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Improvement of principal component analysis modeling for plasma etch processes through discrete wavelet transform and automatic variable selection

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ABSTRACT

To cope with a cost-effective manufacturing approach driven by more than Moore's law era, plasma etching which is one of the major processes in semiconductor manufacturing has developed plasma sensors and their applications. Among the plasma sensors, optical emission spectroscopy (OES) has been widely utilized and its high dimensionality has required multivariate analysis (MVA) techniques such as principal component analysis (PCA). PCA, however, might devaluate physical meaning of target process during its statistical calculation. In addition, inherent noise from charge coupled devices (CCD) array in OES might deteriorate PCA model performance. Therefore, it is desirable to pre-select physically important variables and to filter out noisy signals before modeling OES based plasma data. For these purposes, this paper introduces a peak wavelength selection algorithm for selecting physically meaningful wavelength in plasma and discrete wavelet transform (DWT) for filtering out noisy signals from a CCD array. The effectiveness of the PCA model introduced in this paper is verified by comparing fault detection capabilities of conventional PCA model under the various source power or pressure faulty situations in a capacitively coupled plasma etcher. Even though the conventional PCA model fails to detect all of the faulty situations under the tests, the PCA model introduced in this paper successively detect even extremely small variation such as 0.67% of source power fault. The results introduced in this paper is expected to contribute to OES based plasma monitoring capability in plasma etching for more than Moore's law era.

1. Introduction

With an advent of sub-20 nm device era, Moore's law that predicts the number of transistor in an integrated circuit doubles approximately every sixteen months becomes difficult to follow. The reasons are physical difficulties to shrink gate width physically and electrically. Instead, the concept of more than Moore's law which proposes an equivalent scaling approach rather than shrinkage technology has become prevalent in semiconductor industry (Kahng, 2010; Ramm et al., 2010; Waldrop, 2016). The equivalent scaling approach has three main directions such as introduction of innovative process schemes like 3D transistor, additional chip and system-level architectural design, and cost-effective manufacturing.

As a cost-effective manufacturing approach, plasma etching, which is one of the major processes in semiconductor manufacturing, has developed real-time monitoring and control techniques (Gaman et al., 2015; Keville et al., 2013; Lynn et al., 2012). Specifically, inherent complexity of plasma has driven this activity to mostly focus on development of plasma sensors and their applications (Baek et al., 2005; Booth et al., 2000; Klick et al., 1997; Lee et al., 2007; Oh et al., 2010; Sobolewski, 2006).

Among plasma sensors, optical emission spectroscopy (OES) which measures emission from plasma and analyzes chemical composition in plasma has been widely utilized in plasma etching for endpoint detection and process monitoring (Litvak, 1996; White et al., 2000; Yue et al., 2000, 2001). Since OES detects light from ultra violet (UV) to visible ranges with less than 1 nm spectral resolution, size of data generated during a typical plasma etching process is larger than 1 megabyte and the number of variable to consider is around 2048. Therefore, a multivariate analysis (MVA) technique such as principal component analysis (PCA) has been studied for

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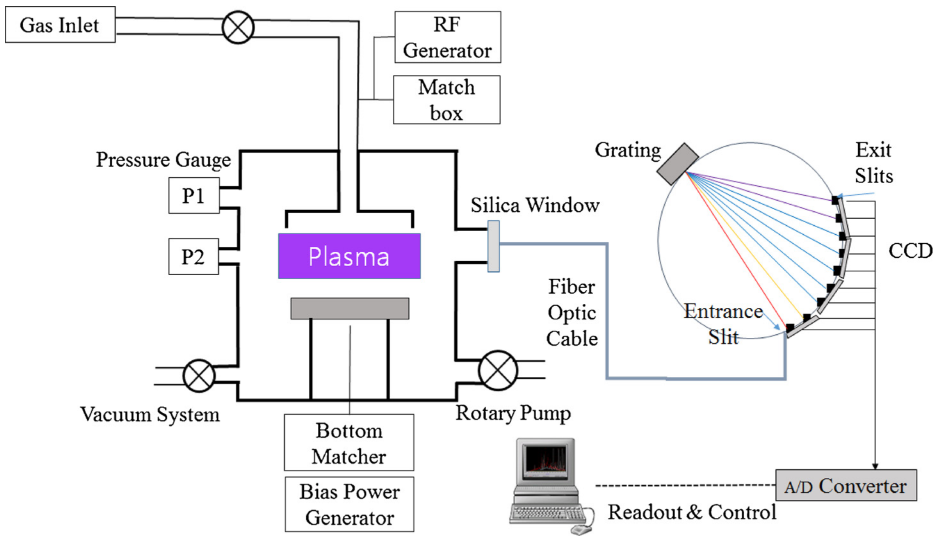

Fig. 1. Schematic of a plasma reactor and an OES installation, in which inside of OES system is also described.

dimension reduction and variable selection (White et al., 1997, 2000; Yue et al., 2000, 2001).

PCA, however, might devaluate physical meaning of target process during its statistical calculation. In addition, inherent noise from charge coupled device (CCD) array in OES might deteriorate PCA model performance. For these reasons, it is desirable to preselect physically important variables and to filter out noise signals in modeling OES based plasma data.

This paper introduces improvement of PCA performance by developing a pre-variable selection technique and by applying discrete wavelet transform (DWT) in modeling OES based plasma data. In Section 2, issues in PCA modeling of OES based plasma data are described especially in terms of huge data size and inherent noise. In Section 3, theoretical background of developed techniques in this paper is explained and how they are integrated into PCA is described. After a brief description of experimental conditions in Section 4, performances of conventional and this paper-introducing PCA model are compared under various test conditions in Section 5.

2. Issues in PCA modeling of OES based plasma data

Fig. 1 shows a schematic of a plasma reactor and OES installation in this paper. Emission in plasma is transported to an entrance slit in an OES system via an optical fiber which is attached on the viewport of plasma etcher. The incoming light at the entrance slit in OES system travels to the collimating mirror where the light is reflected to a diffraction grating. The diffraction grating then spreads the light to the focusing mirror where the spread light is transported to a CCD array. The CCD array which is assigned as each wavelength convert light to electrical signal.

In current plasma etch processes, a high resolution OES which can measure wider range of spectrum ranging from 150 nm to 1000 nm with less than 0.8 spectral resolution is employed for process monitoring. Accordingly, huge data from the high resolution OES makes it difficult to manually identify useful features and key wavelengths. Therefore, these high volumes of OES data in plasma etching requires to develop robust and automated data reduction, feature extraction and analysis techniques.

Principal component analysis (PCA) has been applied for those purposes in plasma etching (Rangan et al., 1997; White et al., 1997; Yue et al., 2000). PCA, however, might devaluate physically important parameters during its statistical calculation. Specifically, in consideration of the previous results that core plasma parameters can explain plasma etch processes well, it is desirable to include plasma variables in PCA (Baek et al., 2014; Park et al., 2015). Thus variable selection techniques which can extract physically meaningful wavelength from OES data should be incorporated into PCA in modeling plasma etching processes.

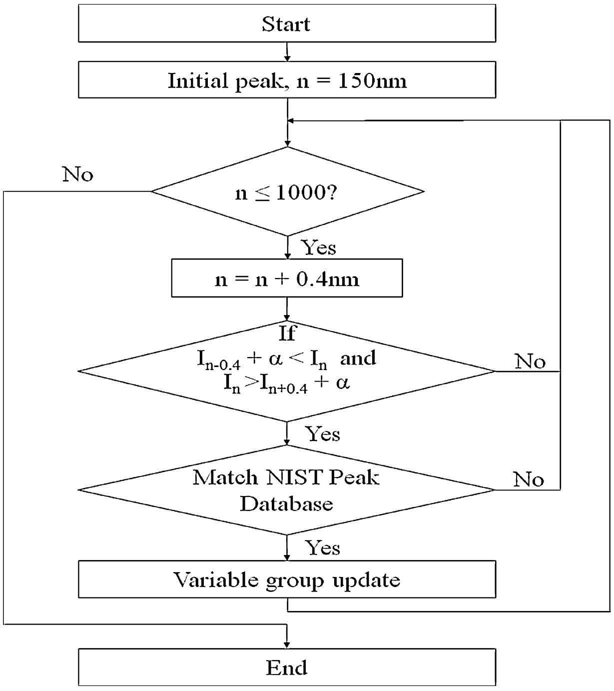

Fig. 2. Flow chart of a peak wavelength selection algorithm.

In addition, inherent noise from a CCD array in OES system might deteriorate PCA model performance. There are several types of noise associated with a CCD array (Ma et al., 2010; Goodlin, 2002). Firstly, photon shot noise arises from quantum detection of photons. Secondly, spontaneous photoelectron in the absence of photons is generated, which is called as dark current. Readout noise is also generated through electronic processing of signal. Lastly, there is pixel shift and drift, which is change in the location of the pixel as a function of time, possibly due to subtle mechanical vibrations.