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Obtaining X-ray Shadow Images Using High-Resolution Enlargement Kumakhov Optics

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Abstract—X-ray shadow images have been obtained using cone-shaped polycapillary structures of high-resolution Kumakhov optics. The proposed method develops a substantially new direction in X-ray microscopy. This technique does not require using expensive microfocus X-ray sources employed in the traditional X-ray imaging systems characterized by spatial resolution on a level of 5–6 μm. The images obtained in this study show resolution on a level of 1 μm. © *2004 MAIK "Nauka/Interperiodica".*

In order to obtain images with spatial resolution on a micron level using the existing X-ray shadow imaging microscopes, it is necessary to use special expensive X-ray sources based on synchrotrons or microfocus X-ray tubes [1, 2]. This circumstance significantly increases the price and complicates the design of X-ray microscopes. One solution of this problem is offered by developing X-ray optical systems for microscopes based on Kumakhov optics [3–7]. This polycapillary optics provides for an increase in both contrast and resolution of X-ray images.

In contrast to the projection scheme of enlargement in air gap, where the resolution is determined by the source size, the resolution of a scheme employing capillary optics is determined for the most part by the entrance dimensions of capillaries. Using polycapillary structures in the optical scheme of a transmission microscope, it is possible to obtain X-ray images with a resolution on the level of two to three entrance diameters of the channel [5, 6].

Since the first experiments in polycapillary X-ray microscopy [5, 6], the technology of polycapillary structures has been significantly developed. This progress provides for a significant increase in the performance of X-ray microscopy schemes implementing the principles of Kumakhov optics. Therefore, it is expedient to study the possible applications of modern Kumakhov optics to high-resolution X-ray microscopy.

This paper presents the results of experiments showing the possibility of using high-resolution cone-shaped polycapillary structures of Kumakhov optics for obtaining X-ray shadow images.

The experimental optical scheme comprised an X-ray source, a test object, a polycapillary cone structure, and an X-ray image converter (Fig. 1). The operation of this scheme of X-ray microscopy is based on projecting an X-ray shadow image onto the entrance of a polycapillary cone structure with a large ratio of the exit (D_k) and entrance (d_k) diameters: $M_k = D_k/d_k = 5–15$. The lattice of the entrance holes of the polycapillary structure divides the image into elements, thus forming an array. Each capillary accepts an element of the image and transfers it with enlargement to a detector (X-ray film or image converter). This provides for the first stage of image enlargement (in the X-ray range). This enlargement is determined by the ratio $M_0 = D_0/d_0$, where d_0 and D_0 are the entrance and exit diameters of the capillaries, respectively (note that $M_0 = M_k \equiv M$).

The cone function is to form and enlarge the image, improve the resolution, and increase the contrast. The length L and magnification M of the polycapillary cone structure are related to the focal distance f (a distance from the X-ray tube focus to the cone entrance) by the formula $f = L/(M - 1)$. For example, a structure with $M = 10$ and $L = 45$ mm has $f = 5$ mm. The imaged area is determined by the entrance area of the polycapillary cone structure.

On the existing level of technology developed at the Institute of X-ray Optics (Moscow), it is possible to obtain polycapillary cones with an entrance channel

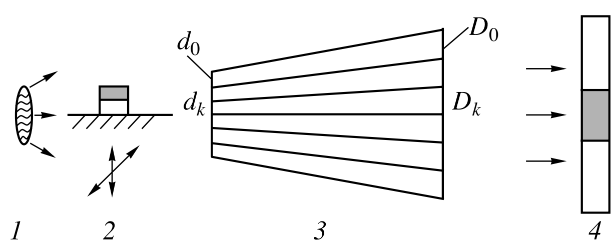

Fig. 1. Schematic diagram of the experimental arrangement: (*1*) focal spot of the X-ray tube; (*2*) test object; (*3*) polycapillary cone structure: (*4*) X-ray image converter.

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diameter of d_0 = 0.15 μm and the ratio of the exit and entrance diameters D_0/d_0 = 10–15.

In these experiments, we used a polycapillary cone with an entrance channel diameter of $d_0 \approx 0.3$ μm and an exit diameter of $D_0 \approx 4.5$ μm. The whole assembled structure had an entrance diameter of d_k = 0.3 mm and an exit diameter of D_k = 4.5 mm, so that M_k = 15. Using this structure, it is possible to obtain a magnification of M = 15 in the X-ray optics tract. Previously, Nikitin [6] used a polycapillary cone structure with d_0 = 0.8 μm, D_0 = 4 μm, and L = 23 mm, for which M = 5.

The X-ray source was a microfocus tube (BS-13) of the transmission type with a copper anode and electromagnetic beam focusing operating in the regime of 2.5 W, 40 kV. The X-ray tube provided for a focal spot size of about 200 μm; the exposure duration was 10 s.

The X-ray pattern obtained at the polycapillary cone exit is converted into an optical image on the scintillation screen of the X-ray image converter. Then, the image of the object studied is further enlarged by a microobjective in the optical tract and the image brightness is enhanced in an electrooptical converter. Finally, the enlarged and enhanced image is detected by a CCD camera and converted into a digital form. The total resolution of the X-ray image converter in the phosphor-coated plane was ~5 μm.

The video image from the CCD camera is fed into a personal computer and processed using a program package with pixel accumulation, averaging, and division, after which the final enlarged image is displayed on the computer monitor.

Figure 2 shows the X-ray shadow image of a test object representing a 2-μm-thick tungsten plate on a 2.5-μm-high silicon pedestal protruding above a thick silicon plate. The silicon pedestal had a small thickness (~10 μm) in the direction of the X-ray beam, which explains the much lower contrast of the pedestal as compared to that of the ~0.5-mm-thick base silicon plate. The thickness of the tungsten sample in the X-ray beam direction was about 10 μm, which was sufficient for obtaining a good contrast. As can be seen in Fig. 2, the image displays clearly resolved details on a micron level, which agrees with theoretical estimates of the resolution ($R = 3d_0$ = 0.9 μm). The image also displays a network formed due to the polycapillary structure walls. Methods aimed at eliminating this network at the computer processing stage are in progress.

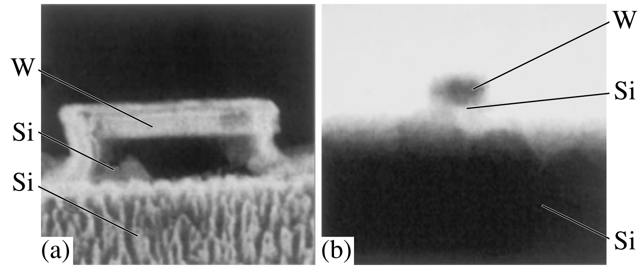

Fig. 2. Enlarged images of the test object (a) in the electron microscope and (b) in the X-ray shadow projector with high-resolution polycapillary Kumakhov optics.

Nikitin *et al.* [5] obtained images of two gold wires with a diameter of 10 μm spaced by 3 μm. However, an analysis of the obtained pattern allowed the real resolution to be evaluated at 1.5–2 μm. The images of the test object obtained in this study are directly indicative of the micron resolution. The results of our experiments indicate that the resolution can be further improved to reach a level on the order of 0.1 μm through optimization of the optical scheme and the characteristics of important components, in particular, the polycapillary cone structure.

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