AN EXPERT SYSTEM FOR REAL-TIME PROCESS CHARACTERIZATION AND CONTROL

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1. Abstract

Harris Semiconductor is committed to the development of expert system technology which combines the concepts of real time data acquisition, recency-weighted process characterization, and automated system tuning. The Semiconductor Products Division, located in Melbourne, Florida, has targeted the photolithographic area for the implementation of such an expert system. In line with a philosophy of continuous improvement, this system will monitor, characterize, and control front-end photoresist cells towards optimal product throughput, quality, and yield.

A primary concern of any system allowed to control itself is the validity of the data it uses to build the process characterization. Although recency-weighted characterization is desirable to quickly respond to process variations and mean shifts, the system must not be permitted to respond to products contaminated with assignable causes of uncontrolled variation. Including this data would result in uncontrolled products, and the process drift possibly going undetected. Actual response is to hold the suspect run, recommend a corrective action, and advise engineering of where to look to isolate the cause of variation.

A key feature of this expert system is its ability to detect out-of-control products while continuously improving the process aim and tightening the process variation. Techniques of statistical process control combined with customer requirements and the expertise of our photolithographic engineers make up the expert system's rule-base. This paper discusses technical aspects of the expert system along with the problems involved in allowing a process to control itself. It explains the physical computer implementation along with detailed descriptions of major decision points. A discussion of statistical process control as implemented in this expert system is also included.

2. Introduction

In striving to become a world class semiconductor manufacturer, it is vital to create systems that manage the lack of standardization and chaos which can occur in high mix manufacturing lines. In general, the more standardization, the more manufacturable the process. Figure 1 illustrates a typical flow for a photolithography process used in semiconductor manufacturing. In this simple example, a silicon wafer which has been diffused to provide an oxide layer of silica glass is coated with a photosensitive organic compound called photoresist (PR). The desired circuit pattern is then transferred to the resist by passing UV light through a quartz and chromium mask selectively exposing the PR. The PR, which has been made soluable, is removed in a develop solution leaving a positive image of the mask pattern on the wafer. The next processing step involves HF etching which removes the oxide in uncoated areas. Finally, the organic resist is stripped leaving the original silicon wafer with a complex pattern of insulating glass diffused on top.

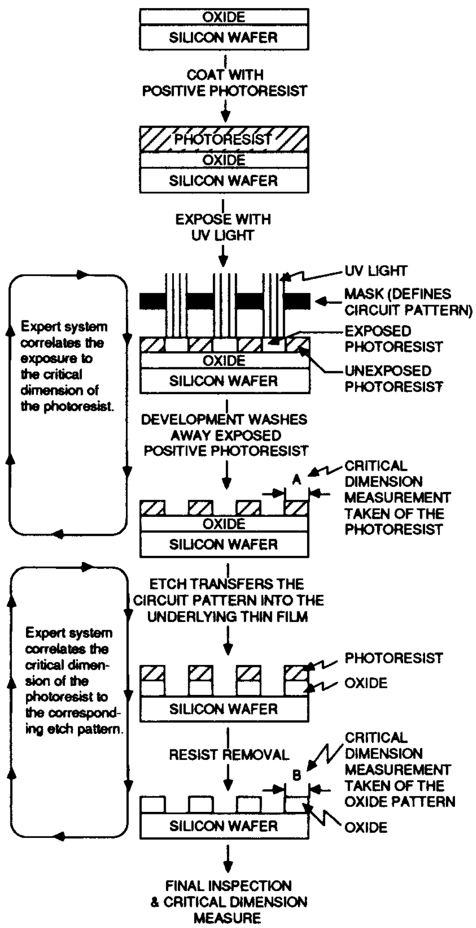

Figure 1. Photolithography Process Flow

In this high mix wafer manufacturing line, referred to as a fab, the process of controlling the UV energy required to transfer the mask pattern onto the photoresist is a difficult system to maintain. Out of over 220 different products types and over 2,600 masks, there are at least 50 active products in the line at any given time, most with their own unique process flow, including CMOS and bipolar. Associated with these 50 different products are over 700 masks. Although this assortment of products, processes, and masks provides maximum flexibility for customer requirements, the difficulty of managing such a system with paper-based instructions and specifications is monumental. In addition, within the lithography room itself, there are two different wafer sizes, six different resist types (3 positive, 2 negative, and 1 image reversal), and five different develop process. With all these variables, it is difficult to choose the correct exposure and necessitates an iterative process to obtain the desired result.

With the old "paper system," a production lot arrives in the lithography room on one of 40 different lithography/etch process flows. After the production lot is coated with photoresist, an operator looks up the suggested exposure parameters (aperture and scan speed) on a paper chart posted at each exposure tool. The operator uses that exposure on one production wafer to ensure the exposure posted on the paper chart is appropriate. This wafer is referred to as a pilot. If the pilot is visually acceptable and the critical dimension measurements as shown in Figure 1 are correct, the entire lot is processed at that energy. If not, the exposure is adjusted and another pilot is tried. This cycle continues until a correct energy is determined, or the operator gets frustrated and pulls the lot off the machine. In the latter case, the lot might be tried on another exposure tool, or the photoresist might get stripped off and reapplied in hopes of better results during the next pass.

After the production lot is exposed, developed, and visually inspected, the critical dimensions are measured again on a random sample from the run. The specifications for the upper and lower limits are kept in a 700 page paper document located at the measurement tool. The limits in this document are not based on statistically obtained process data, but instead are loosely based on what produces good electrical data, and what produces visually acceptable circuits. After the wafers are measured and deemed acceptable, the lot is sent to etch to transfer the photoresist pattern permanently onto the wafer. After etch, the critical dimensions of the final circuit pattern are measured. Theses dimensions are specified by the customer and are difficult to change. Again, these are not based on statistical data.

This inadequate "paper system" is unacceptable when striving for world class manufacturing. In order to maintain the correct exposure energies by incorporating real-time feedback from critical dimension measurements and process capabilities, a computerized Expert System called PREXPERT (pronounced P-R-Expert) was designed.

3. Computer Implementation

3.1 CAM Environment

The corporate philosophy of on-line Computer-Aided Manufacturing (CAM) systems at Harris Semiconductor is undergoing an evolution from purely Work In Process (WIP) and Engineering Data Collection (EDC) activities to include real-time intelligent control and characterization. The driving force behind this evolution in this wafer fab is the photolithography expert system. The photolithography area utilizes twelve CAM stations to log measurement data and lot movement into Consilium's On-Line Manufacturing and Engineering Tracking System (COMETS). During the design of PREXPERT, a major emphasis was placed on minimizing any perceived impacts on production and engineering. The impact of the expert system on production was addressed in part by enabling the operators to simply switch between two active sessions on their CAM station, one being the COMETS system and the other the PREXPERT system. Redundant and inconsistent data entry between the two systems was eliminated by internal queries of the COMETS data base to retrieve lot history and product information. In addition, measurement data required by PREXPERT was eliminated from the EDC of COMETS. The impact on engineering was addressed by updating current engineering data bases with the measurement data that was transferred to PREXPERT. In a few cases, additional information about how the product was processed is required by PREXPERT to generate a directive for further processing. Production was receptive to this additional data entry after they understood that this information was necessary for the expert system to learn about the process and bring it under tighter control. Figure 2 shows an operator at the OSI critical dimension measurement tool. One terminal screen is captive to the imaging system contained in the OSI, the other provides the interface to both the COMETS and PREXPERT systems.

Figure 2. PREXPERT in use at CD Measurement Tool

3.2 Database Overview

As shown in the database block diagram of Figure 3, there are five logical views of interest to PREXPERT. The two read-only structures include the COMETS data base and a four month forecast of production starts. The COMETS database is updated on a real-time basis as WIP and EDC data are logged on-line. The production forecast is updated each month and is used by PREXPERT to prioritize detected control problems based on projected volume. The category key used for the three modifiable databases consists of a product identifier (primary key) and photolithography mask level (alternate key). Each product may have as many as fourteen mask levels throughout it's processing cycle. These keys uniquely categorize the state of processing at a level used throughout the decision processes of PREXPERT, and are used to query the appropriate database for customer and process specifications, historic correlation parameters, and detailed product information. The regression model and CD spec database contains the regression parameters used in the expert's decision processes along with details of customer regulated specifications. The increased repeatability of first-pass product, compliant to these specifications, is a major focus of this expert system. The exposure data base contains a history of exposure energies that produce acceptable product on non-critical mask levels. Although the major emphasis of PREXPERT is on controlling levels with critical dimension requirements, a simple algorithm is discussed later which is helping to eliminate pilots on these levels as well. The remaining database is an event log which records all transactions processed by PREXPERT. Information from this database can be pulled up as needed on-line or down-loaded into a statistical analysis tool such as SAS or RS/1.

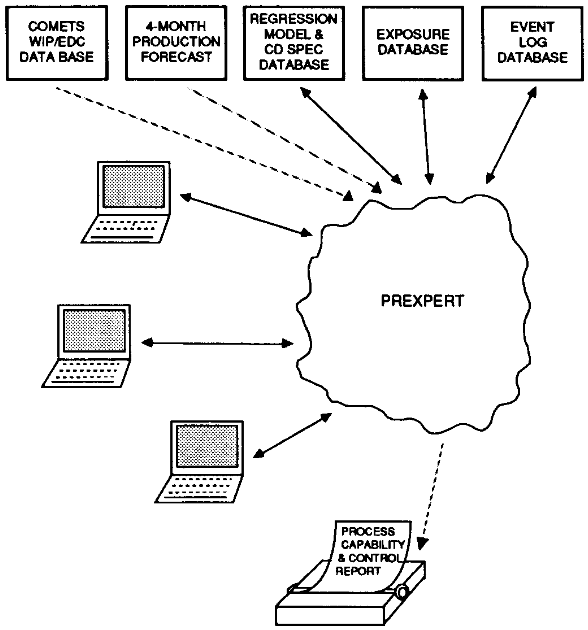

Figure 3. Database Block Diagram

Elmer and reduce unnecessary photoresist reworks caused by an incorrect exposure energy.

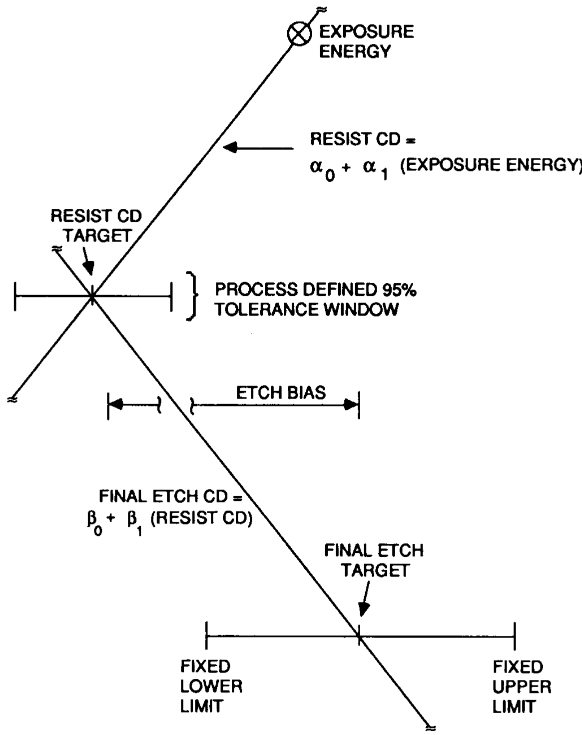

Figure 4. Regression Model Diagram

4.0 Expert Control in Photolithography

4.1 Goals of PREXPERT

The final etched dimensions of the circuit are specified by customer requirements as shown in Figure 4. One goal of the expert system is to drive the process mean toward the specified target value and reduce the variability as indicated by the capability indices, C_p and C_{pk}. By finding a relationship between the resist dimension and the final etched dimension, PREXPERT will be able to predict the final etched dimension with a 95% confidence and decide whether or not to send the lot on or rework the photoresist. The resist dimension will also be predicted by a linear regression model as shown in Figure 4. By knowing the energy used to expose the photoresist, PREXPERT can predict what the resist measurement will be after develop. With the linear regression from exposure energy to the resist measurement and the regression model from the resist measurement to the final etched measurement, PREXPERT will be able to use those two equations, and produce a correct exposure energy to produce the target critical dimension after etch for a production lot ready for processing on the Perkin-Elmer exposure tool. Once a repeatable exposure energy is determined on a given product/mask level combination, PREXPERT will instruct the operator not to take a pilot wafer at expose. This will increase throughput at the Perkin-

4.2 Determining Resist CD Target

Using linear regression on historical process data, it is shown that for each processing substrate category (eg. aluminum, polysilicon, silicon dioxide), a linear relationship exists between the measurement of the photoresist pattern and the measurement of the final etched pattern. For example, all the products that are processed with 10,000-14,000 angstroms of aluminum were studied. Figure 5 shows the linear regression line for this aluminum level along with the equation for the best fit line and its corresponding 95% confidence interval. The multiple R-square, or adjusted R-square, is 0.95 indicating that 95% of the variability has been accounted for in this model. According to the t-statistic, both the slope and the intercept are significant terms in the model. In another example, Figure 6 shows the linear regression for a polysilicon level. The multiple R-square is 0.87, and according to the t-statistic, both the slope and intercept are significant terms in the regression model. In the third example, Figure 7 shows the linear regression for a silicon dioxide level with a multiple R-square of 0.99. Again, both the slope and intercept are needed in the model. Each model is used to predict the final etched dimension based on the resist dimension, given the etch process is in statistical control.

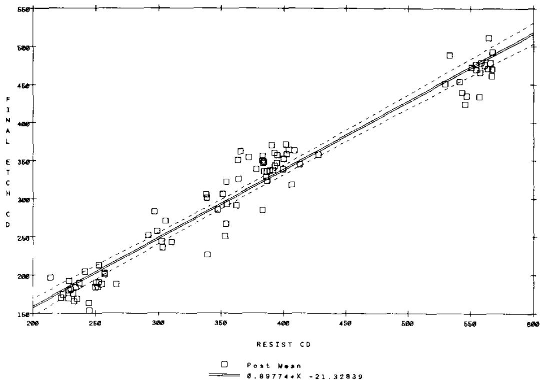

Figure 5. Aluminum Level Linear Regression

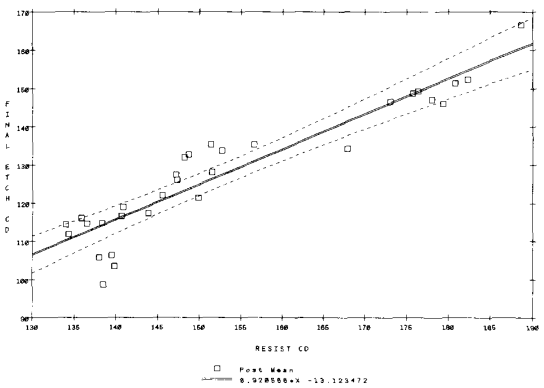

Figure 6. Polysilicon Level Linear Regression

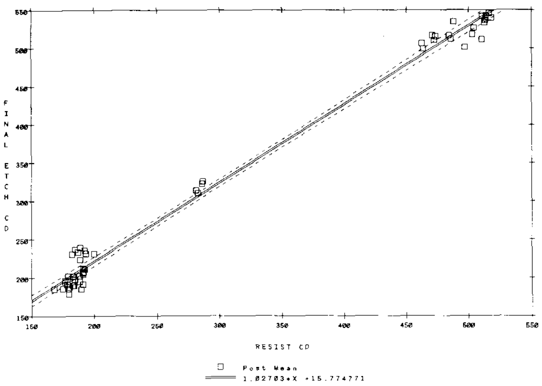

Figure 7. Silicon Dioxide Level Linear Regression

The slope and intercept for each regression model will be based on the last 30 production lots, each lot weighted equally. By basing the regression on the latest 30 lots, the slope and intercept of each model will change as improvements to processes are made or trends in the process develop. In order to prevent a model from running uncontrolled, z based control charts will be used for each substrate category. A discussion of these control charts are described in section 5. For the resist measurement, PREXPERT will be plotting subgroups against the fixed process control parameters on an internal chart. The mean of the resist dimension which produces the mean of the final etched measurement will also be controlled by PREXPERT using a z-chart.

PREXPERT is also programmed to analyze the capability of final etch measurements for every product/mask combination and notify engineering of any less than capable product. Two capability indices that the expert system will use to detect a less than capable process are C_p and C_{pk}. The C_p of a process is defined as the ratio of engineering tolerance to natural tolerance, and the C_{pk} is a scaled distance between the process mean and the closest spec limit [1]. Figure 8 shows the relationship between these two values and how the PREXPERT interprets them [2].

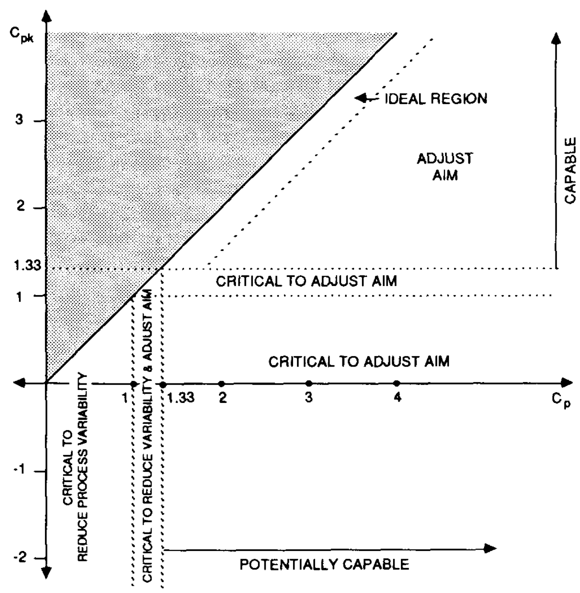

Figure 8. Capability Intrepretation

From the aluminum example, Figure 9 shows the process capability of the final etch measurements for one device. In this case there is no upper limit for the final etched dimension. For processes with one sided limits, the C_p and the C_{pk} are equal to each other, and in this example are equal to 2.00 falling into the ideal region of Figure 8. The expert system will keep its eye on this process, and no notification is given to engineering.

In the polysilicon example, the C_p is 0.65, and the C_{pk} is 0.55. The expert system will notify engineering of the less than capable process, and instruct them to look at reducing the variability of the process. As shown by Figure 10, the mean is centered between the upper and lower spec limits, but the variability causes 5.86% of the material to be out of spec. In order to increase the capability of this process, the engineer could investigate opening up the spec limits as long as customer requirements and electrical data permit. If widening the limits is not desired, the engineer can do something to the process to reduce the variability of the measurements. This could mean switching the etch process to another piece of equipment which has inherently less variability, or making other modifications to the existing process.

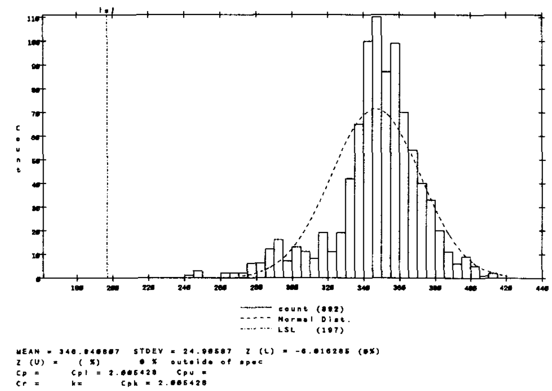

Figure 9. Aluminum Level Capability

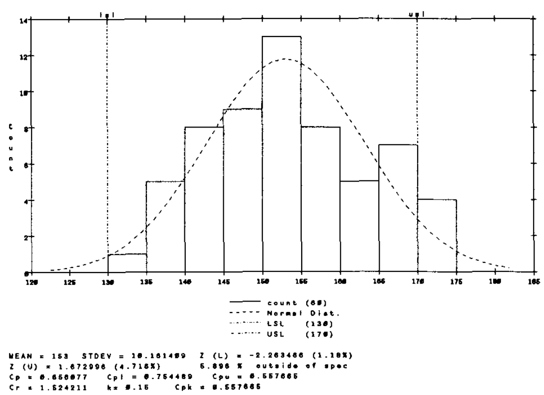

Figure 10. Polysilicon Level Capability

In the third example, the C_p is 1.15 and the C_{pk} is 0.42. According to Figure 11, it is critical to adjust the aim and possibly make an adjustment to the variability. In this case, the system may try to center the mean within the spec limits by adjusting the starting exposure at align. If that didn't work because of visual reasons, the engineer would have to try other ways to center the mean. The engineer could order a new mask with a smaller dimension to shift the mean towards the lower limit, or investigate shifting the spec limits.

Because of the large mix of products in this fab, the expert will internally create hundreds of capability plots, many of which could have a C_p or C_{pk} less than 1.0. This could drive the engineer crazy trying to pick out which product/mask to respond to. PREXPERT will take the 4 month plan and active WIP into consideration and prioritize all less than capable processes by volume, allowing the engineer to work on levels that will benefit the manufacturing line most. A report generated by PREXPERT will indicate whether to look into shifting the mean or reducing process variability.

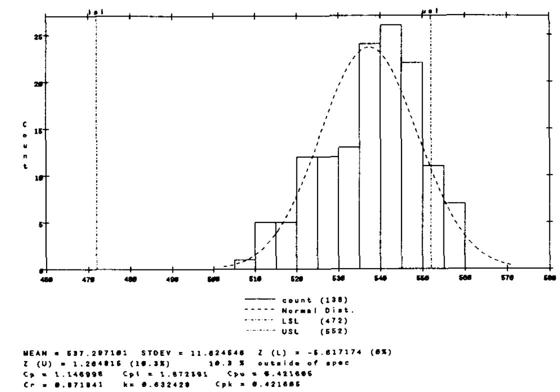

Figure 11. Silicon Dioxide Level Capability

4.3 Determining Exposure Energy

As a production lot leaves the photoresist coat area and enters the realm of PREXPERT, an accurate exposure energy is required to transfer the circuit pattern onto the PR. In a process similar to that described above for determining the correct resist CD target from the final etched target, a linear regression model is built to relate the exposure energy to it's corresponding resist target. Once this relationship is modeled, piloting is not required to determine the correct starting exposure, satisfying one goal of the system.

Until now, the only levels discussed in this paper were levels requiring a critical dimension measurement. This accounts for only about 25% of all levels processed in the fab. Even though a level may not require a critical dimension measurement, it is still necessary that the correct exposure energy is determined to minimize the number of photoresist reworks for exposure related problems. In order to do this, PREXPERT uses a simple recency weighted algorithm based on the exposure energy of the last ten successful production lots [3]. PREXPERT uses a linear weighting technique shown below to calculate the correct exposure energy for levels not requiring a critical dimension measurement.

$$E = \frac{15E_0 + 14E_1 + \ldots + 5E_9}{15 + 14 + \ldots + 5}$$

where,

E = new starting energy for the next production lot,

E_0 = most current successful exposure energy.

Complicating the task of determining the correct exposure energy are eleven exposure tools that exhibit both a fixed machine-to-machine variation and a deterministic day-to-day drift of the energy delivered at similar exposure settings. Each Perkin-Elmer (P&E) exposure tool in this manufacturing line has a total of four apertures and 1000 scan speeds available for exposure. The smallest aperture (ap 4) gives the best quality of resist profile (Figure 12), but has the slowest throughput. The largest aperture (ap 1) results in a profile that is unacceptable for certain mask levels, but has a much faster throughput. All machines are calibrated to match as closely as possible using ap 3 [4]. The fixed machine-to-machine variation is attributed to differences in the machine's internal optics. Delivered energy for a fixed scan at ap 1, 2, and 4 on a given P&E is a fixed ratio of the energy for the same scan at ap 3. Energy readings were taken on every P&E at each of the four aperture settings using a scan speed of 999. The percentage energy difference of ap 1, 2, and 4 from ap 3 was calculated for each machine (Table 1). For example, on P&E #8, the energy at ap 1 using scan speed of 999 is 301.2% of the energy at ap 3 using the same scan speed, and the energy on ap 4 using the same scan speed is 47% of the energy at ap 3. To illustrate how PREXPERT uses this information, Table 2 was constructed. If 137 millijoules of energy is needed to expose a certain mask level to achieve the correct resist CD measurement, and ap 1 is the standard aperture used for exposure on this level, the expert system will direct the operator to use a scan speed of 527 on P&E #8 or 441 on P&E #11. This phenomena is expected because the machines are calibrated to match on ap 3, resulting in increased variability on ap 1. If 48 millijoules were needed on ap 3, the expert system would instruct the operator to use a scan speed of 500 on any of the P&Es in the fab.

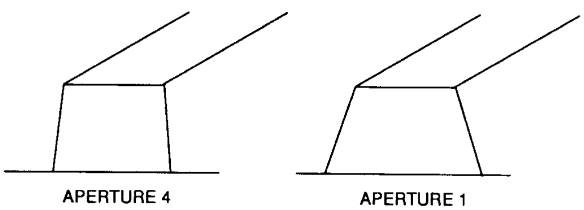

Figure 12. Resist Profile

Perkin-Elmer	ap1/ap3	ap2/ap3	ap3/ap3	ap4/ap3
PE 1	272.5 %	201.2 %	100 %	49.0 %
PE 2	293.2 %	206.3 %	100 %	51.3 %
PE 3	278.8 %	198.4 %	100 %	48.7 %
PE 4	277.6 %	202.0 %	100 %	48.9 %
PE 5	280.0 %	195.4 %	100 %	50.6 %
PE 6	278.0 %	203.7 %	100 %	48.3 %
PE 7	297.6 %	207.0 %	100 %	54.6 %
PE 8	301.2 %	210.6 %	100 %	47.0 %
PE 9	256.5 %	187.1 %	100 %	51.2 %
PE 10	285.0 %	199.7 %	100 %	50.8 %
PE 11	252.2 %	183.1 %	100 %	50.8 %

Table 1. Percentage Energy Difference of Ap 1, Ap 2, Ap 4 from Ap 3

PE	AP	Energy	Scan Speed Given by the Expert System	Difference in Scan Speed from PE 8 to PE 11
8	1	137 MJ	527	
11	1	137 MJ	441	86
8	2	97 MJ	519	
11	2	97 MJ	453	66
8	3	48 MJ	500	
11	3	48 MJ	500	0
8	4	24 MJ	470	
11	4	24 MJ	510	40

Table 2. Illustration of how PREXPERT uses Perkin-Elmer Data

The deterministic day-to-day drift is caused by an aging of the UV lamp, causing it to lose some of its energy output capability over time. This drift is kept under control and is currently not a concern to PREXPERT, although the drift is somewhat deterministic and may be included in a future revision. Each P&E is calibrated periodically to within an acceptable engineering tolerance.

In order to detect process shifts, a control chart is used in conjunction with each regression model. As PREXPERT continually strives to optimize the linear relationship between exposure energy and it's corresponding resist CD, a sudden shift or non-random trend in the regression model will cause the control chart detection algorithm to notify engineering as appropriate.

5.0 Statistical Process Control

All of the control charts generated by PREXPERT use the methods described in this section to effectively keep a process under statistical control. Internal control charts are maintained by PREXPERT with engineering notification in the case of developing trends, and process shutdown capability in the case of out-of-control detection. These internal control charts are completely invisible to the production operator, and do not require any additional effort on their part. The charts are automatically updated every time the operator inputs data into PREXPERT.

As described by Wheeler, [1], the following six basic control chart parameters can be estimated using four quantities obtained from the raw measurements: The grand average, the average range, the median range, and the subgroup size. Because of possible control limit inflation caused by an average range based on inconsistent data, two independent sets of control limits are calculated with the narrower of the two chosen. The following equations define the control limits as determined by PREXPERT:

Notation:

X"	=	grand average, the average of subgroup averages
R'	=	range average
R-	=	range median
UCL	=	upper control limit
LCL	=	lower control limit
CL	=	center line

X-BAR Control Chart

if (A2*R′ < A4*R^{-})
then
UCL = X″ + A2R′
LCL = X″ - A2*R′
CL = X″
else
UCL = X″ + A4*R^{-}
LCL = X″ - A4*R^{-}
CL = X″

Rolling Range Control Chart

if (A2*R′ < A4*R^{-})
then
UCL = D4*R′
LCL = D3*R′
CL = R^{-} *
else
UCL = D6*R^{-}
LCL = D5*R^{-}
CL = R^{-}

* although not a true center line, the range median is used to increase the sensitivity to non-random runs.

Subgroup Size	A2	A4	D3	D4	D5	D6
2	1.88	2.22	0.00	3.27	0.00	3.87
3	1.02	1.09	0.00	2.57	0.00	2.75
4	0.73	0.76	0.00	2.28	0.00	2.38
6	0.48	0.50	0.00	2.00	0.00	2.06
9	0.34	0.34	0.18	1.82	0.19	1.85

These limits are fixed once 30 subgroups are available. Decisions are made based on 'trial control limits' calculated from the first n < 30 subgroups, but these limits are susceptible to adjustment as the number of subgroups increases to 30. Future adjustments are initiated only after a notification of trend or an out-of-control alarm is determined by engineering to have been caused by a deliberate process change. Also, a notification to engineering is made to request tighter control limits when the most recent 30 subgroups define process control limits that are narrower than those on the active chart. Analysis is currently being done to determine if PREXPERT should assume the responsibility of automatically tightening these control limits, and what hueristics should be applied to ensure accurate representation of the actual process.

Out of a library of over 2600 masking levels, approximately 700 are measured for CD compliance. Of these 700, there are currently 75 categories of substrates (eg. aluminum, AlSiCu, polysilicon, silicon dioxide) that provide a logical breakdown for the monitoring of process control. An example is the 10-14 kA aluminum level which is in use by 35 product types, each with its own target CD measurement. To combine these 35 products into a single control chart, normalization using z values is employed [5]. This normalizing technique plots each control point in terms of standard deviation units from their mean and eliminates a need for separate charts on all product/mask combinations.

The current implementation of PREXPERT utilizes internal control chart techniques to monitor continuous adjustments made to the expert's regression models. These adjustments are made to optimize the prediction accuracy that drives PREXPERT's process directives. Any out-of-control points or non-random patterns are an indication of assignable causes of variation and should be addressed. An enhancement under consideration is the use of a time series analysis technique called sequential hypothesis testing [6]. In the case of PREXPERT's regression model, this technique will not only detect uncharacteristic parameter shifts, but also indicate the appropriate parameter (slope or intercept) and augment troubleshooting reports generated for the process engineer.

Besides the obvious out-of-control alarm caused by a point falling outside the three-sigma control limits, PREXPERT has the ability to detect non-random patterns that could be leading indicators of process instability or inconsistency. Runs tests about the center line is currently the only non-random pattern detection implemented by PREXPERT, justified in-part by being consistent with the paper control charts currently being maintained by the operators on-line. Eight points that fall on the same side of the center line on the X-BAR chart or the range median on the RR chart will cause the runs detection algorithm to proceed with further analysis. The RMS, root mean square, value of the detected run, calculated as a percentage of the distance between the center line and the closest control limit, is calculated. In addition, a line is fit through the subgroup points. Based on these two parameters (RMS and slope), a decision is made whether or not to notify the engineer and to its prioritization (process shutdown, immediate notification, or daily/weekly report). This heuristic filtering technique is illustrated in Figures 13 and 14. In Figure 13, the RMS value of 0.70 will cause a notification to engineering as will the slope of 30°, shown in Figure 14, qualified by a correlation coefficient of greater than 0.75. If these two parameters were dropped to zero, the control chart detection algorithm will respond in a classical manner. As the photolithography process improves, these rules can be easily modified to cause a more sensitive reaction to the detection of non-random runs. Monitoring the process control on 75 different substrate categories using control charts is not feasible without PREXPERT.

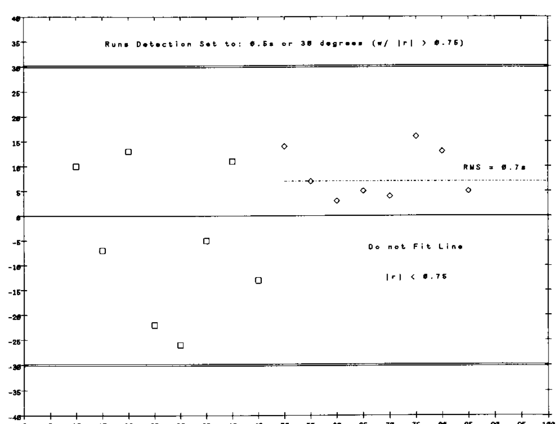

Figure 13. Mean Shift Filtering

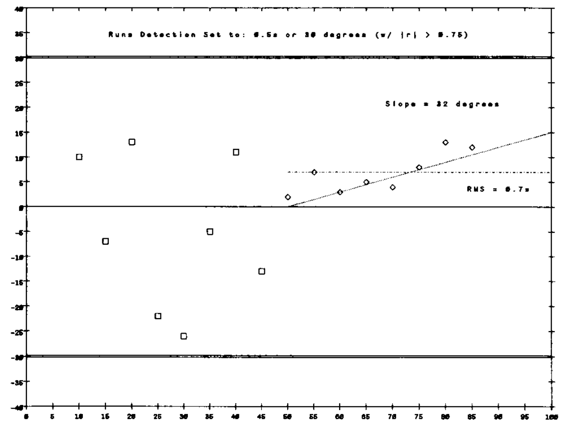

Figure 14. Process Trend Filtering

6.0 Future Enhancements

The photolithography room is currently set-up in three sections according to the wafer processing sequence. First, all the coaters used for dispensing photoresist are lined up together. Then, all the Perkin-Elmer exposure tools are grouped in the center of the room. On the other side of the Perkin-Elmers, are the developers followed by the inspection and measurement stations. One or two operators are usually dedicated to the coat process. Several more are assigned to run only the Perkin-Elmers, and the rest of the operators are assigned to develop, inspect, and measure. CAM movements are also required at each of these locations.

The layout of the room is currently undergoing a redesign. When the redesign is completed, the photolithography room will be set up in a series of workcells. One work cell will contain a coater, exposure tool, developer, microscope, and computer terminal, with one operator to run the entire cell. PREXPERT will fit nicely into this work cell concept. When a production lot is ready for photolithography, PREXPERT will tell the operator which coat recipe, mask, exposure energy, and develop program to use, and any special instructions. If the lot requires a measurement, PREXPERT will inform the operator of that, and will tell them if the measurements taken on that run were passable or rejectable.

Currently, PREXPERT takes energy differences from P&E to P&E into account for exposures processed on apertures other than aperture 3. With the work cell, one coater will always supply the same P&E, and that P&E will always supply the same developer. PREXPERT will be able to take the entire cell into account when determining starting exposures instead of just the Perkin-Elmers. This should further reduce variability in critical dimension measurements leading to more capable processes.

The work cell will also be monitored using measurements of contrast, E_t, and retention. For positive resist, retention is the measurement of the resist solubility in the developer at a zero exposure energy. E_t is the minimum energy required to make the resist completely soluble in developer, and contrast is the slope of a tangent line drawn adjacent to the curve formed when going from zero exposure to E_t [7] & [8]. These indicators will monitor the cell process and not just the Perkin-Elmers, as with the current system. PREXPERT will use this data in addition to the calibration data already in the system.

7.0 Acknowledgements

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