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Laboratory X-ray characterization of a surface acoustic wave on GaAs: the critical role of instrumental convolution

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Surface acoustic waves of micrometre wavelength travelling on a monocrystal give diffraction satellites around each Bragg peak in an X-ray diffraction diagram. By using a four-crystal monochromator, a secondary two-crystal analyser and masks reducing the footprint to the part of the crystal containing the acoustic modulation, it is possible to observe these satellites on a GaAs (001) surface using a laboratory diffractometer. The finite extension of the satellite diffraction rods and of the crystal truncation rod perpendicular to the surface leads to geometrical correction factors when convoluted with the instrumental resolution function, which had previously been ignored. The calculation of these geometrical correction factors in the framework of the kinematic approximation allows the determination of the surface acoustic wave amplitude, and the study of its attenuation and its dependence on radiofrequency power and duty cycle. The ability to perform such determinations with a laboratory diffractometer should prove useful in optimizing surface acoustic waves, which are presently used in a broad range of condensed matter physics studies.

1. Introduction

Since the pioneering work of Hauer & Burns (1975), a great deal of effort has been devoted to studying the interactions between acoustic waves and X-rays (see e.g. Entin et al., 1990; Roshchupkin & Brunel, 1993; Tucoulou et al., 1997, 1998, 2001; Zolotoyabko & Polikarpov, 1998; Sauer et al., 1999; Roshchupkin, Irzhak, Snigirev et al., 2011; Bojahr et al., 2012). One of the main motivations of these studies has been the tailoring of synchrotron light. For this reason and because of the high brilliance of synchrotron light, most of the recent studies have been performed using synchrotron facilities. Tucoulou et al. (2001) showed that a surface acoustic wave of some 10 μm wavelength propagating on an LiNbO3 crystal leads to satellite diffraction peaks around each Bragg peak in a rocking curve. The q separation between satellites being some thousandths of nm⁻¹, the very close proximity of the satellites to the Bragg peak implies the use of both a high-resolution diffractometer and a good-quality monocrystal. While these authors analysed their results in the framework of the kinematic theory of diffraction, some subsequent work has been analysed using the dynamic theory (Schelokov et al., 2004; Tucoulou et al., 2005).

In the meantime, interest in surface acoustic waves (SAWs) has grown. Excited electrically using interdigitated transducers (IDTs), they are routinely used as band-pass filters in radiofrequency (RF) microelectronics up to 3 GHz. In more
academic environments, they have recently emerged as an efficient tool for carrier and spin control in semiconductor and metallic nanostructures, with applications foreseen in quantum information technology (Sanada et al., 2011; Hermelin et al., 2011). Their versatility and the wide possibilities of tailoring their interaction with electronic or magnetic excitations by using the toolbox of wave mechanics (interference, focusing, wavefront and pulse shaping etc.) make SAWs appealing to a growing number of condensed matter physicists (Li et al., 2014; Schülein et al., 2015). Recently, SAW studies have been performed on a substrate that quantitative measurements of the acoustic modulation. We placed glass masks with an aperture of some mm width gap just above the surface but not touching it in order not to disturb the acoustic wave propagation. The spot size in the direction of the SAW propagation was measured to be 548 ± 3 MHz.

Operando measurement of the acoustic wave propagation was achieved by collecting rocking curves and reciprocal-space maps. The crossed slits did not allow us to define a sharp X-ray probe. Therefore, the use of masks for X-rays was required to limit the diffraction to the part of the crystal containing the acoustic modulation. We placed glass masks with an and for symmetric reflections are simplified as where is the acoustic wavevector and is the normal components of . The satellites appear for low values of of some hundredths of a degree, the components of for symmetric reflections are simplified as and . Therefore, the rocking curves are equivalent to scans and intensity maps are equivalent to .

Because of this active development of SAW studies, there is a real need for an easy and versatile method to quantitatively measure their amplitude in view of optimizing the design of IDTs. This has been done in the past using optical light diffraction or interferometry (Lean & Powell, 1972; Royer & Dieulesaint, 2001). In this work, we have explored instead the right side of the IDT, using X-rays. The period of the IDT fingers was nominally , the metallization ratio 0.5, the aperture and the number of IDT finger pairs . The electrodes were made of Cr/Au of nominal thickness 100 nm. The excitation signal was brought to the IDTs by means of coaxial cables and coplanar waveguides with straight round bond-wires. Unless specified, the RF power was applied continuously (CW SAW mode). Otherwise it was modulated at low frequency by a square wave of period . The resonance frequency of the was measured to be 548 ± 3 MHz.

2. Experimental setup and procedure

2.1. Experimental setup

High-resolution X-ray diffraction measurements were carried out on a PANalytical X’pert Pro diffractometer equipped with a sealed Cu tube and in a triple-axis geometry. A primary four-crystal Ge(220) monochromator and a secondary two-crystal Ge(220) analyser were used. Such a geometry allows one to select Cu Kα1 radiation of X-ray wavelength .

Using the piezoelectric properties of GaAs, we deposited two IDTs parallel to the (110) direction of an epiready substrate. The first IDT, , allows the excitation of an acoustic wave propagating perpendicularly to this direction. The second IDT was deposited mm to its left (Fig. 1). This is the standard SAW filter configuration which allows electrical monitoring of the transmitted SAW shape (Royer & Dieulesaint, 2001). In this work, we have explored instead the right side of the IDT using X-rays. The period of the IDT fingers was nominally , the metallization ratio 0.5, the aperture and the number of IDT finger pairs . The electrodes were made of Cr/Au of nominal thickness 100 nm. The excitation signal was brought to the IDTs by means of coaxial cables and coplanar waveguides with straight round bond-wires. Unless specified, the RF power was applied continuously (CW SAW mode). Otherwise it was modulated at low frequency by a square wave of period . The resonance frequency of the was measured to be 548 ± 3 MHz.

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rapid analysis of the (002) \(Q_y\) scans (Fig. 2) shows that, as expected, the satellite features are symmetric around the Bragg position, periodic with a period almost equal to the nominal acoustic wavevector, and that their intensities increase with the incoming RF power. The conclusions are less clear for the (004) \(Q_y\) scans (Fig. 3) since the satellite features are not so well separated, but once again the diffuse intensities outside the Bragg condition increase with the incoming RF power. In order to carefully check that no thermal drift appears on the diffraction patterns when applying the electrical power on the IDTe, we also excited it off its resonance, at 570 MHz. Diffraction patterns identical to the one without any RF excitation were then recovered.

Fig. 4(a) shows an \((\omega/2\theta, \omega)\) intensity map around the (002) Bragg peak in the presence of the acoustic wave. Satellite rods parallel to the \(Q_z\) direction clearly appear. Note that the extension of these rods in the \(Q_z\) direction varies with the satellite order. In the next two sections, we will describe how to perform a quantitative analysis of these experimental features in order to extract the acoustic wave amplitude and to study its physical behaviour as a function of different parameters: incoming RF power, distance to the IDTe, and SAW duty cycle (ratio of the ‘on’ time to the modulation period).

3. Modelling and data reduction

In order to obtain a good estimate of the X-ray diffracted intensity, the first step is to get an accurate description of the atomic displacements associated with the SAW travelling in the crystal. Note that, for a wavelength of the order of 5 \(\mu m\), harmonic displacements of the order of 0.05 nm lead to a strain of the order of \(6 \times 10^{-5}\). For such a small strain, the acoustic branch of the phonons can be calculated in the framework of linear elasticity of continuous media. In the case of cubic symmetry, for a (001) surface and propagation in the (110) direction, the surface acoustic mode is a Rayleigh mode and one obtains for atomic displacements (Royer & Dieulesaint, 2001)

\[
\begin{align*}
\mathbf{u}(x, y, z) &= \begin{pmatrix} u_x \\ u_y \\ u_z \end{pmatrix} = \begin{pmatrix} U_x(z) \cos(q_x x - \omega_s t) \\ 0 \\ U_z(z) \sin(q_x x - \omega_s t) \end{pmatrix} \\
&= \begin{pmatrix} 2U \exp(-p_z q_x z) \cos(p_z q_x z + \varphi/2) \cos(q_x x - \omega_s t) \\ 0 \\ 2\rho U \exp(-p_z q_x z) \sin(p_z q_x z + \varphi/2 - \psi) \sin(q_x x - \omega_s t) \end{pmatrix},
\end{align*}
\]
where \( q_s = 2\pi/\lambda_s \) and \( \omega_s \) are the wavevector modulus and the angular frequency of the SAW, respectively, and \( r, p_s, p_1, \varphi, \psi \) are coefficients which depend on the elastic constants but are independent of the wave amplitude \( U \). For GaAs using \( C_{11} = 118.4 \text{ GPa}, \ C_{12} = 53.7 \text{ GPa}, \ C_{44} = 59.1 \text{ GPa} \) (Cottam & Saunders, 1973), one obtains \( r = 1.34, \ p_s = 0.5, \ p_1 = -0.48, \ \varphi = -2.10, \ \psi = 2.61 \), so that the surface atomic \( x \) and \( z \) displacement amplitudes at \( z = 0 \) are simply obtained as a function of \( U \) by \( u_s(z = 0) = 0.99U \) and \( u_z(z = 0) = -1.33U \). It is worth noting that (i) the expression of \( u \) differs noticeably from a simple exponential damping used by previous authors (Tucoulou et al., 2001) and (ii) a calculation performed in the framework of elasticity of continuous media implicitly assumes that all the atoms of the crystallographic unit cell have the same displacement.

Since the sound velocity, \( v_s = \omega_s/q_s \), is much lower than the light velocity, the acoustic strain can be considered as quasi-static (Tucoulou et al., 2001). Using the description of the atomic displacements, we can evaluate the amplitude \( A(\mathbf{Q}) \) of the diffracted X-ray wave in the framework of a kinematic approximation. The principle of the calculation was developed by Tucoulou et al. (2001), on the basis of earlier work of Entin et al. (1990). For a semi-infinite crystal \( A(\mathbf{Q}) \) can be written

\[
A(\mathbf{Q}) \propto F(\mathbf{Q}) \sum_{G_s} \sum_{n_z=-\infty}^{\infty} \sum_{n_x=-\infty}^{\infty} \sum_{n_y=-\infty}^{\infty} [\exp(-\mu n_z a_z) \exp(i\mathbf{Q} \cdot \mathbf{R})]
\]

\[
\propto F(\mathbf{Q}) \sum_{n_z=-\infty}^{\infty} \sum_{n_x=-\infty}^{\infty} \sum_{n_y=-\infty}^{\infty} \left[ \exp(-\mu n_z a_z) \right] \}
\]

\[
\times \exp[i(Q_x n_x a_x + Q_y n_y a_y + Q_z n_z a_z)]
\]

\[
\times \exp[i(Q_x U_x(n_x a_x) \cos(q_s n_x a_x))]
\]

\[
\times \exp[i(Q_y U_y(n_y a_y) \sin(q_s n_y a_y))]
\]

(2)

where \( F(\mathbf{Q}) \) is the structure factor of the elementary mesh, \( \mathbf{R} \) is the position of the \((n_x, n_y, n_z)\) crystal node, \( \mathbf{R}_s \) is its position in the absence of the SAW and \( a_x, a_y, a_z \) are the elementary vectors of the direct lattice, \( \delta \) is the Dirac distribution, \( G_s \) is the y component of a reciprocal-lattice node \( \mathbf{G} \) and \( \mu = (1/2) \mu_{GaAs}[1/\sin(\omega) + 1/\sin(2\theta - \omega)] \) is the effective absorption coefficient for the X-ray amplitude. The 1/2 factor accounts for the fact that \( \mu_{GaAs} \), the standard absorption coefficient, is defined with respect to the diffracted X-ray intensity (not amplitude), the importance of which will become apparent in the following since the satellite intensities are controlled by a subtle balance between X-ray absorption and acoustic wave amplitude decrease.

Defining \( \rho_Q (n_x a_x) \) and \( \zeta_Q (n_z a_z) \) by \( \rho_Q \sin(\zeta) = U_z Q_z \) and \( \rho_Q \cos(\zeta) = U_z Q_z \), \( A(\mathbf{Q}) \) yields

\[
A(\mathbf{Q}) \propto F(\mathbf{Q}) \sum_{G_s} \sum_{n_z=-\infty}^{\infty} \sum_{n_x=-\infty}^{\infty} \sum_{n_y=-\infty}^{\infty} \left[ \exp(-\mu n_z a_z) \right] \}
\]

\[
\times \exp[i(Q_x n_x a_x + Q_y n_y a_y + Q_z n_z a_z)]
\]

\[
\times \exp[i(\rho_Q (n_x a_x) \sin(q_s n_x a_x) + \zeta_Q (n_z a_z))]
\]

(3)

Using the identity \( \exp(it \sin \theta) = \sum_{p=-\infty}^{\infty} J_p(t) \exp(ip\theta) \), where \( J_p \) is the Bessel function of the first kind of integer order \( p \), \( A(\mathbf{Q}) \) can be written

\[
A(\mathbf{Q}) \propto F(\mathbf{Q}) \sum_{G_s} \sum_{n_z=-\infty}^{\infty} \sum_{n_x=-\infty}^{\infty} \sum_{n_y=-\infty}^{\infty} \left[ \exp(-\mu n_z a_z) \right] \}
\]

\[
\times \sum_{n_z=-\infty}^{\infty} \exp(iQ_x n_x a_x) \exp(-\mu n_z a_z)
\]

\[
\times J_p(\rho_Q (n_x a_x)) \exp[i\zeta_Q (n_z a_z)].
\]

(4)

Since we have \( q_s a_z \ll 1 \), the variation with \( n_z \) of \( \zeta_Q \) is slow. Similarly, we have \( \mu a_z \ll 1 \) and the variation with \( n_z \) of \( \rho_Q (n_x, a_x) \) is slow. Therefore, for each rod, satellite rod or crystal truncation rod, \( A(\mathbf{Q}) \) has strong maxima around each Bragg value \( G_z \) of \( Q_z \). For the calculation of the profiles of these maxima, the summation on \( n_z \) can be replaced by an integral, leading to

\[
A(\mathbf{Q}) \propto F(\mathbf{Q}) \sum_{G_s} \sum_{p=-\infty}^{\infty} \delta(Q_{jj} + p q_s - G_{jj}) H_p,4(Q_z - G_z)
\]

(5)

with

Figure 4
Measured (a) and calculated (b) (\omega/2\theta, \omega) intensity maps around the (002) Bragg peak (x = 2.1 mm, \( P_{elec} = 160 \text{ mW} \)). Note that, as the colour scale is logarithmic, the \( q_z \) width of the fundamental peak is much lower than that of the satellite peaks.
\[ H_{p,q}(z) = \int_0^\infty \exp(iq_z z) \exp(-\mu z) \rho \exp[i\xi_0(z)] \, dz. \]  

This expression shows that every Bragg peak is decorated by satellites in the \( q_x \) direction at positions \( p q_x \). While Bragg peaks and satellites have a \( \delta \) profile in the \( Q_{yi} \) plane, their extension and their profile in the \( Q_x \) direction are controlled both by the finite penetration of the X-rays due to absorption and by the finite extension of the Rayleigh mode in the \( z \) direction. For the sake of simplicity, we will consider, in the following, the case of symmetric reflections for which \( Q_z = 0 \), but the conclusions are valid in the general case. For \( Q_z = 0 \), we have \( \xi = 0 \) and \( \rho = 2 r U Q \exp(-p q_z z) \times \sin(p q_z z + \varphi/2 - \psi) \). Since near \( t = 0 \) we have \( J_0(t) = 1 + O(t^2) \) and \( J_2(t) \approx t^2 \), the integrand factor in \( H \) behaves like \( \exp(-\mu_p q_z z) = \exp(-\mu_p + \mu_0 q_z z) \) for large \( z \) with \( \mu_0 = 0.63 \, \text{mm}^{-1} \). From the NIST Standard Reference Database 126 (http://www.nist.gov/pml/data/xraycoef/) we have \( \mu_{GaAs} = 0.039 \, \text{mm}^{-1} \), leading to \( \mu_{002} = 0.14 \, \text{mm}^{-1} \) and \( \mu_{004} = 0.067 \, \text{mm}^{-1} \). For small \( U Q \), the asymptotic behaviour of the Bessel functions is reached for small values of \( z \) and the \( q_z \) profile of the diffracted intensity is essentially Lorentzian with a width \((1/2) (\mu + \mu_0) \). The width of the \( q_z \) profiles increases with \( p \), the Bragg peak being significantly narrower particularly in the \( 004 \) case. For larger values of \( U Q \), the oscillations of the Bessel function must be taken into account to precisely describe the \( q_z \) profiles but the main behaviour is kept as can be seen in the intensity map of Fig. 4: the \( q_z \) width increases with the satellite order, the Bragg peak \( q_z \) width being notably narrower than that of the satellite peaks.

So far, we have calculated, like others before us (Tucoulou et al., 2001), the diffracted amplitude \( A(Q) \) and the ‘natural’ intensity \( I_{nat} = AA^* \) in the \( q_x, q_y, q_z \) space. To obtain the effective intensity, \( I_{eff} \), one must convolute the natural intensity with the ‘instrumental’ resolution function. This function accounts for several sources of peak broadening: angular resolutions, monochromaticity of the X-ray beam and finite-size effects (footprint size, crystal defects etc.). The small ratio between \( q_x \) and \( Q \), \( q_x/Q_{002} = 55 \times 10^{-6} \) and \( q_x/Q_{004} = 27.6 \times 10^{-6} \), has two consequences: first, the resolution function can be taken as constant when exploring the intensity landscape around each Bragg peak; second, as already pointed out, for the symmetric diffraction conditions corresponding to the \( 002 \) and the \( 004 \) peaks, \( \omega \) scans can be considered as \( Q_x \) scans. The first point has an important consequence: in an \( \omega \) scan, i.e. a \( Q_x \) scan, all the peaks, the Bragg peak and the satellites, have the same \( Q_x \) profile, \( B(q_x) \), which corresponds to the cross section of the instrumental resolution function in the \( \omega \) direction. This unity of the profile is of major importance when determining the observed intensity of the peaks by least-square fits, \( O^p \). The ‘theoretical’ profile to be fitted can be written \( \sum_{d=-P}^P b \cdot B(Q_x - Q_{002} - q_x)/\Delta Q_x \) where \( \Delta Q_x \) is the profile width. The number of parameters to be fitted for \( 2P \) satellites is therefore \( P + 5 \): the \( P + 1 \) peak intensities, \( b \), \( Q_{002} \), \( q_x \) and \( \Delta Q_x \). This important constraint allows one to determine very weak satellite intensities even when they are poorly separated from each other [for instance, for the \( 004 \) scan, Fig. 5]. Good fits can be obtained with a Gaussian for \( B \). We find \( \lambda_a = 5.0 \pm 0.2 \, \text{\textmu m} \) around the \( 002 \) Bragg peak and \( \lambda_a = 5.2 \pm 0.2 \, \text{\textmu m} \) around the \( 004 \) Bragg peak.

It is of major importance to examine the consequences of the convolution in the \( Q_x \) direction, i.e. the \( \omega – 2\theta \) direction, on the effective intensities. As pointed out before, the natural width in the \( q_x \) direction rapidly varies from peak to peak while the resolution function remains constant. Therefore, the result of the convolution leads to geometrical correction factors, \( GCF = I_{eff}/I_{nat} \), which depend on the satellite order. These factors are similar to the corrections for surface X-ray diffraction measurements (Vlieg, 1997; Robach et al., 2000). In the literature devoted to the X-ray diffraction study of acoustic waves propagating on GaAs (Sauer et al., 1999), LiNbO\(_3\) (Tucoulou et al., 2001), Si (Tucoulou et al., 2000) or \( La_3Ga_5SiO_{14} \) (Roshchupkin, Irzhak, Snigirev et al., 2011), we have not found any example of calculation of such geometrical correction factors. Since the \( q_z \) profile of each peak depends on \( U \), the convolution and the calculation of the geometrical correction factors must be performed for each value of \( U \). An example of such a convolution is given in Fig. 4(b). In order to calculate the geometrical correction factors, we have measured the instrumental resolution function without SAWs, assuming that the profiles of the \( 002 \) and \( 004 \) Bragg peaks are controlled by the instrumental resolution function. For the sake of simplicity, we assumed that these profiles are Gaussian.

![Figure 5](image-url)  
**Figure 5**  
Fit of the rocking curve around the \( 004 \) Bragg peak for an RF power of \( P_{\text{exc}} = 160 \, \text{mW} \) (\( x = 2.1 \, \text{mm} \)). Black diamonds: observed intensity; red line: best fit with \( 2 \times 8 \) Gaussian satellites and one central Gaussian; black dotted line: best fit with only \( 2 \times 4 \) satellites and one central Gaussian.
We find \( \gamma = 4.6 \text{ pm mW}^{-0.5} \).

The different satellite intensities. Note that previous authors have faced the same problem (Tucoulou et al., 2001). This exclusion of the Bragg peak is compensated for by the high number of satellites measurable around the (004) peak.

4. Data analysis

Fig. 6 shows the results obtained for \( U \) from rocking curves around the (002) and (004) Bragg peaks as a function of the square root of the electric power. Two features appear clearly on this figure: first, the analyses around the (002) and (004) Bragg peaks lead to equivalent determinations of \( U \); second, the \( U \) values are proportional to the square root of the incoming RF power, as expected from the expressions of the acoustic Poynting vector (Royer & Dieulesaint, 2001). For the maximum CW power used (320 mW), the parameter \( U = 0.083 \text{ nm} \) implies surface \( x \) and \( z \) displacements of \( u_x(z = 0) = 0.08 \text{ nm} \) and \( u_z(z = 0) = 0.11 \text{ nm} \). Those correspond to surface strains \( \epsilon_{xx} = 9.9 \times 10^{-5} \), \( \epsilon_{zz} = 0 \), \( \epsilon_{xz} = 4.5 \times 10^{-5} \) (absolute values). Moreover, the acoustic power is then 2.44 W m\(^{-1}\) and the electromechanical conversion efficiency of the IDTe is 18 dB. These are good values for SAWs excited directly on GaAs, without the addition of a traditionally more efficient piezoelectric material such as LiNbO\(_3\) or ZnO.

This validation of our data reduction procedure allows laboratory studies of two physical questions:

(a) Using X-rays the absolute attenuation of the Rayleigh mode with distance from the IDTe can be determined. Figs. 7

### Table 1

Values of GCF, the geometrical correction factor, for different satellite orders around the (002) Bragg peak as a function of \( U \).

<table>
<thead>
<tr>
<th>( U ) (pm)</th>
<th>GCF(_0)</th>
<th>GCF(_1)</th>
<th>GCF(_2)</th>
<th>GCF(_3)</th>
<th>GCF(_4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>0.142</td>
<td>0.639</td>
<td>0.708</td>
<td>0.767</td>
<td>0.805</td>
</tr>
<tr>
<td>34</td>
<td>0.139</td>
<td>0.635</td>
<td>0.704</td>
<td>0.766</td>
<td>0.804</td>
</tr>
<tr>
<td>62</td>
<td>0.135</td>
<td>0.621</td>
<td>0.690</td>
<td>0.758</td>
<td>0.799</td>
</tr>
<tr>
<td>86</td>
<td>0.146</td>
<td>0.614</td>
<td>0.671</td>
<td>0.746</td>
<td>0.792</td>
</tr>
</tbody>
</table>
and 8 illustrate this study. For distances larger than $x = 2\text{ mm}$ from the IDTe, we find the Rayleigh mode to be exponentially damped with an attenuation coefficient of $5.9 \text{ dB cm}^{-1}$ at 550 MHz. This value is consistent with existing data: Slobodnik reported about $15 \text{ dB cm}^{-1}$ at 1 GHz for different cut and propagation directions (Slobodnik, 1972). From this value, we derive $4.5 \text{ dB cm}^{-1}$ at 550 MHz, assuming a squared frequency variation of the attenuation [which is valid when the wave interacts with the thermal phonons (Truell et al., 1969)]. This estimation is satisfyingly close to our measured value. We also find the SAW amplitude to be identical on either side of the IDTe, proving that no spurious reflections off the receiving IDT lead to destructive interferences of the wave amplitude.

(b) The important relative variations of the satellite peaks with the Rayleigh mode amplitude allow one to study it as a function of Mod SAW duty cycles, when modulating the RF power, as illustrated in Fig. 9. We obtained rocking curves around the (002) Bragg peak for several duty cycles of constant period, $T_{\text{mod}} = 20 \mu\text{s}$, and of variable ‘on’ time, $T_{\text{on}}$. This implies that, whereas the average displacement should decrease for weaker duty cycles, the instantaneous displacement seen when the SAW is ‘on’ should be identical. As shown in the first two columns of Table 3, for each duty cycle labelled by the ratio $\tau = T_{\text{on}}/T_{\text{mod}}$, we can satisfactorily fit the rocking curve by a linear combination of the rocking curves obtained for the two extreme conditions, $\tau = 0$ and $\tau = 1$. Fig. 10 illustrates the quality of the fit obtained with such a linear combination. This result paves the way to a determination of the acoustic amplitude using non-continuous wave excitation. For this determination, the Bragg peak must be excluded since its intensity depends on the ratio $\tau$, but the relative satellite intensities are the same for any $\tau$ since they are only due to the times during which the incoming power is ‘on’. The third column of Table 3 gives the acoustic wave amplitude, $U$, measured using the first three satellites around the (002) Bragg peak. We verified, using the CW SAW rocking curve, that the determination of $U$ using the three satellites plus the Bragg peak leads to the same result as the determination with only the three satellites. This possibility of determining $U$ under Mod SAW is important since it allows the use of high electric power, which for a continuous wave excitation would damage the transducers.

5. Discussion and conclusion

While a strict justification of our kinematic approach would imply a dynamic calculation, the overall results we obtained – good agreement between the values of $U$ determined around

![Figure 8](image1.png)

**Figure 8**
Variation of the Rayleigh mode amplitude as a function of the distance to the IDTe ($P_{\text{elec}} = 160 \text{ mW}$). Blue dots: variation of the measured acoustic amplitude in dB (left axis) and its corresponding $U$ value in nm (right axis in log scale); black line: exponential fit. The vertical black line at $x = 0$ corresponds to the right edge of the IDTe.

![Figure 9](image2.png)

**Figure 9**
Rocking curves around the (002) Bragg peak for duty cycles of constant period, $T_{\text{mod}} = 20 \mu\text{s}$, and of variable ‘on’ time, $T_{\text{on}} = \tau T_{\text{mod}}$ (x = 2.1 mm, $P_{\text{elec}} = 160 \text{ mW}$).
Table 3
Determination of $U$ using duty cycles.

<table>
<thead>
<tr>
<th>$\tau = T_{\text{me}}/T_{\text{sw}}$</th>
<th>$\alpha$</th>
<th>$U$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.08 ± 0.07</td>
<td>0.057 ± 0.003</td>
</tr>
<tr>
<td>0.25</td>
<td>0.33 ± 0.07</td>
<td>0.051 ± 0.003</td>
</tr>
<tr>
<td>0.5</td>
<td>0.58 ± 0.07</td>
<td>0.051 ± 0.003</td>
</tr>
<tr>
<td>0.75</td>
<td>0.79 ± 0.07</td>
<td>0.050 ± 0.003</td>
</tr>
<tr>
<td>1</td>
<td>0.054 ± 0.003 (0.053$^*$)</td>
<td></td>
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</tbody>
</table>

the (002) and the (004) Bragg peaks, exponential decay of $U$ with distance from the IDT$_c$. determination of a constant $U$ for variable duty cycle – validate our kinematic approach. This approach is based on four main points: (i) good resolution in the $q_x$ direction, $\Delta q_x \simeq 5 \times 10^{-4}$ nm$^{-1}$, obtained using a four-crystal monochromator and a two-crystal analyser; (ii) reduction of the footprint to the crystal region affected by the acoustic wave using appropriate masks; (iii) calculation of the Rayleigh mode in the framework of linear elasticity of continuous media; (iv) taking into account ‘geometrical’ corrections due to finite instrumental resolution in the $q_z$ direction, $\Delta q_z \simeq 10^{-3}$ nm$^{-1}$.

It is worth noting that the determination of $U$ implies measurements of quite low satellite intensities in the immediate vicinity of the Bragg peak, for example $I_s/I_0 = 10^{-3}$ for $U = 0.05$ nm around (002) and $I_s/I_0 = 2 \times 10^{-4}$ for $U = 0.036$ nm around (004). These low values hinder a strict statistical estimate of the errors. Nevertheless, a study of the least-squares dependency on $U$ allows one to estimate the uncertainty $\Delta U/U$ to be of the order of 0.06. The exponential damping of the SAW leads to a relative variation of ±0.07 for $U$ in the 2 mm width of the X-ray spot around the (002) Bragg peak. This variation is quite similar to our statistical uncertainty and allows us to neglect the SAW attenuation along its propagation direction in the data modelling that we have performed. Lastly, the measure of $U$ depends on the correctness of the expression chosen for the acoustic mode. A minute error on the IDT orientation with respect to (110) will lead to a modification of expression (1), the acoustic wave no longer being a Rayleigh mode but a pseudo Rayleigh mode. A quantitative analysis of such an effect is far beyond the scope of this paper.

To conclude, we show that using both a careful experimental procedure and an accurate data analysis including instrumental convolution, measurements of surface acoustic wave amplitude can be performed on a laboratory X-ray diffractometer, provided the SAW spatial frequency is such that $q_x > \Delta q_x/2$. This work was performed on a GaAs monocrystal. However, since the satellite features appear in the in-plane direction, this diffraction technique can be applied to determine acoustic amplitudes in thin strained films. The ability to perform such determinations with a laboratory diffractometer is important given the versatility of experimental studies using surface acoustic waves.

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References


