Microfabrication of thick tungsten films for use as absorbers of deep X-ray lithography masks

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Abstract We fabricated thick (5 μm) tungsten (W) film patterns by sputtering and dry etching, and realized a new deep X-ray lithography mask. The X-ray mask with 5-μm-thick W absorbers could expose about 1-mm-thick resist structures. In the deposition process of W films, the column structure of about 0.2 μm grain size, from which pattern edge roughness originates, disappeared by adding nitrogen into the sputtering gas. W film etching was carried out by reducing gas pressure and cooling the substrate (−40 °C), and a side etch width of below 0.2 μm was obtained. From the results of the pattern edge roughness and the side etch width, a pattern fabrication accuracy below ±0.5 μm was achieved. Furthermore, film stress, which induces pattern distortion, was reduced to below 50 MPa by controlling the sputtering gas pressure. The obtained mask achieved a pattern distortion below ±0.3 μm.

1 Introduction
The fabrication of high aspect ratio microstructures has gained increasing interest in the fields of communications, microelectronics, micromechanics, medical devices, integrated optics and sensors. Fabrication of these devices requires new manufacturing techniques, such as the LIGA process which combines deep X-ray lithography (DXRL), electroforming, and plastic molding (Becker et al., 1986). The role of the DXRL step in the LIGA process is to transfer an absorber pattern from a mask into a resist with high precision and depth using X-rays from a synchrotron radiation (SR) source. These microstructures can be used as master molds in subsequent replication steps. The final metal, alloy, ceramic, or plastic products have a large variety of applications.

The exposed resist in the DXRL is very thick, more than several hundred microns, compared to that used in conventional X-ray lithography for the manufacture of future ULSI, about 1–2 μm. To realize pattern transfer into very thick resists, a much greater absorber thickness is required to ensure sufficiently high mask contrast. This makes the mask absorber technology for DXRL more difficult to apply than that for X-ray lithography for ULSI fabrication.

Usually, absorbers of DXRL masks are fabricated by depositing gold (Au) in a resist mold by electroplating (Becker et al., 1986; Guckel et al., 1991; Malek et al., 1996). However, some problems exist: the electroplating process tends to result in the formation of defects and uneven thickness; thermal deformation of Au absorbers may occur during SR irradiation because of the large thermal expansion coefficient of Au; and complicated processes using intermediate X-ray masks are needed to realize submicron pattern accuracy (Bley and Mohr, 1994).

Tungsten (W), which is used in standard X-ray masks for ULSI, is promising for use as an absorber of DXRL masks. W has an X-ray absorption coefficient comparable to that of Au and is thermally more stable than Au. Moreover, it can be sputtered and patterned by dry etching without the formation of defects and uneven thickness. Although the microfabrication of thin (<0.5 μm) W films used in conventional X-ray masks for ULSI is realized, that of thick (>3 μm) W films has never been reported because of difficulties caused by film thickening.

We have developed a process for the microfabrication of thick W films by sputtering and dry etching and applied this process to DXRL mask fabrication.

2 Requirements for DXRL mask absorbers
The mask absorber films must be sufficiently thick to provide sufficient attenuation of X-rays to obtain an adequate mask contrast. Furthermore, the absorber films should have the capability to form accurate and vertical patterns, and the inner stress of absorbers must be minimized because it causes pattern distortion. The fabrication of highly accurate patterns and the reduction of pattern distortion become more difficult with increasing film thickness.

The required absorber thickness depends on the spectral composition of the SR and the resist thickness to be structured. We have been applying the compact SR source “NIJI-III”, developed by Sumitomo Electric Industries, Ltd. to DXRL (Takada et al., 1997). Figure 1 shows the relationship between absorber thickness and developed
resist depth when using a 2-μm-thick silicon nitride (SiN) blank and a MMA/MAA copolymer resist which we developed (Numazawa et al., 1996). To fabricate nearly 1-mm-high resists, over 5-μm-thick absorber patterns are required.

Considering that the typical applications of the LIGA process have minimum pattern widths in the 5-10 μm range, it is desirable to achieve pattern fabrication accuracy below ±0.5 μm. Pattern edge roughness and side etch width degrade the accuracy. The side etch width means the deviation from the ideal vertical etching profile of a sidewall. As regards pattern distortion, it is estimated that the stress of the absorbers must be reduced to below 100 MPa to achieve a pattern distortion of below ±0.5 μm against a few millimeters’ pattern size, assuming a combination of a 2-μm-thick SiN mask blank and 5-μm-thick W absorbers (Yanof et al., 1986).

3
Absorber film deposition

W absorber films are deposited using a RF-assisted DC sputtering system. It is known that W films deposited by sputtering have columnar structures and a serious problem of stress control. The edge roughness of the patterns originates from the columnar structures (the grain size is about 0.2 μm), and the stress causes pattern distortion.

To reduce edge roughness, we attempted to obtain a structureless film by adding nitrogen (N₂) to the argon sputtering gas (Kanayama et al., 1988). The film was deposited on a silicon (Si) substrate. The deposition conditions were as follows: DC power of 100 W, assisted RF coil power of 100 W and a gas pressure of 0.8 Pa. Total gas flow was set at 30 sccm, and N₂ content was varied from 0 to 30%.

Figure 2 shows the X-ray diffraction (XRD) patterns as a function of N₂ content in the sputtering gas. In the XRD patterns of films obtained at a N₂ content of 15–20%, broad peaks corresponding to an amorphous structure are observed. This result agrees with the cross-sectional views of structureless films observed by scanning electron microscopy (SEM), as shown in Fig. 3.

The obtained structureless W film contains nitrogen and is expected to have lower density compared to bulk W. The density of absorber films is an essential factor, because X-ray absorption strongly depends on the density. Therefore, we estimated the density of the N₂-containing films. As a result, the density of the structureless film is 18–19 g/cm³, which is comparable to that of bulk W.

We also investigated the reduction of stress in W film. The stress in sputtered film is influenced by deposition conditions, especially the pressure of the sputtering gas. Therefore, we performed sputtering by varying the

![Fig. 1. Relationship between absorber thickness and developed resist depth](image1)

![Fig. 2. X-ray diffraction patterns of sputtered W films](image2)

![Fig. 3. Cross-sectional views of W films](image3)