Development of Virtual Metrology Using Plasma Information Variables to Predict Si Etch Profile Processed by $SF_6/O_2/Ar$ Capacitively Coupled Plasma

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In the semiconductor etch process, as the critical dimension (CD) decreases and the difficulty of the process control increases, in-situ and real-time etch profile monitoring becomes important. The measurement and inspection (MI) process to manage the etch profile is essential, but it takes a long time and reduces the manufacturing throughput. In addition, it has limitation in real-time monitoring during the process. It leads to the development of virtual metrology (VM) technology that predicts the etch profile during the process. VM algorithm can predict the process results by statistically processed data of equipment engineering system (EES), sensor, and preceded process MI. Many studies are being conducted to improve the prediction accuracy of VM algorithm, and most of them are being developed through choosing more sophisticate statistical methods and utilizing more sensor data. Alternatively, a new approach is carried out to develop the high prediction accuracy VM model which has reduced the number of input data including plasma information (PI) variables describing characteristics of the process plasma with a basic statistical method and simplified the development procedure.

In this study, VM using PI variables, named PI-VM, was extended to monitor the etch profile and investigated the role of PI variables and features of PI-VM. Data of EES, sensor, and PI variables are obtained during 300 seconds of Si etch process in molar fraction varying condition of $SF_6/O_2/Ar$ capacitively coupled plasma (CCP). The EES data are acquired from the etch process chamber parts such as the MFC flow rate, TVP position, and matcher cap position. PI-OES and $PI_{Density}$ variables which is generated by the optical emission spectrum data and domain knowledge based on plasma spectroscopy are adopted as input data of PI-VM. PI-OES are consists of PI_{Te}, $PI_{Single\ Line}$, and $PI_{Density\ Ratio}$, which represents electron temperature, single line emission intensity, and density ratio of gas species, respectively. $PI_{Density}$ variables are divided into $PI_{Inlet\ Gas}$, $PI_{Radical}$, PI_{ne} which represents densities of inlet gas, radical, and electron. These EES data and PI variables as input data of PI-VM goes through the process of statistical feature selection, training, and validation procedure to predict the etch profile. In order to develop PI-VM (etch profile) and quantify the etch profile, the etch profile model has been proposed that consisted of vertical and horizontal direction and four of etch profile quantified values: Etch depth, bowing CD, etch depth times bowing CD (ED × BCD, rectangular model), and etch area (non-rectangular model). Multi-linear regression and stepwise variable selection (MLR-SVS) method are adopted for regression and statistical feature selection method. Validation and evaluation on prediction accuracy of developed PI-VM was carried out with the R-square value (R^2). A total of five PI-VM (etch depth) models based on statistics of MLR-SVS were developed using five input data sets by including the PI variables. It was demonstrated that the prediction accuracy of PI-VM improved by including PI-OES and $PI_{Density}$ as input data. Since PI variables increased the accuracy of VM effectively rather than using the raw sensor data, it has been revealed that PI variables are essential to develop more precise and rapid process monitoring technology. The features in PI-VM are investigated in terms of plasma physics and etch kinetics. With developed PI variables, PI-VM (etch depth) and PI-VM (bowing CD) demonstrated high accuracy of etch profile monitoring models and were sensitive to etching and passivation induced by ions and radicals. PI-VM (ED × BCD) showed little lower R^2 than PI-VM (etch depth) and PI-VM (bowing CD), implying that the reliable etch profile VM can be developed based on a rectangular model. Although PI-VM (etch area) showed the prediction accuracy R^2 under 0.5, it is significant that physically meaningful monitoring target is newly presented. Furthermore, this implies that more accurate and reliable PI-VM (etch profile) can be developed with the more information of radical and the ion behavior along the etch profile. This research showed that more sophisticated PI-VM (etch profile) can be developed with the PI variables which can trace the behavior of radical and ion in the etch profile. It will contribute to the advancement of technology for end point detection and etch profile control.

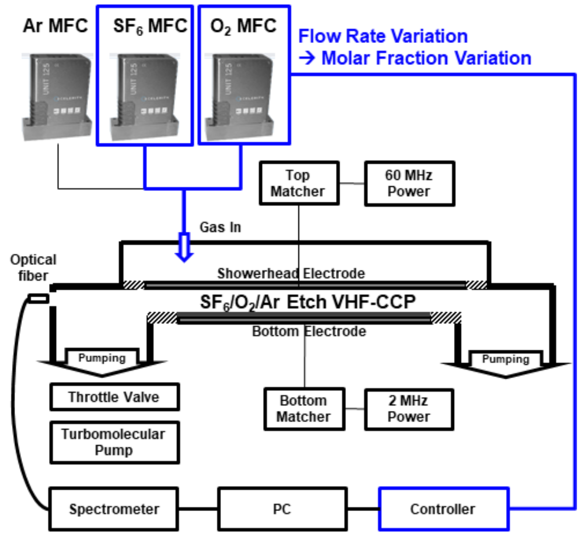

Figure 1 Schematic diagram of the CCP chamber used for Si etching. SF6, O2, and Ar are delivered through the MFC, and the pressure inside the chamber is maintained at 20 mTorr by the throttle valve. The VHF power of 60 MHz is delivered to the top electrode, and the LF power of 2 MHz is delivered to the bottom electrode. The emitted light of the plasma is observed through the OES sensor in which the viewport is located on the outer wall of the chamber.

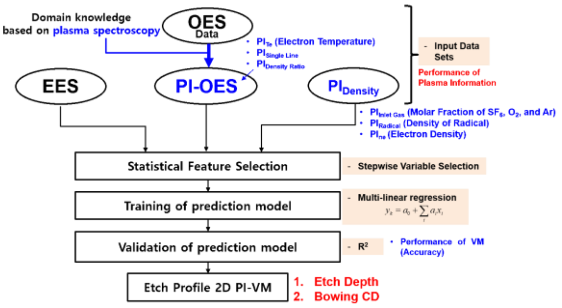

Figure 2 Flow chart of etch profile PI-VM model development.

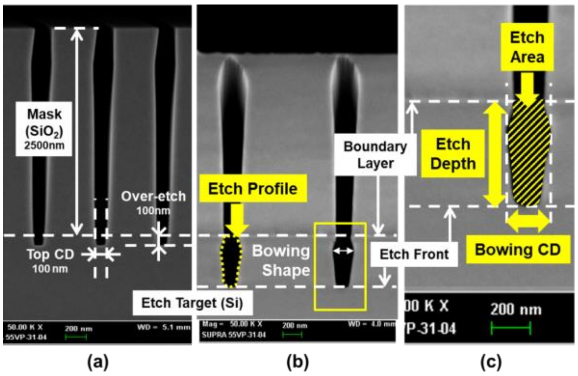

Figure 3 Definition of Si etch profile which is taken from a cross-sectional SEM image of Si with the SiO2 mask. Etch depth, bowing CD, etch area of trench, and etch profile are defined. (a) SEM image before the Si etch process with the etched SiO2 mask. (b) SEM image after the Si etch process. Yellow dotted line indicates etch profile. (c) Quantification of etch profile. Vertical position of etch front and SiO2/Si layer boundary are marked with white horizontal dashed lines. Etch depth, bowing CD, and etch area are marked with yellow box.

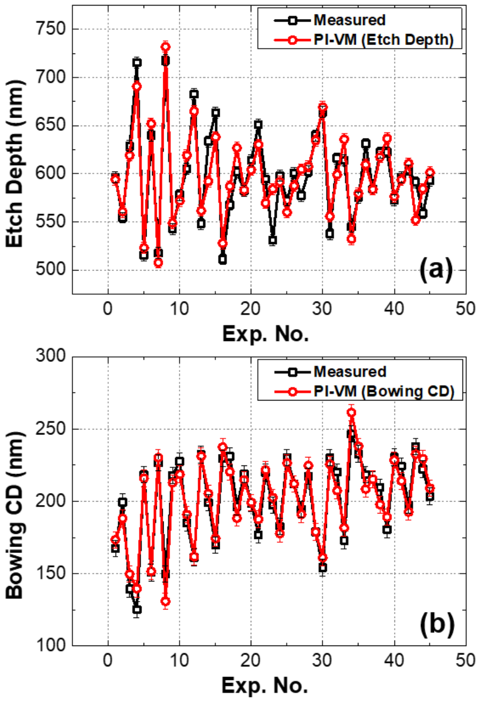

Figure 4 Comparison between the measured values (black) and PI-VM prediction values (red) (a) measured and PI-VM predic-tion values of etch depth (b) measured and PI-VM prediction values of bowing CD. The error of each value is 5.7 nm, which is the pixel size of the SEM image.