with process models, these measurements become a powerful tool for evaluating potential performance differences given by different resist materials and processes, and their implications for the microelectronics manufacturing industry.

REFERENCES

[1] W. P. Hornberger, P. S. Hauge, J. M. Shaw, and F. H. Dill, "The characterization of positive photoresists," Proc. Kodak Microelectronics Seminar, San Diego, Calif., Oct. 1974.
[2] W. Neugebauer *et al.*, "Etchable reproduction coatings on metal supports," U. S. Patent 3 201 239.
[3] A. R. Neureuther and F. H. Dill, "Photoresist modeling and device fabrication applications," Proc. Microwave Research Institute Symp., Brooklyn, Apr. 1974.
[4] F. H. Dill, J. A. Tuttle, and A. R. Neureuther, "Modeling positive photoresist," Proc. Kodak Microelectronics Seminar, San Diego, Calif., Oct. 1974.
[5] C. E. Herrick, Jr., "Solution of the partial differential equations describing photodecomposition in a light-absorbing matrix having light-absorbing photoproducts," *IBM J. Res. Develop.*, vol. 10, pp. 2–5, Jan. 1966.
[6] M. Schaule, private communication.
[7] K. L. Konnerth and F. H. Dill, "IOTA: A new computer controlled thin film thickness measurement tool," *Solid-State Electron.*, vol. 15, pp. 371–380, 1972.

In-Situ Measurement of Dielectric Thickness During Etching or Developing Processes

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***Abstract*—A system has been developed which permits the measurement of dielectric film thicknesses *in-situ* during development or etching processes. This can be extended to growth or deposition processes. Two examples of its uses are presented: the determination of the thickness of phosphosilicate glass layers on silicon dioxide coated silicon wafers by making use of the etch rate differences, and the monitoring of photoresist thickness during development to characterize the photoresist development process.**

INTRODUCTION

A CONSIDERABLE amount of information about the properties of thin films can be obtained by measuring the etch rate as a function of depth into the film. This procedure has some particularly important applications in the semiconductor industry. For example, inhomogeneities or boundaries between films of essentially identical optical properties can be located by examining the changes in the rate of etch. Another important application is in the characterization of the etching (developing) processes in photoresist materials.

Until recently, measurement of etch rate was tedious and time consuming. Conventional thickness measurement techniques were too slow to permit *in-situ* measurement of film thickness during the process under investigation. Therefore, such determinations generally used multi-measurement techniques. Either one sample was etched for a short period of time, the thickness measured and the etching and measurement processes repeated, or multiple identical samples were etched for differing periods, then measured. Such procedures are tedious and inaccurate when compared to *in-situ* thickness measurements while etching.

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MEASUREMENT EQUIPMENT AND TECHNIQUE

The instrument used for performing *in-situ* measurements is a computer-controlled spectrophotometer previously described in the literature for static thickness measurements [1]. A brief discussion of the apparatus is presented here; the reader is referred to the literature for a detailed presentation on the equipment as well as the analysis techniques employed.

Fig. 1 shows a block diagram of the spectrophotometer. The heart of the instrument is a circular interference filter whose transmission wavelength is dependent upon its angular position. The 180° filter segment is alternately rotated through two optical paths, thus producing a wavelength scan from 400 to 800 nm in each. During the first 180° of rotation, light from the source is directed through the rotating filter and then to a photomultiplier by means of fiber optics. During the second half of the rotation, another set of fiber optics conducts the light through the filter and onto the sample under investigation. The light reflected from the sample is then channeled to the photomultiplier. By the use of an analog-to-digital converter triggered from the optical encoder on the filter shaft, readings can be obtained of the photomultiplier signal cor-

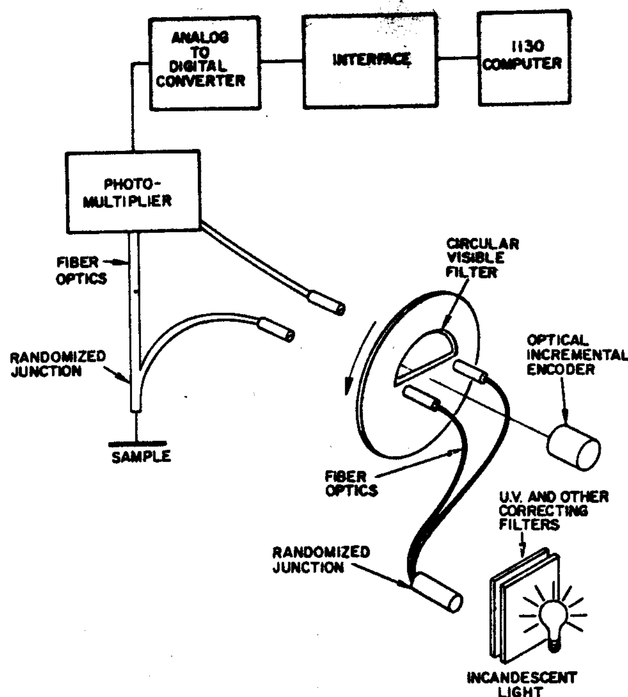

Fig. 1. Block diagram of the automated spectrophotometer used to perform the measurements discussed in this paper.

responding to specific angular positions of the filter and thus to specific wavelengths through either of the two paths. If the photomultiplier signal amplitude corresponding to a given wavelength passing through the sample path is divided by the signal corresponding to that same wavelength for the direct path and an easily determined calibration factor accounting for differences in the two fiber optic systems, the relative reflectivity of the sample as a function of wavelength is obtained.

The relative reflectivity measurement can be changed to absolute reflectivity by multiplying all the reflectivity measurements by a single constant. This constant can be obtained in either of two ways. The first is by measuring a sample of known reflectivity in precisely the same position as the unknown sample. This is normally rather inconvenient except for etching which is carried to completion, when the known reflectivity of the bare substrate can be used to find the constant multiplier used for all the film thickness measurements. With this calibration method, the spectrophotometer can be used down to zero film thickness.

The second method of finding the relative-to-absolute reflectivity multiplier makes use of knowledge of asymptotic relations for the reflectivity curves as described in [1]. All reflectivity curves for a lossless dielectric material on a known substrate must lie between two known limiting curves. As long as there is at least one maximum or minimum in the curve of reflectivity versus wavelength, the calibration constant can be found which places this limit on the appropriate boundary curve. This method is applicable to measurement of films greater than 60 nm thick.

Knowledge of the absolute reflectivity at a given wavelength, together with optical properties of the film and substrate, is sufficient information to determine film thickness to within an integer multiple of $\frac{1}{2}$ wavelength. By use of the multiple wavelength measurement, this ambiguity can be removed for a large range of film thicknesses; an improvement in the measurement accuracy can be obtained by averaging these multiple results.

The reproducibility of the technique for static measurements is of the order of tenths of nanometers. Data acquisition is performed in approximately 0.1 s, data reduction takes up to several seconds depending upon the film thickness and speed of the computer used. To perform the measurements described in this paper, the spectrophotometer was connected to an IBM 1130 computer. This configuration produces a data reduction time of the order of 2 or 3 s. In situations where this was too long to permit reduction while the measurement was in process, the raw data was stored on disk memory as it was acquired and retained for later reduction.

APPLICATIONS

A multiple film structure which is found frequently in semiconductor devices is that of phosphosilicate glass (psg) on silicon dioxide (SiO_2) on silicon. Since the index of refraction of the psg is essentially identical to that of the SiO_2, optical techniques alone cannot be used to measure the thicknesses of the individual layers. However, since there is a significant difference in etch rate of the two materials, this property is generally used to evaluate the films.

In the past, this has been accomplished by measuring the total film thickness, etching for a short period of time, remeasuring, etching again, etc., until a change in etch rate is detected. This determination can be performed much

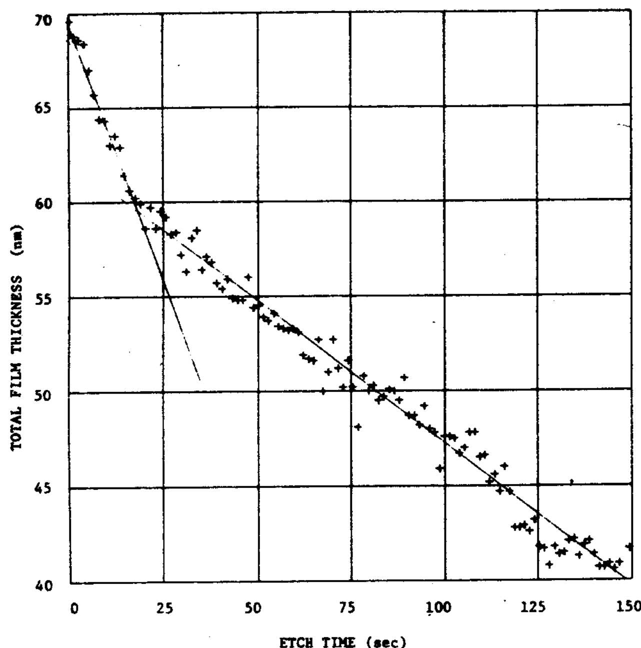

Fig. 2. Measured total film thickness versus time during etching of a silicon wafer coated with silicon dioxide which is in turn coated with phosphosilicate glass. The straight lines drawn through the data show the etch rate for each film component and their intersection occurs at the interface between the films.

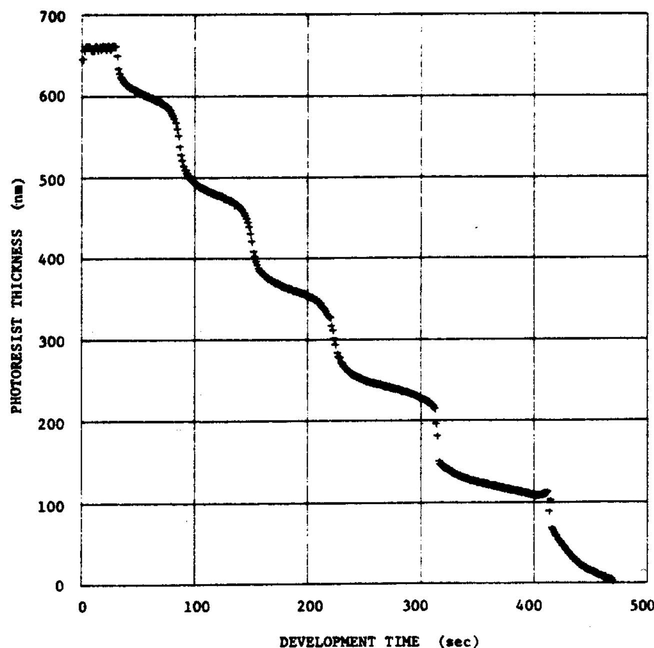

Fig. 3. Measured thickness versus time during development of a photoresist coating on a silicon wafer. Note the stair-step effect caused by interference phenomena during exposure.

more rapidly by using a continuous etch process with *in-situ* thickness measurements. By noting the point at which the slope of the thickness versus etch time curve changes, we determine the thickness of the two components of the film.

An example of this application is presented in Fig. 2. Since the thickness measurement data is acquired in real time, faster etches can be used than with quenched etching techniques. A typical time for data acquisition is 30 s. The thickness calculations can then be performed at a rate of about one every two seconds using the 1130. Since the data only needs to be reduced at enough points to adequately determine the thickness at which the change in slope occurs, the entire measurement cycle can be accomplished in under a minute—significantly less time than would be required to perform even one thickness measurement using conventional techniques.

A major application which we have made of this technique has been for measurement of the rate of development of photoresist. For resist films on silicon, coherent optical interference effects greatly modulate the exposure of the resist vertically. This standing wave exposure variation has a marked influence on the development rate of the resist, as shown in Fig. 3 which is a plot of the thickness of a photoresist film as a function of the time in the developer. The resist develops slowly in regions of low exposure and rapidly in regions of high exposure, creating the stair-step effect seen in the figure.

In order to quantitatively understand this development process, it is necessary to expose resist in an optically matched environment so that an accurately known exposure distribution without standing waves is produced within the resist. We can then characterize the development process by measuring the development rate as a function of the exposure parameter.

The optically matched substrate is exactly opposite to what one wants for thickness measurement. However, exposure of the resist is done at around 400-nm wavelength while the thickness can be measured in the 500–800-nm range. An optical glass substrate is chosen which matches the photoresist index of 1.68 in the 400-nm range but has sufficient mismatch at longer wavelengths to allow measurement.

For the glass chosen, the maximum index difference, which occurs in the red end of the spectrum, was approximately 0.03 (about 2 percent). Thus the interference effects required for the measurements were extremely small. A developing cell was constructed to minimize reflections from the back surface of the substrate and any other spurious signals. Details of the cell are presented in the accompanying paper on "Characterization of Positive Photoresist."

The very small reflected signals combined with the rapid measurement required resulted in rather noisy signals. Typical reflectance signals are presented in Figs. 4 and 5. However, through the redundancy inherent in using each data point for an independent thickness determination, together with some *a priori* knowledge of the variation of thickness with time, very good results have been obtained.

Determination of thickness requires knowledge of the index of refraction of the substrate, film, and ambient (in this case developer). All three of these were independently measured to a high degree of accuracy. However, since terms containing the difference between various pairs of indices occur in the equations for thickness, a slight error in either the substrate or the nearly identical photoresist index can cause a large percentage error in thickness.

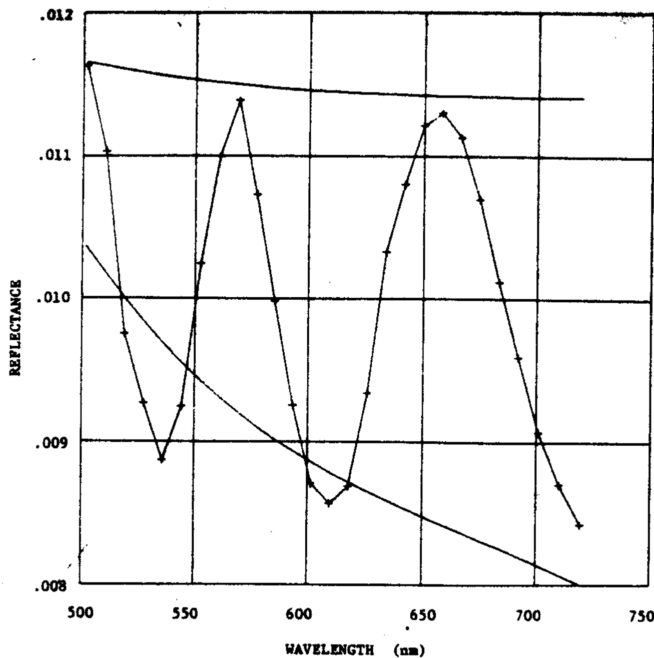

Fig. 4. Typical reflectance curve obtained during development of AZ1350J photoresist on glass substrate. Lower envelope curve determined from measured index of refraction of AZ1350J (see Fig. 5 and text).

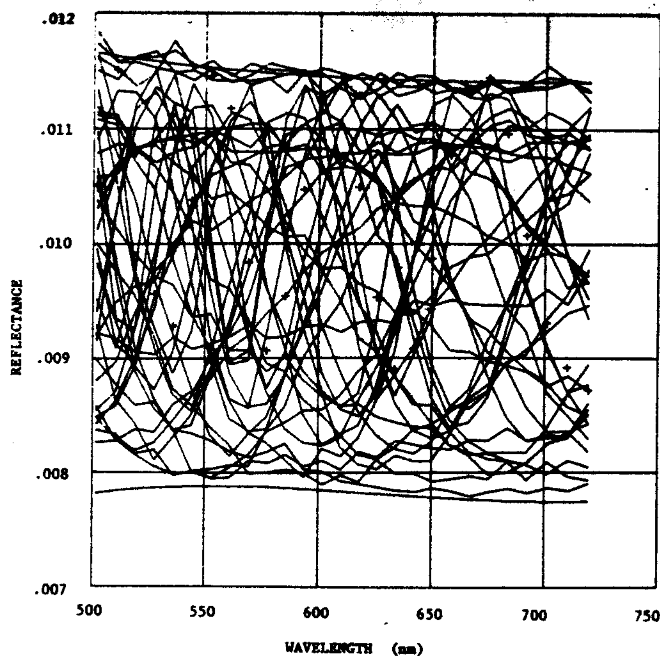

Fig. 5. Plot of every tenth reflectance curve obtained during development of AZ1350J photoresist on glass substrate. Lower envelope curve obtained by adjusting photoresist index to cause curve to fit actual data. (See Fig. 4 and text.)

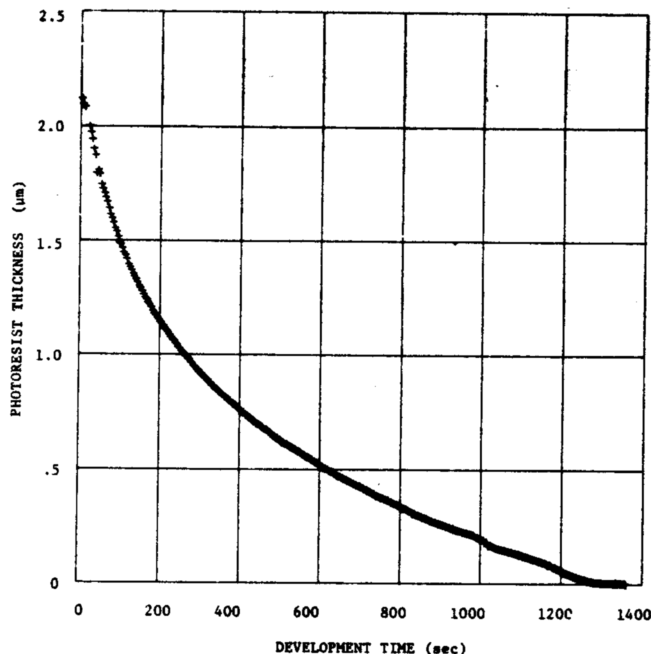

Fig. 6. Measured thickness versus time during development of a photoresist coating on matched glass substrate.

Such differences can come about either from measurement inaccuracy or from variation of the material properties.

Therefore, it was found desirable to incorporate a wavelength dependent correction factor for each individual measurement run. This was accomplished by making use of the fact that the lower envelope of the various reflectance curves is a function of the three indices of refraction. If we assume that we know two of these accurately (in our case, the ambient and the substrate) we can then calculate a pseudo index of refraction for the third parameter (photoresist) from the lower envelope, even through any individual reflectance curve may have significant noise on it. A good approximation to the lower envelope can be found by performing a second-order polynomial least square fit to the lowest reflectance found at each measurement wavelength, as shown in Fig. 5.

The other major piece of *a priori* knowledge used was that the thickness versus time function should be a smooth

monotonically decreasing one. If a good thickness measurement can be performed near the beginning of the run, the subsequent thicknesses can be ascertained by examining the various results obtained from the order ambiguity and choosing the one which would best fit the known characteristics of the curve. Again the technique of calibrating on the bare substrate at the end of the measurement was used.

A typical graph of thickness versus time obtained using these techniques is shown in Fig. 6. The total time required for data acquisition is of course dependent on development rate and thus on exposure time and other related parameters. Data reduction again required approximately one to two seconds per point, with between 50 and 400 points generally used. Thus, in the worst case, 10 min is required for the data reduction. The previous techniques using numerous exposed resist samples and multiple development steps required weeks to complete a series of measurements and still resulted in far less accurate data than the present technique.

Thus a technique has been described which can be used for rapid *in-situ* monitoring of changing dielectric film thicknesses. Several practical examples of the use of this procedure have been given; they are meant to serve as typical applications. With some ingenuity and software modifications, this approach can be extended to other etching reactions as well as film growth processes.

REFERENCES

[1] K. L. Konnerth and F. H. Dill, "IOTA, a new computer controlled thin film thickness measurement tool," *Solid-State Electron.*, vol. 15, pp. 371–380, 1972.

Modeling Projection Printing of Positive Photoresists

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***Abstract*—The accompanying papers "Optical Lithography" and "Characterization of Positive Photoresist" introduce the concepts of modeling using destruction of the photoactive inhibitor compound to describe exposure and a surface-limited removal rate to describe development together with the optical exposure parameters *A*, *B*, and *C* and a rate relationship, *R(M)*, which characterize the photoresist for modeling purposes. This paper applies the model to the projection exposure environment: exposure and development of photoresist are treated with a simulation model that allows computation of image surface profiles for positive photoresist exposed with a diffraction limited real image.**

INTRODUCTION

PROJECTION exposure of photoresist is of growing importance in the drive toward more complex microcircuits with smaller dimensions and fewer defects. It has found common usage in mask making and is beginning to be used for direct exposure of resist on silicon wafers. This paper applies the photoresist exposure and development model to the projection exposure environment, including experimental results supporting the model [1]. The concepts of A, B, C, and $R(M)$ and their determination, contained in the accompanying papers, are useful for any resist exposure technique provided that the optical environment is analyzed with adequate care.

The photoresist process model represents a powerful tool for studying projection exposure, because process control requirements for projection printing are extremely critical. With the model, the important parameters can easily be identified and a quantitative relationship established between them and the resultant image variations. By paying careful attention to the optics of image formation and photoresist exposure, we can use the A, B, and C parameters to calculate exposure distributions within the resist film as expressed by a relative inhibitor distribution, M, after exposure. Making use of the development rate curve, $R(M)$, the removal of the photoresist by the developer can be simulated and image surface profiles resulting from exposure and development can be calculated. These calculations are carried out for line-stripe patterns as commonly used in microelectronics structures.

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PROJECTION PRINTING

Projection exposure of photoresist uses a lens to image a mask pattern onto the photoresist film. This represents one of the more challenging areas of classical optics, for