Invited Paper

Non-Destructive Investigation for Metal Structure in 3D Flash Memory by an Ultra-High Resolution X-ray Microscope

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ABSTRACT

We have developed a high-resolution X-ray microscope with spatial resolution better than 100 nm. The utilized X-ray energy of the microscope is 17.5 keV that can penetrate through standard silicon substrate and enables to observe embedded nanoscale metal structure and defects, nondestructively. We have applied the present X-ray microscope for investigating 3D flash memory devices and observed precise metal filling structure in there. In addition, defects in the circuit area were also found.

Keywords: X-ray microscope, 100 nm resolution, 3D flash memory, metal structure

1. INTRODUCTION

For increasing the capacity of 3D flash memories, the number of memory stack is getting increase and the depth of the memory hole exceeds 5 μm, and continuously to be developing 10 μm or more. Therefore, it is even more difficult to fabricate uniform high aspect ratio (HAR) holes. In addition, the 3D flash memory structure requires hundred or more layers of metal gate electrodes and word lines around the HAR holes. It is extremely difficult to observe the structure of such thick layers nondestructively, which is a major problem of the existing metrologies. In contrast, X-rays are high material permeability, penetrating through standard Si wafers including such thick metal layers. The precise shapes of the HAR holes are tried to measure by transmission small angle X-ray scattering (T-SAXS) and promising performances are obtained as a nondestructive metrology [1, 2] with laboratory source of 17.5 keV (Mo Kα) X-ray. However, T-SAXS can observe only the average structure in the irradiated region and not applicable for the local defect analysis. For investigating defects structure of the metal filling states in the 3D flash memories, it is demanded to use a direct X-ray imaging technique which can resolve each memory holes.

X-ray microscope itself is long history because it is considered to break wavelength limitation of the visible light due to its extremely short wavelength (typically 0.1nm). However, it requires ultra-high precision fabrication technology for producing appropriate X-ray lens. Fresnel zone plate (FZP) is the most developed X-ray lens and has been applied mainly for relatively lower X-ray energy (< 10 keV) [3]. It is because refraction index of higher energy X-ray is almost one (very close to that of vacuum) and difficult to obtain sufficient refraction. Particularly, if we make a realistic FZP with 50 nm resolution (Ta thickness 500 nm) lens for 17.5 keV X-ray, efficiency is less than 2%, and numerical aperture (NA) will be less than 0.001. For higher energy X-rays, multilayer Laue lens is also proposed, but it showed not good imaging quality [4]. The other candidate is reflection lens. Matsuyama, *et al.* developed ultra-high precision polishing technology and realized 50 nm resolution X-ray imaging lens even at 12 keV [5]. However, the focal distance of the lens is very long, and it needed 45 m from the sample to the detector position. Therefore, it could not apply for the laboratory-based system. Yamada proposed combination of the Wolter III lenses could overcome the problem [6]. We have modified his idea with combining Wolter I and Wolter III lenses and realized 50 nm resolution for 15 keV X-ray with sample to camera distance less than 2 m [7]. For applying this idea for the laboratory system, we have developed the same Wolter I and Wolter III combined lens with very precise multilayer coating on the lens surface which reflects Mo Kα line (17.5 keV) X-ray. This energy is the same as we used for the T-SAXS. In this paper, the fundamental concept of the developed X-ray microscope utilizing the reflection lenses will be described. The basic performance of the microscope will be also presented. Finally, the results of the observation for 3D flash memories will be presented.

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2. CONCEPT OF THE REFLECTIVE X-RAY LENS

Figure 1 shows the arrangement of the present X-ray lens which is configured combination of Wolter I and III mirrors with placing Kirkpatrick-Baez (KB) geometry [7]. In the vertical direction focusing, hyperbola and ellipse mirrors are fabricated on the one substrate (Wolter I). In the horizontal direction, two mirrors are arranged to face (Wolter III). The benefit to use this arrangement is the mirror principal plane can be located at outside of the mirror position and enable to coincide the principal planes of both vertical and horizontal mirrors as shown in Figure 1 and distortion of the images can be very small. The surface of the mirrors is coated by iridium for securing total reflection up to the X-ray energy of 15 keV.

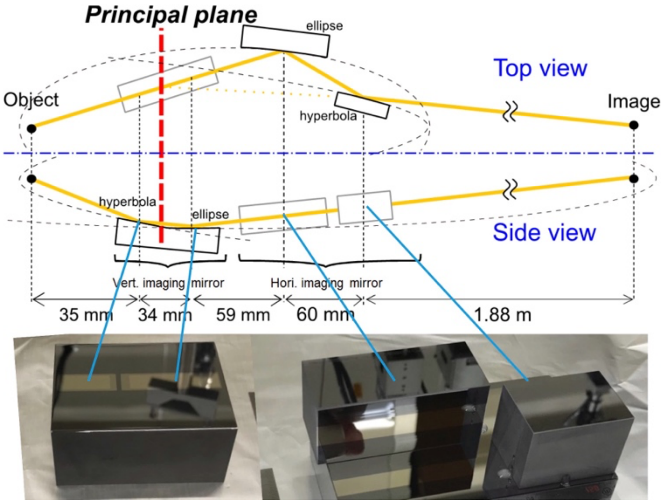

Figure 1. Configuration the presented X-ray reflective lens and photographs of the lens components. The explanation is described in the text.

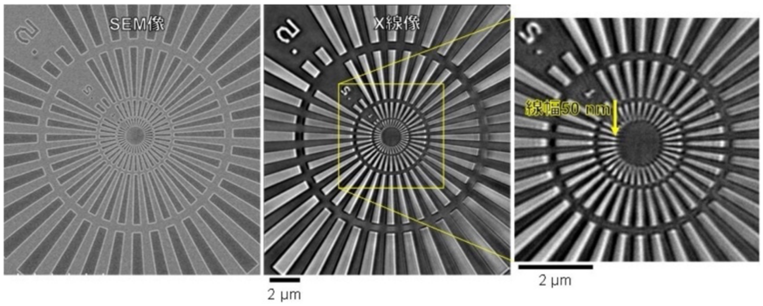

Figure 2. X-ray microscope image of 50 nm test pattern with 15 keV X-ray. The SEM image is also shown. 50 nm line is clearly visible.

We have tested the present concept of the imaging lens at SPring-8 BL29XU using a radial test pattern (XRESO-50HC, tantalum thickness 500 nm, NTT-AT). Figure 2 shows the result of the observed image comparing with SEM image. One can see 50 nm line is clearly resolved and the aspect ratio of the image is almost one (we did not apply any image distortion corrections). This result indicates that the present reflection X-ray imaging lens works well. However, the numerical aperture (NA) of this lens (1.0×10^{-3}) is restricted by the critical angle of the total reflection of the coated material and difficult to increase. Therefore, to apply the present concept for laboratory sources, it is preferable to increase reflection angle of the mirror. It can be possible if we can coat precise controlled *d*-spacing multilayers on the mirror surface. We have redesigned the lens parameters for optimizing Mo Kα radiation (17.5 keV) with multilayer coating, which can be applied for transmission X-ray imaging on silicon substrates and achieved $NA\approx3.0\times10^{-3}$. It means almost ten times brighter images can be expected, and it is very beneficial for realizing X-ray microscope in the laboratory.

3. THE PERFORMACE OF THE MULTILAYER COATED X-RAY LENS

Figure 3 shows the accuracy of the surface polishing of the lens and multilayer *d*-spacing on the mirror surface comparing to the designed value for Mo Kα radiation. One can see the accuracy of the surface profile is almost ideal and discrepancy of the designed value is less than ±1 nm. Absolute *d*-spacing value is also well controlled, and error is less than ±0.2 Å. We also performed the imaging experiment for confirming the performance of the lens system at SPring-8 BL49XU. Figure 4 shows the observed image for the test pattern, of which smallest line width is 20 nm (XRESO-20, tantalum thickness 100 nm, NTT-AT). We can see the smallest 20 nm line is clearly resolved and the performance is good enough for the purpose.

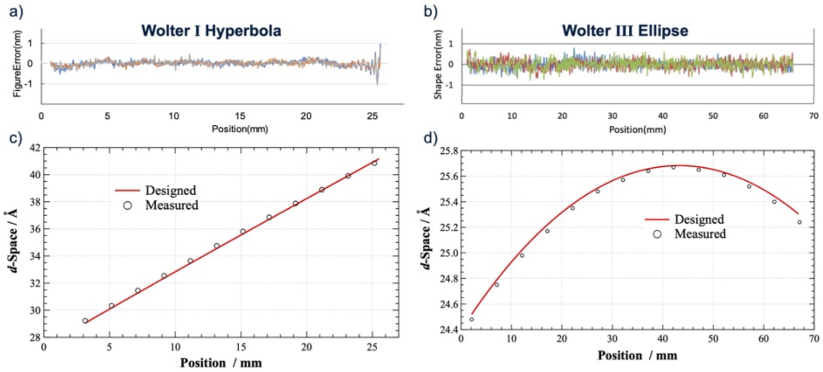

Figure 3. a) Surface figure error from the designed value for Wolter I hyperbola and b) Wolter III Ellipse. Designed and measured multilayer *d*-spacing profile of c) Wolter I hyperbola and d) Wolter III Ellipse mirrors.

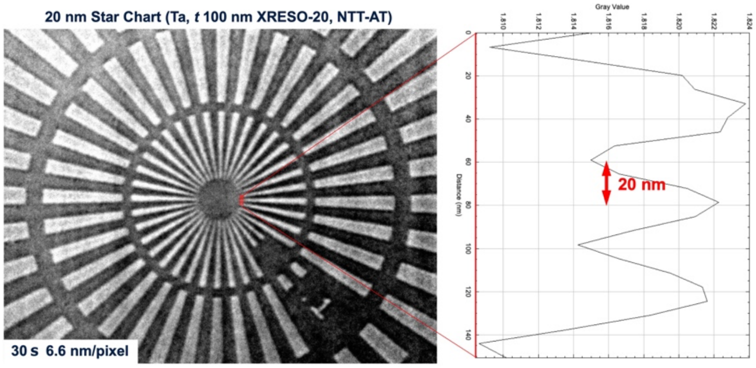

Figure 4. The X-ray microscope image for the minimum 20 nm test pattern. The narrowest pattern is clearly resolved.

The largest difference in the laboratory comparing to synchrotron sources is the lack of photon flux. The difference is more than 10^4 times or more. Therefore, how to create bright illumination source is the key for the development. We have developed a high-brightness rotating anode Mo X-ray source (> 480 kW/mm^2) combined with an accurate point focus optic. The observed image of 200 nm hole pattern (XRESO-50HC, tantalum thickness 500 nm, NTT-AT) on a standard thickness Si wafer is shown in figure 5. Even on through Si substrate, 200 nm holes are clearly visible with laboratory X-ray source.

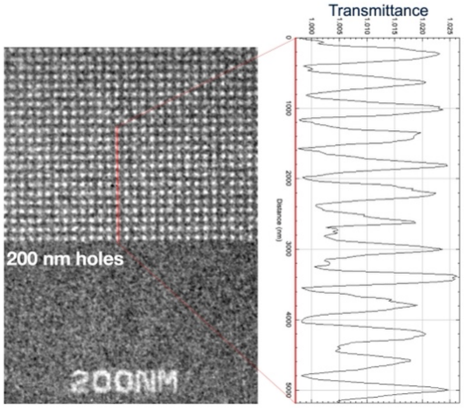

Figure 5. X-ray microscope image for 200 nm holes on Si substrate and line profile of the transmittance.

4. OBSERVATION OF 3D FLASH MEMORIES

Figure 6 shows an X-ray microscope image in 23 μm × 15 μm area of a 3D flash memory with filled metal layers and its enlarged view in the red frame. The left-hand right-hand sides are corresponding to circuit and memory cell area, respectively. Color intensity indicates X-ray absorption rates, and we can estimate area density of the metal filling quantitatively, by calculating X-ray absorption coefficient for Mo Kα. It can be recognized circular dots in both areas. Particularly, in the circuit area, the color intensity of the dots gives large variation. This variation may indicate the existence of defects in this area. Figure 7 shows graphs of X-ray transmittance line patterns for a) yellow horizontal line and b) blue vertical line in the enlarged image, respectively. It can be clearly recognized X-ray transmittance of the center of circular area is higher than that of the surrounded area due to fill of the metal material. White horizontal lines in figure 6 are trenches and show highest transmittance, however both side of the trench area shows lowest transmittance. The latter indicates the metals are concentrated in these areas. In addition, white colored trench area shows undulation. As demonstrated in this section, the present high-resolution X-ray microscope enables nondestructive investigation for nanometer scale embedded metal structures as is.

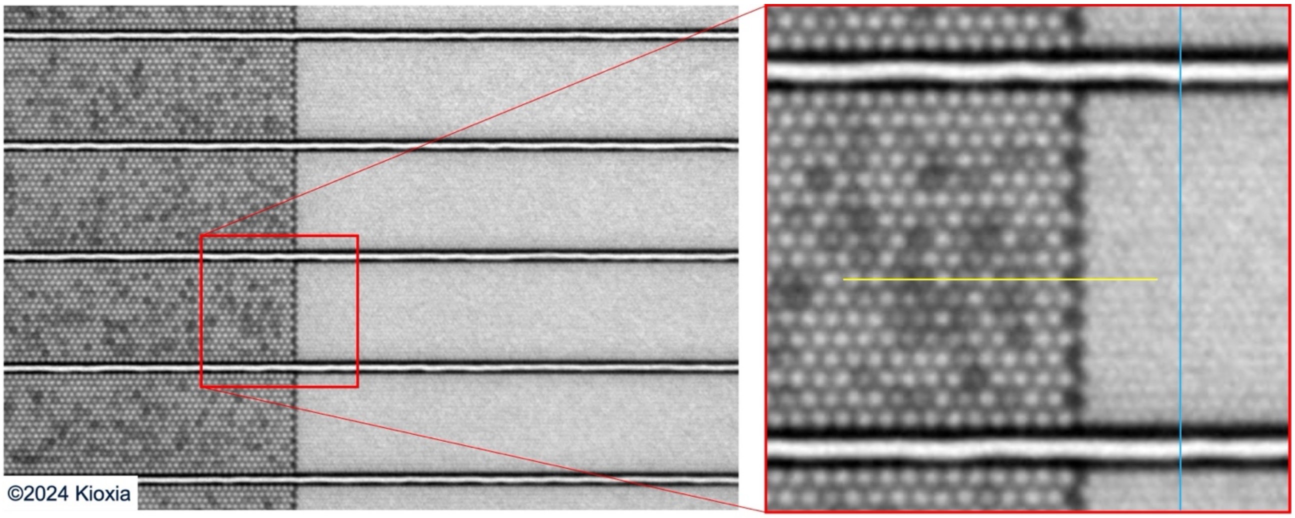

Figure 6. X-ray microscope image of a 3D flash memory in 23 μm × 15 μm area with its enlarged view in the red frame area. The pixel size of the image is 17.6 nm.

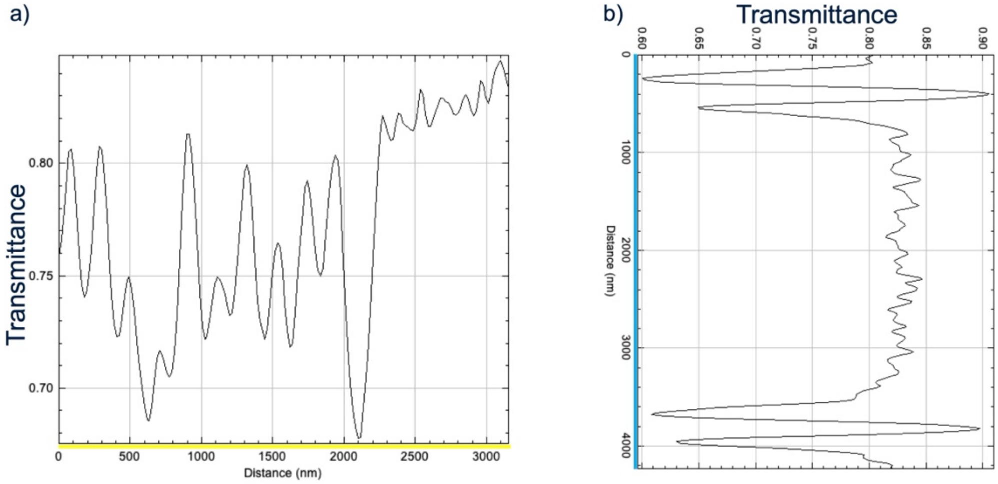

Figure 7. X-ray transmittance pattern indicated by yellow and bule color lines in Figure 6. From the value of the transmittance, we can calculate area density of the embedded metal, quantitatively.

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