ELECTRICAL AND OPTICAL TEST STRUCTURES FOR THE INVESTIGATION OF LITHOGRAPHY OVER TOPOGRAPHY

by

Jaime Ramírez

Memorandum No. UCB/ERL M89/139

18 December 1989

ELECTRICAL AND OPTICAL TEST STRUCTURES FOR THE INVESTIGATION OF LITHOGRAPHY OVER TOPOGRAPHY

by

Jaime Ramírez

Memorandum No. UCB/ERL M89/139

18 December 1989

ELECTRONICS RESEARCH LABORATORY

College of Engineering
University of California, Berkeley
94720

ELECTRICAL AND OPTICAL TEST STRUCTURES FOR THE INVESTIGATION OF LITHOGRAPHY OVER TOPOGRAPHY

by

Jaime Ramírez

Memorandum No. UCB/ERL M89/139

18 December 1989

ELECTRONICS RESEARCH LABORATORY

College of Engineering
University of California, Berkeley
94720

Electrical and Optical Test Structures for the Investigation of Lithography over Topography

Jaime Ramírez

Department of Electrical Engineering and Computer Sciences,
University of California, Berkeley

ABSTRACT

A set of visual and electrical test structures has been designed and has been projection printed onto wafers with different topography characteristics. Processing techniques were explored for producing the various topography characteristics. The structures investigate the scattering and topography effects on the formation of lines parallel and perpendicular to abrupt steps. In particular, the effects due to substrate reflectivity, trench sidewall angle, and trench depth are investigated. The visual test structures will provide a rapid overview of performance, while the electrical test structures will provide more quantitative results. The patterns were printed on a GCA 6200 stepper (NA=0.28, λ=436nm, and σ=0.7. The photoresist used was KTI 820. SEM photographs of the different structures reveal that the sidewall angle has the most dominant effect on lines that run parallel to step edges, and the deeper the trench, the more noticeable the effect. The change in resist thickness due to the trench depth is the most dominant effect for lines crossing steps, and even shallow steps can cause large linewidth variations due to the change in energy coupling on highly reflecting substrates.

December 18, 1989

Dedication

To my parents, Jaime Ramírez Parra and Anne Kindred de Ramírez, with deep appreciation, respect, and thankfulness for teaching me the importance of an education, for the values they have taught me, for their support, and for their love and understanding.

Table of Contents

Chapter 1
Introduction

The effects of underlying topography on resist linewidth and line edge profile shape are well known and have been investigated by numerous authors [1-7]. Good examples of SEM's of topography effects can be found in [1,7]. Linewidth variations due to changes in the thickness of the photoresist have been studied [1-6] and various solutions have been proposed: use of anti-reflection layers below photoresist, multi-level resists, contrast enhancement layers, use of dyed photoresist, post-exposure bake, and multiple wavelength exposures [3,6,7]. Both electrical and visual test structures have been used successfully to characterize the lithography process [8-11].

At Berkeley an effort has been made to take advantage of resist modeling and profile simulations in the design and quantitative interpretation of test structures. This paper extends that work to include the effects of topography. The study of the scattering and topography effects on the formation of lines parallel and perpendicular to abrupt steps will be helpful along with computer simulations [12] in understanding some of the problems that will need to be avoided or solved in industry in the near future.

The mask designed has both visual and electrical test structures, and thus the advantages of both are obtained. The advantages of the visual test structures are that they give a rapid overview of performance, and a few structures can even be quantitatively interpreted with optical inspection. Where effects are noted, SEM photographs of top views and cross sections can give much more detailed insight. The disadvantages are that for most part the results are qualitative unless time-consuming SEM's are used.

With respect to the electrical test structures, we have the following advantages:

reduced operator bias, automated testing, quick analysis, and quantitative results. The main disadvantage is that additional processing steps and factors are involved which may confound the phenomena being investigated.

In this study, processing techniques were also explored for producing various types of underlying topography. This was done to investigate the effects of trench depth (shallow and deep), sidewall angle (small and large), and substrate reflectivity (low and high).

Chapter 2
Types of Structures and Expected Results

Both the visual and electrical test structures can be divided into three main groups: lines parallel to steps, lines crossing trench ends, and lines perpendicular to trenches.

The first group consists of structures where lines run parallel to the edges of a trench, the distance between the trench edge and the line is varied. These structures will help determine the effects of light scattering off the sidewall of the trench, and the importance of the spacing. From these types of structures it is expected that lines in the trench near the edge will be affected by scattering effects and the profile of the photoresist will not be symmetrical, since more light will effectively reach the side of the line which is near the edge. Because of the angle of incidence, it is expected that the effects will be more pronounced as the sidewall angle decreases, and the deep trenches should also provide enhanced results since the area of the photoresist which is affected has been increased, since the photoresist is thicker than the trench depth.

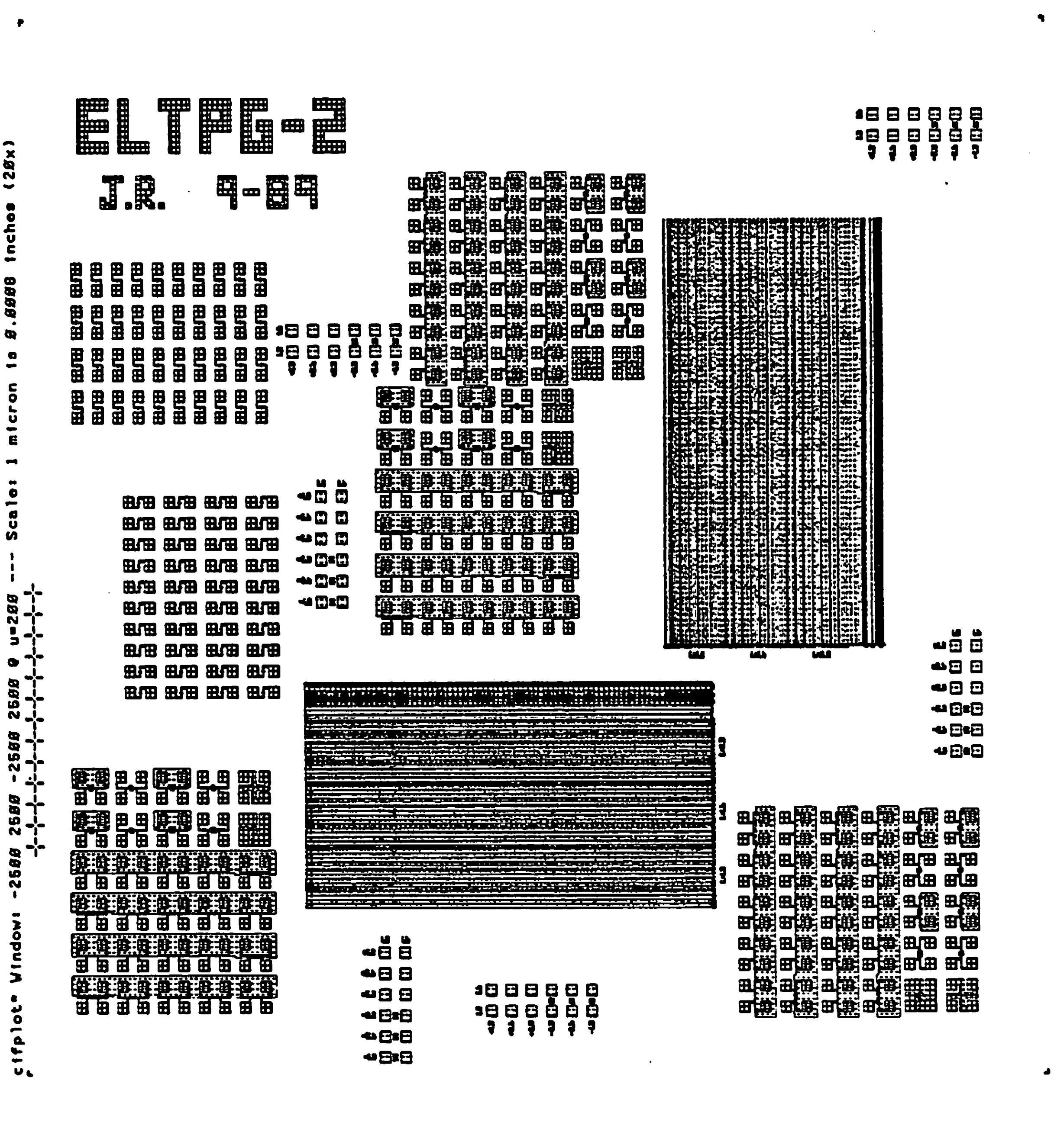
The second group consists of lines which cross thin trenches at various distances from the edge of the trenches. These structures were designed to observe the effects of reflective notching. The width of the trenches is varied, as well as the distance between the line and the edges in order to observe the effects of spacing and trench width. The most dramatic results should be obtained from the test wafer with deep trenches and small sidewall angles.

The third group consists of serpentine and comb structures which are used to observe the effects of lines crossing the edges of a trench. Scattering effects do not affect these structures, but the effects due to the changes in resist thickness (ie.-resist coupling effects) and those due to the abruptness of the step (due to the different sidewall angles) should be present.

In summary, it is expected that the wafer with a highly reflective substrate, deep trenches, and small sidewall angles should produce the most noticeable effects.

Chapter 3
Mask

3.1 ELTPG-2 Chip Layout

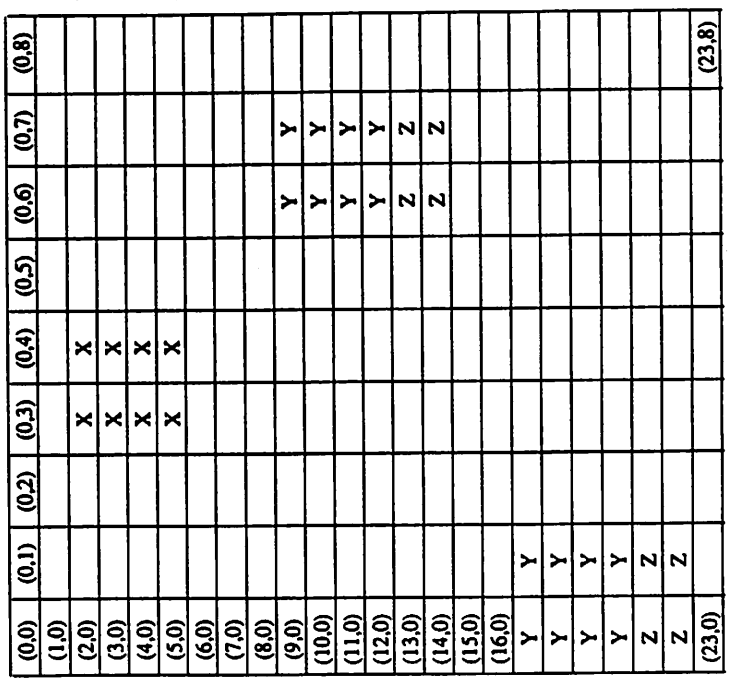


3.2 Chip Floor Plan

Each chip is 1cm x 1cm, and is subdivided into 216 blocks for the purpose of making electrical measurements using the HP automatic probing system. Each block consists of a 2x5 array of 100μm pads on 200μm centers, and the corresponding coordinates are shown in Figure Y. The designs however have been made to be used with a 2x10 probe card, and therefore two blocks are used by each structure. By using 2x5 blocks we can make a better use of the area when structures are oriented in both the X and Y directions, and consistency with previous applications of the AUTOPROB [13] program is maintained.

The coordinates of the lower block of each test structure is sufficient for specifying the location of each 2x10 structure. For the HP testing system, these coordinates should be read as (my,mx), where x=1000mx, and y=400my.

(Label)



Rotated:

(0,8)	Y	Y	Y	Y	Z	Z									X	X	X	X					(23,8)
(0,7)	Y	Y	Y	Y	Z	Z									X	X	X	X					
(0,6)																							
(0,5)										Y	Y	Y	Y	Z	Z								
(0,4)										Y	Y	Y	Y	Z	Z								
(0,3)																							
(0,2)																							
(0,1)																							
(0,0)	(1,0)	(2,0)	(3,0)	(4,0)	(5,0)	(6,0)	(7,0)	(8,0)	(9,0)	(10,0)	(11,0)	(12,0)	(13,0)	(14,0)	(15,0)	(16,0)	(17,0)	(18,0)	(19,0)	(20,0)	(21,0)	(22,0)	(23,0)

(Label)

Structures: X = trenches
Y = parallelb
Z = serpentine

Pad Grid

1	11
2	12
3	13
4	14
5	15
6	16
7	17
8	18
9	19
10	20

3.3 Description of Test Structures

Lines parallel to a step and lines crossing a step

Filename:

corners

References:

None

Purpose:

Determine scattering and topography effects of an edge parallel to a line, of elbows next to corners, and of lines crossing small trenches next to the edges.

Description:

Pad-like structures:

The linewidths and spacing from the edge of the line to the step are as follow: (+ means above the trench, and - means below)

	L=1.2	L=1.6
S=	+1.2	+1.2
	+0.6	+0.6
	+0.0	+0.0
	-0.0	-0.0
	-0.6	-0.6
	-1.2	-1.2

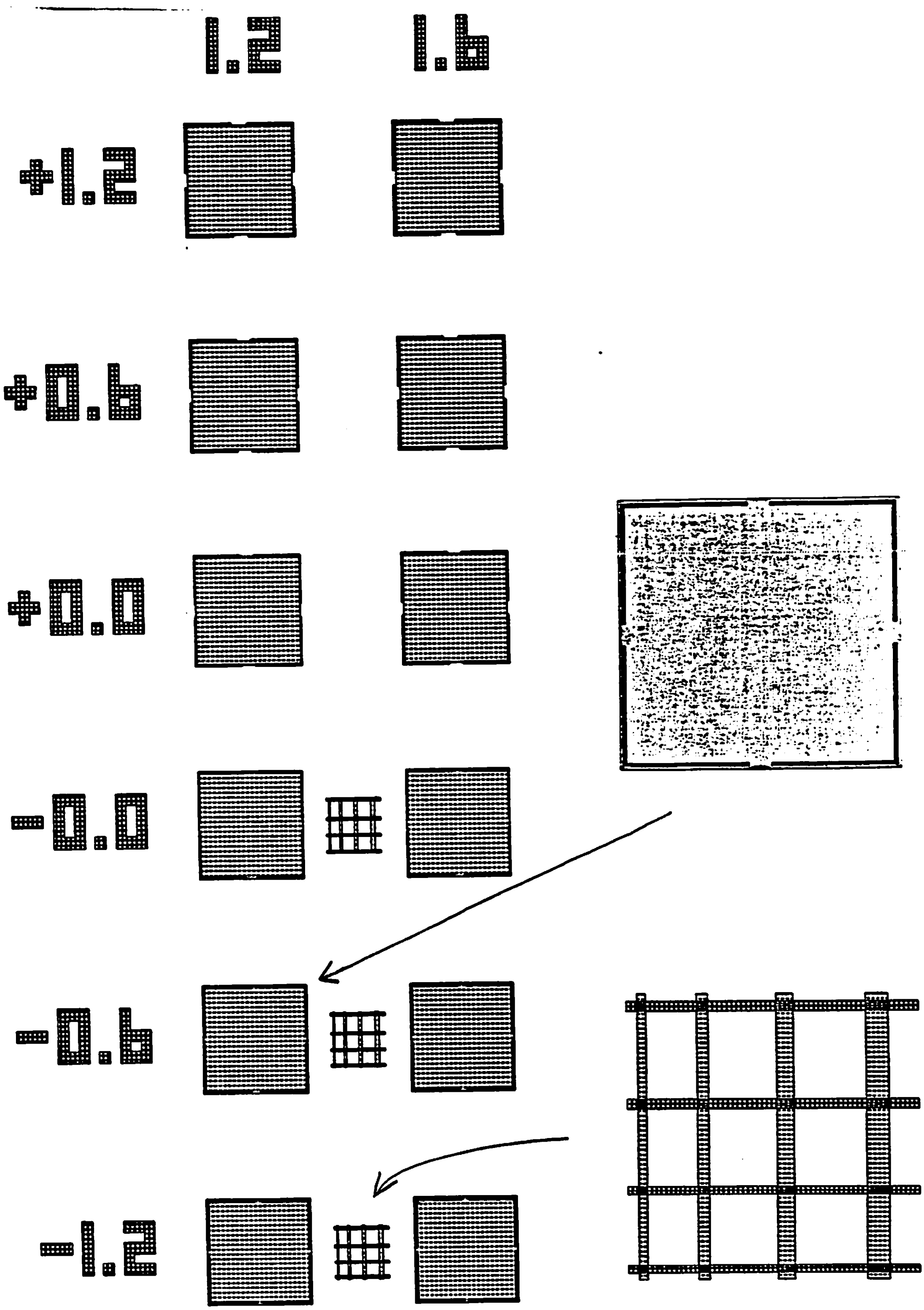
Mesh-like structures:

Four trench widths are studied: W=1.4, 2.0, 3.0, and 4.0 microns. Two linewidths: L=1.2, and 1.6 microns, and three displacements from the edge: 0.0, 0.6, and 1.2 microns. There are also some reference lines which cross these trenches but far away from the edges. See the amplification for a clearer understanding of the layout.

Testing:

Visual inspection and SEM photographs.

corners layout:



Lines parallel to a step

Filename:

parallelb

References:

None

Purpose:

Determine scattering and topography effects of an edge parallel to a line.

Description:

The length of the lines is 100µm, and the linewidths and displacements measured from the center of the line are as follow:

	L=1.2	L=1.2	L=1.6	L=1.6
S=	+20.0	-0.5	+20.0	-0.5
	+1.5	-1.0	+1.5	-1.0
	+1.0	-1.5	+1.0	-1.5
	+0.5	-5.0	+0.5	-5.0
	0.0	-20.0	0.0	-20.0

{parallel1.2b} {parallel1.6b}

Testing:

resistance → linewidth

Test Coordinates:

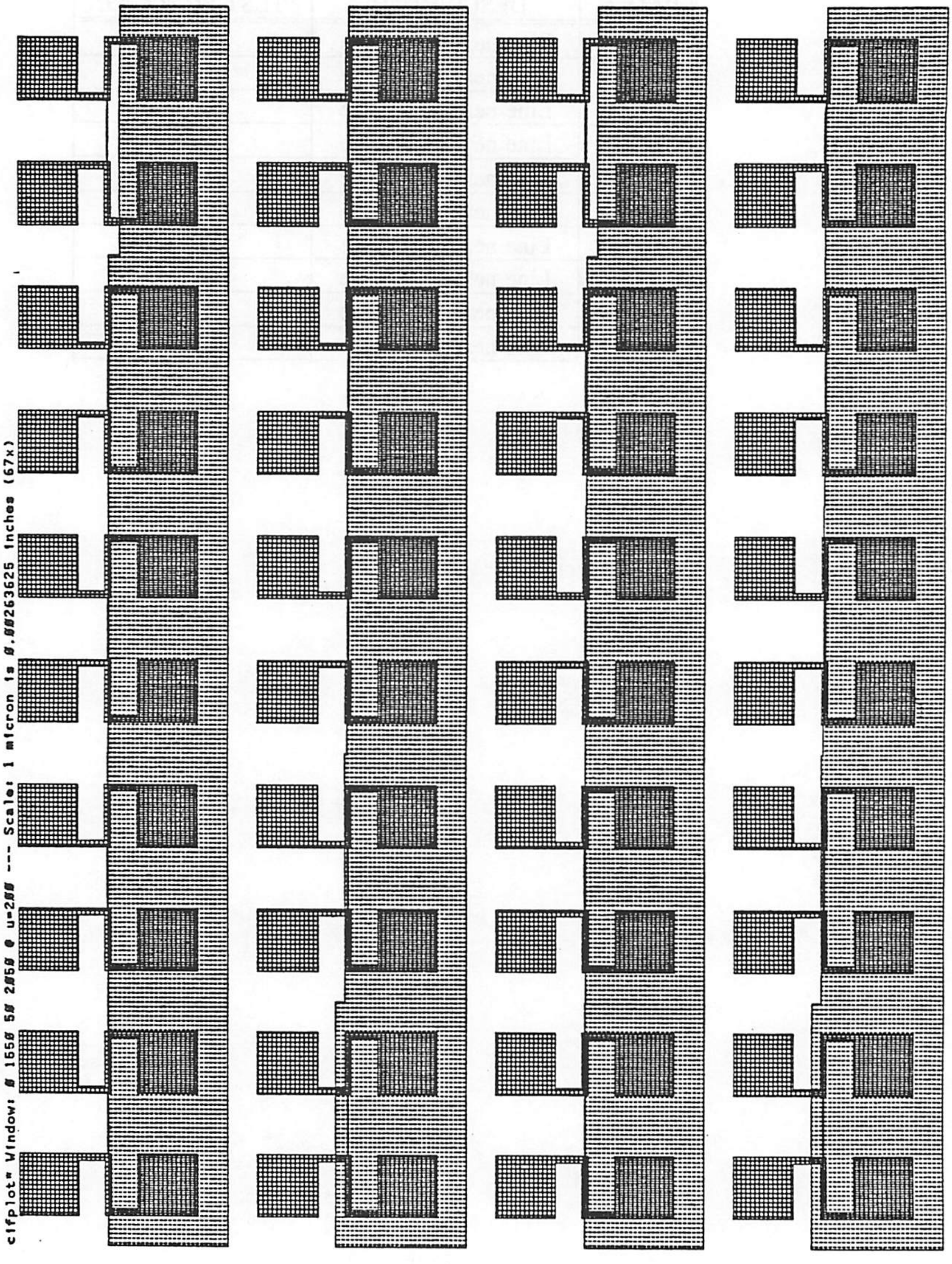
Normal: (9,6),(10,6),(11,6),(12,6),(17,0),(18,0),(19,0),(20,0)

Rotated: (1,7),(2,7),(3,7),(4,7),(10,4),(11,4),(12,4),(13,4)

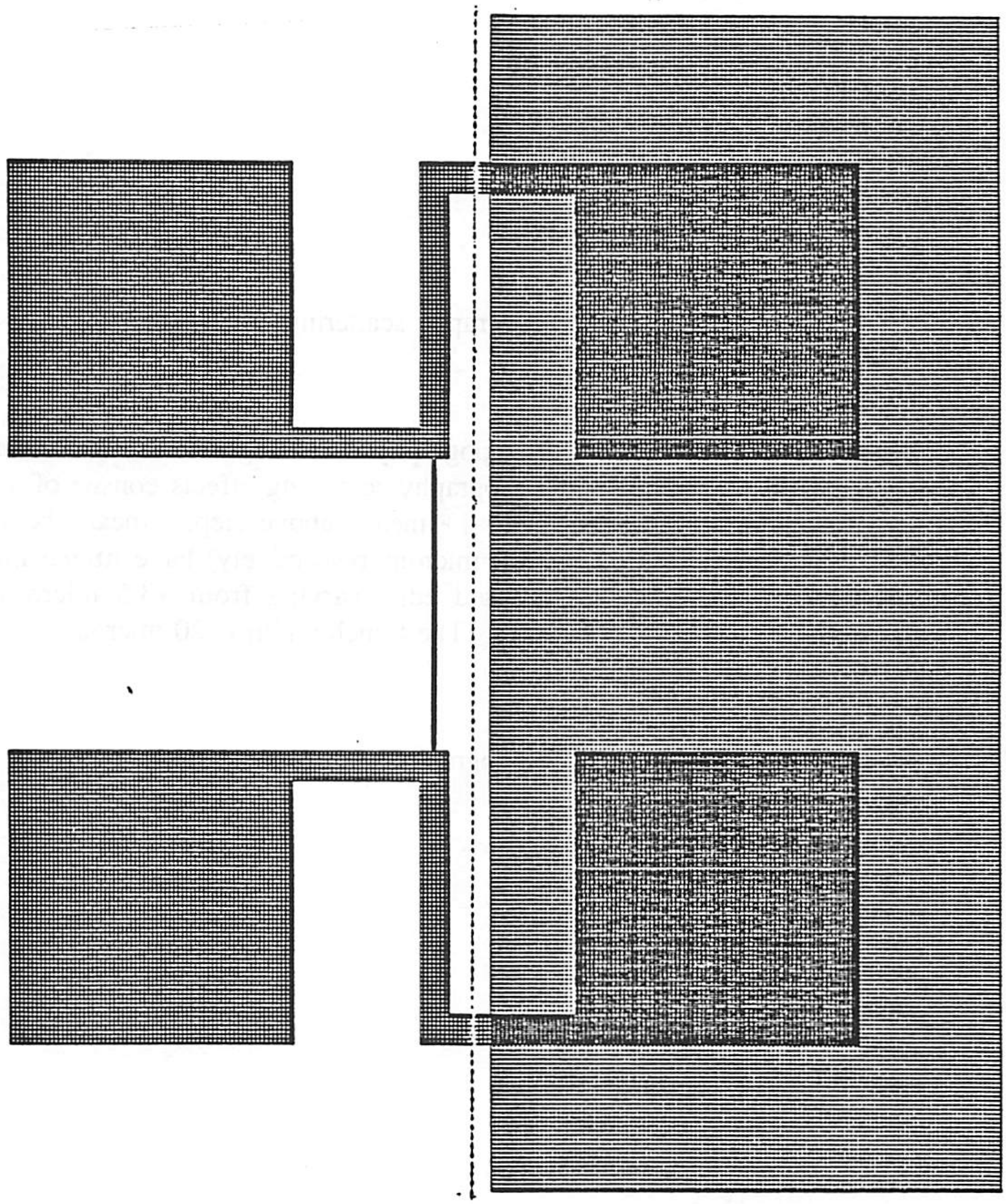
Pad Assignments:

PAD #	DESCRIPTION	TEST FUNCTION
11&12	Line next to an edge	Inject I
1&2	Line next to an edge	Sense V
13&14	Line next to an edge	Inject I
3&4	Line next to an edge	Sense V
15&16	Line next to an edge	Inject I
5&6	Line next to an edge	Sense V
17&18	Line next to an edge	Inject I
7&8	Line next to an edge	Sense V
19&20	Line next to an edge	Inject I
9&10	Line next to an edge	Sense V

parallelb layout:



parallelb layout: (zoom)



SEM measurement lines

Filename:

sem1

References:

None

Purpose:

Cross-section evaluation of topography scattering effects.

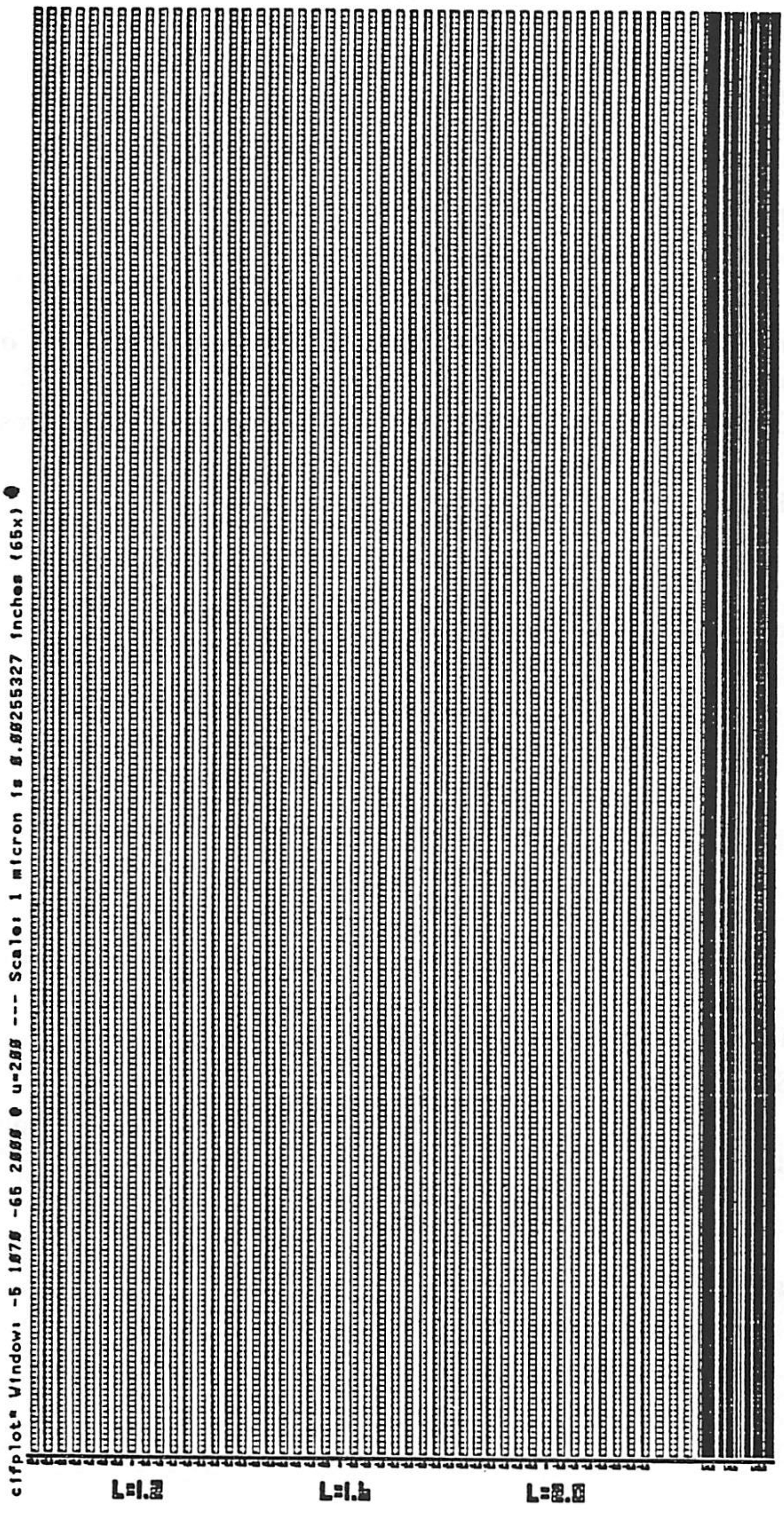
Description:

Four sets of SEM lines with topography scattering effects, and three sets of SEM lines. The SEM lines with topography scattering effects consist of a line displaced with respect to an edge (step) {+ means above step, - means below step}. The first three sets (1.2, 1.6, and 2.0 microns respectively) have fifteen lines each, with the spacing between the line and edge varying from +3.5 microns to -3.5 microns in decrements of 0.5 microns. The trench width is 20 microns.

Testing:

Visual inspection and SEM photographs.

sem1 layout:


cifplot* Window: -5 1070 -65 2000 @ u=200 --- Scale: 1 micron is 0.00255327 inches (65x)
L=1.2
L=1.6
L=2.0

Serpentine, Comb, and Van der Pauw structures

Filename:

serpentine

References:

PROMETRIX

Purpose:

Serpentine - Determine effects of topography with respect to opens on crossings of an edge.

Comb - Determine effects of topography with respect to shorts on crossings of an edge.

Van der Pauw - Measurement of sheet resistance.

Description:

The serpentine and comb structures are designed with L=S.

L=1.2	L=1.6
Serpentine with step	Serpentine with step
Serpentine	Serpentine
Comb with step	Comb with step
Comb	Comb
Van der Pauw 1	Van der Pauw 2

Testing:

Serpentine - Open detection and resistance measurement.

Comb - Short detection.

Van der Pauw - Inject current across one corner of the central square and measure the voltage

across the opposite corner.

Test Coordinates:

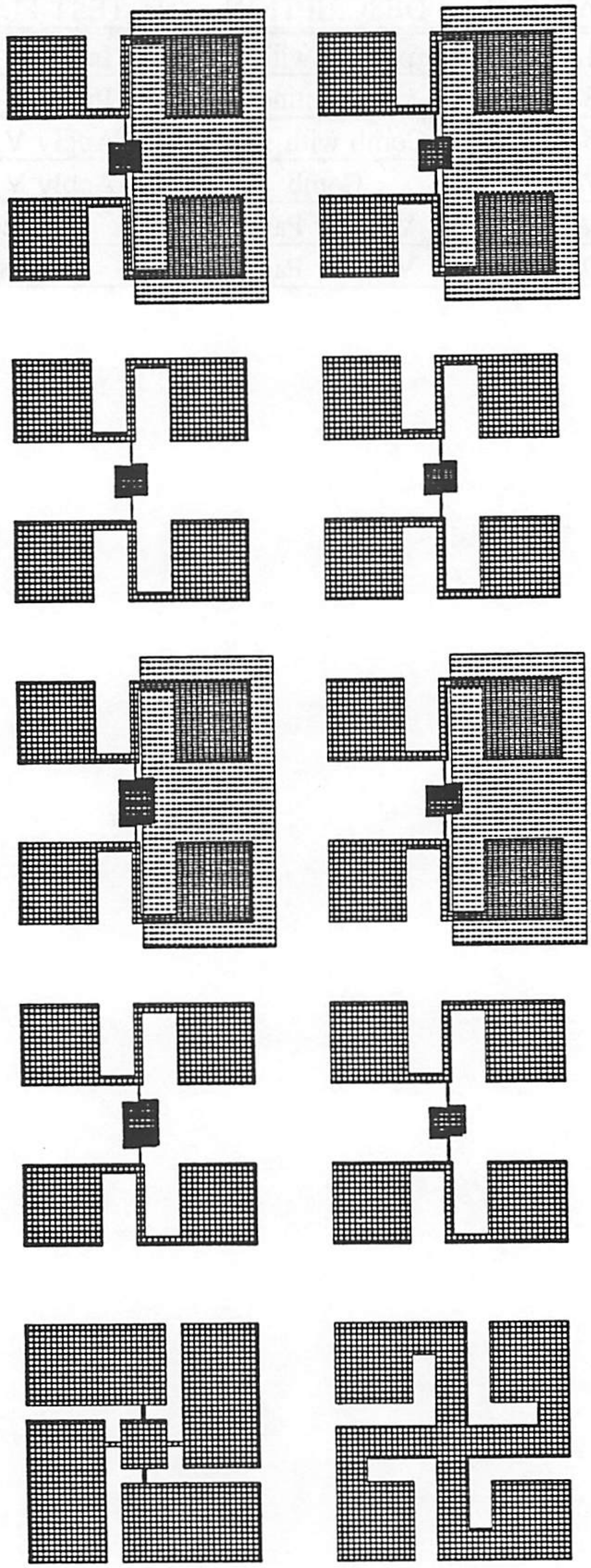
Normal: (13,6),(14,6),(21,0),(22,0)

Rotated: ((5,7),(6,7),(14,4),(15,4)

Pad Assignments:

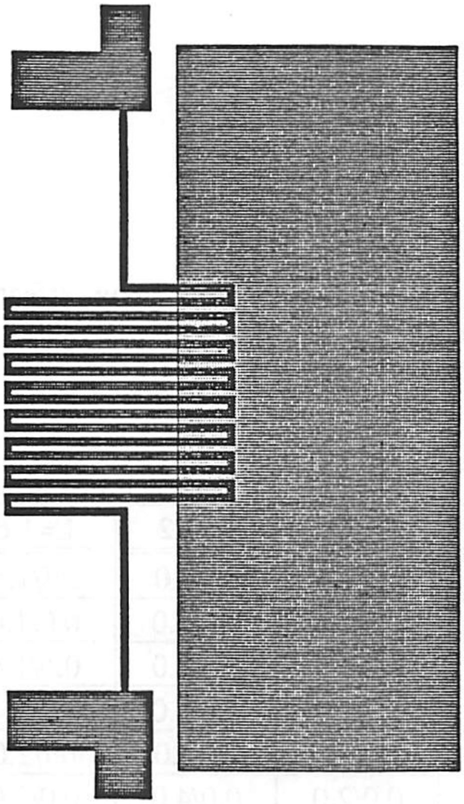
PAD #	DESCRIPTION	TEST FUNCTION
1&2	Serpentine with step	Inject I, Sense V
3&4	Serpentine	Inject I, Sense V
5&6	Comb with step	Apply V, Sense I
7&8	Comb	Apply V, Sense I
9&19	Van der Pauw	Inject I
10&20	Van der Pauw	Sense V

serpentine layout:

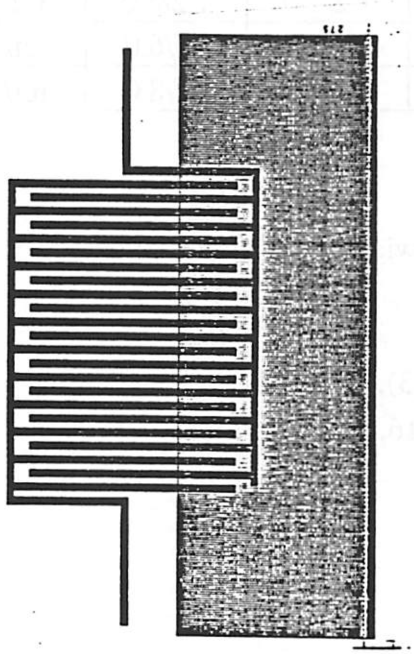


serpentine layout: (zoom)

Serpentine:



Comb:



Lines crossing a step at different spacings from the edge

Filename:

trenches

References:

None

Purpose:

Determine the scattering and topography effects of a line crossing small trenches next to the edges.

Description:

The length of the line is 20μm.

	L=1.2	L=1.2	L=1.6	L=1.6
S/W	ref/1.4	ref/3.0	ref/1.4	ref/3.0
	0.0/1.4	0.0/3.0	0.0/1.4	0.0/3.0
	0.6/1.4	0.6/3.0	0.6/1.4	0.6/3.0
	1.2/1.4	1.2/3.0	1.2/1.4	1.2/3.0
	ref/2.0	ref/4.0	ref/2.0	ref/4.0
	0.0/2.0	0.0/4.0	0.0/2.0	0.0/4.0
	0.6/2.0	0.6/4.0	0.6/2.0	0.6/4.0
	1.2/2.0	1.2/4.0	1.2/2.0	1.2/4.0
	ref/1.2	ref/6.0	ref/1.2	ref/6.0
	ref/1.6	ref/8.0	ref/1.6	ref/8.0

Testing:

resistance → linewidth, or open detection.

Test Coordinates:

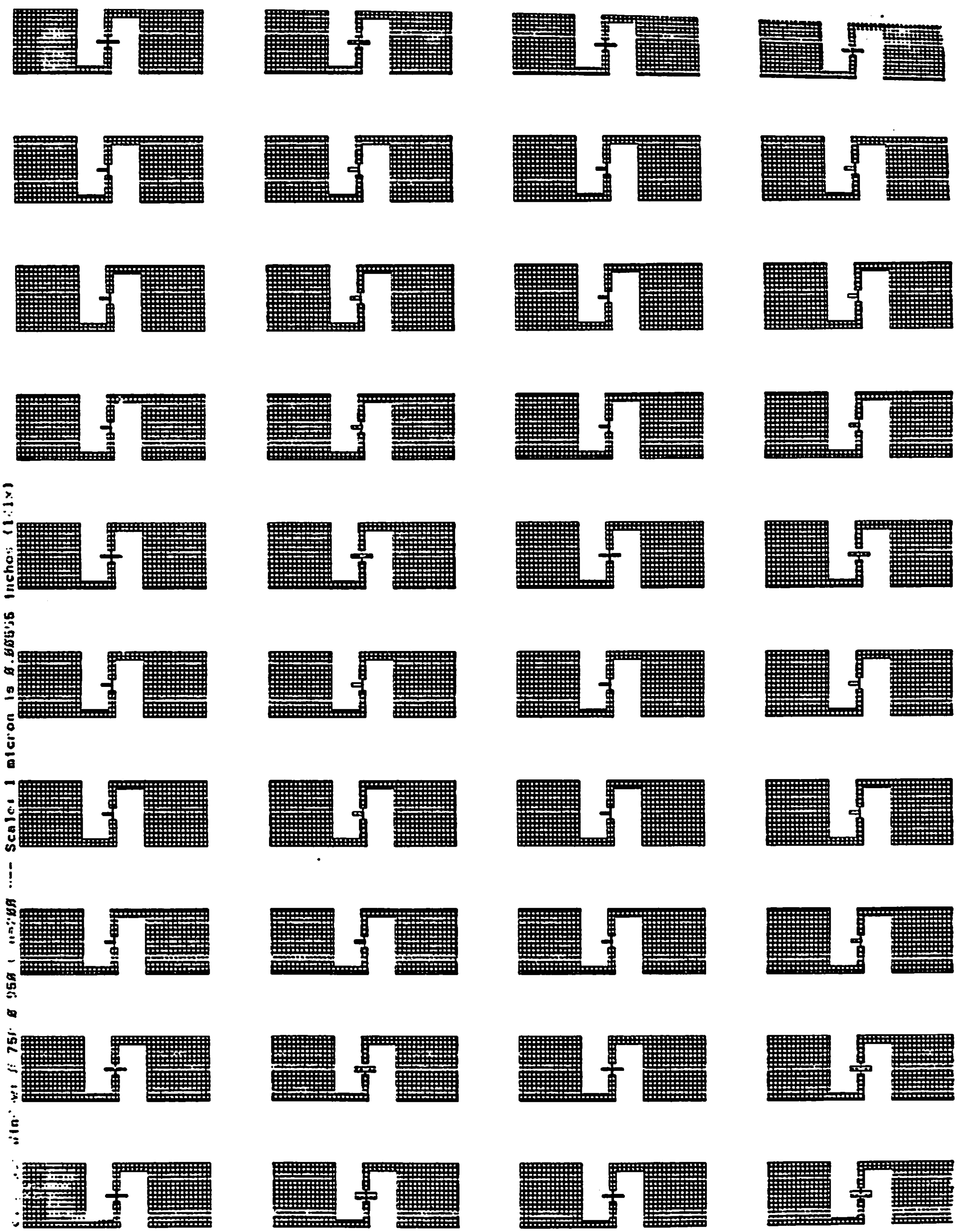
Normal: (2,3),(3,3),(4,3),(5,3)

Rotated: (15,7),(16,7),(17,7),(18,7)

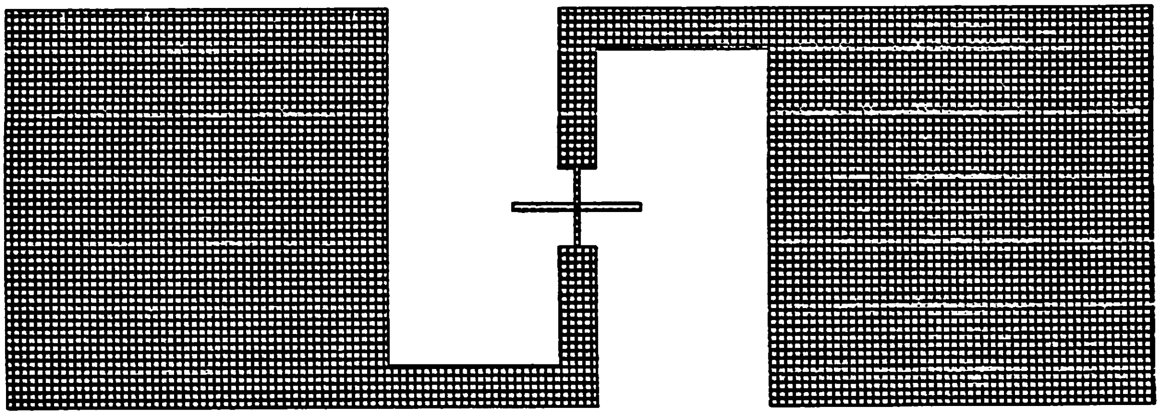
Pad Assignments:

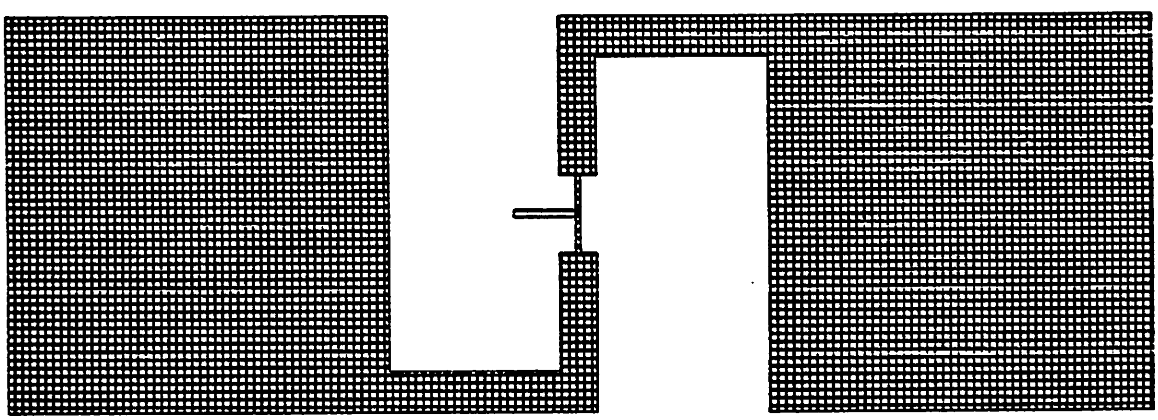
PAD #	DESCRIPTION	TEST FUNCTION
1&11	Line across a trench	Inject I, Sense V
2&12	Line across a trench	Inject I, Sense V
3&13	Line across a trench	Inject I, Sense V
4&14	Line across a trench	Inject I, Sense V
5&15	Line across a trench	Inject I, Sense V
6&16	Line across a trench	Inject I, Sense V
7&17	Line across a trench	Inject I, Sense V
8&18	Line across a trench	Inject I, Sense V
9&19	Line across a trench	Inject I, Sense V
10&20	Line across a trench	Inject I, Sense V

trenches layout:



trenches layout: (zoom)





3.4 Cell Hierarchy

ELTPG-2

- layout3
  - sem1
  - serpentine
  - parallelb
    - parallel1.2b
    - parallel1.6b
  - trenches
  - corners

Chapter 4
Process

4.1 Mask Making

The layout of the test patterns and overall mask was done using the CAD layout tool VEM. VEM uses the OCT Data Manager, and therefore the files were converted from OCT to CIF format, and then converted to a MANN file. The MANN file was then used to obtain a tape which was run on the GCA 3600 pattern generator to obtain the masks. Two chrome masks were produced: the one labeled POLY was generated with 34,391 flashes and is that used for defining the test structures, which will be of photoresist, polysilicon, and aluminum; the mask labeled PWEL was generated with 3,640 flashes, and is the mask used for defining the trench areas (in silicon). On the layout, a dark area represents the trench, this was reversed on the mask since positive photoresist would be used in the processing of the wafers.

4.2 Mask Checking

The ELTPG-2 POLY chrome mask was inspected with the Vickers Image Shearing Microscope to determine if there was a bias in the mask making. There appears to be no difference between the vertical and horizontal lines, they are both consistent, however the chrome on the mask appears to have been overetched by about 0.25μm on each edge. Since we are using the GCA 6200 10X wafer stepper, a 1.2μm design appeared as 11.5μm on the mask; this variation is on the order of 5%, and is therefore acceptable. The important aspect is that bias is consistent and independent of structure orientation, therefore if necessary one could pre-distort the design to get the desired results on the mask. Accuracy was not as important as consistency in the experiment, so the original design was not pre-distorted.

Butting errors were found in the SEM lines because their length was greater than that of the shutter blades and patching was necessary, however it was surprising to see that these errors were hardly noticeable in both the horizontal and vertical directions. The error is very small, as can be seen in Figure 4.2.1.

4.3 Wafer Preparation

Since the reflectivity and topography effects are to be studied, it is necessary to investigate the effects by considering different substrates, different trench depths, and differents sidewall angles.

Two trench depths have been studied: 0.2μm (shallow), and 0.5μm (deep). Two sidewall angles have also been created: a large angle (~80°) using a plasma etch, and a small angle (~54.7°) using a wet etch. Two different substrates have been prepared to consider the effect of different substrate reflectivities; the substrates used were silicon and aluminum.

The resulting eight combinations will produce a visual set of wafers which will be inspected with the SEM. The photoresist used to define the structures, and which will be observed, is KTI 820.

For the electrical set of wafers, only the silicon substrate and deep trenches will be considered; therefore electrical results will compare the effects of sidewall angles and will generate some information regarding the effects of deep trenches, or steps. The structures will be made of two materials, and thereby a comparison of how they behave with respect to each other will also be obtained; the materials used are polysilicon, and aluminum.

A process flow for the fabrication of both the electrical and visual test wafers is shown in Figure 4.3.1. Figure 4.3.2 shows some steps of the process flow for wafer 11 on a cross-section of a section of the SEM lines.

4.4 Exposure

The exposure was done using the GCA 6200 10X wafer stepper at a wavelength (λ) of 436 nm; the numerical aperture (NA) of the lens is 0.28, and the partial coherence factor (σ) is 0.7. All of the wafers were exposed at the same dose (exposed for 0.15 seconds, ~79mJ/cm^2) and focus settings, and all of the die within a wafer were exposed equally.

4.5 Development

Development was done using the MTI Omnichuck Photoresist Development Station and the standard resist developing program (60 second development with pre-mixed 1:1 KTI 934 developer).

4.6 SEM Preparation

The die observed were generally located near the center of the wafer, and the die were cut along the X-axis (label on upper left corner), obtaining a cross-section of the SEM lines, and the upper half was inspected. The plain silicon wafers were then coated with a very thin layer of gold using the Hummer sputtering system in order to avoid charging and thereby obtaining a better resist contrast.

The aluminum coated wafers were immersed in liquid nitrogen and immediately cracked in order to reduce the stretching of the aluminum layer where the cracking took place, since cross-section photographs were to be taken. The aluminum coating caused some difficulty by not allowing the diamond pen to work properly and breaking the wafer at the correct spot was somewhat difficult. Because of the aluminum coating, it was not necessary to coat the wafers with gold.

The photographs were taken using the Nanometric CWIKSCAN II SEM; some are top views and others are cross-sections.

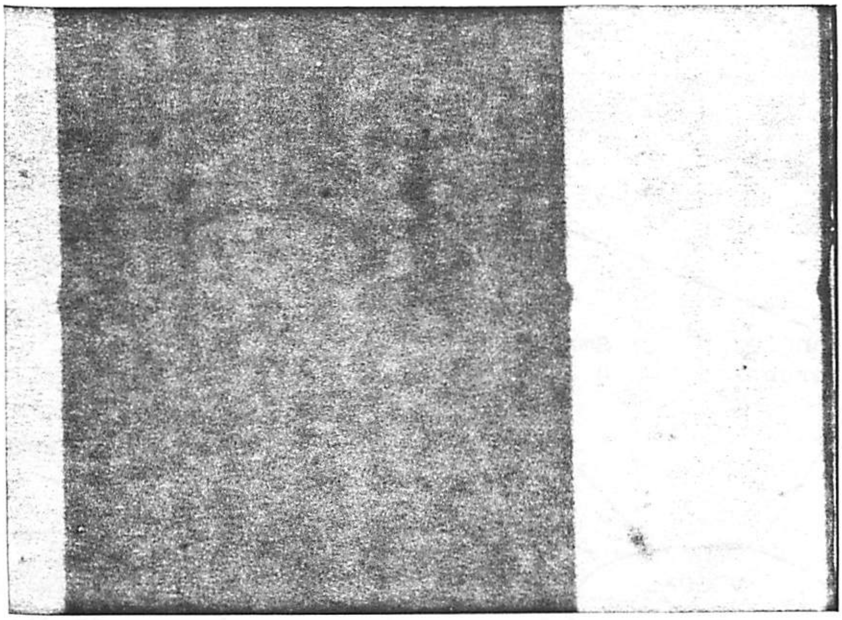


Figure 4.2.1 Butting errors appear in the mask, but are extremely small, and therefore they have no effect on linewidth variation. This occurs only in very long lines, and therefore none of our structures will be affected. The photo is of the SEM lines.

Wafers:

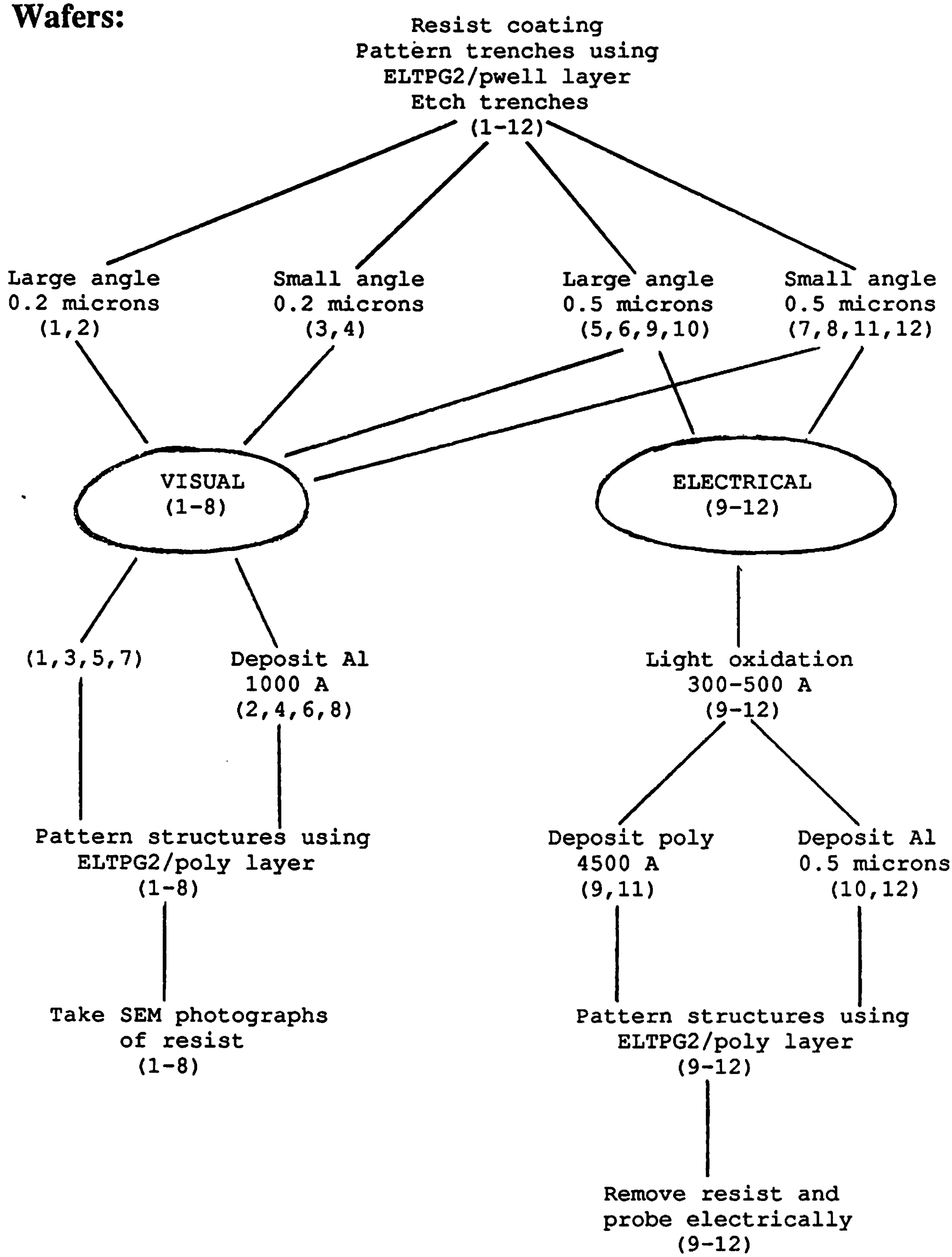
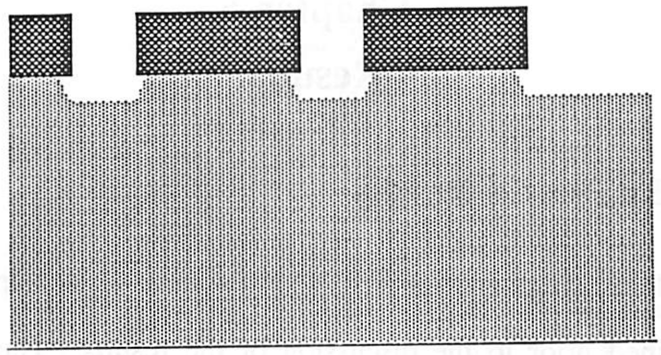
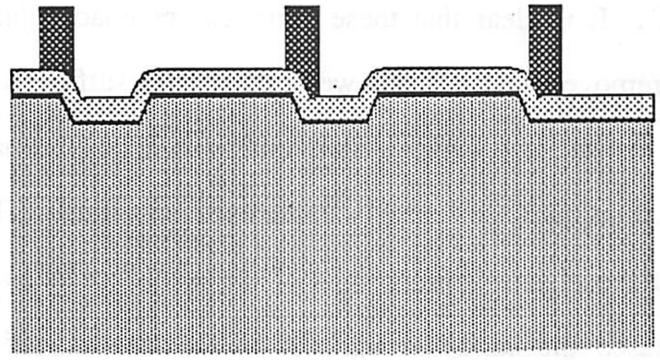


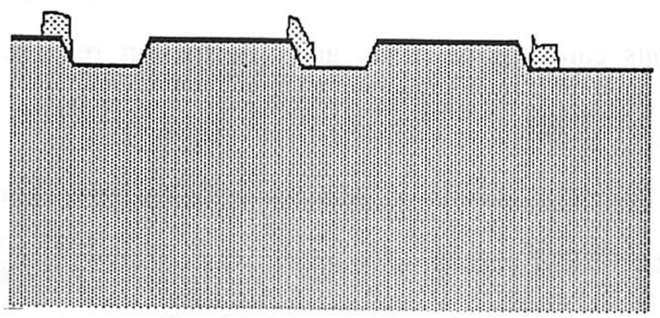
Figure 4.3.1 Process flow for the fabrication of the test wafers, wafer numbers are shown in parenthesis.



(a) Making of the trenches in silicon.



(b) Grow a thin layer of isolating oxide, deposit polysilicon, deposit photoresist and pattern.



(c) Etch polysilicon and remove photoresist.

Figure 4.3.2 Cross-sections showing some of the processing steps for wafer 11 on a section of the SEM structures. These cross-sections were generated with SIMPL-DIX.

Chapter 5
Results

5.1 Topography Process Results

Some problems were encountered with the processing, and these anomalies should be explained prior to the discussion of the results. The first issue is with regard to the use of a plasma etch to create the large angle sidewall trenches; the plasma etch produced surfaces which were full of pyramid-like particles commonly known as "grass". It is clear that these particles are unacceptable in a production process, and to remove them a quick wet etch should suffice. The second problem was that 0.5μm, instead of 0.1μm, of aluminum was deposited on the silicon wafers to simulate an aluminum (ie.- highly reflective) substrate. This large thickness changed some of the physical dimensions of the actual trenches in some structures, as well as increased the surface roughness in the trenches of the plasma etched wafers as the grass particles were covered, as can be seen in Figure 5.1.1. The sidewall angles were not affected as much, but in the case where the trenches were only 1.4μm wide, the dimensions were reduced by roughly 0.7μm. However, qualitative comparisons can still be done, and information relative to the dimensions shown may still be obtained.

The angles of the sidewalls of trenches were measured indirectly through the use of cross-section SEM photographs, and it was observed that the large angle was around 80° and the small angle was around 53°. The angles were similar for the aluminum coated substrates. Figure 5.1.2 shows one of the cross-section photographs used to determine these angles.

The refractive indices for silicon and aluminum were measured at a wavelength of 632.8nm using the Gaertner Ellipsometer with the substrate program, and the following results were obtained: Silicon: n=3.84, k=-0.24, psi=10.51, and del=169.90; Aluminum: n=0.86, k=-5.12, psi=41.36, and del=128.20. Some of the values of these optical constants from the literature at a wavelength of 436nm are: Silicon: n=4.69, and k=0.11; Aluminum: n=0.47, and k=4.84 [2]. It was also found that the thickness of the photoresist was 1.14μm (flat surface above trenches), and the value of its index of refraction was: n=1.61.

The relative reflectivity of the aluminum coated wafers, at a wavelength of 436nm, was measured using the Nanospec/DUV Microspectrophotometer. It was found that the aluminum substrates were from 90% to 110% more reflective than the silicon substrates. One exception was the case of the plasma etched wafers coated with aluminum; due to the roughness created by the grass particles, the effective reflectivity of the aluminum in the trenches was only 25% larger than that of its silicon counterpart. The reflectivity in the trenches of the plasma etched silicon was not affected by the presense of grass. Due to this increase in reflectivity, and the fact that all wafers were exposed at the same dose, there is a linewidth variation between the wafers that are aluminum coated and those that are not. The linewidth of lines on the aluminum substrate is roughly half of that which was designed, while those on silicon are only about 10% smaller.

The effects of substrate reflectivity, sidewall angle and trench depth will be discussed for each set of test structures, thereby identifying how different structures are affected by different topographies.

5.2 Visual Inspection of Topography Effects

Lines Parallel to Steps

In order to evaluate the cross-section photographs that were taken, it is useful to observe the behavior of the photoresist lines at different spacings from the step. Wafer 1 was chosen for this purpose because it provided with what was expected to be the least affected structures due to the topography characteristics (large sidewall angle and shallow trench) and because of the low reflectivity of its substrate. It was observed that the photoresist adapted to the contours of the substrate quite well, and the skirts of the profile of the lines that were in the trench were somewhat wider than those of the lines above the step due to the difference in photoresist thickness. It was also observed that the profiles of the lines were symmetric when these were far from the step. Figure 5.2.1 shows some resist profiles at various spacings from the edge, and the mentioned results can be observed here. The behavior of the resist on the other wafers followed the same trend. The interesting profiles are those of lines that are in the trench, but near the step edge, since we are interested in observing the scattering of light off the trench edge.

The substrate played an important role in the behavior of the resist. Since all of the wafers were exposed equally, the lines on the aluminum coated wafers were much more narrow, and the profiles were somewhat more vertical. The effects of the reflections off sidewalls were also increased due to the higher reflectivity; the substrate effect can be observed in Figure 5.2.2. The increase reflectivity has reduced the width of the line and some scattering effects off the sidewall are becoming evident, notice that the edge of the line that is closest to the trench sidewall has a more vertical edge.

The effect that the sidewall angle had on the resist profiles was dramatic, although still not as dramatic as was hoped for. It was expected that the wafers with a deep trench and an aluminum substrate would show the most dramatic results, and this turned out to be the case, as can be observed in Figure 5.2.3. Here one can see that the sidewall angle plays a very important role, and that the closer the angle is to 45°, the clearer the effect.

The trench depth also played an important role in shaping the resist. The deeper the trench, the more noticeable the effect, since more light would be reflected off the sidewall and would help expose one side of the resist more. If the trench depth is comparable to the height of the resist, then the entire side of the resist would be affected uniformly and although a decrease in linewidth would occur, no undercut would be present. The reflection off the silicon sidewalls isn't very large, but the effects are still noticeable, and the effect of trench depth can be noticed, as is shown in Figure 5.2.4.

All of the mentioned effects appeared in both linewidths; however the actual resist profiles varied slightly because the wider lines were better defined and the resist sidewall angles were slightly larger. This was expected because the resolution of our system is around 1.17μm on a silicon substrate and 1.7μm on an aluminum substrate [4]. Figure 5.2.5 shows the effect of linewidth on resist profiles.

The distance between the lines and the steps can be observed by comparing Figure 5.2.4 (b) with Figure 5.2.5 (a). It is clear that the closer the line is to the edge, the more noticeable the effect; an explanation for this is that the light reflected from the sidewall doesn't need to travel as far to expose the unexposed photoresist.

All of the above mentioned effects affect the profile of the resist, a photograph that helps determine the relative effects of each is shown in Figure 5.2.6. This figure can be compared with Figure 5.2.2 to see the effect of linewidth on an aluminum substrate; by comparing it with Figure 5.2.3 (b) we see the effect of trench depth, and we see that indeed trench depth is very critical; however, by comparing the relative effects of trench depth and sidewall angle, and looking at Figure 5.2.3 we can conclude that the sidewall angle is the most dominant effect, followed by the trench depth, and of course the higher the reflectivity of the trench sidewall, the larger the effects.

Lines Crossing End Corners

The corners structures were designed to capture the effects of reflective notching under different conditions. Some of these effects are noticeable in the structures with the smallest trench width, as can be observed in Figure 5.2.7 (a,b). By looking at (b) and (d) one can conclude that the linewidth does not play a very important role, since both are affected in the same way. If one looks at (c) and (d) we see that the effect due to the spacing of the line relative to the corner is minimal.

The substrate plays a very important role in these structures, as observed in Figure 5.2.8. As a result of an effective overexposure of the resist in the aluminum substrate, the sidewalls of the resist are very vertical on both sides, and a linewidth variation due to the change in resist thickness is hardly noticed. The behavior of the resist is again independent of the line width.

The sidewall angle effect is present, and can best be observed in the silicon substrate wafers. If we compare Figure 5.2.9 with Figure 5.2.8 (a,b), we can see that the small angle produces a greater effect than the large angle because the linewidth at the bottom of the trench is narrower (a vs. a); this is probably due to the extra reflection from sidewalls perpendicular to the line, right next to the line. It is clear that the sidewall has an effect, as can be observed in Figure 5.2.8 (a,c), and in Figure 5.2.7 (b,c,d), the semi-circular shape of the resist that bulges out at the bottom of the trench is due to the reflections off the sidewalls perpendicular to the line that are very close to it.

The effect of the trench depth is very noticeable when the trench sidewall angle is small, as can be seen by comparing Figures 5.2.7 (b) and 5.2.9 (a) with 5.2.8 (a) and 5.2.10 (a). If we compare Figure 5.2.10 with Figure 5.2.8 (a,b) we see the trench depth effect. This leads to the conclusion that on a silicon substrate, a deep trench and a small angle are necessary in order to observe the reflective notching effects. The aluminum substrates were too reflective and this effect was dominant and covered up the others.

Lines Crossing Steps

The serpentine and comb structures were designed to observe the topography effects of lines crossing edges. Topography affects the resolution of a system drastically, as can be observed by comparing Figures 5.2.11 and 5.2.12 (b).

The substrate plays an important role in these structures when the linewidths are small, as can be seen in Figure 5.2.12. The effective overexposure of the resist on aluminum decrease the linewidth of the structures (L=S in design). The amount of linewidth variation at the crossing of the steps was much greater for the aluminum substrate, as can be observed by comparing Figures 5.2.14 and 5.2.15.

The sidewall angle does not seem to play an important role in the behavior of the resist as it crosses the trench. There is a slight difference that can be observed for the small linewidth structures; the lines just at the bottom of the trench initially thicken more. The sidewall angle effect and its effect on different linewidths may be observed in Figure 5.2.13.

The trench depth plays a very important role in the behavior of the resist. It affects the behavior of the resist right at the step, and also affects the lines near the edge. Depending on the trench depth will be the resist thickness at the area neighboring the step, and the this resist thickness variation will no only affect the part of the structure which is below the step, but also that which is above the step but near it. The resist profile across the step plays a very important role since the energy coupling and interference effects depend on the thickness of the resist. The distance on the top of the trench from the edge where bad energy coupling within the resist occurs varies depending on the trench depth; for the shallow trenches this distance was smaller than for the deep trenches, as is shown in Figures 5.2.12 (b) and 5.2.13 (b). At the edge, some differences were also noticed; for the deep trench the line became thin two times as it crossed the step but for the shallow trench it only became thin once. This is due to the large resist thickness variation which occurs in the case of the deep trench, and there are more occurrences of multiples of ¼ λ, and therefore good and bad energy coupling in the resist occurs more frequently. The effect of linewidth variation at the step due to trench depth may be observed in Figures 5.2.12 (a) and 5.2.15.

5.3 Future Electrical Testing

Electrical probing of the wafers is planned at a later stage; however it is possible to forecast some results in a qualitative manner by observing the effects that were present in the photoresist patterns on the visual wafers.

From the top views of the serpentine and comb structures it is expected that the structures with a linewidth of 1.2μm will be shorted at the bottom of the trench near the edge, but the 1.6μm structures will be well defined, as is showed in Figures 5.3.1 and 5.3.2. The effect of the sidewall angle is hardly noticeable, and therefore it doesn't seem that the electrical measurements will provide any information regarding the effect of the sidewall angle; however they should provide some information regarding the change in linewidth which occurs from crossing the step, since these structures can be compared to their corresponding reference structures which are placed on a completely flat surface.

With regard to the trenches layout, it appears that there will be very small differences in the measured resistances, and it may be difficult to separate what is due to the effects of reflective notching, and what is due to measurement error. However it is too early to say, and would need to make the measurements to see if this is the case.

The parallelb structures should be able to determine linewidth variations due to scattering effects. The differences in resist thickness which pattern these lines will also produce some effects, but the effects are contrary to those caused by scattering effects, and therefore if a line that is smaller near the edge will give strong evidence that scattering effects play a dominant role; however, since the substrates aren't highly reflective the effects may not be as noticeable as expected. The electrical measurements would surely help answer some of these questions and would be very helpful in designing new structures that were to be more sensitive to particular effects.

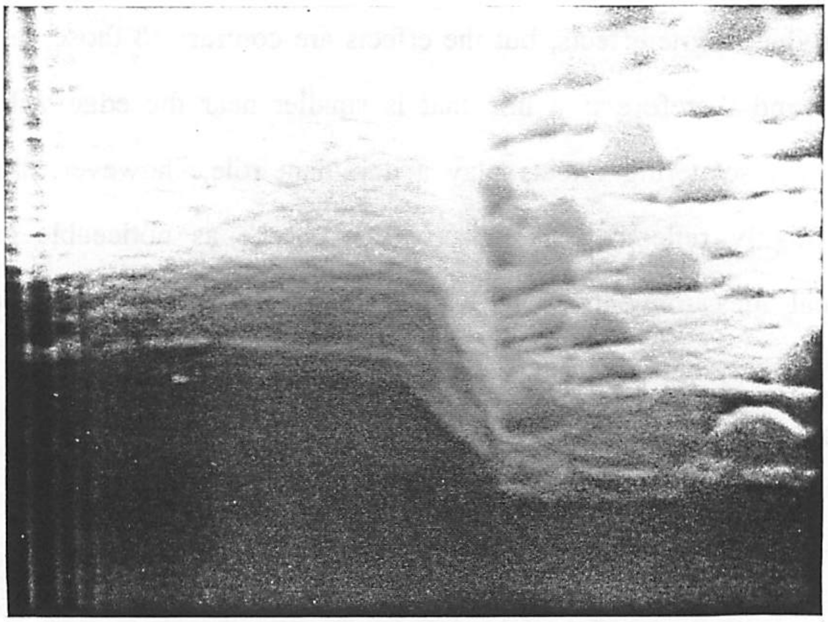


Figure 5.1.1 Roughness caused by the covering of "grass" produced during plasma etch by aluminum. Wafer 6.

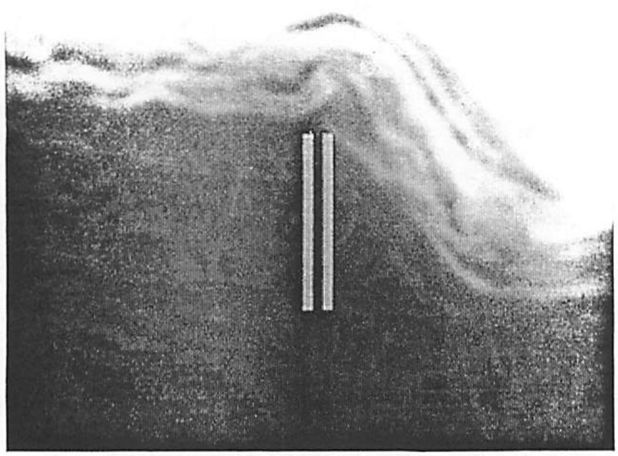
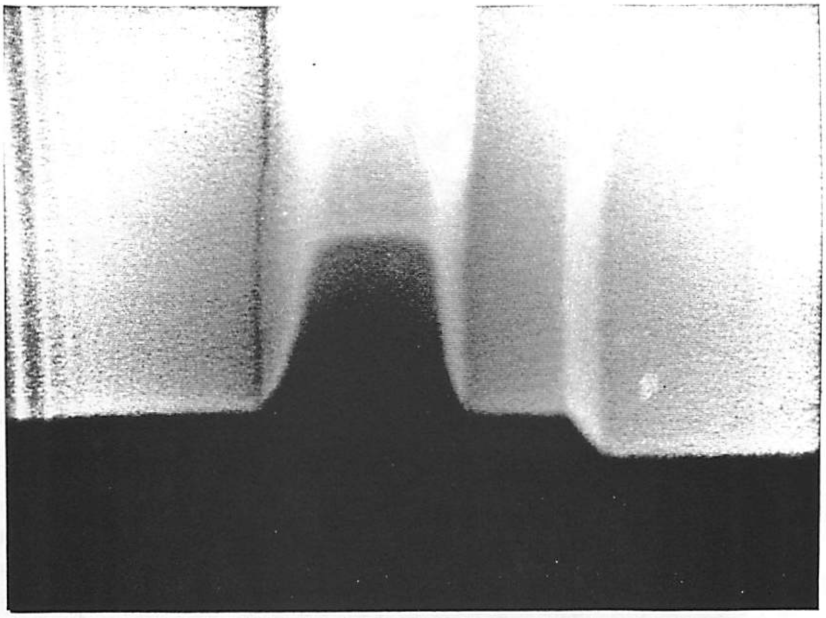
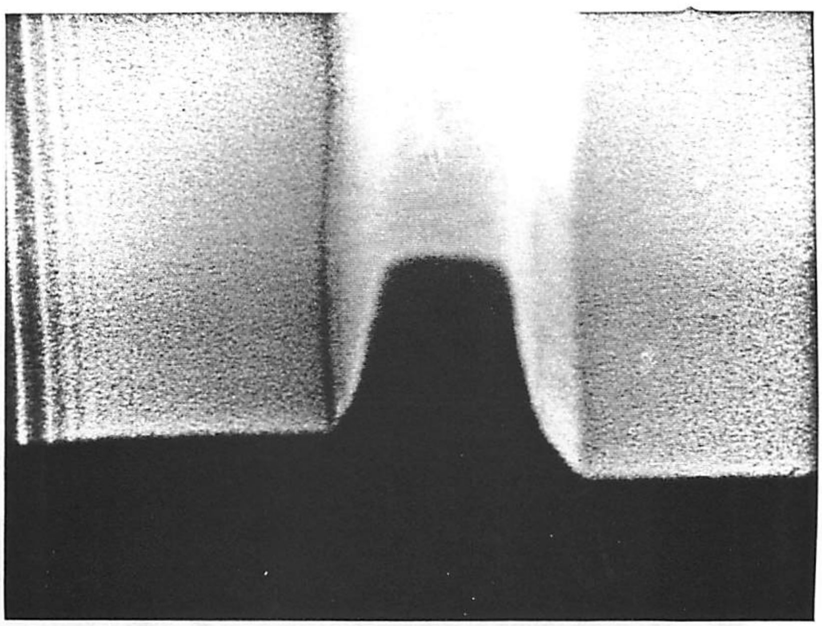


Figure 5.1.2 SEM used to calculate the angle of the sidewall for wafer 8 (angle ~53°).

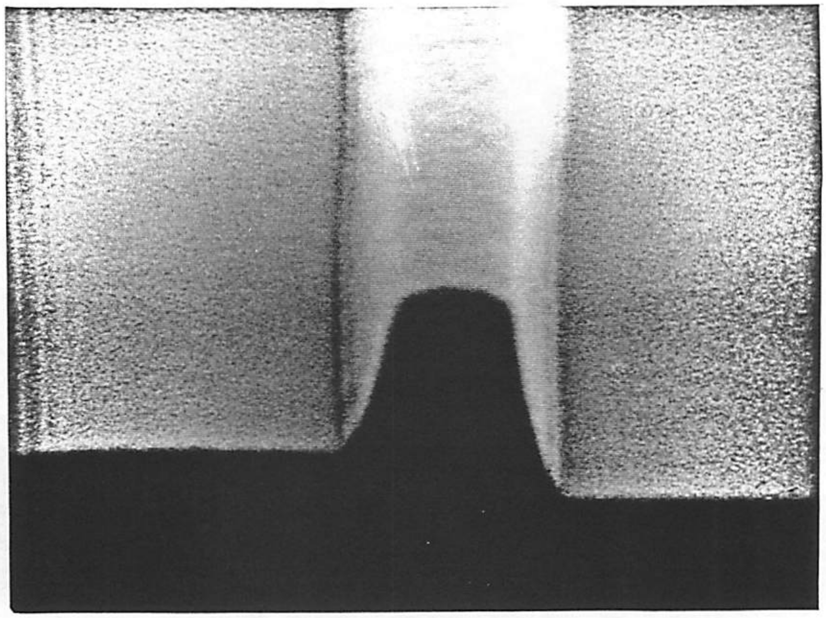


(a) S = 1.5μm

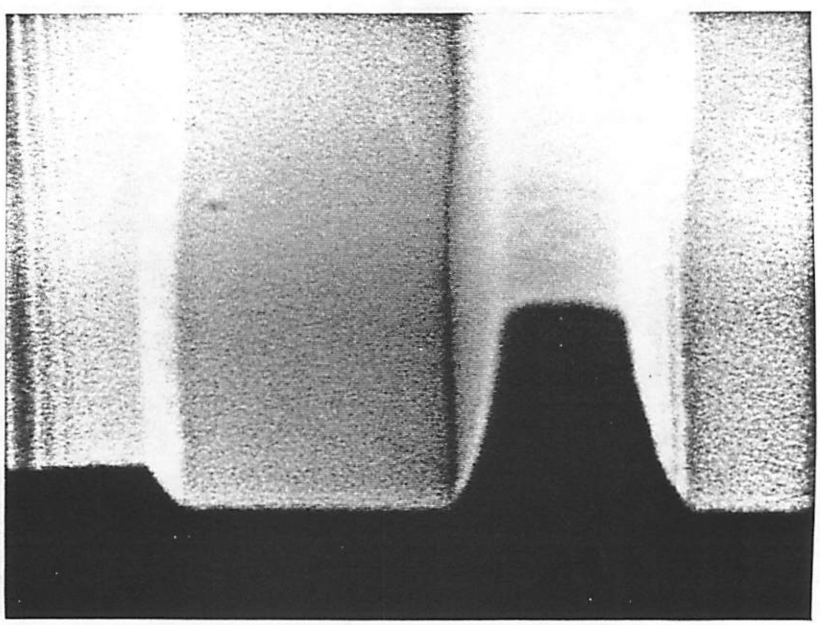


(b) S = 1.0μm

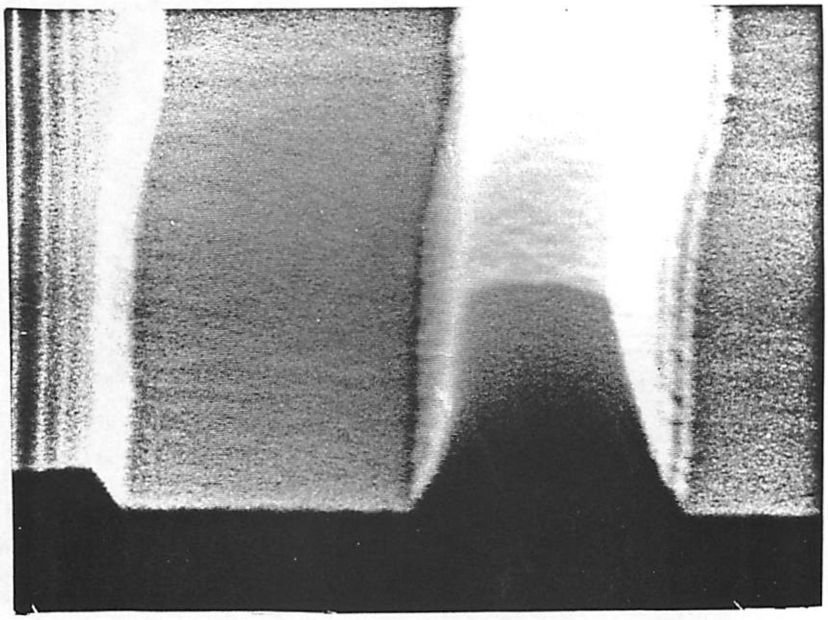
Figure 5.2.1 Photoresist profiles for different separations between the line (L=1.2μm) and the step (note that the spacing is from the center of the line to the edge). Wafer 1: large angle, shallow trench, silicon substrate.



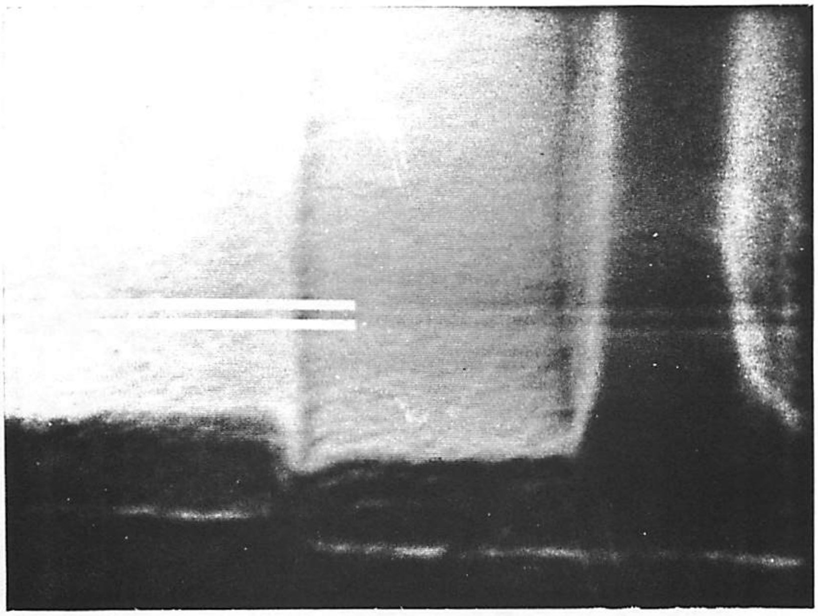
(c) S = 0.0μm



(d) S = -1.5μm

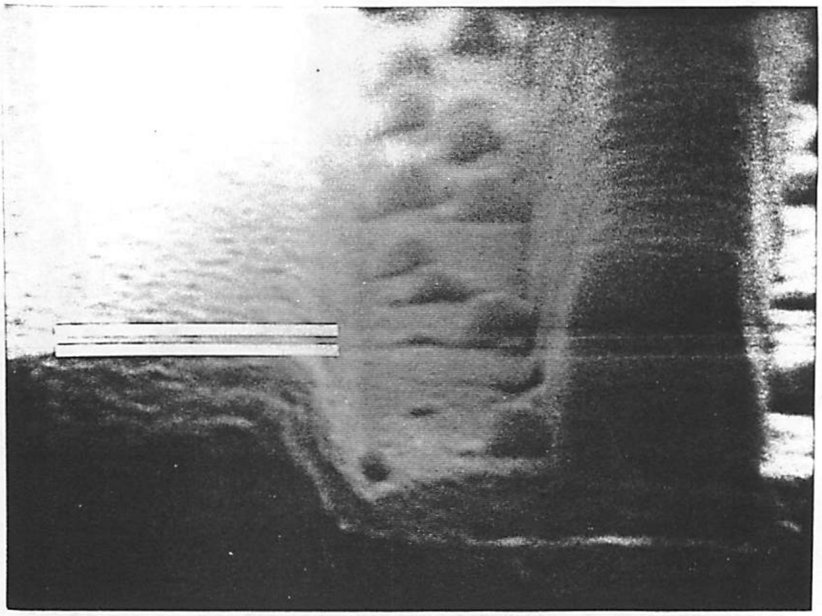


(a) Wafer 3: small angle, shallow trench, silicon substrate.

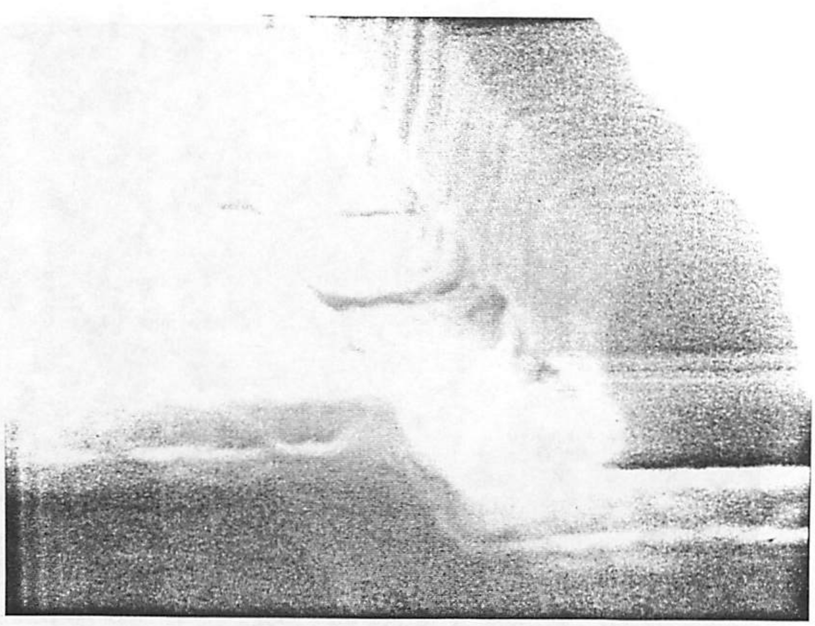


(b) Wafer 4: small angle, shallow trench, aluminum substrate.

Figure 5.2.2 Substrate effect. The higher the reflectivity of the substrate, the larger the effect. L=1.2μm, S=-1.5μm.

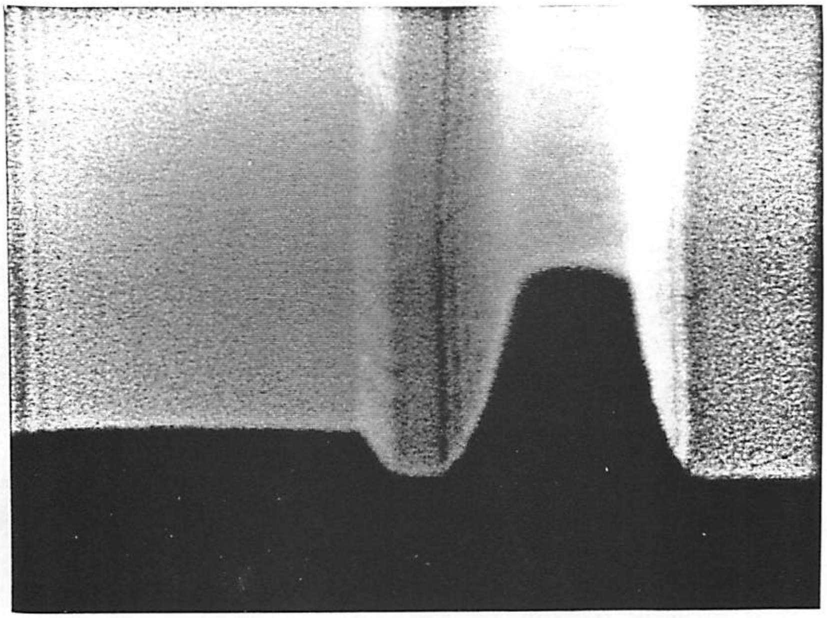


(a) Wafer 6: large angle, deep trench, aluminum substrate.

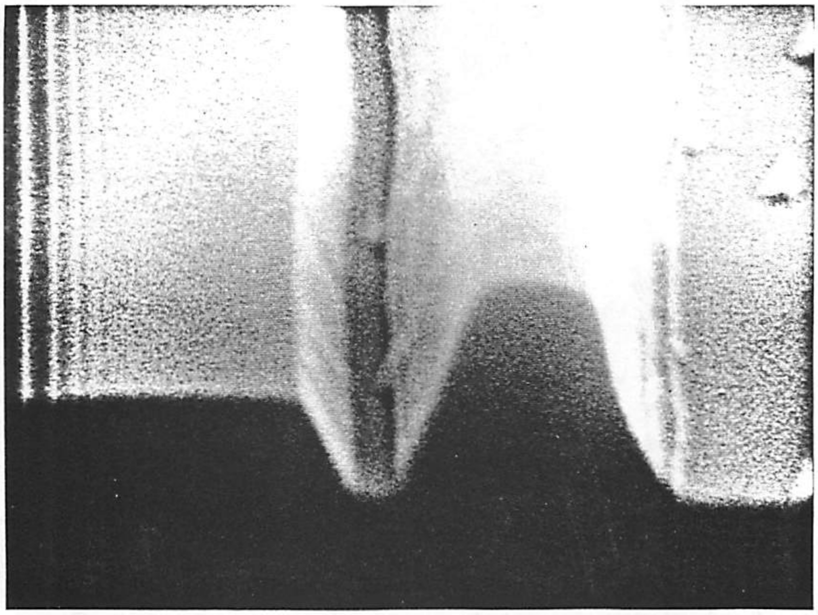


(b) Wafer 8: small angle, deep trench, aluminum substrate.

Figure 5.2.3 Effect of sidewall angle. The smaller the angle, the larger the effect. L=1.6μm, S=-1.5μm.

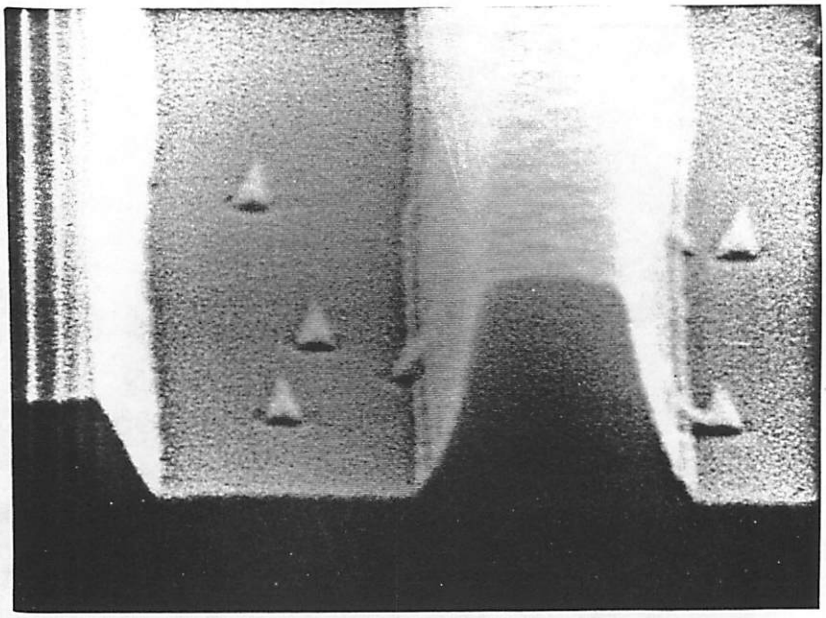


(a) Wafer 1: large angle, shallow trench, silicon substrate.

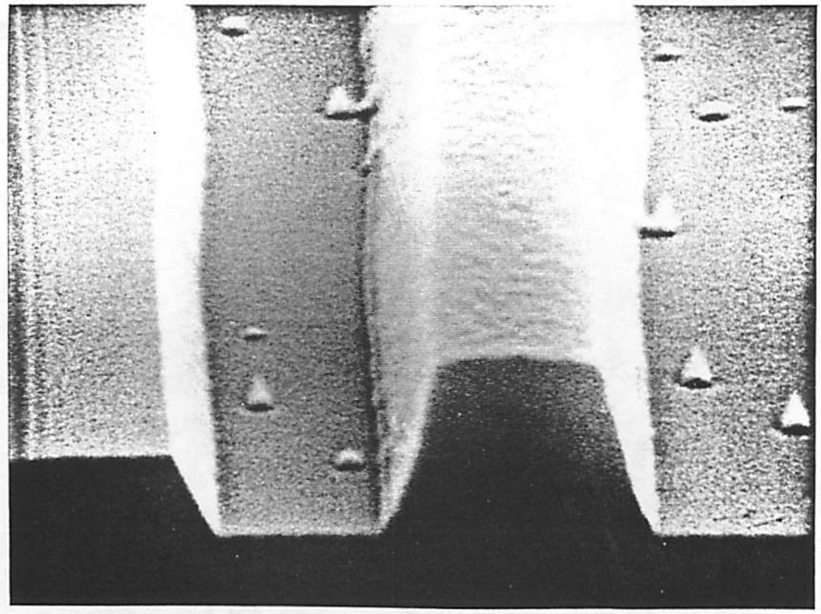


(b) Wafer 5: large angle, deep trench, silicon substrate.

Figure 5.2.4 Effect of trench depth. The larger the trench depth, the larger the effect. L=1.2μm, S=-0.5μm.



(a) L=1.2μm, S=-1.5μm



(b) L=1.6μm, S=-1.5μm

Figure 5.2.5 Effect of line width. The wider lines are better defined, and the difference in resist profiles means that when comparing effects the same linewidth structures should be compared. The same general pattern of effects is observed in both linewidths. Wafer 5: large angle, deep trench, silicon substrate. (Grass due to plasma etch is present)

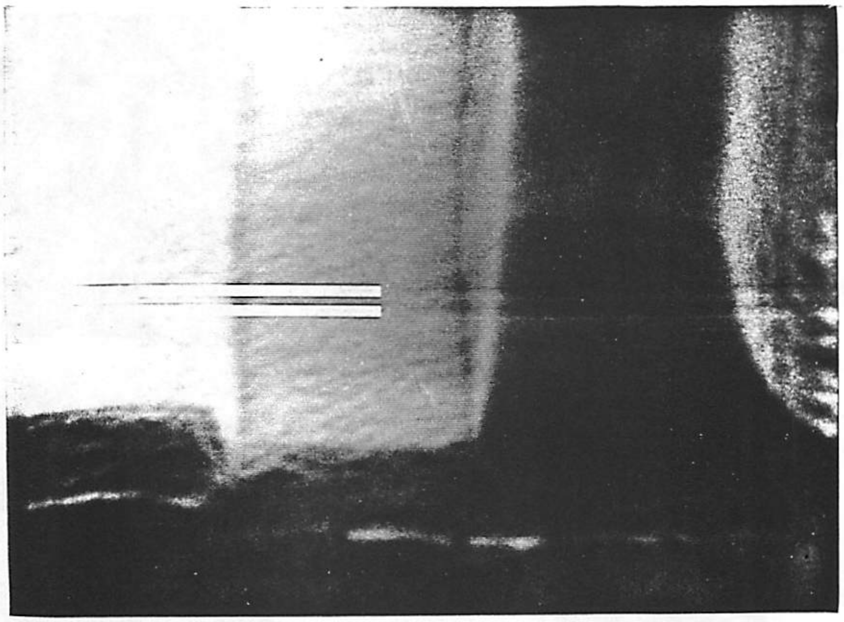
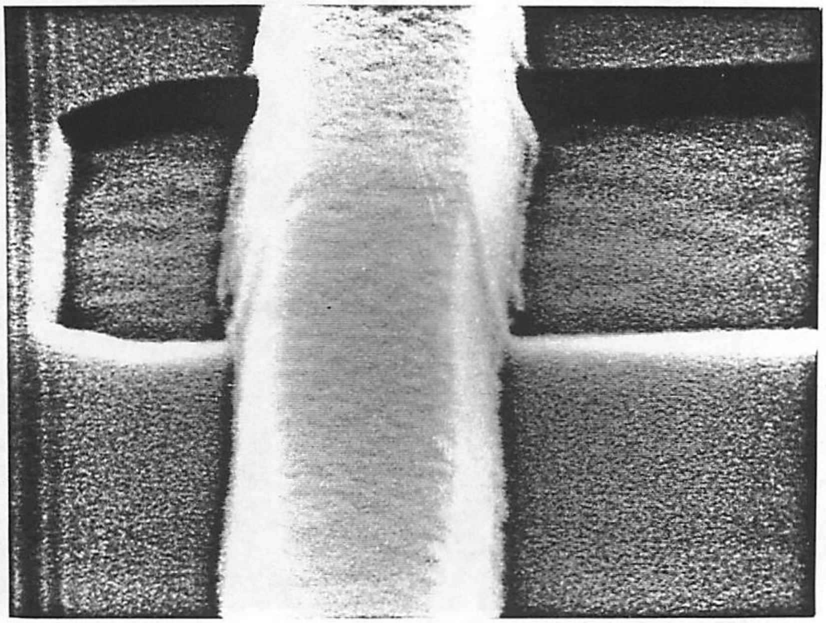
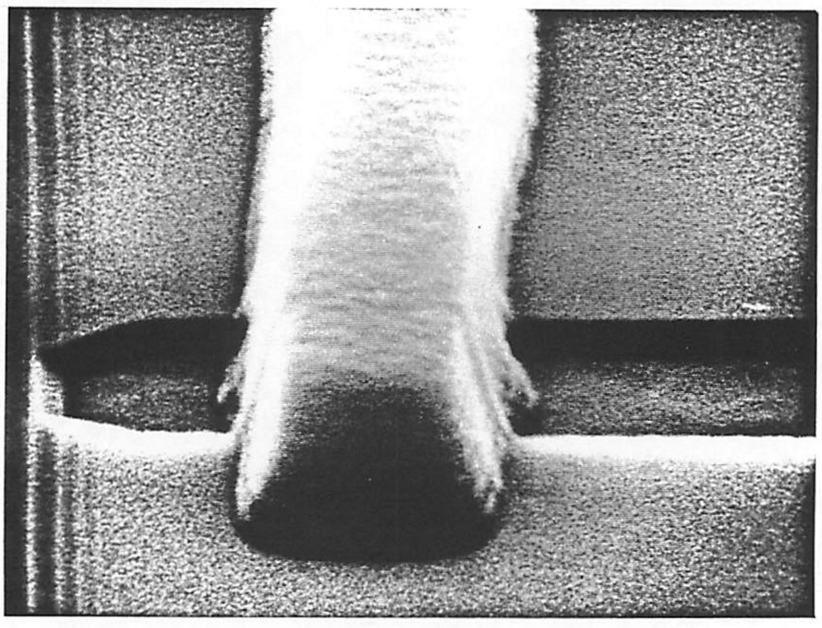


Figure 5.2.6 Wafer 4: small angle, shallow trench, aluminum substrate. L=1.6μm, and S=-1.5μm. Compare with Figure 5.2.2 (b) to see the effect of linewidth, and with Figure 5.2.3 (b) to see the effect of trench depth.

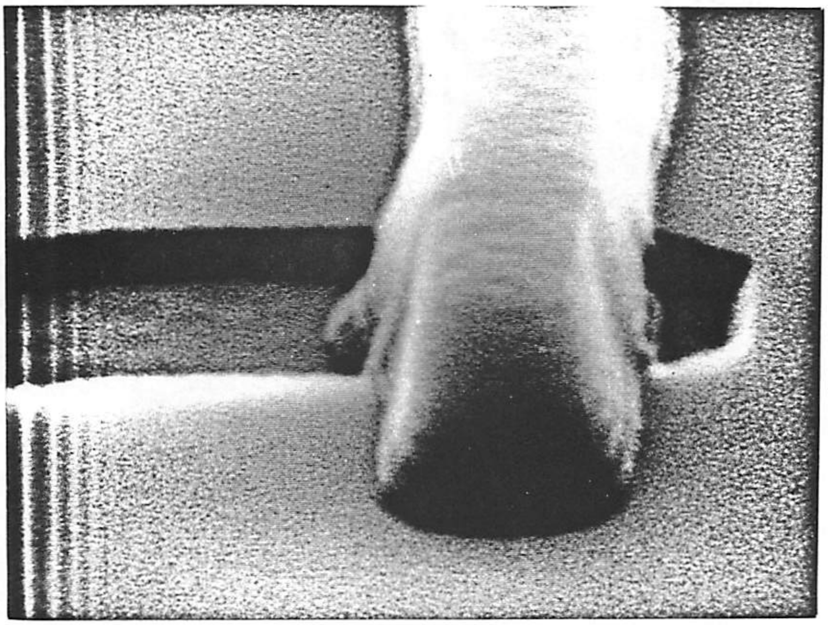


(a) L=1.6μm, W=4.0μm, S=-0.6μm

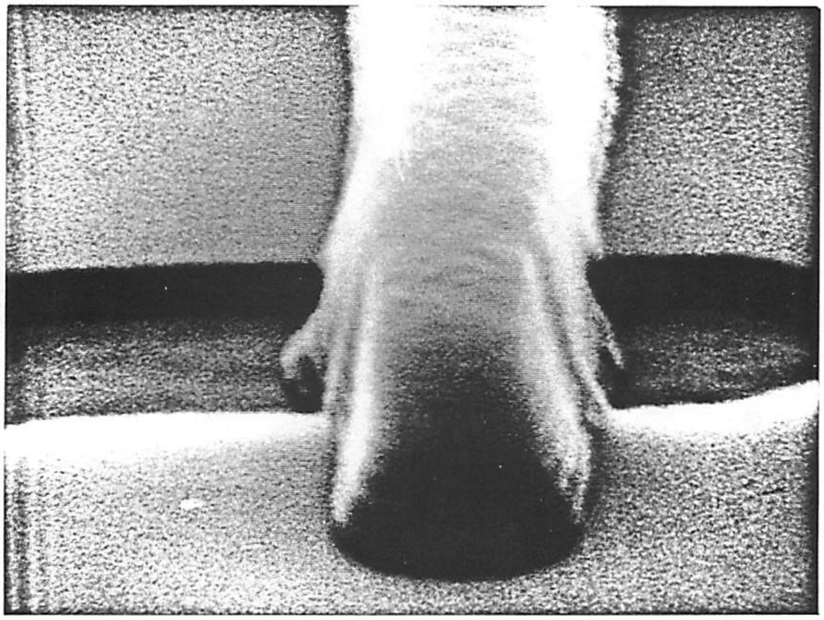


(b) L=1.6μm, W=1.4μm, S=-0.6μm

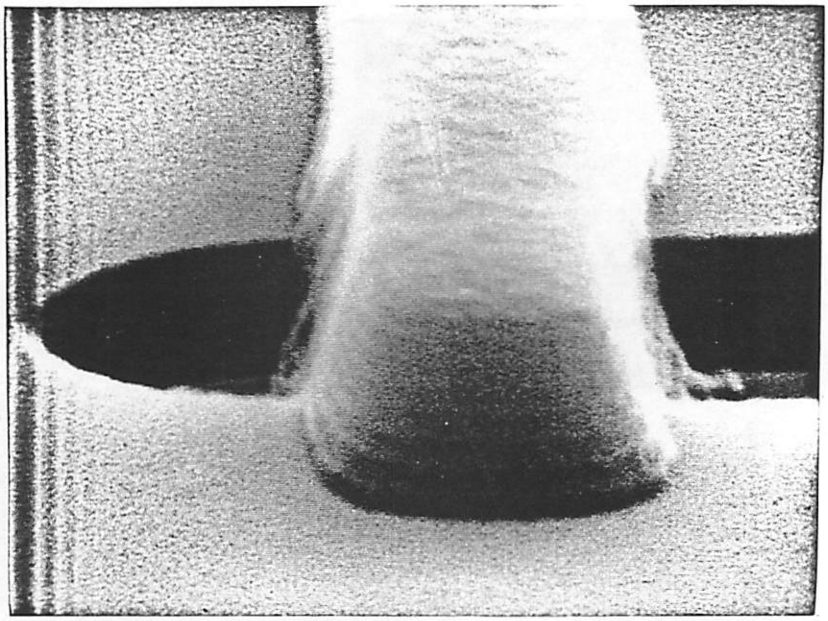
Figure 5.2.7 Lines crossing a small trench; different linewidths (a,d), different trench widths (a,b), and different displacements from the corner (c,d). Wafer 3: small angle, shallow trench, silicon substrate. L=linewidth, W=trench width, and S=separation from edge.



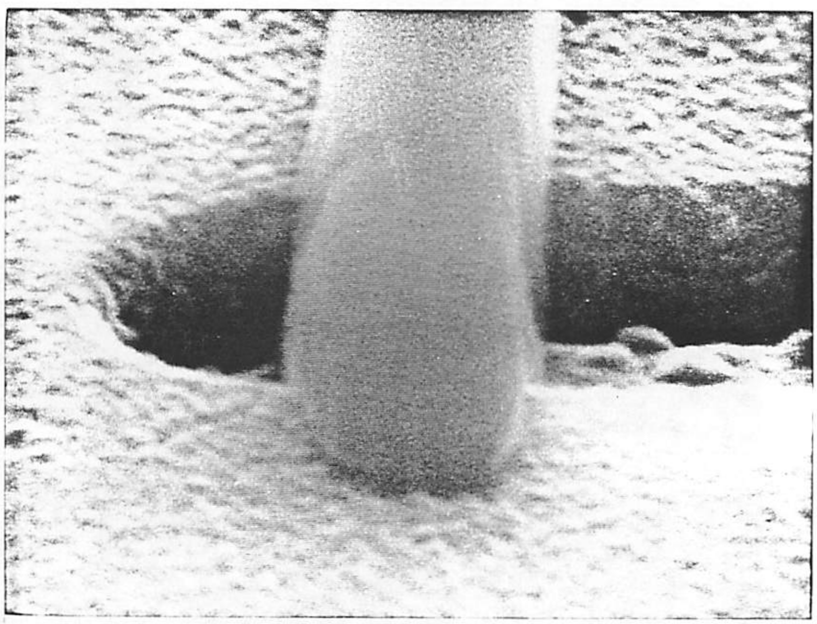
(c) L=1.2μm, W=1.4μm, S=0.0μm



(d) L=1.2μm, W=1.4μm, S=-0.6μm

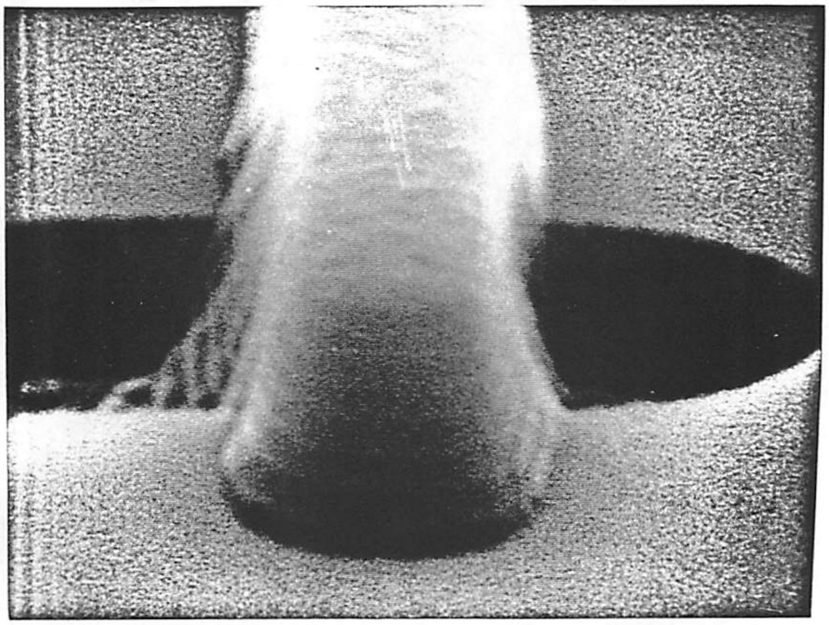


(a) L=1.6μm, silicon, wafer 5.

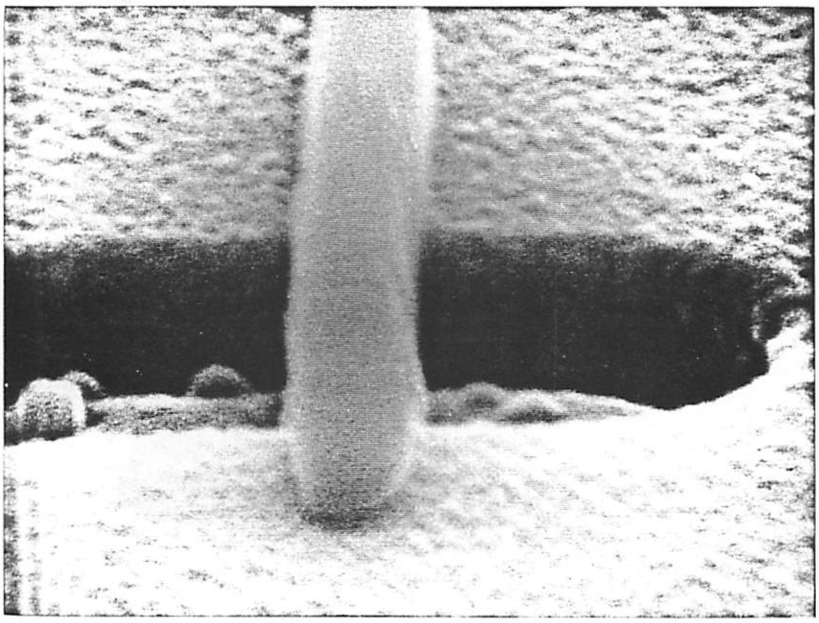


(b) L=1.6μm, aluminum, wafer 6.

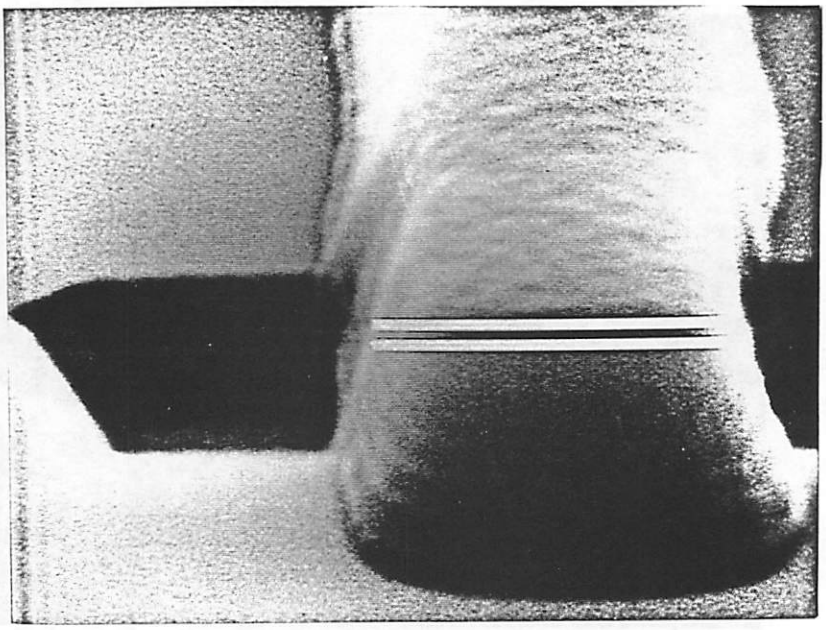
Figure 5.2.8 Substrate effect. The effect is shown for two linewidths, and the results are similar. Wafers have deep trenches and large angles.



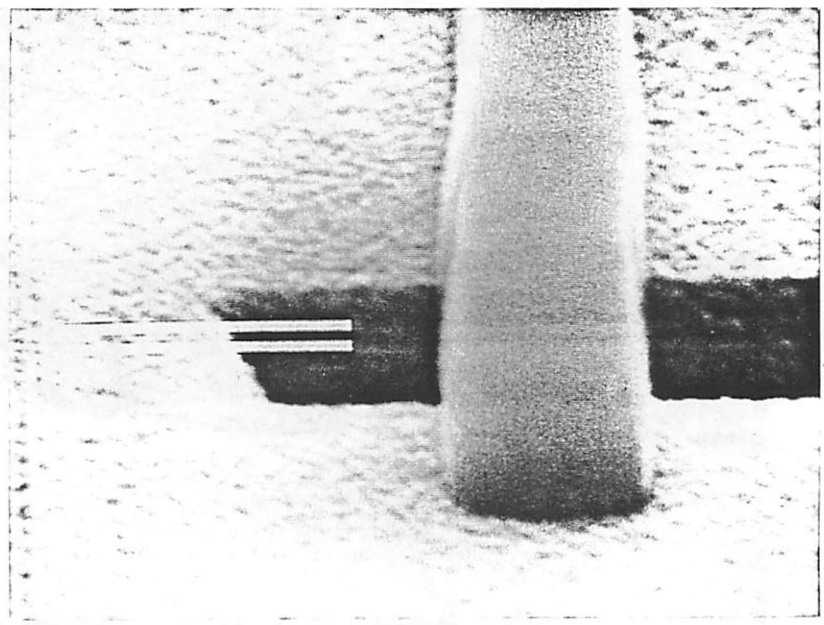
(c) L=1.2μm, silicon, wafer 5.



(d) L=1.2μm, aluminum, wafer 6.

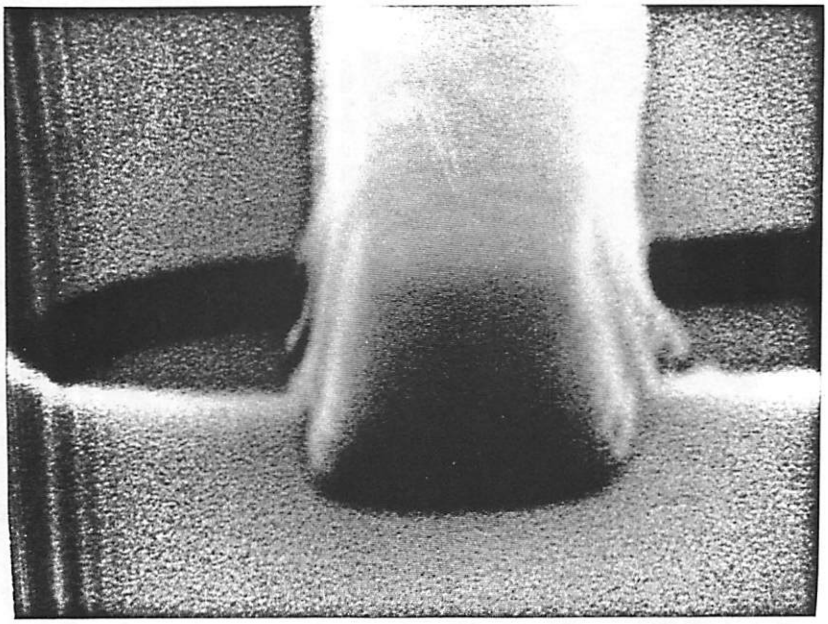


(a) L=1.6μm, silicon, wafer 7.

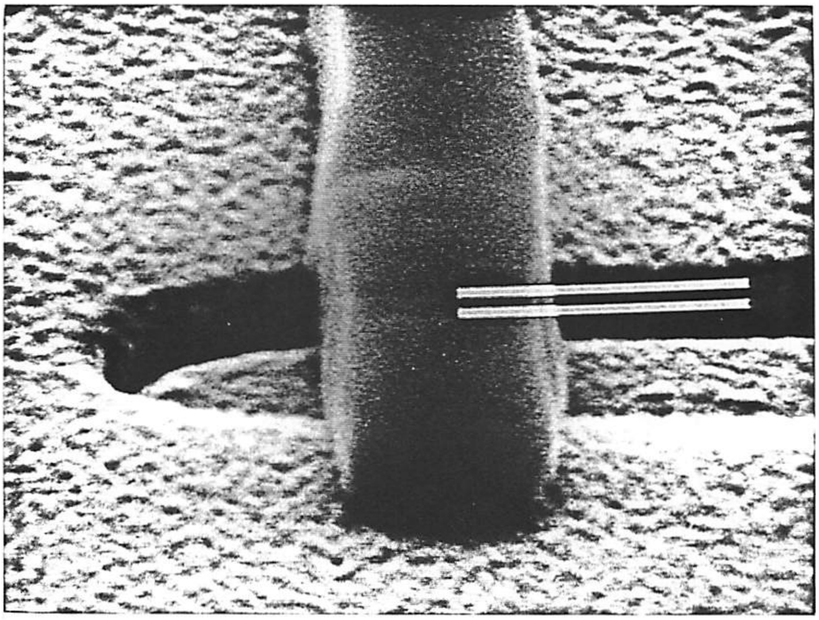


(b) L=1.6μm, aluminum, wafer 8.

Figure 5.2.9 Sidewall angle effect. Compare with Figure 5.2.8 (a,b). The small angle produces a larger effect than the large angle.



(a) Wafer 1: large angle, shallow trench, silicon substrate.



(b) Wafer 2: large angle, shallow trench, aluminum substrate.

Figure 5.2.10 Substrate effect, extremely sensitive to aluminum substrate and therefore it covers up other effects. Compare with Figure 5.2.8 (a,b) to see trench depth effect, and compare (a) with 5.2.7 (b) for differences due to sidewall angle. L=1.6μm, W=1.4μm, S=-0.6μm.

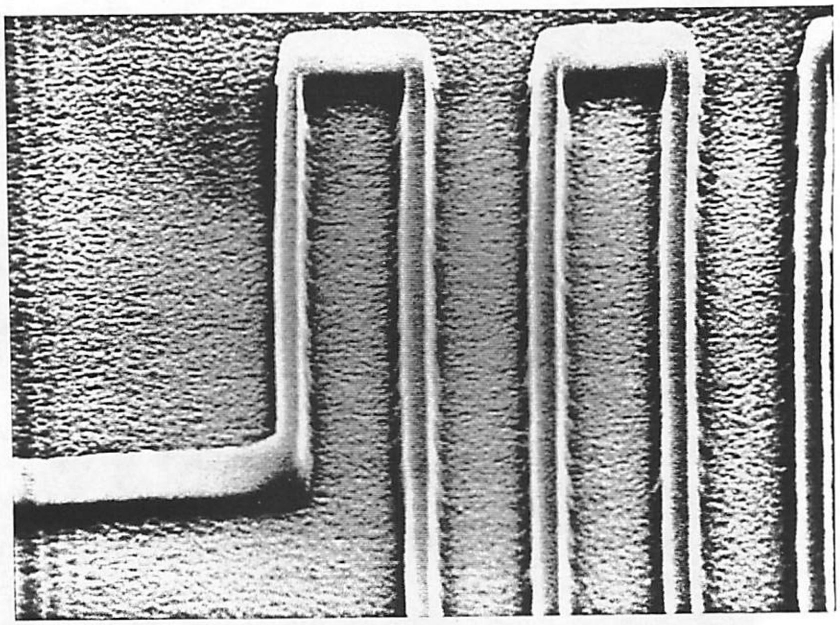
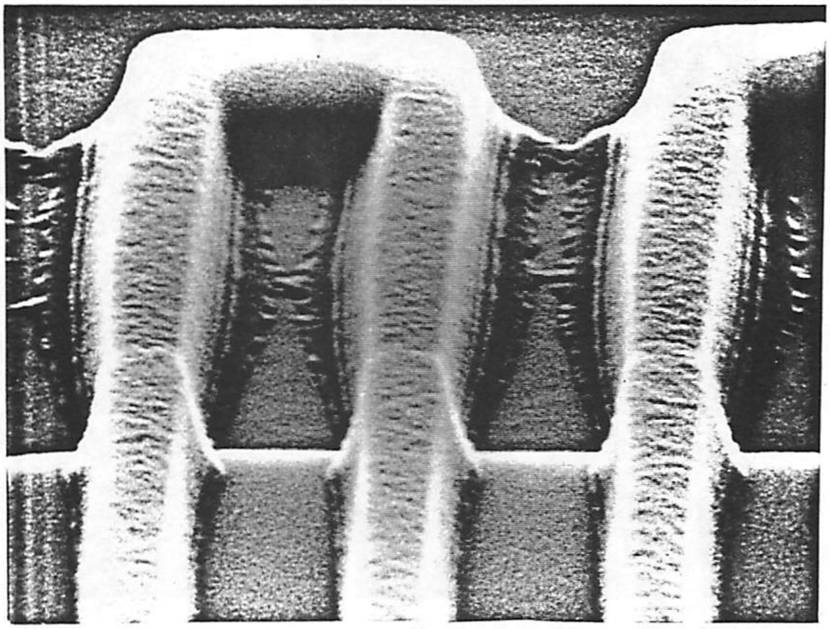
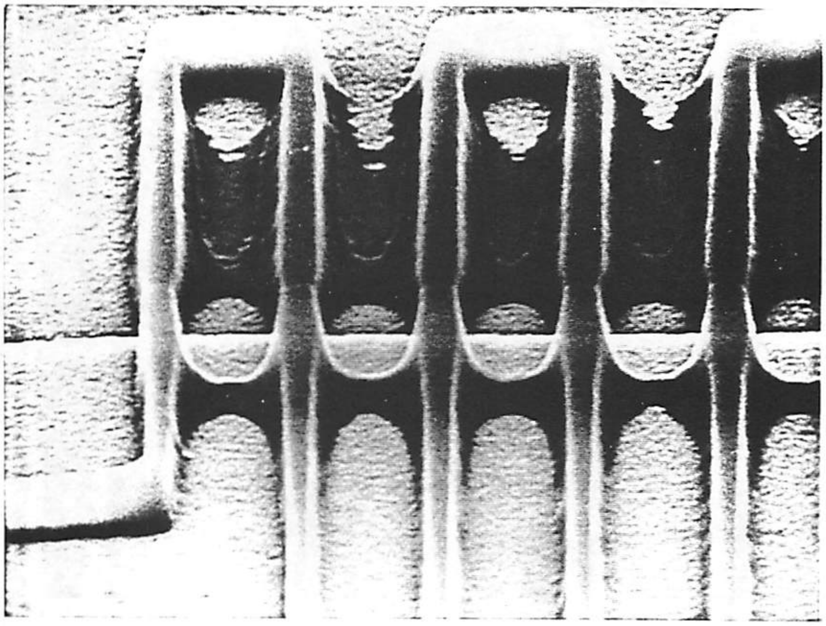


Figure 5.2.11 The effect of topography can be observed by comparing this figure with Figure 5.2.12 (b). A 0.2μm step affects the structure image drastically. Wafer 4, aluminum substrate, L=1.2μm.

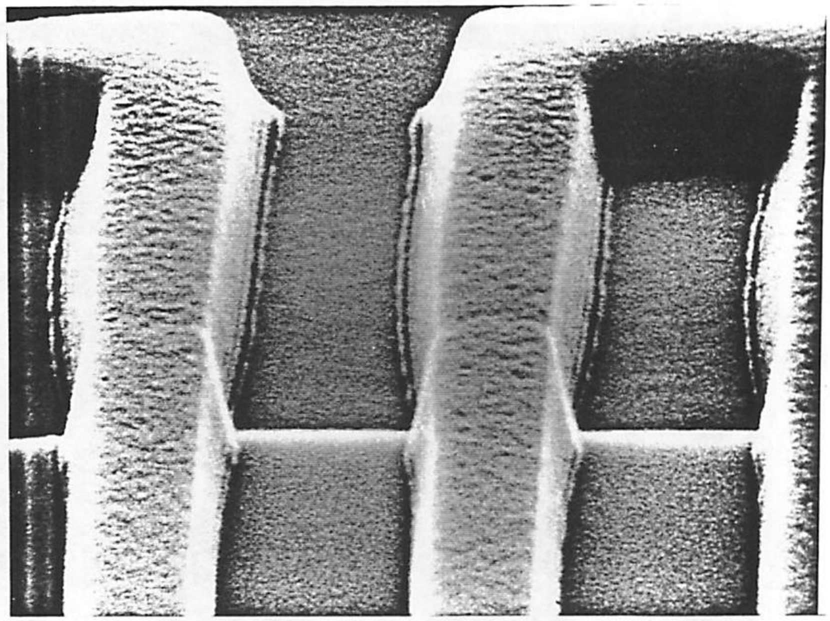


(a) Wafer 3: silicon, shallow trench, small angle; L=1.2μm.

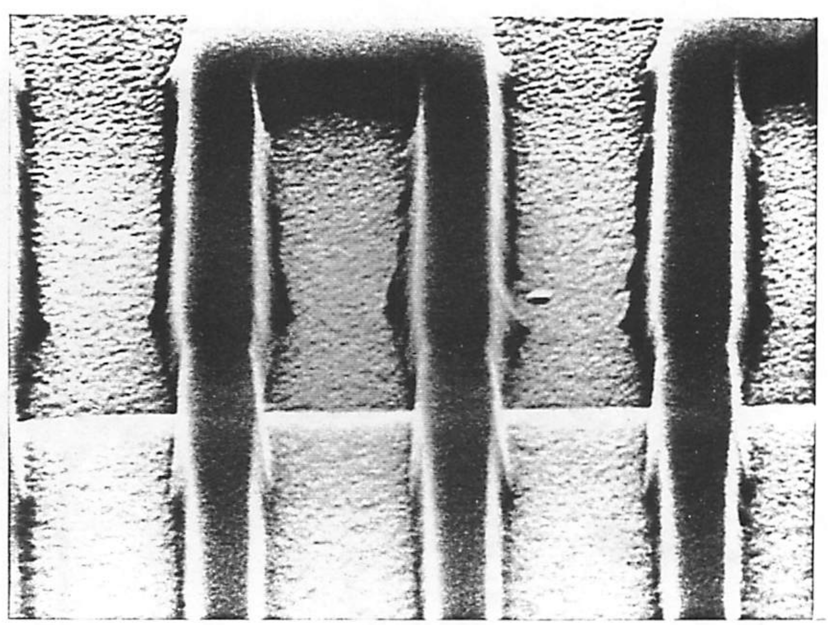


(b) Wafer 4: aluminum, shallow trench, small angle; L=1.2μm.

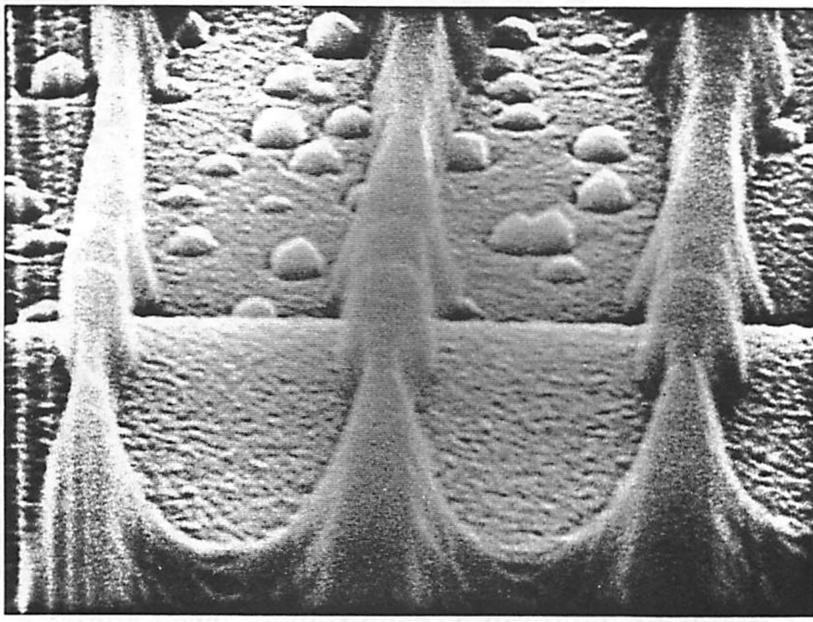
Figure 5.2.12 Substrate effect. The linewidths are smaller on the aluminum substrate due to the effective overexposure, however the 1.2μm lines were better defined on the silicon substrate due to the difference in effective resolution resulting from the standing wave effects.



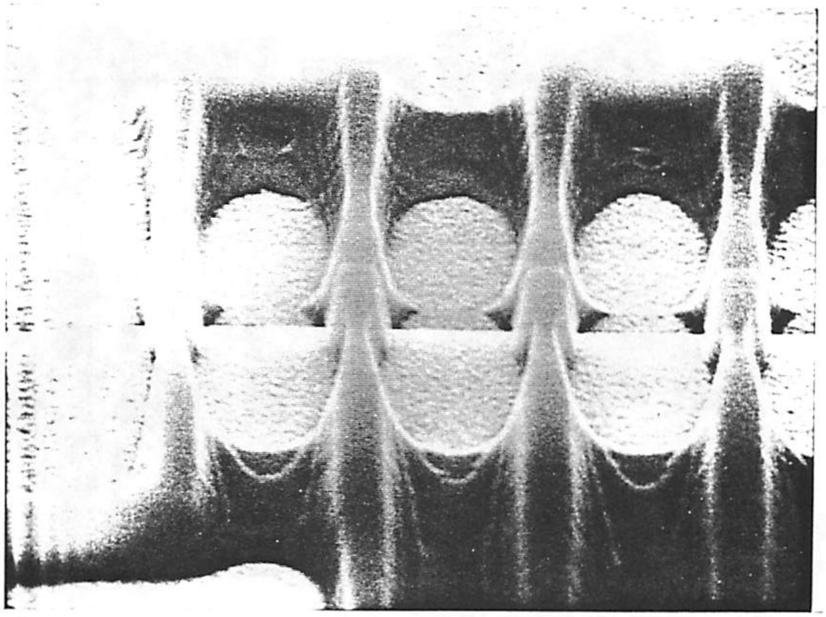
(c) Wafer 3: silicon, shallow trench, small angle; L=1.6μm.



(d) Wafer 4: aluminum, shallow trench, small angle; L=1.6μm.

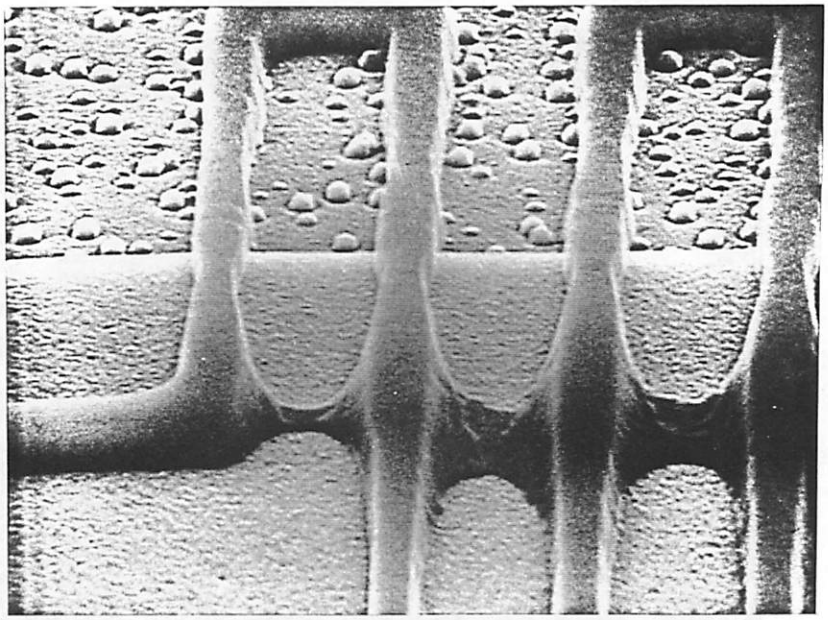


(a) Wafer 6: aluminum, deep trench, large angle; L=1.2μm.

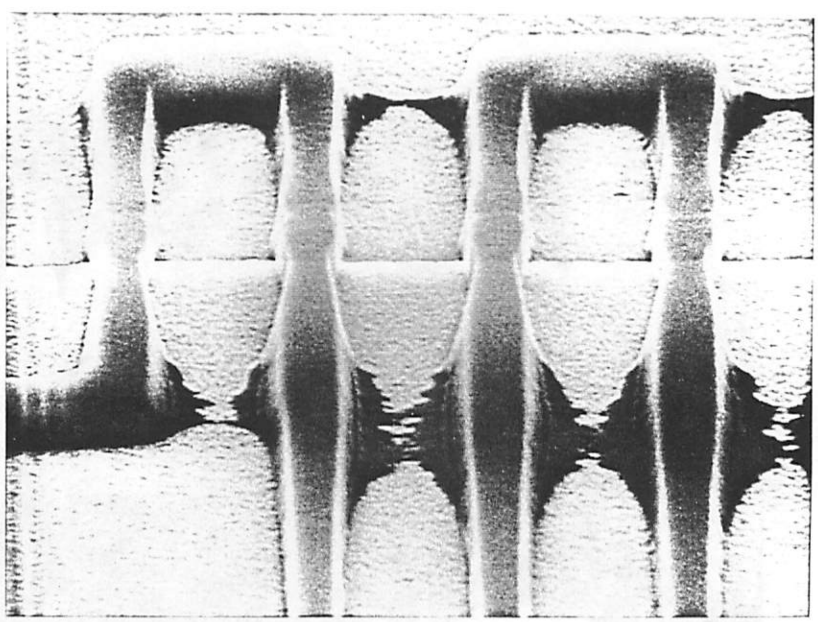


(b) Wafer 8: aluminum, deep trench, small angle; L=1.2μm.

Figure 5.2.13 Sidewall angle effect. The effect is hardly noticeable, but the effect of the linewidth is indeed noticeable. The effect of the sidewall angle can also be noticed by comparing Figures 5.3.1 and 5.3.2.



(c) Wafer 6: aluminum, deep trench, large angle; L=1.6μm.



(d) Wafer 8: aluminum, deep trench, small angle; L=1.6μm.

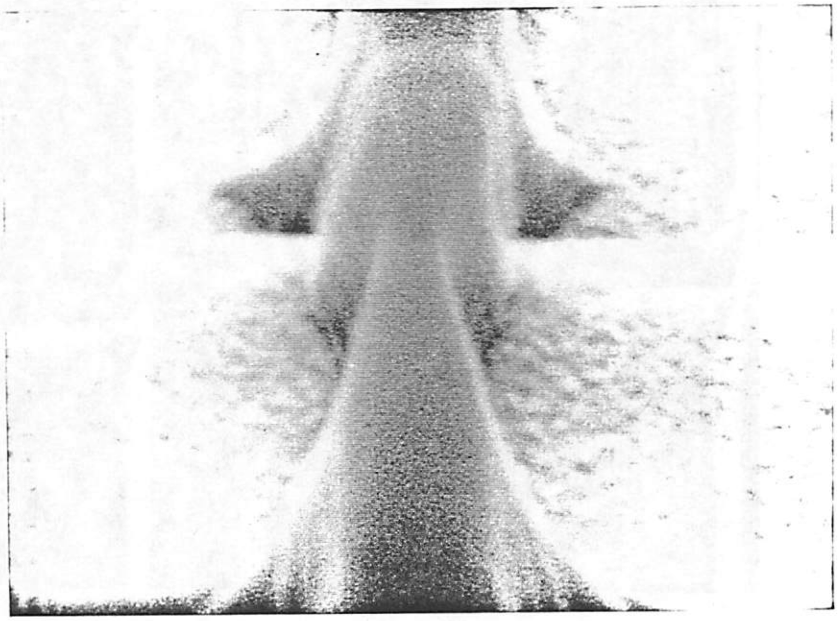


Figure 5.2.14 Interference effects at different resist thicknesses cause a variation of total energy coupled to the resist, and linewidth variation is present. Wafer 8: aluminum, deep trench, small angle; L=1.2μm.

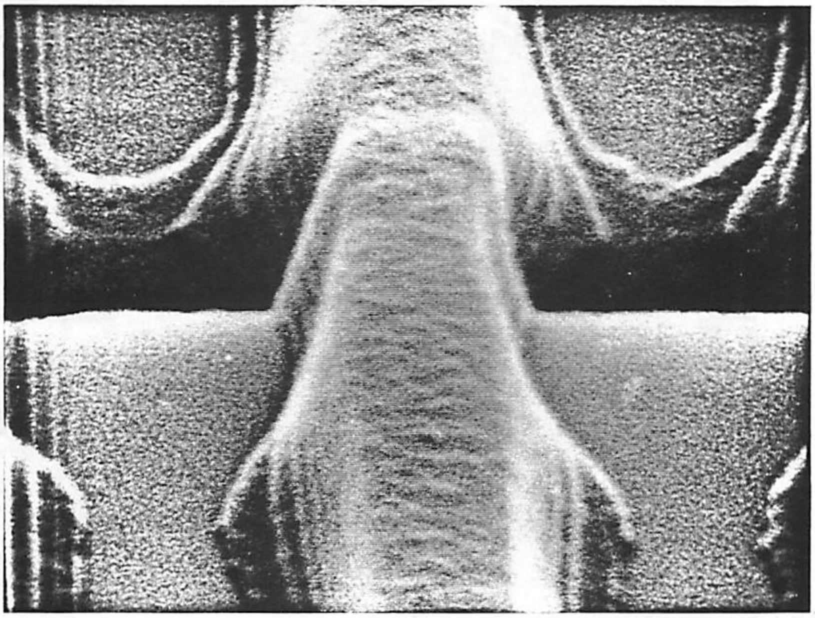
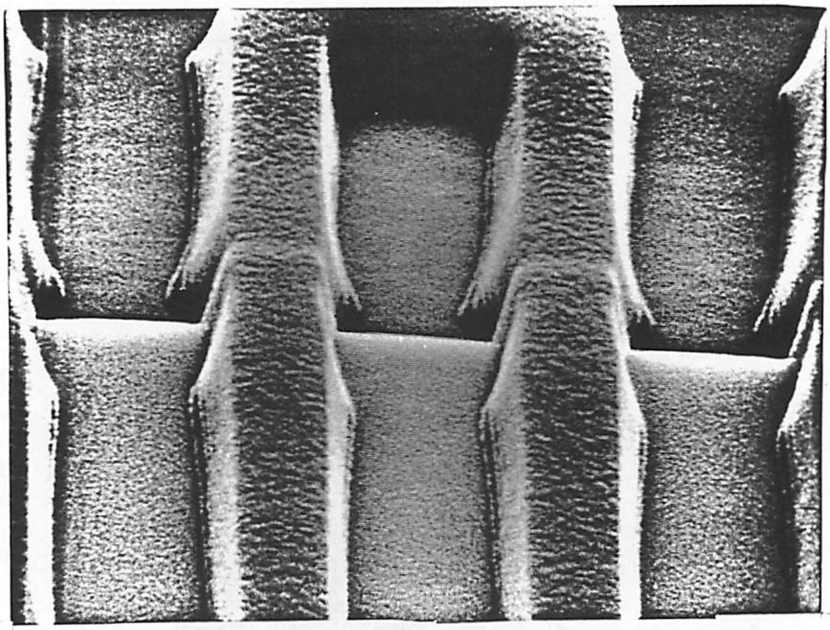
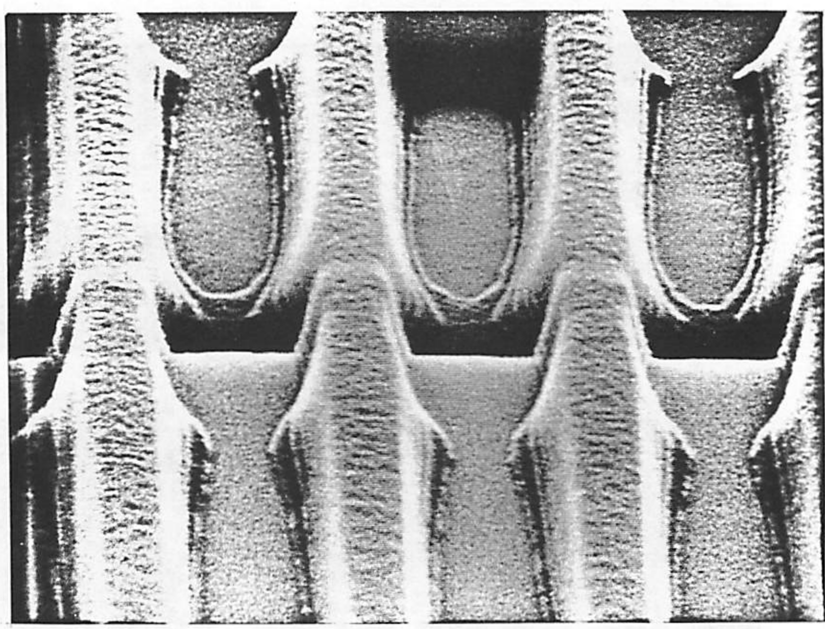


Figure 5.2.15 Effect of trench depth. Compare with Figure 5.2.12 (a); the small angle presents greater interference effects, since the line becomes thin at two points when crossing the step, and with the large angle it only thins once. Wafer 7: silicon, deep trench, small angle; L=1.2μm.

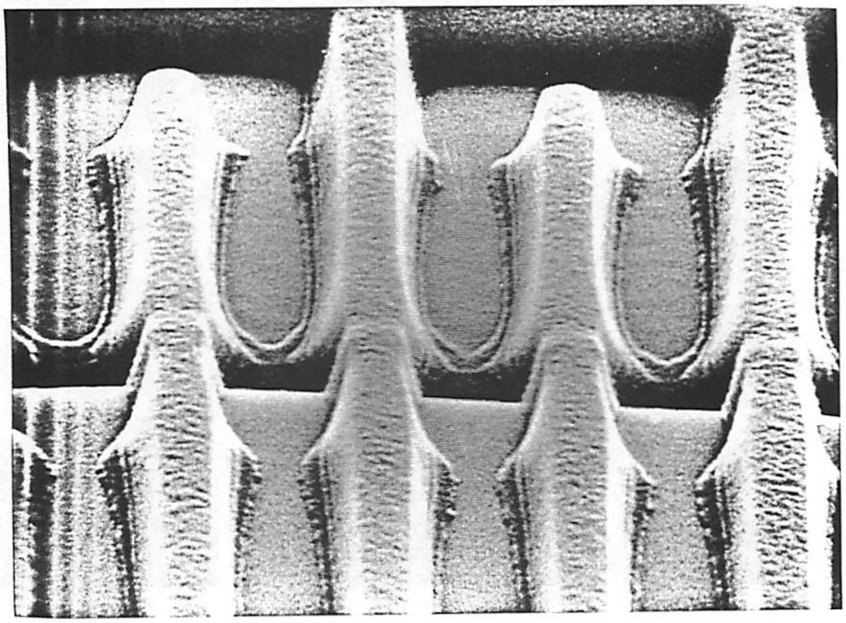


(a) Serpentine with L=1.6μm

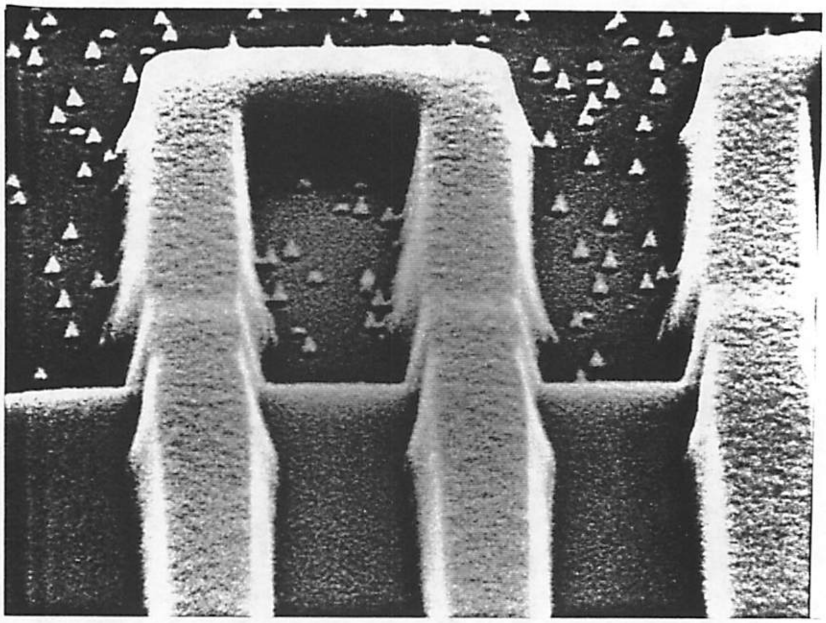


(b) Serpentine with L=1.2μm

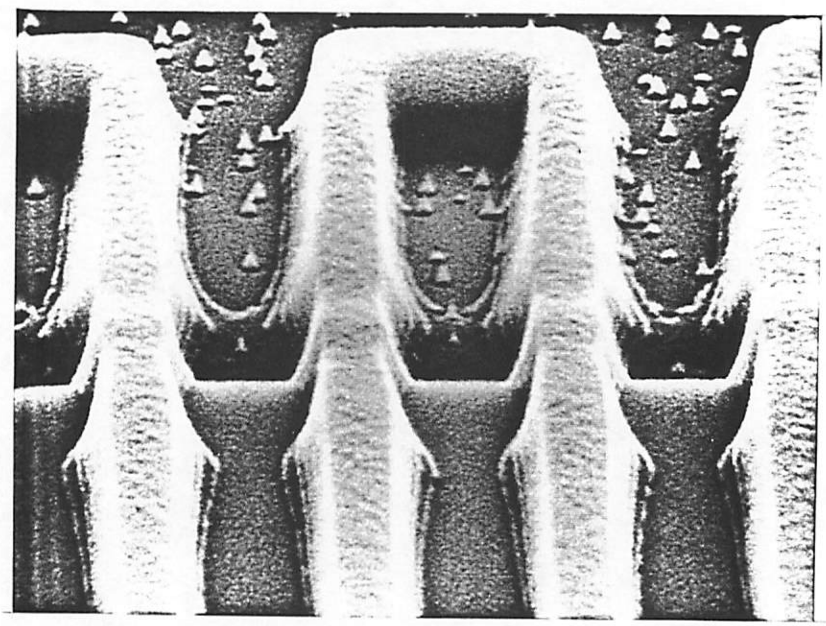
Figure 5.3.1 Wafer 7, trench depth = 0.5μm, sidewall angle ~53°, silicon substrate.



(c) Comb with L=1.2μm

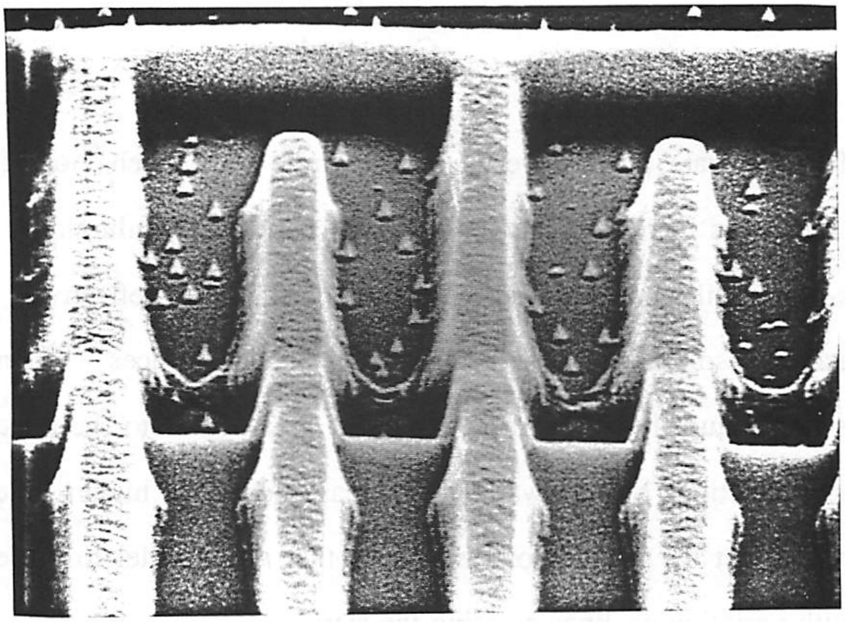


(a) Serpentine with L=1.6μm



(b) Serpentine with L=1.2μm

Figure 5.3.2 Wafer 5, trench depth = 0.5μm, sidewall angle ~80°, silicon substrate.



(c) Comb with L=1.2μm

Chapter 6
Conclusion

The substrate plays a very important role in the behavior of the photoresist. The differences in resist behavior observed between the aluminum and silicon substrates can easily be observed. Because of the high reflectivity of aluminum, a decrease in resolution is observed even on planar surfaces. When the topography effects are included, the distortion is much greater due to the enhanced reflectivity effects. Reflections off sidewalls are increased with the higher reflection substrates, and they affect the profiles of resist lines that run parallel to the edges, and affect linewidth variation on lines crossing the steps.

The sidewall angle is a very important factor when lines run parallel to the steps. The smaller angle produced larger anomalies due to scattering from the sidewall, since it re-directed the normal incident waves to an almost horizontal direction, thereby affecting the profiles of the lines running parallel to the edges. The sidewall angle did not affect lines crossing the edges in a significant manner.

The trench depth is important relative to the thickness of the resist. When lines run parallel to the step, the deeper the trench, the more noticeable the effect. This is a result of the increased amounts of light that reach the resist line from the side due to the scattering of light off the sidewall of the step. The effects of sidewall reflection are noticeable for both substrate materials, although it is much more noticeable in the case of the aluminum substrate. When lines run across steps, areas above and below the step are affected by the variations in resist thickness. The resist thickness variations cause good and poor energy coupling in the resist, and linewidth variations result. These linewidth variations are also a function of the substrate reflectivity, and are therefore more noticeable when the substrate is aluminum. In the serpentine and comb structures, shorts occurred both above and below the step, and at different distances from the step depending on the trench depth.

The distance between the lines and edges is very important, the smaller the distance, the large the effects due to scattering off the sidewalls. The smaller linewidths are the most affected in all cases, probably because the resolution limit was being challenged and therefore the effects appeared in a clearer fashion.

The higher the substrate reflectivity, the larger the effects. The sidewall angle has the most dominant effect on lines that run parallel to step edges, and the deeper the trench, the more noticeable the effect. The change in resist thickness due to the trench depth is the most dominant effect for lines crossing steps, and even shallow steps can cause large linewidth variations due to the change in energy coupling on high reflecting substrates.

Improvements:

Now that an idea has been obtained as to how topography effects affect the behavior of photoresist, some improvements to the structures can be made. Following will be the filename and the improvements suggested for the structures in that file:

Trenches: design with four pads to use a 4 point probe to increase measurement accuracy. Have a reference that is not affected by a trench.

Serpentine: Need serpentine and comb structures completely in trenches, to observe if they clear or not.

Sem1: Only need lines at the following spacings (and note that spacings should be from edge of the line, not from the center to maintain distance from the edge relatively constant): +3.0, 0.0, -0.5, -1.0, -1.5, and -3.0.

Corners: Use wider resist lines so that overexposure does not hide the effects due to sidewall scattering.

Regarding the processes used, it would be interesting if we could have cases where only the sidewall is of a highly reflective material, but not the substrate, and therefore the effect due only to the sidewall scattering may be observed.

Acknowledgements

I would like to thank Professor Andrew Neureuther for his help, advice, and encouragement. I would also like to thank Kenny Toh for helping me become familiar with numerous programs, Kim Chan for fabricating the wafers, and Tom Booth for taking the SEM photographs.

This work was supported by the National Science Foundation, Sandia National Laboratories, and Siemens AG. Their support is gratefully acknowledged.

Correction to wafer numbers

The actual numbers on the wafers are different than those reported in this report, the relationship is as follows:

# in report	# on wafer
1	14A
2	15A
3	7A
4	8A
5	5A
6	6A
7	1A
8	13A
9	9A
10	10A
11	11A
12	12A

References

[1] D. W. Widmann and H. Binder, "Linewidth Variations in Photoresist Patterns on Profiled Surfaces," *IEEE Trans. on Electron Devices*, ED-22, No. 7, pp. 467-471, July 1975.

[2] R. M. Finnila, S. C. Su, and A. I. Braunstein, "Projection Printing," *Proceedings of SPIE: Technological Advances in Micro and Submicro Photofabrication Imagery*, Vol. 55, pp. 68-74, 1975.

[3] W. Arden and L. Mader, "Linewidth Control in Optical Projection Printing: Influence of Resist Parameters," *Advances in Resist Technology and Processing II*, SPIE Vol. 539, pp. 219-226, 1985.

[4] L. F. Thompson, C. G. Willson, and M. J. Bowden, *Introduction to Microlithography*, 1983, pp. 290-293.

[5] S. Wolf and R. N. Tauber, *Silicon Processing for the VLSI Era*, Vol. 1, Process Technology, pp. 438-441.

[6] A. R. Neureuther, P. K. Jain, and W. G. Oldham, "Factors Affecting Linewidth Control Including Multiple Wavelength Exposure and Chromatic Aberration," *Proceedings of SPIE: Semiconductor Microlithography*, Vol. 275, p. 110, 1981.

[7] M. Toukhy, S. Tadros, and C. Guglielmo, "High temperature positive photoresist for use on reflective topography and sputter applications," *Advances in Resist Technology and Processing II*, SPIE Vol. 539, pp. 74-82, 1985.

[8] T. F. Hasan, S. U. Katzmann, D. S. Perloff, "Automated Electrical Measurements of Registration Errors in Step-and-Repeat Optical Lithography Systems," *IEEE Trans. Electron Devices*, ED-27, pp. 2304-2312, December 1980.

[9] C. P. Ausschnitt, "Electrical Measurements for Characterizing Lithography," Chapter 8 in VLSI Electronics: Microstructure Science, Vol. 16, Ed. N. G. Einspruch and R. K. Watts, Academic Press.

[10] K. K. Toh, Two-Dimensional Images with Effects of Lens Aberrations in Optical Lithography, University of California - Berkeley, May 20, 1988. M.S. Thesis.

[11] B. Huynh, Calibrated Exposure, Focus and Defect Test Patterns for Optical Lithography, University of California - Berkeley, May 27, 1988. M.S. Thesis.

[12] J. Gamelin, R. Guerrieri, and A. R. Neureuther, "Exploration of Scattering from Topography with Massively Parallel Computers," Submitted to *J. Vac. Sci. Technol. B.*, Nov/Dec 1989.

[13] J. Fleishman, Electrical Probing of Test Structures for Optical Lithography, University of California - Berkeley, September 7, 1988. M.S. Thesis.