Imaging Surface Acoustic Waves on GaAs by X-ray Diffraction Techniques

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Abstract – Surface acoustic waves (SAWs) are excited on the GaAs (001) surface by using interdigital transducers, designed for frequencies of up to 900 MHz. The emitted surface phonons with wave-lengths down to 3.5 μm are visualized and characterized by combined x-ray diffraction techniques. By increasing the amplitude of the SAW, high resolution x-ray diffraction profiles show up to 12 phonon-induced satellite reflections besides the GaAs (004) reflection with a width of 9 arcsec each. The diffraction pattern is simulated numerically, applying the kinematical scattering theory to a model crystal of a size adapted to the experimental situation. From fits to measured diffraction profiles at different excitation voltages, the SAW amplitudes were calculated and found to be in the sub-nm range.

Using stroboscopic topography, the SAW emission of a focussing transducer geometry is imaged.

INTRODUCTION

Phonon excitation in crystals have been investigated for some time by x-ray, neutron and light diffraction methods. Of interest is the visualization of the wave field and the determination of the amplitude of the surface wave. Possible applications are tunable monochromators for x-rays [1] or neutrons [2].

Surface acoustic waves (SAWs) on the most prominent SAW material $LiNbO_3$ were studied by different x-ray methods: topography in the MHz frequency region [3,4] and at 300 MHz [5]. Under grazing incidence angles, x-ray beam modulation was demonstrated [6] and the influence on surface reflections was shown [7].

Here we describe x-ray diffraction experiments under SAW excitation on GaAs. The orientation of the surface is (001) and the direction of SAW propagation is [110]. The efficiency of both parallel and focussing transducers is demonstrated and it is shown, that the mechanical amplitudes below 1 nm can be detected. Due to its properties as a direct band-gap semiconductor, GaAs is a very promising material for further SAW-applications [8], as well as a material for a SAW-tunable x-ray monochromator.

DIFFRACTION TOPOGRAPHY

The synchrotron x-ray source at the European Synchrotron Radiation Facility (ESRF), Grenoble, offers the possibility to perform time resolved experiments. In the 16-bunch mode, out of 992 positions, only 16 uniformely distributed positions of the ring are populated by electron bunches. One bunch packet passes the insertion device in less than 100 ps. In this mode of operation, the source provides well defined x-ray pulses with a repetition frequency of 5.68 MHz. As described elsewhere [9], the driver frequency of the synchrotron was multiplied 102 times by a phase-locked loop (PLL), amplified and used as excitation frequency for the SAW-device.

Thus the surface wave in phase to the x-ray pulses and one obtains a standing image of the propagating wave. The large x-ray spot size of 45×15 mm^2 at the beamline ID19 allows to illuminate the whole sample surface. For both topography and high-resolution diffraction, the energy was adjusted by a double-crystal Si(111) monochromator to 12 keV. Using the symmetric (004) reflection of the GaAs single crystal, the penetration depth of the x-rays is below 5 μm and about the same as the penetration depth of the surface acoustic wave.

In figure 1, an image obtained from a sample with a focussing transducer structure is shown. Due to the projection of the sample surface at the Bragg angle of 20.7°, the image is compressed and tilted in the vertical direction.

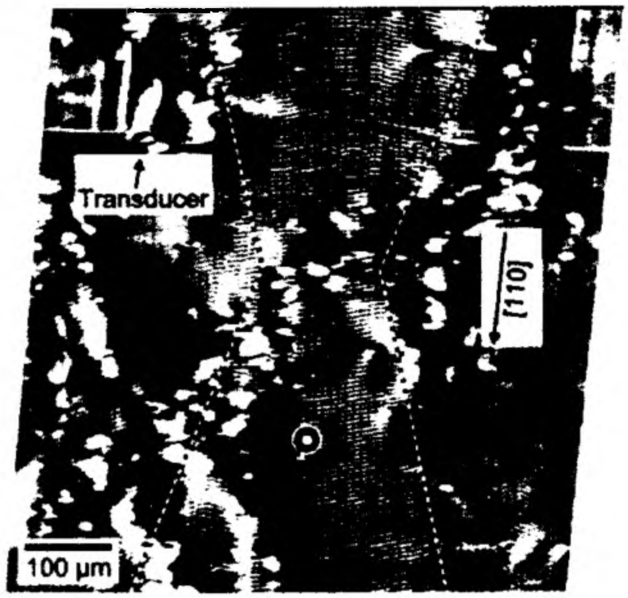

Figure 1
X-ray topograph of GaAs (reflection (004), λ = 0.10 nm) with SAW excitation, emitted from a focussing transducer on the top of the image, propagating along [110].

The SAW-propagation direction [110] is indicated, and the SAW is imaged by a strain-induced variation in contrast with the same period as the wavelength, Λ_{SAW} = 5.0 µm. The shadow lines on the top mark the edges of the transducer. Beyond the SAW induced contrast variation, the defect structure of the substrate becomes visible. It represents a dislocation network typical for Bridgeman grown GaAs, which is distributed over the whole crystal. The SAW is focussed to a spot 500 µm away from the transducer, marked by a point.

HIGH RESOLUTION DIFFRACTION

Besides topography, high resolution reciprocal space intensity maps were collected at the GaAs (004) reflection with excitation of surface waves with a wavelength of Λ_{SAW} = 3.5 µm. For this purpose, a four-crystal setup including a Si(111) double monochromator, the sample crystal and a Si(111) analyser was used. For a detailed description see [10]. In order to illuminate only the fraction of the acoustic path on the sample surface, the beamsize was restricted to a spot of 0.2 × 0.2 mm^2.

Rocking the sample and the analyser stage allows to record mappings in the area including the direction of SAW propagation $\boldsymbol{q}_x$, and the direction perpendicular to it $\boldsymbol{q}_z$. A logarithmically scaled mapping of the region around the GaAs(004) reflection with SAW excitation is shown in figure 2.

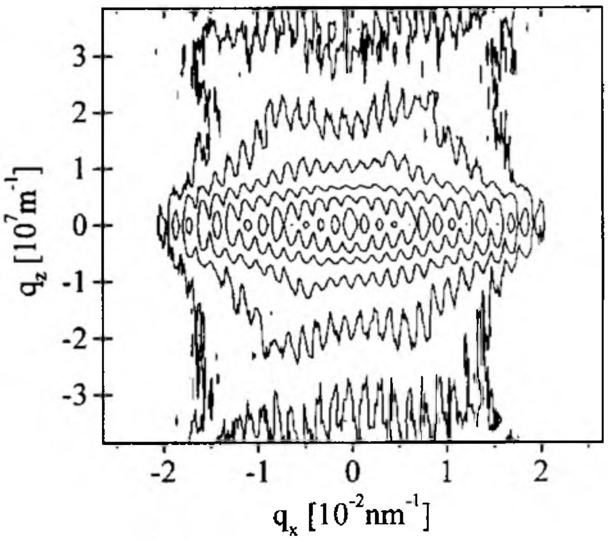

Figure 2
Log.-scaled, reciprocal space intensity map at the GaAs (004) reflection with SAW excitation.

The mapping shows the GaAs reflection with a width of 9 arcsec in the center, where $\boldsymbol{q} = \boldsymbol{Q} - \boldsymbol{K} = 0$ holds, with $\boldsymbol{Q}$ being the diffraction vector and **K** the reciprocal lattice vector (004). With an SAW excitation voltage of 4V$_{p\text{-}p}$, 12 symmetric satellite peaks with an amplitude of up to 50% of the (004) reflection appear along $\boldsymbol{q}_z$ at the positions:

$$\boldsymbol{Q} = \boldsymbol{K} + N \cdot \boldsymbol{q}_{SAW}$$

For an evaluation of the diffraction data, the scattering process was treated kinematical and the fourier transform over the crystal lattice was performed numerically. The x-ray scattering amplitude is given by the Fourier transform of the electron density and can be written in the general form:

$$F(\boldsymbol{Q}) = \sum_{j=1}^{N} f_j \cdot \exp[i\boldsymbol{Q} \cdot \boldsymbol{r}_j] \qquad (1)$$

The sum runs over all N atoms in the crystal, where f_j is the atomic form factor and r_j is the position of the atom i. The sum is calculated at each point q along q_x. With surface phonons of Rayleigh type, propagating along q_x, the transversal displacements of the atoms are along q_z and the longitudinal displacements are along q_x.

The third coordinate remains constant. The displacement field can be calculated [11] and is introduced in the model for the calculation of the scattering amplitude. To restrict the sum to a reasonable number of Fourier terms, the atoms are grouped to cells, which contain 5 elementary cells along q_x and 10 along q_z.

The third direction can be ignored, because the diffraction vector Q has no component in this direction. Thus the Fourier sum of equation (1) can be written in the following way:

$$F(Q) = \sum_{j=1}^{N} f_S(Q) \cdot \exp[iQ \cdot (r_S + u(r_S))] \qquad (2)$$

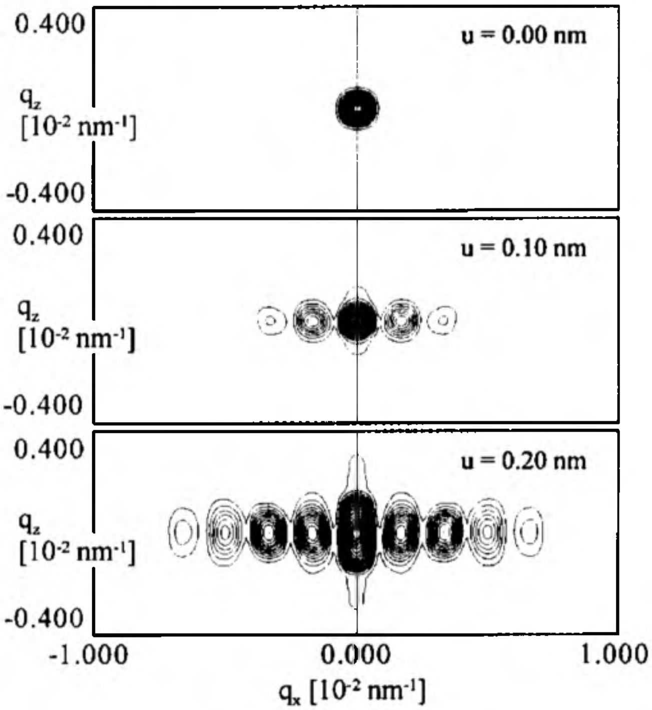

Figure 3

Calculated reciprocal space maps of the GaAs (004) reflection for SAW amplitudes of 0.00 nm, 0.10 nm and 0.20 nm. The contour lines show iso-intensity levels on a linear scale.

Here the sum extends over N_S cells. f_S denotes the structure factor of one cell at the position r_S. The displacement of the SAW is taken into account by adding the displacement vector $u_S(r_S)$ at each position of a cell.

The structure factor f_S of the cell is calculated by summing over all the atoms inside:

$$f_S(Q) = \sum_{j=1}^{N_C} f_j(Q) \cdot \exp[iQ \cdot r_j] \qquad (3)$$

The comparatively small displacements due to the SAW within one cell of the specified size can be neglected, because the total amplitude of the SAW over its wavelength of some microns is below 1 nm.

With this concept, we are able to calculate the scattering pattern for the performed scans numerically by summing over about $N_S = 2.5 \cdot 10^6$ cells. Periodic boundary conditions along q_x have to be considered, which leads to a sum of cells along a length of multiples of Λ_{SAW} in this direction. Of course, the width of the peaks in the calculation depends on the number of scattering cells along q_x, which were used.

To match the measured width of 9 arcsec, which is limited by the resolution of the experimental setup, it is sufficient to sum over a number of cells equivalent to the length of Λ_{SAW}.

Along q_z, a sum of cells according to a length of 4.5 µm from the crystal surface is required, because this is approximately the x-ray penetration depth. Using the optimized routines implemented in the software package *Discus* [12], the calculation is performed in less than an hour. Figure 3 shows the results of the calculations for SAW amplitudes of 0.00 nm, 0.10 nm and 0.20 nm. Hereby the calculated intensity distribution is convoluted with the measured resolution function. This resolution function can be described by a Gauss distribution curve with a half-width of $1.5 \cdot 10^{-3}$ nm^{-1}.

In figure 4, the results of calculations for SAW amplitudes of 0.00 nm up to 0.20 nm are shown together with measured q_x-scans at a from top to bottom linear increased excitation voltage.

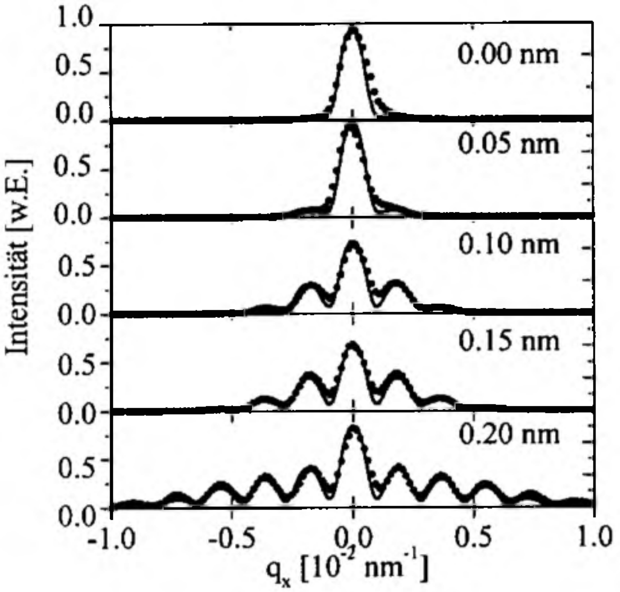

Figure 4
Measured cuts through the reciprocal space map of figure 2 along q_x *(points) at* $q_z=0$ *together with simulations (lines) for SAW amplitudes from 0.00 nm to 0.20 nm.*

SUMMARY AND ACKNOWLEDGEMENT

In summary, the experiment demonstrates the potential of imaging surface waves on GaAs both in direct and in reciprocal space. By topography, the efficiency of focussing transducers was probed. As there exists the technology for structurizing the GaAs surface, a further application will be the imaging of SAW amplitude and velocity changes by interacting with beam-steering structures in the path of the SAW and with overlays.

By high-resolution-diffraction with an x-ray of small spot-size, the amplitude of the SAW can be measured with a high lateral resolution, even below surface layers.

One of the authors (W.S.) acknowledges support by the German-Israelian-Foundation under project no. I-006-401.02/95.

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