Part I

RTP Equipment: Modelling and New Concepts

COMPARISON OF THE PERFORMANCE OF SINGLE WAFER AND BATCH SYSTEMS FOR IDENTICAL PROCESSES

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ABSTRACT

We compare single wafer systems, conventional batch systems and fast ramp batch systems in terms of throughput, cycle time and cost per wafer for four different processes. Comparison is based on dynamic fab simulations done with proprietary software package.
The results show that vertical furnaces are the best choice in terms of throughput and cost per wafer for those processes for which both a single wafer and a batch process exist. Fast ramp furnaces are an attractive option to conventional batch furnaces in case a shorter cycle time is needed. Single Wafer systems show a substantially lower cycle time, but a higher cost per wafer. These additional costs might be justified by short cycle times in e.g. ASIC's manufacturing and in product development.

INTRODUCTION

Rapid Thermal Annealing (RTA) has been introduced some two decades ago as a tool to improve the thermal budget while maintaining a reasonable throughput. In the mean time other types of rapid thermal processing (RTP) like rapid thermal oxidation, nitridation (RTO, RTN) and single wafer RTCVD has been introduced. The rate of introduction of these various new technologies has not been as rapid as was originally anticipated. This might be due to problems related to temperature non-uniformity and other equipment imperfections.
The attractiveness of single wafer (SW) technology for a given type of fab depends on the type/quantities of the devices manufactured. For ASIC's and other, similar products which are produced in relatively small quantities but require a short cycle time, equipment which can rapidly process small batches is attractive. For large-scale production of e.g. memory devices the cost per wafer is the most dominant factor and longer cycle times are acceptable.
In an earlier paper (1) a comparison was made between single wafer and batch processing for typical DRAM manufacturing processes assuming a single process sequence for the fab. In practice, fabs runs several different process sequences each with a number of different products. In this paper we will make a comparison between throughput/cycle time/cost per wafer for single wafer and conventional and fast ramp batch systems for such a multiproduct fab using a dynamic fab simulation. Of course, such a comparison only makes sense for those processes for which both single wafer and a batch process exists. This obviously limits the choice.

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TOOLS

We have considered a number of different tools. For the batch furnaces we looked at the following types of vertical furnaces:

1. the standard A400 dual boat (100 wafers) vertical furnace produced by ASM
2. the Fast Ramp (A400 FR) version of A400 system (100 wafers) produced by ASM
3. two conventional single boat (150 wafers) vertical furnaces as produced by other vendors.

For the single wafer RTO system we basically used data from the literature (2) and customer information. For the poly system we used the stand alone ASM poly system based on our Epsilon reactor and now also available as module on a cluster tool like the ASM Advance 800.

PROCESSES

For our evaluation we have chosen the following processes:

1. thin dry oxide
2. thin wet oxide
3. nitrided oxide
4. poly deposition

A detailed description of the process and equipment data used is given in Tables I and II. Note that we have kept the process conditions identical.

WAFER FAB MODELLING

Modeling and simulation have become indispensible tools for the design and development of new equipment but also for the evaluation of the characteristics and optimization of existing fabs. It is of course also an important ingredient in the planning of a new fab. ASM uses its proprietary software to work together with customers to find optimum solutions.
Our fab level modeling includes all relevant features of the fab like operator characteristics, details of cleaning and process equipment, measurement and inspection etc. We also use the factory times for intra- and inter area material transport, equipment time constants and process driven constraints.
The model, written in an object-oriented language, uses process-interaction diagrams in which processes and interaction are defined in a very general sense. Examples of processes are: equipment, operators, control units, examples of interactions are material flow and control flow. Using this concept a hierarchical model of a fab can be built. A very similar model is used for equipment modeling. Both models use statistical data of the fab logistics like the arrival time of material. This enables us to arrive at realistic figures of the number of tools and their utilization.

Table I: Summary of the process data for 100 wafer batch processing used in this study. The same process data is also used for 150 wafer batch processing.

	Dry oxide	Thin wet oxide	NO	Poly
Process input:				
Layer [A]	115	30	50	1000
Dep temp. 1 [C]	920	700	800	620
Dep. temp. 2 [C]	-	-	900	-
Load/Unload temp. [C]	775	400	650	620
Ramp-up rate [C/min]	10	10	10	-
ibid: fast ramp	40	40	40	-
Ramp-down [C/min]	3.5	2.5	3	-
ibid. fast ramp	40	25	35	-
Steps:				
Boat load [min]	16	16	16	16
Boat push [min]	12	12	12	12
Recover [min]	10	10	15	-
Pump [min]	-	-	-	10.5
Heat-up 1 [min]	14.5	30	15	-
ibid. fast ramp [min]	3.6	7.5	3.75	-
Stab. [min]	8	6	15	28.5
Process [min]	26.6	10	10	10
Purge [min]	-	-	20	-
Heat-up 2 [min]	-	-	10	-
ibid. fast ramp [min]	-	-	2.5	-
Temp. stab. [min]	-	-	15	-
Process [min]	-	-	10	-
Anneal [min]	5	5	-	-
Purge [min]	-	-	20	4
Back fill [min]	-	-	-	7.5
Cool down [min]	41.4	120	83.3	-
ibid. fast ramp [min]	3.6	12	7.1	-
Delay [min]	-	10	-	2
Boat pull [min]	12	12	12	12
Boat cool [min]	15	15	15	15
Boat unload [min]	16	16	16	15
Total cycle time A400, 100 wafers [hr]	2.9	4.4	4.7	2.2
Total cycle time A400 FR, 100 wafers [hr]	2.1	2.2	3.2	-

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Table II: Input data for single wafer processing used in this study.

	Dry oxide	Thin wet oxide	NO-gate	Poly
Process input:				
Layer [A]	115	30	50	1000
Dep. temp. [C]	1100	950	1100	650
Load/Unload temp. [C]	700	700	700	650
Ramp rate [C/s]	10	10	10	-
Steps:				
Cassette load [s]	60	60	60	60
Wafer load [s]	10	10	10	12
Recover [s]	2	2	2	2
Power ctrl [s]	20	20	20	-
Ramp-up [s]	40	25	40	-
Stabilization [s]	10	10	10	60
Process [s]	42	15	40	60
Ramp down [s]	40	25	40	-
Delay [s]	5	5	5	20
Wafer unload [s]	10	10	10	12
Etch, per each run [s]	-	-	-	110
Cassette unload [s]	60	60	60	60
Total cycle time, 25 wafers [hr]	1.3	0.9	1.3	2

For the purpose of the modelling of the wafer fab we have made the following assumptions: we simulate a factory with 5000 wafer starts per week (WS/W) and single out one of the processes which covers 20% of the total production of the fab (1000 WS/W). We lump the other 4000 WS/W together in a process sequence which gives us a fab load representing an average product. The 1000 WS/W product follows an external process step (e.g. litho) with an average duration of 10± 3 hrs, with a Gaussian distribution. For the duration of the external process steps preceeding all furnace process steps in the 4000 WS/W product flow, we took 20± 6 hrs, again with a Gaussian distribution. Other, more realistic skewed distributions would change the results somewhat but since in our experience this depends very much on the logistics and scheduling employed in a particular fab we limit ourselves to the symmetrical Gaussian distribution. Lots of both product flows can be mixed in a furnace. The applied scheduling strategy imposes a maximum waiting lot time before creating a batch. This maximum waiting time was chosen as 1.5 times the minimum cycle time of the process in question with a limit of 8 hrs. The details used for maintenance are shown in Table III.

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Table III: Maintenance data used in this study (mtbf=mean time between failures, mttr= mean time to repair, mtbpm= mean time between preventive maintenance, mttpm= mean time to do preventive maintenance).

	OXIDATION			
	mtbf [hr]	mttr [hr]	mtbpm [hr]	mttpm [hr]
ASM dual boat furnaces	750	8	250	3
Other (single boat) furnaces	750	8	250	5
RTP machine	375	4	250	2

	POLY			
	mtbf [hr]	mttr [hr]	mtbpm [hr]	mttpm [hr]
ASM dual boat furnaces	600	8	150	3
Other (single boat) furnaces	600	8	150	5
RTP machine	300	4	250	2

Cost of Ownership, Cost per Wafer

The througput/cycle time data are obviously important but provide only part of the answers needed to make a balanced choice. E.g. the relative costs of consumables, like quartzware, process gases etc. depend strongly on the application.
Cost per Wafer (Cpw) was calculated for the various options: dual boat A400 furnace and its fast ramp version: the A400i, two conventional single boat furnaces, and single wafer tools for the above defined processes. Since the results for the two conventional furnaces are very similar we have only presented one set of data.

RESULTS AND DISCUSSION

We have first computed the following items:

1. Cycle time, defined as the average time it takes to process the load of a reactor.
2. Non-idle time of a tool, defined as the average time during which a tool is busy with processing, scheduled maintenance and unscheduled maintenance. It is given as a fraction of the total available time.
3. Average load size, defined as the average number of cassettes processed by a given tool in one step. For batch systems this number deviates from the ideal load size because one cannot let furnaces standing idle indefinitely until enough material has arrived to fill the furnace boat completely. Different scheduling rules can be used to define batching strategy (see previous paragraph).
4. Throughput, defined as the average number of processed wafers per hour per tool.

An overview of all results is given in Table IV.

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Table IV: Overview of results per process type and equipment type.

	AVERAGE CYCLE TIME [HOURS]			
Type Eq.	Dry oxide	Wet oxide	NO-gate oxide	Poly
A400	5.14 ± 0.07	6.64 ± 0.10	7.03 ± 0.11	4.64 ± 0.05
A400(FR)	4.49 ± 0.07	4.50 ± 0.07	5.62 ± 0.10	4.64 ± 0.05
Conv.1	5.66 ± 0.07	7.45 ± 0.10	7.79 ± 0.13	5.27 ± 0.06
Conv.2	6.02 ± 0.09	8.02 ± 0.12	8.07 ± 0.13	5.02 ± 0.05
RTP	1.99 ± 0.04	1.55 ± 0.03	1.97 ± 0.03	2.75 ± 0.03

	PERCENTAGE NON-IDLE TIME							
	Dry oxide		Wet oxide		NO-gate oxide		Poly	
Type Eq.	Non-idle	Nr react.	Non-idle	Nr react.	Non-idle	Nr react.	Non-idle	Nr react.
A400	65%	3	61%	5	68%	5	69%	2
A400 FR	66%	2	66%	2	70%	3	69%	2
Conv.1	58%	3	59%	4	65%	4	71%	2
Conv.2	73%	3	69%	4	62%	5	64%	3
RTP	67%	7	65%	5	67%	7	69%	10

	LOAD SIZE [LOTS]			
Type Eq.	Dry oxide	Wet oxide	NO-gate oxide	Poly
A400	3.8	4.0	4.0	3.6
A400 FR	3.7	3.5	3.9	3.5
Conv.1	5.5	5.8	5.9	4.8
Conv.2	5.1	5.9	5.9	4.8
RTP	1	1	1	1

	THROUGHPUT [WF/HR]			
Type Eq.	Dry oxide	Wet oxide	NO-gate oxide	Poly
A400	25.9	15.3	15.5	38.3
A400 FR	38.9	37.3	25.8	38.3
Conv.1	25.9	18.6	19.3	38.1
Conv.2	25.9	18.5	15.5	25.4
RTP	11.1	14.7	11.0	7.6

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Cycle time

The results for the average cycle time are summarized in Table IV. Note that the errors given hold for the expected deviation in average cycle time. The actual values per individual run show much larger deviations because of the variation in material arrival time. We would like to draw the reader's attention to the following observations:

1. Obviously the cycle time for single wafer systems is the shortest: between 40 to 60 percent of competing processes. Note however that this depends on the way a lot is defined: in our example a lot for a SW-tool is identical to one 25 wafer cassette. Some companies use larger lot sizes e.g. 2 cassettes. In that case one wants, for obvious reasons, to process the two cassettes immediately after one another and the cycle time is double the time for a single cassette 25 wafer lot.
2. Conventional vertical furnaces (150 wafer load size) with single and dual boats (100 wafer load size) all give roughly the same cycle time for a given process. This result is however strongly dependent on the scheduling rule. If a more aggressive scheduling rule is applied from the one used in the simulations substantial differences can occur. Decreasing the load size to 100 wafers (A400) gives a reduction in cycle time of 15 to 20% depending on the process.
3. The improvement in cycle time for the A400 fast ramp (100 wafer load size) vertical furnace depends strongly on the process chosen: e.g. in the case of wet oxide the relative decrease exceeds 30% and is considerably larger than for dry oxide.

Utilization (non- idle time) and load size

The utilization of the tools is not dramatically different for the various tools. This should not be surprising since one tries to optimize the number of tools (also given in Table IV) w.r.t. to throughput. In practice a utilization of 70% is close to optimum, if these percentages are significantly higher, one soon runs into bottle-necks. We have defined a minimum number of tools to be two to avoid the risks of failure (which is common practice in industry). The average load size is an indication of how often a tool is started with less than the maximum load (note that the maximum load is 4 lots for the A400/A400i (Fast Ramp), and 6 lots for the conventional single boat furnaces).

Throughput

The throughput is dramatically different for single tools compared to vertical furnaces. On the average the single wafer RTO systems have a throughput which is about 40 and 60% of the conventional and fast ramp systems. This translates also in cost per wafer figures. Single wafer poly systems have about three times lower throughput than the conventional and fast ramp systems. However, due to an aggressive product development programme this difference will be substantially reduced in the near future.

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Table V: Comparison of annual costs and Cost per Wafer (Cpw) between different tools.

	Dry oxide			
	1/2 A400	1/2 A400 FR	Conv. furnace	Single wafer
Load size	100	100	150	1
Test wafers/load	1	1	1	0.02
Gross throughput	44	70	45	20
Ann. depreciation (k$)	141	153	141	156
Oper. costs (k$/yr)	100	111	56	520
Test/Scrap wfrs (k$/yr)	304	479	426	289
Cpw ($)	1.5	1.3	1.1	6.1

	Thin wet oxide			
	1/2 A400	1/2 A400 FR	Conv. furnace	Single wafer
Load size	100	100	150	1
Test wafers/load	1	1	1	0.02
Gross throughput	26	67	31	27
Ann. depreciation (k$)	148	159	208	156
Oper. costs (k$/yr)	48	107	42	722
Test/Scrap wfrs (k$/yr)	188	459	151	417
Cpw ($)	1.8	1.3	1.6	5.6

	Nitrided oxide			
	1/2 A400	1/2 A400 FR	Conv. furnace	Single wafer
Load size	100	100	150	1
Test wafers/load	1	1	1	0.02
Gross throughput	24	40	29	19
Ann. depreciation (k$)	159	168	159	156
Oper. costs (k$/yr)	59	82	55	525
Test/Scrap wfrs (k$/yr)	172	280	140	292
Cpw ($)	1.9	1.6	1.5	6.1

	Poly		
	1/2 A400	Conv. furnace	Single wafer
Load size	100	150	1
Test wafers/load	1	1	0.02
GR (nm/min)	10	10	100
Gross throughput	63	57	11.9
Ann. depreciation (k$)	163	163	183
Oper. costs (k$/yr)	137	110	453
Filler wfs (k$/yr)	143	382	-
Test/Scrap wfrs (k$/yr)	447	279	189
Cpw ($)	1.7	2.0	8.2