RC 20076 (05/26/95)
Engineering and Technology

IBM Research Report

High Resolution X-ray Mask Repair

Patricia G. Blauner

IBM Research Division
T.J. Watson Research Center
Yorktown Heights, NY 10958

LIMITED DISTRIBUTION NOTICE

This report has been submitted for publication outside of IBM and will probably be copyrighted if accepted for publication. It has been issued as a Research Report for early dissemination of its contents. In view of the transfer of copyright to the outside publisher, its distribution outside of IBM prior to publication should be limited to peer communications and specific requests. After outside publication, requests should be filled only by reprints or legally obtained copies of article (e.g., payment of royalties).

Research Division
Almaden · T.J. Watson · Tokyo · Zurich

HIGH RESOLUTION X-RAY MASK REPAIR

Patricia G. Blauner
IBM Watson Research Center
Yorktown Heights, NY 10598 USA

Abstract

Repair of gold absorber x-ray masks with ground rules down to 250 nm is now accomplished using commercially available focused ion beam (FIB) tooling. Chief among the challenges in extending this technology below 250 nm is that presented by the redeposition of absorber material during opaque repair. This paper examines several techniques which have been proposed to minimize redeposition, including the use of thinner absorbers, gas assisted etching, and simple post-repair trimming. In addition, the capabilities of the current tooling is demonstrated and a comparison of the FIB etch characteristics of several different absorber materials proposed for future mask fabrication (Au, 2W and TaSiN) is presented.

1. Introduction

Focused ion beam (FIB) repair of x-ray masks has developed to the point where gold absorber masks with feature sizes down to 250 nm are now being repaired in manufacturing using commercially available tooling[1-3]. FIB repair of a large variety of defects is routinely accomplished using simple physical sputtering of the absorber to remove excess material (opaque repair) and ion beam induced deposition to replace missing material (clear repair)[4-5]. This paper presents data related to several issues associated with extending FIB repair to even higher resolution masks. The work includes a demonstration of the capabilities of the current tooling, an investigation of several techniques to minimize the effects of absorber redeposition, and a comparison of the repair characteristics of several different absorber materials proposed for future mask fabrication. The studies presented have been confined to opaque repair, since higher resolution clear repair can be accomplished, at the very least, as a two step process: deposition followed by sputter removal of excess material.

There are two classes of sub-250 nm defects whose repair would be expected to be a straightforward extension of the current technology and techniques: those whose repair involves etching a missing feature into absorber, and those which are not in close proximity to other features. The main challenge in accomplishing these sorts of repairs will be to meet required placement accuracy. The repair 180, 150, and 100 nm defects was recently demonstrated on both a prototype repair tool at IBM Yorktown and on a commercial tool (Micrion 8000XR[6]) using a high resolution defect test mask written in 600 nm thick electroplated gold (section 2). Figure 1 shows an example of the repair of missing features. 150 nm contact holes have been added to the 2nd and 3rd arrays shown in the SEM micrograph. In this case, the placement accuracy of the repair was limited by the pixel resolution and stage

stability of the prototype repair tool. Figure 2 shows an example of the repair of relatively isolated defects, 180 nm protrusions removed using the 8000XR. The figure shows scanning ion micrographs (SIM) taken by the repair tool before (left) and after (right) repair. Although detailed measurements of the placement accuracy of such fine repairs have not been made, it is clear that the repair of such features is well within the reach of the current technology.

The repair of defects which are in close proximity to mask features presents the most serious challenge to the repair of high resolution masks. In these cases, the high aspect ratio of the features results in redeposition of sputtered material from defects onto edges of nearby mask features[4]. A minor issue at critical dimensions of 250 nm, redeposition becomes a serious problem at smaller ground rules. In Fig. 3, a 150 nm protrusion into a 250 nm space is shown before (left) and after (right) it is sputtered etched using the prototype repair tool. As is clearly illustrated, a large proportion of the gold removed from the bump is redeposited on the adjacent line. In effect, the defect has been moved from one line to the other. Figure 4 shows the problem at smaller ground rules. Here, a bridge across a 100 nm space has been etched by the ion beam. Although the 100 nm space has been reconstructed, "birds beaks" of redeposited gold pinch off the space above and below the repair.

Several techniques proposed to minimize the effects of redeposition, including the use of thinner absorbers, gas assisted focused ion beam etching (GAE), and post repair trim, are examined below. The use of thinner absorbers should minimize the problem of redeposition because the effect is highly dependent on the aspect ratio of the features being repaired[4] . Since reduced absorber thickness also offers advantages in mask patterning, pattern placement, and printing[7], a study comparing redeposition in patterns written in two different thickness' of electroplated gold was conducted. Gas assisted FIB etching also reduces redeposition during opaque repair, since the process serves to volatile material removed[8-9]. Although the technique is not applicable to gold absorbers, it can be used on masks fabricated from refractory metals. Early work showed that GAE of W masks using xenon difluoride succeeded in significantly reducing redeposition[8-9] However, the work was done using a low resolution FIB system, so it was not possible to evaluate resolution related issues. This paper presents results of a study of high resolution etching of W using XeF_2. Post-repair trimming, a straightforward approach whereby redeposited material is sputter etched by the FIB after the initial defect repair[5], is already used in some critical repairs. Its efficacy at yet higher resolution is examined.

Finally, a study is presented comparing opaque repair of 3 different absorber materials currently being considered for the fabrication of future masks: electroplated gold, W, and TaSiN. This study is limited to a comparison of the normal (not gas assisted) FIB etch characteristics of the three materials.

2. Apparatus and Materials

The results presented in this study were achieved using two different FIB systems, a prototype repair tool developed at IBM's Watson Research Center[4-5], and a commercial tool, the Micrion 8000XR, installed at the Microlithograhic Mask

Development Center (MMD) at IBM's Essex Junction, Vermont site[1-3]. The 8000XR incorporates many of the processes and tooling developed on the prototype, but includes such improvements as a differential laser interferometer controlled stage and beam deflection system to improve repair placement and stability, along with numerous additional software automated features[2-3]. The prototype FIB uses 60 nm beam of 100 keV Ga^+. The commercial FIB uses a 40 nm beam of 30 keV Ga^+, both typically operate with 10-20 pA of beam current.

The gas assisted etching experiments were done on the prototype tool, using the same gas introductory system used for gold deposition. XeF_2 is fed from an external manifold at room temperature, through a variable leak valve and into a 3 mm ID tube closed off at one end with two holes, 1/2 and 1 mm, on its top and bottom. The tube is positioned with its bottom hole 200 μm above the substrate surface and centered on the beam axis. The ion beam passes directly through the 2 holes in the gas feed tube[10]. The gas pressure is measured in the manifold, just down stream from the leak valve, and is used to control flow through the leak valve. In these experiments, the manifold pressure was held at 30 mTorr. The ion beam was scanned with a pixel dwell time of 250 ns and a refresh time (the minimum time allowed before returning the beam to a given pixel) of 1 ms or greater, as indicated.

CD metrology measurements where done on a Hitachi S4000 equipped with a PGT linewidth measurement system[11]. Pitch calibration and identical measurement algorithms were used for all measurements.

Absorber materials for these studies were obtained from 3 sources. High resolution 500-600 nm thick electroplated gold masks and wafers were obtained from IBM' Watson Research Center. Patterning was done on the VS-5 100 keV electron beam system[12]. Masks were written on standard IBM format substrates (2.5 μm thick boron doped Si membrane). A tungsten sample was obtained from AT&T Bell Laboratories[13]. This was an unpatterned Si wafer coated with a multilayer stack of (bottom to top) 20 nm Cr / 300 nm W / 30 nm of Cr. A second sample was fabricated from a small piece of this sample by wet chemical etching of the top Cr layer. Two amorphous TaSiN samples were obtained from Motorola Phoenix Corporate Research Laboratories[14]. These were unpatterned Si wafers coated with a multilayer stacks of (bottom to top) 30 nm Cr / 460 nm TaSiN / 30 nm Cr, and 30 nm Cr / 460 nm TaSiN. Ion beam channeling in FIB images and SEM inspection revealed no grain microstructure in the TaSiN films, a columnar microstructure with a grain size of approximately 50 nm in the W film, and a large grained (1-10 μm) polycrystalline microstructure in the electroplated gold films.

3. Redeposition and Thin Gold

A high resolution gold mask was fabricated which consisted of a set of programmed defects repeated on a single mask, but plated to different thickness' from 340-560 nm[7]. The pattern used in this study consisted of 100 nm protrusions on 1000 nm lines patterned with spacings varying from 1000 nm down to 100 nm (see fig. 5). Protrusions in 340 and 590 nm thick patterns were sputter etched using the prototype repair tool and the widths of the opposite lines were measured. The

results are shown in Figure 5. If no redeposition occurred, the line would measure its nominal width of 1000 nm, regardless of the line spacing. As expected, however, the measured linewidth increases as the spacing decreases and more material is redeposited (below 250 nm spacing no data is shown, since the redeposited material actually begins to extend into the region being etched by the FIB). Although the increase in linewidth is systematically less for the thinner absorber (about 10 nm), the effect in this limited range (590 vs. 340 nm thickness) is not large. Redeposition is not significantly reduced by decreasing absorber thickness to 340 nm.

4. Gas Assisted Etching

It was observed early in this study that XeF_2 exposed clean W surfaces exhibit significant spontaneous etching even in the absence of ion beam irradiation. A concern developed that spontaneous etching would limit the resolution obtainable using the chemistry of this GAE process, since it implies that some degree of lateral sidewall etching will occur even if the top surface is protected by a non-reactive overlayer such as Cr.

Figure 6 shows SEM's of one end of 5 x 20 μm boxes milled through the W layer of the Cr/W sample. The boxes were milled using identical conditions: 250 ns dwell time, 27 ms refresh time, a spot spacing of 30 nm (approximately 1 beam radius), and a dose of 1 x 10^{16} ions/cm^2. For the left hand box, the flow of the reactive gas was stopped immediately after milling and the sample was moved 2 mm away from the gas tube. For the right hand box, the gas was allowed to flow over the sample for 5 min. after milling. Note that small holes in the absorber can be seen extending 1 μm out from the box which received the additional gas exposure. Presumably, the light ion dose received by the area surrounding the box (from the tails or wings of the ion beam) produces pinholes in surface contamination or native oxide which would otherwise protect the surface from spontaneous etching by XeF_2.

Further evidence of spontaneous etching can be seen in profilometry data taken over a range of ion doses (Fig. 7). The etch rate measured at ion doses below 3 x 10^{15} is approximately 2 times larger in data taken with the gas left on for 5 min. after milling. In both cases, the etch rate slows dramatically as the W/Cr interface is approached. From the data taken at low dose with the reactive gas shut off immediately after etching, a GAE tungsten etch rate of approximately 210 atoms/ion can be inferred. This represents an enhancement of a factor of approximately 35 over that measured without the presence of the reactive gas (a sputter yield of approximately 6 atoms/ion).

Given the observed spontaneous etching in the area surrounding a repair, GAE using XeF_2 will require that the Cr overlayer on the absorber be left in place, rather than removing it in the final stages of mask fabrication. In order to investigate the effects of spontaneous etching on the sidewalls of absorber with the Cr overlayer left in place, 250 nm features were etched into the Cr/W/Cr multilayer using a range of ion doses. The features, shown in Fig. 8, were milled in the same manner as those shown in Figs. 6 and 7, but with a refresh time of 1 ms. The shorter refresh time resulted in a smaller etch rate enhancement, approximately 17x the physical sputter rate of W. The series of high tilt SEM micrographs in Fig. 8 shows the

development of a pronounced undercut in the feature. Although the Cr overlayer measures the intended 250 nm, the width of the x-ray absorbing W layer is reduced by 50% at the ion dose sufficient to remove the surrounding W. Although repair bias could be used to compensate, the undercut is large enough that biasing would not be possible for features below 250 nm. It is concluded that if GAE is to be useful for high resolution x-ray mask repair, then more complicated processes which allow some form of sidewall passivation will need to be developed. The existing process using XeF_2 is not adequate.

5. Post-Repair Trim

Post repair trim is used occasionally to remove redeposited material in critical repairs of defects in close proximity to mask features. Typically, after removing the initial defect, a low dose ion mill is done to redefine critical edges that have had material redeposited on them. Sometimes, it is necessary to iterate the process several times as material is removed from one edge and redeposited on another. Figure 9 shows an example of such a process performed on programmed defects in an electroplated gold mask. A sequence of FIB images taken in the 8000XR shows a 180 nm space containing 3 defects before repair, after sputter etching the defects, and after trimming the repairs. In this case, trimming was done by etching the entire 180 nm space using a low ion dose (about $1x10^{17}$ ions/cm^2). As can be seen, the 180 nm space has been reasonably reconstructed. Note the small "birds beak" of redeposited material remains where the trim itself terminates.

As the defect size shrinks, several cases were observed where, because of the small amount of material contained in the defect, no post-repair trim was required. In one such case, 100 nm features were removed from the centers of 250 nm spaces. Redeposited material could not be detected in the post-repair image.

6. Etching of Au, W, and TaSiN Absorbers

Because gold is a serious source of contamination in IC fabrication facilities, an attempt is underway to develop a refractory absorber for use in future x-ray mask fabrication. In this study, the FIB etch characteristics of two such absorbers, W and TaSiN are compared to that of the electroplated gold used for masks currently fabricated at the MMD. Using the prototype repair tool, identical patterns were sputtered into 5 different samples: Au, Cr/W/Cr, Cr/W, Cr/TaSiN/Cr, and Cr/TaSiN (section 2). The pattern consists of 3 sets of equal line/space gratings each containing five 2 μm long spaces. The spaces have nominal (designed) widths of 237, 178, and 119 nm which are etched as arrays of pixels spaced 30 nm apart (a beam radius). Each absorber was FIB etched using a range of ion doses extending from a dose insufficient to fully remove the absorber to a dose well exceeding that required.

The linewidths of all of the spaces in the gratings (3 center spaces for the 237 nm pattern) were measured using SEM CD metrology at a magnification of 60 kX . Measurements taken consisted of the mean linewidth of each space in each grating measured at 100 points along its central 1.75 μm and the 1 σ variation in the mean linewidth. The mean linewidths and 1 σ variations were then averaged over the

spaces measured in each pattern. It is these averages (mean linewidth and mean 1 σ) which are referred to below. In addition, 30 kX SEM micrographs were taken of all patterns. Since no significant differences were seen in data obtained from the refractory samples with and without Cr overlayers, the discussion will be confined to 3 of the samples examined, Au, Cr/W/Cr and Cr/TaSiN/Cr.

SEM micrographs of the FIB etched gratings sputtered with the optimum ion dose for each material are shown in Fig. 10. Visual inspection of these images shows that all three materials can be FIB etched to linewidths of approximately 100 nm. However, it appears that the TaSiN material sputters with the least edge roughness. The edge roughness in the Au and W samples correlates with their respective grain structure. Since the grain size of the Au sample is large compared to the sizes of the etched features, it appears to have less edge roughness than the smaller grained W sample.

An attempt was made to quantify the differences in edge roughness using the measured linewidth variations. Figure 11 compares the linewidth variation of the 3 different sized features etched into the 3 materials, each at its optimum ion dose. The difference in edge roughness apparent in the micrographs appears as a 5 nm difference in linewidth variation for the different materials.

Figure 12 shows the mean linewidths themselves for the 3 different size gratings. In all cases, the lines measure 30-60 nm smaller than the designed width. This difference, due to interior redeposition and to the use of discrete pixels[4], can be accounted for by biasing the repair designs, a process already incorporated in the repair software, but not used in these experiments. All of the metals show similar linewidth sensitivity to ion dose. However, the gold absorber requires approximately 5 times less ion dose to etch through, reflecting the extremely high sputter yield of gold[5]. For masks with similar x-ray absorption, the difference will be even greater. This would be reflected in increased repair times for opaque defects in the refractory films.

7. Conclusions

Using the current tooling, repairs of several types of defects down to 100 nm has been demonstrated. Although redeposition of removed material continues to be a problem for some types of repairs, opaque repair of sub 250 nm x-ray masks appears to be a straightforward extension of the existing FIB tooling and technology. Gas assisted FIB etching is not currently well enough developed to be implemented for high resolution repair. The use of thinner absorbers, though helpful, does not significantly reduce redeposition. Post-repair trimming helps substantially by removing redeposited material. Finally, all of the absorber materials considered in this study performed well under high resolution FIB etching. Because of its amorphous microstructure, repairs made in TaSiN show significantly less edge roughness than those in W or Au. Both of the refractory materials etch more slowly than the gold used in current mask technology.

Acknowledgments

The author is grateful for the assistance and lively technical discussions of Al Wagner, Pete Longo, Mark McCord, Peter Levin and Phil Flanigan. I would like to thank Doug Resnick and Lee Trimble for supplying the refractory metal samples, and Mark McCord and Tom Donahue for the patterned gold samples. The author wishes to acknowledge the support of the Advanced Research Projects Agency (ARPA) under the Defense Advanced Lithography Program (DALP), NAVAIR Contract N00019-91-C-0207.

References

1. S. Nash, T. Faure, J. P. Levin, D. Puisto, J. Rocque, K. Kimmel, M. McCord, and R. Viswanathan, Jpn. J. Appl. Phys., **33,** 6878-6887 (1994) .
2. D. Stewart, J. Doherty, A. Doyle, J. Morgan, "State of the Art in focused ion beam mask repair systems," Proc. Int. Soc. Opt. Eng., Photomask Japan (1995) in press.
3. D. Stewart, T. Olson, and B. Ward, Proc. Int. Soc. Opt. Eng. **1294**, 98-111 (1993) .
4. P.G. Blauner and J. Mauer, IBM J. of Res. and Dvlp. **37**, 421-434 (1993).
5. A. Wagner, J.P. Levin, J.L. Mauer, P.G. Blauner, S.J. Kirch, and P. Longo, J. Vac. Sci. and Technol. **B8**, 1557-1564 (1990).
6. Micrion Corporation, Peabody, MA. USA.
7. M.McCord, A. Wagner, D. Seeger, J. Vac. Sci. Technol. **B11**, 2881-2887 (1993).
8. L.R. Harriott, Jpn. J. Appl. Phys. **33**, 7094-7098 (1994).
9. L.R. Harriott, R.R. Kola, and G.K. Celler, Proc. Int. Soc. Opt. Eng. **1294**, 76-81 (1993).
10. A. Wagner, J. P. Levin and S. J. Kirch, "Gas Delivery for Ion Beam Deposition and Etching," U.S. Patent #5,149,974, September 1992.
11. Princeton Gamma-Tech, Inc., Princeton, N.J. USA.
12. M.A. McCord, R. Viswanathan, F.J. Hohn, A.D. Wilson, R. Naumann, and T.H. Newman, J. Vac. Sci. and Technol. **B10**, 2764 (1992) .
13. R.R. Kola, G.L. Miller, and G.K. Celler, Mat. Res. Soc. Sym. Proc. **306**, 275-287 (1993).
14. W. Dauksher,D. Resnick, K. Cummings, J. Baker, R. Gregory, N. Theodore, J.A. Chan, W. Johnson, C. Mogab, M.-A. Nicolet, J.S. Reid, "Method for Fabricating a Low Stress X-Ray Mask Using Annealable Amorphous Refractory Compounds," these proceedings.

Figure Captions

1. SEM micrograph of opaque repair by non-assisted FIB etching: missing features in an Au mask. 150 nm contact holes have been added to the second and third arrays.
2. SIM micrographs of opaque repair by non-assisted FIB etching: isolated defects in an Au mask. Four 180 nm protrusions before and after FIB etching.

3. SIM micrographs of redeposition: 150 nm protrusion in a 250 nm space before and after non-assisted FIB repair.
4. SEM micrograph of redeposition after non-assisted FIB repair of a bridge in a 100 nm space.
5. Redeposition as a function of line spacing for two different thickness' of gold absorber. A 100 nm protrusion is removed from one line. The amount of material redeposited is then characterized by the linewidth of the adjacent line.
6. SEM micrograghs of the ends of 5x20 μm boxes milled through Cr/W using XeF_2 gas assisted etching where in (a) the gas was shut off immediately after ion beam irradiation and in (b) the gas was allowed to flow for an additional 5 minutes.
7. Profilometry data from GAE boxes like that shown in Fig. 6, but taken over a range of ion doses with and without additional gas flow.
8. SEM micrographs of 250 nm features etched in Cr/W/Cr using XeF_2 GAE and ion doses of (a) $8x10^{16}$ ions/cm^2 , (b) $9x10^{16}$ ions/cm^2 , (c) $1x10^{17}$ ions/cm^2, and (d) $1.2x10^{17}$ ions/cm^2. At a dose sufficient to remove the surrounding W, the 250 nm feature has developed a pronounced undercut.
9. SIM micrographs illustrating the process of post-repair trimming used to repair programmed defects in a 180 nm space: (a) before repair, (b) after initial repair, (c) after final trim. In this case, trimming was done by etching the entire 180 nm space using a low ion dose.
10. SEM micrographs of 250, 180, and 120 nm gratings etched into Au, Cr/W/Cr, and Cr/TaSiN/Cr absorbers .
11. Edge roughness of gratings etched into the three absorbers as quantified by the average variation in linewidth of the spaces as measured at the optimum ion dose for each material (2.5×10^{17} ions/cm^2 for Au, 1.25×10^{18} ions/cm^2 for W and TaSiN).
12. The mean linewidth of the spaces in gratings etched into the three absorbers over a range of ion doses. The dashed lines indicate the intended linewidths. There is a difference of approximately a factor of 5 between the ion dose required to etch the Au material and that required to etch the refractory materials.