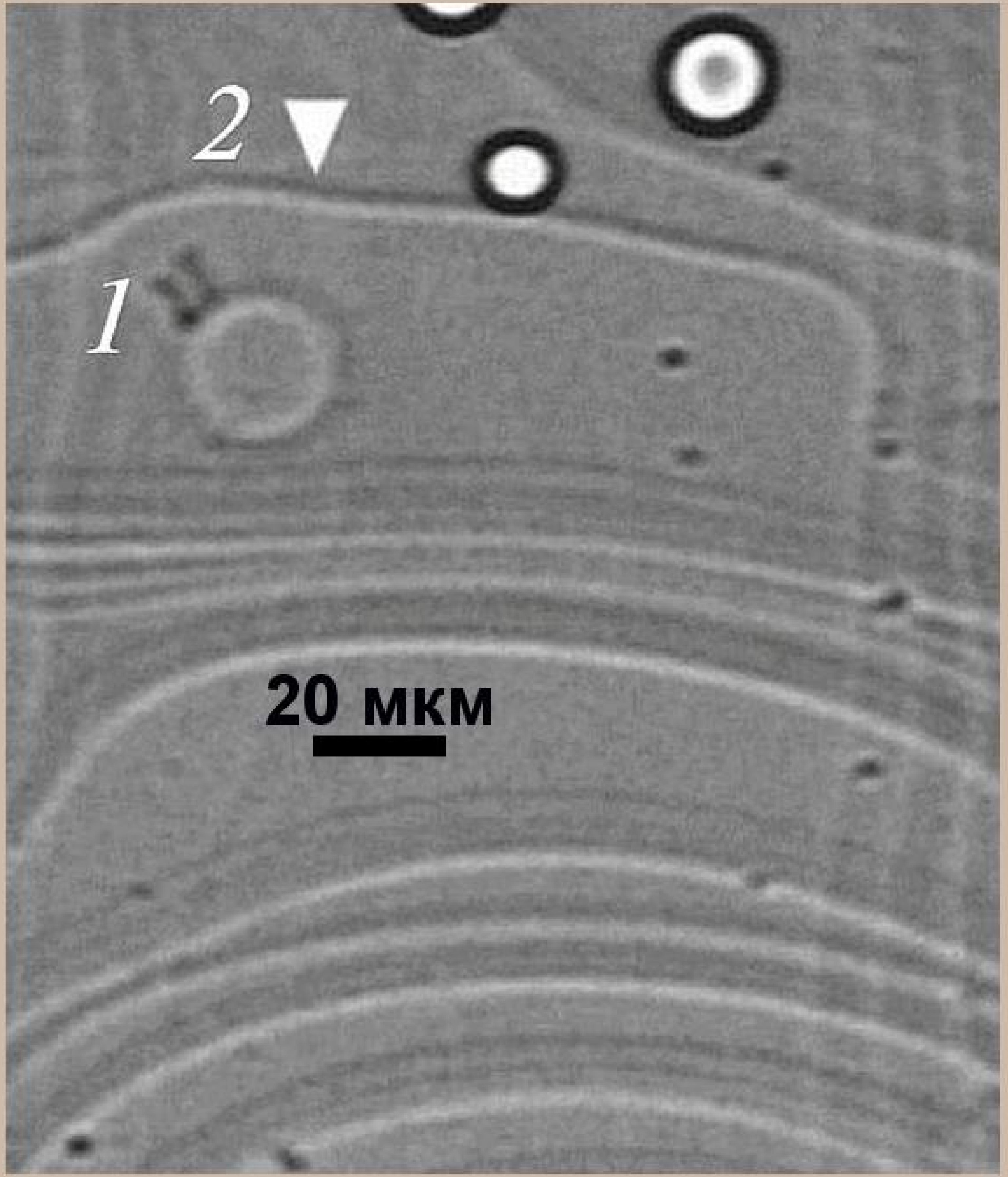
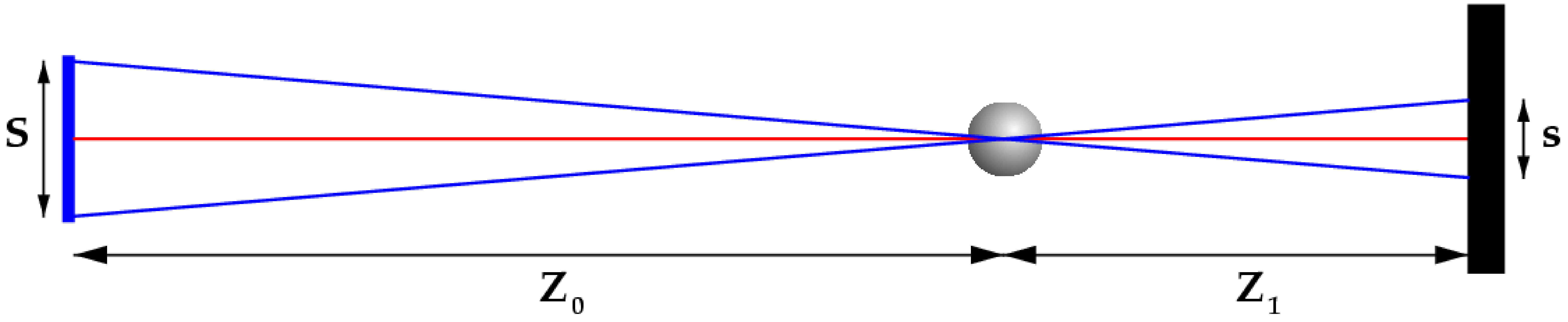
КОГЕРЕНТНОСТЬ, Фазовый контраст, и Наблюдение микробъектов в кристалле.



Виктор Кон

НИЦ Курчатовский Институт

The problem of spatial coherence due to the source size

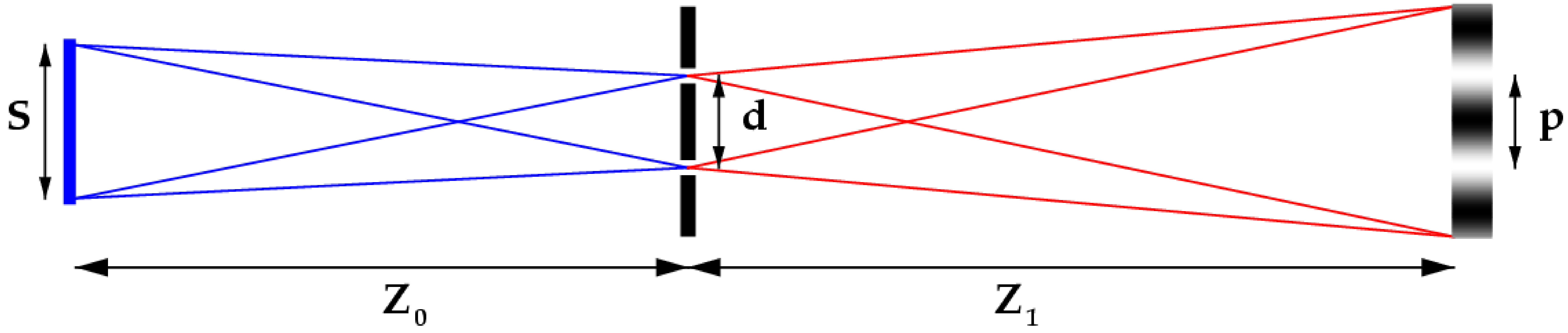


S is the source transverse size, s is the source projection.

$s = S\ Z_1/Z_0$ – this relation follows from geometry

Each point source has an own optical axis. Each point source creats the same image of the object which is shifted from the main optical axis. A convolution of image over a source projection can kill the contrast because a mean intensity is not changed.

How to understand Coherence

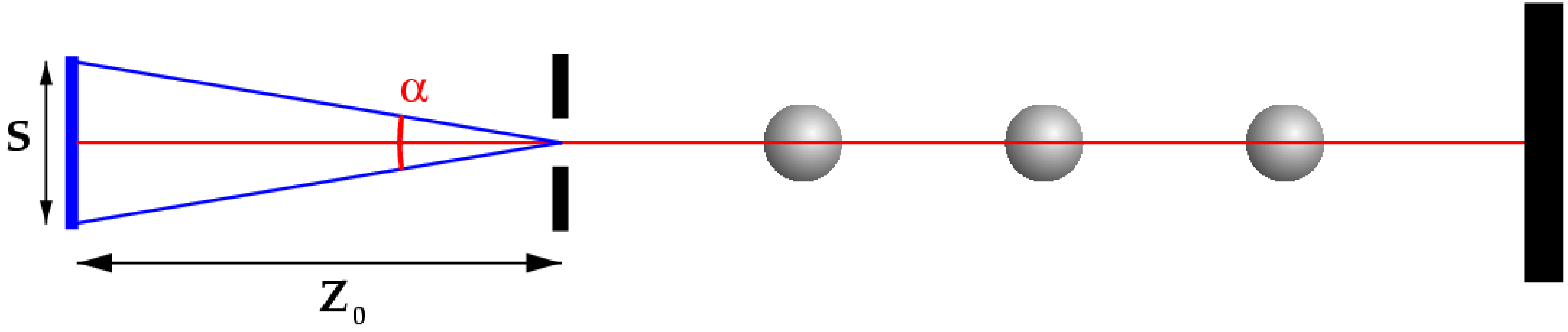


A simple example with a two slits interference (Young's experiment). It is followed from Fresnel propagator that period of fringes $p = \lambda Z_1/d$. The source projection is $s = SZ_1/Z_0$. A convolution of fringes over the distance s does not kill the contrast if $s < p$ or $d < L_{tc} = \lambda Z_0/S$.

Coherence is a condition to observe interference.

It is necessary for the phase contrast because a phase does not change the integral intensity.

Transverse Coherence Length



A very useful parameter is a transverse coherent length $L_{tc} = \lambda/\alpha$, where λ is a wave length, $\alpha = S/Z_0$ is an angle of source. If a transverse size of object $d < L_{tc}$, then a radiation diffracted by object is coherent.

If the object is a slit then it plays a role of secondary coherent source for all subsequent objects. The 2D slit or a pinhole is a standard way to obtain a coherent source.

В ПРОСТОЙ СХЕМЕ ЭКСПЕРИМЕНТА ПО ФАЗОВОМУ КОНТРАСТУ (ИСТОЧНИК, ОБЪЕКТ, ДЕТЕКТОР) ПРОЕКЦИЯ РАЗМЕРА ИСТОЧНИКА – ЕДИНСТВЕННАЯ ПРИЧИНА ПОТЕРИ КОГЕРЕНТНОСТИ, КОТОРУЮ НЕВОЗМОЖНО УСТРАНИТЬ. НО РЕАЛЬНЫХ ПРИЧИН ПОТЕРИ КОГЕРЕНТНОСТИ НАМНОГО БОЛЬШЕ.

1. ИЗМЕНЕНИЕ ПОЗИЦИИ САМОГО ИСТОЧНИКА В ПРОЦЕССЕ ИЗМЕРЕНИЯ
2. ВИБРАЦИИ ПОЛОЖЕНИЯ ПУЧКА ИЗЛУЧЕНИЯ ПРИ ОТРАЖЕНИИ В КРИСТАЛЛАХ МОНОХРОМАТОРА
3. ВИБРАЦИИ ДЕТЕКТОРА И ВСЕГО ЗДАНИЯ, ГДЕ ПРОВОДЯТСЯ ИЗМЕРЕНИЯ
4. РАССЕЯНИЕ ПУЧКА НА ПОСТОРОННИХ ОБЪЕКТАХ В ВОЗДУХЕ, НА ПОВЕРХНОСТЯХ И В ОБЪЕМЕ КРИСТАЛЛОВ (ШЕРОХОВАТОСТЬ И НЕОДНОРОДНОСТЬ)
5. ШИРИНА СПЕКТРА ИЗЛУЧЕНИЯ (НЕМОНОХРОМАТИЧНОСТЬ)

APPLIED PHYSICS LETTERS **91**, 171901 (2007)

Study of micropipe structure in SiC by x-ray phase contrast imaging

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Phase contrast images of dislocation micropipe in SiC crystal are experimentally studied at various distances from the sample using synchrotron white beam. Computer simulation of these images enabled us to understand the peculiarities of image formation and measure the diameter of the micropipe. The phase contrast imaging of micropipes without monochromator is explained by the absorption of x rays in a thick (490 μm) SiC crystal, effectively forming a high brilliance radiation spectrum with a pronounced maximum at 16 keV.

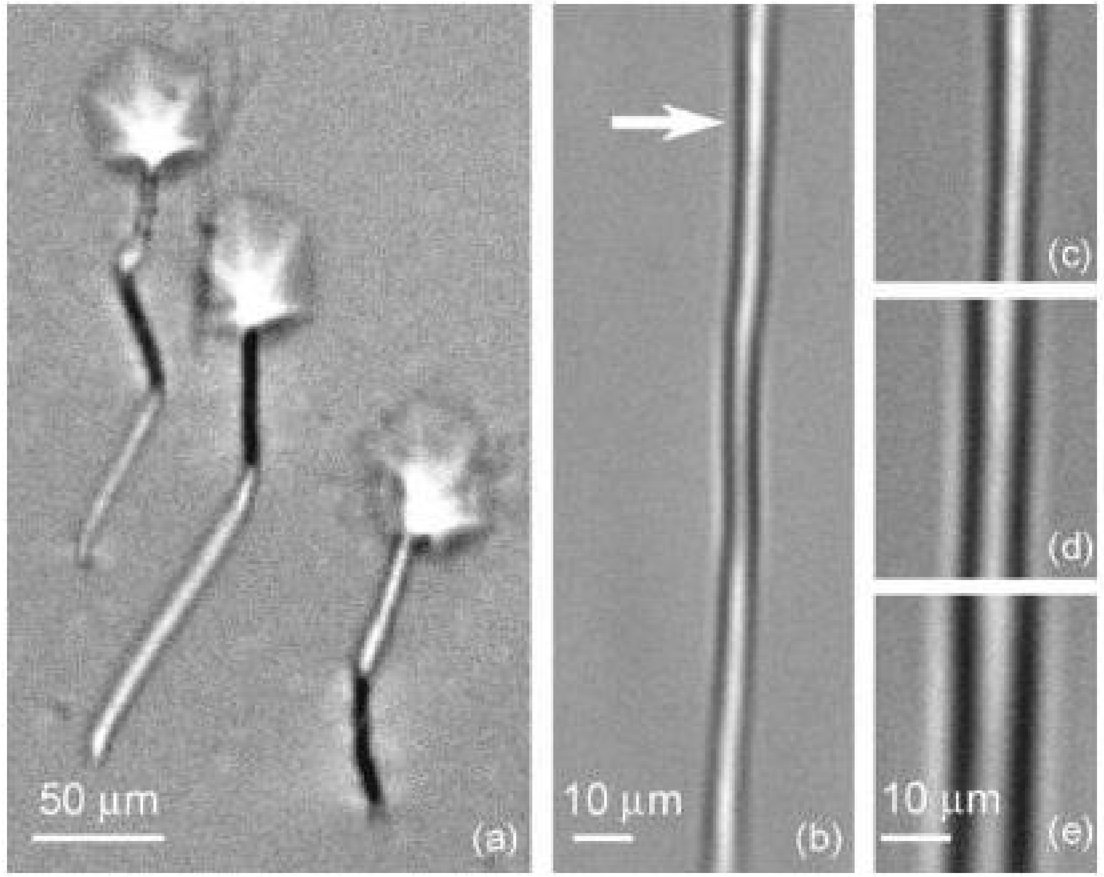


FIG. 1. Typical images of micropipes in SiC wafers cut perpendicular to the [0001] growth direction (a) and along the growth direction (b). The arrow in (b) indicates the fragment shown in (c)–(e) at various sample-to-detector distances: 10, 30, and 50 cm, respectively. Halos in (a) correspond to etch pits on the wafer surface.

Компьютерное моделирование фазово-контрастных изображений в белом синхротронном излучении на примере микротрубок в карбите кремния

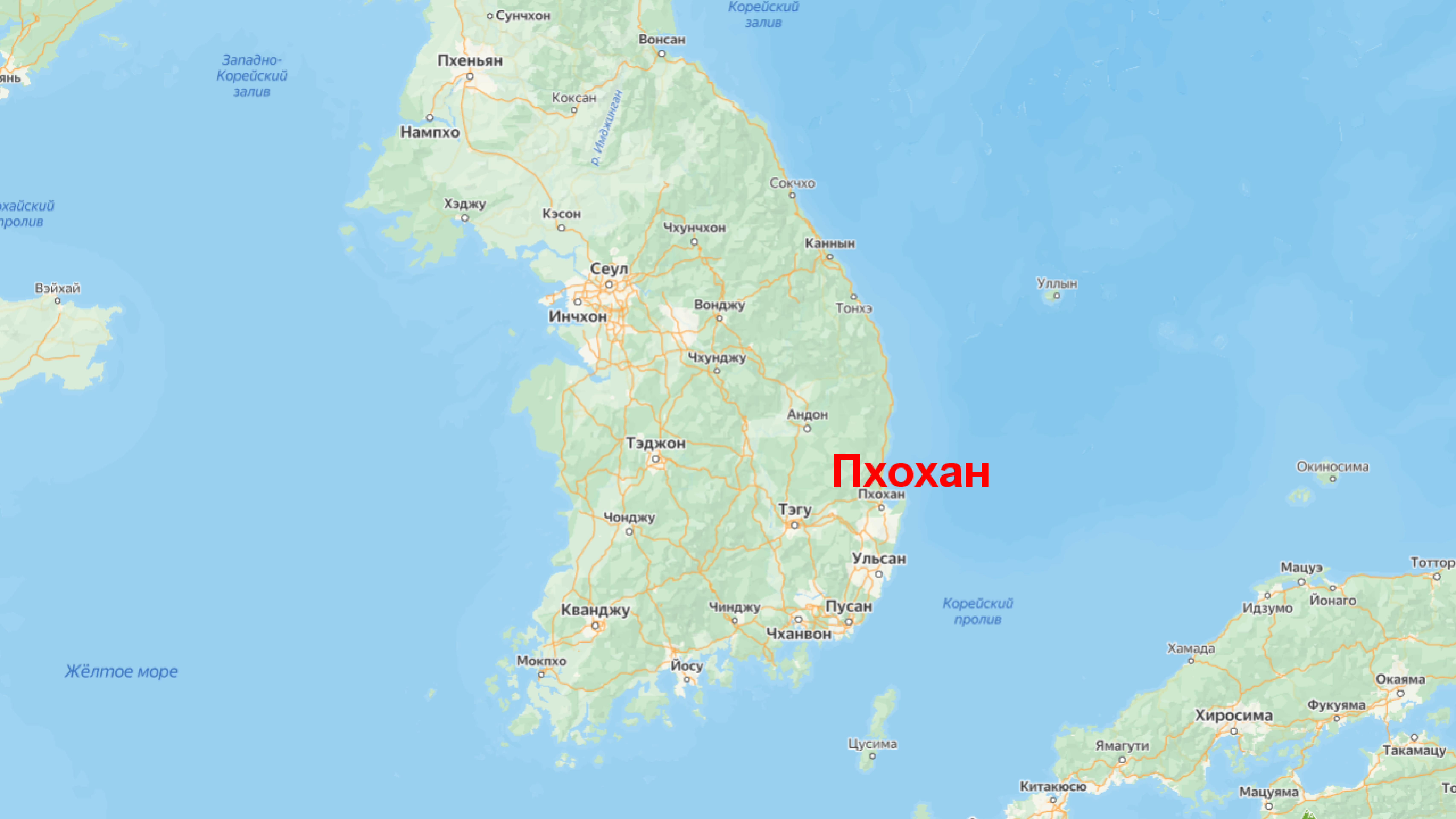
Т. С. Аргунова, ФТИ РАН им. А. Ф. Иоффе, С-Петербург

В. Г. Кон, РНЦ "Курчатовский Институт", Москва

Jung Ho Je, X-ray imaging center, Pohang University, Korea

Pohang Light Source-II (PLS-II)

The Pohang Light Source (PLS), the only third-generation light source in Korea and the fifth one in the world, has been playing its role faithfully as the heart of Korean high-tech science since September 1995.
The PLS is the national user facility, owned by the Korean Government and operated by Pohang Accelerator Laboratory (PAL) and POSTECH. PAL has been conducted an upgrade project on the PLS since 2009, and it has been providing as the PLS-II in 2012. There is also a FEL facility in Pohang called PAL-XFEL.


Пхохан
Корейский залив
Сунчхон
Вонсан
Пхеньян
Западно-Корейский залив
Коксан
р. Имджинган
Нампхо
Сокчхо
Хэджу
Кэсон
Чхунчхон
Каннын
Сеул
Инчхон
Вонджу
Тонхэ
Уллын
Вэйхай
Чхунджу
Андон
Тэджон
Пхохан
Тэгу
Чонджу
Ульсан
Кванджу
Чинджу
Пусан
Чханвон
Корейский пролив
Мокпхо
Йосу
Жёлтое море
Цусима
Окиносима
Мацуэ
Йонаго
Идзумо
Хамада
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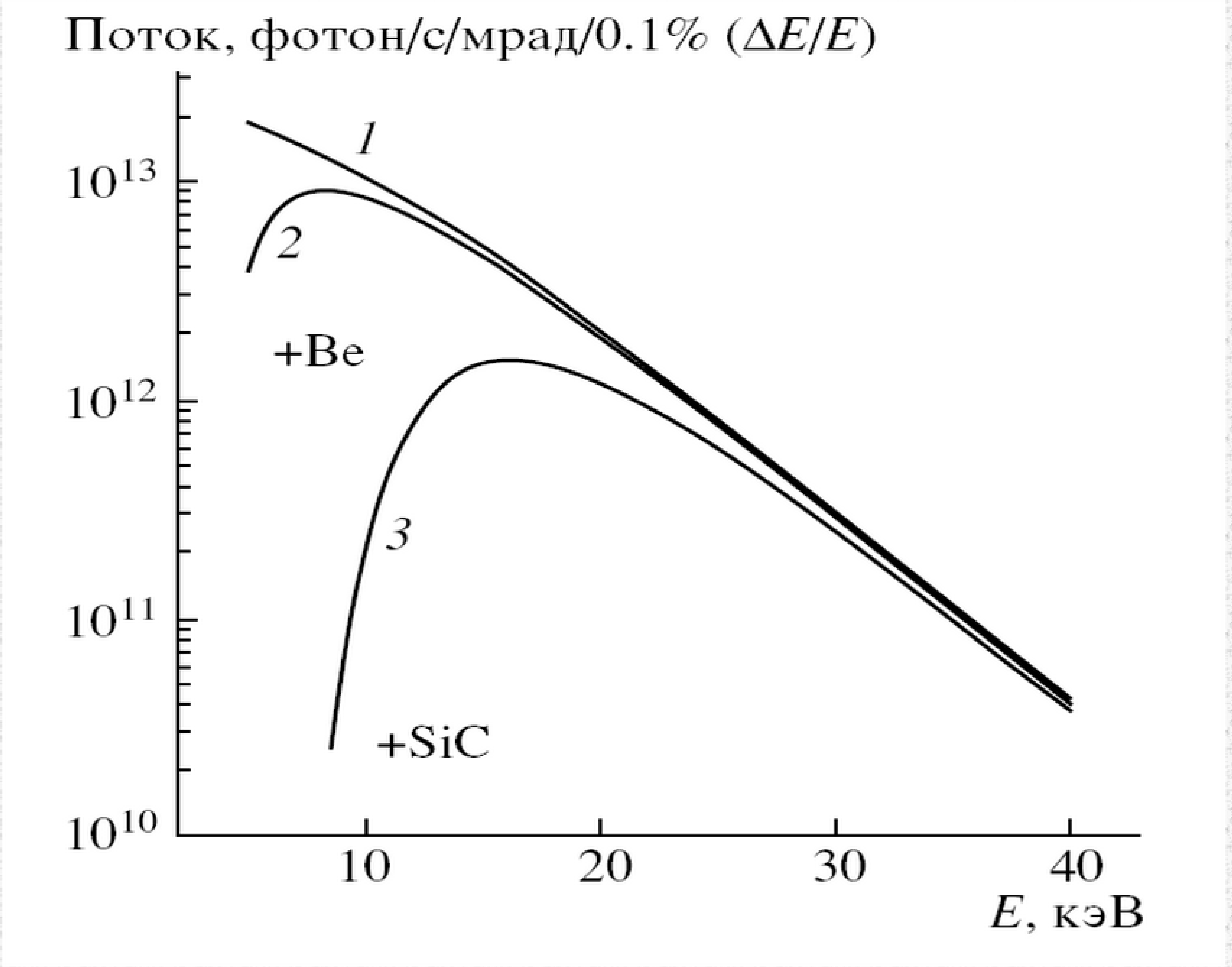
Ямагути
Такамацу
Китакюсю
Мацуяма



1 - исходный спектр

2 - спектр с учетом поглощения в Be окне

3 - спектр с учетом дополнительного поглощения в образце.

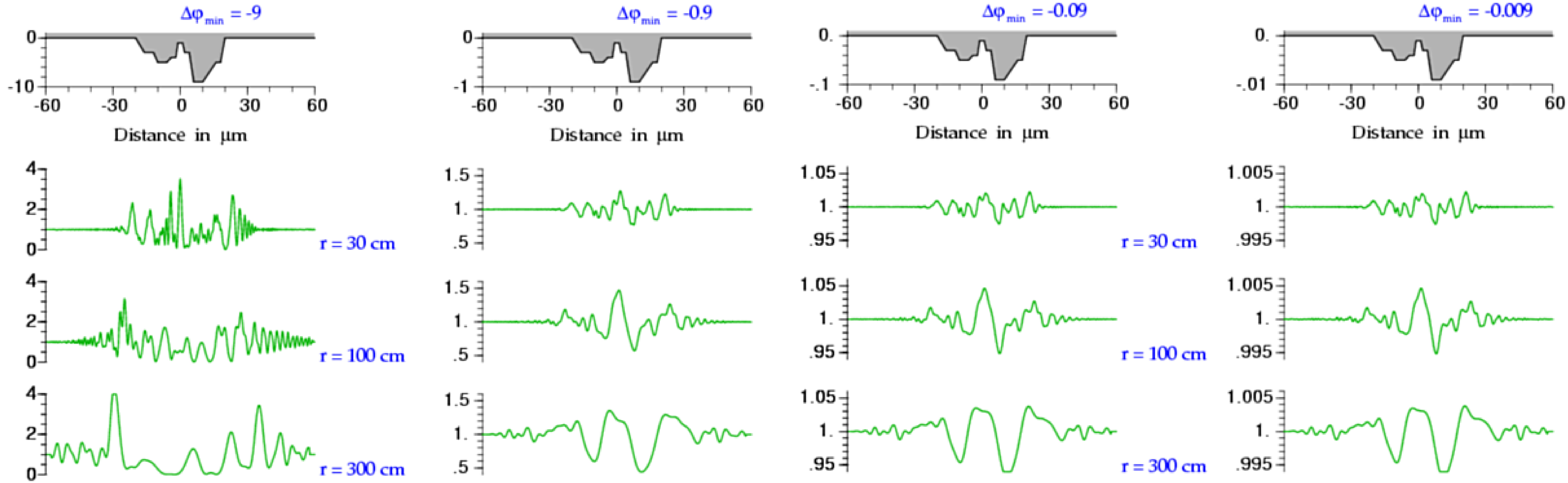
Спектр имеет четко выраженный максимум при энергии 16 кэв.

We see that the phase shift profile $\Delta\varphi(x)$ creates the intensity profile $\Delta I(x)$ In general it is necessary to solve the inverse problem, i.e. to obtain $\Delta\varphi(x)$ from $\Delta I(x)$. There are some approaches to this task. If $|\Delta\varphi(x)|_{\max} \ll 1$ then the problem is more easy because a dependence is linear and the inverse problem can be solved by one step.

Image of complex transparent object

X-ray energy 20 keV, source distance 50 m, source size 30 μm.

Intensity depends on object thickness Δφ and detector distance r



FAST TRACK COMMUNICATION

Far-field x-ray phase contrast imaging has no detailed information on the object

IOP PUBLISHING

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$$I(x) = 1 - (\pi RP/r_1)\cos(\pi(x/r_1)^2 + \pi/4)\, B(x), \quad r_1 = (\lambda Z)^{1/2},$$

$$Z = z_0 z_1 / (z_0 + z_1), \quad P = 4\pi\delta R_0/\lambda, \quad B(x) = 2(x_c/x)\, J_1(x/x_c),$$

R – радиус эллипса в сечении микротрубки поперек пучка (ось x),

R_0 – радиус вдоль пучка, $x_c = r_1^2/(2\pi R)$,

$\delta = 1 - n$, n – коэффициент преломления, λ – длина волны

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Letter

Imaging of micro-steps on as-grown surface of sapphire with X-ray phase contrast technique

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ABSTRACT

Basal-faceted sapphire ribbons grown using the Stepanov–LaBelle technology have a low density of surface steps. We present our results on a study of steps on the surface of a ribbon, misoriented relative to the singular face (0001) by several arc minutes. The ribbon has been characterized by means of in-line phase contrast imaging technique at Pohang Light Source, South Korea. It was shown for the first time that a step height of about 1 μm can be determined directly from an image. The step height obtained using the phase contrast method was confirmed by atomic force microscopy measurements. We have found that the experimental contrast matches the theoretical simulations only if the calculated intensity profile has been convolved with a Gaussian function. The full width at half maximum of the Gaussian was independently got from previous measurements. We have obtained an analytical solution in the case of theoretical fully coherent phase contrast image. The inverse problem is easy to solve, since there is a direct proportionality between the contrast and the step height.

Физика твердого тела, 2024, том 66, вып. 12 **2201-2294**

Измерение высоты ступенек на поверхности монокристаллов методом фазового контраста в синхротронном излучении

© *Т.С. Аргунова*[1], *В.Г. Кон*[2], *Д.-Х. Лим*[3], *В.М. Крымов*[1], *А.В. Анкудинов*[1]

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Проведено экспериментальное и теоретическое исследование синхротронных фазово-контрастных изображений микроступенек на поверхности базисно-ограненной сапфировой ленты, выращенной по методу Степанова. Обсуждается сравнение полученных результатов с данными метода атомно-силовой микроскопии. Установлено, что высоту ступенек порядка $1\,\mu m$ можно определить с помощью простой схемы метода фазово-контрастного изображения на просвет.

Materials Physics and Mechanics. 2024;52(5): 64–73.

Surface study by x-ray scattering technique and phase contrast imaging: the examples of graphene and sapphire

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The paper presents results of solving two problems: nano-roughness evaluation for the surface of epitaxial graphene and height measurement for a microstep on as-grown surface of sapphire in order to provide homogeneous graphene films on large areas of silicon carbide or sapphire substrates. To investigate dissimilar surface properties, different approaches have been used: off-specular grazing incidence X-ray scattering and in-line phase contrast imaging with synchrotron radiation. Statistical and local parameters of two types of surface morphology are measured. For the graphene surface, the dependence of the root-mean-square roughness of terrace-step nanostructure on the direction of the steps is estimated. For the vicinal face of sapphire, a surface step height of about one micron is determined directly from a phase contrast image, proving for the first time that the phase contrast imaging resolves surface morphology on a micrometer scale. Atomic force microscopy confirmed the obtained results.

Journal of Surface Investigation: X-ray, Synchrotron and Neutron Techniques, 2024, Vol. 18, Suppl. 1, pp. S16–S23.

Study of the Surface Morphology and Inclusions of Heavy Metals in Basal-Faceted Sapphire Ribbons Using In-Line X-Ray Phase-Contrast Imaging

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Abstract—This study presents the results of research concerning microsteps on the surface and the inclusions of heavy metals in the volume of sapphire ribbons grown using Stepanov's method. Basal-faceted sapphire ribbons exhibit a low density of steps, which are caused by small changes in the orientation of the growth surface or the thickness of the ribbon. Phase contrast imaging using synchrotron radiation is employed to study the defects. It is shown for the first time that the height of a step of 1 μm can be determined directly from the image. An analytical solution for the intensity distribution of the step in the case of fully coherent X-ray radiation is obtained. When the phase shift is small, there is a direct proportionality between contrast and step height, and the inverse problem is easily solved. The height obtained using the phase-contrast-imaging method is confirmed by measurements using atomic force microscopy. To analyze microinclusions, a computer simulation program is used, which allows for assessment of their sizes. We find that the experimental contrast matches the theoretical calculations only if the calculated intensity profile is convolved with a Gaussian function. The full width at half maximum of the Gaussian is independently obtained from preliminary measurements.

Информация по Эксперименту.

Pohang Light Source (PLS) является источником 3-го поколения, с энергией электронов на кольце 3.0 ГэВ. По времени начала работы он 5-й на планете.

Экперименты по фазовому контрасту проводятся на 2-х станциях: BL9D и BL6C.

BL9D – поворотный магнит, нет монохроматора, максимум интенсивности 7-10 кэВ

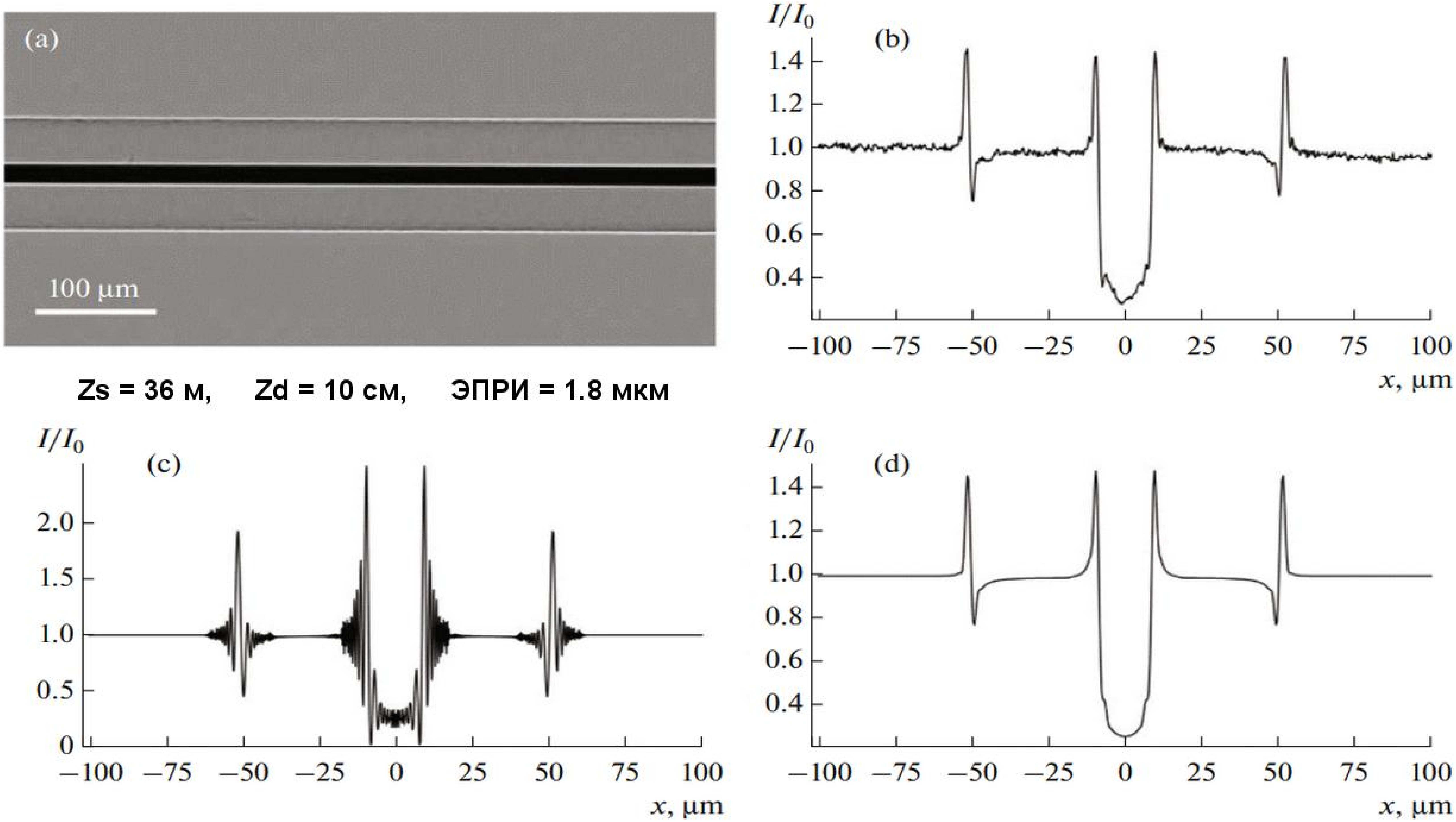
BL6C – виглер, монохроматор $\Delta E/E = 2.9\times10^{-4}$, диапазон энергий 23 – 50 кэВ

Детектор – матрица 2560×2160 пикселей размером примерно 0.325 мкм после оптического увеличения в 20 раз. Измерения проводились на станции BL6C при энергии 23 кэВ.

Когерентность проверялась с помощью опт. волокна W (15 мкм) B (100 мкм)

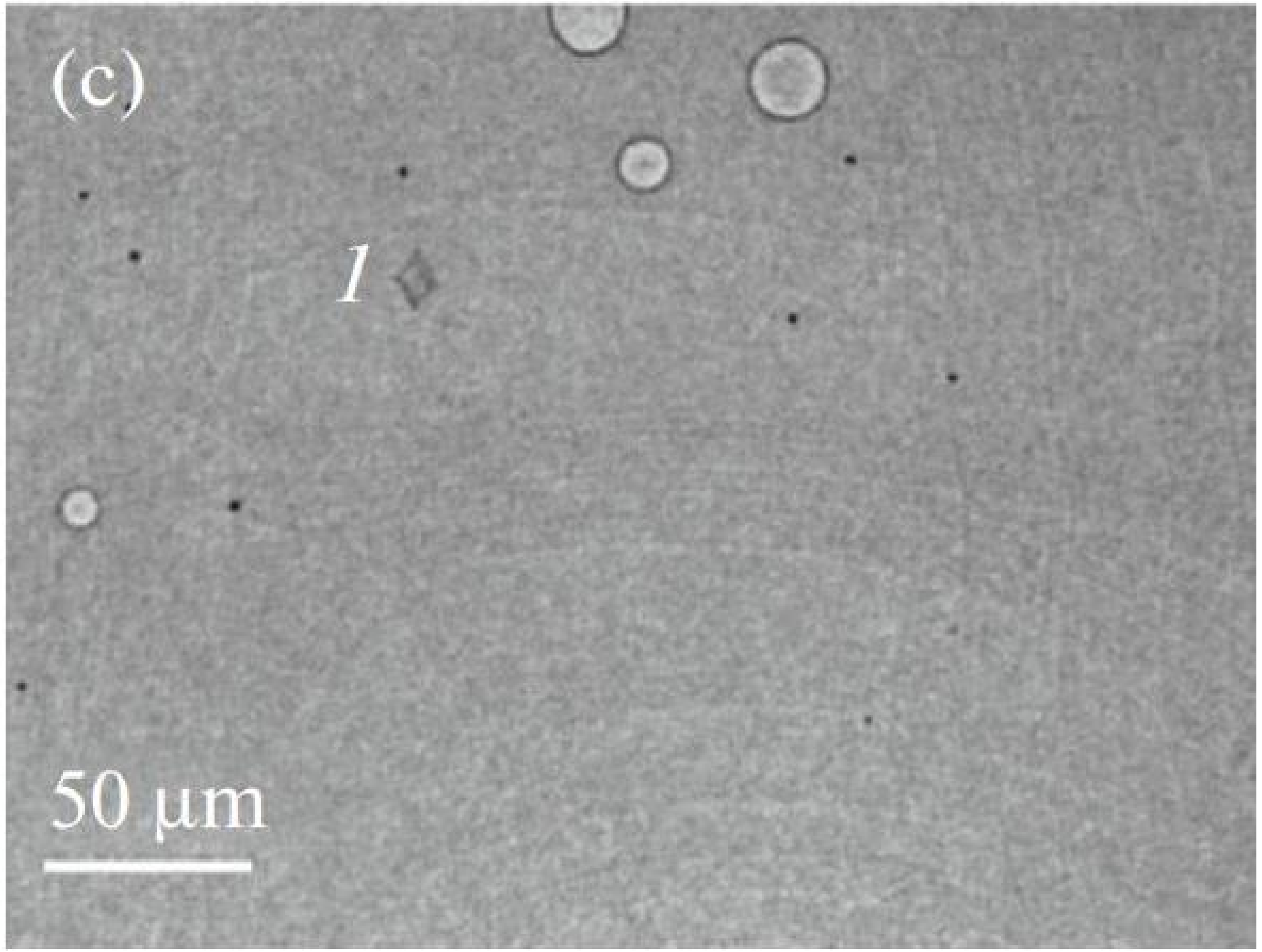
Эффективная проекция размера источника == 1.8 мкм (10 см) 2.0 (20 см) 3.6 (40 см)

Это прямо показало, что когерентность портится не только размером источника

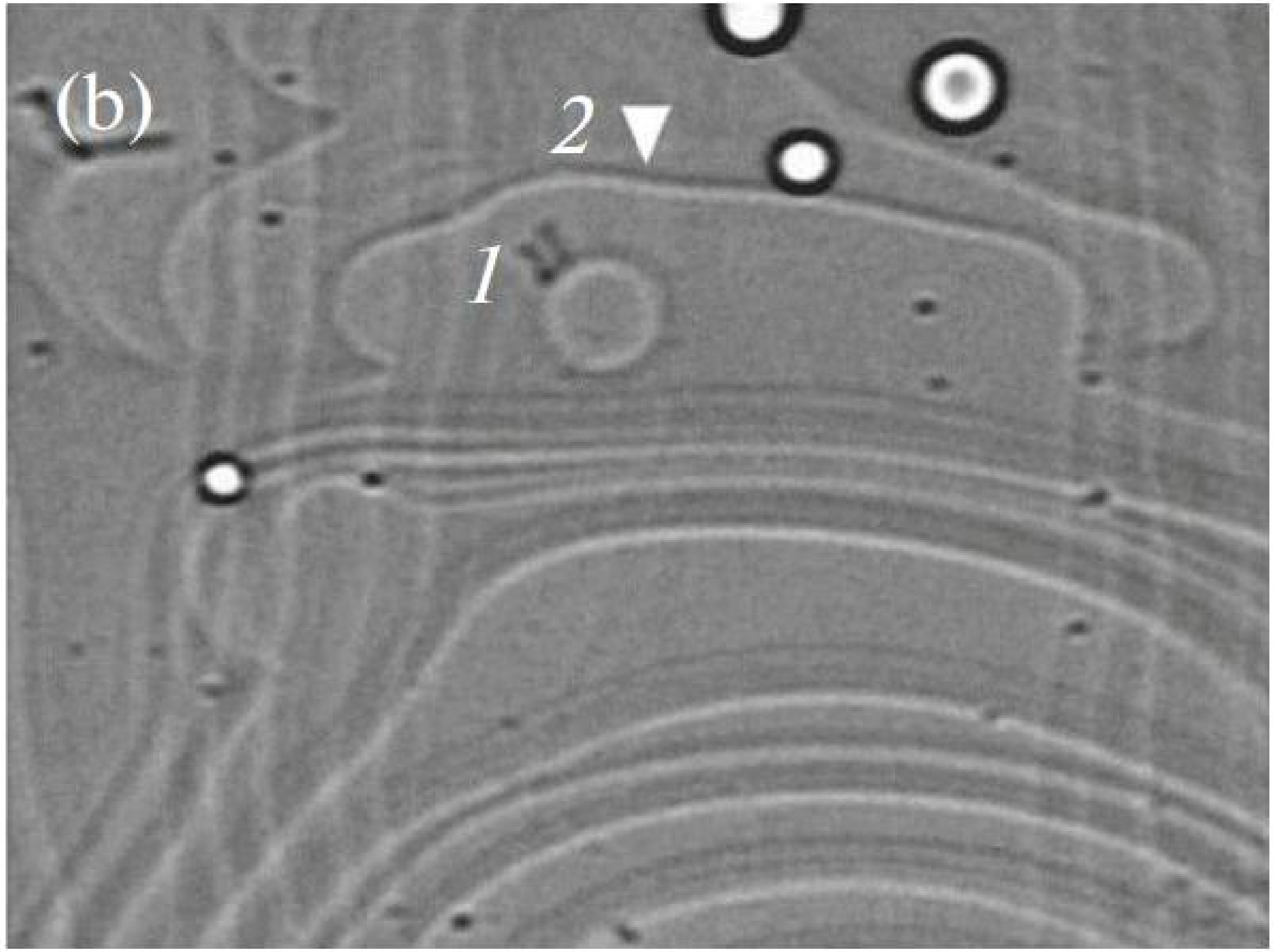


(a)
100 μm
(b)
I/I0
x, μm
Zs = 36 м, Zd = 10 см, ЭПРИ = 1.8 мкм
(c)
I/I0
x, μm
(d)
I/I0
x, μm

Фазово-контрастное изображение кристалла на разных расстояниях



Zd = 8 мм.

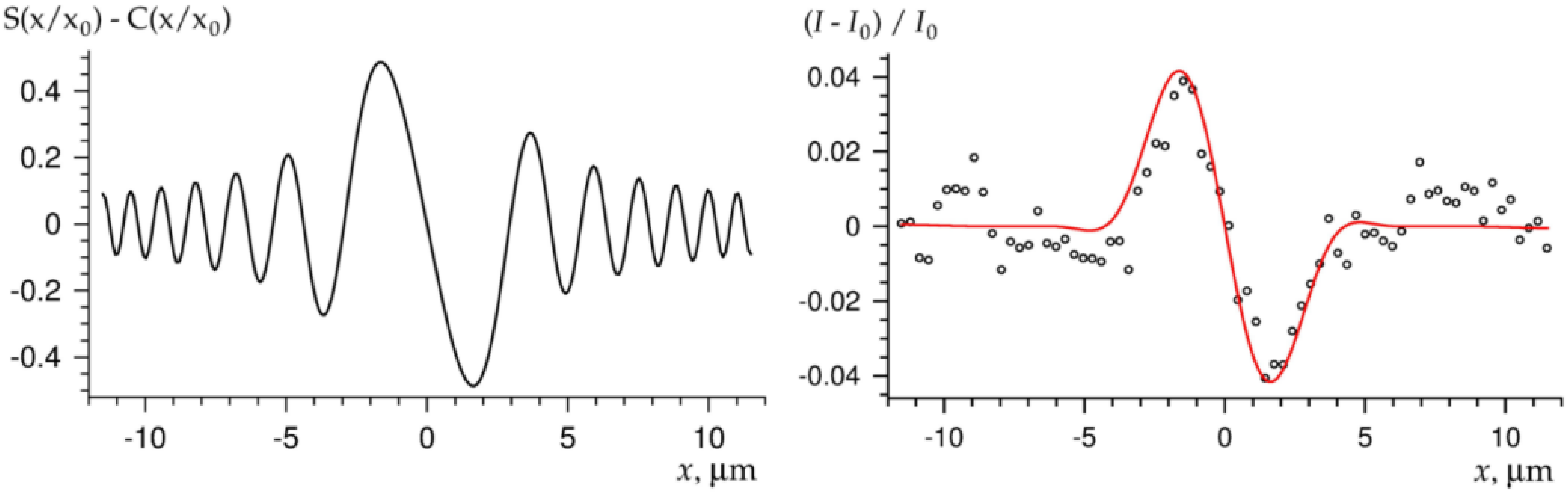


Zd = 20 см.

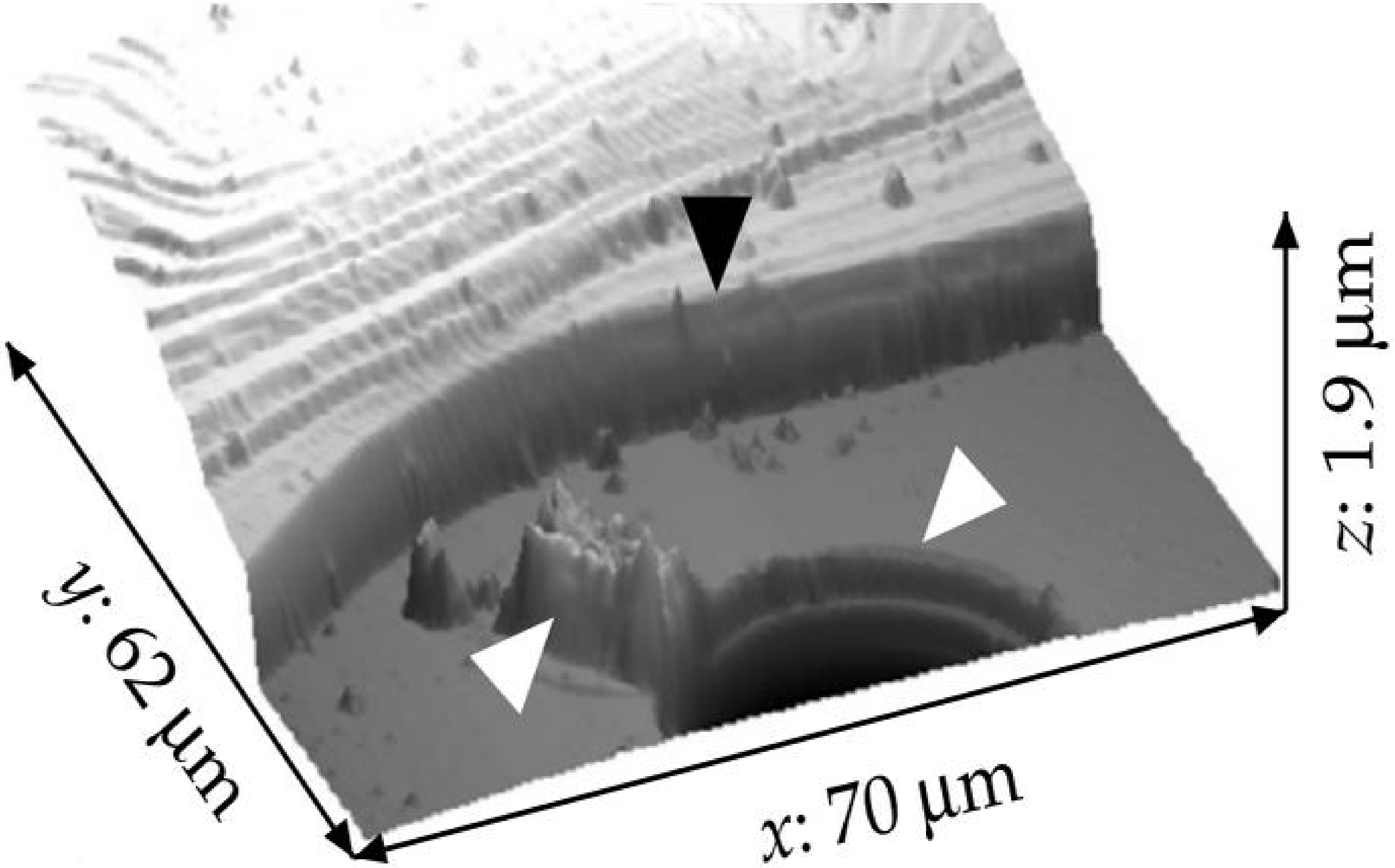
Когерентный фазовый контраст от резкой ступеньки толщины материала вычисляется аналитически и равен

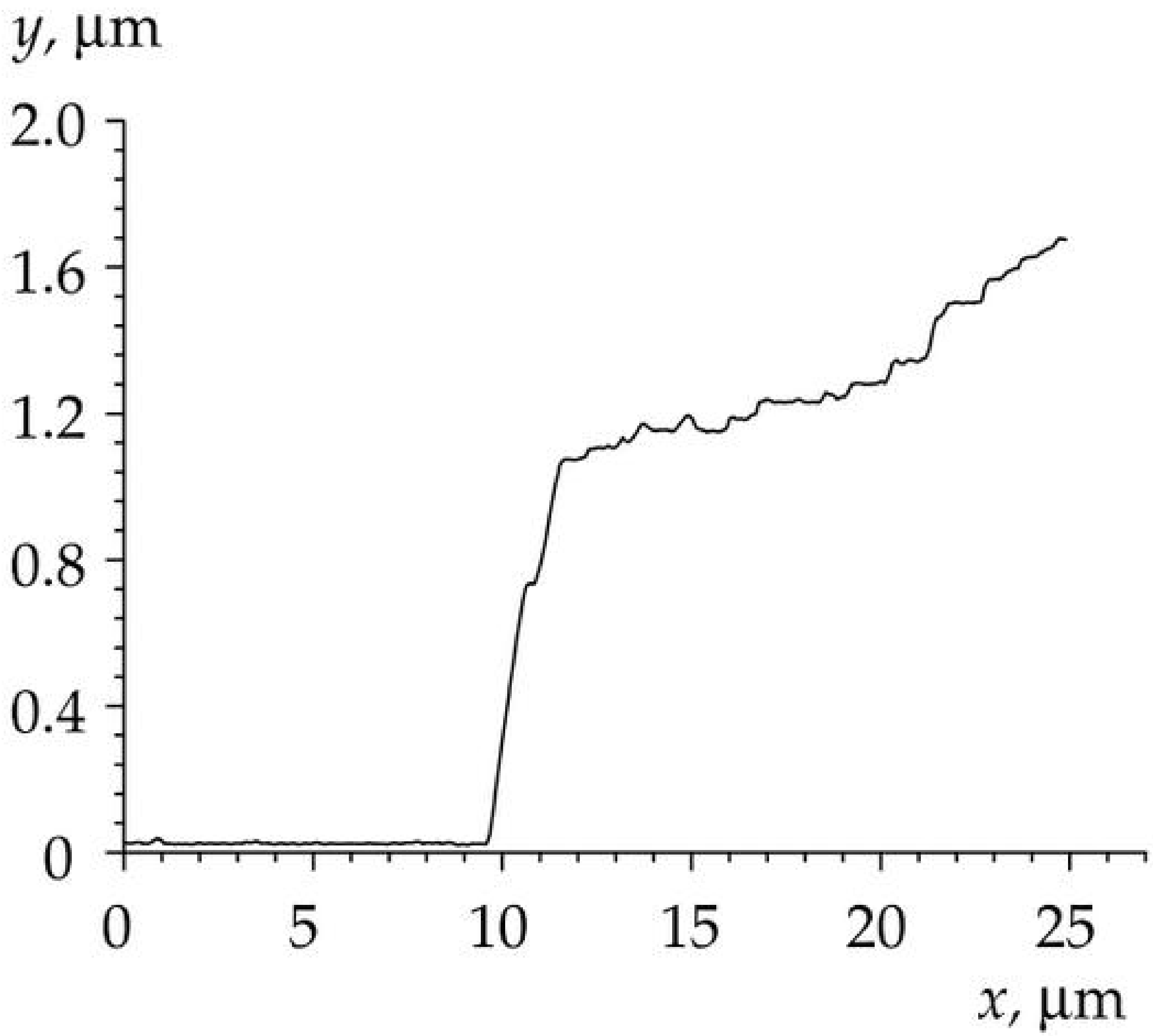
$$I / I_0 = 1 + \varphi\,[S(x/x_0) - C(x/x_0)], \quad \varphi = K\delta\,\Delta t, \quad x_0 = (\lambda z_d / 2)^{1/2}$$

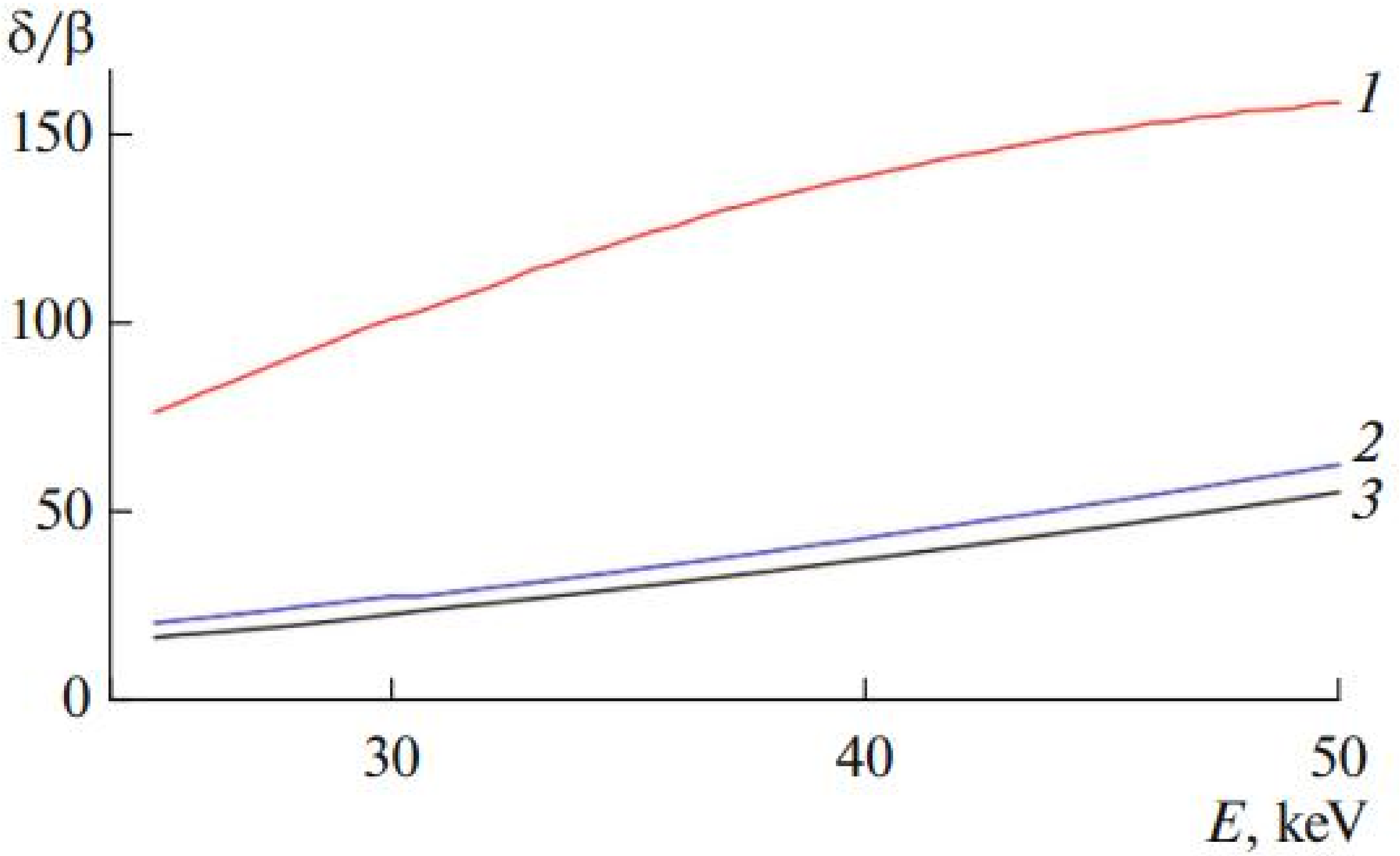
$S(x)$, $C(x)$ – синус, косинус интегралы Френеля. Конкретно $x_0 = 2.32$ мкм, ЭПРИ = 3 мкм, $\varphi = 0.2$, $\Delta t = 1.12$ мкм.



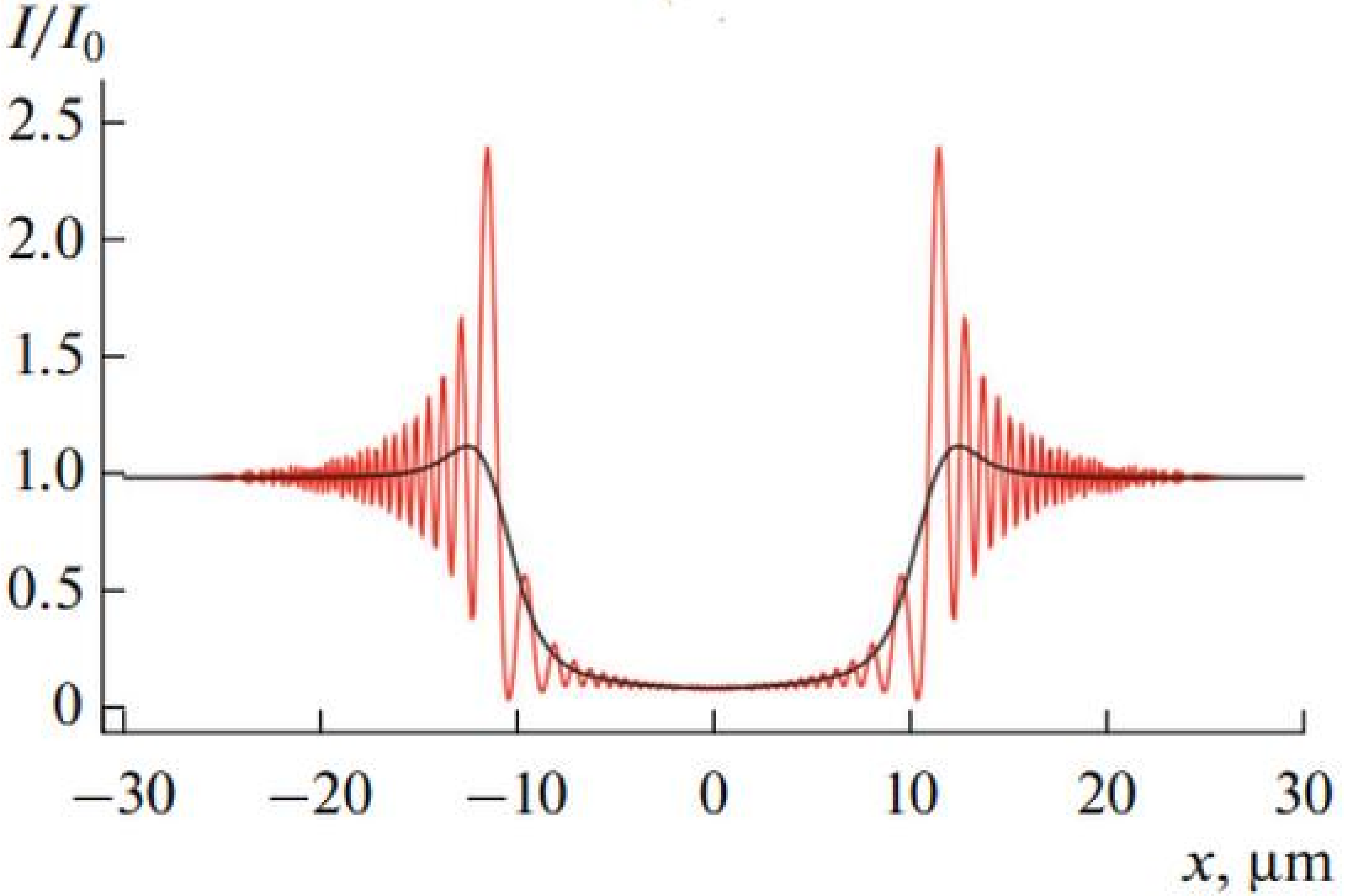
Результаты исследования выбранного участка методом атомно силовой микроскопии Высота ступеньки полностью соответствует рентгеновскому анализу, который проще, быстрее и информативнее. Продольное разрешение лучше поперечного.

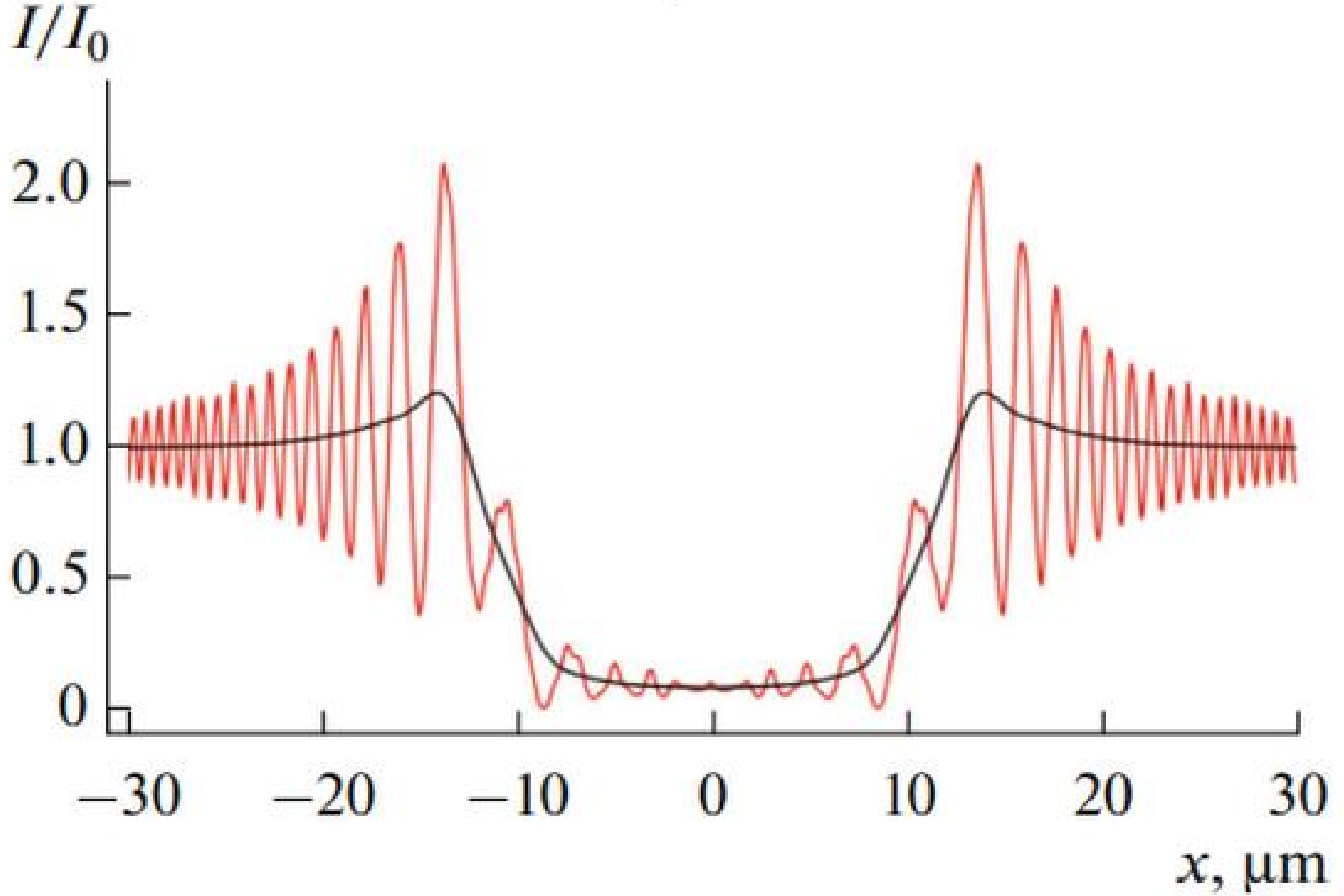






Изображение сферических включений тяжелых металлов W (2) и Mo (3) в сапфире Al_2O_3 (1). Для сапфира кривая умножена на 0.1 для уплотнения графика. Внизу ФК для частиц W в сапфире на расстояниях 5 (слева) и 20 (справа) см. Красная кривая когерентная, черная кривая для ЭПРИ 3 мкм. E = 23 кэВ.






Благодарю
за
внимание