

CONTROL OF OXIDE GROWTH BY REAL-TIME SIMULATION

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SUMMARY

As critical device features are reduced in size, it becomes increasingly important to control the uniformity and reproducibility of the critical layers which determine device performance. The gate oxide is one such layer, and this paper outlines a technique which has been developed to provide more direct control of oxide growth by taking into account all the major process variables encountered during the growth process. Data available through the growth furnace digital process controller is supplied to a growth simulation program which is used to control the time the wafers spend in the furnace. Results are presented for a wet oxidation process which involves oxide growth under non-steady-state conditions.

1. INTRODUCTION

Computer simulation of semiconductor process is an important tool in process development. By allowing 'what if' analysis over a variety of fabrication steps, simulation can save costly and time consuming experimentation. However, as models become refined and more accurate, simulation need not be limited to only this role. This paper considers an application where a conventional negative feedback control loop has been replaced by a simulation model. Providing the whole system response is slow compared with trial time of the simulator, many system variables can be continuously monitored and used as inputs to the simulator. The simulated results may then be used to provide real-time control and to predict process end points.

The chosen application is thermal growth of thin silicon dioxide films. The oxide thickness appears as a first order term in all principal MOS device equations. As features in VLSI circuits are reduced, thinner oxides are required as shown

in Table 1. Growth times may be reduced, but transient effects become progressively more important and conventional oxidation control systems are not sufficient to maintain thickness tolerances.

Table 1

Min Device Feature (μm)	Gate Oxide Thickness (\AA)	Required Tolerance (\AA)	Dry Oxidation time at 950°C (min)
5	800	40	245
2.5	400	20	90
1.25	250	12.5	40
0.5	100	5	9

2. CONTROL OF OXIDE GROWTH

If improved control of oxide growth is to be achieved the causes of thickness variability should be separately examined. If the mechanisms are independent, they may be controlled separately. The main factors are:

i) Variations within a single batch of wafers

These are usually due to furnace 'individuality' and factors such as non-uniform temperature caused by a hydrogen torch or the effective increase in oxidation based on the first-in/last-out principle. If this variation is to be reduced, it would require changes to furnace hardware and this is not considered here.

ii) Batch-to-batch variation

This is present because furnace treatments are not completely reproducible, despite elaborate digital control systems. The basic mechanism for furnace control is a negative feedback loop (Fig 1), which attempts to maintain a constant temperature. Other loops control the remaining furnace variables: gas flows and boat position. Assuming that these control loops are well-behaved, ie that deviations from set-point are small, then control of oxide thickness may be achieved with accurate process timing. Characteristic oxide growth curves at different temperatures are frequently used to predict the oxidation time for any specified thickness.

However, temperature disturbances frequently occur - for example by loading cold wafers into a furnace at 950°C . The temperature controller responds, but requires a period of time to fully recover to its set-point temperature. This has an influence on oxide thickness which is not assessed in oxide growth curves, and results in variations between furnace

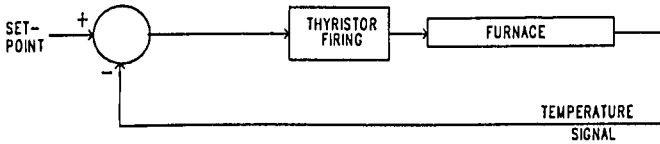


Figure 1
Negative Feedback in Temperature Control

treatments. Likewise, oxide growth during periods of process change - for example, temperature ramping or gas purging - has similar effects. If the oxidation time remains fixed, the result is an unpredictable deviation of oxide thickness from the value expected using oxide growth curves. With thinner oxides, the time during which steady-state conditions exist in the furnace is reduced and these transient effects become increasingly significant.

Control can be improved by careful assessment of the complete oxidation process. In the method presented here this is realised by simulation. An oxide growth simulation programme may be used to calculate the effect of interacting process parameters such as oxidising ambient and wafer temperature. A set of rules can be applied to determine these parameters from measured furnace variables. If measurements are made during processing, a real-time estimate of the oxide thickness can be obtained. This can then be used to determine the conditions for the remainder of the oxidation and to terminate the process under conditions which will give the required film thickness.

3. IMPLEMENTATION

Furnace data is readily available from most digital furnace systems. Figure 2 shows how measured variables are collected by a digital temperature controller (DTC) and digital process controller (DPC) then passed to a remote computer (Apricot PC) housing the simulation program. The simulation is based on an increment form of the Deal-Grove oxide growth model, with additions to allow simulation over a wider range of oxidations.

$$\frac{\Delta x_o}{\Delta t} = \frac{B}{2x_o + A} + R$$

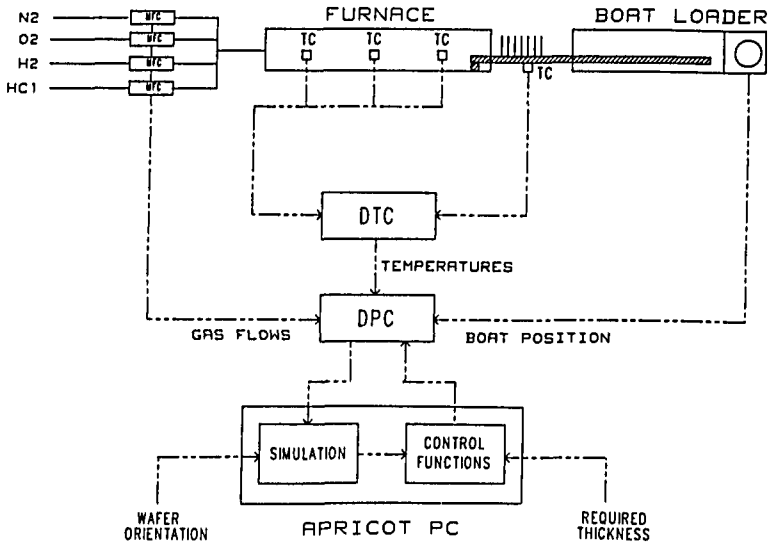


Figure 2

Data collection for computer simulation

where $R = C e^{\left(\frac{-x}{L}\right)^0}$ models the rate enhancement observed for thin dry oxides.

The rate constants A and B are calculated from exponential expressions for the linear and parabolic constants.

$$K_L = B/A = C_L e^{-E_{AL}/kT} \cdot H_L \cdot \gamma \cdot P^n$$

$$K_P = B = C_P e^{-E_{AP}/kT} \cdot H_P \cdot P$$

where H_L and H_P are rate enhancement factors which model the variation in oxidation rate upon addition of HCl gas to the oxidising ambient. γ is a factor to model the oxidation rate for different crystal orientations of silicon. P is the partial pressure of oxidant.

The values of activation energy and pre-exponential constant depend primarily on the oxidising ambient. This is determined from flow rates of N₂, O₂, H₂ and HCl provided by mass-flow-controllers. P , H_L and H_P are also determined from gas flow data. A thermocouple positioned at the wafer-boat

provides data on wafer temperature, allowing the simulated oxidation rate to model more accurately that seen at the wafers.

During every 5 second time interval, current furnace data is passed to the computer to update the simulation. Rate constants are evaluated. The change in oxide thickness for that time increment is then determined. When the total oxide thickness approaches the required value, appropriate signals are sent back to the DPC to switch the furnace to an inert ambient and/or unload wafers from the furnace.

Since the whole oxidation process is continuously monitored, the system can automatically adjust for transient thermal effects and so enhance process accuracy and repeatability.

RESULTS

The feasibility of the simulation control procedure was examined by testing its ability to deliver a specified oxide thickness. Although any oxidation process would be suitable as a trial, one which involves substantial oxide growth under dynamic conditions gives a much more demanding test of the system capability. A convenient method of performing this is to incorporate a temperature ramp in an oxidising ambient into the furnace treatment. The furnace treatment used therefore consisted of the following sequence of steps:

1. Load wafers into furnace at 700°C in O₂.
Step time = 10 min.
2. Ramp temperature to 950°C at 10°C/min in H₂O.
Step time = 25 min.
3. Oxidise at 950°C in H₂O until the total oxide thickness equals 1000Å (see below).
4. Anneal at 950°C in N₂. Step time = 10 min.
5. Unload wafers from furnace at 950°C in N₂.
Step time = 5 min.

Determination of the oxidation time in step 3 requires estimation of the oxide grown during temperature ramping (step 2). This presents difficulty if a conventional furnace system is used, but the simulation control procedure will automatically and accurately take this oxide growth into account.

A recipe based on the above treatment was loaded into the DPC of a furnace configured for simulation control. This

recipe is needed to manage the individual furnace components: gas flows, temperature and boat loading. After being cleaned in boiling H_2O_2/H_2SO_4 , followed by an HF dip then rinsing and drying, thirty <100> silicon wafers were placed in a quartz boat on the furnace boat loader. The simulation program was supplied with values for the required oxide thickness and wafer orientation then the furnace treatment was started. After the load and ramp steps, wet oxidation (step 3) continued until the simulation had predicted the growth of 1000A. An instruction was then automatically sent from the Apricot-PC to the DPC to cease the oxidation and begin the anneal. After the anneal the wafers were unloaded from the furnace.

Four wafers equally spaced in the boat were selected for measurement. The oxide thickness on each was determined, at five sites using a Nanospec. The mean thickness was 1008A with a variation of 2.2%.

Figure 3 show the temperature measured at the wafer boat during processing and figure 4 shows the corresponding oxide growth, computed real-time using temperature and gas flowdata.

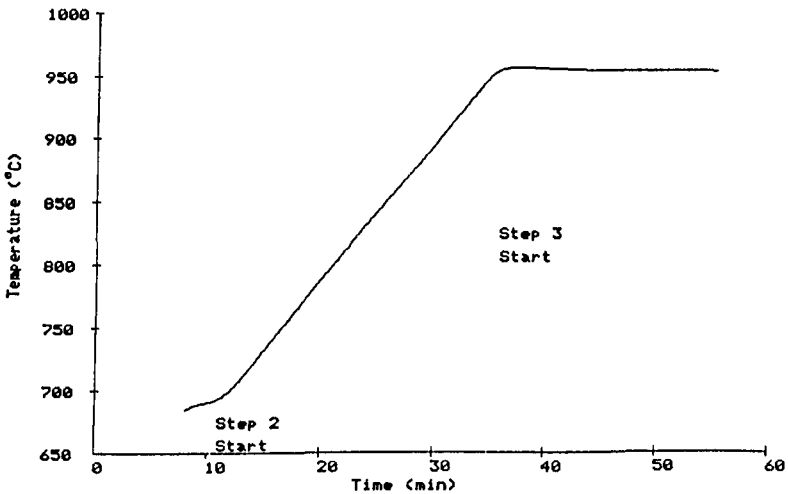


Figure 3
Temperature measured at wafers

At the end of the temperature ramp, it can be seen that an estimated 290A of oxide has grown. This is a significant proportion of the total oxide thickness, emphasising the need for careful assessment of oxide growth during temperature ramping. Oxidation has continued for a further 18 minutes

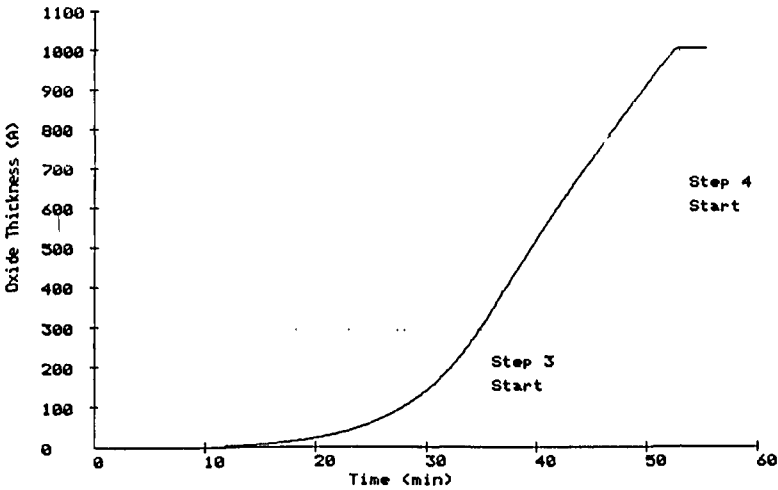


Figure 4
Simulated oxide growth

before the change to an inert ambient for annealing. This time has been proven correct, but it is based on furnace conditions during this particular run only and does not represent the 'standard' time required for step 3 of this process. Simulation control will always adjust this time as necessary to ensure growth of 1000Å oxide.

CONCLUSIONS

The agreement between desired oxide thickness and the value obtained after processing demonstrates the feasibility of simulation in a control application. The technique has accommodated dynamic process conditions in the form of a deliberately introduced temperature ramp. Other transient periods can similarly be assessed. This effective improvement in process control over conventional systems, which rely entirely on negative feedback loops, is an important factor in achieving the thickness tolerances required for VLSI.