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An effective procedure for sensor variable selection and utilization in plasma etching for semiconductor manufacturing

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ABSTRACT

Plasma etching processes have a potentially large number of sensor variables to be utilized, and the number of the sensor variables is growing due to advances in real-time sensors. In addition, the sensor variables from plasma sensors require additional knowledge about plasmas, which becomes a big burden for engineers to utilize them in this filed. Thus an effective procedure for sensor variable selection with minimum plasma knowledge is needed to develop in plasma etching. The integrated squared response (ISR) based sensor variable selection method which facilitates collecting and analyzing sensor data at one time with regard to manipulated variables (MVs) is suggested in this paper. The reference sensor library as well as sensor ranking tables constructed on the basis of ISR can give insight into plasma sensors. The ISR based sensor variable selection method is incorporated with relative gain array (RGA) or non-square relative gain array (NRGA) for effective variable selection in building a virtual metrology (VM) system to predict critical dimension (CD) in plasma etching. The application of the technique introduced in this paper is shown to be effective in the CD prediction in plasma etching for a dynamic random access memory (DRAM) manufacturing. The procedure for sensor variable selection introduced in this paper can be a starting point for various sensor-related applications in semiconductor manufacturing.

1. Introduction

In today's semiconductor manufacturing environment, many in situ sensors are employed for monitoring plasma etch equipment operation and process results due to the inherent complexity of plasmas (Baek et al., 2005; Chen, Huang, Spanos, & Gatto, 1996; Klick, Rehak, & Kammeyer, 1997; Park, Grimard, & Grizzle, 2003; Sobolewski, 2006; Yue, Qin, Markle, Nauert, & Gatto, 2000). The potential number of measurements in plasma etching is greater than several hundred. Despite the large number of existing sensors, process and equipment engineers in plasma processing continue to evaluate newly developed state-of-the-art sensors because they believe that current sensors do not provide enough information about plasma states. Therefore, the number of in situ sensors in plasma processes is expected to increase, which provides an incentive to develop an effective procedure for sensor variable selection and utilization.

Because plasma etch processes are complex multivariable processes, manipulated variables (MVs) can be adjusted considering state variables (SVs) and performance variables (PVs). Since SVs measure hardware and plasma states through various in situ sensors, their proper utilization is invaluable for process set-up, process and equipment control, and fault detection. However, utilization of SVs in practice is limited because interpretation of them regarding MVs and PVs requires additional knowledge. Therefore, a general and efficient approach to selecting proper SVs and their utilization needs to be developed.

This paper discusses an effective procedure for sensor variable selection and utilization in plasma etching. Firstly, several issues in sensor variable selection for plasma etching will be addressed in terms of complexities of plasma etch processes, variety of in situ sensors and scaling issues. Then, in Section 3, brief theory overview which is suggested in this paper will be made. In Section 4, the results applied in a critical dimension (CD) virtual metrology (VM) for manufacturing a dynamic random access memory will be shown, which proves the effectiveness of our methodology. The proposed sensor variable selection technique can be utilized as a starting point in building a reference sensor library for fault

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detection and classification, evaluating sensor performance, and selecting MVs–PVs for equipment control. Hopefully, the results in this paper will encourage development of general, user-friendly sensor variable selection techniques for process and equipment engineers.

2. Issues in sensor variable selection for plasma etching processes

2.1. Complex multivariate plasma etch process

Plasma etching is a key process together with photolithography for patterning in semiconductor manufacturing (Lieberman & Lichtenberg, 2005). This process uses a plasma to generate highly reactive ionized species from relatively inert molecular gases to remove material from surfaces. The ionized species are accelerated in a perpendicular direction to wafer by the sheath potential of the plasma, which enables performing anisotropic etching processes. However, the plasma etch processes are complicated due to the inherent complexity of plasmas. That is, in addition to the physical and chemical reactions in plasma etching, the electrical interaction between charged particles and the electromagnetic fields within the plasma, which can be reflected to plasma state variables from plasma sensors, are not simple to interpret. Therefore, plasma etch processes must consider plasma state variables together with input and output variables to better understand their processes.

Fig. 1 illustrates the three groups of variables in a plasma etch process, where the plasma is a medium connecting MVs and PVs with several hundred SVs. Until recent years, a group of equipment state variables from built-in hardware gauges have been mainly utilized for equipment monitoring and process readiness check. However, with the narrower process window due to the semiconductor device shrinkage, the detection capability of those SVs is now insufficient to measure process performance. As a result, plasma state variables from plasma sensors, which are more representative of process results, are emerging as alternatives. Utilization of plasma state variables, however, is limited because it requires additional knowledge to interpret in terms of their relationships to MVs and PVs. In addition, the limited number of plasma sensors currently available in an industrial environment makes this situation worse because of the lack of information on the plasma. Therefore, the number of new plasma sensors will continue to increase and with the increased number, an efficient and affordable sensor variable selection and utilization technique needs to be developed in plasma etch processes.

2.2. Various sensor variables in plasma etching equipment

The schematic of the plasma etching equipment and additional in situ sensors employed in this paper is shown in Fig. 2. The etching equipment is an inductively coupled plasma reactor from Applied Materials, Inc., which uses the rf power of 13.56 MHz to generate plasma through inductive coupling and has optical emission spectroscopy (OES) and VI-probe built in the equipment. The OES sensor measures emission spectra ranging from 200 nm to 800 nm, which reflects chemical properties in plasma (Coburn & Chen, 1980). The VI-probe sensor measures the voltage, current and phase of the rf power of 13.56 MHz and its harmonics, with which the sheath potential of plasma can be estimated (Semmler, Awakowicz, & Keudell, 2007). The self-excited electron resonance spectroscopy (SEERS) from Plasmetrex GmbH is an additionally installed sensor, which measures electrical and chemical properties of the plasmas such as electron density, and electron collision rate, and so on (Baek et al., 2005; Klick, 1996; Klick et al., 1997). The other sensors that monitor equipment states like pressure and temperature are not shown in Fig. 2, but they are also evaluated together in this paper.

Table 1 lists sensor variable categories employed in this paper, which shows the total number of sensor variables is 1308 and each sensor variable has the different physical properties. As discussed in Section 2.1, the total number of sensor variables in plasma etching has been continually growing, so their proper utilization will be difficult if effective variable selection techniques do not exist.

2.3. Variable selection through principal component analysis

Principle component analysis (PCA) is a mathematical procedure that uses orthogonal transformation. It convert a set of observations of possible correlated variables into a set of values of linearly uncorrelated variables called principal components (Jolliffe, 2002; Wold, Esbensen, & Geladi, 1987). This transformation is defined in such a way that the first principle component accounts for as much of the variability in the data as possible and each subsequent component in turn has the highest variance possible under the constraint that it should be orthogonal to the preceding components. Often, its operation can be thought of as revealing the internal structure of the data in a way that best explains the variance in the data. Thus the loading of the first PC can be analyzed in terms of importance of sensor variables which accounts for the variability of the data set.

PCA is sensitive to the scaling of the variables. This might lead to arbitrary decision of sensor selection in plasma etching where more than hundreds sensor variables with different physical properties exist like that shown in Table 1. Fig. 3 illustrates how the weightings of each sensor variables in the loading vector of the first PC are changing according to scaling methods of the data set in plasma etching. For example, the negatively or positively highest weighting sensor variable is changed from sensor variable number 250 in the no-scale case to sensor variable number 122 in the mean centered case, or to sensor variable number 100 in the mean centered and unit variance case. Therefore, unless any additional techniques about scaling is built in PCA to handle the scaling issue, the statistic based PCA cannot be applied to sensor variable selection in plasma etching. In addition, relaying on the statistics without considering physical properties of sensor variables may lead to a wrong decision in plasma etching where nonlinear behavior of plasma governs reaction of process. Thus an affordable sensor variable selection technique which can reflect physical properties of sensor variables and analyze the interaction between variables within a plasma needs to be develop in plasma etching processes.

3. Brief theory overview

3.1. Integrated squared response (ISR) based sensor variable selection method

Under the consideration of the circumstances in sensor variable selection described in Section 2, several factors should be taken into account in plasma etching. The first factor is the heterogeneity of SVs. This comes from various sensors to measure plasma characteristics and equipment states as well and might cause scaling issues of variables due to the different unit and sensitivity of each sensor variable. The second factor is the redundancy in the data. This might cause the collinearity issues which lead to numerical instabilities in calculation and poor prediction performance in regression modeling. The third factor is the presence of interactions and non-linearities among SVs due to the inherent complexity of the plasmas. Therefore, a new variable selection method should be developed for plasma etching processes in such a way to minimize the bad effects from the factors above.