Business of Safety

SH&E Life-Cycle Cost Model

An internal study from the semiconductor manufacturing industry

By Anthony Veltri, Daren Dance and Michael Nave

AS THE FIRST HALF OF A TWO-PART SERIES examining the development and use of a safety, health and environmental (SH&E) life-cycle cost model, this article outlines the research effort (i.e., problem, study design, data analysis and results). The second part discusses how to effectively and efficiently implement a cost-modeling initiative and presents a template of SH&E life-cycle phases, cost factors and activity drivers to guide SH&E cost-modeling efforts. It will appear in the July 2003 issue of Professional Safety.

For the last 10 years, the electronics industry has been the largest single contributor to the durable-goods manufacturing segment of the U.S. gross domestic output. Since 1996, it also has been the largest contributor to U.S. manufacturing output (U.S. Bureau of Economic Analysis). The prominence of electronics in U.S. manufacturing is driven by the increased role of semiconductors in both industrial and consumer durable goods. The U.S. semiconductor industry has been challenged, however, by years of declining selling prices. As a result, U.S. semiconductor firms constantly focus on cost reduction, yield quality and operational logistics as the primary drivers of enhanced manufacturing performance.

In addition to these primary drivers, existing and emerging SH&E issues are increasingly affecting manufacturing performance. In certain semiconductor-processing steps, the elements that address SH&E issues can represent as much as 20 percent of the total cost of manufacturing (Helms and Shaw). However, costs associated with SH&E issues have not been categorically accounted for throughout the productive/economic life cycle of semiconductor manufacturing technology and process designs, meaning their economic impact is only partly understood (Semiconductor Industry Assn.). The inability to estimate SH&E costs linked to manufacturing technology and process designs causes fabrication managers to make manufacturing decisions with an incomplete understanding of their economic impact.

The underlying assumption for this study was that semiconductor fabrication managers can leverage manufacturing performance advantages by profiling the cost of SH&E issues and practices associated with manufacturing technology and process designs. The following opportunities were found as a result of this study:

1) A refined understanding of the manufacturing technology and process sources and circumstances that tend to drive internal SH&E life-cycle costs.

2) A more complete and objective data set on internal SH&E costs, enabling improvements to manufacturing technology and process designs.

3) A new way of eliminating customary cost-of-ownership bias by providing more representative direct and indirect SH&E cost information.

4) An enhanced method of determining which

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Table 1

Study Design

Study assumption: Semiconductor fabrication managers can leverage manufacturing performance advantages by profiling the cost of SH&E issues and practices associated with manufacturing technology and process designs.

Problem statement: To construct a model profiling the cost of SH&E issues and practices associated with semiconductor manufacturing technology and process designs over the productive/economic life cycle of the technology and the processes.

Research purpose: To enhance the ways in which experts in the semiconductor industry—SH&E specialists, design/process engineers and financial specialists—present the financial (i.e., cost burden-profitability potential) aspects of SH&E issues and practices to fabrication managers.

Semiconductor Industry Review Board (n = 15)
(Evaluate scientific, strategic and technical soundness of the study)

Procedure 1	Procedure 2(a)	Procedure 2(b)	Procedure 3(a)	Procedure 3(b)
Model Construction	*Peer Review*	*Peer Review*	*Pilot Testing Stage 1*	*Pilot Testing Stage 2*
Activities:	**Activities:**	**Activities:**	**Activities:**	**Activities:**
Conduct status study/needs assessment. Construct model architecture/template of life cycle phases, cost factors, activity drivers. (Rev. 1 version)	Conduct (Rev. 1 version) peer review. Reconstruct model architecture/template. (Rev. 2 version) based on (Rev. 1 version) peer review.	Conduct (Rev. 2 version) peer review. Reconstruct model architecture/template. (Rev. 3 version) based on (Rev. 2 version) peer review.	Create cost estimation software based on final architecture/template rollout for Stage 1 pilot testing. Reconstruct cost estimation software based on results of Stage 1 pilot testing.	Create financial software-incorporate cost software rollout for Stage 2 pilot testing. Reconstruct financial analysis software based on results of Stage 2 pilot testing.

SH&E management strategies and technical tactics to pursue and what level of financial resources will be required.

5) A new structure in which fashioning and promoting SH&E issues and practices become a way of making business decisions about that technology and those processes—and in which business needs associated with manufacturing technology and processes become a way of making SH&E business decisions.

Despite these performance advantages, organizational barriers need to be overcome in the profiling of SH&E costs associated with manufacturing technology and process designs. The barriers encountered during this study were:

1) A fabrication management-level perspective that SH&E issues are regulatory compliance problems and play a small part in the business-decision-making aspects of semiconductor manufacturing.

2) A design/process-engineering-level perspective that existing industry tools for performing a financial impact analysis of SH&E issues and practices are qualitatively and quantitatively immaterial in enhancing competitive performance.

3) A senior-level-executive perspective that the costs of SH&E issues and practices are not financially structured and reported in a manner that allows the SH&E function to compete with other manufacturing performance challenges for available budget.

These barriers were significant. The strategy found to be most effective in overcoming them was to deploy the SH&E cost model in a manner that 1) disclosed the internal SH&E costs throughout the productive/economic life cycle of manufacturing technology and process designs and 2) revealed the financial impact of SH&E costs on the standards established by fabrication managers and senior-level executives for manufacturing-technology-and-process performance.

This study was set up to construct a model that profiles the cost of SH&E issues and practices associated with semiconductor manufacturing technology and process designs over their productive/economic life cycle. The purpose was to enhance the ways in which SH&E specialists, design/process engineers and financial specialists present the financial (i.e., cost burden-profitability potential) aspects of SH&E issues and practices to fabrication managers.

No attempt was made to profile the cost impact of externalities during research and development of the model. This study limitation was due to the project review board's desire to profile the internal private costs rather than the external societal costs incurred by the manufacturing technology and process designs.

Internal private costs are those costs a semiconductor manufacturer can incur as a result of fabrication processing activities that result in yield quality and logistical performance problems as well as environmental incidents and injury/illnesses accidents. External societal costs are the costs a semiconductor manufacturer can incur as a result of fabrication processing activities that cause 1) air, water or soil pollution; 2) natural resource depletion or degradation; 3) chronic or acute health effects; 4) alteration of environmental habitat; and 5) socioeconomic-welfare effects.

Review of Literature

Concern about profiling SH&E costs in the semiconductor industry surfaced in the early 1990s and continues to the present (Henn; Cohan and Gess; Warren and Weitz; Cobas, et al; Brouwers and Stevels; Mizuki, et al; Van Mier, et al; Lashbrook, et al; Hart, et al; Timmons; Nagle; and Warburg). During the last 10 years, the industry has recognized the growing need to understand the financial impact that SH&E issues and practices have on manufacturing technology and process performance, yet the economics of those issues and practices is one of the least-understood subjects in the industry (Tipnis).

Increasingly, the U.S. semiconductor manufacturing industry has taken steps toward better understanding the competitive impact of SH&E issues and practices. This trend is evidenced by the development of SH&E sections of national technology roadmaps (SIA) that incorporate initiatives to reform the profiling of costs associated with SH&E issues and practices.

A review of industry efforts to model SH&E costs during the 1990s revealed no formal cost models. Various cost-of-ownership models have been developed and used since the early 1990s (Venkatesh and Phillips; Dance and Jimenez), but all versions of these models fall short in profiling SH&E costs associated with semiconductor manufacturing technology and process designs.

Study Design

Table 1 illustrates the repeated baseline study design that was selected to guide the research and development of the model. Throughout the project, an industry review board made up of 15 SH&E specialists evaluated the scientific, strategic and technical soundness of the research, development and pilot testing of the model.

Existing and emerging SH&E issues are increasingly affecting manufacturing performance in the semiconductor manufacturing industry.

Results & Discussion

Procedure 1: Model Construction

Before the model's architecture was constructed, a status study and a needs assessment were conducted. This procedure, carried out at SEMATECH, with SEMATECH member companies located throughout the U.S., involved a series of meetings with SH&E

Table 2

Efficacy of the Model to Capture & Estimate SH&E Costs

Fabrication, Operational & Financial Default Values Used:

Process Support and ESH Labor Rate: $50.00/hr — Discount Rate: 12% — Annual Corporate Tax Rate: 40% — Depreciation Life Years: 3 yrs.

Types of Technologies and Processes Selected

(Design and Test — Process Integration, Devices, and Structures — Front-End Processes — Lithography — Interconnect — Factory Integration — Assembly and Package)

Technology/Process (*n* = 15)		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	*Median Cost*
Productive/Economic Life Yrs.		3	5	5	3	3	5	5	5	5	5	5	5	5	5	10	*5*
Wafers/Month		1,000	55,000	7,000	15,000	3,000	60,000	40,000	20,000	3,000	40,000	4,000	35,000	10,000	35,000	40,000	*20,000*
Section A. Life-Cycle Phase & Cost-Factor Collection, % Estimation Rate and Median-Cost Analysis																	
Capture / Estimate Rate (number of pilot tests)		(Cost % Estimates Rounded to Nearest 2 Decimal Places) Example 0.25%															
I. UP-FRONT			1.00%				2.00%	3.00%	3.00%		3.00%		0.60%		0.30%	1.00%	***$1,000***
1. DfESH	*8*		100.00%				100.00%	100.00%	100.00%		100.00%		100.00%		100.00%	100.00%	*1,000*
II. ACQUISITION			30.80%				24.00%	25.00%	15.00%		35.00%		18.60%		36.90%	33.20%	***15,000***
2. Permits	*8*		10.00%				15.00%	17.00%	34.00%		13.00%		16.60%		10.00%	11.10%	*5,000*
3. ESH Capital	*8*		90.00%				85.00%	83.00%	66.00%		87.00%		83.00%		90.00%	88.80%	*10,000*
III. USE/DISPOSAL		80.00%	56.00%	66.00%	70.50%	66.00%	57.00%	62.00%	67.00%	100.00%	50.00%	100.00%	62.00%	82.00%	51.60%	55.30%	***70,000***
4. CoO ESH Capital	*8*		4.80%				4.00%	6.00%	7.00%		8.00%		10.00%		3.50%	3.30%	*5,000*
5. Resources Used	*15*	41.00%	48.38%	41.00%	66.00%	41.00%	46.00%	55.00%	53.00%	72.00%	43.00%	41.00%	40.00%	54.00%	27.60%	53.30%	*40,000*
6. Consumables Used	*15*	9.00%	4.80%	9.00%	10.00%	9.00%	4.00%	3.00%	7.00%	14.00%	7.00%	9.00%	10.00%	2.00%	7.10%	6.60%	*5,000*
7. Strategic/Technical	*15*	9.00%	6.40%	8.00%	8.00%	9.00%	6.00%	6.00%	7.00%	14.00%	8.00%	9.00%	10.00%	10.00%	7.00%	10.00%	*5,000*
8. Waste Disposal	*14*	41.00%	36.48%	42.00%	16.00%	41.00%	40.00%	30.00%	26.00%		34.00%	41.00%	30.00%	34.00%	54.00%	26.60%	*15,000*
IV. POSTDISPOSAL			3.70%		11.00%		7.00%	4.00%			4.00%		6.00%		3.60%	5.00%	***10,000***
9. Waste Compliance	*8*		100.00%		100.00%		100.00%	100.00%			100.00%		100.00%		100.00%	100.00%	*10,000*
V. CLOSURE		20.00%	8.00%	34.00%	17.60%	34.00%	10.00%	6.00%	15.00%		8.00%		12.00%	18.00%	7.30%	5.50%	***15,000***
10. Decommissioning	*13*	66.00%	65.00%	83.00%	66.00%	83.00%	71.00%	66.00%	66.00%		50.00%		50.00%	50.00%	50.00%	66.60%	*10,000*
11. Remediation	*13*	34.00%	35.00%	17.00%	34.00%	16.00%	29.00%	34.00%	34.00%		50.00%		50.00%	50.00%	50.00%	33.30%	*5,000*
Incident Area																	***0***
12. Internalities	*0*																*0*
13. Externalities	*0*																*0*
14. Noncompliance	*0*																*0*

Section B. Summary Analysis of Life-Cycle-Phase Median-Cost Estimation

Life-Cycle Phase	Life Cost	Years	Annual Cost/Year	Annual Cost/Wafer	Process Staff Cost/Year	ESH Staff Cost/Year	Internal Billing Cost/Year	External Billing Cost/Year	Internal Incidents Cost/Year	External Incident Cost/Year	% Annual	% Life-Time
I. Up-Front	1,000	1	200	0.00	500	500	0	0			0.23%	0.21%
II. Acquisition	15,000	1	3000	0.01	500	500	1,000	13,000			3.48%	3.12%
III. Use/Disposal	350,000	5	70,000	0.29	2500	4,500	250	62,500			81.21%	72.77%
IV. Postdisposal	100,000	10	10,000	0.04	0	10,000	0	0			11.60%	20.79%
V. Closure	15,000	1	3,000	0.01	250	750	300	11,000			3.48%	3.12%
	481,000		86,200	0.36	3,750	16,250	4,250	86,750				
ESH Incident Area	0	5	0	0	0	0	0	0	0	0	0.00%	0.00%
	481,000		**86,200**	**0.36**	**3,750**	**16,250**	**4,250**	**86,750**	**0**	**0**	**100%**	**100%**

specialists, design/process engineers and financial experts. The status study focused on obtaining information on two topics: What existing industry conditions and practices are related to SH&E cost modeling? What existing manufacturing technology and process sources and circumstances tend to drive SH&E costs?

The needs assessment focused on obtaining information that addressed two other topics: What are the needs and expectations within the industry for profiling the cost of SH&E issues and practices linked to manufacturing technology and process designs over the productive/economic life cycle of that technology and those processes? What are the expected logistical requirements within the industry for using a cost-modeling tool? Several major findings were extrapolated from the status study and needs assessment:

1) SH&E specialists, design/process engineers and financial experts are not as effective as they would like to be in profiling the impact of internal private costs arising from SH&E issues and practices. They also are not as effective as they would like to be at using internal cost information to enhance decision-making capabilities.

2) SH&E specialists, design/process engineers and financial experts are not as effective as they would like to be in profiling the impact of external (societal) costs of SH&E issues and practices over the productive/economic life cycle of the manufacturing technology and process designs, nor are they as effective as they would like to be at using external cost information to enhance decision making. It should be noted, however, that these stakeholders desire tools that assess societal impact costs in a timely manner and that are practical to implement.

3) SH&E specialists, design/process engineers and financial experts are extremely interested in useful, low-maintenance ways to present the financial aspects of SH&E issues and practices to senior-level executives and mid-level fabrication managers. However, such modeling tools were not available to them. The information supporting such efforts should come from design/process engineers, who are in a strategic position to supply such data. However, SH&E specialists must design and provide these tools to enable design/process engineers to contribute effectively.

4) SH&E specialists, design/process engineers and financial experts do not explicitly account for SH&E costs throughout the life cycle of manufacturing technology and process designs, nor do they include these costs in integrated cost accounting systems. As a result, the integrated and concurrent design-engineering, decision-making capabilities required to aggressively control SH&E costs are limited and incomplete.

Manufacturing Technologies/Processes & Mutually Exclusive Alternatives Pilot Tested

1) Preplasma Enhanced Deposition of the Inner Layer Dielectric (ILD) Clean

Mutually exclusive alternatives:
a) N-methylpyrrlidone (NMP)
b) Cryogenic aerosol system (CAS)

2) Deep Ultraviolet (DUV) Lithography and Pattern Transfer

Mutually exclusive alternatives:
a) Chemical-vapor deposition (CVD)
b) Dry plasma-polymerized methylsilane (PPMS)
c) Top-surface imaging (TSI)

3) Copper Metalization

Mutually exclusive alternatives:
a) Tungsten chemical vapor deposition (TCVD)
b) Physical-vapor deposition (PVD)
c) Electroplating deposition (EPD)

4) Wafer Spent Rinse Water Recycling

Mutually exclusive alternatives:
a) No-recycle strategy (NRS)
b) Recycle strategy (RS)

5) SH&E cost accounting practices focus on aggregating cost data. As a result, costs are hidden in general overhead accounts and fail to account for the full life-cycle range of costs so that these costs can be allocated to the manufacturing technology or process design responsible for their generation.

6) SH&E cost accounting practices focus on the same short-term time horizons as other semiconductor manufacturing cost accounting practices. A longer time horizon is needed to capture reduced risk and recurrent costs and savings. However, the willingness of semiconductor manufacturers to extend their investment analysis strategy to this expanded time frame depends on available capital and other competing capital and organizational improvement investment options. At a minimum, a longer time horizon should be applied to capture near- and longer-term returns on an investment in SH&E.

An abridged life-cycle assessment method that incorporates activity-based costing and present-value financial analysis techniques was selected as the foundation for constructing the cost model. This method provides an enhanced way of comparing, in real time, mutually exclusive alternatives (i.e., accepting one alternative means not accepting others). Several abridged assessment methods have been described in the literature (e.g., Graedel, et al), ranging from primarily qualitative approaches to quantitative ones in which expert judgment, a limited scope and a system boundary keep the assessment effort manageable.

Experience demonstrates that life-cycle assessment of a complex manufactured product or an industrial manufacturing process works most effectively when done semi-quantitatively and in modest depth. Unlike the full life-cycle assessment method, an abridged method is less quantifiable and less thorough.

However, it is more practical to implement. An abridged assessment will identify 80 percent of the useful SH&E actions that could be taken in connection with corporate activities, and the resources consumed will be small enough that the assessment has a good chance of being conducted and its recommendations implemented (Graedel, et al). The foundation for the abridged architecture was based on the unabridged life-cycle framework developed by the Society of Environmental Toxicology and Chemistry (SETAC).

A new view of cost accounting—activity-based costing—was selected because it is a useful and proven method for determining what activities cause costs to occur, rather than merely allocating what has been spent. The idea is to understand cost drivers better, then relate costs to products, technologies, processes and services [Cooper and Kaplan; Compton(a), (b)]. This technique provided the means for allocating SH&E costs to manufacturing technologies and processes that incurred those costs during the pilot-testing portion of the study. The principal activities used to account for SH&E costs during that phase were identifying and tracing the resources, the activities and their costs, and quantities used to produce outputs by specific manufacturing technologies and processes.

Present-value financial analysis provided the final link in the architecture. This method provides the most reliable means of comparing the financial performance of mutually exclusive alternatives (Newman). This analysis helped delineate the long-term financial impact of SH&E investments by presenting the after-tax cash flow and the present-cost value of the investment over a sufficient time horizon.

After the model's architecture was determined, an initial template was constructed for assigning the SH&E cost factors and activity drivers most associated with a given life-cycle phase. This template was based on: 1) review of the literature on SH&E cost modeling; 2) findings extrapolated from the status study and needs assessment; and 3) input from members of the semiconductor industry review board about what circumstances drive SH&E costs.

Technology Pilot Test 1*

Description

Two process alternatives—a traditional wet-bench (NMP) method and a novel cryogenic aerosol system (CAS)—were studied for the pre-ILD deposition clean step. This step is designed to remove particles from the aluminum-metalized surface of a silicon wafer prior to plasma-enhanced deposition of the inner-layer dielectric (ILD). The particles result from prior processing steps and will result in nonuniformity or distortion of later wafers.

Mutually Exclusive Alternative Process A

The NMP predeposition clean is a traditional wet-batch process in which a batch of 20 to 25 wafers is immersed in N-methylpyrrlidone (NMP) at about 85°C for 10 minutes. Immersion is followed by several rinses with ultra-pure water and a spin rinse/dry. NMP is an amine-based acid, not a solvent. It has a flash point of 93°C, and NMP mists can be flammable or explosive, with a lower explosive limit of 1.3 percent and an upper explosive limit of 9.5 percent. NMP is an eye and skin irritant, although it has no reported carcinogenicity. As a result, NMP wet cleans are conducted in enclosed, vented hoods with fire suppression equipment present. The exhaust air must be scrubbed prior to release into the external environment. Wafers are immersed and removed from the NMP bath with robotic handlers, and a carefully controlled transfer speed is needed to prevent splashing or other motions, which would generate mists or droplets. NMP is less than desirable for processing because it can attack metal-device structures if mixed with water.

Financial Analysis for N-Methylpyrrlidone (NMP)

Operational & Financial Values Used

Expected life use/ Disposal phase: 5 yrs.	Discount rate: 15%
Process labor rate: $100/ ESH labor rate: $100	Tax rate: 40%
Wafers produced/yr.: 470,688	Depreciation: 3 yrs.

Estimated Cost & Financial Findings

Lifetime costs: $1,612,560/ Annual costs: $322,412	Discounted present value after tax: $659,746
Life process staff costs: $5,100/ Life ESH staff costs: $33,300	Lifetime costs: Upfront: 46,500; Acquisition: 12,000; Use/disposal: 1,548,260
Annual cost/wafer: $0.68	

Mutually Exclusive Alternative Process B

The cryogenic aerosol system is a novel single-wafer process in which wafers are loaded into a vacuum chamber and warmed on a heated chuck. After a brief out-gassing period, the wafer is cycled beneath a spray nozzle and cleaned with a combination of liquid nitrogen, liquid argon and solid argon pellets. The expansion of the liquid nitrogen and argon from the nozzle into a vacuum chills the wafer surface to near the triple point of argon (-189°C, 0.68 atm). Particles are removed from the wafer surface by a combination of physical action, thermal expansion and gas flow. The nitrogen and argon may be captured for cryogenic recycling after exiting the process chamber, or the gases may be released to the environmental atmosphere.

The only safety requirement other than for handling of cryogenic liquids is that the process equipment be located in a room with continuous ventilation to avoid oxygen depletion in case of a liquid-nitrogen or argon leak. The disadvantage of the cryogenic process is that single, one-by-one wafer processing is slower than batch processing with NMP.

Financial Analysis for Cryogenic Aerosol System (CAS)

Operational & Financial Values Used

Expected life use/ Disposal phase: 5 yrs.	Discount rate: 15%
Process labor rate: $100/ ESH labor rate: $100	Tax rate: 40%
Wafers produced/yr.: 265,920	Depreciation: 3 yrs.

Estimated Cost & Financial Findings

Lifetime costs: $347,500/ Annual costs: $69,500	Discounted present value after tax: $150,324
Life process staff costs: $1,600/ Life ESH staff costs: $27,900	Lifetime costs: Upfront: 46,500; Acquisition: 6,800; Use/disposal: 294,200
Annual cost/wafer: $0.26	

**Pre-plasma enhanced deposition clean of the inner layer dielectric*

Technology Pilot Test 2*

Description

Fabrication of semiconductor devices requires that layers of materials (conductors) be deposited in sequence and that a lithographic patterning process follow each deposition. Patterning processes generally are subtractive: A resist layer is deposited on the surface of the material layer, photographically patterned, and used to protect islands/stripes of material layers while unwanted areas are etched away. The resist layer is removed, and the surface is cleaned prior to deposition of the next layer. Three process alternatives were studied for deep ultraviolet (DUV) lithography and pattern transfer: traditional chemical-vapor deposition (CVD), dry plasma-polymerized methylsilane (PPMS), and top-surface imaging (TSI).

Mutually Exclusive Alternative Process A

The chemical-vapor deposition (CVD) process is a conventional process in which a layer of dielectric oxide is deposited by reacting a vapor containing chemical constituents of the material on the wafer surface. The material is coated with a layer of resist and patterned by a stepper. After exposure on the stepper, the resist is developed, and plasma etching removes unprotected oxide. Oxygen ash removes the residual photo resist. The chemicals used for CVD include silane, tetraethyl orthosilane (TEOS) and dichlorosilane. These chemicals have toxicity and flammability characteristics that require enclosure in a low-pressure reaction vessel. Process exhaust must be scrubbed and neutralized.

Financial Analysis for Chemical-Vapor Deposition (CVD)

Operational & Financial Values Used

Expected life use/ Disposal phase: 5 yrs.	Discount rate: 15%
Process labor rate: \$100/ ESH labor rate: \$100	Tax rate: 40%
Wafers produced/yr.: 480,000	Depreciation: 3 yrs.

Estimated Cost & Financial Findings

Lifetime costs: \$1,617,800/ Annual costs: \$323,560	Discounted present value after tax: \$734,960
Life process staff costs: \$6,000/ Life ESH staff costs: \$33,500	Lifetime costs: Upfront: 172,300; Acquisition: 177,600; Use/disposal: 1,265,500
Annual cost/wafer: \$0.67	

Mutually Exclusive Alternative Process B

The plasma-polymerized methylsilane (PPMS) process is an additive process. Thus, instead of removing unwanted areas of a layer, this process deposits only the desired areas. Unpolymerized methylsilane is deposited by chemical-vapor deposition and exposed with a stepper to define the PPMS structures. After exposure on the stepper, the layer is developed in chlorine plasma to define the structures and remove unexposed PPMS. Then the patterned PPMS are converted to a dielectric oxide in oxygen plasma. This process eliminates the need for fluorine-containing plasma-etch gases (CF_4, C_2F_6), which may have global-warming potential, but does require the use of chlorine gas at low pressures. The process must be completely anhydrous; on exposure to moisture, chlorine forms weak hydrochloric acid, which has the potential to damage both the semiconductor device and the processing chamber.

Financial Analysis for Dry Plasma-Polymerized Methylsilane (PPMS)

Operational & Financial Values Used

Expected life use/ Disposal phase: 5 yrs.	Discount rate: 15%
Process labor rate: \$100/ ESH labor rate: \$100	Tax rate: 40%
Wafers produced/yr.: 480,000	Depreciation: 3 yrs.

Estimated Cost & Financial Findings

Lifetime costs: \$796,900/ Annual costs: \$159,380	Discounted present value after tax: \$389,974
Life process staff costs: \$5,000/ Life ESH staff costs: \$37,000	Lifetime costs: Upfront: 129,800; Acquisition: 155,200; Use/disposal: 509,500
Annual cost/wafer: \$0.33	

Mutually Exclusive Alternative Process C

The top-surface imaging (TSI) process is a modification of the conventional DUV lithography process. It uses a three-layer structure. A layer of dielectric oxide is deposited by CVD. The dielectric oxide is coated with a layer of resist and patterned by a stepper. After exposure on the stepper, the resist is silylated, forming a surface layer of patterned silyl ether. The patterned image is dry-developed in oxygen plasma. The oxygen reacts with the silyl ether to form an oxide, which acts as a hard etch mask in the exposed areas. Plasma etching patterns the dielectric oxide, and oxygen ash removes the residual photo resist. The hard etch mask allows the formation of smaller, more delicate structures than does the standard polymeric photoresist mask; however, the TSI process has materials-safety issues similar to those of the CVD process.

Financial Analysis for Top Surface Imaging (TSI)

Operational & Financial Values Used

Expected life use/ Disposal phase: 5 yrs.	Discount rate: 15%
Process labor rate: \$100/ ESH labor rate: \$100	Tax rate: 40%
Wafers produced/yr.: 480,000	Depreciation: 3 yrs.

Estimated Cost & Financial Findings

Lifetime costs: \$1,440,300/ Annual costs: \$288,060	Discounted present value after tax: \$669,986
Life process staff costs: \$6,000/ Life ESH staff costs: \$42,200	Lifetime costs: Upfront: 204,800; Acquisition: 77,600; Use/disposal: 1,055,500
Annual cost/wafer: \$0.60	

**Deep ultraviolet lithography and pattern transfer*

Procedure 2: Peer Review

Peer review was used to evaluate and modify the template of life-cycle phases, cost factors and activity drivers. This approach provided an effective means of collecting expert-experience-based insight through a consensus-building approach. Peer reviewers participated in two rounds of review; the reviewers were three SH&E specialists from the semiconductor industry who were engaged in manufacturing-technology-and-process research and development and three university professors engaged in SH&E cost accounting research.

They looked at the following aspects of the model that represent the life-cycle phases of a manufacturing process: upfront activities arising from safety and environmental design reviews; regulatory compliance; life-cycle analysis; risk assessment and cost modeling; acquisition of capital equipment, buildings, structures and permits; use of resources (e.g., energy, water, chemicals), SH&E consumables and waste treatment supplies; activities arising from waste disposal; and decommissioning. [Part 2 of this article (July 2003) will discuss the entire template of life-cycle phases, cost factors and activity drivers.]

Procedure 3: Pilot Testing

Pilot studies were essential to this effort and provided relevant information about the usefulness of the cost model. A two-stage approach was used to conduct the pilot tests. Stage 1 focused on demonstrating the model's efficacy—its ability to capture and estimate SH&E costs incurred by manufacturing technology and process designs. Stage 2 focused on substantiating the model's financial robustness—its ability to compare, in real time, SH&E alternatives that are mutually exclusive, and linked to manufacturing technology and process designs.

Stage 1 Pilot Test Results: Demonstrate Efficacy

Table 2 (pg. 25) summarizes

the rates at which the model was able to capture data on and estimate SH&E costs. The fabrication, operational and financial default values used during this stage were based on industry average rates provided by those who had ownership in the technology or process: fabrication managers, design/process engineers, SH&E specialists and financial specialists. The expected productive/economic life years for each manufacturing technology and process and the number of wafers manufactured were based on information provided by the fabrication manager's records.

Stage 1 pilot-study cost data were collected, aggregated and analyzed in a manner that revealed the consolidated cost impact associated with the various manufacturing technologies and process designs tested. Because of the uniqueness of the technologies and processes studied, the data did not lend themselves to estimates of variability. In each cost analysis, the data were aggregated in a manner that represented essentially what is needed by fabrication managers to understand the full range of SH&E life-cycle costs.

Section A of Table 2 displays the life-cycle phases for each technology or process that was pilot-tested. It gives the rate of data collection and cost estimation for cost factors associated with each life-cycle phase. It also identifies the median cost per year of SH&E practices for each phase and each associated cost factor. Section B displays a summary of life-cycle phase cost estimates using the median values from the 15 pilot studies. In addition, annual and lifetime cost estimates, percentage breakdown and cost impact per wafer were calculated.

Examination of the data in Table 2, Section A reveals several findings about the model's ability to capture and estimate SH&E costs incurred by the manufacturing technology and process designs:

Technology Pilot Test #3*

Description

Three process alternatives for copper metalization were studied: tungsten chemical-vapor deposition (TCVD), physical-vapor deposition (PVD) and electroplating (EPD). Copper metalization may replace aluminum as a less-resistive interconnect for complex, multi-interconnect layer processes.

Mutually Exclusive Alternative Process A

The tungsten chemical-vapor deposition (TCVD) process deposits a layer of copper by reacting a vapor containing metal-organic copper, such as (trimethylvinylsilyl) hexafluoroacetylacetonato copper, on the surface of the wafer. The metal-organic vapor decomposes in a heated low-pressure process chamber to produce a uniform, bright copper film on the wafer and various volatile organic by-products, which must be scrubbed from the vacuum pump exhaust stream. Since metal-organic metals are typically toxic irritants and may be corrosive, they must be completely contained with double-contained piping from source to use. In addition, maintenance technicians must use personal protective equipment, including SCBA systems, in certain cases.

Financial Analysis for Tungsten Chemical-Vapor Deposition (TCVD)

Operational & Financial Values Used

Expected life use/ Disposal phase: 5 yrs.	Discount rate: 15%
Process Labor Rate: $100/ ESH Labor Rate: $100	Tax Rate: 40%
Wafers produced/yr.: 324,576	Depreciation: 3 yrs.

Estimated Cost & Financial Findings

Lifetime costs: $101,100/ Annual costs: $20,120	Discounted present value after tax: $56,085
Life process staff costs: $8,400/ Life ESH staff costs: $25,400	Lifetime costs: Upfront: 45,700; Acquisition: 25,400; Use/disposal: 25,000
Annual cost/wafer: $0.06	

Mutually Exclusive Alternative Process B

The physical-vapor deposition (PVD) process uses electron-beam evaporation or charged-ion sputtering to physically move copper molecules from a source electrode to the wafer surface. All PVD metal deposition must be processed in a vacuum chamber. PVD is nonselective, however, the copper is just as likely to deposit on process chamber walls as on the semiconductor device. Thus, the PVD vacuum process must periodically be disassembled, and the waste copper must be removed with hydrochloric acid or other corrosive chemicals. This maintenance cleaning generates significant amounts of copper-containing waste liquid, which must be properly treated for disposal.

Financial Analysis for Aluminum/Titanium Sputtering (PVD)

Operational & Financial Values Used

Expected life use/ Disposal phase: 5 yrs.	Discount rate: 15%
Process labor rate: $100/ ESH labor rate: $100	Tax rate: 40%
Wafers produced/yr.: 146,880	Depreciation: 3 yrs.

Estimated Cost & Financial Findings

Lifetime costs: $112,000/ Annual costs: $21,200	Discounted present value after tax: $57,732
Life process staff costs: $8,400/ Life ESH staff costs: $26,500	Lifetime costs: Upfront: 45,700; Acquisition: 25,400; Use/disposal: 25,000
Annual cost/wafer: $0.14	

Mutually Exclusive Alternative Process C

The electroplating deposition (EPD) process is a simple variation of the copper electroplating process that is used by the electronics industry for print circuit boards. EPD requires that the wafer first be covered with a conducting seed layer. The seed layer may be applied with CVD or PVD. An electric current applied to the seed layer attracts copper from a solid-copper electrode, through an ionic plating solution and to the wafer surface. The ionic plating solutions generally contain proprietary additives to enhance the uniformity, smoothness and brightness of the plated copper. The plating solutions can periodically be replenished instead of being replaced. This option significantly reduces the overall waste treatment load. However, the post-plating rinse in ultra-pure water does generate some liquid waste requiring treatment and disposal.

Financial Analysis for Electroplating Deposition (EPD)

Operational & Financial Values Used

Expected life use/ Disposal phase: 5 yrs.	Discount rate: 15%
Process labor rate: $100/ ESH labor rate: $100	Tax rate: 40%
Wafers produced/yr.: 254,112	Depreciation: 3 yrs.

Estimated Cost & Financial Findings

Lifetime costs: $513,670/ Annual costs: $101,534	Discounted present value after tax: $247,699
Life process staff costs: $8,400/ Life ESH staff costs: $26,500	Lifetime costs: Upfront: 45,700; Acquisition: 125,400; Use/disposal: 326,570
Annual cost/wafer: $0.40	

**Copper metalization*

Technology Pilot Test 4*

Description

Recycling of spent ultra-pure rinse water (UPW) used for wafer-rinsing purposes was studied as a way to decrease net feed water and ultra-pure water use, sustain water resources and lower water purification costs. Rapid industry growth, increases in wafer size and process steps, and the need for higher water purity indicate a trend toward higher water usage per wafer.

Financial Analysis for No-Recycle Strategy (NRS)

Operational & Financial Values Used

Expected life use/ Disposal phase: 15 yrs.	Discount rate: 15%
Process labor rate: $100/ ESH labor rate: $100	Tax rate: 40%
Wafers produced/yr.: 480,000	Depreciation: 3 yrs.

Estimated Cost & Financial Findings

Lifetime costs: $42,909,822/ Annual costs: $2,860,655	Discounted present value after tax: $10,036,384
Life process staff costs: $0/ Life ESH staff costs: $26,040	Lifetime costs: Upfront: 0; Acquisition: 0; Use/disposal: 42,909,822
Annual cost/wafer: $5.96	

Mutually Exclusive Alternative Process A

A no-recycle strategy was formulated or implemented.

Mutually Exclusive Alternative Process B

The recycling involves segregating, collecting and monitoring spent rinse waters from manufacturing processes; removing any organics that have been introduced into the spent rinse waters by the wafer fabrication process; and returning this water to the inlet of the ultra-pure-water system for purification into ultra-pure water that can be used again in the manufacturing process.

Financial Analysis for Recycle Strategy (RS)

Operational & Financial Values Used

Expected life use/ Disposal phase: 15 yrs.	Discount rate: 15%
Process labor rate: $100/ ESH labor rate: $100	Tax rate: 40%
Wafers produced/yr.: 480,000	Depreciation: 3 yrs.

Estimated Cost & Financial Findings

Lifetime costs: $30,985,957/ Annual costs: $2,065,730	Discounted present value after tax: $7,450,959
Life process staff cost: $73,200/ Life ESH staff costs: $32,460	Lifetime costs: Upfront: 21,000; Acquisition: 399,840; Use/disposal: 30,552,917
Annual cost/wafer: $4.30	

**Wafer spent rinse water recycling*

1) Data on 11 of the 14 cost factors (78 percent) were collected and costs were estimated. No incident-area-related costs were linked to any of the 15 manufacturing technology or design processes studied; therefore, data on cost factors 12 (internalities), 13 (externalities) and 14 (noncompliance fines) were not collected and costs were not estimated. Had an incident occurred in one of the 15 manufacturing technologies and processes studied, it would have been highly feasible for data on these cost factors to have been collected and for the costs to have been reasonably estimated.

In fact, discussions with participants in the Stage 1 pilot studies revealed that information on private direct and indirect incident costs (e.g., workers' compensation, fines, incident investigation, damaged property) could be accessed from company records and that values could be reasonably estimated. However, the participants perceived that the societal costs generated by an incident would be difficult to capture and estimate.

2) Data on cost factors 5 (resources used), 6 (consumables used) and 7 (strategic and technical support) were captured and costs estimated in all 15 (100 percent) of the pilot studies. Data on cost factor 8 (waste disposal) were captured in 14 of the 15 pilot tests (93 percent).

Data on cost factors 10 (decommissioning) and 11 (remediation) were captured and costs estimated in 13 (86 percent) of the pilot tests. Data on cost factors 1 (DfESH), 2 (permits), 3 (capital) and 9 (waste compliance) were captured and costs estimated in eight (53 percent) of the pilot tests.

Examination of the data in Table 2, Section B reveals the following additional findings:

3) The median annual SH&E cost per year was $86,200. Some 81 percent—$70,000—occurred in the use/disposal phase. The annual median cost per wafer manufactured was $0.36, of which $0.29 occurred in the use/disposal phase. In addition, the annual median SH&E staff labor costs generated and charged back to the manufacturing technologies and processes was estimated to be $16,250; the internal staff process costs were estimated to be $3,750. These internal labor costs reflect collateral-duty SH&E activities.

4) The median lifetime (e.g., five-year) SH&E cost was estimated to be $481,000, of which $350,000 (72 percent) occurred in the use/disposal phase. Post-disposal lifetime costs were estimated to be $100,000 or 20 percent of total lifetime costs. This increase resulted from required long-term (10-year) monitoring of technology or process waste.

Stage 2 Pilot Tests: Substantiate Financial Robustness

Stage 2 pilot testing focused on assessing the model's ability to financially evaluate mutually exclusive manufacturing-technology and process-design options. A present-value indicator was used to determine the discounted present value of costs for the pilot tests. Industry specialists (design/process engineers, SH&E specialists, financial specialists, purchasing and supply chain agents, fabrication managers) provided the operational/financial default values used during this stage. In each cost analysis, the data were aggregated in a manner that represented essentially what fabrication managers need in order to compare mutually exclusive alternatives. The sidebar on pg. 26 displays the technologies and designs that were pilot-tested to substantiate the model's financial robustness.

Each table provides primary descriptions of these manufacturing technologies and process designs to show the process and to portray the typical issues involved. To ensure a rigorous analysis of the cost results, these steps were followed:

1) Comparison of the annual and like-time SH&E costs, SH&E costs per wafer and discounted present value with the four scenarios.

2) Sensitivity analysis comparisons to establish which cost factors and activities in the life-cycle system are sensitive to a change in market values (e.g., the

highly volatile waste shipping and disposal market).

Stage 2 data reveals:

1) Stage 2 pilot tests reconfirmed findings of Stage 1 testing about the model's ability to capture and estimate the costs of mutually exclusive alternatives.

2) In eight of 10 pilot tests, acquisition costs were lower than use/disposal costs. Acquisition costs were 12 percent of the total lifetime costs, compared with use/disposal costs of 97.7 percent. Thus, the traditional approach of basing SH&E decisions solely on capital costs relies on incomplete financial information.

3) Use/disposal costs are generally the most significant costs of SH&E alternatives and are a better cost-driver indicator than are acquisition costs.

4) Total SH&E life-cycle costs provide a clear discriminator in all four comparisons attempted. Total life-cycle cost of ownership is based on the most complete source of information for decision making.

Table 3 compares the financial performance of the mutually exclusive technology and process alternatives that were pilot-tested. As this table shows, the present-value financial analysis provides the long-term financial impact of SH&E investments over a sufficient time horizon. Pilot test 4 (wafer spent rinse water recycle) provided a sensitivity analysis that showed the net present-value effect of a 10-percent increase in price for waste shipping and disposal over the productive/economic life of the recycling strategy. On the basis of this calculation, it is apparent that the decision to move to a recycle strategy actually increases the incremental net present value to $459,490 from the original $247,699 net present value.

Table 3

Present-Value Comparisons

Values today of a future stream of costs: Discount rate: 15%; tax rate: 40%; depreciation yrs.: 3.

Manufacturing Technology/Process	Mutually Exclusive Alternative	Present Value
1) Preplasma enhanced deposition clean (productive/economic life: 5 yrs.)	A) N-Methylpyrrlidone (NMP)	$659,746
	B) Cryogenic Clean System (CLS)	$150,324
2) Deep ultraviolet lithography and pattern transfer (productive/economic life: 5 yrs.)	A) Chemical-Vapor Deposition (CVD)	$734,960
	B) Dry Plasma-Polymerized Methylsilane (PPMS)	$389,973
	C) Top Surface Imaging (TSI)	$669,985
3) Copper metalization (productive/economic life: 5 yrs.)	A) Tungsten Chemical Vapor Deposition (TCVD)	$56,085
	B) Aluminum/Titanium Sputtering (PVD)	$57,732
	C) Electroplating (EPD)	$247,697
4) Wafer spent rinse water recycle (productive/economic life: 15 yrs.)	A) No-Recycle Strategy	$10,036,384
	B) Recycle Strategy	$7,450,960
	NPV:	**$2,576,445**

Sensitivity Analysis for Wafer Spent Rinse Water Recycle

10 percent price increase (waste shipping/disposal)

	A) No-Recycle Strategy	$11,261,689
	B) Recycle Strategy	$8,216,775
	NPV:	**$3,035,935**

Summary

Questions and uncertainties related to SH&E practices create business challenges for fabrication managers, who need to understand the issues and circumstances that drive these practices. They also need to know how to depict financial outlays; how to attribute them to accounting periods; when to recognize them as liabilities that may require future financial outlays; and how to measure those expected financial outlays.

The researchers believe development of SH&E cost modeling in this industry currently falls between the stage of understanding what factors drive costs and the stage of using that information to enhance decision making. Continued developments in this area will require that SH&E specialists, working in conjunction with design/process engineers and financial experts, help fabrication managers make SH&E investments for the same reasons they make other investments—because they expect those investments to enhance competitiveness and reduce risk.

In this study, changes in manufacturing practices and SH&E practices were interwoven. Changes in manufacturing affect SH&E and changes in SH&E in turn force logistical changes and changes in manufacturing technology and process design. It was also found that when the topic of modeling SH&E cost of ownership was first discussed with fabrication personnel, many thought the process would involve a trade-off of operations-related costs versus SH&E-related costs. This study was able to show these personnel that they can set acceptable SH&E performance criteria, then compare the life-cycle cost of ownership for mutually exclusive alternatives that meet or exceed those criteria. The comparative approach provided these managers with an improved way to decide between alternative methods of meeting a specific set of criteria.

While this study provided an enhanced way to profile costs of SH&E issues and practices associated with semiconductor manufacturing technologies and process designs, it did have limitations. For example, *Fabrication managers can leverage manufacturing performance advantages by profiling the cost of SH&E issues and practices associated with manufacturing technology and process designs.*

not all design parameters are known, nor are all technology transfer, implementation strategy and evaluation components. Further advancements in SH&E cost modeling will depend on research-and-development activities in these areas. Nevertheless, because of the complex and diverse nature of the technologies and processes studied, the researchers believe the research design and architecture of the model is generalizable to other types of manufacturing firms and other types of industries.

Recommendations for Future Research

1) Study ways of broadening the template of cost factors and activity drivers throughout the model's various life-cycle phases, specifically focusing on decommissioning and remediation cost factors and related activities.

2) Explore ways to standardize procedures related to the collection and estimation of cost factors and activity drivers.

3) Develop cost-modeling efforts that specifically profile the cost and profitability potential of new and upgraded manufacturing technology engineering designs.

4) Develop methods of estimating and integrating risk costs, including algorithms, into SH&E cost-modeling and software platforms.

5) Study ways to effectively transfer the technology developed from SH&E cost-modeling efforts to design/process engineers.

6) Research the circumstances under which particular kinds of SH&E investments deliver benefits to shareholders.

7) Determine the financial impact of upfront design and concurrent engineering activities on downstream (manufacturing-disposal) costs. ■

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