Integrated Metrology and Advanced Process Control in Semiconductor Manufacturing

Arulkumar P Shanmugasundram Ph.D.,
Moshe Sarfaty Ph.D.,
Alexander Schwarm Ph.D.
Joseph Paik

Applied Materials,
3050 Bowers Ave, Santa Clara, CA 95054

Traditional semiconductor manufacturing relies on a fixed process-recipe combined with a classical statistical process control that is used to monitor the production process. Leading-edge manufacturing processes require higher levels of precision and accuracy, which necessitate the use of a tighter process control. Advanced Process Control (APC) has become a critical component to improve the performance, yield, throughput, and flexibility of the manufacturing process through run-to-run, wafer-to-wafer and within wafer control. The complexity of device manufacturing process as well as the strong coupling effect of several input parameters on the final process outputs prohibit the use of a classical single variable feedback control method. Therefore, a multivariate, model-based APC system has been developed in conjunction with feed-forward and feedback mechanisms to automatically determine the optimal recipe for each wafer based on both incoming wafer and tool properties. The APC system uses wafer metrology, process models and sophisticated algorithms to provide dynamic fine-tuning of intermediate process targets that enhance final device targets. The design of the APC system enables scalability of the control solutions from the levels of a single chamber, a tool, multi-tools, a module and multi-modules using similar building blocks, concepts and algorithms.

APC corrects for any systematic variations in process output due to variations in either tool-state or incoming wafer-state as shown in Fig.1. Typical tool-state example is consumable lifetime, such as pad and pad-conditioning disk life in CMP, and wafer-state relates to incoming wafer thickness and uniformity. Tool-state and wafer-state information is incorporated into the process model and compensated for accordingly. Wafer-state information can be either pre-measured prior to processing in the tool itself or fed-forward from an upstream process tool. Connecting the process tools enables better overall flow integration and optimizes the use of integrated metrology for both feedback control on the upstream tool and feed-forward control to the downstream tool.

Another benefit of APC is its potential to enhance tool productivity. In manufacturing environment, tool operators will typically pre-determine the tool maintenance schedule for each process tool and shut down the tool for regular maintenance regardless of its process performance. With integrated metrology monitoring parameters like deposition thickness, film properties and particle adders, a process chamber can often be run well beyond the established maintenance schedule. Any process drift due to chamber cleaning state can be stopped in real time without losing valuable product wafers, thereby, increasing tool utilization and reducing the need for non-product monitor wafers.

APC can be classified by the frequency of the control action, i.e. real time, wafer-to-wafer, lot-to-lot. In all three cases the film properties to be controlled can be average per wafer or within wafer uniformity. See Fig.2

(i) Traditional lot-to-lot process control monitors wafers after processing, using external metrology, and does not provide a rapid response back to the process tool. Thus, potentially allowing some scrapped lots. This is particularly unacceptable for larger wafer sizes.

(ii) Wafer-to-wafer control provides control every wafer within a lot independently, since wafers are monitored as they exit the processing chamber and adjustments are made rapidly to the process for subsequent wafers. In this case, integrated metrology (inline) is of critical importance to achieve quick feedback of any process variation or excursion. The integrated metrology can be used to measure both average and within wafer uniformity.

(iii) Real time process control enables change of the processing parameters for each wafer while it is being processed based on information from in-situ sensors monitoring the conditions of the process chamber and/or the film properties. This technique is the most powerful for process control. Existing in-situ sensors have been used primarily to control average wafer-level film properties. Currently development is underway to extend in-situ sensors to enable within wafer control.

Results using Applied Materials' *i*APC^{TM} and ProcessModule^{TM} products will be discussed to illustrate both wafer-to-wafer and within wafer control using integrated and in-situ metrology for various critical semiconductor applications.

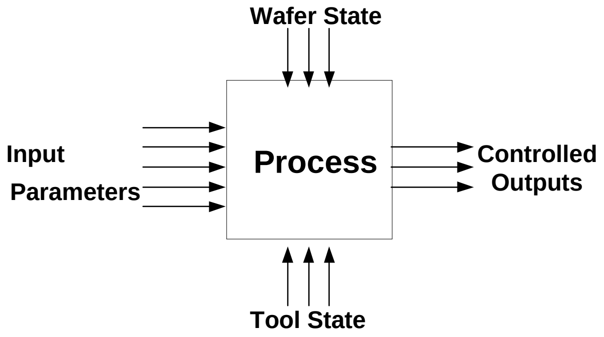

Fig.1 APC Inputs and Outputs

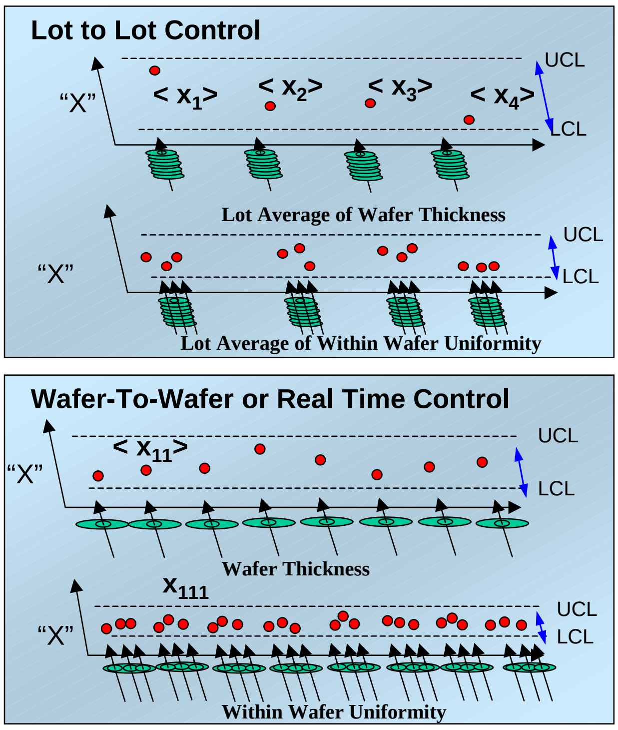

Fig 2. APC Classification