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Ricardo Toledo-Crow

Rochester Institute of Technology

Mehdi Vaez-Iravani

Rochester Institute of Technology

Bruce W. Smith

Rochester Institute of Technology

Joseph Summa

Rochester Institute of Technology

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Characterization of atomic force microscopy and electrical probing techniques for IC metrology

Ricardo Toledo-Crow^{a)}, Mehdi Vaez-Iravani^{a)}
Bruce W. Smith^{b)}, Joseph R. Summa^{b)}

^{a)} Center for Imaging Science

^{b)} Microelectronic Engineering Department
Rochester Institute of Technology
Rochester, New York 14623

ABSTRACT

A novel atomic force microscope (AFM) is used to image a microlithographic sample. The AFM operates in the non destructive non-contact mode, uses glass tips as opposed to tungsten or silicon, and has an optical interferometric detection system. Its estimated lateral resolution is under 10 nanometers and much better in the z direction. A sample consisting of chrome features on quartz was produced for measurements using AFM and electric probe techniques. The features are single and grouped lines on the order of 1 μm incorporated into an electric probe pad layout. Dimensions of these features are determined from the AFM images by relating their sizes in pixels to the excursions of the scanners during the formation of the images. These results are compared with measurements obtained through electric probing techniques.

1. INTRODUCTION

Atomic force microscopy¹ (AFM) has recently been employed as a technology for integrated circuit observation and metrology^{2,3}. At R.I.T. several non-contact scanned probe microscopy techniques have been developed that have a lateral resolutions of under 10 nanometers. These techniques offer the possibility of three dimensional measurements on the nanometer scale through the non-destructive non-contact mode of imaging. The versatility of the system for measuring and observing various types of defects and dimensional information make it well suited for IC work. The work presented here is a comparison of this technology with electric probing metrology for sub-micron feature characterization. Measurements of linewidths of IC samples using these two techniques were obtained and the results are presented and compared. The possibility of using the results as a calibration of the AFM and the overall validity of comparing these two methods is discussed.

2. ATOMIC FORCE MICROSCOPE: SYSTEM DESCRIPTION

The atomic force microscope used for this work is a research instrument fitted with a glass tip as opposed to the more conventional tungsten or etched silicon tips. The tips are fabricated by heating and pulling a glass fiber to form a sharp tapered end. The estimated resolution of the images obtained with these tips is of order 10nm. This is determined essentially by the larger of two factors: the separation between the tip and the sample, and the size of the tip itself.

The schematic of the AFM is shown in figure 1⁴. The optical detection mechanism for tip vibration comprises a differential interferometer, using a Wollaston prism. The prism is used to split a linearly polarized laser beam into two orthogonally polarized beams each at 45° with respect to the incoming light. The plane of splitting is placed at the back focal plane of an objective lens which brings the beams to two foci on the glass tip, approximately 100 μm apart. The tip is vibrated at a frequency just below its main resonance and the resulting tip oscillation amplitude phase-modulates the two cross polarized beams. The reflected light is then passed back through the objective and Wollaston recombining the two beams which are then passed through an analyzer, with its pass axis crossed with respect to the laser polarization, and onto a detector. The differential phase between the two beams is transformed into an AC signal at the vibration frequency whose amplitude is linearly proportional to the vibration amplitude in the following way. Decomposing the incident linearly polarized beam into its two orthogonal components we have:

$$E_o = Ae^{-i\omega_o t} = \left| \frac{A}{\sqrt{2}}e^{-i\omega_o t} \hat{\mathbf{i}} + \frac{A}{\sqrt{2}}e^{-i\omega_o t} \hat{\mathbf{j}} \right|.$$

Each orthogonal beam is phase-modulated by the tip's excursions, and the beams after reflection off the tip can be expressed as:

$$E_r = \frac{A}{\sqrt{2}}e^{-i\omega_o t} \left| e^{-i(\theta_a \sin \omega_m t + \beta_a)} \hat{\mathbf{i}} + e^{-i(\theta_b \sin \omega_m t + \beta_b)} \hat{\mathbf{j}} \right|$$

where ω_m is the modulation frequency, θ is the amplitude of the phase modulation imparted on each beam by the tip; and β is a constant phase term that depends on the lateral position of the Wollaston prism relative to the reflected beams. On passing through the analyzer the field is given by:

$$E_a = \frac{A}{2}e^{-i\omega_o t} \left[e^{-i(\theta_a \sin \omega_m t + \beta_a)} - e^{-i(\theta_b \sin \omega_m t + \beta_b)} \right]$$

Thus, the resulting intensity is given by:

$$I_o \propto \frac{A^2}{4} \left[2 - 2 \cos(\Delta\theta \sin \omega_m t + \Delta\beta) \right]$$

where $\Delta\theta = \theta_a - \theta_b$ and $\Delta\beta = \beta_a - \beta_b$. Expanding this expression we obtain:

$$I_o \propto \{ 1 - J_0(\Delta\theta) \cos \Delta\beta + 2J_1(\Delta\theta) \sin \Delta\beta \sin \omega_m t - 2J_2(\Delta\theta) \cos \Delta\beta \cos 2\omega_m t + \dots \}$$

For small values of $\Delta\theta$ the resulting amplitude variations at ω_m can be considered to be linearly proportional to $\Delta\theta$. The maximum signal is obtained when $\Delta\beta$ is made equal to $\frac{\pi}{2}$ which can be achieved by varying the position of the Wollaston prism. As the tip is brought into close proximity of the sample, the local topography results in variations of the lateral forces acting on the tip, which in turn reduce the amplitude of the oscillations resulting in a lower AC signal at the detector. A feedback circuit is used to regulate the separation between tip and sample so as to maintain the vibration amplitude at a set level. The tip is scanned in a raster fashion over the sample and the feedback signal is used to form the image.

The dimensions of the sample are determined by linearly relating the image dimensions (in pixels) to the excursions of the sample through the manufacturer's parameters of the scanning stages and tip positioning elements. In the present case, the desired motions were obtained with piezoelectric positioners which tend to have some hysteresis of movement that can produce distortions of more than 10%². However, this non linear phenomenon is of concern mainly during large scans involving the full range of the devices and its effects were not too apparent during the present case. In some instances, these nonlinearities of the stages are apparent from a certain amount of "warpage" present in the images, particularly of the regular features of I.C. patterns. It should be noted that one could either correct for the non-linearity, or calibrate the motion of the piezo-scanners to account for them.

The limiting factors for accuracy of measurement are the apparent tip size and the noise present in the signal. The latter can be remedied through averaging, or in the case of imaging, the average value for the measurement in the image can be considered. The former is more problematic. It stems from the fact that the resulting image can be considered as a "convolution" of the surface topography of the sample with the tip's shape as is illustrated in figure 2. However, as the tip size is estimated to be of the same order of magnitude as the minimum resolvable element this is not a major problem in the present case.

3. SAMPLE

The sample used for this work consists of 80nm of chrome on 0.5mm thick fused silica. The sample was patterned directly using a MEBES e-beam system and wet etching of the thin chrome. The features are isolated lines of varying widths on the order of 1 μm and groups of lines of the same dimensions. The lines of interest connect the probe pads used for the electrical characterization. Two groups of samples were measured, each consisting of eight isolated lines and eight grouped lines of decreasing width resulting in a total of 32 lines measured. In the case of the grouped lines only the central line of the group was measured.

4. MEASUREMENT PROCEDURES

4.1 Electrical measurements

The electrical measurements were done with a Prometrix EM1 electrical line width probing instrument. Structures were designed with isolated and grouped linewidths from 0.6 to 1.8 μm in addition to Van Der Pauw structures.

4.2 Atomic Force Microscope measurements

The AFM measurements were made by taking 25 line scans each with 125 pixels (effectively forming a 25x125 pixel image) of each line to be measured. For each image, the total scan range was deduced from the voltage applied to the piezoelectric stages. The relation between the voltage and the resulting displacement was assumed to be linear and the constant of proportionality was taken from the device's specifications⁵ (30 microns per 1000 volts). In this way, the number of microns per pixel was established. The next important step was to determine the width of the lines, in pixels, from the images. The criterion for this was to take the halfway points between the height of the line and that of the substrate as determined from the images. This was done for each line scan and the results were averaged

to obtain the line width. Because many of the line scans presented a certain amount of tilt due to slight misalignments of the sample on the scanning stages, the line scans were first 'flattened' by subtracting a mean square linear approximation from their values. This made the process of determining the halfway points considerably simpler. When measuring the grouped line samples, only the central line was considered relative to the adjacent substrate and only the groups with a clearly defined central line were measured.

5. RESULTS

The resulting measurements are presented in tables 1 and 2 and graphically in figures 3 and 4 for the two measured samples. There are no electrical probe results for the smaller single lines because the lines were broken and there was no continuity which is required for these measurements. As for the grouped lines, lithographic processing caused scumming below 1 μm giving false values for the electrical measurements. However, AFM results were obtained for all but the worst cases of the grouped lines in which no central line is discernible. Figures 5 and 6 show the actual images from which the AFM measurements were obtained for sample 1. Figure 7 is the complete image (125x125 pixels corresponding to 10.5 μm) of group 5 in sample 1. Note the tilt and the irregularities in the linewidths. The AFM results are consistently lower than the values obtained with electrical probing which is probably an indication of a systematic error in the piezoelectric scanner measurement. However, as can be seen from figure 10 the lines exhibit some edge roughness and thus the AFM measurements will have variations according to where on the line the measurement is made. On the other hand, the electric measurements represent by nature an average width over the entire line. Considering the aforementioned it can be stated that these two methods are not easily comparable.

CONCLUSIONS

Measurements were obtained for microlithographic samples with two different techniques, the results are presented, and discrepancies between the results are noted. If we consider the electric probe measurements as reference, the results could be employed to calibrate the piezoelectric transducers. Future work will determine the precise nature of these differences and the feasibility of such a calibration. Nevertheless, figure 12 probably best illustrates the strength of the AFM techniques which lies in capability to image the details in microlithographic samples.

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Figure 1. Schematic diagram of the atomic force microscope used.

Figure 3. AFM and electric probe measurements for single and grouped lines in sample 1

Figure 4. AFM and electric probe measurements for single and grouped lines in sample 2

Table 2

SAMPLE 2										
(microns)										
single lines					grouped lines					
LINE	ELECTRIC PROBE			AFM		LINE	ELECTRIC PROBE			AFM
1		1.78		1.34		1		1.79		1.00
2		1.23		1.36		2		1.76		1.01
3		1.49		1.17		3		1.54		0.95
4		0.88		1.04		4		1.26		0.80
5		0.98		0.88		5		1.12		0.78
6		0.55		0.68		6		0.87		0.54
7		0.67		0.67		7		n		n
8		n		n		8		n		n

Table 1. Results of sample 1

Table 1

SAMPLE 1										
(microns)										
single lines					grouped lines					
LINE	ELECTRIC PROBE			AFM		LINE	ELECTRIC PROBE			AFM
1		1.73		1.47		1		1.74		1.01
2		1.67		1.38		2		1.73		1.01
3		1.48		1.15		3		1.51		0.94
4		0.92		1.25		4		1.36		0.87
5		0.95		0.87		5		1.07		0.67
6		0.63		0.61		6		3.06		0.71
7		n		0.75		7		n		n
8		n		0.33		8		n		n

Table 2. Results of sample 2

Figure 5. This image shows 12.5 μ m scans of the grouped lines in sample 1. As the linewidths get smaller, the are observed to join. The reported results correspond to the center line only, when it applies. Irregular linewidths are apparent.

Figure 6. These are the images taken of the single lines in sample 1. The total scan sizes are: line 1: $3.5\mu\text{m}$, line 2: $3.5\mu\text{m}$, line 3: $2.7\mu\text{m}$, line 4: $2.7\mu\text{m}$, line 5: $2.1\mu\text{m}$, line 6: $1.4\mu\text{m}$, line 7: $1.4\mu\text{m}$, line 8: $.7\mu\text{m}$

Figure 7. A 15 μ m image of group 5 in sample 1.