5-1-1994

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Recommended Citation

Ricardo Toledo-Crow, Bruce W. Smith, Jon K. Rogers, Mehdi Vaez-Iravani, "Near-field optical microscopy characterization of IC metrology", Proc. SPIE 2196, Integrated Circuit Metrology, Inspection, and Process Control VIII, (1 May 1994); doi: 10.1117/12.174165; <https://doi.org/10.1117/12.174165>

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Near Field Optical Microscopy Characterization of IC metrology.

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ABSTRACT

Images of a microlithographic sample obtained using a new near field scanning optical microscope (NSOM) that uses force regulation of the sample-tip separation are presented. The NSOM is a research instrument fitted with a metal covered glass tip probe that defines a small aperture at the sharp end. The aperture is estimated to be on the order of 100 nanometers in diameter resulting in a resolution exceeding that of diffraction limited systems. This form of microscopy can be done both in the transmission and the reflection modes. The force regulation mechanism produces a simultaneously obtained scanned force microscope (SFM) image of the topography thus permitting correlative imaging of the sample. The samples are imaged in transmission and reflection near field optical format, with white light and with coherent light. The results are compared with other forms of IC imaging and characterization, namely scanned force microscopy (SFM) and scanning electron microscopy (SEM).

1. INTRODUCTION

The resolution limit of optical microscopy is set by the wavelength of the imaging light and is given, according to the Rayleigh criterion, by $0.61 \lambda / na$ (λ = wavelength, na = numerical aperture). This is because spatial frequencies conveying higher resolution information cannot be collected in the far field for imaging. In the near field, however, the optical radiation can have frequency components that are higher than the light's frequency and which are caused by the interaction with the sample's sharp features. These components are absent in the far field because they propagate as evanescent waves that decay exponentially with distance.¹ Near field scanning optical microscopy (NSOM) can obtain super-resolved images by probing the sample in the near field and so within range of these evanescent components. This is done by scanning the illuminated sample in close proximity with a detector that is smaller than the wavelength of the light used. Alternatively, by optical reversion, the sample can be illuminated with a source that is smaller than the wavelength of the radiation.²⁻⁹ A sharp glass tip is used to such an end, in illumination or collection mode. An important issue of operation is the positioning of the tip close to the sample so as to scan the near field. Several positioning methods have been proposed. These include the use of the detected optical signal in a correction feedback mechanism reminiscent of the scanning tunnelling microscope or even the use of a tunnelling current for this purpose.² The first method is incapable of decoupling the sample's topography from its optical properties while the second requires conducting samples and is subject to instabilities. A solution to these problems is the incorporation of a lateral force regulating mechanism^{10,11} operating in the non-contact mode. In this way, the probing tip simultaneously images the optical and topographical properties of the sample and uses the latter for the tip/sample distance regulation.

The force regulation has made NSOM a much more useful tool by preventing the probing tip from crashing into the sample, previously a common occurrence. It is now able to image samples with considerable variations in topography and, as the two images are simultaneously obtained, it permits correlative imaging of topographical and optical information. We have been using microlithographic samples of known characteristics to characterize our system's performance. By the same token, we present the NSOM characterization of the samples and its particular effects. In the following we present descriptions of the NSOM system, the samples used, the imaging procedures and the results. Finally the main conclusions are summarized.

2. NEAR FIELD SCANNING OPTICAL MICROSCOPE: SYSTEM DESCRIPTION

The NSOM used is shown in figure 1(a). It is based on the orthogonal sample cantilever force microscope.⁹ We shall now discuss the important features of the system.

2.1 Probe

The probe is a single mode or multimode fiber that is heated and pulled to form a sharp tip and subsequently covered with 100 nm of aluminium to define the aperture and improve the optical confinement. We have estimated the resulting apertures to be between 50 and 100 nm in diameter, at best, as determined by the optical resolution of the images. The sharpness of these tips is reduced by the aluminium coating and the tip size is estimated to be between 250 and 300 nm. This adversely affects the resolution of the simultaneously obtained SFM images.

2.2 SFM microscope and regulation

The tip end of the fiber is mounted on a bimorph element driven by a sinusoidal signal ω_S . The resulting vibration of the tip is detected by a differential interferometer. It consists of a low power (1 mW) polarized laser beam that is passed through a Wollaston prism placed so that its axes are at 45 degrees to the polarization of the incident light. This results in the formation of two beams of the same intensity that are orthogonally polarized to each other. A lens, placed so that its back focal plane coincides with the two beams' plane of splitting in the prism, focuses the beams onto the tip's shaft with a separation of 100 μm . The reflected beams are recombined by the Wollaston. The recombined beam is reflected by a beam splitter toward an analyzer (at right angles to the incident beam's polarization) and onto a photodetector. As the tip oscillates, the beams' path lengths vary by different amounts due to the bending of the tip. This alters the polarization of the recombined beam and results in an oscillating component in the signal at the photodetector. A lock-in amplifier detects the first harmonic of the signal ω_S which is set just below the resonance frequency of the tip. As the tip is brought into close proximity of the sample, the forces between tip and sample will alter the mechanical properties of the tip changing its resonance frequency and reducing the AC signal detected by the lock-in. The signal is compared to some previously set reference and the difference is sent, in a feedback correction system, to the Z piezoelectric positioner that regulates the tip/sample separation. In this way the separation is kept constant and the correction signal is used to image the sample's topography as two other piezoelectric positioners scan the sample in the X and Y directions.

2.3 Optical microscope

The optical image is obtained by launching light into the other end of the fiber probe tip. For this, the end is cleaved and placed into a launching mount. The light sources used are a medium powered HeNe laser (5 mW) and a xenon (75 W) broadband source. When using the laser source, a single mode fiber is used for the probe. For the broadband source, a multimode fiber is required. The transmitted or reflected light is collected in the far field by a microscope objective and detected with a photomultiplier tube (PMT). Because the SFM regulation is based on an optical interferometer that uses a light source of its own, a means of decoupling it from the light of the optical microscope is needed. A straightforward solution is to modulate the NSOM light by chopping it before launch at a frequency ω_C , that is not harmonically related to ω_S , and detecting it with another lock-in amplifier.

3. IMAGED SAMPLES

The samples imaged in reflection were doped polysilicon structures on a silicon substrate. They consisted of regular patterns formed by lines of constant width, and a height to width ratio of near unity. In one case, the lines were in a serpentine arrangement that wound back and forth (figure 2). In the other, the pattern was the inverse: a canal etched into the polysilicon (figure 3). For transmission, our samples consisted of a 80 nanometer thick chrome mask on a fused silica substrate. The structures were Van der Pauw test patterns of different sizes. In their fabrication, certain lines had partially fused together leaving interline imperfections that were on the order of 300 nanometers (figure 4).

4. IMAGING PROCEDURES

All the samples were simultaneously imaged optically and with scanned force microscope. Both laser (633 nm) and white light sources were used for illumination of the optical images. The effective optical power was estimated to be a few nanowatts for the laser illumination using single mode fiber tips, and about 100 nanowatts for the white light using multimode fiber tips. For the reflection images, a long working distance objective, placed at approximately 45 degrees to the tip, was used to collect the reflected light (see figure 1 (a) and (b)). In this way, only light reflected into the collection cone defined by the

objective was used. For the transmission images, light was collected with an objective placed in line with the tip (see figure 1). Transmission images were also taken with the white light source through red, green and blue 40 nm wide bandpass filters at center wavelengths of 450, 506 and 650 nm. Finally, an SFM image of the sample used for the reflection images was taken with a sharp, uncoated optical fiber tip. The tip was scanned in all cases with an estimated separation from the sample of 8 to 10 nm.

5. RESULTS

5.1 Reflection images

The images obtained in reflection are presented in figures 5 to 7. As can be seen in figure 5, the system was able to resolve optically the individual lines of the sample which are estimated to be between 300 and 400 nm wide. The irregularities that appear along the edges of the lines can be attributed to the unevenness of the polysilicon lines that is present in the SEM images of figures 2 and 3. The simultaneously obtained SFM image, however, shows a poor contrast between the lines and the intervening spaces. This is a phenomenon seen in all the image pairs; a good NSOM tip is usually a bad SFM tip. This can be attributed to two reasons: i) The optical confinement requires the deposition of a metal film onto the tip. A deposited layer of 100 nanometers of aluminium increases the diameter of the tip by twice that amount. Hence, if we have a tip of 50 nanometers initially, it becomes 250 nanometers in diameter after coating, and the SFM resolution afforded by it decreases. ii) In order to deliver as much optical power as possible to the aperture, the NSOM tip must have a wide angle at the apex so that the optical losses associated with the decrease in fiber's diameter are kept at a minimum. Hence, tips that have a short taper will have the best characteristics for NSOM. However, such tips will be unable to penetrate into features that have significant depth to width ratios like the sample in this case. The important result of these images is that, even though the tip was physically unable to enter into the interline troughs, the optical radiation could still provide ample contrast to resolve and image them. It could be argued, however, that the sample at the troughs would no longer be in the near field of the aperture and hence the system would be unable to resolve any features there.

The reflection images taken at the edges of the serpentine show particularities of this form of microscopy. As can be seen from figure 6 certain artifacts appear as the tip scans the sample features that are perpendicular to the general direction of the lines. These can be attributed to the way that the light is collected after reflection. Figures 7 (a) and 7 (b) are of a similar but larger structure and they illustrate better what is occurring at these sites. Figure 1 (b) shows the relative position of the tip, the sample and the collection objective. When the tip is scanning a flat section, it shadows the light reflected off the sample and this results in a low optical signal. Whatever light is collected may come from scattering by unresolved particles or it could come from light that penetrates the sample, is internally scattered, and then exits at a certain distance from the tip, enough so as not to be shadowed. As the tip approaches a line, the bulk of the line obstructs whatever light was previously reaching the objective and a shadow will result. When the tip is on the line itself, more light will be able to escape from the sample through internal scattering because of the reduced size of the structure. Finally, as the tip scans the end of the line and 'descends' to the substrate, there will be several points where the aperture is no longer 'in close proximity' to the sample and the light emitted will actually begin to spread considerably (far field effects) thus illuminating a large area of the sample that will produce an increased optical signal. When these images were retaken with coherent illumination, the bright areas presented interference patterns as can be seen in figure 7 (b). The patterns are caused by the simultaneous illumination of several features (the edges of the lines possibly) that act as secondary coherent sources.

5.2 Transmission images

The images obtained in the transmission mode are shown in figures 8 and 9. As can be appreciated, the overall resolution is somewhat lower than the reflection images and we attribute that to an enlargement of the aperture (accompanied by an increase in the optical power available). Our purpose here is to demonstrate the capabilities of the NSOM system. As in the previous results, the SFM images do not show much contrast which is due to the tip's shape and also to the thickness of the chrome layer (80 nm). The transmission images with coherent light also show signs of interference effects, as shown in figure 8 (a), that are absent in the white light illumination mode (figure 8 (b)). As the width to height ratio of these samples is negligible (on the order of 0.1) the tip is never out of the near field of the chrome mask or the surface of the quartz substrate. However, within the bulk of the quartz some scattering may be occurring that produces the interference patterns. Finally, the images of figure 9 were obtained from a different area of the sample with white light and with narrow band red, green and blue

filters. The purpose of this was to show the independence of the NSOM's resolution from the wavelength used. Figure 10 is an SFM image of the sample taken with an uncoated fiber tip that was pulled so as to have a long narrow taper. Such a tip is the ideal tip for SFM, as can be seen from the image, but is inefficient for NSOM.

6. CONCLUSIONS

Imaging of microlithographic samples has been carried out with a force regulated near field optical microscope. In reflection mode, the interpretation of the images is somewhat more complicated than in transmission because of their marked dependance on the sample's topography.¹² Nevertheless, as the topographical information is simultaneously obtained, the two images could, in principle, be used to decouple the optical information from the topography. The reduced resolution and contrast of the SFM images is a technical problem that can be remedied without sacrificing optical resolution or power by reducing the thickness of the aluminium layer (the penetration depth of aluminium at $\lambda = 633$ nm is about 10 nm). Sub-wavelength features such as interline troughs yield excellent images with NSOM because, even if the probe itself is unable to enter the trough, the near field radiation will convey the feature's characteristics making the NSOM image a more truthful representation of the sample.

7. ACKNOWLEDGMENTS

The authors would like to thank Mr. Scott Blondell of the Microelectronic Engineering Department at R.I.T. for his assistance in obtaining the SEM images of figures 2, 3 and 4.

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(2)

(3)

figure 2 and 3. SEM images of the sample used in the reflection mode: **2.** Polysilicon lines on silicon substrate. **3.** Lines etched into the polysilicon.

figure 4. SEM image of the sample used for the transmission mode. 80 nm thick chrome on fused silica.

figure 5. Simultaneously obtained SFM (left) and reflection mode NSOM (right) images of the polysilicon line sample.
Coherent illumination.

figure 6. Simultaneously obtained SFM (left) and reflection mode NSOM (right) images of the polysilicon line structure edge.
Coherent illumination.

(a)

(b)

figure 7. Simultaneously obtained SFM (left) and reflection mode NSOM (right) images of the polysilicon line structure edge.
 (a) White illumination. (b) Coherent illumination.

(a)

(b)

figure 8. Simultaneously obtained SFM (left) and transmission mode NSOM (right) images of the chrome mask on fused silica sample. (a) White illumination. (b) Coherent illumination.

figure 9. Chrome mask on fused silica. (a) SFM, (b) white, (c) red, (d) green, and (e) blue illumination, transmission mode NSOM images. (a, c, d, and e, are 12 μm scans. b is an 8 μm scan).

figure 10. SFM image of polysilicon lines taken with an uncoated glass fiber tip.