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AMERICAN SOCIETY FOR TESTING AND MATERIALS
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Standard Practice for Determination of Uniformity of Thin Films on Silicon Wafers [1]

This standard is issued under the fixed designation F 1618; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice covers a set of site distribution patterns for measuring the uniformity of a property of a thin film on a silicon wafer, as well as simple procedures for analyzing and reporting the results of those measurements. The purpose of this practice is to promote commonality of approach to the analysis of uniformity among all parties needing to generate or assess such information, including manufacturers of the basic test instrumentation to be used.

1.2 This practice is intended for use as a template for the evaluation of the uniformity of intrinsic film properties such as thickness or composition, and also film functional characteristics such as sheet resistance and reflectivity. The resulting information may be used to assess the uniformity of the film itself or of the layer formation process. This practice is not directly applicable to evaluating wafer-to-wafer or lot-to-lot variations.

1.3 This practice is intended for use with any thin film or layer type, or formation technique, for which basic measurement instrumentation and capability exists that is appropriate to the film parameter of interest. This practice is intended for layer growth and deposition techniques such as epitaxy, implantation, thermal and chemical vapor deposition (CVD) oxidation, and metallization, as well as for layer modification such as various means of layer etching.

1.4 This practice can be used with any measurement method, procedure or instrumentation that can measure the needed film property or characteristic with sufficient precision and spatial resolution to reveal the needed information on spatial nonuniformity of the film. This practice does not itself contain details on performing any specific measurement.

1.4.1 Not all types of measurements that may need to be used for evaluation of the uniformity of a thin film have formal procedural standards. Test Methods F 374, F 576, F 1392, F 1393, and F 1529 give details of measurement procedures that may be applied to evaluating the uniformity of thin film properties.

1.4.2 This practice does not deal with acquisition or analysis of uniformity data where it is desired to take more than one measurement per specified spatial cell such as is commonly done for wafer site flatness measurements.

1.5 This practice is written for evaluation of planar or blanket films, but it may be applied to patterned films if the pattern size, shape, and distribution do not interfere with the spatial resolution of the selected measurement technique and the specified measurement site selection. If either of these interferences occur, the user may adapt the principles of the method to the needed application, but the interpretation of the results may change.

1.6 This practice makes no recommendations regarding the interpretation of the statistics that result from analysis of the data acquired with regard to the goodness or badness of given values of the test statistic, nor does it make recommendations regarding decisions about the process cycle or equipment used to produce the thin film that was measured.

1.7 The principles of this practice may be adapted to determine the uniformity of bulk silicon wafer properties such as interstitial oxygen content and resistivity, but depending on the desired property and the chosen measurement technique, depth-dependent variations may be misinterpreted as lateral variations.

1.8 The principles of this practice may be adapted to other semiconductor wafers, such as gallium arsenide, but particular concerns with those other materials may not be addressed adequately in this practice.

2. Referenced Documents

2.1 ASTM Standards:

F 81 Test Method for Measuring Radial Resistivity Variation on Silicon Wafers [2]

F 374 Test Method for Sheet Resistance of Silicon Epitaxial, Diffused, Polysilicon, and Ion-Implanted Layers Using an In-Line Four-Point Probe [2]

F 576 Test Method for Measurement of Insulator Thickness and Refractive Index on Silicon Substrates by Ellipsometry [2]

F 1392 Test Method for Determining Net Carrier Density Profiles in Silicon Wafers by Capacitance-Voltage Measurements with a Mercury Probe [2]

F 1393 Test Method for Determining Net Carrier Density in

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[1] This practice is under the jurisdiction of ASTM Committee F-1 on Electronics and is the direct responsibility of Subcommittee F01.06 on Silicon Materials and Process Controls.

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[2] *Annual Book of ASTM Standards*, Vol 10.05.

Silicon Wafers by Miller Feedback Profile Measurements with a Mercury Probe [2]

F 1529 Test Method for Sheet Resistance Uniformity Evaluation by In-Line Four-Point Probe with the Dual-Configuration Procedure [2]

3. Summary of Practices

3.1 Measurements are made at the sites specified in the chosen sampling plan using the appropriate instrumentation and measurement procedure for the film parameter of interest. Measures of the dispersion of the values are obtained by simple statistics specified for the sampling plans.

4. Significance and Use

4.1 The fabrication of semiconductor, dielectric, and metal thin films is a critical part of silicon integrated circuit production. The variation of film properties across the surface of a wafer can have significant impact on the further processing of the wafer and on the ultimate yield of acceptable chips from the wafer, as well as on their reliability.

4.2 This practice is intended for process control, research and development, and process equipment evaluation purposes. It is intended for the benefit of semiconductor device and equipment manufacturers alike so that acquisition, reduction, and communication of thin film data is consistent among various parties who may need to concur on interpretation of the results of a thin film fabrication-process step.

4.3 Measurement of the uniformity of one or more thin film properties such as thickness, sheet resistance, reflectivity, dielectric constant or index of refraction enables the monitoring of a critical aspect of the results of a given process step. This information can be used to determine the behavior of individual process steps; it can be used with similar information from earlier process steps to determine their interaction with respect to final product uniformity. Also it can be used in conjunction with historical data from the same process step to determine loss of control of the piece of equipment or the process cycle being used with respect to producing product having a required level of uniformity. Further, it can be used to determine the adequacy of new or modified process cycles, materials or equipment for a given film deposition or film modification requirement.

4.3.1 It is common practice to monitor the value of a simple statistic, such as the standard deviation that results from layer uniformity measurement data and to compare the current value of the statistic with historical values for the same layer formation process. An increase of the current value over historical values is taken as an indication of possible deterioration of the quality of the layer formation process. It is then common to convert the data into a contour or similar map of uniformity to aid in diagnosing changes in the process that caused the increase in standard deviation (or similar statistic). This practice does not treat the interpretation of the statistic resulting from data analysis, nor does it give procedures for converting the data to a uniformity map.

4.4 The nonuniformities of a film property on a given wafer are primarily systemmatic, not random, in their spatial shape or distribution and arise from spatially systemmatic variations in such process variables as temperature, gas flow, pressure, or electric field. As a result, the simple statistic standard deviation that is specified for analysis of data acquired with this practice will not generally have the normal interpretation for the standard deviation of a sample from a random population. It is a figure of merit for comparing data sets of a similar type, but it cannot be used for computing confidence or tolerance intervals.

4.5 This practice is intended for use with all silicon wafer sizes and types when measuring uniformity of film properties and characteristics. This practice describes measurement site patterns and determination of their spatial coordinates on the wafer, as well as the statistics to be used when reducing the measurement data to determine uniformity. For each of the sampling plans, the exact number of measurement sites is chosen based on the size of the wafer being used, the desired spatial resolution of the measurement instrument, and whether maximal, or somewhat lesser information density is desired. However, in all such choices, the pattern of measurement sites, the rules for selecting their coordinates on the wafer, and the statistical calculations of the results should remain consistent with the procedures of this practice.

5. Interferences

5.1 Individual test instruments and test methods that may be used to measure properties or characteristics of thin films are subject to various interferences that may affect measurement precision consistency, resolution, and accuracy. These may include such things as sensitivity to stray illumination, rf-fields, and variations in temperature. It is the responsibility of the user of this practice to consult instrument manuals and appropriate ASTM test methods in order to identify and control potential interferences with that instrument or method.

5.1.1 It is also the responsibility of the user to devise a test for the inherent precision of the measurement being made so that imprecision in the measurement is not misinterpreted as nonuniformity of the thin film being evaluated by this practice. This is particularly important for application of this practice to evaluating films from process steps that are capable of a very high degree of uniformity, for example, 1 % across a wafer. Such tests may involve using known uniform or nonuniform test specimens whose spatial pattern of nonuniformity has been found to be very stable over extended periods of time.

5.2 Uniformity measurements from certain types of measurements may be misinterpreted if the user is not aware of the full nature of the basic measurement being made. For example, sheet resistance is a function both of the inherent resistivity of the film being measured and of its thickness value. Nonuniformity in sheet resistance values across the wafer may result from nonuniformity in resistivity (layer composition or structure) or layer thickness (deposition rate) alone, or it may result from simultaneous variations of both parameters.

5.3 Changes in test equipment performance, or changes in test procedure or conditions over time may detrimentally affect the ability to compare test results from this practice over time for a given film property or fabrication step. It is the responsibility of the user to ensure that the measurement system and process remains in sufficient control to allow time-wise comparison of uniformity results, if such comparisons are needed.

5.4 Sampling area, or sampling spot-size may cause misinterpretation of the cause of thin film nonuniformity if the magnitude of the nonuniformity and its spatial scale, or rate of variation is not well matched to the sampling spot size and the selected distribution of measurement sites. While this should not be a serious concern for most modern film deposition processes, and tools, which are operating in control, the principles of this interference are worth elaborating.

5.4.1 If the sampling area or the spot size of the test instrument is large compared to rates of film parameter change (gradients) that are important to identify, it must be recognized that such large sampling area instruments will generate some form of spatial average response that may understate macroscopic film nonuniformity, and that will fail to respond to microscopic film nonuniformities.

5.4.2 If the sampling area or spot size is small it will generally be possible to quantify the full scale of macroscopic film nonuniformities. However, should spatial fine-scale systemmatic film variations be present, they may affect the individual measurements in an inconsistent manner unless the measurement sampling plan is tailored to the spatial size scale of the fine variations. Such tailoring of the sampling plan will generally be incompatible with the requirements of this practice.

5.5 For the most meaningful interpretation of uniformity data, all sampling sites should represent equal wafer areas, and the available area of the wafer should be fully sampled. The existence of wafer flats will cause a failure of the first requirement with all concentric circle sampling plans. The need of the semiconductor industry to establish as large a quality area as possible on wafers will also cause a failure of the first requirement for the outermost circle of concentric circle sampling plans because of the need to measure right up to a very small edge exclusion value. The second requirement is not met near the perimeter of Cartesian sampling plans.

5.6 Ideally, measurements would be made at the specified sites in a random sequence so that instrument drift or changes in other environmental parameters that may affect measurement results would have a random correlation with measurement positions. It is normally not practical to acquire data in this fashion. Therefore, any instrumental or environmental change that may occur will have a correlation with the spatial ordering of the measurement sequence. While such changes are expected to have about the same effect on both concentric circle and Cartesian sampling plan measurements, providing the number of data points are about the same, they would nevertheless have different effects on two-dimensional contour maps that resulted from these two different types of sampling plans.

6. Apparatus

6.1 *Four-Probe Sheet Resistance, Eddy-Current Mercury Probe CV, Spectroscopic Reflectometers, Ellipsometers, Interferometers, Stylus Profilometers* are typical apparatus chosen according to the type of material parameter being monitored. Others may be chosen according to need. The instrumentation should include such features as temperature monitoring and control, EMI shielding, shielding from illumination, etc. as is necessary for good practice of that type of measurement. In addition, all instrumentation must include the following:

6.1.1 Center the wafer on the measurement stage to an accuracy of 0.5 mm or better. Vacuum chuck, or similar fixture, to secure the wafer to the instrument stage during measurement is required.

6.1.2 Locate the measurement points specified in the chosen sampling plan to an accuracy of 0.5 mm or better, and

6.1.3 Store all measurement data to perform the required calculation of uniformity required.

6.2 Capability of the instrumentation to perform one or more of the following auxilliary data presentations is highly recommended.

6.2.1 Generating a two-dimensional contour map of the acquired data,

6.2.2 Generating a histogram of the raw data values, and

6.2.3 Presenting the raw data as a time-series plot.

6.3 Capability to edit data and to blend/interpolate data in conjunction with two-dimensional mapping may be useful, but it should be done with caution.

7. Procedure

7.1 Calibrate the measurement system in accordance with the manufacturer's instructions or with the applicable test method.

7.2 Place the wafer on the instrument stage so as to locate the wafer center within 0.5 mm of the center of the stage. For the purposes of this procedure the wafer center is considered to be defined by the intersection of any two diameters that do not intersect a wafer flat or orientation notch.

7.3 Select the sampling plan to be used from those listed in Annex A1 and proceed to take measurements at all the specified locations. It may be necessary to enter the coordinates of the desired sampling plan into instrument software, or to work with the manufacturer of the equipment to modify its software if the sampling plans available in the instrument do not match the requirements of Annex A1.

7.4 Take measurements at all locations specified for the selected sampling plan. Then quantify the uniformity from the acquired data using the calculations specified in Section 8.

8. Calculation

8.1 Calculate the mean, $\bar{X}$, and the standard deviation, *S*, of the N measurement values as follows:

$$\bar{X} = \sum_{i=1}^{N} \frac{X_i}{N}, \text{ and} \tag{1}$$

$$S = \left[\sum_{i=1}^{N} \frac{(X_i - \bar{X})}{N - 1} \right]^{1/2} \tag{2}$$

8.2 Examine the data. If agreed upon between parties to the test, reject values that are more than three times the standard deviation calculated in 8.1. Recalculate the mean and standard deviation using Eq. 1 and Eq. 2, where *N* is now the reduced number of data points.

NOTE 1—It is generally advisable, through use of a time series plot of the original data, or similar means, to inspect the data just rejected for determination of measurement site location and relation to adjacent measurement values.

NOTE 2—The calculation for standard deviation may be made regardless of any systemmatic behavior of the underlying distribution of