Experimental observation of two-dimensional focusing of x rays in backscattering

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A focusing of Co $K\alpha_1$ x radiation has been achieved with a spherically curved Ge(620) single crystal reflecting in a backscattering mode ($2\theta \approx \pi$). A point focus $\sim 10\,\mu$m in size has been obtained. The theoretical diffraction limit of the width of the focus in this arrangement is 120 Å. The luminosity is high.

Soft x radiation ($\lambda \sim 20$–100 Å) can be focused with Fresnel zone plates, mirrors operating at grazing angles of incidence, or multilayer mirrors. This approach has already led to the development of x-ray telescopes and microscopes with a resolution as high as 500 Å (Ref. 1). In the middle x-ray range ($\lambda \approx 1$ Å), it is natural to use high-quality single crystals as optical elements, although the experimental use of zone plates in this range has also been reported.[2] The development of crystal focusing optics has been the subject of a large number of studies (see Ref. 3, for example, for a bibliography), but in all of the experiments the focusing has been one-dimensional; i.e., the focus has had the shape of a line segment. The possibility of achieving two-dimensional focusing with a point focus, the approach which is of most practical importance, has been studied theoretically.[3-7] None of these schemes has been implemented experimentally. The scheme of Ref. 3, for example, has not been implemented because of its complexity and low luminosity. The reason for the low luminosity is that crystal optics is capable of focusing only the radiation which falls in the angular interval of the Bragg reflection, whose width is typically on the order of 10^{-5}; the rest of the radiation is wasted. In experiments on one-dimensional focusing, this limitation usually affects only the divergence in the horizontal plane, while the vertical divergence is on the order of 10^{-2}. In experiments on two-dimensional focusing, a collimation $\sim 10^{-2}$ is required in two planes; the effect should be to reduce the intensity by another three orders of magnitude, but no such reserve has been available in experiments on one-dimensional focusing.

In 1972 Kohra and Matsushita[8] showed that at diffraction angles $\theta \approx \pi/2$ ("backscattering") the dynamic width of a Bragg reflection is $\Delta\theta = 2\sqrt{\chi_{HKL}} \sim 10^{-2}$ as has been verified by subsequent calculations[9,10] and as has been observed experimentally.[11] The use of backscattering raises the luminosity of crystal optics by 2.5 to 3 orders of magnitude and opens up the possibility of achieving two-dimensional focusing of x radiation. This was the goal of the present study.

Figure 1 shows the x-ray-optics layout in the experiments. An x-ray beam from a BSV-29 tube, operating at 30 kV and 32 mA, is incident on crystal Si_1, which is a horizontal asymmetric Bragg collimator. The cylindrical curvature of this crystal makes it possible to use this crystal as a stigmator. Crystal Si_2 is a vertical collimator.

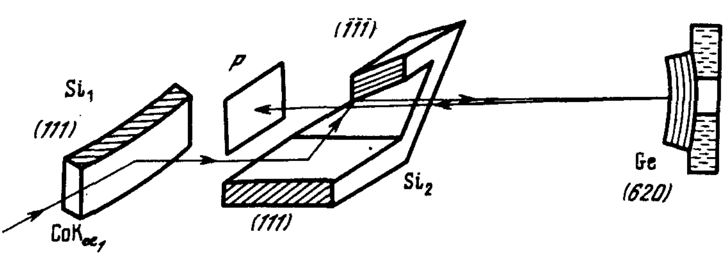

FIG. 1. The x-ray-optics layout for observing two-dimensional focusing. Si$_1$—horizontal collimator-stigmator, angle of incidence $\theta - \alpha = 0.4 \pm 0.05°$ (α is the asymmetry); Si$_2$—vertical collimator, with asymmetric reflection at the first arm ($\theta - \alpha = 0.4 \pm 0.05°$) and $\alpha = 0. \pm 1°$ at the second arm; Ge(620)—mirror cemented to a concave glass lens with a central hole 5 mm in diameter, $\alpha = 0 \pm 0.03°$ (the radii of curvature of the mirror are ≈ 45 cm; the difference between the radii is $\sim 10\%$; P—MR photographic plate.

The reflection from the second arm of this crystal is used to turn the beam in the horizontal plane. The beam then strikes a biaxially curved Ge(620) mirror cooled with nitrogen to $-40\,°\mathrm{C}$ in order to satisfy the condition $\lambda = 2d_{620}$. This crystal is positioned in a vacuum $\sim 10^{-2}$ torr in a cryostat with a window of a material equivalent to Mylar (the cryostat is not shown in Fig. 1). The incident and diffracted beams are deflected from the normal to the plane within the dynamic width of the reflection:

$$\pi/2 - \theta < \sqrt{\chi_{HKL}} \ . \tag{1}$$

This is the condition for workability of the mirror. The mirror doubles as a

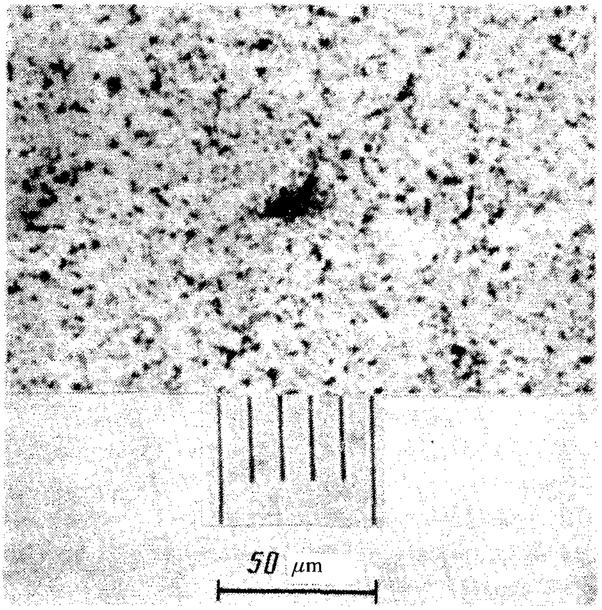

FIG. 2. Photograph of the focus. The intensity is 10 photons/s, and the exposure time is 1 min.

monochromator with a resolution[12] $\Delta\lambda/\lambda=\chi_{HKL}$, which in our case is 1.4×10^{-5}, i.e., 3% of the width of the Co $K\alpha_1$ line. Figure 2 shows a photograph of a focus produced on photographic plate P. Estimates of the contributions of various factors to the width of the focus show that the diffraction broadening is $\lambda/4\sqrt{\chi_{HKL}}=120$ Å, the finite divergence of the "plane" wave is 1.05 μm, and the finite monochromaticity is 1.1 μm. We believe that the limiting factors responsible for the focus size found experimentally, ~10 μm, are vibration and drift of the x-ray-optics layout and the quality of the polishing of the crystals.

In summary, this study has resulted in the first experimental implementation of two-dimensional focusing of x rays in the angstrom range. This study demonstrates the promising outlook for the use of x-ray backscattering to raise the luminosity of x-ray optics. It also opens up the possibility of developing a scanning x-ray microscope.

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