Abstract A need for analysis techniques, complementary to secondary ion mass spectrometry (SIMS), for depth profiling dopants in silicon for ultra shallow junction (USJ) applications in CMOS technologies has recently emerged following the difficulties SIMS is facing there. Grazing incidence X-ray fluorescence (GIXRF) analysis in the soft X-ray range is a high-potential tool for this purpose. It provides excellent conditions for the excitation of the B-K and the As-L_{iii,ii} shells. The X-ray standing wave (XSW) field associated with GIXRF on flat samples is used here as a tunable sensor to obtain information about the implantation profile because the in-depth changes of the XSW intensity are dependent on the angle of incidence. This technique is very sensitive to near-surface layers and is therefore well suited for the analysis of USJ distributions. Si wafers implanted with either arsenic or boron at different fluences and implantation energies were used to compare SIMS with synchrotron radiation-induced GIXRF analysis. GIXRF measurements were carried out at the laboratory of the Physikalisch-Technische Bundesanstalt (PTB) at the electron storage ring BESSY II using monochromatized undulator radiation of well-known radiant power and spectral purity. The use of an absolutely calibrated energy-dispersive detector for the acquisition of the B-Kα and As-Lα fluorescence radiation enabled the absolute determination of the total retained dose. The concentration profile was obtained by ab initio calculation and comparison with the angular measurements of the X-ray fluorescence.

Keywords Ultra shallow junctions · Elemental depth profile · Grazing incidence X-ray fluorescence analysis

Introduction

The tremendous progress of silicon ULSI technology (ultra large scale integrated circuits) has mainly been made possible by the ongoing downsizing of their components, e.g., MOSFETs [1]. This reduction is realized by a downscaling of typical parameters such as gate width and length. However, as these parameters and thus the distance between source and drain decrease, their influence on the distribution of the electrostatic potential under the gate electrodes increases. As a result, short-channel effects occur and the threshold voltage of the device rolls off [2]. This can only be avoided if the junction depth of the source and drain diffusion is also scaled down. Therefore so-called ultra shallow junctions (USJ) were introduced for the realization of junction depths in the 20-nm regime and below. Such USJs can be formed by ultra low energy (ULE) ion implantation of boron, arsenic, and other elements into the silicon followed by a low thermal budget annealing such as a rapid thermal process, e.g., spike or laser annealing to remove lattice damage and electrically activate dopant atoms.
These ultra shallow dopant distributions represent a challenge for secondary ion mass spectrometry (SIMS), the well-established depth profiling technique and method of choice for implantation and diffusion profiles. Uncertainties in the profile as well as the dose determination are mainly caused by transient effects, leading to the so-called transient width, which corresponds to the depth (from 1 to 3 nm depending on sputtering conditions, e.g., primary ion impact energy and incidence angle) to be sputtered before the erosion becomes stationary and a steady equilibrium between implanted and re-sputtered primary ions has been established [3]. Prior to that, especially if reactive ions such as Cs⁺ or O₂⁺ are used to enhance the sensitivity, neither the sputtering yield nor the ion yield are constant and deviations on the measured profile shape are due to those variations and not necessarily due to actual compositional changes. Furthermore, the usually unavoidable presence of a native or induced thin SiO2 layers at the surface introduces more variations on sputtering and ion yield. Consequently, both the near-surface depth and concentration calibration are often heavily distorted.

Various approaches to try to improve SIMS in order to overcome or at least reduce these difficulties are reported in the literature [4–6]. In parallel to that, the search for complementary techniques, capable of delivering information about dose and distribution in the first few nanometers has been intensified [5, 7–9].

Grazing incidence XRF, which is used here as the analytical method, was first used to significantly reduce scattering background contributions when analyzing small amounts of material on top of a flat support [10]. This corresponds with total reflection XRF, where the incident angle is well below the critical angle for total external reflection. Since then, GIXRF has been widely used for the analysis of periodic multilayers [11], adsorbed molecules [12] as well as thin layers [13] on substrates. Dopant profiles have also been the subject of nondestructive analysis with GIXRF [14] in the hard X-ray range. An alternative approach towards dopant depth profiling using GIXRF has recently been developed by Steen et al. [15, 16] who sequentially etched the Si surface and repeated the GIXRF characterization in order to extrapolate the As depth distribution from the decrease of its signal after each etching. However, this approach seems relatively time consuming and is not nondestructive. Klockenkämper et al. [17] compared hard X-ray GIXRF applied to high energy Co implants with other methods and observed significantly differing results. These differences were mainly caused by the high penetration depth with respect to the sensitivity of GIXRF and the non-reference-free approach in combination with inappropriate standard samples used for calibration. Such standards have to be very similar to the actual sample in terms of the dopant distribution of interest and are not easily available.

In the present work, an approach for the characterization of USJ by using synchrotron radiation-induced GIXRF analysis is presented and compared with SIMS and other methods. Since GIXRF does not suffer from problems such as transient width, it is a promising alternative technique for USJ characterization. In fact, GIXRF is very sensitive to near-surface layers because in-depth changes of the underlying X-ray standing wave (XSW) field intensity are dependent on the angle of incidence between wafer surface and the X-ray beam. This method was developed by the Physikalisch-Technische Bundesanstalt, Germany’s national metrology institute, in its laboratory at the electron storage ring BESSY II. The GIXRF quantitation of the elemental depth profile is based on ab initio calculations, using the simulated XSW field intensity, all relevant fundamental parameters involved, and an assumed dopant profile. The shape of the assumed profile serves as a fitting parameter and is varied to fit the calculated curves to the measured ones.

**Theory**

Total-reflection X-ray fluorescence (TXRF) and grazing incidence XRF (GIXRF) are powerful techniques if surface contaminations [18, 19], thin buried layers with thicknesses in the nanometer range [20], or elemental depth profiles of main matrix constituents are to be investigated [21]. In TXRF, total reflection of the exciting radiation is realized by a shallow angle of incidence between X-ray beam and sample surface. This angle should be well below the critical angle θ_{crit} for total external reflection, which is a photon energy- and material-dependent parameter [22]. By applying such a setup, penetration of only the first few nanometers of the sample can be achieved, resulting in a low scattering background in the spectra detected.

Low-divergence incident radiation interferes with the reflected beam leading to an X-ray Standing Wave field (XSW) arising above the reflecting surface, which can modify the effective excitation intensity at the surface and below considerably. The characteristics of the XSW field, e.g., its wavelength and the position of the maxima and minima, depend on the photon energy of the incident radiation as well as the angle of incidence. The basic theory of XSW is explained in detail elsewhere [22–25].

In GIXRF, the angle of incidence is varied around the critical angle for total external reflection θ_{crit}. In this work, values between 0° and 35° were used to modify the characteristics of the XSW field, leading to a deeper penetration into the sample as the angle of incidence θ increases. In GIXRF, the penetration depth as well as the
intensity distribution of the incident radiation inside the sample is strongly dependent on the angle of incidence and the photon energy. Thus, the measured fluorescence radiation of the elements of interest is also an angle-dependent quantity. This enables a depth-dependent quantification of layers or elements if all relevant fundamental and geometrical parameters as well as the field distribution are known.

The model used in this work assumes a dopant profile and calculates the resulting GIXRF curve as a function of the incident angle. This curve is then compared with the measurement and fitted by varying the dopant profile. All relevant fundamental and experimental parameters are obtained from databases [26] or are known due to PTB’s fully calibrated instrumentation [19]. Windt’s IMD software package [27] is used to perform the necessary XSW field calculations.

The physical model used for the description of an implant-induced GIXRF signal is shown in Eq. (1). The angle-dependent count rate of the detected boron Kα or the arsenic Lα fluorescence radiation \( F_{\text{imp}}(\theta) \) is determined by a geometrical-experimental factor \( G \) and the depth integration of the product of an assumed implant profile \( P_{\text{imp}}(t) \), the depth-dependent intensity modification of the XSW field \( I_{\text{XSW}}(t, \theta) \) as well as an absorption correction term for the induced fluorescence radiation. This term includes both the density \( \rho \) and the total mass attenuation coefficient \( \mu_{\text{tot}}(t) \) as well as the sine of the detection angle \( \theta_{\text{det}} \). The parameter \( \mu_{\text{tot}}(t) \) is calculated at every depth position depending on the weight fraction of implant and silicon.

\[
F_{\text{imp}}(\theta) = G \int_0^{l_{\text{max}}} P_{\text{imp}}(t) \cdot I_{\text{XSW}}(t, \theta, E_0) \cdot \left( e^{-\mu_{\text{tot}}(t) / \sin \theta} \right) dt
\]  

(1)

with

\[
G = \frac{\varepsilon_{E_t} Q_I \Omega N_0}{4\pi \sin \theta}
\]  

(2)

where

\[
Q_I = \omega_{\text{X}}, \tau_{\text{X}}, E_t g_{\text{X}}.
\]  

(3)

The detailed form of the factor \( G \), which contains all relevant fundamental, geometric, and instrumental parameters, is shown in Eq. (2). It consists of different factors including the solid angle of detection \( \Omega / 4\pi \) and the efficiency of the detector \( \varepsilon_{E_t} \) for fluorescence radiation with photon energy \( E_t \). The factor \( G \) also includes the incoming photon flux \( N_0 \) measured with calibrated photodiodes and an incident angle-dependent sinusoidal correction. The fundamental parameters including \( Q_I \) are characteristic for the implanted element \( i \). They are either obtained from published data [26] or derived from dedicated experiments at PTB [28] and are described in Eq. (3) and Table 1.

The as-implanted depth distributions \( P_{\text{Imp}}(t) \) for boron and arsenic ion implantations into silicon were derived from SRIM (the stopping and range of ions in matter) calculations [29]. A modified Gaussian distribution, whose area \( (A_0) \), maximum position \( (A_1) \), and its sigma width \( (A_2) \) are the parameters, was used to model the boron implant profiles into silicon. These modifications include the influence of the scattering oxide on the near-surface part as well as a potential channeling of boron ions for the deeper parts of the distribution. The model used for arsenic implants consists of an asymmetric Gaussian with two different sigmas, one for each flank. Its area \( (A_0) \), maximum position \( (A_1) \), and the two sigmas \( (A_2, A_3) \) are the parameters. The characteristic depth for the mean projected range \( (R_p) \) equals the position of the maximum of the profile \( (A_1) \). SRIM calculations showed that the influence of the top oxide layer was not as large for the used implantation energies as for boron and were therefore neglected to keep the model simple. Channeling is also be neglected as As bombardment rapidly amorphizes the crystalline silicon, and channeling is drastically lower than for boron and therefore not easily detectable by GIXRF. Respective equations for \( P_B(t) \) and \( P_{\text{As}}(t) \) are shown in Eq. (4) and Eq. (5).

\[
P_B(t) = \begin{cases} 
A_0 e^{-\left(\frac{(t-A_1)}{\tau_{\text{As}}}\right)^2} \left( 1 + [C_1 t^2 + C_2 t + C_3] \right) & \text{if } t \leq t_{\text{ox}} \\
A_0 e^{-\left(\frac{(t-A_1)}{\tau_{\text{As}}}\right)^2} + A_3 e^{-A_3(t-A_1)} & \text{if } t > t_{\text{ox}} 
\end{cases}
\]  

(4)

\[
P_{\text{As}}(t) = \begin{cases} 
A_0 e^{-\left(\frac{(t-A_1)}{\tau_{\text{As}}}\right)^2} & \text{if } t \leq A_1 \\
A_0 e^{-\left(\frac{(t-A_1)}{\tau_{\text{As}}}\right)^2} & \text{if } t > A_1 
\end{cases}
\]  

(5)

The profiles \( P_B(t) \) and \( P_{\text{As}}(t) \) are modified within a forward calculation in order to match measured and calculated curves by a \( \chi^2 \) minimization. The \( A_i \) values serve as the fitting parameters determining the shape and location of the respective profile. The characteristic depth for the oxide layer thickness \( t_{\text{ox}} \) is kept fixed during the curve fitting. The \( C_i \) values in \( P_B(t) \), which determine the shape of the distribution inside the silicon oxide on the wafer surface, are not fitted; they were determined by the use of SRIM calculations [29] for boron implants with implantation energies from 0.1 to 5 keV into silicon covered by 1.5 nm of an assumed native SiO2 layer.
A relation between \( R_p = A_1 \) and the FWHM and thus \( \sigma \) and \( A_2 \) (FWHM = \( 2\sqrt{2\ln 2}\sigma \)) of the boron implantation profile was also introduced in order to improve the convergence of the fit by reducing the number of free parameters. The value for \( C_4 \) and the power of the FWHM were obtained from SRIM calculations (see Fig. 1) into the above-mentioned SiO\(_2\)/Si material combination. The derived relation, which is shown in Eq. (6), allows the coupling of parameters \( A_1 \) and \( A_2 \) (see Eq. (7)) whereby the fitting procedure was stabilized.

\[
C_4 = \frac{A_1}{\text{FWHM}^2} \approx \text{constant} \tag{6}
\]

\[
A_2 = f(A_1) = \frac{1}{2\sqrt{2\ln 2}} \left[ \frac{A_1}{C_4} \right]^{1/2} \tag{7}
\]

The necessary XSW field simulations were performed assuming a layer system of 1.5-nm SiO\(_2\), 100 nm of either B\(_1\)Si\(_{1,000}\) or As\(_1\)Si\(_{1,000}\), and a silicon substrate. Between the layers, discrete interfaces with no roughness are assumed and the dopant distribution inside the doped silicon is approximated to be constant. A more realistic model with RMS roughness of 0.3 nm at the SiO\(_2\)–Si interface and a discrete dopant distribution derived from the fitted profile by adopting multiple layers with a different dopant/silicon ratio was also employed. The influence on the XSW field distribution and thus the determined total retained doses was well below the estimated uncertainty of the present method. The simulations were carried out with photon energies of 275 eV for boron and 1,540 eV for arsenic, identical to the measurements. A plot of the distribution calculated for the boron samples is shown in Fig. 2. The wafer surface or the SiO\(_2\) layer is on the left-hand side at the smallest depth values. The near-surface regions are very sensitive to incident angle variations, whereas in the deeper regions the field intensity and the angle-dependent gradient are lower. Thus, GIXRF is well suited for ULE implants close to the surface. Deeper implants will not be characterizable by this method.

**Experimental**

For the further development of a GIXRF-based technique for USJ characterization, two sets of silicon wafers were used, one with boron and the second with arsenic ion implants as shown in detail in Table 2. The lateral homogeneity of the implantation is expected to be better than 2%.

The GIXRF measurements were performed in PTB’s irradiation chamber [19] for 200-mm and 300-mm silicon wafers at the plane grating monochromator (PGM) beamline for undulator radiation at BESSY II [30]. This beamline provides monochromatized undulator radiation in the photon energy range from 78 to 1,860 eV. The main

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**Table 1** Fundamental parameters used for the calculation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau_{X_i, E_0} )</td>
<td>Photoelectric cross section of edge ( X_i ) of element ( i ) for photons of energy ( E_0 )</td>
</tr>
<tr>
<td>( \omega_{X_i} )</td>
<td>Fluorescence yield of edge ( X_i )</td>
</tr>
<tr>
<td>( \gamma_{l, X_i} )</td>
<td>Transition probability of line ( l ) belonging to ( X_i )</td>
</tr>
</tbody>
</table>

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**Fig. 1** Calculated values for \( R_p \) and FWHM of boron implants into 1.5 nm of SiO\(_2\) on Si for various implantation energies. The relation between the two parameters, as shown in Eq. (6), is also plotted

**Fig. 2** XSW field distribution for a B sample with an incident photon energy of 275 eV. The plot shows the relative intensity as a function of the depth (x-axis) and the incident angle (y-axis). The gray scale coding on the right-hand side shows the local relative intensity \( I/I_0 \).
features of this irradiation chamber for TXRF, GIXRF, and XRF measurements on silicon wafers are [19]: an eight-axes manipulator which enables TXRF, GIXRF, and XRF measurements at any desired point on the surface of silicon wafers with an electrostatic chuck mounted on it. A commercial equipment front-end module is used to handle the wafers directly out of their respective transport box (FOUP or SMIF). It also ensures class 1 cleanroom conditions to minimize unintentional cross-contamination of the samples. The detection of element-specific fluorescence radiation is realized by a thin window Si(Li) detector or a windowless silicon-drift detector (SDD). They are attached to the ultra high vacuum (UHV) chamber and can be changed over as needed.

This work takes advantage of the fact that the sample manipulator allows precise adjustment (the uncertainty is 0.001°) of the incident angle between the wafer surface and the X-ray beam from 0 to 45°, which is necessary to ensure the grazing incidence conditions.

GIXRF measurements were performed at the center of each wafer. The incident angle between the X-ray beam and the wafer surface was varied between 0 and 35° with varying step width, which was adapted to the changes of the intensity of the fluorescence radiation of interest. For the boron-implanted samples an incident photon energy of 275 eV was used for optimal excitation of the B K-shell. Boron depth profiling was carried out using a 500-eV O$_2^+$ primary beam (≈70° incidence) and collecting 11B$^+$ secondary ions. The analysis was carried out in ultra high vacuum (10$^{-8}$ mbar) and a Zalar rotation was used in combination with O$_2^+$ bombardment in order to prevent or minimize the formation of ripples and roughness on the crater bottom [33]. Depth scales were calibrated measuring the final crater depth by a mechanical stylus profilometer, whereas the concentration scale was calibrated using a relative sensitivity factor (RSF) approach: for As profiles, the RSF value was determined from an As 5-keV implant with a known dose, whereas for B profiles the RSF value was obtained from the analysis of a uniformly B-doped Si reference sample traceable to the NIST standard reference material no. 2137. No corrections were introduced for the surface SiO$_2$ layer in both cases: SiAs$^-$ curves were simply normalized to the average intensity of the $^{28}$Si$^+_2$ matrix species, whereas the $^{11}$B$^+$ intensity was converted to concentration after a point-by-point normalization to $^{28}$Si$^{16}$O$^+$.

### Results and discussion

Initial results obtained on the As- and the B-implanted wafers 1 to 5 with different implant energy but constant $1.0 \times 10^{15}$ cm$^{-2}$ dose are shown in Fig. 3. In addition, SIMS profiles obtained on the same samples are shown. The expected growth in $R_p$ and FWHM values with increasing...
implant energy are confirmed, and the measured doses are also in line with the nominal values considering an estimated relative uncertainty of 10% (see Table 3) for As and 15% (see Table 4) for B. The main contributors to the total uncertainty are the IMD calculation and the fundamental atomic data. The higher uncertainty for boron samples is mainly due to demanding spectra deconvolution because the B-K\text{\textalpha } peak is superimposed on a pileup peak of Si-L\text{\textalpha } radiation.

The depth profiles determined with various techniques on sample wafer As-3 (see Table 2) are shown in Fig. 4. Along with SIMS and GIXRF, these techniques include medium energy ion scattering (MEIS) and Z-contrast tilted sample annular dark field scanning transmission electron microscopy (TSADF-STEM) [35]. Additionally, the SRIM calculated depth distribution is included in the figure. A more detailed description of the application of these techniques to USJ characterization can be found elsewhere [34]. A cross comparison of these results shows that the soft X-ray GIXRF technique is well suited for USJ characterization. The profile determined with this technique (thick curve) is very similar to the MEIS and TSADF-STEM ones. This lends substantial support to the model applied for arsenic implantations into silicon used in this work being adequate since the characteristic values for \( R_p \) and FWHM are very similar to those determined by MEIS and TSADF-STEM. However, the SIMS depth profile is slightly shifted towards the surface and its near-surface flank is influenced by the transient width effect.

A comparison of the depth profiles determined with the soft X-ray GIXRF method and SIMS (see Fig. 3) also indicates that large differences are observed mainly for low implant energies. Boron depth profiles determined with SIMS are much higher, shifted to the surface, and contracted compared with GIXRF, whereas arsenic SIMS profiles are all shifted towards the wafer surface. The As profiles also show a non-Gaussian step in the near-surface flank.

### Table 3
Comparison of As dose values determined by the reference-free soft X-ray GIXRF technique with nominal and SIMS values (obtained with Cs\(^+\) primary ions)

<table>
<thead>
<tr>
<th>Nominal</th>
<th>GIXRF Dose (10(^{14})/cm(^2))</th>
<th>SIMS 0.5keV Dose (10(^{14})/cm(^2))</th>
<th>SIMS 0.25keV Dose (10(^{14})/cm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>9.8±1.0</td>
<td>9.3±0.6</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>10.8±1.1</td>
<td>10.8±0.7</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>9.2±0.9</td>
<td>10.2±0.7</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>9.6±1.0</td>
<td>10.6±0.7</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>10.5±1.1</td>
<td>10.7±0.7</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>1.0±0.1</td>
<td>1.07±0.05</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>4.9±0.5</td>
<td>5.5±0.3</td>
</tr>
<tr>
<td>8</td>
<td>50</td>
<td>42.7±4.3</td>
<td>45±2</td>
</tr>
</tbody>
</table>

Consult [34, 36] for detailed results.

### Table 4
Comparison of B dose values determined on wafers 1 to 5 by the reference-free soft X-ray GIXRF technique compared with nominal and SIMS values

<table>
<thead>
<tr>
<th>Nominal</th>
<th>GIXRF Dose (10(^{14})/cm(^2))</th>
<th>SIMS A Dose (10(^{14})/cm(^2))</th>
<th>SIMS B Dose (10(^{14})/cm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>8.2±1.2</td>
<td>9.6±1.1</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>10.4±1.6</td>
<td>10.5±1.2</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>9.8±1.5</td>
<td>10.4±1.4</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>8.8±1.3</td>
<td>8.1±1.0</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>8.6±1.3</td>
<td>8.5±1.1</td>
</tr>
</tbody>
</table>

SIMS measurements were conducted using \( O_2^- \) with an impact energy of 0.5 keV and a 68° impact angle combined with Zalar rotation. SIMS A was measured under UHV conditions and SIMS B under \( O_2 \) flooding. Consult [34, 36] for detailed results.

Fig. 3 GIXRF-determined implantation profiles for As (left) and B (right) for the wafer with varying implantation energy. Additionally SIMS profiles determined on the same samples are shown (dotted lines).
parts of the depth profile for all implant energies. These differences can be partly explained by the nonconstant sputtering rate in SIMS during the erosion of the first few nanometers close to the sample surface. Since in SIMS analysis the depth scale is normally calibrated by reference to the total measured final crater depth, the derived sputtering rate \( \frac{\text{total sputtered depth}}{\text{total sputtering time}} \) underestimates the depth in the initial faster erosion. This leads to a SIMS profile that is shifted towards the surface and is contracted compared with the actual profile, although variations of the ion yield (number of ions emitted per sputtered atom) can also cause higher or lower secondary ion signals in SIMS analysis as seen for the B depth profiles in Fig. 3. The GIXRF curves and the underlying SRIM model do not yet take into account effects like collisional mixing due to the energy deposition during the stopping process (resulting in profile broadening), and range shortening due to the increasing stopping power for the As ions as the composition changes from Si to As-doped Si. These effects lead to a redistribution of implants, especially As which leads to a broadened near-surface flank of the profile as observed in the measured As graphs in Fig. 3.

For the boron-implanted samples, the spike at the SiO\(_2\)--Si interface is also not visible in SIMS measurements. This could either mean that in the SRIM calculation this is an artefact resulting from the different stopping powers in SiO\(_2\) and Si, causing the step, or if it is real that SIMS does not have the resolution to resolve this. The accuracy of the presented SRIM-based model for B implants will be further investigated regarding this issue by means of the application of different alternative analytical methods. The SIMS profiles for the higher energy implants also show longer tails than GIXRF. This is primarily due to the broadening of the peak measured by SIMS due to collisional mixing caused by the injection of the SIMS-probing beam particles. Additionally, differences in the determined profile shape increase with higher implant energy because the GIXRF method is reaching its depth sensitivity limit. Profiles where a significant fraction of implants are deeper than 10 nm below the surface are found to be difficult to fit. The mean projected range parameter \( A_1 \) was therefore set to SRIM-determined values for the 2-keV and the 3-keV B implant in order to retrieve reasonably shaped profiles.

The determined dose values for the As and B samples are shown in Tables 3 and 4. The GIXRF-obtained doses are well in line with the nominal (see Table 2) and SIMS values for both implant species. The total relative uncertainty was estimated to be 10% for As and 15% for B.

In general, the soft X-ray GIXRF technique works very well for dopant profiles, implanted with energies lower than 2 keV for boron and lower than 3 keV for arsenic implants. This is due to the fact that the dopant distributions are very close to the surface at such low implantation energies and only small parts of the distribution reach a depth at which the depth sensitivity of this GIXRF method is decreasing. In this first run of measurements, dopant profiles with higher implant energies could not be fitted without the adjustment of the fitting parameter which determines the mean projected range. Hence, for B wafers 4 and 5 this parameter was set to SRIM-calculated values. The fitting of part of the As profiles had to be stabilized by setting tight ranges for parameters \( A_2 \) and \( A_3 \). A more sophisticated measurement technique is likely to weaken this need for the chosen parameter constraints.

**Conclusion**

We have demonstrated that USJ characterization using synchrotron radiation-induced GIXRF in the soft X-ray range is capable of achieving comparable results to SIMS regarding the accuracy of the determined total retained doses of boron- and arsenic-type implants into silicon. An evaluation of the shape and the positioning of the profiles determined by this technique was also done for arsenic implants by comparison with SIMS-, MEIS-, and STEM-determined profiles (see also [34]). To further improve the accuracy of the modeling of implantations into crystalline silicon, parts of the results of SIMS measurements related to higher depth values will be used to build more reliable models of the depth distribution rather than the SRIM calculations since they work only supposing an amorphous matrix. A combination of SIMS and the presented GIXRF method could also improve the results on samples with implantation energies above 3 keV for B and 5 keV for As by determining the near-surface part of the profile by
GIXRF and the deeper part by SIMS. Both methods would complement each other perfectly because soft X-ray GIXRF is very sensitive near the surface where SIMS struggles and SIMS becomes highly accurate at the deeper parts where soft X-ray GIXRF becomes insensitive. An improved spectra deconvolution, able to better discriminate Si-Lα pileup counts from the B-Kα counts is also a topic for further research. Further improvements of the soft X-ray GIXRF-based approach are to be expected with the help of dedicated measurements to improve the accuracy of the IMD calculation. Further improvements to be made are measurements of the optical constants as well as the density of the implanted layers for each sample by X-ray reflectometry in combination with an enhanced strategy for performing the GIXRF measurements by increasing the point density in selected incident angular ranges.

The presented technique should be able to improve SIMS combined with GIXRF analysis for tabletop instruments. The combination of both methods can provide corrections for the distorted parts of SIMS-determined profiles. Furthermore, the implantation profiles of reference samples for non-synchrotron-radiation-based devices can be characterized by employing the presented reference-free GIXRF method. With the help of such reference samples, the accuracy of tabletop GIXRF instruments will be improved.

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References
