for <100> larger than for <111>
CERN scenario: model description possible for total $\Phi$ range
$\beta$ compatible with ROSE results, independent of [O] for 24 to 72 h/1150°C

Comparison with ATLAS wedge reasonable, ? for high $\Phi$
Measurements: $N_{\min} = <N_{\text{eff}}>$ for $t_{\text{anneal}} = 4$-8 minutes
This talk:

- SRD project is getting under way!
- Wacker FZ shows less ρ dispersion than Topsil
- Resistivity not affected by DOFZ process
- New SIMS technique reliable, [O]-results ≡ IR
- Reliable annealing only after relax of bistable defect
- Analysis reveals 1\textsuperscript{st} instead of previous 2\textsuperscript{nd} order
- Extracted parameters compatible with ROSE results
- Cz can be used for processing taking care of TD

Many thanks to: M.Moll, M.Glaser (CERN), V. Cindro (JSI); E. Nossarzewska, B. Surma (ITME), A. Barcz (ITE) and M. Zielinski (SIMS Lab, Warsaw)

Further Results:
- SIMS, see talk given by A. Barcz
- Characterization of unirradiated diodes: J. Stahl
- Co-60 gamma irradiation macroscopic: E. Fretwurst
- Co-60 gamma irradiation microscopic: I. Pintilie