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**Improvement of depth resolution of the positron beam spectroscopy by a sputtering technique**

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• implantation profile often approximated as Makhov profile
• extreme broad distribution of implanted positrons at $E > 3$ keV

$$P(z, E) = \frac{mz^{m-1}}{z_0^m} \left[-\left(\frac{z}{z_0}\right)^m\right]$$

$$\bar{z} = A \frac{E^r}{\rho}$$

Implantation Profile

$E = 1.5$ keV

$E = 3$ keV

$E = 5$ keV

$E = 10$ keV

Depth $z$ [μm]
Example for limitation of depth profiling: Rp/2 effect in Si self-implantation

- after self-implantation of Si in Si @3.5 MeV – two defect-rich layers are found
- at Rp: Si self-interstitials form dislocation loops
- at Rp/2 (1.7 µm): ???
- the defect layers are in a depth of 1.7 µm and 2.8 µm corresponding to $E_+ = 18$ keV and 25 keV
- implantation profile too broad to discriminate between the two zones
- simulation of $S(E)$ curve gives the same result for assumed defect profile

Surface removal by sputtering

- Ar⁺ ions penetrate into surface
- create displacement cascades
- some cascades reach surface
- surface atoms are released
Simulated defect profiles created during sputtering

- in the moment: 1 keV @ 42° ⇒ defect depth ≈ 25 nm in Si
- only change of surface $S$ parameter
Sputter process changes surface parameter only

- sputter conditions: 2 keV @ 60°
- no change of positron diffusion length due to sputtering
- depth resolution is limited by $e^+$ diffusion, not by implantation profile or diffusing defects

\[ S/S_{\text{bulk}} \]

\[ S = S_{\text{bulk}} \]

\[ L_+ = 221 \pm 13 \text{ nm} \]

\[ L_+ = 213 \pm 18 \text{ nm} \]
**Results**

Prove of principle with layer system Au/Cr/Au/Cr/Si

- with S(E) no defects measurable
- better depth resolution then S(E)-scan
- Interfaces sharply visible

![Graph showing S(E) vs. sputter time with layer system Au/Cr/Au/Cr/Si]

Sputter parameters: $I_B = 4 \text{ mA}; \ U_B = 400 \text{ V}$
Simulation of vacancy profile by Ar bombardment in CIGS

SRIM-Simulated defect profile for CIGS

- CIGS = Cu(In,Ga)Se2 photovoltaic layer
- no vacancies beyond of 10 nm
- e⁺ energy so that:
  - no influence of surface
  - still sharp e⁺ implantation profile
- eventually several positrons energies at one sputter depth ...

Sputtering conditions:
- \( E_{\text{Ar}^+} = 1\text{keV} \)
- Incident angle: 42°
Results

Cu(In,Ga)Se$_2$ - (CIGSe)

- direct semiconductor
- $E_g=1.04$ eV – 1.67 eV
- used in thin film solar cells
Results

- Investigation of the whole solar cell, especially near the back contact
- In-situ sputtering
  - no air contact between the measurements
  - no degradation on the surface
  - shorter overall measurement time

Sputter parameters: \( I_B = 6 \text{ mA}; U_B = 400 \text{ V} \)
Results

- First sample of a CIGS series
- Result of today
Conclusions

- distinctly **better depth resolution** is possible by sputtering

  -> **real defect profiling**

- interfaces become sharply visible

- **depth resolution is no more limited by positron implantation profile** but only by effective positron diffusion length (fundamental barrier)

- chemical information independent of defects by surface annihilation parameters

- disadvantage: not nondestructive

- depth scan over 4 µm last about 40 h (100nm/h)
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