Model-based Control for Semiconductor and Advanced Materials Processing: An Overview

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Abstract: **A semiconductor wafer undergoes a wide range of processes before it is transformed from a bare silicon wafer to one populated with millions of transistor circuits. Such processes include Physical or Chemical Vapor Deposition, (PVD, CVD), Chemical-Mechanical Planarization (CMP), Plasma Etch, Rapid Thermal Processing (RTP), and photolithography. As feature sizes keep shrinking, process control plays an increasingly important role in each of these processes. We have found the model-based approach to be an effective means of designing commercial controllers for both semiconductor and advanced materials processing. It is our experience that the best models for control design borrow heavily from the physics of the process. The manner in which these models are used for a specific control application depends on the performance goals. In some cases (e.g., RTP), the closed-loop control depends entirely on having very good physical models of the system. For other processes, physical models have to be combined with empirical models or are entirely empirical. The resulting controller may be *in-situ* feedforward-feedback or run-to-run controller, or a combination thereof. The three case studies that are presented in this tutorial session (RTP, CMP, and PVD) are representative of the applications in this industry. Highlights of the session include physical modeling, model reduction and sensor selection, and feedback and run-to-run controller design.**

I. Introduction

A semiconductor wafer undergoes a wide range of processes steps before an integrated circuit is produced. Figure 1 illustrates some of the steps in the manufacturing of an Ultra Large Scale Integrated (ULSI) Circuit such as a microprocessor. The key steps are deposition (physical and chemical vapor), lithography, etch, rapid thermal processing, and chemical-mechanical planarization. The standard practice for many years has been to perform these steps in batches on many wafers at a time to produce large numbers of identical chips. In response to the demand for ever smaller critical dimensions of the devices on the chip, and to give more flexibility in the variety and number of chips to be produced, the makers of the tools for fabrication of integrated circuits have turned to single-wafer processes which require precise control. *Interestingly, the processes that make the chip are now beginning to use controllers which require the computational power of the chips being fabricated.* Another trend is to conduct several related steps in a "cluster" comprising of several chambers integrated into a single machine.

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The processes that deal with producing the integrated circuit (IC) on the wafer are commonly referred to as "front-end" processes, whereas "back-end" processes deal with wire bonding and packaging the IC. In this paper, we will focus on the "front-end" processes that produce the IC on the silicon wafer, and the increasingly important role of control. These front-end tools are used in a few hundred process steps to produce a ULSI circuit on a wafer. Thin layers of electrical conductors, semiconductors, and insulators are deposited with intervening steps that implant and activate dopants, anneal, etch patterns, or polish the wafer surface. A thin film deposition process may be a Physical Vapor Deposition (PVD) where the source atoms are transported to the wafer by various means or may involve chemical processes in which case it is called Chemical Vapor Deposition (CVD). Both PVD and CVD can be driven by thermal processes such as Rapid Thermal Processing (RTP) for post-implant anneal and Rapid Thermal CVD for oxidation, silicon epitaxy, etc. Plasmas are also used to drive PVD and CVD processes, and used for etching dielectrics and metal in building the ICs, see Figure 1.

For several decades, semiconductor manufacturers focused on finding processes that were passively stable (i.e., processes that were insensitive to input variations). The process engineer used experimental trial-and-error approaches to specify processing protocols (*recipes*) for various process steps. But this approach has become increasingly difficult to sustain over the last decade as the semiconductor industry extended Moore's Law well into the future by increasing the spatial density of ICs as well as increasing the size of wafers to 300 mm in diameter. For example, AMD's new Opteron microprocessor packs over 100 million transistors on a die area of approximately 180 mm^2 [1]. These integrated circuits with 0.13 μm feature size have ultra-shallow junction depths of a few hundred Å. Such increasing densities and shrinking feature sizes result in increasingly tighter tolerances, which means there is less slack (i.e., "error budget") available in the manufacturing process. Hence precision control is becoming a necessity. As a result, integrated computer-controlled wafer fabrication is playing an increasingly important role in the semiconductor industry [3].

The starting point for such a model-based control design strategy is to understand the physical processes, followed by derivation of mathematical models. The high-order models are tailored for control through model-order reduction and are validated using experimental data. Finally, feedback controllers are designed using these reduced-order models and tested in closed-loop simulations before the control code is downloaded on to the real-time computer used for equipment control.

The objective of the tutorial session is to describe the use of control technology in semiconductor and advanced materials manufacturing. In this overview paper, we briefly survey the control issues for some of the important front-end tools followed by discussions on modeling for control and some of the control strategies adopted in the industry including feedback and run-to-run control. In the three following papers we describe in greater detail the application of modeling and model-based control to three processes: RTP, CMP, and sputter PVD.

II. Overview of Typical Wafer Processing Equipment

As described earlier, there are many process steps required to produce a ULSI circuit on a wafer. The physical processes can be organized into groups that approximately correspond to the type of equipment that would be used to perform that process. In this section we discuss some of the important types of semiconductor processing equipment and the related control issues. Specifically we discuss PVD, CVD, thermal, etch, photolithography, and CMP systems.

An understanding of the aims of various semiconductor processes helps one better understand the function of the associated equipment. At the start of the wafer processing chain, large cylinders of single-crystal silicon are sliced into wafers, ground to a specific thickness (e.g., 300 mm diameter wafers are 0.775 mm thick) and polished to be smooth. A thin layer of epitaxial (i.e., single crystal) silicon, or "epi", is deposited using chemical vapor deposition (CVD) and the wafer is ready for use in a fabrication facility (commonly called a fab). All the transistors (and diodes, resistors, etc.) are fabricated on this epi layer. After fabrication, the transistors are electrically interconnected. Figure 1 shows a sample sequence of the processing steps. This example illustrates how one can produce a localized region in the wafer that has different electrical properties (P- or N-doped) than its surroundings. Figure 1 shows an oxide layer being deposited (or formed by oxidizing surface silicon), a pattern being etched into the oxide to expose a specific pattern of silicon, impurities being subsequently implanted into the exposed silicon, and finally those impurities being diffused to form a localized region that is electrically distinct.

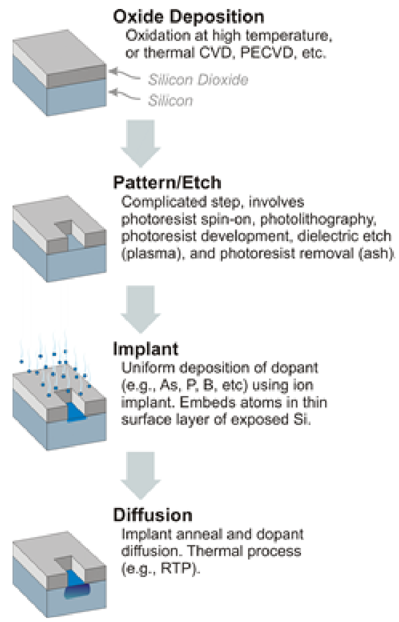

Figure 1. Some representative process steps for producing an integrated circuit.

In a typical IC there can be hundreds of steps and multiple layers of metal interconnect inlayed into patterned dielectric [6]. However, the main point to be made here is that many iterations of deposition, planarization, photolithography, etch, and more deposition and planarization is a central characteristic of integrated circuit fabrication. A more detailed exposition here is beyond the scope of this paper, and the interested reader should consult a standard book on this subject, e.g., [6]–[8].

For the control engineer interested in controlling the processing equipment, the main issues can be summarized with the following five questions:

1. What is the process (physics)?
2. What are the actuators (inputs)?
3. What sensors are available (outputs)?
4. What is the performance metric?
5. What are the disturbances and uncertainties?

In the remainder of this section, we will briefly discuss these five aspects for the functional classes of semiconductor equipment that were noted earlier.

A. PVD

Physical vapor deposition (PVD) systems are used to deposit thin layers of material on the wafer, and share a few common characteristics that include vapor production at a source (or sources), vapor transport to the wafer, and surface layer growth without any chemical reaction taking place either in the gas phase or on the wafer surface. Whether the system be electron-beam evaporative PVD, sputter PVD (Radio Frequency (RF) diode or magnetron sputtering), thermally evaporated PVD, or Molecular Beam Epitaxy (MBE), all involve transport of a non-reacting vapor from a source (e-beam, sputter target, etc.) to a destination (i.e., the wafer). Models for PVD systems generally involve vapor generation at the source and transport between the source and wafer. Other models may involve film growth.

Most of these PVD systems have low chamber pressure. Chamber pressure and gas flows are usually the actuators. Additionally, electrical power for producing the vapor is commonly an important dynamic actuator. In plasma sputter systems, an electrical gas discharge (plasma) interacts with one of the electrodes (the sputter source) to produce a vapor that is transported across the chamber to deposit on the wafer. In thermal sources, a material is heated until the evaporation (or sublimation) from its surface is at a desired level. This evaporation usually depends exponentially on source temperature – an important non-linearity and sensitive actuator. Apart from chamber pressure and gas flow rates, the most important variable is usually deposition rate and its spatial distribution. For most PVD systems it is difficult to accurately measure deposition rate directly, although techniques are available (quartz crystal rate monitors, optical ellipsometers, tunable diode laser atomic absorption (TDLAA), and reflective high energy electron diffraction (RHEED)). A considerable signal processing effort is usually needed for real-time feedback control of PVD. As in all deposition systems, the primary performance metric for PVD is commonly the thickness (and its uniformity) of the deposited layer as well as the throughput (wafers per hour). The conflict between these two goals (uniformity and throughput) often contribute to disturbances: if one could wait until temperatures, pressures, and gas flow rates were completely steady, then one would not experience drift in these variables during process. However, this approach would reduce throughput. Therefore, a common source of disturbance is that the systems never reach steady-state.

B. CVD

In contrast to PVD, *chemical vapor deposition* (CVD) involves chemical reactions as part of the film deposition process, either in gas phase or on the surface of the wafer. As with PVD, there are several types of CVD processes. In atmospheric pressure CVD (APCVD), the chamber is at atmospheric pressure and the gas flow is invariably horizontal. The deposition rates with low pressure CVD (LPCVD) are lower than with APCVD but such rates are needed for growing thin films of, say, polycrystalline silicon. In plasma-enhanced CVD (PECVD) processes, a plasma is used to generate ions or radicals that recombine on the wafer surface to create thin films, e.g., of silicon nitride. In recent years, atomic layer deposition (ALD) which promotes self-limiting atomic layer-by- atomic layer growth on the wafer surface is gaining acceptance for deposition of “gap” dielectric materials in thin-film recording heads, capacitors in next-generation DRAMs, and for high-k dielectric gate stacks. Some CVD processes occur at relatively high temperatures (above 600°C), such as silicon epitaxy and oxidation where the growth rate is controlled by the rate at which the participating species are transported to the surface by flow and/or diffusion (i.e., transport-limited growth). At lower temperatures for a fixed pressure, growth rates are lower and there is generally a sufficient supply of reacting species. Here, chemical kinetics control the growth rate, and the process is referred to as kinetically-controlled growth.

Both transport (of fluid, heat and species) and chemical kinetics are important physical phenomena in CVD. Typical actuators in CVD processes include carrier gas flow rate and pressure, flow rates of the reacting species (or precursors) and substrate temperature. The performance metrics are thickness of the deposited film, and uniformity of film thickness and stoichiometry (the relative ratio of chemical species in the film). Possible sensors for CVD process control are the ones mentioned earlier for PVD, as well as Fourier Transform infrared spectroscope (FTIR) for measurement of film thickness. Disturbances and uncertainties include fluctuations in flow, precursor species supply, wafer properties, and substrate temperature.

C. RTP

Another broad class is *thermal processing* systems. These systems typically involve ramping up and ramping down the wafer temperature in a controlled way to facilitate some thermally-driven process such as oxidation, anneal, diffusion, or chemical vapor deposition (CVD). In the case of implant anneal, an ion implant system (a type of PVD process) first implants a layer of dopant (e.g., boron or arsenic atoms) into the surface layers of a wafer. The impact of these atoms (ions) causes damage to the crystal structure that must subsequently be annealed using a thermal process where crystal defects diffuse out of the wafer. To prevent excess diffusion of the dopant away from the surface and provide the thinnest possible layer of doped (and activated) semiconductor material, it is desirable to use RTP to anneal the damage. In RTP equipment, one can typically raise the temperature quickly (200°C/s or more) from a low temperature to 1100°C while maintaining good within-wafer uniformity. In addition to rapid thermal anneal (RTA), rapid thermal oxidation (RTO) and other processes use RTP equipment. Modified single wafer RTP-like systems are also used for CVD (RTCVD). Other types of thermal processing are done using furnaces where large numbers (25+) of wafers (batch) can be processed at once. These batch furnace systems tend to be slower in terms of ramp-up, ramp-down, and process times, but the time per wafer can be high if enough wafers are processed at a time. Historically almost all thermal processing was done using batch furnaces, but the trend is increasingly toward single wafer systems, because of better control of the individual wafers.

The dominant physical phenomenon in RTP is radiative heat transfer. Actuators in RTP are the lamps that heat the wafer. Typically multiple lamps are used to provide a high spatial resolution across the wafer as well as high power to quickly heat the wafer. Sensors typically include pyrometers, which are ideal sensors for measuring radiation of moving objects (rotating wafer). Uncertainties in RTP include radiative properties of wafer and chamber walls.

D. Etch

An important class of equipment is *plasma etch* systems. In these systems, a plasma, which is an ensemble of ions, radicals and electrons in an overall-neutral gas, is "ignited" within the chamber by applying sufficient voltage discharge between two electrodes, one of which maybe the chuck supporting the substrate. The applied voltage usually has an AC component of desired frequency (such as the popular radio-frequency of 13.56 MHz as well as 450 kHz, 2 MHz, 4 MHz, etc.) with a DC bias. The ions that are driven to the wafer surface by the bias may be used to etch the layer on the wafer surface, e.g., a dielectric layer. If the ions do not react at the surface but physically dislodges the surface atoms, the etching is called sputter etching, and is the reverse of sputter deposition. If in addition to sputtering, the ions also react with the surface atoms to form gaseous products, the process is called Reactive Ion Etching (RIE).

The key phenomena governing etch, are plasma physics and chemistry, followed by heat and species transport. While pressure, mass flow, and impedance match controllers are used for subsystems, end-point controllers can be used to control the etch process itself. *In-situ* sensors for end-point control include laser interferometry that uses interference effects of the thin film, laser reflectance measurements that uses differential reflectance between the layer being etched and the underlying layer, optical emission spectrometers (OES) that detect changes in the plasma emission during the etch process, and residual gas analyzers (RGA) that use mass spectrometers to detect changes in the gas composition as etch proceeds. Actuation is achieved using the plasma power, chamber pressure, and the flow of fluorocarbon etch gases. There are several uncertainties and disturbances related to the plasma such as transients and chemistry.

E. CMP

The next class is chemical mechanical planarization (CMP). When multiple layers of oxide and metal are deposited onto etched surfaces the resulting surface is typically not flat. CMP is used to produce a planar mirror-like wafer surface for subsequent processing by smoothing a nominally macroscopically flat wafer to almost atomic level. A typical rotary CMP machine consists of a rotating wafer pressed onto a grooved rotating platen containing abrasive slurry. The slurry chemically reacts with the wafer surface to be polished, and the pressing rotating action typically abrades the surface atomic layer-by-atomic layer. The major problems in CMP are controlling the material removal (or, equivalently, the material removal rate) and the uniformity on each run, and reproducibility from run-to-run. The goal of CMP processing is to achieve a specified thickness and uniformity in a repeatable fashion. Actuators for a rotary CMP machine are applied pressures, wafer and platen rotation speeds and slurry flow rate. Sensors for CMP include eddy current and optical sensors for measuring film thickness, motor current sensors for measuring friction, and temperature sensors.

F. Lithography

Lithography is the semiconductor industry's key enabling technology. It is directly responsible for increasing transistor densities and shrinking feature sizes. Optical lithography continues to extend its application with the use of 157nm technology for 90nm to 65nm nodes. Lithography is the process of defining useful shapes on the surface of a semiconductor wafer. Typically this consists of a patterned exposure into a photosensitive material (photoresist) already deposited on the wafer. Ultraviolet light from an arc lamp passes through a mask bearing the image of the circuit. A complex lens apparatus reduces this image and projects it onto the photoresist. The photoresist, a polymer coating, reacts to the light; the exposed area is then removed with a solvent. This technique is called photolithography, and lithography machines are called wafer steppers, because a wafer is processed in an alternating fashion of moving (stepping) the wafer and exposing that part which is underneath the lens. The positioning of a wafer under the lens is performed by a wafer stage, and the mask can be moved as well using a reticle stage. Since the positioning of a wafer has a large impact both on the achievable throughput and yield, the overall performance of a wafer stepper is largely determined by its stages. Consequently, these stages need to have extremely high positioning performance. Laser interferometry is used to measure the position of a stage with sub-nanometer accuracy. Typically, (linear) electro-motors are used to drive a stage. Control problems include aligning the wafer with the optics, stepping the wafer with high speed, synchronizing the wafer and the reticle stage, and suppressing disturbances such as friction and thermal disturbances [7], [8], [10].

III. Modeling of Semiconductor Processes

Mathematical models that are based on the physics and chemistry of the manufacturing process provide valuable insight into the complex interactions between the various process variables that directly affect the quality (i.e., performance, reliability, etc.) of the final product. Such modeling of semiconductor processes is a prerequisite for advanced sensor-based real-time process control. Predictive process models are crucial to optimal control of such processes.

Over the last decade, extensive modeling studies have been undertaken to understand the fundamental physical processes underlying semiconductor processing. The emergence of the Virtual Integrated Prototyping (VIP) approach in the early nineties for the semiconductor and the advanced materials processing industry has involved the complete design of the processing system first on computer. The designs are tested in simulation for performance, and necessary changes are made to the design. The iterative process is continued until an optimal design that meets the performance specifications is obtained before commencing on the expensive process of building a machine.

Sophisticated multiscale models have been developed for a wide range of processes such as PVD (electron beam, thermal, sputter, MBE), CVD, etch, etc., that predict the dependence of process performance on process parameters. For RTP in particular, detailed thermo-fluid models are now available. If all the model parameters are known with sufficient accuracy, these models can accurately predict important performance metrics, e.g., within-wafer non-uniformities (spatial and temporal) in temperature, film thickness, and stoichiometry as a function of the inputs, e.g., dynamic heater power, gas flow rate, reactant concentration and distribution, etc.

A. Modeling for Control

The increasingly accurate and sophisticated physical modeling activity has been recognized by the semiconductor industry as a laudable effort leading to a better understanding of the equipment and processes in general. However, there persists a perception that physical modeling may not be adding sufficient value to the company's overall goals. Our experience indicates that there is often a significant gap between the modelers (who often happen to be physicists, chemists, and mathematicians), and the equipment designers (who are predominantly material scientists and chemical engineers) and control engineers (mostly mechanical and electrical engineers and software experts). As a result, modeling efforts are often isolated from the activities that directly affect equipment and process development.

The physical models must be usable in four important areas of application: (1) equipment design and development, (2) process development, (3) sensing, and (4) fault diagnostics or troubleshooting. In the first two cases, the models are necessary for control design for robust performance over a wide range of process conditions. The models can also be used for testing limits of performance. As discussed earlier, there is the potential to reduce costs by speeding up the iterative design process by testing designs using models. In the third case, the models can be used as virtual sensors to decrease the number of sensors used and thus decrease costs while increasing robustness (less chance of sensor failure). Finally, models can be used as tools for rapid fault diagnostics that can decrease downtime.

As far as design of such a control system is concerned, processes such as chemical vapor deposition (CVD), physical vapor deposition (PVD), plasma processes (e.g., dry etching), and RTP have one thing in common: the need for modeling *for* control design. The models needed for control design differ somewhat from those used for study of the detailed physics of the system. The models for control design, whether feedback or feedforward, while capturing the essential physical phenomenon, are usually low-order and must be accompanied with uncertainty measures of the model. For use in real-time control, these low-order physical models must execute at least as fast as real-time, i.e., actual process time.

The high-order models, however, are not suited for the above applications because they are too slow. A static simulation of a RTP reactor model consisting of a few thousand state variables that solves the Navier-Stokes equations, the energy equations, and some chemical kinetics rate equations would take several hours on the fastest desktop computer. Closed-loop dynamic performance can be significantly different from open-loop static performance. However, a dynamic simulation for the process would take several days, and inclusion of further physics such as Boltzmann equation would make the simulation even slower. Consequently, these models, while valuable for studying the process physics or chemistry, are not used in an integrated modeling and control environment. The absence of fast but accurate low-order models has been strongly felt in the industry.

B. Types of Modeling

One distinguishes several types of modeling depending on the amount of information used from the real system. One side of the spectrum consists of physical modeling, also called analytical modeling or "white box" modeling, or first principles modeling. The model tries to describe the physics of the process, typically in the form of (coupled) partial differential equations (PDEs). Experimental modeling is on the other side of the spectrum, also called system identification or "black box" modeling or empirical modeling. No physical structure is imposed on the model, but a model is obtained on the basis of a finite amount of data extracted from the physical plant. Typically, a model for semiconductor processing equipment is a combination of the two types of modeling. In practice, we incorporate as much physical modeling as possible, and supplement physical models with empirical models as needed.

C. Model Reduction

The need for efficient algorithms for real-time model-based control design calls for fast, low-order, non-linear system models that approximate the behavior of the full-order nonlinear models in sufficient detail. A variety of techniques are available for model order reduction including aggregation, Hankel singular value using Gramians, principal orthogonal decomposition (POD), and even imagination! The POD method is a nonlinear model-order reduction method where reduction of the size of the state space is achieved using a singular value decomposition of a matrix of snapshots of the state vector. The state trajectory is projected into a lower dimensional hyperspace. Also in the linear case with infinite horizon, the POD is the same as the balanced model order reduction. We have successfully applied POD to RTP model reduction [9]. Although the order of the model is reduced by the use of the POD method, the number of computations typically remains high because the linear operators do not translate through the non-linear system equations. Since it is important that the low-order model be *fast* for control purposes, the POD method in its direct form is often not suitable for models needed for real-time feedback control for RTP. In contrast, aggregation is a technique in which both the number of state variables and the computational burden are reduced. In aggregation, multiple control volumes are combined into fewer larger control volumes to reduce the number of state variables. Invariably some engineering judgment is involved in this process, but with the proper tools for comparing results for various aggregations, it should be relatively easy to arrive at a suitable aggregation.

D. Model Validation & Tuning

Physical models often involve material and transport properties that are not available to the modeler. In such situations, one may use the closest data available in the literature. Additionally, it may not be possible to model all aspects of complex physical phenomena. Consequently, one often uses phenomenological relationships (e.g., heat transfer coefficients) which may work very well for control purposes. A multi-step chemical reaction mechanism may be very well modeled by considering only two or three of the important reactions. Depending on the relative importance of the various physical phenomena in a model, better estimates of these approximate values of the properties and parameters are obtained by *tuning* the model using experimental data from an actual system. Subsequently, the tuned model is *validated* by comparing model response with further experimental data for the same set of input signals. This model validation is performed over the full process space.

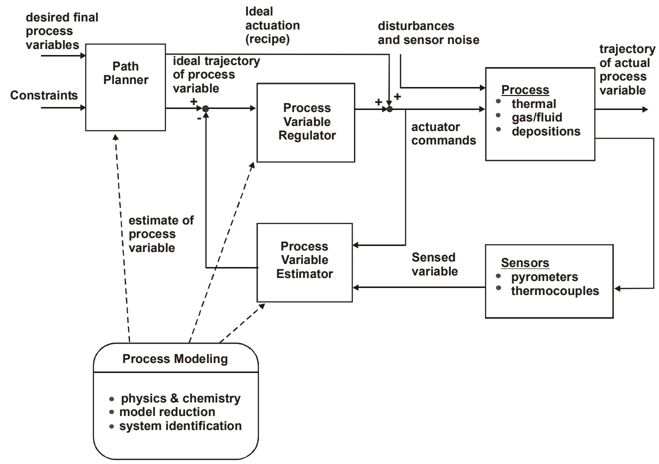

Figure 2. General control structure for semiconductor industry.

IV. CONTROL OF SEMICONDUCTOR PROCESSES

Figure 2 shows a general control structure that addresses the process control requirements. The three components of the controller are (1) the planner, (2) the regulator, and (3) the estimator. The feedback controller consists of the regulator and the estimator. The *planner* translates the desired product characteristics into an ideal (or nominal) set of process inputs (controls) and reference signals and is the feedforward controller. Depending on the process, the inputs might be constant or follow a very complex time history. If the model and the planner were perfect *and* there were no process disturbances, the planner would be all that would be required—but in the real world this is never the case. Thus, the *regulator* uses the difference between the desired product characteristics and those actually being produced to compute corrections to the nominal process inputs computed by the planner and is the feedback controller. Together, the planner and the regulator constitute the model-based control portion of the solution. A further complication arises because in many cases it is impossible to measure the relevant product characteristics *in-situ* (either because it is too expensive or the sensor has nor been invented yet). Thus, the *estimator* uses a model of the process conditions that can be measured in real-time. The estimator constitutes the model-based sensing portion of the solution. By using a process model, the estimator can be designed to infer the critical variables from the sensed variables. Hence, model-based estimation is a means to "transcend" inadequacies in sensing. The regulator and the estimator have to be on-line (real-time) functions. The planner is nominally designed off-line, but it could also be constructed to utilize feedback on a run-to-run basis.

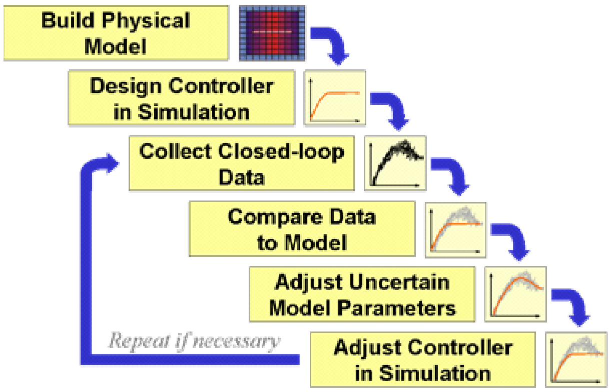

Figure 3. Model-Based control system design.

A. Model-Based Control

There are many advantages of the model-based control approach. The controller can be "tested" for a wide range of wafer/process variations in simulation. A physical model of the system can be modified to answer "what if" tests for equipment/process modifications. The approach provides the ability to perform controller development in parallel with chamber (reactor) development. In the semiconductor industry access to the equipment is a premium and it is a great advantage to be able to carry out the control system design without access to the equipment. The approach provides a tool for trouble shooting to respond to problems in the field. The model-based approach provides the opportunity for model-based fault detection isolation accommodation. It is generally true in the semiconductor industry that the next generation equipment is a modification of the current system. Hence the availability of the model provides a path for continued product improvement.

Figure 3 shows the model-based control design cycle. The first step in the development of a model-based controller is the development of a *physical* model which accurately reflects the actual behavior of the system to be controlled. For example, for a Rapid Thermal Processing System (RTP) a detailed thermal model of the system is developed. The model contains unknown physical variables that are identified from experimental data. A comparison of the model response with the actual system output provides a measure of model accuracy. The next step in the cycle is the development of the model-based controller. Using the model, we use a variety of advanced feedback control designs to derive candidate controllers. The closed-loop system is then simulated in a graphical block diagram simulation environment to assess the merits of various candidate controllers. Once a satisfactory controller has been identified which meets the specifications (e.g., temperature uniformity for RTP), real-time code can be generated automatically to run on a rapid prototyping platform which will control the equipment directly. The controller's performance on the actual equipment can be determined and design iterations can be carried out if necessary. When satisfied with a controller performance, the controller can be targeted to a variety of computers or embedded microprocessors.

B. Sensor & Actuator Selection

The key impediment in the use of feedback control in the semiconductor industry has been the lack of *in-situ* sensing. Fortunately, the industry has recognized the need for *in-situ* sensor development. An example is temperature sensing in RTP where pyrometric techniques are now the most commonly employed. Among the advantages of pyrometers are that they have very fast response time, and can be used to measure the temperature of moving objects (e.g., a rotating semiconductor wafer). The new trend in semiconductor equipment is the incorporation of Integrated Metrology (IM), which is the incorporation of a measurement system with a process equipment to take measurements during a process (i.e., *in-situ*), or at its conclusion without removing the wafer from the equipment (i.e., *in-line*). This is in contrast to traditional metrology where wafer is carried to the machine (i.e., *off-line or ex-situ*). We have already addressed the choice of actuators in several processes. Another new trend in semiconductor industry is to increase the number of actuators in order to obtain a higher spatial resolution across the wafer. Examples are the number of lamps in RTP, or the number of pressure zones in CMP. Increasing the number of actuators and sensors typically renders the control problem multi-input multi-output (MIMO) with strong coupling between all inputs and outputs.

C. Types of Control

At the highest level, control of a fab involves the control of wafer movements and scheduling of the individual pieces of processing equipment. Highly sophisticated and flexible manufacturing can only be achieved by a combination of complex scheduling and real-time control systems. The nature of the scheduling involves discrete event systems theory and related optimization. Robots are routinely used to automate wafer transport between process equipment, wafer handling within a process equipment, and within a cluster. Hence robotic control plays an important role in a fab. The next level is the control of the individual pieces of process equipment. Finally there are control of fluid and material flow, temperature, and pressure where the use of Proportional plus Integral (PI) [4] is ubiquitous. As already mentioned, there are at least five types of control strategies employed in the use of the process equipment: open-loop, end-point, *in-situ* feedback, feedforward, and run-to-run control.

Open-loop control has been the most common strategy until recently. End-point control uses an *in-situ* sensor to detect the end-point of the process, i.e., to detect when the desired process has been achieved, at which point in time the process is stopped. This type of control is common in processes such as etch.

In-situ feedback control is used for real-time feedback control using real-time sensors. Examples include temperature control in RTP using pyrometers and metal layer thickness control in CMP using eddy current sensors.

Feedforward control is employed through provision for nominal control settings as discussed above. Since we wish to move the system from one operating point to another along a specified trajectory, we can determine the approximate inputs to accomplish this. Consequently, we can apply this input directly to the system. The feedforward controller should approximate the inverse dynamics of the plant. An example in RTP is the use of nominal lamp settings and the associated temperature profiles. Another form of feedforward is the use of information on the end product from the previous equipment. An example in CMP is the use of incoming copper profile from the electroplating for the start of the planarization step.

Run-to-run control is a form of discrete process control in which a product recipe is modified using *in-line* or *ex-situ* metrology between "runs" to minimize or eliminate process drifts, and variability (due to the nonlinear nature of the relationship between product characteristics and what can be measured in real-time in the system) [11]. In effect the discrete process "sample rate" is the length of the process run. An example of run-to-run control is adjustment of sensor or reference temperature "bias" in RTP or adjustment of polish time in CMP.

D. Control Implementation

The use of custom embedded feedback control is becoming more critical in semiconductor manufacturing equipment. The controls for critical subsystems are performed by dedicated subsystem controllers. Rather than bringing back all the sensor information to a central computer, critical computations are done via dedicated microprocessor-based digital controllers.

V. Summary and Conclusions

As an introduction to the three papers to follow, we have provided a brief overview of the process modeling and control system design issues for some of the important semiconductor manufacturing equipment. Run-to-run control is now commonly used in the fabs. Due to increasingly stringent performance requirements, model-based feedback-feedforward control system design is becoming more prevalent. It is anticipated that during the current decade many more of the semiconductor fabrication equipment will employ sophisticated *in-situ* feedback control as new sensors become available. In parallel, sophisticated fault detection isolation accommodation algorithms will be implemented. It is anticipated that some process equipment, such as photolithography, will employ sophisticated iterative learning controllers. This adoption of complex closed-loop control systems by the semiconductor and advanced materials processing industries presents new challenges and opportunities for control system engineers. Progress in equipment scheduling and APC promise to bring the industry closer to the dream of "all light out" automated fab operations. It is important to emphasize that success depends on a multidisciplinary approach with material scientists, mechanical design engineers, process engineers, physicists, and control engineers all working closely toward providing an overall optimized system.

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