PARALLEL X-RAY NANOTOMOGRAPHY

Priority is claimed from Provisional Application Ser. No. 60/135,639, filed May 24, 1999 and entitled "Parallel X-Ray Nanotomography".

FIELD OF THE INVENTION

The present invention relates to a method and apparatus for nanotomography.

BACKGROUND OF THE INVENTION

Various techniques for three-dimensional ("3D") tomography are known. In such 3D tomography techniques, typically several two-dimensional ("2D") views of a specimen to be imaged are taken at several determined angles of rotation of the specimen. Alternatively, the imaging apparatus is rotated around the specimen to generate plural 2D views. These 2D views can be stored in a computer understandable form in a readable computer memory. A 3D image of the specimen is then reconstructed by combining the multiple 2D images, such as using one of various known mathematical image reconstruction techniques.

One deficiency in the known 3D nanotomography apparatus is that a very large, relatively expensive apparatus is required for generating the images. For example, in one known computerized tomography apparatus that uses a synchrotron, a beam of particles, typically x-rays, is passed through a sample. In two such known embodiments, the transmission through the sample is detected by several detectors, or by a raster scan and a single detector. The sample can be rotated or shifted at various angles in order to provide a range of exposure orientations of the sample.

A variety of known mathematical techniques are performed on the acquired data. For example, a three dimensional reconstruction of the x-ray absorption as a function of position may be obtained, as discussed in G. T. Herman, *Image Reconstruction from Projections: the Fundamentals of Computerized Tomography,* Academic Press, 1980. Such three-dimensional reconstruction of the x-ray absorption of a sample can be used, for example in medical diagnosis, industrial sample acceptance, industrial process analysis, and industrial research. Good spatial resolution has been achieved in tomography using synchrotron radiation sources has achieved resolutions starting from 15 μm, as described in Flannery et al., U.S. Pat. No. 4,883,698, to as low as 50 nm as described in J. Lehr, *Optik* 104, 166 (1997) and Haddad et al, *Science* 266, 1213 (1994). The use of tomography in analyses of integrated circuit interconnects is described in Levine et al., *Applied Physics Letters* 74, 150 (1999). The use of a zone plate has been contemplated in laser plasma imaging. See Nakamaya et al., "Zone Plate X-Ray Microscope Using a Laser Plasma Source", Japan J.App.Physics 33, 1280 (1994).

As presently understood, the most brilliant x-ray sources are from synchrotrons, the most recent of which are characterized as third-generation synchrotrons. However, the cost of a third-generation synchrotron typically is very high, exceeding $100,000,000 and so there are very few of them and typically they are owned by governmental bodies or other highly capitalized organizations. In addition, the time required to construct such devices can be quite long, such as exceeding two or three years, and a large space is required to house the synchotron, resulting in relatively large overhead and cost.

In x-ray nanotomography a very high resolution typically is required, such as measured in nanometers. One demonstrated technology for an objective lens is a Fresnel zone plate. X-ray spot sizes below 50 nm have been demonstrated with these lenses, as described in J. Kirz, C. Jacobsen, and M. Howells, *Quarterly Reviews of Biophysics,* 28, 33 (1995). Grazing incidence optics are limited at present to approximately 1 μm resolution as described in P. Dhez et al., *Review of Scientific Instruments,*70, 1907 (1999). However, the Fresnel Zone Plate has a limited acceptance angle, and in particular it has an acceptance angle much smaller than that of the best x-ray collecting optics.

The ability to perform a tomographic reconstruction is limited by several factors, the most fundamental of which is x-ray photon counting statistics. Large numbers of x-rays are required to make accurate reconstructions. One wants to detect as large a fraction of the x-rays exiting the sample as possible.

Accordingly, there is a need for an x-ray based imaging system which can generate an x-ray image of very high resolution, without resorting to synchrotrons in the creation of the shaped illumination field. Moreover, there is a need for a system that can use a more compact and more economical apparatus, that requires less space than a typical known synchotron.

SUMMARY OF THE INVENTION

The present invention alleviates to a great extent the disadvantages of the known tomography systems and methods, using a composite objective lens comprising an array of micro-objectives, such as an array of Fresnel zone plates, and in the preferred embodiment a laser plasma x-ray source that provides a point-like x-ray source is used. Other x-ray generating sources may be used as well, such as an electron beam microfocus x-ray source.

In particular an x-ray source is provided outputting generated x-rays. Preferably the x-ray source includes a laser exciting a plasma x-ray source. The emitted x-rays are collected in a collector, which preferably includes one or more multi-layer coated reflective surfaces. A sample to be imaged is situated on a rotatable and translatable mounting assembly. The x-rays transmitted through, scattered or reflected from the sample are directed with a composite objective lens assembly. Preferably the composite objective lens assembly includes an array of micro-objectives, such as preferably Fresnel zone plates arranged in an array. The x-rays are directed by the composite objective lens assembly and optionally pass through one or more apertures for further refinement. An image formation and acquisition apparatus forms an image based on the received x-rays.

Among the advantages of this apparatus and technique of imaging is improved speed of 3D image acquisition and generation achieved by matching the etendue of the x-ray source (the product of the emitting area of the source and the solid angle of emission) with the etendue of the collector (product of the area of the optic and its acceptance solid angle). Since the micro-optic lens such as the Fresnel zone plate array has a small etendue, a plurality of Fresnel zone plates may be used to match the much larger etendue of the collector optic. This plurality of Fresnel zone plates or micro-objectives will be called a "composite objective" in this description of the invention. The etendue of typical x-ray sources is larger than that of collector optics. In the present invention, the etendue of the x-ray source is selected to be relatively close to that of the collector. In order to accomplish that, a point-like x-ray source preferably is selected. As described in greater detail below, such suitable x-ray sources include a laser-plasma x-ray source or an electron beam microfocus x-ray source.