Characterization of Irradiated Doping Profiles

Wolfgang Treberspurg, Thomas Bergauer, Marko Dragicevic, Manfred Krammer, Manfred Valentan
Content:

• **Experimental Procedure**
  • Sample Irradiation
  • Spreading Resistance Profiling (SRP)

• **Theoretical Background**
  • The Electrical Neutral Bulk (ENB)
  • The Space Charge Region (SCR)

• **Results**
  • Irradiated Profiles of Shallow Impurities
  • Effective Doping Concentration

• **References**
Experimental Procedure
Irradiated Doping Profiles

- **Experimental Procedure: Irradiation**

  - **Samples:**
    - Floating-zone, p-on-n diodes
    - 1 kΩcm bulk resistivity
    - Produced by HPK
    - Bulk and backside implant doped with phosphor
  
  - **Overview:**
    - Sample irradiation
    - Annealing of 8 minutes at 60°C
    - Mechanically cut
      - Preparation for SRP measurements
      - Common capacitance voltage measurements

Sample Selection  
Irradiation and Annealing  
SRP Measurements  
CV Measurements
Irradiated Doping Profiles

- Experimental Procedure: Irradiation
  - Irradiation facility:
    - TRIGA Mark-II nuclear reactor
    - At the Institute of Atomic and Subatomic Physics (ATI) Vienna
    - Previous fluence calibration with similar diodes
    - 27°C during irradiation place
    - Spectrum approximately known

![Graph showing neutron energy spectrum](image-url)
Irradiated Doping Profiles

• Experimental Procedure: Irradiation

• Calculation:
  • Hardness factor $\kappa$ has been measured during calibration
  • Calculation of $\kappa$ confirmed calibration results
  • Damage mainly caused by thermal and fast neutrons

$$\kappa = \frac{\int D(E)\Phi(E)\,dE}{D(1\text{MeV})\int \Phi(E)\,dE} = \frac{\alpha V}{\Phi \Delta}$$

<table>
<thead>
<tr>
<th>Sample</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi_{eq} \text{ [n}_eq\text{/cm}^2\text{]}$</td>
<td>$1.10^{11}$</td>
<td>$5.10^{11}$</td>
<td>$2.10^{12}$</td>
<td>$3.10^{12}$</td>
<td>$1.10^{13}$</td>
<td>$5.10^{13}$</td>
<td>$1.10^{14}$</td>
<td>$5.10^{14}$</td>
</tr>
</tbody>
</table>
• Experimental Procedure: SRP

• Preparation:
  • The samples are mechanically grinded and polished with a small bevel angle
  • During preparation no temperatures above 30°C are expected

• Measurement:
  • Two closely aligned probes are stepped along the beveled surface
  • The probes are contacted with reproducible weight
  • The probes are made of hard material (tungsten carbide)
  • The resistance is measured at each position
• **Experimental Procedure: SRP**

  • **Data Extraction:**
    - The measured resistance is dominated by current spreading effects ($R_{sp}$)
    - Very small radii ($a$) of the probe tips result in a high sensitivity on the material resistivity
    - Depth resolution of about 100 nm can be easily achieved (10 µm planar)
    - SRP measurements deliver no absolute data, the accuracy depends on the calibration effort
    - Only electrically active dopants contribute to the measurement

  • **Performance:**
    - The measurements have been done in a custom designed setup [1]

\[
R_{sp} = 2a\rho
\]

\[
\rho(x) = (qn(x)\mu)^{-1}
\]
Theoretical Background
Irradiated Doping Profiles

- **Theoretical Background: ENB**
  - The electrical neutral bulk
    - Non depleted silicon volume
    - At sensor operated with voltages smaller than the full depletion voltage
    - The ionization of traps is determined by the Fermi level occupancy function at equilibrium
    - Suited for direct resistivity measurements
  - Modelling of resistivity
    - The shift of the fermi level \((E_F)\) after irradiation is determined by the charge neutrality equation
    - Ionization of acceptor \(N_a^-\) and donor traps \(N_d^+\) has to be taken into account
    - The resistivity is determined by concentration of free charge carrier inside the ENB (n,p)
    - Models have to assumed the number and energy level of traps \([2,3]\)
• **Theoretical Background: SCR**

  • **The space charge region**
    - Inside the SCR the ionization of deep traps is regulated by band bending in respect to the potential distribution
    - Almost all deep traps contribute to the effective doping concentration $N_{\text{eff}}$

  • **Donor removal processes**
    - Vacancies or self interstitials remove dopants from regular sides
    - Donor removal takes place until a non removable amount of donors is reached, which depends on the presence of other elements inside the bulk [4]
    - In turn the donor removal constant $c$ also depends on the initial concentration $N_{\text{eff,0}}$
• Theoretical Background: SCR

• Capacitance measurements at the presents of deep traps
  • Deep trap usually only contribute at low frequencies, in respect to their time constant
  • As the dc bias voltage correlates to very small frequencies most traps inside the SCR ($X_{\text{Trap}}$) are ionized
  • Only traps inside the volume $dX_{\text{Ampl}}$ which is depleted by the ac test signal are sensitive on the measurement frequency [5]

• Example
  • The contribution to capacitance measurements of one deep donor like trap is shown
  • Strong influence of measurement parameters:
    • Frequency (responding traps)
    • Amplitude (sensitive volume)
    • Temperature (time constant changes with $T$)
    • Measurement mode (serial or parallel)
Measurement Results
Irradiated Doping Profiles

• Results: Shallow Impurities

• Profiles after irradiation
  • Due to donor removal the expected resistivity decrease is observed
  • The donor removal process results in an decreasing implantation depth for increasing fluences

• Explanation
  • Uniformly distributed defects are expected to shift the profile only
  • Shifting a profile results in a linear correlation of the initial concentration to the resulting one
  • Effect can be understood by assuming that the resulting bulk concentrations converges to the non removable donor concentration
  • Another approach is to assume spatial effects due to high resistivity gradients
• **Results: Shallow Impurities**

• **Annealing study**
  - To investigate a possible influence of annealing on this effect several subsequent annealing steps have been performed (0, 8, 28, 120 minutes at 60°C)
  - No further changes of profiles could be observed, the effect has to take place during irradiation
  - Only shallow impurities are measured, especially after high fluences the electrical behaviour is dominated by deep traps
• **Results: Effective Doping Concentration**

  • **Electrical behaviour**
    • The influence of the observed effect on the electrical performance is studied by using capacitance voltage measurements
    • Samples irradiated with more than last ones type inverted $1.10^{13} \text{n}_{eq}/\text{cm}^2$ have been observed to be type inverted
    • Capacitance measurements become strongly frequency dependent, which make it advisable to use capacitance voltage frequency surfaces

![C-V Measurement: Parallel mode, -15°C, Amplitude: 200mV, Frequency: 1k](image)
**Results: Effective Doping Concentration**

C-V Measurements on diodes irradiated with increasing fluencies: Parallel mode, -15°C Amplitude: 200mV
• **Results: Effective Doping Concentration**

  • **Electrical behaviour**
    - The influence of the observed effect on the electrical performance is studied with capacitance voltage measurements.
    - Type inverted samples feature a peak at low frequencies due to dominant deep traps.
    - The capacitance stabilize at high frequencies for all samples at a value associated with the geometrical capacitance [6].
    - High fluences result in an decreasing dependence on the bias voltage.

![C-V Measurement: Parallel mode, -15°C, Amplitude: 200mV, Frequency: 1k, Bias Voltage: 50V](image-url)
• **Results: Effective Doping Concentration**

  • **Doping profiles of** $N_{\text{eff}}$
    • By differentiating $C^{-2}$ a profile of the effective doping concentration inside the SCR is calculated [7]
    • At the presented low fluence range donor removal effects are dominant and the concentration decreases
    • With increasing fluences the profiles become inhomogeneous, especially close to the backside, where donor removal mainly takes place

![Graph showing C-V measurement results](image.png)

**C-V Measurement:**
- Parallel mode, -15°C, Amplitude: 200mV,
  Frequency: 1k
• Conclusion and Outlook

• Conclusions
  • It could be shown, that SRP measurements are suited to characterize profiles of shallow donors after irradiation
  • An effect of decreasing implantation depth of shallow impurities with increasing fluences could be observed
  • To evaluate the influence of this effect on the sensor performance capacitance voltage measurements are suited

• Outlook
  • Capacitance voltage measurements have to be investigated in future and may serve for more detailed impurity characterization
  • The measurement of shallow impurities only with high spatial resolution may be used for investigating their correlation to other impurities
References


