Moving Multi-Input, Multi-Output Advanced Process Control from Pilot Line to Production Line

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The need for advanced process control (APC) in the semiconductor industry has been established, and the benefits have been demonstrated. Multiple-input, multiple-output (MIMO) control is rapidly becoming mandatory for semiconductor manufacturers.[1] The question facing decision-makers is not whether to adopt MIMO APC, but rather what form of MIMO APC to adopt and where to adopt it in a manner that minimizes cost and risk while maximizing payback.

This paper reports on the recent technology transfer of a multi-input, multioutput (MIMO)[2] control scheme from R&D and pilot production to full-scale production. We concur with semiconductor industry leaders[1] that MIMO control is becoming mandatory. MIMO control extends single-input, single-output (SISO) control[3] to overcome its inherent control limitations, including the lack of simultaneous control of multiple output parameters by varying multiple-recipe parameters at run time using integrated feed-forward and feedback loops. With integrated feed-forward and feedback, the feed-forward loop compensates for variation in input material, and the feedback component takes care of temporal (drift over time) and spatial (chamber-to-chamber and device-to-device [i.e., part/number (P/N)-to- P/N]) variations.

To compensate for all the sources of process variation, semiconductor manufacturers need to immediately adopt MIMO control for reducing lot-to-lot (L2L) variation and rapidly move from L2L and wafer-towafer (W2W) control to real-time wafer-level (WL) control.[4] Given the availability of BCT's real-time controller, the only impediment to implement all three levels of control (L2L, W2W, and WL) is the availability of adequate metrology data. L2L control requires measurements for each incoming lot; W2W requires measurements for each wafer of a lot; and real-time WL control requires several integrated measurements.

I. Model-Based Control for Etch

The etch process, with its complex interactions between the plasma and the substrate surface, does not lend itself easily to first-principles modeling. It is possible, however, to build phenomenological models and design experiments to derive relationships between etching characteristics such as microloading (difference between the CD on dense structures vs. isolated structures) or post etch CD (FI CD), or within wafer CD uniformity and carefully selected process variables.

Building the Feed-Forward Model

The BCT feed-forward (FF) control model was built using the well-known technique of response surface modeling. The general flow of building and deploying a control model is illustrated in Figure 1. The control goals are the output parameters essential for device performance. For polygate etch, the primary process control goal is the final inspect gate width (FI CD) target. The process will also have other secondary goals including within wafer uniformity, gate profile, and microloading, which measures the etch dependency on pattern density.

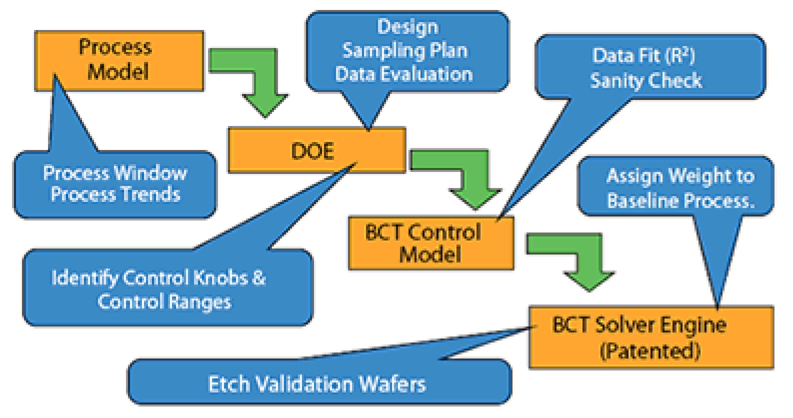


Figure 1. BCT Feed Forward Model Development Flow

Building the Control Model at the Pilot Facility

At the pilot facility, BCT's FF control model was built to control FI CD variation, microloading, within wafer CD uniformity, and line end shortening (LES). Although FI CD variation was the primary goal, it was imperative to achieve control of the primary goal without deteriorating multiple secondary goals performance. This is where the power of MIMO control is realized – all process output goals can be simultaneously controlled for optimal results.

The function of BCT's MIMO control engine is to produce real-time recipe adjustments for each run that, according to the control model, will produce an output satisfying all process constraints and goals. Each run is characterized by measured data such as DI CD values, resist profile, and film thickness. An engine capable of solving models with both nonlinear as well as linear equations and constraints is desirable. BCT's patented engine is particularly wellsuited for solving semiconductor manufacturing problems because it finds solutions to control challenges by searching the process window efficiently in order to find adjustments that meet the specifications for all process goals simultaneously and in real time.

Validation of the Feed-Forward Model at the Pilot Facility

Model validation is performed after model construction. The validation step provides quantitative performance improvement data that can be used to validate the correctness and efficacy of the MIMO controller.

Figure 2 displays the benefits of BCT's MIMO control on the primary (FI CD) and secondary (microloading) control goal when compared with uncontrolled lots during model validation at the Cypress R&D facility in San Jose, Calif.

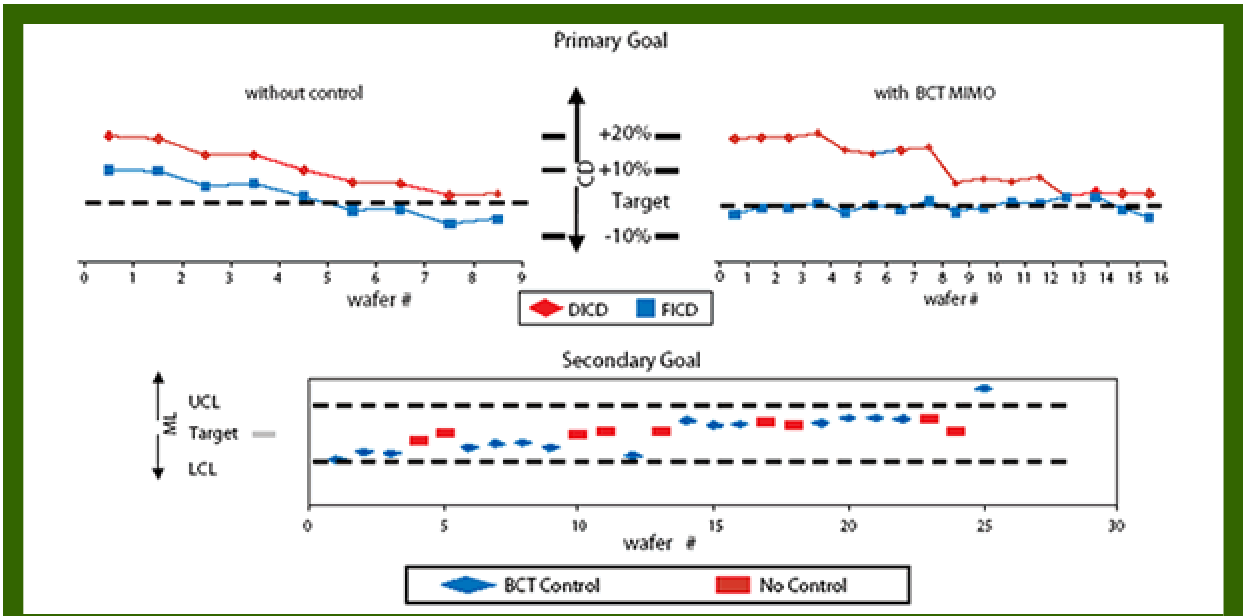


Figure 2.Model Validation Results. Data Courtesy of Cypress Semiconductor

Building the Feedback System

In feedback (FB) control systems, the actual (measured) results are compared with the desired (target) results, and control actions are based on the difference between measured and desired outcomes (so-called "error"). BCT uses negative feedback to control actions that minimize the error so that the system maintains homeostasis.

The BCT FB system is composed of three distinct components: outlier detector; average error estimator; and FF integrator. The outlier detector uses filtering algorithms to reduce the probability of making control decisions based on faulty data. The average error estimator uses a weighted moving average of the recorded error history to estimate the current error. The challenge in building high-fidelity error estimators is to build algorithms that minimize the penalties of out-of-order data and metrology data lag. Finally, the BCT FF integrator receives the vector of error estimates and forwards it, so that the BCT FF controller can modulate its recipe parameter adjustments to eliminate the observed error by adjusting the FF model or defining adjusted targets.

The BCT FF control model is augmented with two functions for modeling and handling chamber-to-chamber and device to-device (P/N-to-P/N) variation.[5] The chamber-to-chamber and device-to-device functions can be as simple as constants or as complex as the full-scale response surfaces of the available control knobs. Initial estimates for calibration functions can be obtained by running one to three wafers. (One wafer suffices for relatively noise-free environments.) To maintain initial simplicity, BCT suggests that semiconductor manufacturers use constant functions to gain immediate benefits and gradually migrate to non-constant functions as part of continuous improvement.

II. Manufacturing Integration

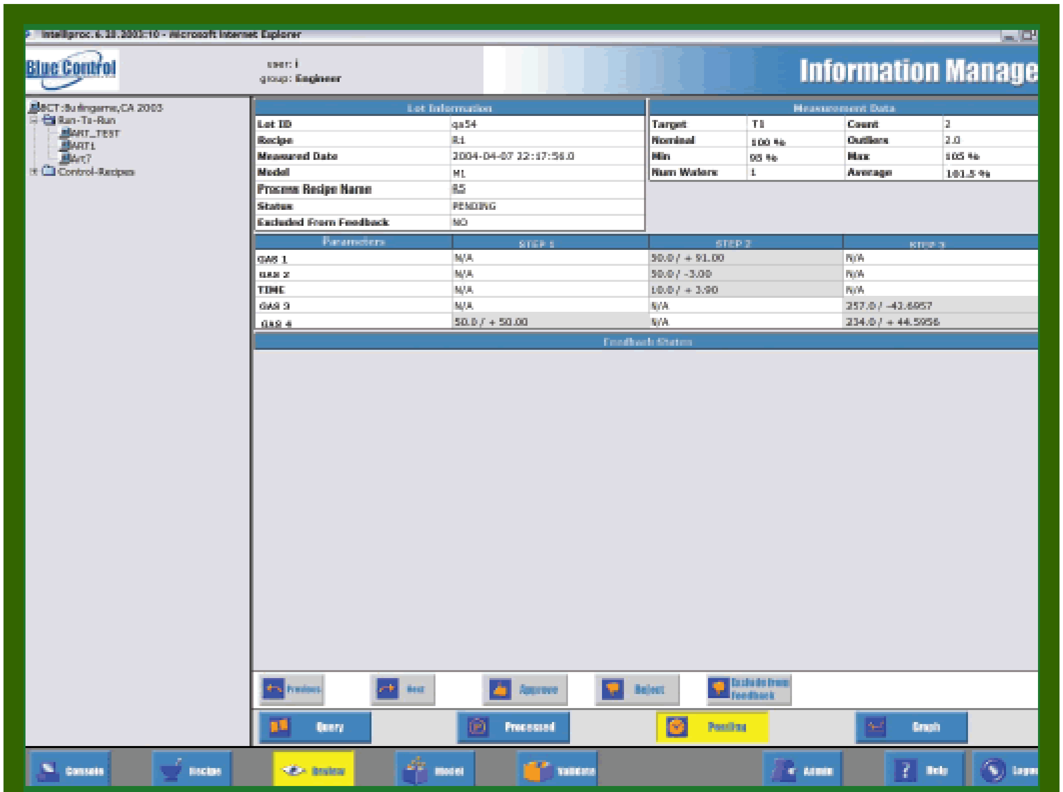
It is necessary to address both technical and user-adoption issues when transferring APC technology from configuring the system for the wafer workflow and line logistics, and determining total system reliability. Dominant user acceptance issues include suitably designed GUIs, enduser training, and overcoming psychological barriers to the adoption of technology.

Technical line-integration risks are minimized when the architecture of the APC system supports well-documented “standards compatible” interfaces. Each connection point is likely to support a different application-level protocol (SECSI/II, HSMS, InterfaceA, InterfaceB, etc.) and the APC system’s native interface must also support these common interface protocols and include capabilities to communicate over a variety of transaction/transport mechanisms (HTTP, SOAP, JMS, CORBA, COM/DCOM, ODBC).

Adaptation to wafer workflow to support specific automation requirements must be done carefully. Different lines have different material handling practices and procedures (e.g., rework lots, “hot lots”, etc.) and this variation can be significant from line to line. BCT’s APC products address this concern by including an adaptable workflow engine. Such an approach retains the ability to adapt to existing wafer workflow but also enables the incorporation of business rules to support the unique practices of individual production lines.

Our approach to overcome resistance to adoption is based on end-user education and training, user-centered GUI design, and semi-automated (“test drive”) deployment.

User education and training provides users with the knowledge necessary to understand the system. Involving end users early in the system-design process enables the creation of more acceptable user interfaces. The importance of BCT’s semi-automated deployment cannot be over-emphasized. Here, the end user is given the ability to see incoming material measurements and the recommended recipe adjustments. The end user can either use the APC recommendations or reject them to use the default recipe. After the material has been processed, the user can review the input measurements, recommended adjustments, and output results. Such a semi-automated mode provides users with the ability to incrementally gain confidence with the APC system. Figure 3 shows a screenshot for semi-automated model deployment.



Lot Information	
Lot ID	qa54
Recipe	R1
Measured Date	2004-04-07 22:17:56.0
Model	M1
Process Recipe Name	R5
Status	PENDING
Excluded From Feedback	NO

Measurement Data			
Target	T1	Count	2
Nominal	100 %	Outliers	2.0
Min	98 %	Max	105 %
Num Wafers	1	Average	101.5 %

Parameters	STEP 1	STEP 2	STEP 3
GAS 1	N/A	50.0 / + 91.00	N/A
GAS 2	N/A	50.0 / -3.00	N/A
TIME	N/A	10.0 / + 3.90	N/A
GAS 3	N/A	N/A	257.0 / -41.6957
GAS 4	50.0 / + 50.00	N/A	234.0 / + 44.5956

Figure 3. IntelliProc MIMO APC in semi-automated mode

BCT transferred the MIMO control from the pilot line to the full-scale production line with a copy-and-calibrate process. The model was copied exactly to the production line and calibrated with three wafers to compensate for tool-to-tool changes. Finally, the distributed-service-oriented architecture was adapted and configured to comply with the production line wafer flow and IT infrastructure. This resulted in a transfer that delivered the same quality of results as seen in pilot production without manufacturing line changes.

III. Conclusions

Transferring any technology from R&D pilot production to manufacturing production is always challenging – in particular when the technology purports to improve manufacturing efficiency. This paper demonstrates that BCT's MIMO control eliminates the limitations of SISO control. Integrated feed-forward and feedback loops with MIMO control must be considered mandatory for today's manufacturing facilities where control of critical parameters is essential for a guaranteed output of "good devices." This becomes even more critical at reduced operating nodes - below 90 nm.[6] BCT's MIMO control results are indicative of the power of the technique for real-time APC in semiconductor manufacturing (see Table 1).

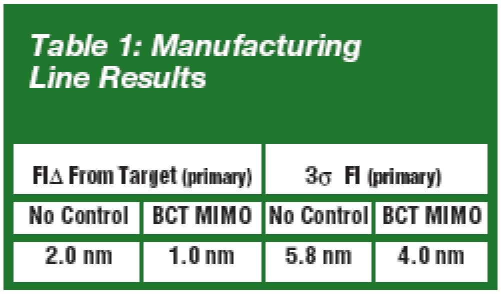


Table 1: Manufacturing Line Results

FIΔ From Target (primary)		3σ FI (primary)	
No Control	BCT MIMO	No Control	BCT MIMO
2.0 nm	1.0 nm	5.8 nm	4.0 nm

Current metrology throughput limitations can impede semiconductor manufacturers' ability to address all sources of process variation. Today, most semiconductor manufacturers support lotlevel metrology. Although this can be acceptable for 130 nm L2L control, the induced error for not compensating for W2W effects can be devastating for sub-100 nm manufacturing lines with aggressive specifications. With FI targets below 45 nm, it is also important to plan for WL control. Real-time control places demands on both metrology (in situ measurements) and control algorithm performance.

APC has come a long way since the days of weekly look-ahead wafers and periodic manual adjustments to single-recipe parameters. Semiconductor manufacturing control challenges of costs and yield in the future will be met only by semiconductor manufactures that actively seek opportunities to rapidly implement and deploy state-of-the-art MIMO APC solutions in their fabs.

IV. References

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