S. Middelhoek

Projection Masking, Thin Photoresist Layers and Interference Effects*

Abstract: Projection masking is used for producing microwave semiconductor devices with micrometer or submicrometer structures. In contrast to contact masking, the mask is projected onto the silicon wafer by means of a high quality microscope objective. Since the chromatic errors of such a lens cannot be fully corrected, monochromatic light has to be employed. This, however, causes standing light waves to occur in the SiO_2 and photoresist layers, leading to unexpected effects. This report describes some of these effects and the experimental conditions under which satisfactory masking results can be obtained.

Introduction

The standard method of generating patterns on semiconductor wafers is called *contact masking.* A mask containing the transistor patterns is positioned on top of the photoresist-covered wafer and exposed to light. Because of diffraction of the light at the pattern edges and the gap between mask and wafer, this technique permits the manufacture of structures as small as 2 to 5 μm (1 μm = 0.04 mil) on a production scale. Some time ago Schuetze and Hennings[1-3] showed that another method, which we shall call *projection masking,* can be used for production of smaller structures. Projection masking is the method by which an image of the photomask is projected directly onto the photoresist-covered wafer by means of a high-resolution lens. Two main applications can be distinguished:

1) By using a high quality camera lens, an entire 1-inch wafer can be exposed, giving patterns as small as 2.5 μm.
2) By using a high quality light microscope lens, patterns as small as 0.5 μm can be produced on an area of approximately 0.5 × 0.5 mm.

In order to obtain maximum resolution (in contrast to contact masking) monochromatic light has to be used for all the experiments. This, however, introduces new problems because of interference effects in the thin SiO_2 and photoresist layers. The light intensity not only varies across the wafer in accordance with the projected structure but also in a direction normal to the wafer plane. An optimum form for the three-dimensional intensity profile in the resist layer must be obtained for maximum results. The theory of these interference effects and some experimental results, utilizing the projection masking technique,[3] are the subjects of this paper.

Theory

Thin films of SiO_2 or photoresist observed in white light show distinct colors because certain wavelengths are attenuated more than others due to interference effects between the light reflected from the upper and rear sides of the layers. Methods for measuring the thickness of such layers are based on the color[4] or intensity[5] of the reflected light. With respect to our experiments we are more interested in the light intensity inside the resist layer than in the reflected intensity. Figure 1 shows the experimental situation schematically. A silicon wafer is covered by a SiO_2 layer, obtained by oxidizing the wafer in wet oxygen, and by a resist layer. For reasons of simplicity we assume the refractive index of SiO_2 and that of the resist to be equal. No light is then reflected at the SiO_2-resist interface. The violet mercury line with λ = 4353 Å is used for the experiments and for this wavelength the index of refraction of SiO_2 and of Si is 1.467 (Ref. 5) and 4.85 (Ref. 6), respectively. The photoresist layer is exposed by the light intensity resulting from interference of J_2 (the fraction of light not reflected at the air-resist interface) and J_3 (light reflected at the SiO_2-Si interface). When we assume that

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This work was done at the IBM Zurich Research Laboratory, 8803 Rüschlikon-ZH, Switzerland.

The author is now at Electrical Engineering Department, Delft University of Technology, Delft, Netherlands.

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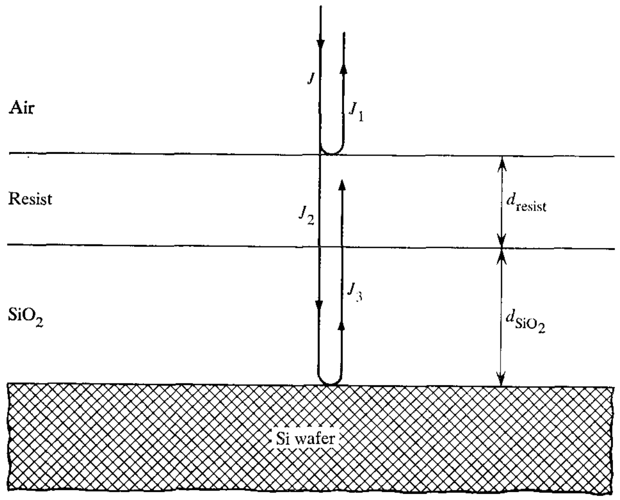
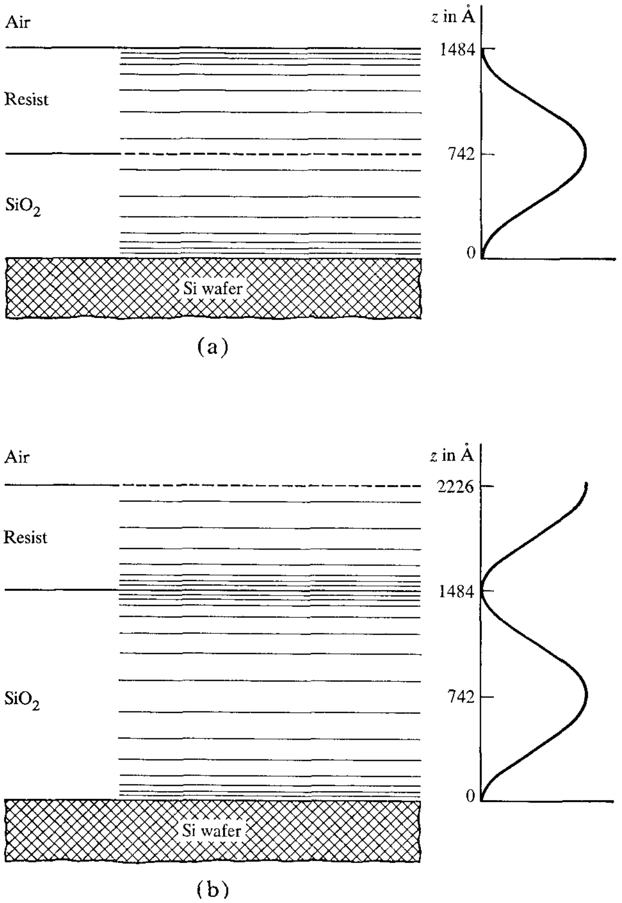


Figure 1 Sketch of light distribution SiO_2 and resist layers.

Figure 2 Schematic representation of light distribution in a 742 Å resist film on top of a) a 742 Å SiO_2 layer and b) a 1484 SiO_2 layer.



(a)

(b)

no light absorption occurs, and neglect the light due to reflection of J_3 at the resist-air interface, the relation between the amplitudes is:

$$\frac{A_3}{A_2} = \left(\frac{n_{Si} - n_{SiO_2}}{n_{Si} + n_{SiO_2}}\right) = \left(\frac{4.85 - 1.467}{4.85 + 1.467}\right) = 0.536.$$

The relation between the light amplitudes at the maximum and at the nodes is:

$$\frac{A_2 + A_3}{A_2 - A_3} = 3.3,$$

and the intensity at the maximum is thus about ten times larger than at a node.

We also wish to know the positions of the maxima and the nodes.

Taking the z-axis normal to the wafer and realizing that a phase jump of π occurs at the SiO_2-Si interface at $z = 0$, we obtain for the position of the nodes:

$$(2N + 1)\pi = \pi + \frac{2 \cdot 2\pi z_{min} n_{SiO_2}}{\lambda_{air}} \qquad N = 0, 1, 2, 3, \cdots$$

or

$$z_{min} = \frac{2N \cdot \lambda_{air}}{4n_{SiO_2}}.$$

For the maxima we find

$$z_{max} = \frac{(2N + 1)\lambda_{air}}{4n_{SiO_2}}.$$

When we take $\lambda = 4353$ Å and $n_{resist} = n_{SiO_2} = 1.467$ we find nodes at $z = 0$, 1484, 2967, 4451, 5935 Å, etc. and the maxima at $z = 742$, 2225, 3709, 5193 Å, etc. The fact that the light intensities in the nodes and the maxima differ so much cannot be without influence on the masking process.

We wish to illustrate this for two extreme cases and for both negative and positive resists.

In the first case a resist layer with a thickness of 742 Å lies on top of a SiO_2 layer also 742 Å thick (Fig. 2a). The light intensity is indicated in arbitrary units at the right side of the Figure and by the number of lines in the picture, such that the smaller the light intensity the larger the line density. From Fig. 2a we find that the light intensity is large at the resist-SiO_2 interface and small at the resist-air interface. In the second case a 742 Å resist layer lies on top of a 1484 Å SiO_2 layer. Figure 2b shows the light intensity is now small at the resist-SiO_2 interface and large at the resist-air interface. The underlying SiO_2 layer determines the light intensity distribution in the photoresist layer. How this affects the masking process will be discussed for negative and positive resist with the help of Figs. 3 and 4, respectively. For the projection of micrometer structures, high quality lenses are used. If the desired structure dimensions and the resolving power of the lenses are of the

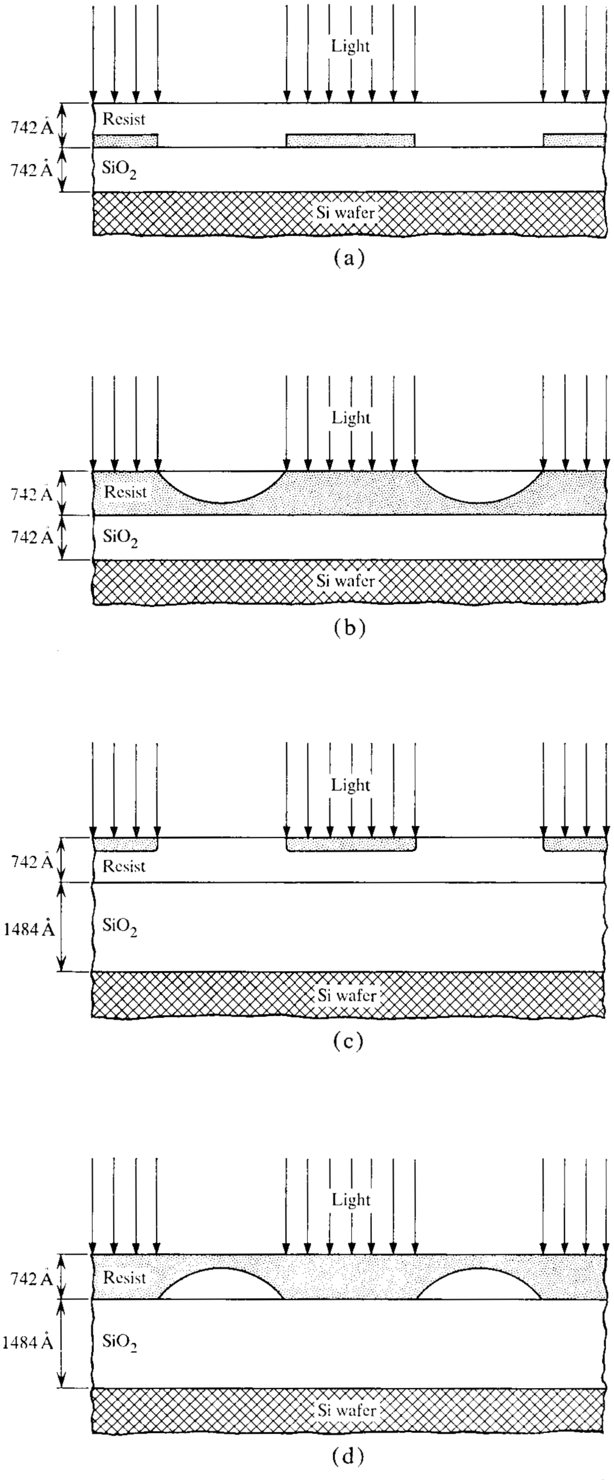


Figure 3 KTFR patterns for different exposure times and SiO$_2$ layer thicknesses (d_{resist} = 742 Å):

a) short exposure time d_{SiO_2} = 742 Å
b) long exposure time d_{SiO_2} = 742 Å
c) short exposure time d_{SiO_2} = 1484 Å
d) long exposure time d_{SiO_2} = 1484 Å

In the shaded areas the KTFR is polymerized and unsoluble in the developer.

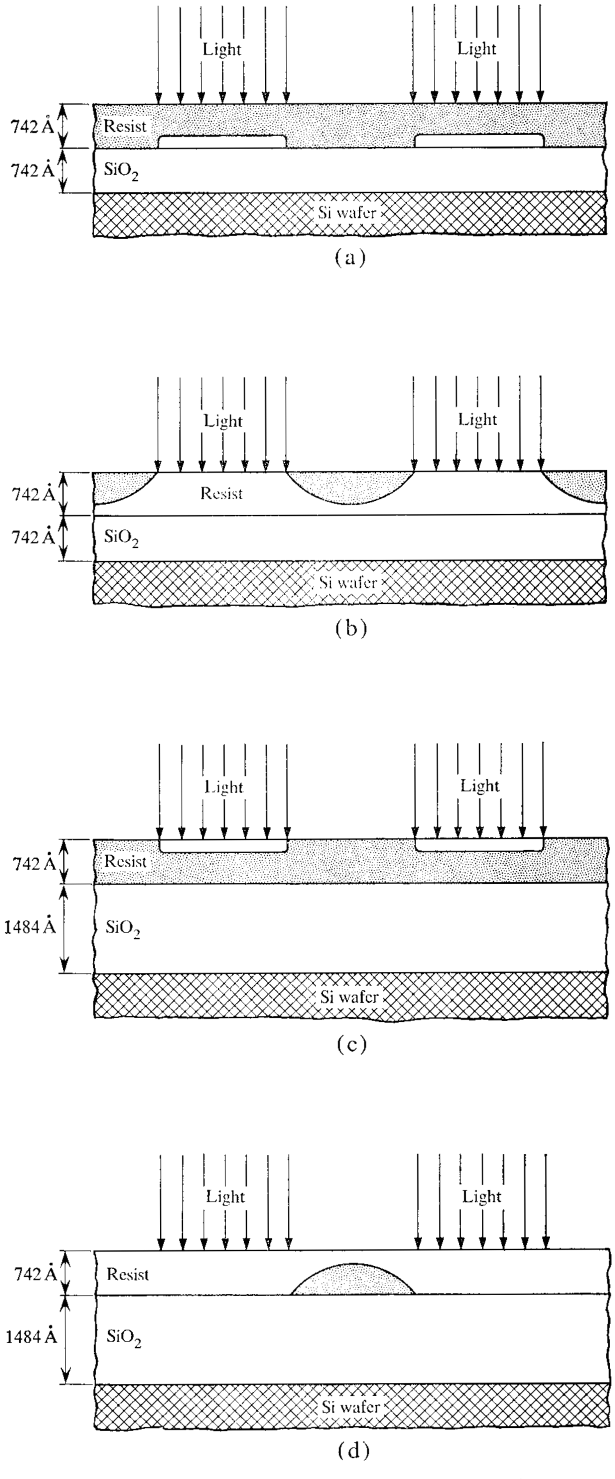


Figure 4 AZ 1350 patterns for different exposure times and SiO$_2$ layer thicknesses (d_{resist} = 742 Å):

a) short exposure time d_{SiO_2} = 742 Å
b) long exposure time d_{SiO_2} = 742 Å
c) short exposure time d_{SiO_2} = 1484 Å
d) long exposure time d_{SiO_2} = 1484 Å

In the shaded areas the AZ 1350 is not dissociated and remains unsoluble in the developer.

same order of magnitude, a structure of sharp dark and light lines will not be transmitted as such.

The actual projected image will have less distinct minima and maxima, with soft transitions between them. Furthermore, light scattering occurs in the optical system and in the resist layer. These effects cause broadening of the exposed areas in the case of over-exposure. The smaller the structures, the more relatively severe this broadening. As the light intensity in the resist layer due to interference effects is inhomogeneous, over-exposure and line broadening will vary along a direction normal to the wafer.

In the case of a negative resist and $d_{\mathrm{SiO_2}} = d_{\mathrm{resist}} =$ 742 Å, a small light intensity will polymerize the resist layer close to the $\mathrm{SiO_2}$-resist interface (Fig. 3a). After development the shaded part of the layer remains and a correct resist image results. However, in practice, this image is not usable because this resist layer is much too thin to withstand etching solutions. When a longer exposure time or larger light intensity is used, so that the resist layer at the resist-air interface is also polymerized, the bottom resist layer is very much overexposed and severe broadening of the line occurs (Fig. 3b), neither can the resulting image be used for masking purposes.

When the thickness of the $\mathrm{SiO_2}$ layer is chosen to be 1484 Å, a short exposure time polymerizes only the upper surface (Fig. 3c). After development the whole resist layer is removed. Neither will a longer exposure time lead to a useful resist image (Fig. 3d). Here the nonpolymerized area is enclosed by polymerized (shaded) material and cannot be removed.

The tentative conclusion is that, with negative photoresists, because of the interference effects in thin resist layers, no useful micrometer or submicrometer resist images can be obtained when monochromatic light is used.

When positive resist is used, the situation is less critical. For $d_{\mathrm{SiO_2}} = d_{\mathrm{resist}} = 742$ Å a short exposure dissociates the resist only near the $\mathrm{SiO_2}$-resist interface (Fig. 4a). These areas are enclosed by nondissociated areas and therefore no useful masking structure is obtained. A longer exposure time leads to dissociation of the resist at the resist-air interface, but owing to overexposure at the resist-$\mathrm{SiO_2}$ interface, upon development the whole resist layer is removed (Fig. 4b).

When the $\mathrm{SiO_2}$ layer thickness is 1484 Å, a short exposure only dissociates the upper surface. A longer exposure also dissociates the bottom layer. As Fig. 4d illustrates, a pattern occurs with a reasonable thickness, though the edges are rounded off.

The tentative conclusion here is that with positive photoresist, only with sufficient exposure and with $\mathrm{SiO_2}$ thicknesses of about 1484 Å can usable resist images be obtained.

The above conclusions are correct when we assume that the light intensity along a direction normal to the wafer results only from interference between the incident and reflected light. However, when light scattering along an axis normal to the wafer occurs, the light intensity in the resist layer may be averaged out to a greater extent. Therefore we shall also examine the extreme case where the light intensity in the resist layer is the exact average of the light distribution in the resist due to interference.

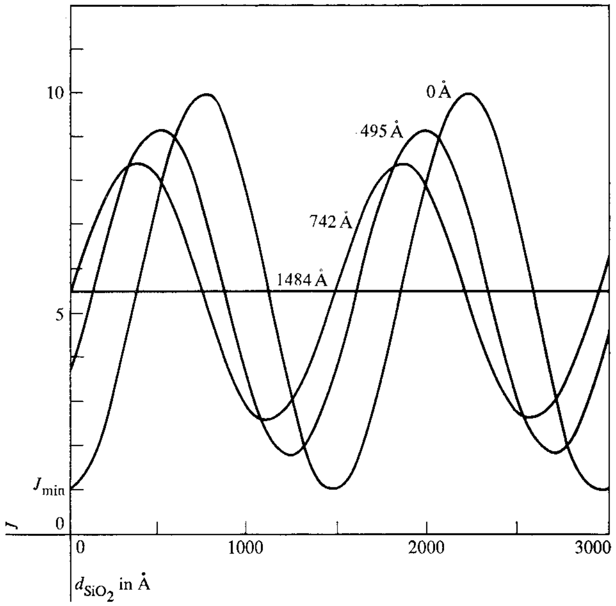


Figure 5 Average light intensity as a function of the thickness of the underlying $\mathrm{SiO_2}$ layer for different resist thicknesses.

As we have seen, the maximum light intensity is ten times the minimum intensity. Therefore, for the light intensity along the z-axis normal to the wafer, we can write

$$J = J_{\mathrm{min}} + (J_{\mathrm{max}} - J_{\mathrm{min}}) \sin^2 \frac{2n_{\mathrm{SiO_2}}\pi}{\lambda} z .$$

As $J_{\mathrm{max}} = 10\ J_{\mathrm{min}}$, $n_{\mathrm{SiO_2}} = 1.467$ and $\lambda = 4353$ Å, we obtain when z is expressed in Å,

$$J = J_{\mathrm{min}} \left[1 + 9 \sin^2 \frac{z}{1484} \pi \right] .$$

The average intensity is

$$J_{\mathrm{av}} = \frac{1}{d_{\mathrm{resist}}} \int_{z=d_{\mathrm{SiO_2}}}^{d=d_{\mathrm{SiO_2}}+d_{\mathrm{resist}}} \cdot J_{\mathrm{min}} \left[1 + 9 \sin^2 \frac{z}{1484} \pi \right] dz .$$

In Fig. 5, J_{av} is plotted as a function of $d_{\mathrm{SiO_2}}$ for different d_{resist}. In Fig. 6 the exposure time, being the reciprocal of J_{av}, is plotted as a function of $d_{\mathrm{SiO_2}}$ for different d_{resist}. For thin resist layers the exposure time depends very

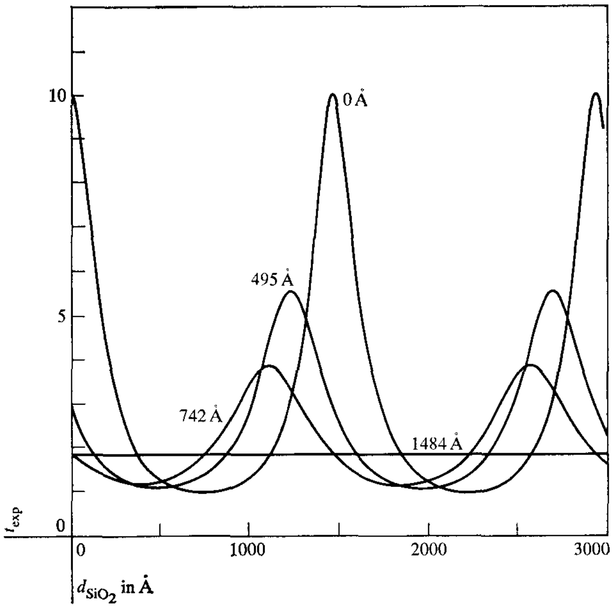


Figure 6 Exposure time in arbitrary units as a function of the thickness of the underlying SiO_2 layer for different resist thicknesses.

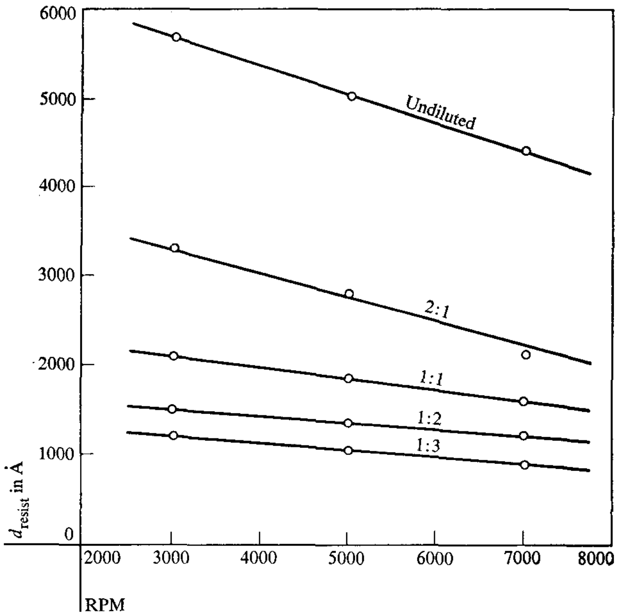


Figure 7 Thickness of AZ 1350 photoresist as a function of spinner speed for different dilutions. 1:3 means 1 part resist and 3 parts resist thinner.

strongly on the thickness of the SiO_2 layer, whereas for $d_{\text{resist}} = \lambda/2n_{\text{SiO}_2} = 1484$ Å there is no dependence.

When we assume that to obtain a proper resist mask, the light intensity at the SiO_2-resist interface, rather than the average light intensity, determines the exposure time, the exposure time should depend on d_{SiO_2} as indicated by the curve $d_{\text{resist}} = 0$ of Fig. 6. In the following section we shall discuss the technology of thin photoresist layers and some exposure time experiments.

Experiments

The reason for studying the theory and experimental behavior of thin photoresist layers was the desire to make Schottky-barrier FET's with very high cutoff frequencies, which have been reported in the literature.[7,8] In order to obtain cutoff frequencies above 10 GHz, the gate width has to be as small as 1 micrometer.

Two photoresists were examined as to their suitability, namely KTFR of Kodak, which is a negative resist, and Azoplate 1350 of Shipley Co., which is a positive resist and is referred to here as AZ 1350.

Preliminary experiments indicated that the use of KTFR involves three problems when very small structures are required. In the first place, the behavior of the negative resist was roughly in agreement with results in Fig. 3. For those SiO_2 thicknesses where a reasonable resist pattern was obtained, the resist proved to be very thin. In the second place, the use of KTFR was hampered by the so-called *oxygen effect*. When KTFR is exposed to light in the presence of the oxygen of the ambient air, the resist at the air-resist interface is photo-oxidized, and crosslinking does not occur. The photo-oxidized resist remains soluble in the developer. The depth at which this photo-oxidation occurs is of the same order as the resist thicknesses which have to be used. Photo-oxidation can be partially reduced, but not fully suppressed, by directing a flow of nitrogen towards the wafer during exposure. The third problem, which makes KTFR less suitable for micrometer structures, is the lack of acuity of the edges compared to that of AZ 1350.

Though usable patterns with KTFR could sometimes be obtained, the positive resist AZ 1350 was much easier to use and gave superior results. Therefore this resist was further used for all micrometer and submicrometer work.

Since very thin resist layers have to be employed, information such as developer dilution, developing time, etc., recommended by the manufacturer cannot be utilized. Thus, in this experimental section, we at first describe our techniques of processing very thin positive resist films.

For the preparation of these resist layers a spinner is used with a very high maximum speed (7000 rpm) and an extremely fast acceleration. In Fig. 7 the resist thickness is plotted as a function of the speed for different resist dilutions. High speed and large dilutions are needed to obtain the thin resist thicknesses required. The curves of Fig. 7 were obtained for SiO_2-covered wafers cleaned with acetone.

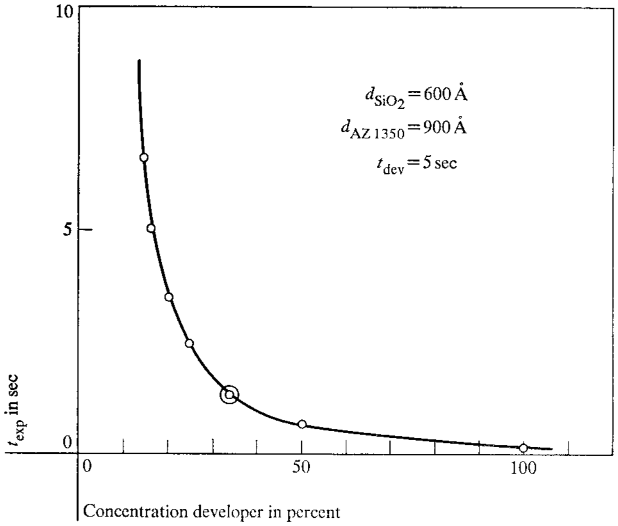


Figure 8 Experimental optimal exposure time as a function of the concentration of the developer (developer is diluted with deionized water). The large circle indicates the preferred concentration.

The next two parameters are developing time and developer dilution. First, with the help of an actual transistor structure (Fig. 12) we determined how the optimal exposure time was measured. The transistor consists mainly of a 1-μm-wide gate contact separated by two 1-μm-wide SiO_2 strips from the large source and drain areas. To fabricate this structure, the first step is to produce a resist pattern having a 1-μm-wide elongated hole separated by 1-μm-wide resist strips from the large source and drain holes. The optimal exposure time was now defined as that time which, on visual inspection, gave the 1-μm-wide gate hole and the 1-μm-wide resist strips.

A longer than optimal exposure time increased the gate hole width and decreased the width of the resist strips, while a shorter time had the opposite effect. This method of width control proved to be quite useful in practice. The resist structures were obtained by projection masking. An instrument very similar to that described by Schuetze and Hennings[3] was employed. The microscope lens used was a standard Zeiss Epiplan 25× with an aperture of 0.45.

Figure 8 shows how the optimal exposure time of a 900 Å resist film on a 600 Å SiO_2 layer depends on the developer dilution; the developing time was 5 sec for all measuring points. The AZ developer was diluted with deionized water. For large dilutions the dependence is very strong. This is disadvantageous because then the AZ developer concentration must be most accurately controlled. However, neither is a large concentration advisable, because then the nonexposed areas of the resist are also attacked during development.

Therefore, for most work a developer concentration of 33.3% (1 part developer, 2 parts H_2O) was preferred. Developing time was also an important parameter. Figure 9 shows the optimal exposure time as a function of the developing time for different photoresist thicknesses on a 750 Å SiO_2 layer. Here the dependence is also very strong, especially for short developing times.

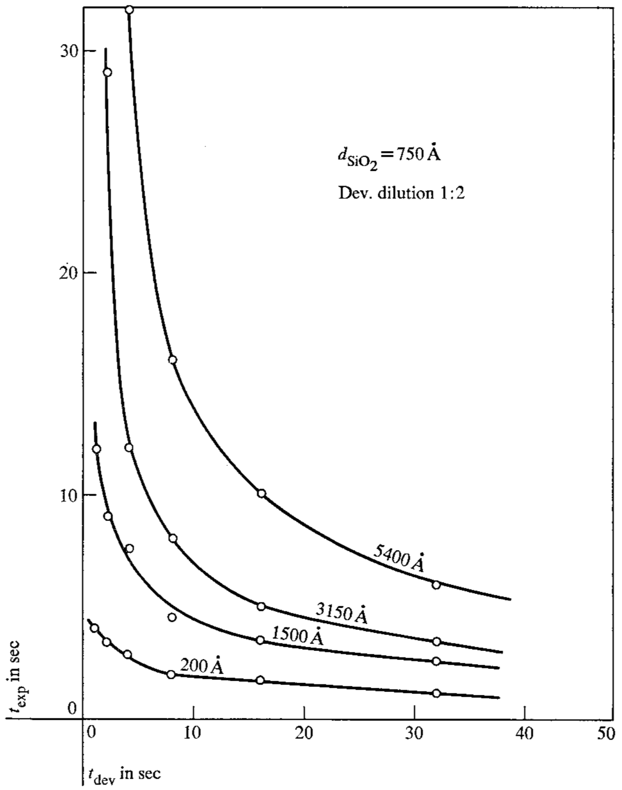
Further one observes that the exposure time increases for increasing photoresist thicknesses at constant developing time, which is not unexpected.

Development was performed by holding the wafer with tweezers and immersing it in the developer. The development time is therefore not well defined and it is advisable to use developing times which are not too short. However, neither did long developing times lead to nice resist patterns, because the nonexposed areas of the resist started to dissolve. For a 900 Å resist layer, maximum permissible developing time is about 32 sec. For most of the transistor work, a developing time of 5 sec was used.

It was also observed that the patterns obtained with the thick resist layers, e.g., 3150 Å and 5400 Å, did not have very sharp edges and were not suitable for producing 1 μm patterns. A ratio of film thickness to structure width of at least 1:5 seemed to be desirable.

Having established the optimum conditions under which thin resist layers have to be processed, we can start to examine how the interference effects influence the pattern generation process.

Figure 9 Experimental optimal exposure time as a function of the developing time, for different photoresist thicknesses.



As already mentioned we have to restrict ourselves to positive resist. At first it would be of interest to study the shape of the resist pattern edges. However, this is not possible because the resolution of the light microscope is too small to observe the detailed geometry of these edges.

The only other possibility to check the theory is to measure the optimal exposure time for different resist thicknesses as a function of the SiO_2 thickness. Figure 10 shows such a curve. The optimal exposure time depends very strongly on the thickness of the underlying SiO_2 layer. In order to obtain comparable results a wafer was prepared on which the SiO_2 thickness changed in steps. Because only a restricted number of steps can be located on one wafer, two wafers had to be used to cover the SiO_2 thickness range from 0 Å to 4000 Å. Though the photoresist layers were not of exactly the same thickness, the results obtained on the two wafers matched rather well around the thickness 2000 Å.

The difference in exposure time between the maxima and minima is most apparent, and we want to compare the experimental results with the results of Fig. 6, the ratio between maxima and minima compared with the theoretical curve for 0 Å resist thickness. These results would indicate that the light intensity at the resist-SiO_2 interface is decisive. However, comparing the SiO_2 thicknesses at which the exposure time extremes occur, better agreement is obtained with the theoretical curve for $d_{resist} = 495$ Å. It is difficult with these experimental results to conclude what kind of model is appropriate. It seems that the optimal exposure time is neither only determined by the average of the light intensity in the resist, nor only by the light intensity at the SiO_2-resist interface. It is more probable that the exposure time depends in a complex way on both parameters. This is fortified by the experimental curve obtained when a resist layer with a thickness of 1500 Å is used. When the average intensity is most important, the exposure time should not depend on the SiO_2 thickness. As Fig. 11 shows, this is not the case, although the dependence is much less than in the case of a 600 Å resist layer. When the intensity at the SiO_2-resist interface is decisive, the exposure time dependence should be congruent to that for the 600 Å resist layer. This is not observed either, therefore, here also, a mixed behavior is apparent.

Finally, from Fig. 4 it was concluded that suitable resist patterns can be obtained only for SiO_2 thicknesses around 1484, 2987, 4451 Å, etc. In practice this is not as critical, though the exposure time varies very much with SiO_2 thickness. With a 600 Å resist film for all SiO_2 thicknesses a usable resist pattern is obtained. This can occur only when some averaging of the light intensity in the resist layers occurs.

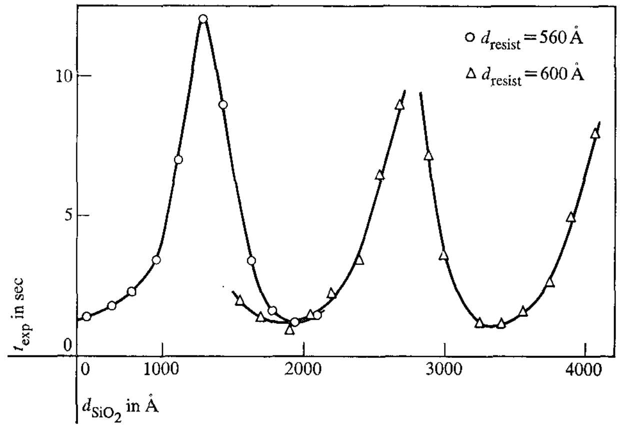
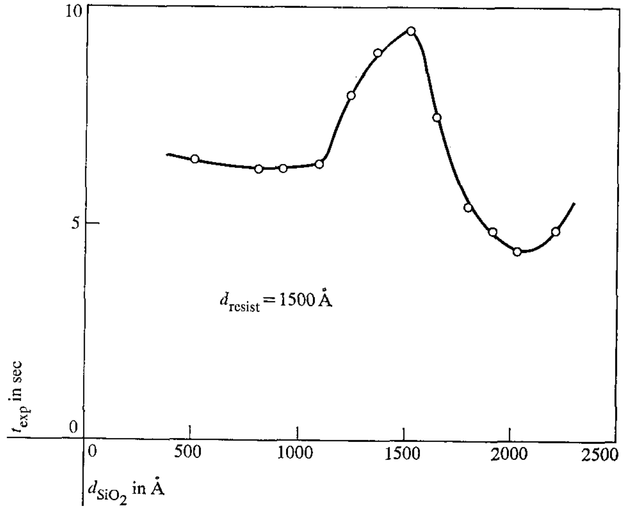


Figure 10 Experimental optimal exposure time as a function of the thickness of the SiO_2 layer for a 560 Å and a 600 Å resist layer.

Figure 11 Experimental optimal exposure time as a function of the thickness of the SiO_2 layer for a 1500 Å resist layer.



Because of the rather substantial dependence of the structure on the exposure time, usually a set of slightly differing exposure times was tried at the edge of the wafer. Figure 12 shows a Schottky-barrier field-effect transistor obtained with this technique which has a cutoff frequency of 12 GHz. The gate width is only 1 μm. Current goes from the two source contacts passing the four segments of the gate contact to the central drain.

Conclusions

For the production of micrometer and submicrometer patterns on semiconductor wafers by projection masking, photo-resist layers with thicknesses below 2000 Å have to be used.

Because of photo-oxidation, interference effects and less satisfactory resolution capabilities, negative KTFR is less suitable than positive resist AZ 1350. To successfully

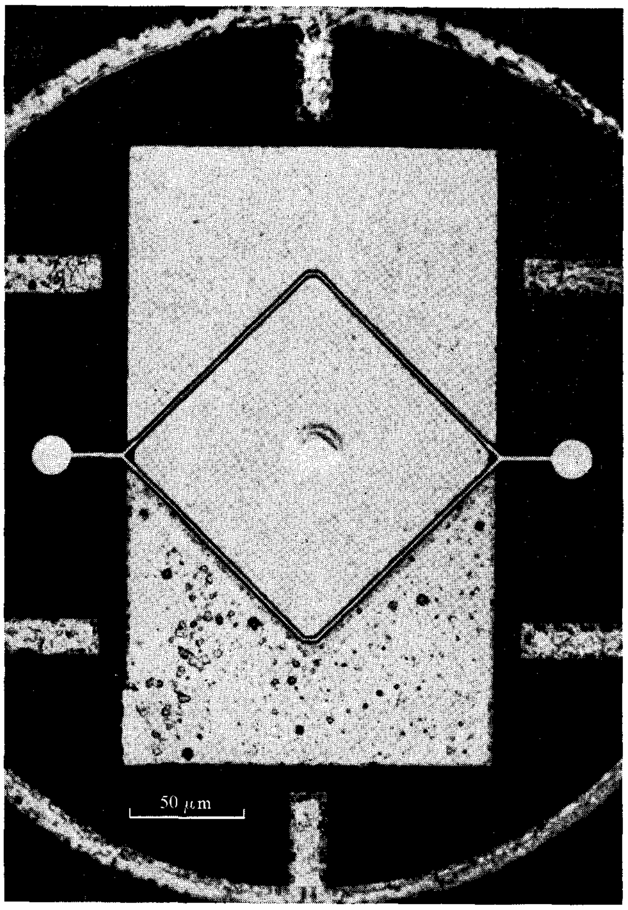


Figure 12 Schottky-barrier FET with 1μm wide gate structure.

use AZ 1350, appropriate developing time and developing dilution must be chosen. The exposure time of very thin (600 Å) resist layers depends strongly on the underlying SiO_2 thicknesses. For thicker (1500 Å) films this dependence is much less; whereas with KTFR only seldom can well defined structures be obtained, with AZ 1350 for almost all SiO_2 layer thicknesses, when the exposure time is properly chosen, the resist patterns are usable. The experimental results indicate that the optimal exposure time probably depends on the average light intensity in the resist, as well as on the intensity at the resist-SiO_2 interface.

Acknowledgments

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