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PHOTORESIST CHARACTERIZATION METHOD FOR HYBRID MICROCIRCUITS

L. E. Schantz

Untrimmed hybrid microcircuit networks require dimensional control to maintain critical electrical parameters within the required tolerances. Dimensional integrity can be maintained by parameter manipulation and control. Five processing parameters affect the dimensional stability of the pattern: the prebake time-temperature product, exposure energy, developing time and concentration, resist thickness uniformity, and etchant undercutting. By adjusting the relative dominance of those parameters and by optimizing the value of each, the total dimensional deviation can be made relatively insensitive to normal process variations. Thus, process characterization and control methods which will maintain one-percent dimensional control on lines as narrow as 5.0 mils (127 μm) can be established.

INTRODUCTION

When photolithographic techniques are used to define thin-film electronic networks, the dimensional accuracy of the pattern is often an important measure of process quality. Quality is influenced also by other factors such as pinholes or electrical shorts; however, dimensional accuracy is generally the predominate consideration. The most critical dimensional requirements are in the line widths necessary to maintain

specific tolerances in passive elements, particularly thin film resistors.¹ Conductor tolerances are less critical and are determined principally by circuit density, available space on the substrate, and required current carrying capacity.

A photoresist characterization method has been developed to determine the effects of the photoresist and the associated photolithographic processing upon the dimensional stability of thin-film hybrid microcircuits. This method also provides a basis for selecting a photoresist and processing methods for compatibility with specific dimensional requirements.

Dimensional accuracy begins with the photomask and continues through the photolithographic processing and thin-film etching procedures. Based on the mask being accurate to better than one percent, the photolithographic processes must be controlled to maintain thin film patterns with less than a one-percent deviation from the mask. There are thirteen processing parameters in photolithography, each of which is subject to normal process variations; however, only five parameters directly influence the dimensional integrity of the circuit. The dimensional accuracy of the completed circuit is therefore dependent upon the overall control of five processing steps.

Although other requirements may influence the choice of the photoresist and the processing procedures, the proposed method is essentially limited to the effects of the photoresist and associated processing methods on dimensional control of the circuit pattern. In the absence of other requirements, the photoresist and the associated processing can be selected to permit the greatest parameter variations that are possible without violating the dimensional tolerance requirements.

This method has been proven for positive photoresist with tantalum nitride, chromium, and gold thin films on 99.5-percent unglazed ceramic substrates.

PARAMETER CONTROL APPROACH

The resistance value of a thin film resistive element is governed by

$$R = R_s \ell / W, \quad (1)$$

where

R is the resistance value in ohms,

R_s is the sheet resistivity in ohms per square,

ℓ is the length in convenient units of measure, and

W is the resistor width in the same units of measure.

The above equation affirms that, assuming a constant sheet resistivity, a specific resistance value can be obtained by adjusting the length/width ratio. Since the length is usually much greater than the width and is largely fixed by the resistor termination points, the width becomes the principal determining factor.¹ Generally, resistor widths are less than 20 mils (508 μm), and are typically 5.0-mils (127 μm) wide. Resistor values with tolerances of one percent require a corresponding one-percent control of resistor line width. A typical 5.0-mil (127 μm) line therefore requires a tolerance of ± 0.05 mil (1.27 μm).

The five distinct photolithographic processing parameters that affect the dimensional quality of thin film patterns are listed below in the order of decreasing effect:

- Total exposure light energy;
- Prebake time-temperature product;
- Photoresist development time and solution concentration;
- Etchant undercutting; and
- Photoresist thickness uniformity.

The general approach to dimensional control is to choose the set of all parameter values (called a processing schedule) that will retain one-percent line-width control. The actual schedule boundaries are those parameter values which maintain the required dimensional control; however, machine or photoresist limitations may set some schedule boundaries. After the required dimensional tolerances are

defined, the process parameters are manipulated and controlled to ensure that the schedule boundaries are not exceeded under worst-case machine and operator variations. When two or more process steps are interdependent, the schedule is defined by the limits of each process parameter.

Figure 1 represents a typical processing schedule. By adjusting the shape of the schedule without changing the criteria by which the limits were established (mainly those of one-percent dimensional control), the standard deviation associated with each process can be fitted into the schedule. An understanding of equipment limitations and possible operator variations is essential in establishing a priority structure upon which to base parameter control.

The priority structure should primarily control the photoresist image, with secondary attention given to selective etching. Although some degree of undercutting is inherent in all etching processes, it can be minimized and controlled. With the best available processing equipment, the most easily controlled processing parameters are as follows:

- Prebake time-temperature product;
- Exposure light energy;
- Photoresist development time and solution concentration;
- Photoresist thickness uniformity; and
- Etchant undercutting.

PHOTORESIST PREBAKE

The prebake is used to dry the photoresist and to ensure adequate resist adhesion to the thin-film surface. The prebake can also be used to change the photoresist light sensitivity.^{2, 3, 4} As shown in Figure 2, increasing the prebake temperature decreases the sensitivity to variations in exposure at an exponential rate. Therefore, the prebake time and temperature (usually expressed as the time-temperature product) can be selected to ensure adequate photoresist drying and adhesion and to reduce the effects of light-source and timer irregularities.

When establishing the prebake/exposure relationship and when checking the prebake consistency, the actual substrate temperature must be considered. The dependence of line width deviation as a function of prebake temperature is shown in Figure 3. Oven temperature fluctuation, nonuniform heat distribution in the oven, operator error, and inconsistent methods of holding the substrates can cause substrate temperatures to vary more than 10°C. The prebake time-temperature product consistency at the substrate is most important.

Substrate temperatures can be measured by means of thin-film thermocouples on the substrates or by using infrared (IR) pyrometers. These methods provide an accurate substrate temperature profile, and can be used to check the substrate temperature gradients.

High substrate temperature gradients can destroy photoresist continuity. Rapid evaporation of the resist solvents cause disruptions

in the film surface, and the protection thus provided for the underlaying thin film is inadequate. There are no exact limits on the maximum allowable temperature gradient. Different types of ovens and substrate holding methods will accommodate widely varying temperature gradients. Each different process requires separate evaluation.

The effect of prebake time on photoresist sensitivity is considerably less than that of prebake temperature; however, when temperature limits are imposed on the prebake function, the prebake time can be used to control the photoresist light sensitivity. A line width deviation can be detected after prebake temperatures as low as 25°C if the substrate is exposed to that temperature for 24 hours or more.

Although the prebake/exposure relationship is established by using substrate temperatures, production control can still be maintained by using oven temperature and time. Preset oven time and temperature can be used as effective process control parameters when heat distribution in the oven is uniform and when the temperature is the same on all substrates.

The oven should be selected for ability to obtain uniform temperatures, to regulate the substrate temperature gradients, and to regulate the total time in the heating chamber. The oven that provides the most consistent prebake time-temperature product is a conveyorized, infrared system which has forced air (Class 100) blown across the

resist surface. The IR source must provide a $\pm 2^{\circ}\text{C}$ temperature uniformity across the entire work area, and the conveyor speed must be consistent within ± 50 mils (1.27 mm) per second.

PHOTORESIST EXPOSURE

Photoresist exposure alters the resist solubility as a function of the total light energy density ($\text{joules}/\text{cm}^2$) available to the resist. Light energy is the product of the light intensity (watts/cm^2) and the exposure duration (seconds).⁴ Both intensity and time are subject to variations that can cause any one of three exposure conditions:

- Underexposed--a condition of insufficient light energy that incompletely exposes the resist and prevents etching;
- Overexposed--a condition of too much light energy that causes an extreme reduction in the photoresist image dimensional quality; or
- Properly exposed--a condition in which the total light energy causes less than the maximum allowable deviation from the nominal line width.

Prebake and Exposure Relationship

The proper exposure energy is found by generating a family of curves such as that shown in Figure 4. These curves establish the prebake/exposure relationship and provide the basis for selecting the parameter value limits of the exposure schedule. The prebake time-temperature product is stepped in small increments from the point of acceptable resist adhesion to the point where the resist is nearly

insensitive to the exposure light. At each prebake time-temperature setting, the exposure also is varied in small increments over a range sufficient to cause positive and negative 0.1-mil ($2.54\ \mu\text{m}$) line width variations. The standard deviation in the line width is computed at each exposure setting and displayed as shown in Figure 4. The curves show that, as exposure range increases, line width deviation decreases with an increasing prebake time-temperature product. The slope of the line at the zero-crossing point and the standard deviation decrease with increasing prebake time-temperature, thus demonstrating a decrease in the photoresist light sensitivity. The dashed lines show the arbitrarily chosen limits of plus and minus one-half of the total allowed dimensional tolerance. A single prebake/exposure curve can now be chosen to establish the prebake/exposure schedule.

Exposure Schedule

The schedule constraints are those values of prebake time-temperature product and exposure energy which will produce one-half of the allowable dimensional deviation. The exposure schedule domain is the set of all possible prebake time-temperature products and exposure energies that holds the dimensional change to one-half of the required tolerance. Figure 1 is an example of the exposure schedule established from curve T_3 on Figure 4. Looking at the envelope defined by connecting the standard deviation points, the lower limit of allowable exposure energy is the intersection of the positive standard deviation

limit envelope and the positive line width deviation limit. The upper exposure energy limit is the intersection of curve T_3 and the negative line width deviation limit. These limits are represented by lines C and D in Figure 1. The limits of the prebake time-temperature product are determined by Figure 3 and/or by adhesion or exposure time limitations. The operating point of both parameters is chosen inside the schedule so that the combined standard deviations do not exceed the schedule limits. The schedule limits are not chosen in consideration of the standard deviation, but for adequate dimensional tolerance, and controls are then imposed on each process to minimize the process variation.

Control

Process control is assured by regulating the exposure light quality and the intensity-time product. The photoresist may be exposed through a photomask placed either in direct contact with the resist or spaced a small distance away. The advantages of a collimated light source are not fully realized with the photomask placed in direct contact with the photoresist; however, collimated light tends to compensate for small discrepancies in total surface contact, and becomes necessary when the photomask is spaced away from the photoresist surface.

The point source approximation and the lens system determine the intensity uniformity and the collimation. Regardless of the system used, the light intensity must be uniform within the limits defined by

the exposure schedule (generally ± 2 percent is sufficient). It can be checked by plotting the intensity over the entire light field. Where the light uniformity is not satisfactory, an adjustment of the approximated point source (such as using an iris to decrease the point source diameter) will help; however, the total intensity will decrease.

A well regulated light-source power supply with a closed-loop intensity regulating system will help maintain the proper exposure energy when used in conjunction with an accurate timer. An integrating photometer is an alternate, more-accurate method of controlling the proper exposure energy. A fast-response integrating photometer which integrates the light intensity over real time in the 3500 Å to 4500 Å wavelength range is the most suitable method of measuring and regulating the exposure energy.

PHOTORESIST DEVELOPMENT

Positive photoresist becomes soluble in properly exposed areas and is dissolved by the developing solution. The developing solution may react with the unexposed portions of the photoresist, or may incompletely dissolve the exposed areas. In either case, the line edges are degraded to some extent by the developer, which results in imperfectly defined lines. With positive resists, overdevelopment causes a dimensional decrease, whereas underdevelopment produces an increase.

To determine the significance of development time and developer concentration, a family of curves similar to those of Figure 4 is generated by using developer concentration and developing time as variables. The developer concentration is decreased in small increments from full strength to less than half strength, and the exposed photoresist patterns are developed in small time increments from extreme underdevelopment to severe overdevelopment. The measured deviation of the developed resist image as compared to the dimensions of the photomask image at each condition of solution strength and development time is shown in Figure 5. Solution temperature is maintained at approximately room temperature.

Assuming the limits on the line width deviation to be the remaining half of the allowable tolerance, ± 25.0 microinches on a 5-mil line ($127\ \mu\text{m}$), an analysis is made to this set of curves, as with the prebake/exposure curves. A developing time and concentration schedule is established, as shown in Figure 6. Lines A and B in Figure 6 represent solution concentrations that produce positive and negative line width deviations of ± 25 microinches ($0.635\ \mu\text{m}$), and lines C and D represent development times that produce the same deviations. The operating point is located at the centroid of the developing schedule.

The curves R_1 through R_4 of Figure 5 show the decreasing dependence of the line width deviation on the developing time as the

developing solution concentration is decreased. Since it is possible to dilute the developer, it is possible to allow for large variations in developing time. Therefore, adjusting the developing solution concentration causes the shape of the developing schedule to be altered so that tight control of the concentration is required, while relaxing the required control of developing time.

The manner in which these controls are imposed depends upon the method used for developing the substrates. Either immersion or spray developing can be used with equal success; however, the spray method is faster and, since the diluted developer is used only once, the problems of concentration control and contamination are eliminated.

PHOTORESIST THICKNESS UNIFORMITY

The photoresist must protect the thin film surface of the circuit pattern area during etching. The actual thickness of a positive resist is not a significant factor in line resolution (line pairs per millimeter); however, thickness uniformity does influence the dimensional stability of the photoresist image.

Thickness uniformity is important in both the prebake/exposure relationship and in the developing processes. A specific exposure energy is valid only for a particular photoresist thickness. Any change in thickness will cause either an overexposed or underexposed condition. The exposure and development parameters require adjustment if the photoresist thickness is changed. For these reasons, the thickness

of the photoresist must be uniform within prescribed limits, depending upon the type of resist used.³

For selected values of operating thickness and thickness variability, the prebake, exposure, and developing parameters are adjusted to maintain the proper tolerance; however, there will be some line-width deviation as a result of thickness nonuniformity. Generally, a thickness variability of $\pm 0.10 \mu\text{m}$ will not cause a dimensional deviation greater than ± 20 microinches ($0.508 \mu\text{m}$).

The methods used to control photoresist thickness are contingent upon the size, shape, and surface roughness of the substrate. Photoresist application by spinning normally is suitable for round or square substrates that do not exceed 3.0 inches (76.2 mm) in the major dimension. Spray coating or roller application is required for larger or irregularly shaped substrates and for those that have extremely rough surfaces.

ETCHANT UNDERCUTTING

Etching solutions begin to etch under the resist-covered areas as they etch through the thin film. The degree of undercutting depends upon several factors that include the method of etching, type and concentration of etchant, film thickness, and thickness uniformity.⁵ Since all etching procedures produce some degree of undercutting, it is necessary to minimize undercutting if line widths are to be controlled within the required tolerance.

When undercutting has been minimized and is under control, adjustment may be made in the photomask dimensions to compensate for the reduction in line width caused by undercutting. Small width compensations can be made by adjusting the prebake and exposure relationship; however, this is not normally advisable.

Spray etching usually provides the best line width control and produces the best etch factors; however, excessive spray force should not be used, and there should be no consistent flow pattern across the substrate surface.

DEVIATION MEASUREMENT METHODS

Since dimensional measurements become more prone to error as the dimension to be measured becomes smaller, it is difficult to measure line width deviations in microinches. The repeatability of such measurements also leaves much to be desired. A microscope and filar eyepiece can be used to establish process schedules. By using a special test pattern and extreme care, the measurement accuracy can be adequately verified.

With ability to measure repeatability and to assure that the data distribution at each processing parameter setting is distinct and separate from the two adjacent parameter distributions, it can be shown with a calculated degree of confidence that the measured change

in line width deviation is a function of the different process parameter settings, and is not dependent upon the method of measurement.⁶

A specially-designed test pattern measured with a filar eyepiece at a magnification of more than 600X can be used successfully. The test pattern consists of five concentric square frames, each 0.5-mil (12.7 μ m) wide and spaced 0.5-mil from the adjacent frames. The largest frame is approximately 0.2-inch (5.08 mm) square, and is repeated at 0.5-inch (12.7 mm) orthogonal intervals across the entire substrate. This arrangement provides two mutually-perpendicular sets of five 0.5-mil (12.7 μ m) lines and equal spaces for measurement. Each side of all five frames is measured with the filar eyepiece and compared to a measurement of the same lines on the photomask.

CONCLUSION

All photoresists may not offer sufficient stability to establish the processing schedules described herein. However, they can be characterized in terms of dimensional control parameters. This method may be used to select the most suitable photoresist and to develop production processing schedules for dimensional tolerance requirements on thin-film hybrid microcircuits. Because thin-film

resistor trimming techniques may be employed to obtain the required resistance values, ± 1 -percent control of line widths may not be absolutely necessary; however, the line width control techniques developed are applicable to any desired tolerance, and may be useful in establishing a photolithographic operation.

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- A = Required exposure too long
- B = Minimum resist adhesion temperature or too sensitive to exposure light irregularities
- C = Unexposed or $> +25$ microinch deviation
- D = Greater than -25 microinch deviation

Figure 1. Typical Process Schedule

Figure 2. Required Light Exposure Versus Prebake Temperature

Figure 3. Line Width Deviation Versus Prebake Temperature

Figure 4. Line Width Deviation Versus Exposure Energy for Four Prebake Schedules

Figure 5. Line Width Deviation Versus Development Time for Four Developer Concentrations

Figure 6. Development Time Versus Developer Concentration