Characterization of Al-implanted Si wafers by using high resolution grazing emission x-ray fluorescence combined with synchrotron radiation

Y. Kayser[1], W. Cao[1], J.-Cl. Dousse[1], J. Hoszowska[1], P. Jagodzinski[2] , M. Kavcic[3],

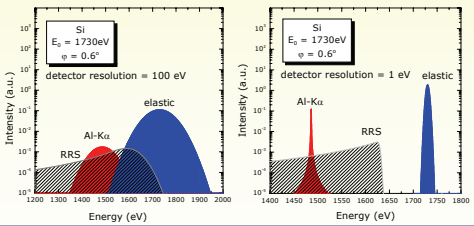
A. Kubala-Kukus[2], M. Pajek[2], J.-L. Schenker[1], J. Szlachetko[2,4]

1) Department of Physics, University of Fribourg, CH-1700 Fribourg, Switzerland
2) Institute of Physics, Jan Kochanowski University, 25-406 Kielce, Poland
3) J. Stefan Institute, P.O. Box 3000, SI-1001 Ljubljana, Slovenia
4) European Synchrotron Radiation Facility, BP 220, F-38400 Grenoble, France

Motivation

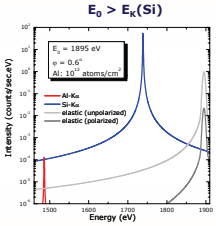
Progress in semiconductor microelectronic technology requires improved diagnostic tools for the depth profiling of doping elements in semiconductor materials. In this perspective high-resolution grazing emission x-ray fluorescence (GEXRF) combined with synchrotron radiation was tested in order to develop an effective method for studying the depth profiles of Al atoms implanted in Si.

Why high-resolution is useful for the detection of the weak Al signal?



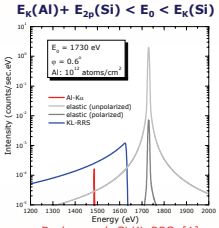
Optimization of the photon beam energy

$E_0 > E_K(Si)$

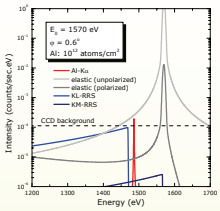


Background: Si-Kα tail

$E_K(Al) + E_{2p}(Si) < E_0 < E_K(Si)$



Background: Si KL-RRS [1]

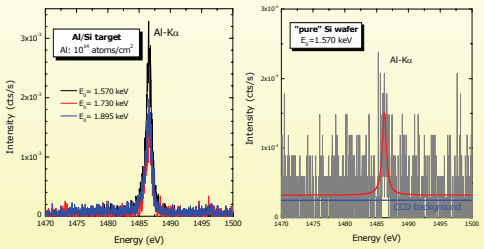


$E_K(Al) < E_0 < E_K(Al) + E_{2p}(Si)$

Residual background:

- elastic scattering (small thanks to SR polarization and $\theta_B \approx 45°$)
- CCD noise (2×10^{-5} s^{-1} ≈ 10^{-4} counts/(s×eV))
- Si KM-RRS

Detection Limits for Al



Al Kα-lines were measured for 3 different energy regimes (1895 keV, 1730 keV and 1570 keV). As expected the best peak-to-background ratio was found for the lowest beam energy where we recorded also the Al signal from a "pure" Si wafer [2].

Detection limit (1000 s):

$$C_{DL} = \frac{3\cdot\sqrt{N_{bckg}}}{N_{peak}}\frac{\sqrt{t}}{\sqrt{1000}}\cdot C$$

Measured detection limit:

$$C_{DL} \approx 10^{12}\ \frac{atoms}{cm^2}$$

Extrapolated detection limit by using the VPD preconcentration technique for D=300 mm Si wafer and d=1 mm beam diameter:

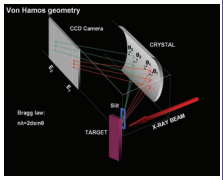
Enhancement factor: $\left(\frac{D}{d}\right)^2 \approx 10^5$ → $C_{DL} \approx 10^7\ \frac{atoms}{cm^2}$

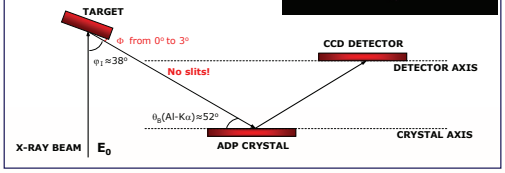
GEXRF high-resolution experimental setup

The high-resolution measurements were performed by means of a von Hamos spectrometer [3] with a cylindrically bent crystal (R = 25.4 cm). The spectrometer was installed at the beamline ID21 of the European Synchrotron Radiation Facility (ESRF) in Grenoble, France.

Photon beam (ID 21):
- energy 1570–1895 eV; photon flux 10^{10}–10^{11} s^{-1};
- energy resolution ≈ 6 eV (two 20Å Ni/B_4C multilayers);
- size 1 mm^2, horizontally polarized;
- Si mirror for suppression of higher order harmonics.

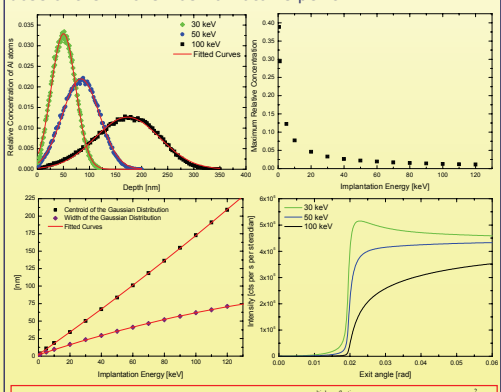
von Hamos spectrometer:
- energy resolution: ≈ 1 eV;
- ADP(101) crystal (2d=10.642Å);
- Bragg angle: $\theta_B \approx 52°$ for Al-Kα;
- Back Illuminated CCD camera.





Ion Implantation

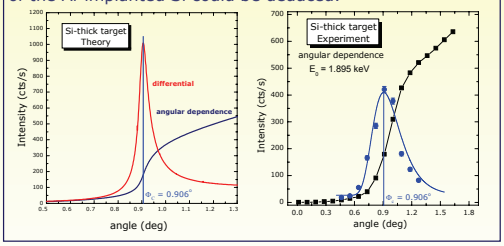
There are two ways to implant ions in a substrate: diffusion and ion implantation [4]. The last one has the advantage to allow a more precise control of the implantation profile in terms of depth and dose. The shape of the profile is determined by the implantation energy (see figures with theoretical values below) whereas the concentration of implanted ions depends upon the implantation dose. The theoretical implantation profiles have been calculated with the TRIM (**TR**ansport of **I**ons in **M**atter) software [5]. For the considered implantation energies of 30 keV, 50 keV and 100 keV a Gaussian distribution of the implanted ions can be considered instead of the more complicated Pearson IV distribution. Starting from the Al ion distribution given by the TRIM output it is possible to calculate the expected angular dependence by using the equation below [6] and assuming an incident flux of 10^{10} photons per s with an energy of 1559 eV and a beam resolution of 6 eV. The implantation dose of the Al ions was 10^{16} atoms per cm^2.



$$I(\theta) = \int_{z_1}^{z_2} p(z_1)\left|t_0\right|^2 \mathrm{Exp}\left[-2\,\mathrm{Im}\,k_{z,1}(z_0 - z_1)\right] \times \underbrace{\frac{1}{1-r_0' r_1 \mathrm{Exp}\left[-2\,\mathrm{Im}\,k_{z,1}(z_0 - z_1)\right]} + \frac{r_1' \mathrm{Exp}\left[-2\,\mathrm{Im}\,k_{z,1}(z_1 - z_1)\right]}{1-r_0' r_1 \mathrm{Exp}\left[-2\,\mathrm{Im}\,k_{z,1}(z_0 - z_1)\right]}}_{\text{multiple reflections}}{}^2 dz_1$$

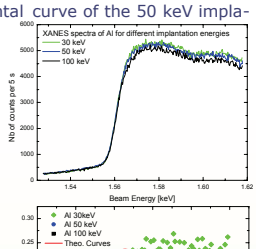
Critical angle for GEXRF

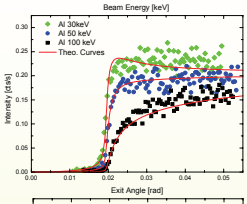
The critical angle corresponds to the inflection point in the angular evolution of the intensity. Below the critical angle ϕ_c the emitted radiation is reflected from the boundary back into the medium. From the critical angle of the bulk Si Kα-line the exit angles for the measurements of the Kα-line of the Al-implanted Si could be deduced.

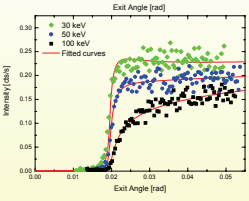


Experimental Results

The Al-K edges of the implanted samples are close to the ones of bulk Al (+1.3 eV, +1.2 eV and +0.9 eV for the 30 keV, 50 keV and 100 keV implanted sample) so that the implanted Al does not have chemically reacted with Si (shift of the K edge by +6 eV at least). Furthermore the calculated angular dependences predict the relative experimental intensities pretty well. This can be seen in the second figure below where the theoretical curves are normalized to the experimental curve of the 50 keV implanted sample. The discrepancy may be explained by a slightly different ion implantation energy than the assumed one. In this perspective the experimental curves where fitted by a model based on the simplified equation below assuming a Gaussian distribution of Al. Multiple reflections can indeed be neglected since there is no sharp Al/Si interface. The fitted curves show a good agreement with the experimental curves and the parameters of the experimentally determined ion distribution can be found in the table below where they are compared to theoretical values.







$$I(\Delta x, \varphi) \sim \int_0^T \left|t_0\right|^2 e^{-2k\left[\mathrm{Im}\left(\sqrt{n^2 - \cos^2(\varphi)}\right)\right]\cdot z} dz$$

The financial support of the Swiss National Science Foundation is acknowledged. The authors would also like to thank the ESRF for support.

	Theo.	Exp.	Theo.	Exp.	Theo.	Exp.
Ion En. [keV]	30	35.47	50	48.73	100	97.21
Center [nm]	50.25	59.70	83.67	81.95	172.8	167.2
Width [nm]	23.38	26.30	35.56	34.64	61.93	60.77
Max. R. C.	0.0330	0.0297	0.0220	0.0230	0.0126	0.0129

References

[1] J. Szlachetko et al., Phys. Rev. Lett. 97, 073001 (2006).
[2] A.Kubala-Kukus et al, Application of grazing emission x-ray fluorescence for high resolution detection of Al impurities in Silicon, 12th Conference on Total Reflection X-Ray Fluorescence Analysis and Related Methods TXRF 2007, June 18-22, 2007 Trento, Italy.
[3] J. Hoszowska, J.-Cl. Dousse, J. Kern and Ch. Rhême, Nucl. Instr. Meth. **A376**, 129 (1996).
[4] J.M. Poate and L. Rubin, Ind. Phys. **9**, 12 (2003).
[5] J.F. Ziegler et al., The stopping and range of ions in solids, Pergamon Press, New York, 1985.
[6] H.P. Urbach, P.K. de Bokx, Phys. Rev. B **53**, 3752 (1996).