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SOME ASPECTS OF PROCESS CONTROL IN SEMICONDUCTOR MANUFACTURING

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ABSTRACT

This paper outlines some aspects of process control in semiconductor manufacturing. Starting with an outline of the semiconductor manufacturing process, the contribution will discuss temperature control of the chemical vapour deposition stage and the control of the wafer etching process, based on the industrial experience of the first two authors. Subsequently, the authors draw the attention of the semiconductor manufacturing community to the potential of properly tuned PID controllers for the achievement of simple and high performance control solutions.

KEYWORDS: Semiconductor manufacturing, process control, PID

1. INTRODUCTION

To be competitive in the global marketplace, semiconductor manufacturing increasingly relies on advanced process monitoring, modelling and control due to shrinking feature size and increasing wafer diameters [1]. In a similar comment, a 'future trends' report suggests that "high performance feedback control will be needed to achieve the small length scales required for the next generation of microelectronic devices" [2]; indeed, materials and processing issues are identified as one of the six applications, opportunities and challenges in the years ahead in this report. Similar comments are made by other such recent reports [3],[4]. Considering process control, it is suggested [1] that two distinct approaches are applied: statistical process control (SPC) and automatic process control. SPC refers to a collection of statistically based techniques that rely on quality control charts to monitor process quality [5]; the method is declared to be more a monitoring technique than a control technique, as no automatic corrective action is taken after an abnormal situation is detected. SPC is used widely in semiconductor manufacturing. Automatic process control uses process variable measurements to implement feedback and/or feedforward control to keep the process variable at a desired value in the presence of unmeasured disturbances. A number of review publications explore either or both methods, as applied to semiconductor manufacturing, in detail [1], [6]-[12].

This paper will give an outline, in Section 2, of the semiconductor manufacturing process. In Sections 3 and 4, respectively, the authors will report their experiences of how process control is used in the control of temperature for chemical vapour decomposition and in the wafer etching process. In Section 5, the authors will suggest that automatic set-up of PID controllers, using tuning rules, as a way forward. Conclusions are drawn in Section 6.

2. OUTLINE OF THE SEMICONDUCTOR MANUFACTURING PROCESS

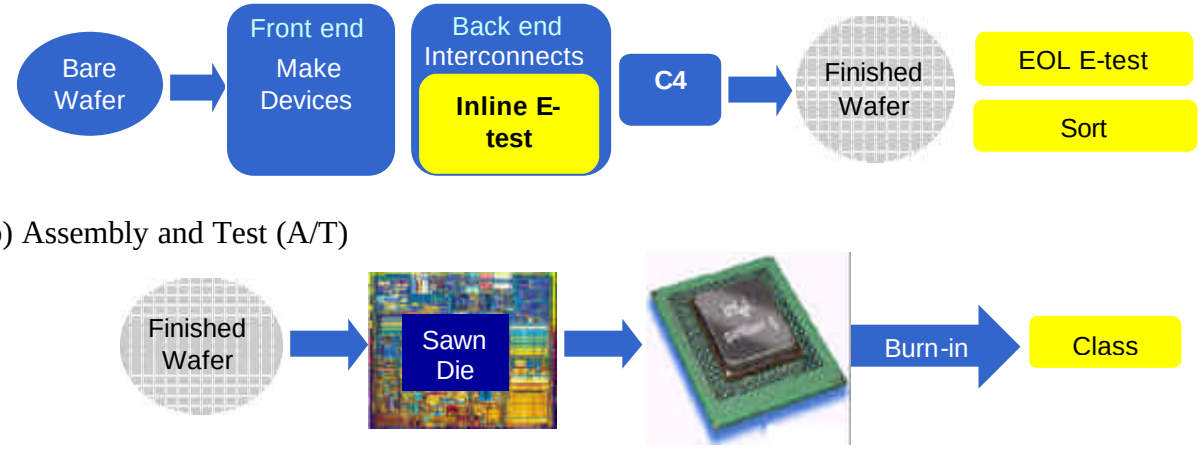
Process control is assuming more importance in semiconductor manufacturing as:

- Lost capacity due to system downtime, scrapped wafers and test and quality assurance activities is very expensive.
- The latest technology uses 65 nm feature sizes on 300 mm wafers. As devices get smaller, the margin of error becomes smaller, driving the need for accurate transient control systems that will facilitate the production of uniform, defect-free, semiconductors.
- Each wafer is subjected to an average of over 300 process steps in a number of weeks; each process step has to be controlled satisfactorily.

The "silicon to processor" stages may be summarised as shown in Figure 1. Figure 2 shows these stages in more detail. Further details are available [1].

The processing sequences vary, depending on the desired device characteristics. Most devices require multiple steps through the same process at different manufacturing stages. Important stages are the chemical vapour decomposition (CVD), lithography, etching and chemical mechanical polishing (or planar) stages. The control of the lithography stage is well documented in [1].

(a) Fabrication (Fab)



(b) Assembly and Test (A/T)

Figure 1: Manufacturing process (a) Fabrication (Fab) (b) Assembly and Test (A/T)

3. TEMPERATURE CONTROL FOR CHEMICAL VAPOUR DECOMPOSITION

Chemical vapour decomposition (CVD) is a chemical process that deposits a thin film of material onto a wafer. Reactant gases are introduced into a chamber and undergo chemical reactions with the heated wafer surface to form the desired thin film (Figure 3). Taking the example of plasma enhanced CVD, the final thickness of the film is a function of time, temperature, pressure and RF power.

One control objective is to maintain a uniform temperature distribution at all times inside the furnace, following a command signal that ramps up and down, with minimal overshoot. Temperature is measured using two thermocouples, one next to the heating element ('spike') and one inside the heating tube ('profile').

A cascade control structure is used (Figure 4). The outer (profile) controller receives commands from the processing recipe. Both controllers are in proportional integral (PI) form. The furnace model is determined using a least squares indentification approach. Saturation due to heating power constraints is overcome by using an anti-windup scheme. A typical closed-loop response is shown in Figure 5.

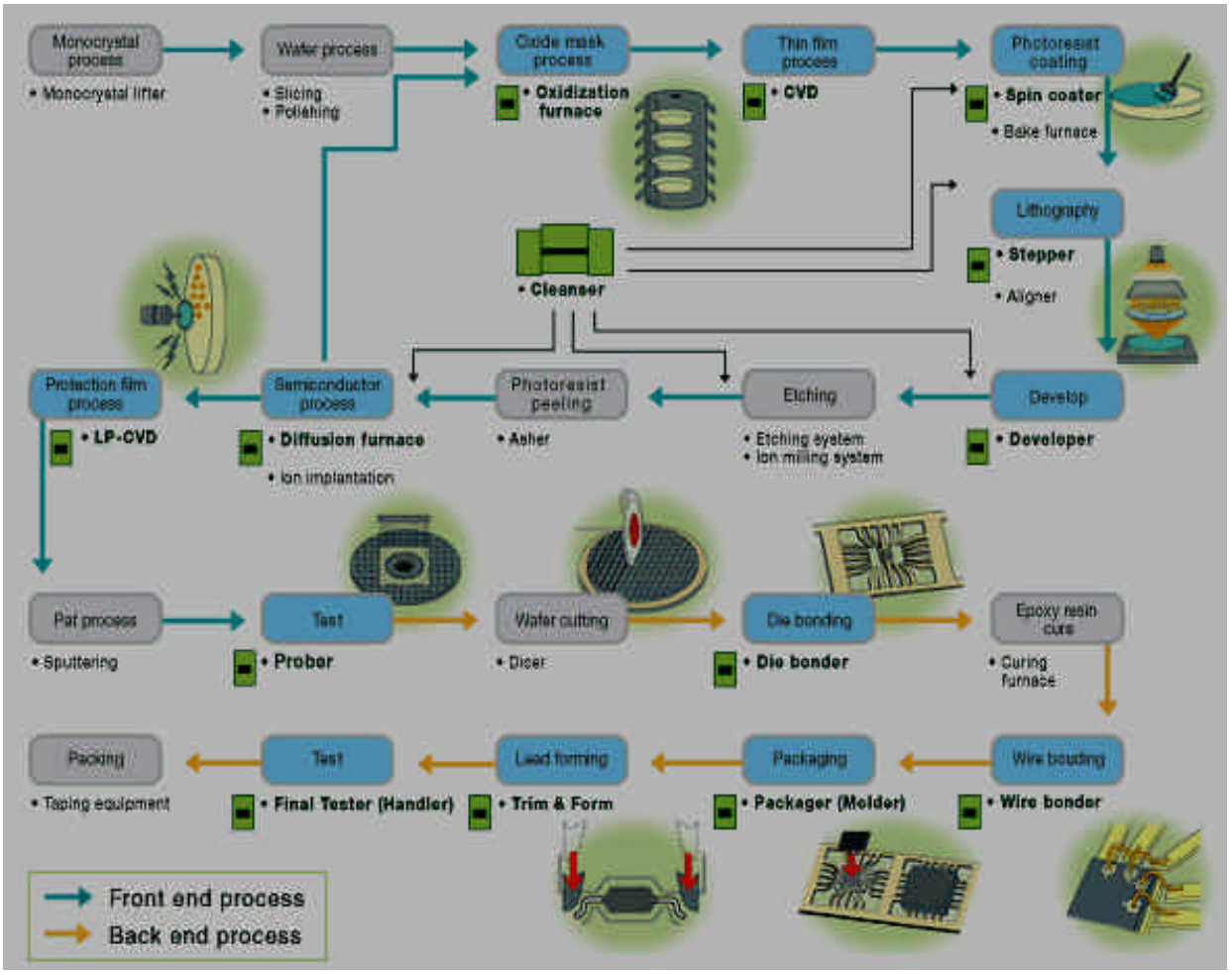


Figure 2: Manufacturing process: more details

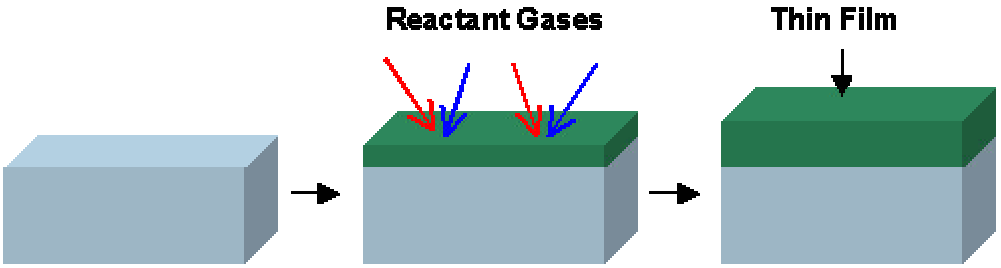


Figure 3: Chemical vapour decomposition

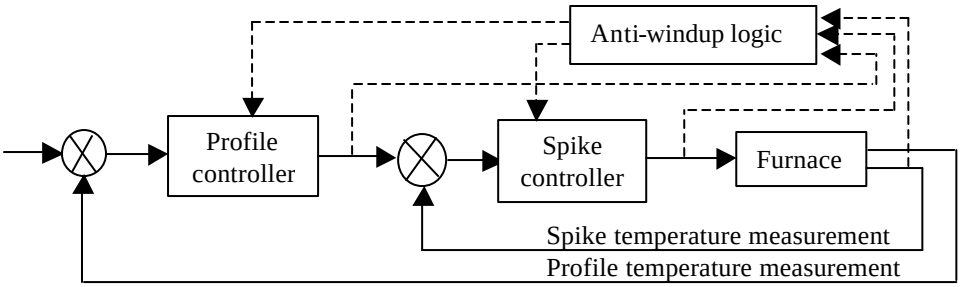


Figure 4: Temperature controller implementation

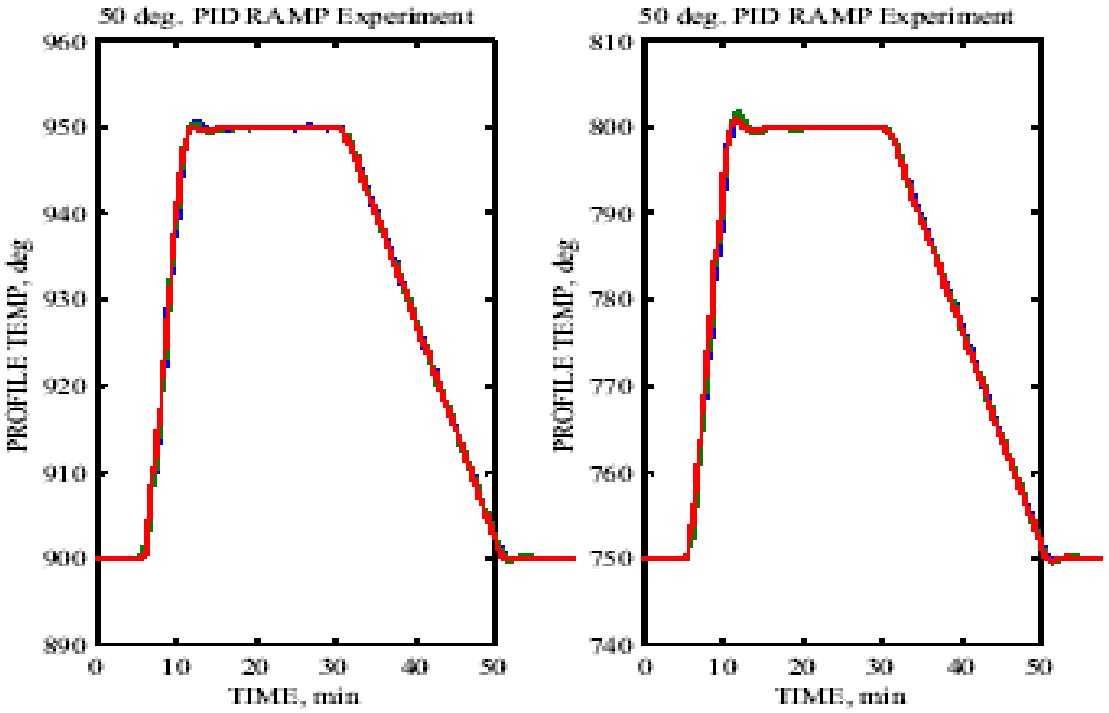


Figure 5: Typical servo response – profile temperature

4. THE CONTROL OF THE WAFER ETCHING PROCESS

Wafer etching is performed after photolithography; it allows selective wafer surface removal from the area not covered by photoresist material. It provides reliable device isolation and interconnections within the chip. Boron trichloride (BCl_3) is a typical etching gas.

During etching, the resist is consumed, preventing covered areas from been etched away. Boron trichloride is used to form a polymer on sidewalls, generating a barrier that inhibits lateral chemical etching. Figure 6 is a photograph of the result.

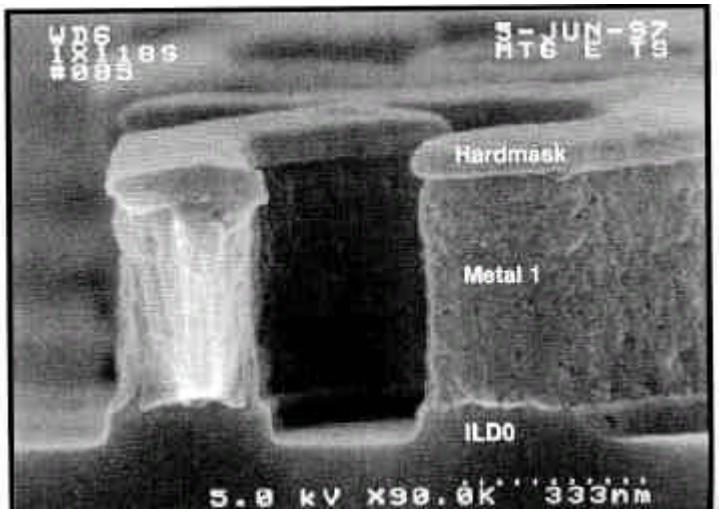


Figure 6

The amount of etching depends on chamber RF power, pressure, gas flow and temperature; the pressure control loop will be considered. SPC charts are used to ensure that pressures are within specified limits. Figure 7 shows the implementation of the pressure control system; the throttle valve is adjusted to maintain the chamber pressure. Typical charts, supplied by the first author, are shown in Figures 8 and 9.

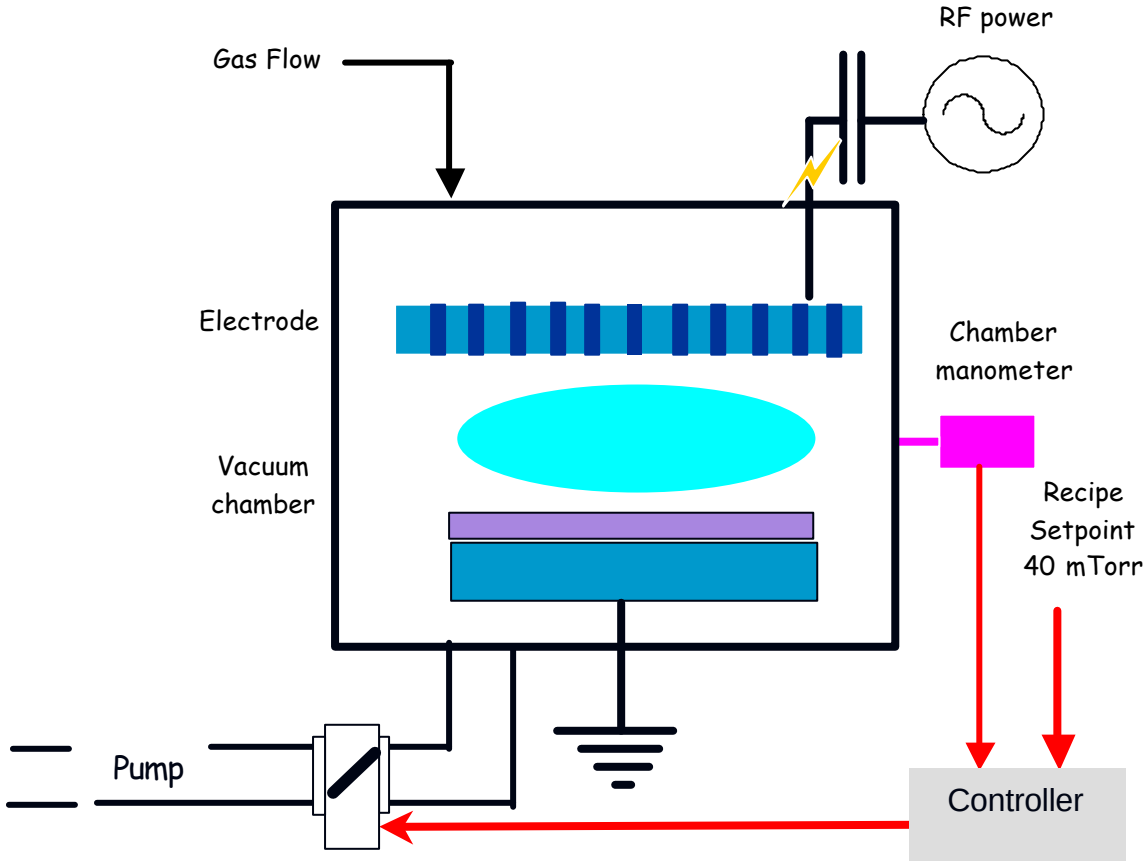


Figure 7: Implementation of the pressure control system

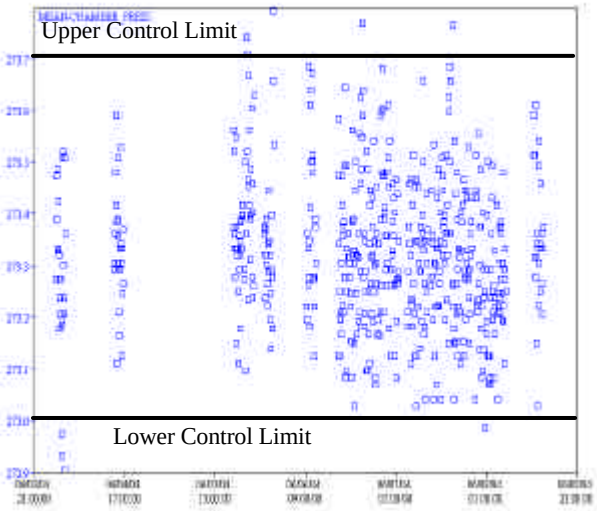


Figure 8: Mean chamber pressure

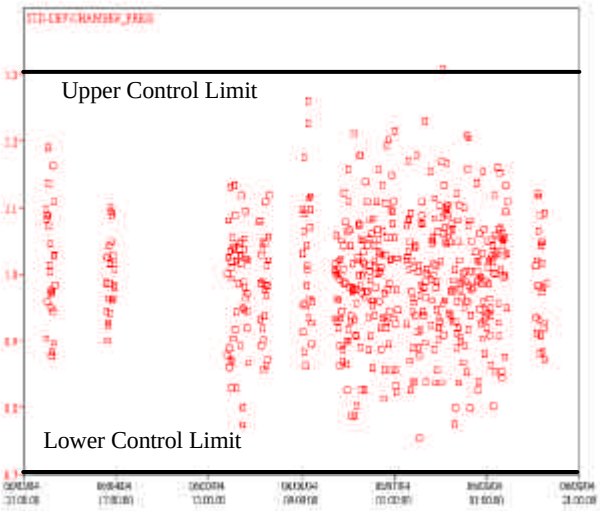


Figure 9: Chamber pressure – standard deviation

The SPC software is resident on the station controller. The software collects parameters such as pressure in real time. The SPC software summarises the data, and if limits exist, will check the data against the limits. Warning or abort alarms are posted to the station controller; the latter alarms halt the process and require action. All data files are uploaded to a central server.

5. TUNING RULES FOR PI AND PID CONTROLLERS

In Sections 3 and 4, two applications where process control is currently used have been considered. Though only one of these applications uses a feedback arrangement, the authors contend that such controllers will play a greater role in aspects of semiconductor manufacturing in the future. The use of feedback controllers require measurement of process variables, and the lack of real-time measurements has constituted a barrier [9]. Assuming this barrier can be overcome, perhaps with the use of non-invasive measurement methods [9], attention will shift to the best controller algorithm to use. The wide range of operations carried out in semiconductor manufacturing suggests that control strategies and systems will need to be robust enough to be used across a range of processes, yet be simple enough so that they can be implemented and used by non-experts. These factors suggest that the PI and PID controller, with their proven success in delivering control solutions over six decades, will become the dominant implementation strategy. Experiences with the use of PI and PID controllers have been reported in aspects of semiconductor manufacturing [9], [11], [13]-[15].

The action of the PID controller is briefly reviewed. Consider the ideal PID controller, for example, which is given by

$$G_c(s) = K_c(1 + \frac{1}{T_i s} + T_d s),$$

with K_c = proportional gain, T_i = integral time constant and T_d = derivative time constant. If $T_i = \infty$ and $T_d = 0$ (that is, P control), then the closed loop measured value is always less than the desired value for processes without an integrator term, as a positive error is necessary to keep the measured value constant, and less than the desired value. The introduction of integral action facilitates the achievement of equality between the measured value and the desired value, as a constant error produces an increasing controller output. The introduction of derivative action means that changes in the desired value may be anticipated, and thus an appropriate correction may be added prior to the actual change. Thus, in simplified terms, the PID controller allows contributions from present, past and future controller inputs.

PI and PID controllers require the choosing of either two or three controller parameters, respectively. It is necessary to adjust these parameters according to the nature of the process, a procedure known as *controller tuning*. Controller tuning is easily and effectively performed using tuning rules (i.e. formulae for controller tuning, based on process information). Such tuning rules allow the easy set up of controllers to achieve optimum performance at commissioning. Importantly, they allow ease of re-commissioning if the characteristics of the process change. A large number of tuning rules have been proposed for different processes; the third author, in a number of contributions, has collated these tuning rules [16]-[18].

Many tuning rules require process models. Of the 1,134 tuning rules collated in [16], 1,005 of them require such a model. However, in many cases, a model is difficult to obtain for many semiconductor processing stages due to significant levels of nonlinearity [14]. Thus, non-model based tuning rules are indicated, 129 of which are available; 44 tuning rules exist for various versions of the PI controller and 85 exist for various versions of the PID controller. Many of these tuning rules are based on recording appropriate parameters at the ultimate frequency (that is, the frequency at which marginal stability of the closed loop control system occurs). The first (and most well known) such tuning rule was defined in 1942 [19] for the tuning of P, PI and PID controller parameters. Briefly, the experimental technique is as follows:

a) Place the controller in proportional mode only.

b) Increase K_c until the closed loop system output goes marginally stable; record K_c (calling it K_u, the *ultimate gain*), and the *ultimate period*, T_u; a typical marginally stable output, recorded on a laboratory flow process, is shown in Figure 10.

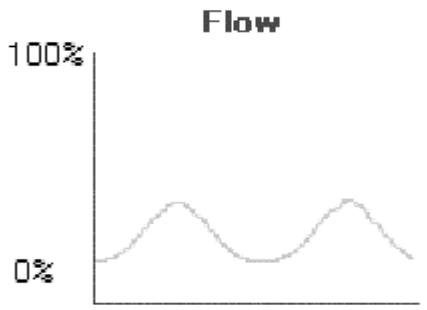


Figure 10: Typical marginally stable process variable pattern. Note that the pattern exhibits evidence of a process nonlinearity, which is common in real applications.

Simple formulae are used to define tuning parameters for PI and PID controllers. The PI controller settings are given by

$$K_c = 0.45K_u,\ T_i = 0.83T_u,$$

with the (ideal) PID controller settings given by

$$K_c = 0.6K_u,\ T_i = 0.5T_u,\ T_d = 0.125T_u.$$

Though there are disadvantages to the tuning approach [17], [18], the method has the major advantage of simplicity.

6. CONCLUSIONS

As feature sizes of 65 nm and lower are manufactured, good process control will be an important part of meeting the associated technical challenges. The paper has considered two applications where process control is currently used; CVD temperature control uses a feedback controller in a cascade configuration, while wafer etching control uses a statistical process control strategy. The authors propose that feedback controllers will have a greater role in aspects of semiconductor manufacturing in the future, with the development of possibly non-invasive measurement techniques. Of particular interest is the use of PI or PID controllers, with their proven success in delivering control solutions over many decades. The authors draw the attention of the semiconductor manufacturing community to the use of tuning rules to set up these controllers.

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