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Abstract. We present the numerical optimization and the technological development progress of x-ray optics based on asymmetric germanium crystals. We show the results of several basic calculations of diffraction properties of germanium x-ray crystal monochromators and of an analyzer-based imaging method for various asymmetry factors using an x-ray energy range from 8 to 20 keV. The important parameter of highly asymmetric monochromators as image magnifiers or compressors is the crystal surface quality. We have applied several crystal surface finishing methods, including advanced nanomachining using single-point diamond turning (SPDT), conventional mechanical lapping, chemical polishing, and chemomechanical polishing, and we have evaluated these methods by means of atomic force microscopy, diffractometry, reciprocal space mapping, and others. Our goal is to exclude the chemical etching methods as the final processing technique because it causes surface undulations. The aim is to implement very precise deterministic methods with a control of surface roughness down to 0.1 nm. The smallest roughness (~ 0.3 nm), best planarity, and absence of the subsurface damage were observed for the sample which was machined using an SPDT with a feed rate of 1 mm/min and was consequently polished using a fine polishing 15-min process with a solution containing SiO_2 nanoparticles (20 nm). © 2015 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.OE.54.3.035101]

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1 Introduction

Weakly absorbing objects (such as biological, polymers, and so on) typically have ~ 1000 times stronger contrast in the x-ray region in the so-called phase-contrasted imaging mode as compared to the absorption imaging mode.¹ This was the motivation for the x-ray microscopy setup we developed, which is based on an x-ray microfocus generator attaining a spatial resolution down to $3\text{ }\mu\text{m}$ with an average lateral coherence length of 0.3 to $13\text{ }\mu\text{m}$ and up to a 140-fold geometrical magnification.^{2,3} However, such a setup uses broad polychromatic radiation, therefore, the extracted quantities from the x-ray images, such as attenuation coefficient and the retrieved phase, are affected by beam hardening effects and the x-ray images have usually a reduced contrast due to the presence of scattering. The use of monochromatic radiation will, therefore, be of benefit but at the cost of a significant photon flux loss. However, the recent developments and start-ups of more intense laboratory x-ray sources using liquid anode⁴ reaching brilliance of the bending magnet sources in combination with collimation Montel optics⁵ and high-efficient direct conversion integrating or single-photon counting x-ray detectors^{6,7} allow us to employ in an efficient way the x-ray crystal optics for imaging

applications in laboratory conditions. Such a setup will allow for quantitative scattering-free x-ray imaging. This approach using an Incoatec microfocus generator with a copper anode, Montel optics, inline germanium channel-cut two-dimensional (2-D) magnifier, and Medipix detector was recently demonstrated under laboratory conditions, providing an effective pixel size of $\sim 4\text{ }\mu\text{m}$ and reaching an acquisition time of 60 s for a single image frame.⁸ With further optimization of the parameters and by employing more brilliant sources (e.g., liquid jet source), monochromatic imaging with a high resolution ($\sim 1\text{ }\mu\text{m}$) and short acquisition time (reaching ~ 1 s) can be performed in the laboratory. In this work, we are numerically analyzing the properties of single germanium reflections with an aim toward designing an optimized compact in-laboratory system for x-ray imaging based on germanium (Ge) crystals. The main objectives of the compact laboratory x-ray imaging system are to effectively increase the propagation distance and decrease the effective pixel size of the detector (below $1\text{ }\mu\text{m}$) to achieve a sufficient magnification of the sample and to improve coherence and increase the output intensity. For this purpose, high-asymmetry x-ray crystal germanium monochromators can work as efficient image magnifiers in the grazing incidence mode close to the critical angle of total external reflection.⁹ The

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use of Ge crystals offers several advantages over silicon crystals. The germanium crystals have an integrated reflectivity up to three times larger than that of silicon crystals. The spatial resolution of Ge crystal magnifiers is typically two times better than the spatial resolution of Si crystal magnifiers.¹⁰ The maximum spatial resolution attainable with an asymmetric crystal magnifier is reached when the input acceptance for a given energy is at the maximum. The input acceptance varies with the asymmetry angle according to the Rustichelli equation,¹¹ reaching a local maximum in the vicinity of the critical angle. We refer to this value as the high-resolution optimum. The calculations of the optimal magnification factor, asymmetry factor, information depth, and spatial resolution for selected germanium crystal lattice orientations and x-ray energies are presented in Sec. 2. Simulation and comparison of the intensity throughput of the proposed analyzer-based imaging (ABI)^{12,13} system using the first optical element as the high-asymmetry magnifier and the second optical element as the symmetrical analyzer were done. The angular sensitivity of the selected symmetrical analyzer crystals was calculated as well. Calculations of ABI images using the X-tract software package¹⁴ are shown. It is possible to use two V-channel monochromators in a crossed configuration or as an alternative, “artificial” V-channel monochromators for 2-D magnification of the x-ray beam. Four pieces of highly asymmetric germanium crystal imaging monochromators built in a V-channel configuration were prepared by planar technology and successfully applied for high-resolution holographic imaging using synchrotron radiation sources.^{15,16} One disadvantage of such a system is the finite distance between crystals magnifying in the horizontal and vertical directions which causes the effective propagation distances between the horizontal and the vertical directions to be different.¹⁶ This problem can be solved by further development of monolithic V-shaped¹⁷ or Z-shaped¹⁸ monochromators, for which we are able to set the horizontal and the vertical diffractions as close together as possible while preserving the inline configuration. The very important parameter of highly asymmetric monochromators as image magnifiers is the crystal surface quality, because the long-range surface undulations⁹ deteriorate the final image quality.^{8,19} We are also developing the surface processing technologies which can solve the problematic preparation of channel-cut monochromators and consequently allow the production of surfaces of such quality as those prepared by the conventional planar technology. We have applied advanced nanomachining using single-point diamond turning (SPDT) to prepare the crystal surfaces and using several finishing methods including conventional mechanical lapping, chemical polishing, and chemomechanical polishing. We have evaluated these methods by means of atomic force microscopy (AFM), surface profilometry, Raman spectroscopy, and reciprocal space mapping and show the results in Sec. 3.

2 Basic Calculations of Germanium Magnifiers

2.1 Optimal Magnification Factor

The calculation of the optimal magnification factor for various lattice parameters and energies was done according to the equation $M_{\text{opt}} = \sin(2\theta_B)/\theta_C\sqrt{2}$, where θ_B is the Bragg angle and θ_C is the critical angle for total external

Fig. 1 Dependence of the optimal magnification factor on x-ray energy for selected germanium crystal lattice orientations of (400), (220), and (111).

reflection.²⁰ Figure 1 shows the dependence of the optimal magnification factor on x-ray energy for selected germanium crystal lattice orientations of (400), (220), and (111). We can observe an increase of the optimal magnification factor near the absorption K-edge energy (11.1 keV) for germanium. The increase is caused by a decrease of the critical angle for total external reflection, which is dependent on the real part of the atomic scattering factor.

In the following, we will consider only selected x-ray lines: CuK α 1 (8.05 keV), GaK α 1 (9.25 keV), and MoK α 1 (17.48 keV), and selected lattice orientations for which the optimal magnification factors are shown in Table 1.

2.2 Optimal Asymmetry Angle

To select the optimal asymmetry angle, the accuracies of the cutting and the surface finishing techniques of the crystal have to be considered. For the determination of the suitable asymmetry factor, the equation for magnification factor m in one-dimension (1-D) can be used:

$$m = \frac{\sin(\theta_B + \delta_h + \alpha)}{\sin(\theta_B + \delta_i - \alpha)}, \quad (1)$$

where θ_B is the Bragg angle, α is the asymmetry angle (the inclination angle of the diffraction planes with respect to the surface), $\delta_i = 0.5(1 + m)\delta_S$ is the refraction correction for the input beam and $\delta_h = 0.5(1 + 1/m)\delta_S$ is the refraction correction for the output beam, and δ_S is the deviation of the center of the Darwin–Prins curve from the Bragg angle θ_B for a symmetrical diffraction ($\alpha = 0$).^{21,22} Typical values of δ_i and δ_h are in the order of 10^{-3} to 10^{-6} . Table 2 shows the values of magnification factors calculated according to Eq. (1). The values of magnification factors were selected to be as close as possible to the optimal

Table 1 Optimal magnification factors for selected x-ray lines and lattice orientations.

	CuK α 1	GaK α 1	MoK α 1
Ge(400)	120.23	127.13	135.39
Ge(220)	93.58	96.18	97.32
Ge(111)	60.34	61.18	60.20

Table 2 Optimal asymmetry angles with associated magnification factors for selected x-ray lines and lattice orientations.

	CuK α 1			GaK α 1			GaK α 1		
	θ_B (deg)	α (deg)	m	θ_B (deg)	α (deg)	m	θ_B (deg)	α (deg)	m
Ge(400)	32.996	32.5	88.08	28.276	27.9	101.21	14.521	14.3	102.59
Ge(220)	22.648	22.2	72.94	19.571	19.2	76.92	10.212	10.0	75.64
Ge(111)	13.639	13.2	47.30	11.837	11.4	43.64	6.233	6.0	46.54

magnification factors shown in Table 1. The decrease of the magnification factors shown in Table 2 is caused by setting off refractive corrections which are not considered in the equation for the optimal magnification factor and by considering the manufacturing accuracy of the asymmetry angle of 0.1 deg, reducing the magnification value as well. We can determine the optimal asymmetry angle α after considering the refractive corrections and the manufacturing accuracy, as shown in Table 2.

2.3 Calculations of Information Depth

The information depth z_{id} is the perpendicular distance from the surface of the crystal for which the sum of the attenuation factors for incident and diffracted waves, μ_{e0} and μ_{eh} , respectively, is equal to $1/e$ and can be expressed as follows:

$$\frac{1}{z_{id}} = \frac{1}{z_{e0}} + \frac{1}{z_{eh}} \Rightarrow z_{id} = \frac{\gamma_0 + \gamma_h}{\gamma_0 \mu_{eh} + \gamma_h \mu_{e0}}, \quad (2)$$

where z_{e0} and z_{eh} are the penetration depths for the incidence and diffracted waves, and γ_0 and γ_h are the direction cosines of the incidence and diffracted wave vectors, respectively.^{23,24}

When the diffraction occurs, the information depth has a local minimum at the center of the reflective domain. The minimal information depth is equal to the extinction depth Λ_L in the angular dependence of the information depth (Fig. 2). The extinction depths are shown in Table 3.

Using the MoK α 1 radiation results the smallest extinction depth, which is shown in Table 3. The penetration depth, information depth, and also the extinction depth directly affect the spatial and temporal resolutions of x-ray imaging systems; therefore, in this case, it can be assumed that the use of MoK α 1 radiation will increase the spatial resolution

Table 3 The evaluation of the extinction depth Λ_L for selected x-ray characteristic lines, asymmetry angles, and crystal lattice orientations.

	CuK α 1		GaK α 1		MoK α 1	
	α (deg)	Λ_L (nm)	α	Λ_L (nm)	α	Λ_L (nm)
Ge(111)	13.2	68.6	11.4	78.8	6.0	60.8
Ge(220)	22.2	71.6	19.2	74.7	10.0	59.3
Ge(400)	32.5	97.0	27.9	98.3	14.3	74.5

of the x-ray imaging system. We should note that the imperfections on the surface and also subsurface damage of the x-ray optics may significantly impair the values of the information depth compared with the calculated theoretical values.

2.4 Spatial Resolution

The spatial resolution limit of the magnifier can be calculated according to Abbe's resolution criterion $d = \lambda/2 \text{ NA}$, where λ is the wavelength and NA is the numerical aperture. The numerical aperture of the crystal optics equals to half the width of the diffraction curve, thus $d = \lambda/\omega_i$, where ω_i is the angular acceptance (FWHM) of the magnifier.¹⁰ Angular acceptances and output divergences for selected x-ray characteristic lines and crystal lattice orientations are shown in Table 4.

The calculated spatial resolution for selected x-ray characteristic lines, asymmetry angles, and crystal lattice orientations is shown in Table 5. The values are comparable for Ge(111) and Ge(220) using all selected characteristic x-ray lines. In case of the GaK α 1 x-ray line, the difference between

Fig. 2 Angular dependences of information depths for (a) CuK α 1, (b) GaK α 1, and (c) MoK α 1 x-ray characteristic lines for selected germanium crystal lattice orientations of (400), (220), and (111).

Table 4 Results of acceptance and divergence calculations for selected x-ray characteristic lines, asymmetry angles, and crystal lattice orientations.

	CuK α 1 x-ray line			GaK α 1 x-ray line			MoK α 1 x-ray line		
	Asymmetry angle (deg)	Acceptance (s)	Divergence (s)	Asymmetry angle (deg)	Acceptance (s)	Divergence (s)	Asymmetry angle (deg)	Acceptance (s)	Divergence (s)
Ge(111)	13.2	93.90	2.21	11.4	87.14	1.99	6.0	49.40	1.14
Ge(220)	22.2	102.08	0.99	19.2	86.72	1.11	10.0	48.55	0.66
Ge(400)	32.5	74.04	0.85	27.9	62.92	0.63	14.3	36.00	0.37

Table 5 Results of spatial resolution calculations for selected x-ray characteristic lines, asymmetry angles, and crystal lattice orientations.

	CuK α 1 x-ray line		GaK α 1 x-ray line		MoK α 1 x-ray line	
	Asymmetry angle (deg)	Spatial resolution (μm)	Asymmetry angle (deg)	Spatial resolution (μm)	Asymmetry angle (deg)	Spatial resolution (μm)
Ge(111)	13.2	0.338	11.4	0.317	6.0	0.296
Ge(220)	22.2	0.311	19.2	0.319	10.0	0.301
Ge(400)	32.5	0.429	27.9	0.439	14.3	0.406

Ge(111) and Ge(220) occurs up to the third decimal place. We have obtained a slightly worse spatial resolution using Ge(400), which is caused by the lower angular acceptance as shown in Table 4.

2.5 Simulation of One-Dimensional Analyzer-Based Imaging System

The 1-D ABI system consists of the first asymmetrically cut crystal for magnification of the sample and the second symmetrically cut analyzer crystal for analyzing the refraction angles and phase contrast. Results of the simulations of intensity throughput passing through the ABI system, which is schematically illustrated in Fig. 3, are shown in Sec. 2.6 of this contribution.

2.6 Simulation of the Intensity Throughput

High-intensity throughput is an important parameter required when using either metrological or imaging applications, where it is needed to shorten the exposure time. The intensity throughput is related to the angular acceptance of the crystal. A higher angular acceptance allows one to collect more divergent x-rays impinging on the crystal. Asymmetrically cut crystals Ge(111), Ge(220), and Ge(400) with selected optimal asymmetry angles, which are shown in Table 2, are proposed as the first optical elements in the ABI system. The comparison of the intensity throughput was done by setting the angular detector with a perpendicular orientation to the diffraction plane using the SKL simulation program.²⁵ The simulation results are shown in Figs. 4(a)–4(c).

Fig. 3 Schematic illustration of one-dimensional (1-D) analyzer-based imaging (ABI) system, where the asymmetrically cut 1-D magnifier for a 20-fold magnification of the sample and symmetrically cut analyzer crystal for observing the phase gradient are used.

Fig. 4 The simulation result of intensity throughput using magnifier crystals Ge(111), Ge(220), and Ge (400) for selected x-ray lines: (a) CuKα1, (b) GaKα1, and (c) MoKα1.

Fig. 5 The simulation result of final intensity throughput using asymmetrically cut magnifier and symmetrically cut analyzer crystals Ge(111), Ge(220), and Ge (400) for selected x-ray lines: (a) CuKα1, (b) GaKα1, and (c) MoKα1.

Figures 5(a)–5(c) show the comparisons of the final intensities which are passing through both the asymmetrically cut magnifier and the symmetrically cut analyzer crystals.

We can conclude that Ge(111) allows the best intensity throughput for all selected x-ray lines, which, after the second diffraction, provides approximately a 10-fold decrease of the intensity. The use of Ge(220) causes as much as a 20-fold decrease of the x-ray intensity and the use of Ge(400) causes an 80-fold decrease of the x-ray intensity after the second diffraction.

2.7 Angular Sensitivity

The important parameter of the analyzer crystal is its angular sensitivity in order to analyze the phase gradient. The steeper slope of the diffraction curve provides a higher angular sensitivity for analyzing the phase gradient.

Calculations of the dynamical angular ranges of Ge(111), Ge(220), and Ge(400) analyzers were done using the left and right sides of the rocking curves (RCs) for selected intensity points (0.3 and 0.8) of CuKα1, GaKα1, and MoKα1 radiation. The angular sensitivity is $\Delta I / \Delta \theta$ [a.u./arcsec], where $\Delta I = 0.8$ to 0.3 and $\Delta \theta$ is the range of angles corresponding to the intensity difference ΔI . The theoretical RCs shown in Fig. 6 were used for calculation. The sigma polarization was used for easier comparison. The results are shown in Table 6.

The comparison in Table 6 shows that the Ge(400) analyzer is approximately two times more sensitive than the Ge(111) analyzer when comparing all selected x-ray lines. The comparison between the (220) and (111) lattice orientations shows that (220) is approximately one decimal point more sensitive than the (111) lattice orientation, except for the MoKα1 radiation on the left side of the RC where the sensitivity is higher.

Fig. 6 The calculations of theoretical rocking curves (RCs) for symmetrically cut analyzer crystals Ge (111), Ge(220), and Ge (400) for selected x-ray lines: (a) CuKα1, (b) GaKα1, and (c) MoKα1.

Table 6 Angular sensitivities $\Delta I/\Delta\theta$ [a.u./arcsec] for selected x-ray lines corresponding to the diffraction curves depicted in Fig. 6. L means the sensitivity on the left side of the curve, and R means the sensitivity on the right side of the curve.

	CuK α 1		GaK α 1		MoK α 1	
	L	R	L	R	L	R
Ge(m)	0.33	0.15	0.41	0.23	0.56	0.15
Ge(220)	0.48	0.21	0.56	0.32	0.86	0.22
Ge(400)	0.73	0.27	0.74	0.43	1.24	0.31

2.8 Calculation of Analyzer-Based Imaging Images

The first step before calculation of the ABI image was the simulation of the phase contrast image of the polymethylmethacrylate sphere [Fig. 7(a)] using SRCLsim, which is the forward imaging simulation program for computed tomography.^{26,27} From the simulated phase contrast image, we reconstructed the intensity [Fig. 7(b)] and phase [Fig. 7(c)] distributions in the object plane using the algorithm based on the transport of the intensity equation suitable for a homogeneous object; the so called “TIE-hom phase/amplitude retrieval method”²⁸ in X-TRACT application. The two images of the intensity and phase are the input images into “OMNI phase microscope dialog” for simulation of the ABI image in X-TRACT application. The result of the ABI image simulation using Ge(111) analyzer and CuK α 1 radiation is depicted in Fig. 7(d).

Simulations of ABI images for selected x-ray lines CuK α 1, GaK α 1, and MoK α 1 were done. Comparison of the images using Ge(111), Ge(220), and Ge(400) analyzers for each x-ray line was done as well. The intensities from line profiles, as are depicted in Fig. 7(d), were evaluated in each ABI image and the results corresponding to the selected x-ray line are shown in Fig. 8.

Evaluation of the Michelson contrast²⁹ was done from the intensity line profiles according to $(I_{\max} - I_{\min})/(I_{\max} + I_{\min})$ and the results are shown in Table 7. We can observe that the values of the contrast are comparable

Fig. 8 Intensity line profile from the red line in Fig. 7(d), which is proportional to the phase gradient of the coherent CuK α 1 radiation propagated through the sample.

Table 7 Michelson contrast calculated from the intensity line profiles depicted in Fig. 8.

	CuK α 1	GaK α 1	MoK α 1
Ge(111)	0.256	0.208	0.069
Ge(220)	0.208	0.183	0.066
Ge(400)	0.180	0.166	0.065

using all selected analyzer lattice orientations for each selected x-ray line. The calculation shows that the best contrast of ~25% can be achieved using the Ge(111) analyzer with a combination of CuK α 1 radiation.

3 Measurements of Crystals Surface Quality

The advanced nanomachining using SPDT to prepare the crystal surfaces was applied. Three series of germanium samples (S1, S2, and S3) with undefined lattice orientations were machined. The speed of spindle rotation (3000 rpm) and the final material removal (2 μm) was the same for all three sets. The difference between the three series was in the feed rate of the diamond tool. The feed rates for S1, S2, and S3

Fig. 7 (a) Simulation of phase contrast image of PMMA sphere using parallel beam CuK α 1 radiation, (b) retrieved intensity image, (c) retrieved phase image (directly proportional to the projected thickness of the sample), and (d) calculated ABI image using Ge(111) analyzer at the left side of the RC.

Fig. 9 AFM images with the selected line profiles of the surface of germanium samples after single-point diamond turning (SPDT) machined with the feed rate: (a) S1 = 2 mm/min, (b) S2 = 1 mm/min, and (c) S3 = 3 mm/min.

were 2, 1, and 3 mm/min, respectively. The AFM images of the samples after SPDT are depicted in Fig. 9. All the samples have a pronounced periodic structure (diamond tool ripples) left within SPDT formation. The periodicity was measured using the HRXRD technique, which is explained at the end of this chapter. Systematic analysis shows RMS roughness values after the SPDT process of 1.5, 0.4, and 0.7 nm for the samples S1, S2, and S3, respectively. The lowest roughness value of 0.4 nm was observed for the feed rate parameter 1 mm/min (sample S2) (see Fig. 13).

Investigation of the surface profile showed good planarity on the scan length 50 μm . Figure 10 shows that the smallest deviation is observed for sample S2 (5 nm). Increasing the

Fig. 10 Comparison of the profiles produced using SPDT machining samples with feed rate parameters S1 = 2 mm/min, S2 = 1 mm/min, and S3 = 3 mm/min.

feed rate to 2 and 3 mm/min (samples S1 and S3) increases the deviation to 10 and 11 nm, respectively. A well-defined periodicity was produced for the high-spatial frequency component.

The surface quality fabricated using the SPDT method is sufficient for, e.g., infrared optics.³⁰ In the case of x-ray optics, the diamond tool ripples are too high compared with the wavelengths of hard x-ray radiation and they can produce undesired scattering of the radiation. It is necessary to perform a postpolishing process after SPDT that uses a fine diamond paste or a colloidal polishing suspension and synthetic polishing pad. We have provided the polishing process using liquid solutions containing (a) SiO_2 (20 nm) and (b) Al_2O_3 (60 nm) particles, which decrease the roughness for all types of samples. The results of the fine polishing process (duration = 15 min) using the solution containing (a) SiO_2 particles and (b) Al_2O_3 particles are shown in Figs. 11 and 12, respectively.

After 10 and 15 min of polishing using the solution containing 60 nm Al_2O_3 , scratches were observed (Fig. 12) which may be caused by some the remains of larger grains in the polishing solution. The scratches subsequently increase the surface RMS roughness (see Fig. 13). However, even after 15 min of polishing using the solution containing SiO_2 or Al_2O_3 , the periodic structure remains. The summary of RMS roughness for all types of samples is shown in Fig. 13. The AFM images were rasterized on the area of $10 \times 10 \mu\text{m}^2$ and are composed of 512×512 pixel points. We observe spatial frequencies in the region of $1/10$ to $512/10 \mu\text{m}^{-1}$. The smallest observable period is $10/512$, which is 19.5 nm, and the resolution of the AFM tip is 5 nm; hence, we can neglect the convolution with the tip resolution.

A sequential 10 s of chemical etching of the SPDT machined samples left a fine periodic structure (Fig. 14), but craters were formed. When increasing the time to 20 s, their sizes were also increasing (Fig. 15). Such randomly

Fig. 11 AFM images of the surface of germanium crystals after 15-min fine polishing using the liquid solution containing SiO_2 -nanoparticles (20 nm) with feed rate parameters: (a) S1 = 2 mm/min, (b) S2 = 1 mm/min, and (c) S3 = 3 mm/min.

formed craters are undesirable, particularly for submicron resolution imaging applications.

A study of the subsurface changes and defects was provided by the method of Raman spectroscopy at the wavelength of 532 nm. The obtained Raman spectrum for Ge crystals was processed by a Lorentz filter. As a result of the filtration, the distribution of the characteristic peak was obtained. Figure 16 shows the micro-Raman images after SPDT surface formation. The dependence of area, center, and width of the peak is shown. The periodicity of the

structure is observed to be similar to the AFM images for samples S1 and S3. Periodic grooves indicate the subsurface damages and microstresses after the SPDT process. However, for the sample with the lowest feed rate (S2 = 1 mm/min), no changes of the characteristic peak can be seen. The polishing process decreases the level of subsurface damages. All subsurface defects and microtensions were released after chemical etching.

XRD analysis was carried out using Bruker D8 DISCOVER diffractometer equipped with an x-ray tube

Fig. 12 AFM images of the surface of germanium crystals after 15-min fine polishing using the liquid solution containing Al_2O_3 -nanoparticles (60 nm) with feed rate parameters: (a) S1 = 2 mm/min, (b) S2 = 1 mm/min, and (c) S3 = 3 mm/min.

Fig. 13 Comparison of RMS (root mean squared) roughness values for pure SPDT processing, SPDT +5, +10, and +15 min of polishing using either polishing solution containing SiO₂-nanoparticles or Al₂O₃-nanoparticles.

with a rotating Cu anode operating at 12 kW. All measurements were performed in a high-resolution setup with a parabolic Goebel mirror and four bounce Ge(022) Bartels monochromators in the primary beam and a triple bounce Ge(022) analyzer crystal in the diffracted beam. The reciprocal space map [Fig. 17(a)] was measured with a step size of 0.0001 rad/Å for both reciprocal coordinates h and l , and the horizontal h scan was measured with a step size of 0.00002. The direction $[-101]$ was selected for the orientation of the h coordinate. The surface texture after SPDT with a periodicity of 720 nm is observable in the linear h scan parallel to the sample surface across the Ge(111) diffraction [Fig. 17(b)]. The periodicity is formed by the diamond tool as the result of the turning machining. The periodicity (P) is the function of the tool's feed rate (FEED) and the

revolutions per minute (RPM) of the spindle and can be express as follows: $P = \text{FEED}/\text{RPM}$. The shape of the grooves is also affected by other parameters, such as the depth of material removal and the shape of the tool.

4 Conclusions

Calculations of the basic parameters and the simulation of the intensity throughput of selected asymmetry cut germanium monochromators have been presented. First, the optimal magnification factors for the selected lattice orientations Ge(111), Ge(220), and Ge(400) and for the energy range of 5 to 20 keV were calculated. Other selected parameters, such as the optimal asymmetry angle, information depth, spatial resolution, intensity throughput, and angular sensitivity, were calculated considering the selected x-ray lines CuK α 1, GaK α 1, and MoK α 1. Simulation of the intensity throughput showed the largest amount of the intensity diffraction for the Ge(111), ahead of Ge(220) and Ge(400). The highest optimal magnification and angular sensitivity can be achieved using Ge(400), but this is at the expense of intensity throughput and spatial resolution, which is required for imaging applications using more sensitive, highly-efficient, single-photon counting x-ray detectors, for example, the Medipix-based detector. Calculation of x-ray images using a 1-D ABI system has been shown as well. The provided calculations will be useful for our future intention, which is to build a portable 2-D ABI system for imaging and metrological applications. This system will allow us to test the x-ray optical elements in the laboratory or under synchrotron conditions. The x-ray optical elements will be tested mainly in high-asymmetry conditions. The high-asymmetry diffraction producing beam magnification in the grazing incidence mode requires a high quality of the crystal surface. We have applied advanced nanomachining using SPDT to prepare the crystal surfaces. Several finishing methods, including conventional mechanical lapping, chemical polishing, and chemomechanical polishing, have

Fig. 14 AFM images of the surface of germanium crystals after 10 s of chemical etching after SPDT with feed rate parameters: (a) S1 = 2 mm/min, (b) S2 = 1 mm/min, and (c) S3 = 3 mm/min.

Fig. 15 AFM images of the surface of germanium crystals after 20 s of chemical etching after SPDT with feed rate parameters: (a) S1 = 2 mm/min, (b) S2 = 1 mm/min, and (c) S3 = 3 mm/min.

Fig. 16 Micro-Raman images for SPDT machined samples: top images respond to area of the characteristic peak, middle to the center of the peak, and bottom to the width of the peak. S1, S2, and S3 mean different feed rate parameters of SPDT: S1 = 2 mm/min, S2 = 1 mm/min, and S3 = 3 mm/min.

Fig. 17 (a) Reciprocal space map of Ge(111), and (b) linear h scan parallel to the sample surface across Ge(111) diffraction.

been evaluated. We can conclude that the smallest roughness (~ 0.3 nm), best planarity, and an absence of the subsurface damages were observed for sample S2 (SPDT feed rate 1 mm/min) using a fine polishing 15-min process with a polishing solution containing SiO_2 nanoparticles (20 nm).

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