Environmental Technologies & Management Systems in the Semiconductor Industry: The Perspective of an Equipment Maker

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Presentation to NSF/SRC Engineering Research Center for
Environmentally Benign Semiconductor Manufacturing

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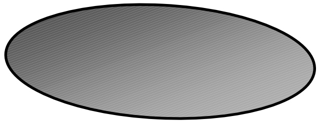
Outline

- Environmental impact and industrial ecology in the semiconductor industry
- Applied Materials’ Environmental Solutions Product Division
- Progress on CVD chamber cleaning
- Solutions for dielectric etch emissions
- Pumps electrical consumption
- Abatement solutions gap analysis and validation
- Drivers for green manufacturing

A Typical Semiconductor Fab

(300k 200mm Wafers/Year)

- **Si wafers**
  - 10 tons/yr



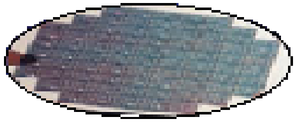
- **Electricity**
  - 1.2kWh/cm^2 of Si produced
  - ~ a town of 10,000

- **Air Emissions**
  - HAPs (max 20 tons/yr)
  - VOCs (40-100 tons/yr)
  - PFCs (>100 kgCE/wafer) (20,000 tons CE/yr)

- **Chemicals**
  - Metal / dielectric precursor chemicals
  - HAPs precursors
  - PFCs precursors
  - Solvents
  - CMP materials

- **Chips**

  ~10,000's $/wafer



- **Water**
  - 15.5 l/cm^2 of Si produced
  - ~ a town of 20,000

- **Solid & Liquid Waste**
  - Producing 1 PC = 63 kg of waste material generated
    - ~43 kg of non-hazardous waste
    - ~20 kg of hazardous waste

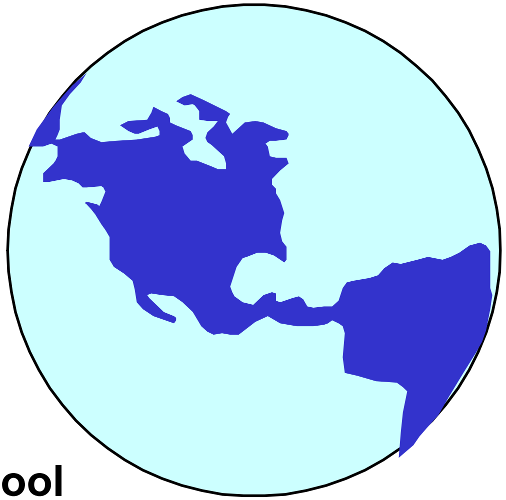
Environmental Issues and Regulations

	HAPs	VOCs	PFCs	Water	Solid Waste	Energy
Regulatory agencies	Regulated on a per fab basis	Regulated on a per fab basis	Memorandum Of Understanding	Regulated (contamination)	Regulated (haz. waste)	Not regulated but local limitations
Chip manufacturers	Want their suppliers to follow industry protocols and provide Product Environmental Assessment (PEA) report prior to buying the tool					
SEMI Standards	SEMI S2 has been revised in 2000 - Require to measure emissions and close the mass balance - demonstrate attempts to reduce emissions - must justify use of chemicals					SEMI E6 revised to include power measurement (03/03)
Industry protocols	Equipment Environmental Characterization Guidelines 3.0					AMAT's protocol proposed to SEMI
	Required	Required but does not define how to measure	Required Protocol initially established by PFC Leadership Group	Required PCW consumption measurement	Required estimate solid waste generated during PM and process	
Applied Materials Product Development Process	**Require Product Environmental Assessment to be performed as part of product development** Follow Equipment Environmental Characterization Guidelines 3.0 - Power Measurement Protocol - Process Cooling Water Measurement Protocol					

- **Summary of the requirements, standards and regulations regarding the environmental impact of semiconductor manufacturing tools**

Typical Customer's Environmental Requirements

- Complete emissions characterization
- Provide POU abatement . . . or at least a suggestion



- Exhaust materials compatible with exhaust gases/byproducts
- Exhausts and drains segregated

- Evidence of water use optimization
- Use of recyclable materials

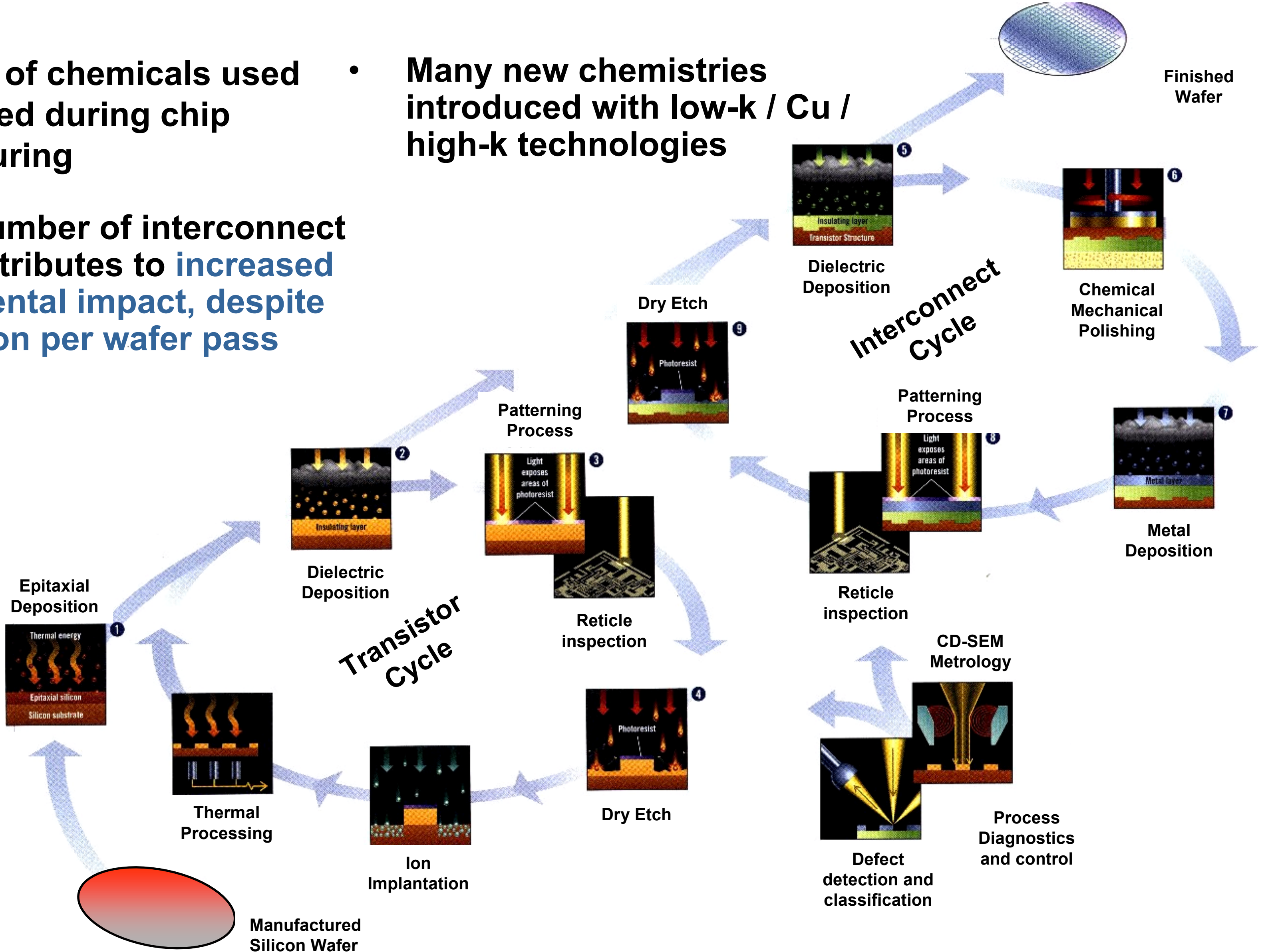
- Disclosure of environmental risks of installing and operating tool
- Supporting environmental data, plans, roadmaps, etc.
- Compliance with environmental requirements

- Sign-off by customer's EHS Manager prior to "tool acceptance"

Need method to provide information with confidence and reduced risk

Environmental Challenges and the Chip Cycle

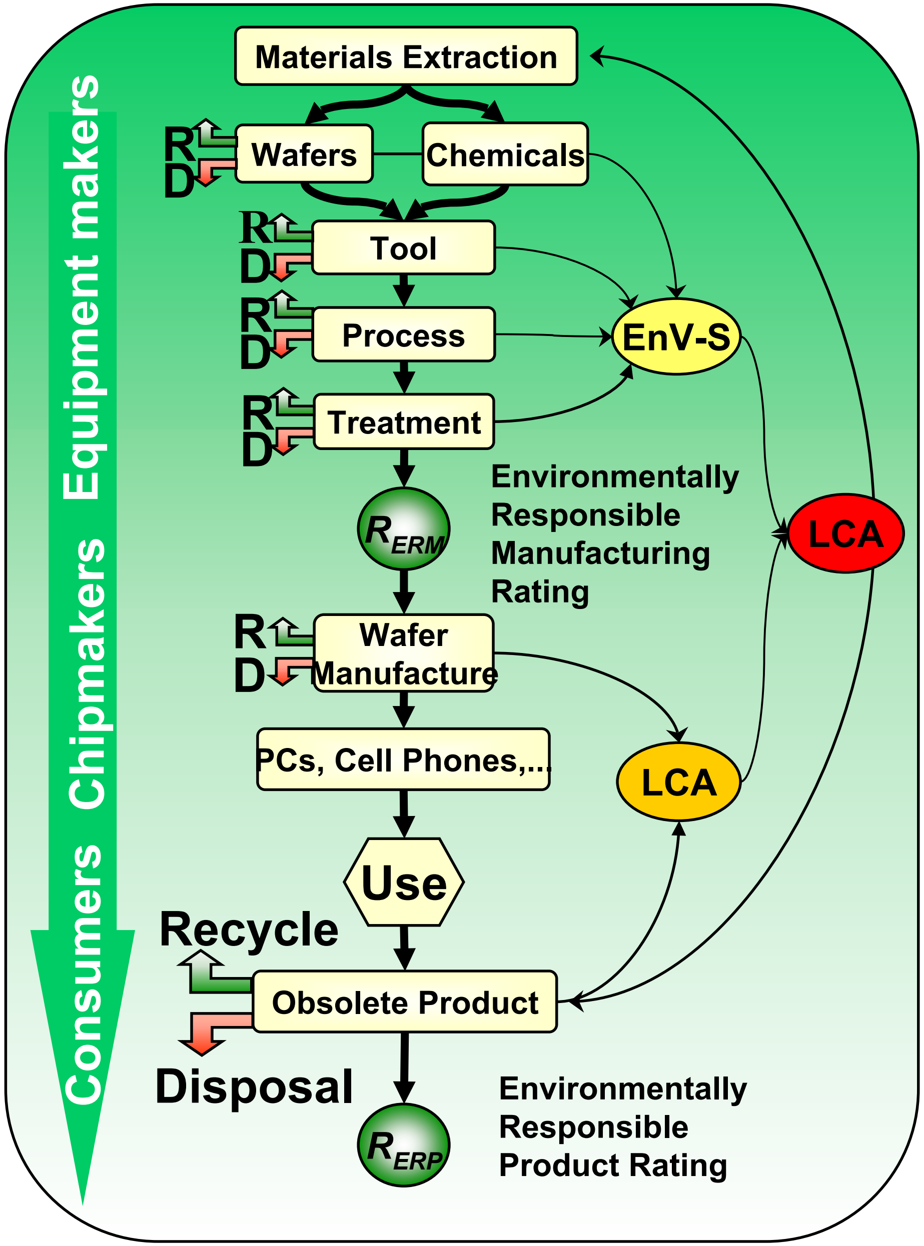
- Hundreds of chemicals used or produced during chip manufacturing
- Greater number of interconnect levels contributes to increased environmental impact, despite progress on per wafer pass basis
- Many new chemistries introduced with low-k / Cu / high-k technologies



Chip Manufacturing and Industrial Ecology

- Life-Cycle Analysis (LCA) is an objective process to evaluate relevant environmental, economic and technological implications of a material, process or product over its entire life span, from creation to waste or, preferably, to recycling*

- Environmental Value System** (EnV-S) is an equipment-centric analysis to aid equipment selection, design, and process evaluations in support of sustainable decision making



* Source: T.E. Graedel, B.R. Allenby, "Industrial Ecology", p.108

** Developed in collaboration between Applied Materials and the University of California at Berkeley

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Environmental Solutions Product Division

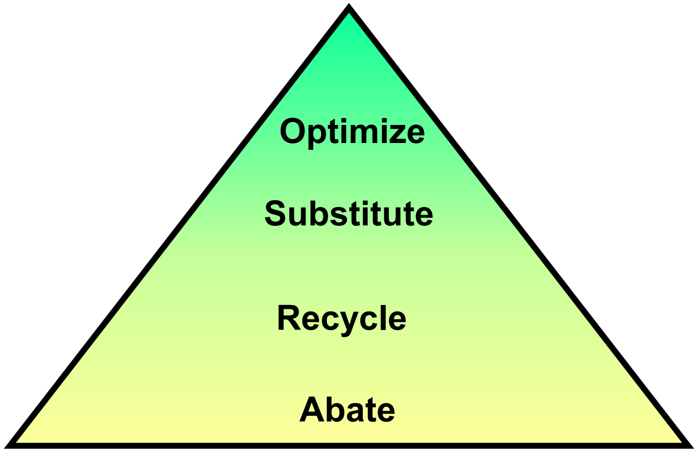
- **Mission**
  - **Demonstrate leadership by providing environmental products and services for the mutual benefit of customers, the environment, and the community**
- **Motto**
  - **Better Environment by Design**

TOTAL SOLUTIONS™

- **ESPD addresses environmental issues by:**
  - **Developing emissions abatement/pump products to solve industry challenges**
  - **Validating other abatement/pump vendors' products through comprehensive characterization**
  - **Measuring gaseous and liquid emissions of Applied Materials equipment for proactive environmental management by product divisions**

Strategies to Reduce Environmental Impact

- Solutions integrated to the process system
  - Address the problem at its source
  - Focus on point of use (POU)
- Efficient use of energy and resources
  - Plasma vs. combustion, POU recycling
  - Adapt to real time operations (idle mode, interface)
- Solutions for increased performance/productivity
  - Increased throughput
  - Reduced maintenance



Optimize

Substitute

Recycle

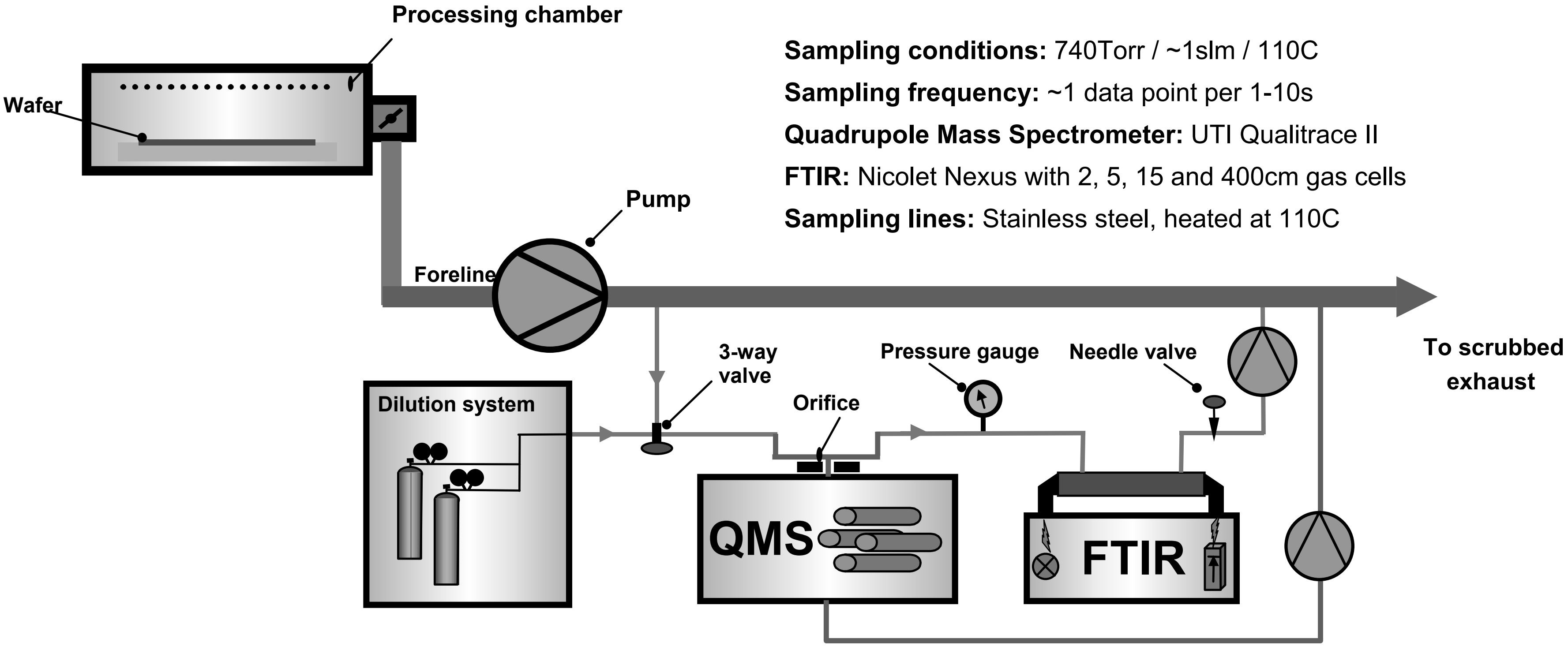
Abate

Hierarchy Of Solutions

Issues, strategies and technology solutions currently being addressed by Applied Materials

Source	Issue	Strategy	Solutions	Benefits
CVD Chamber Clean	PFCs emissions	Optimize	Remote Clean with NF_3	>95% reduction in carbon equivalent emissions, reduced clean time
CVD Emissions	HAPs, PFCs & VOCs emissions	Abate	Combustion with water scrubbing	Reduced fuel and water consumption, energy efficiency
Dielectric Etch	PFCs emisisons	Substitute	Alternative (non-PFC) source gas (C_4F_6)	Better process performance (selectivity)
Dielectric Etch	PFCs emisisons	Abate	Pegasys plasma abatement	>95% reduction in carbon equivalent emissions
Vacuum Pumps	Electrical consumption	Optimize	Integrated point-of-use pumps (iPUP)	Reduced electrical consumption
CMP	Water consumption & contamination	Abate and recycle	Point of use technology	Flexibility, lower cost, water consumption reduction

Emissions Measurement: Connection Hookup Diagram



Sampling conditions: 740Torr / ~1slm / 110C

Sampling frequency: ~1 data point per 1-10s

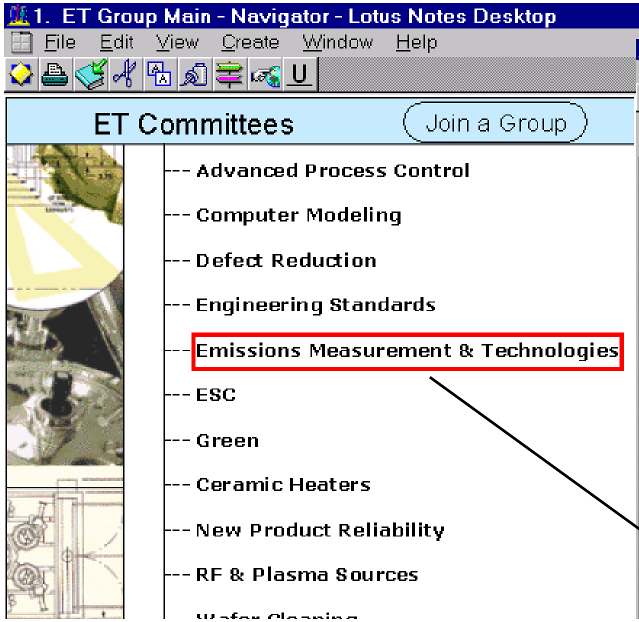
Quadrupole Mass Spectrometer: UTI Qualitrace II

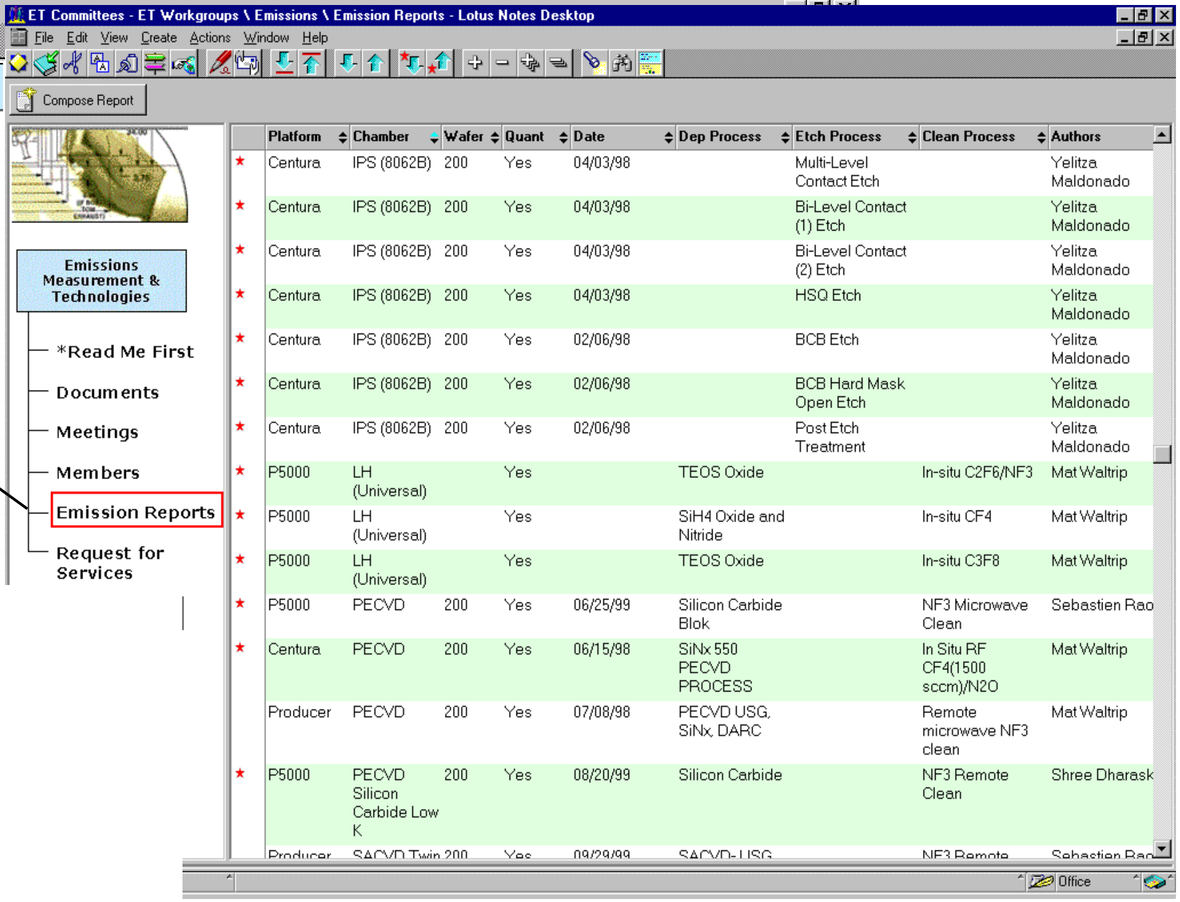
FTIR: Nicolet Nexus with 2, 5, 15 and 400cm gas cells

Sampling lines: Stainless steel, heated at 110C

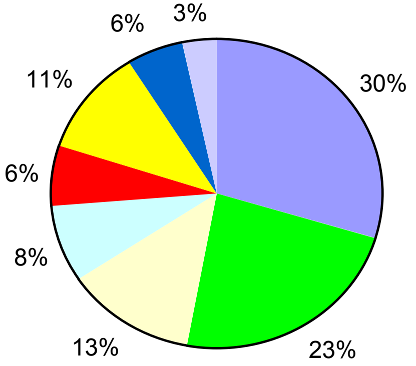
- **Measurements at exhaust of vacuum pump (atmospheric pressure), in real time**
- **Calibrations must be performed on the spot before and after measurement in order to obtain quantitative results**
- **Additional analytical techniques may be used (off line) to confirm effluents composition (GC-MS, ICP-MS, solid residues analysis…)**

Emissions - Lotus Notes Database





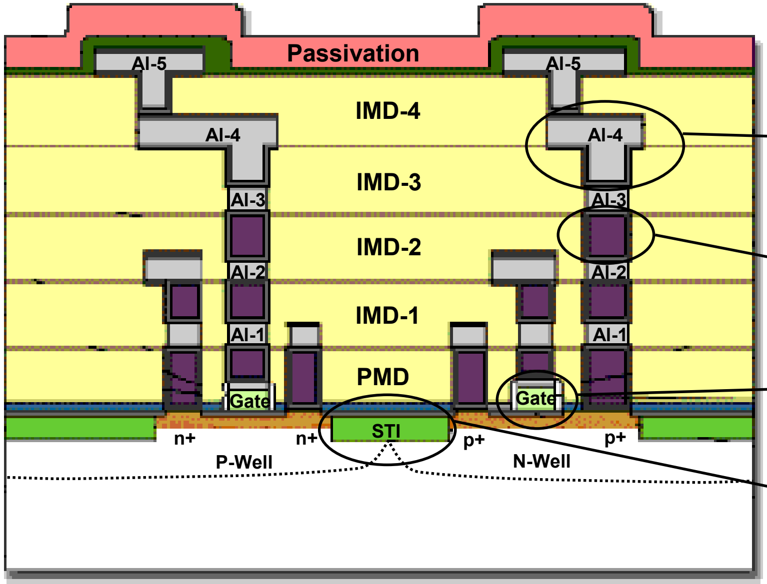
	Platform	Chamber	Wafer	Quant	Date	Dep Process	Etch Process	Clean Process	Authors
★	Centura	IPS (8062B)	200	Yes	04/03/98		Multi-Level Contact Etch		Yelitza Maldonado
★	Centura	IPS (8062B)	200	Yes	04/03/98		Bi-Level Contact (1) Etch		Yelitza Maldonado
★	Centura	IPS (8062B)	200	Yes	04/03/98		Bi-Level Contact (2) Etch		Yelitza Maldonado
★	Centura	IPS (8062B)	200	Yes	04/03/98		HSQ Etch		Yelitza Maldonado
★	Centura	IPS (8062B)	200	Yes	02/06/98		BCB Etch		Yelitza Maldonado
★	Centura	IPS (8062B)	200	Yes	02/06/98		BCB Hard Mask Open Etch		Yelitza Maldonado
★	Centura	IPS (8062B)	200	Yes	02/06/98		Post Etch Treatment		Yelitza Maldonado
★	P5000	LH (Universal)		Yes		TEOS Oxide		In-situ C2F6/NF3	Mat Waltrip
★	P5000	LH (Universal)		Yes		SiH4 Oxide and Nitride		In-situ CF4	Mat Waltrip
★	P5000	LH (Universal)		Yes		TEOS Oxide		In-situ C3F8	Mat Waltrip
★	P5000	PECVD	200	Yes	06/25/99	Silicon Carbide Blok		NF3 Microwave Clean	Sebastien Rao
★	Centura	PECVD	200	Yes	06/15/98	SiNx 550 PECVD PROCESS		In Situ RF CF4(1500 sccm)/N2O	Mat Waltrip
	Producer	PECVD	200	Yes	07/08/98	PECVD USG, SiNx, DARC		Remote microwave NF3 clean	Mat Waltrip
★	P5000	PECVD Silicon Carbide Low K	200	Yes	08/20/99	Silicon Carbide		NF3 Remote Clean	Shree Dharask
	Producer	SACVD Twin	200	Yes	09/29/99	SACVD-USG		NF3 Remote	Sebastien Rao



🟪 PECVD	🟩 Dielectric Etch
☐ Transistor/Capacitor	☐ Conductor Etch
🟥 SACVD	🟨 HDPCVD
🟦 Low k	☐ Metal/Liner Deposition

Modeling Consumption, Emissions (Per Chip Basis)

- **Gas consumption and emissions were measured for over 75 processes**
- **GWGs, HAPs, and VOCs emissions were quantified on a per wafer pass basis**
- **A model of consumption and emissions can be built for the whole chip**



Gas Consumption Per Module:

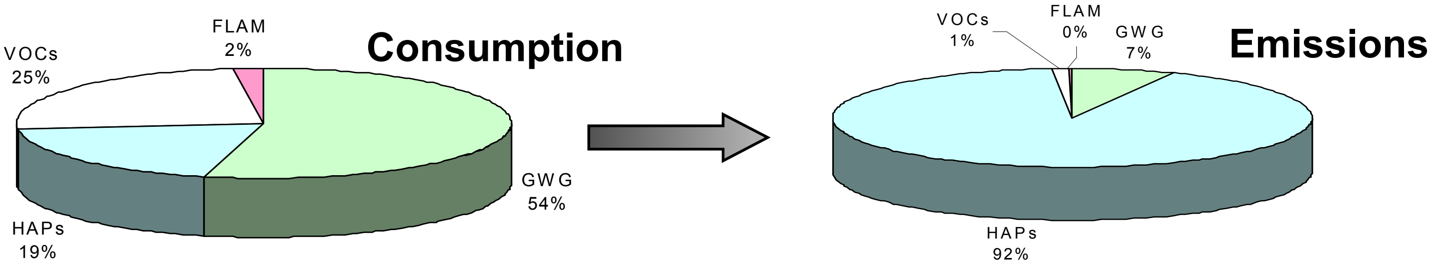
5 Interconnect modules: 47%

5 Via modules: 41%

1 Gate module: 5%

1 Shallow trench isolation module: 7%

Cross section of a generic logic device with 5 levels of metal



Consumption

Emissions

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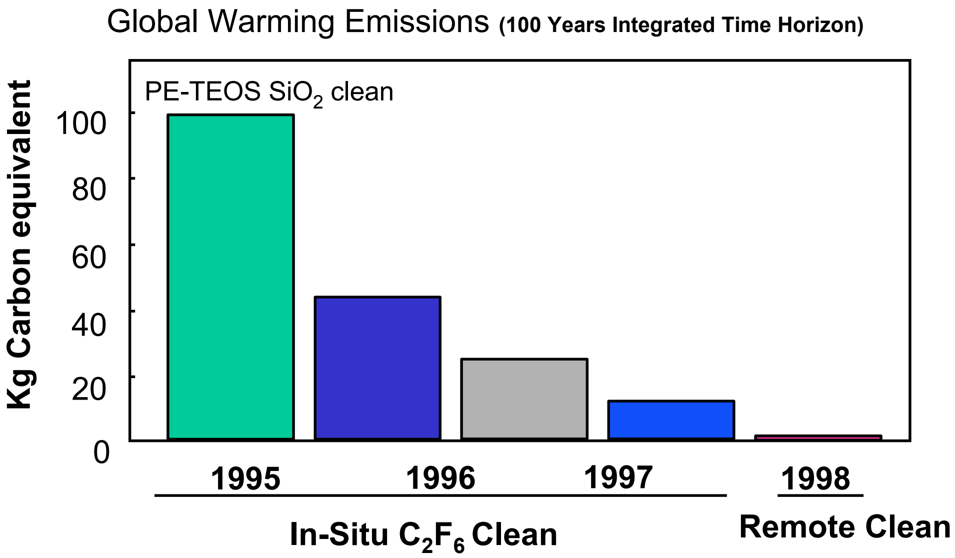
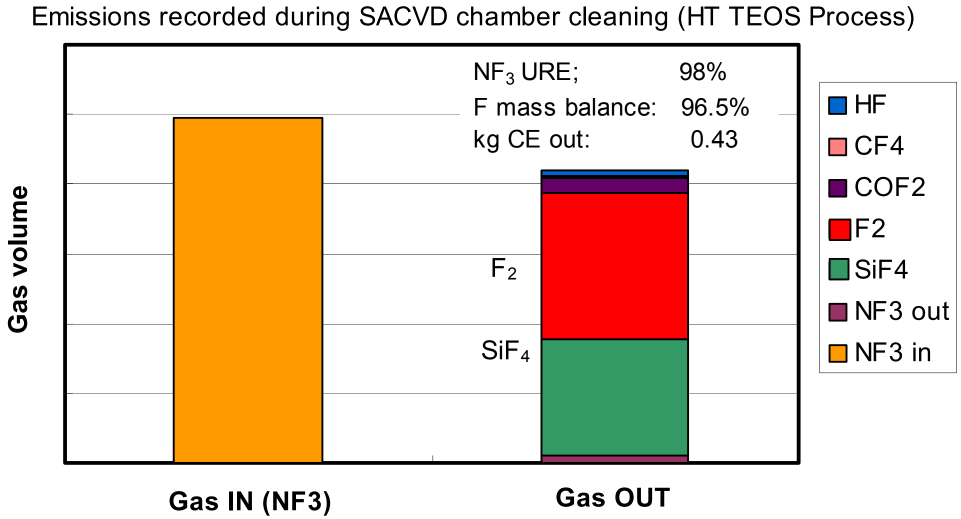
Environmental Impact of CVD Chamber Cleans

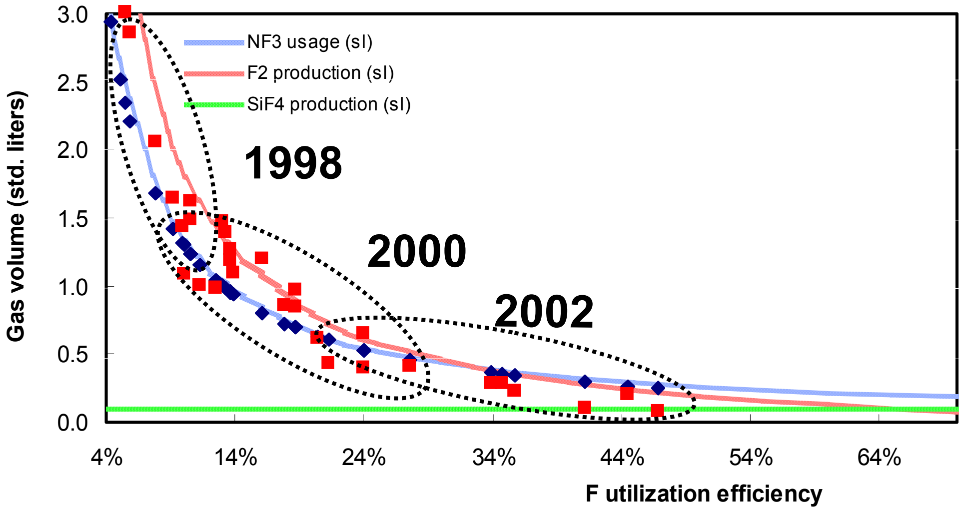
- **Global warming emissions from CVD chamber cleaning were reduced by two orders of magnitude between 1995 and 1998**
    - **1995: One clean = 500 miles ***
    - **1998: One clean = 2 miles**
- **Remote Clean™ technology provides the industry's lowest global warming emissions for CVD chamber cleaning**
- **However, the clean efficiency is still limited by F--->F_2 recombination and F radical utilization efficiency**
    - **Recombination leads to high F_2 emissions**
    - **F_2 emissions must be treated with point of use scrubber**
    - **Also results in undesirably high NF_3 consumption**





* 1 mile driven with average passenger car = 0.8 lb CE

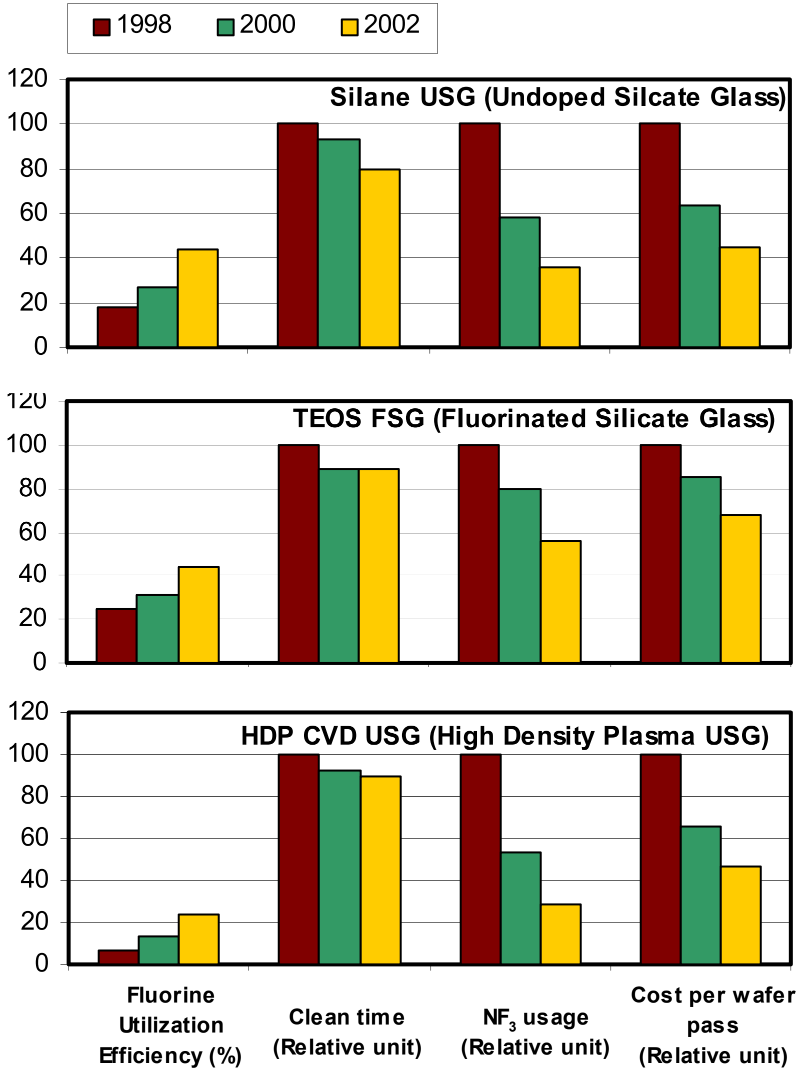
Situation Analysis on CVD Chamber Cleaning



- **Fluorine utilization efficiency used as a metric for optimization**

$$F_{Util.Eff.} = \frac{4xSiF_4 + HF + \left(4xCF_4 + 2xCOF_2 + \ldots\right)}{3xNF_3}$$

- **Up to 70% reduction in clean gas usage demonstrated through process and hardware improvements**
  - **Distance between remote plasma source and CVD chamber, materials to transport F atoms**
  - **Process optimization (multi-step clean concept)**



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C_4F_6 – Alternative PFC Chemistry Implementation / Limitations

	Structure	Boiling Point (Celsius)	Life time (years)	Global Warming Potential (est.)
C_4F_6	$CF2{=}CF{-}CF{=}CF2$	6	<0.003	50

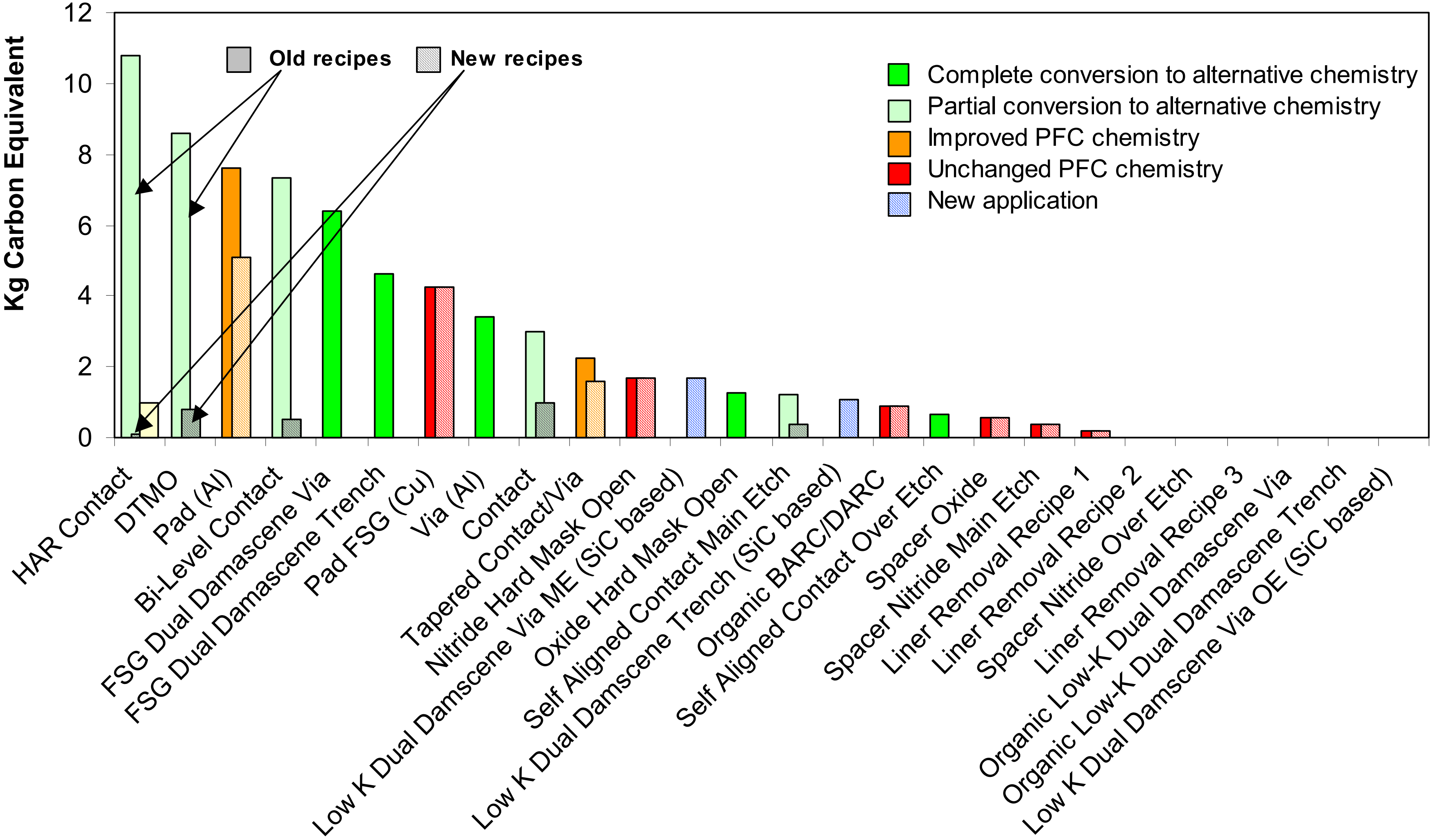
- **Higher etch selectivity**
  - **Pros: Improved selectivity to stop layers, including SiN, SiC (BLoK), TiN**
  - **Limitation: C_4F_6 etch rate limited on carbon-containing materials, nitrides**

☞ **Chemical incompatibility for applications such as low k etch, hard mask open, spacer etch, organic BARC, DARC**

- **Improved resist integrity**
  - **Pros: Minimizes striations, reduces damage to photoresist, preserves CDs, improves profile control (less bowing, tapering), HAR etch**
  - **Limitation: C_4F_6 performance limited on large open area applications**

☞ **Limitations for applications such as PAD etch which require high etch rates and high pressure**

Evolution of PFC Consumption Per Wafer Pass
Dielectric Etch - Old vs. New Recipes (300mm)

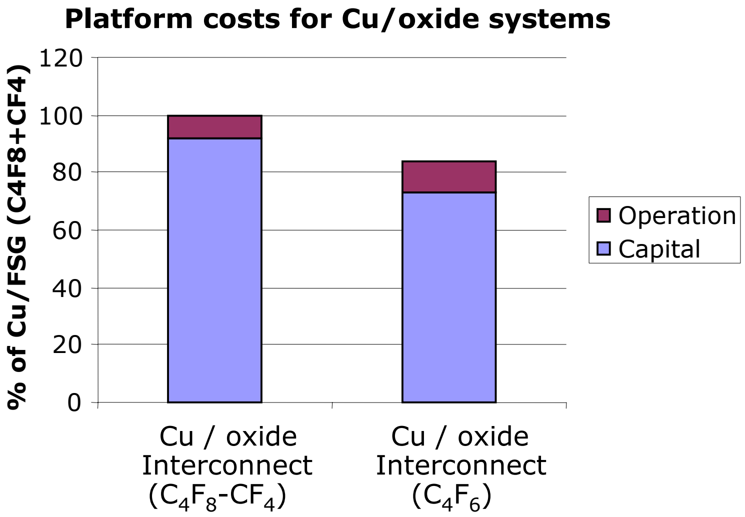


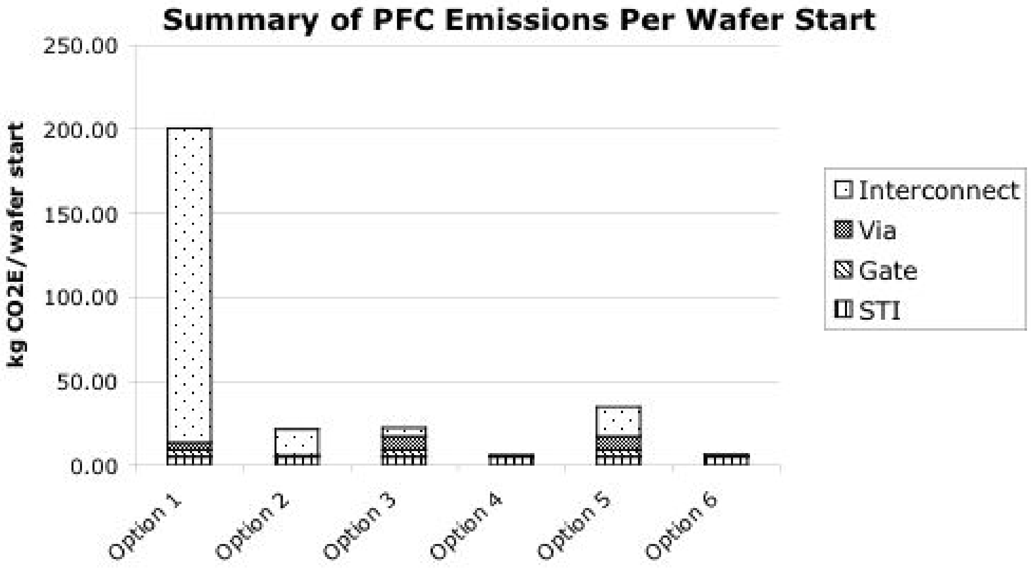
Tradeoffs must be found to balance process performance, cost and environmental impact

Alternative Chemistries and Abatement for Dielectric Etch

- **EnV-S was used to better understand the tradeoffs between alternative PFC chemistry and abatement**
  - **Despite higher gas costs, C_4F_6 chemistry can be cost effective due to higher throughput**
  - **Abatement still required to meet aggressive PFC emissions reduction targets**

Options	1	2	3	4	5	6
Cu / oxide (C_4F_8+C_2F_6)	X	X				
Cu / oxide (C_4F_6)			X	X		
Cu / Low k					X	X
Plasma Abatement		X		X		X

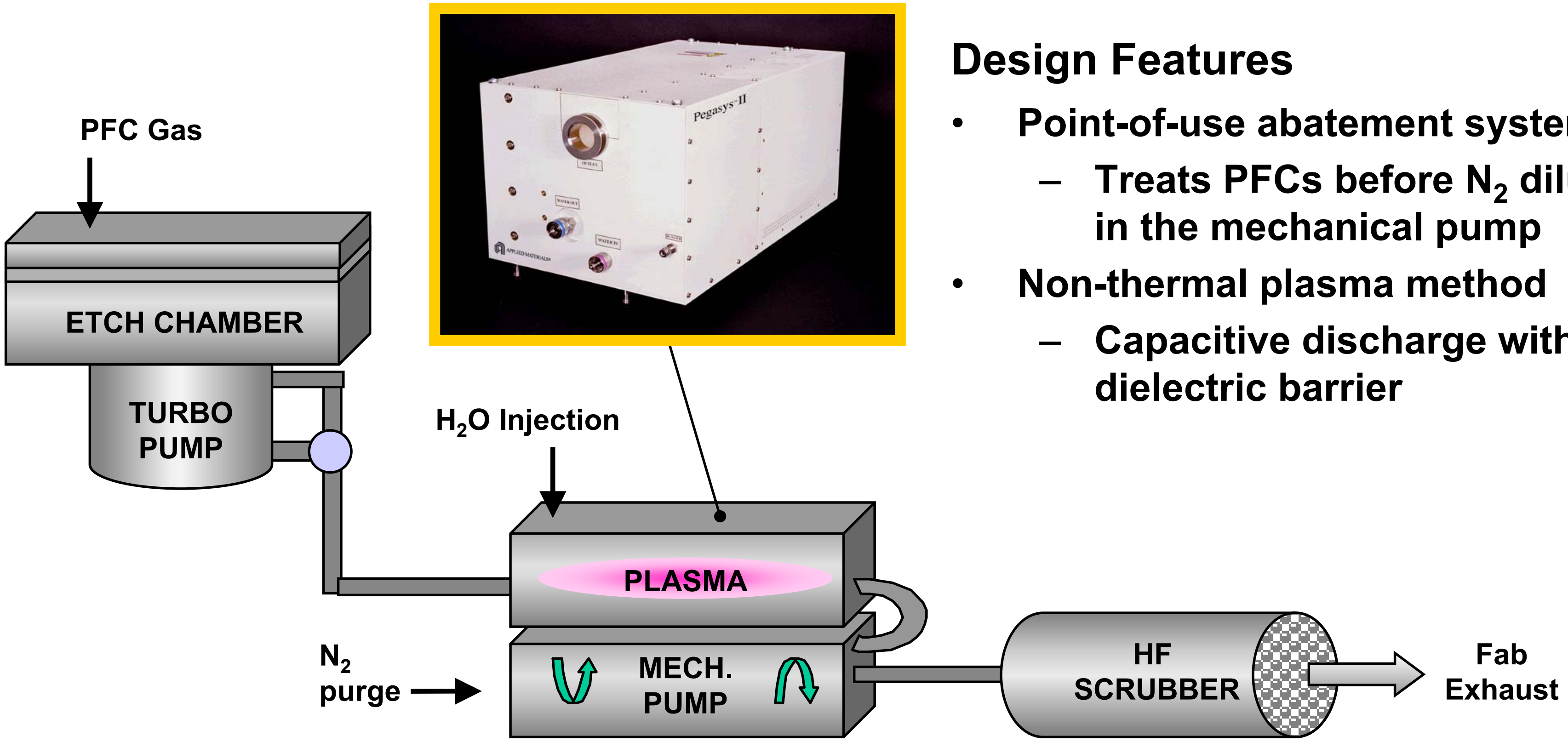




PFC Abatement for Dielectric Etch: Pegasys^{TM}

Design Features

- Point-of-use abatement system
  - Treats PFCs before N_2 dilution in the mechanical pump
- Non-thermal plasma method
  - Capacitive discharge with dielectric barrier



Chemistry

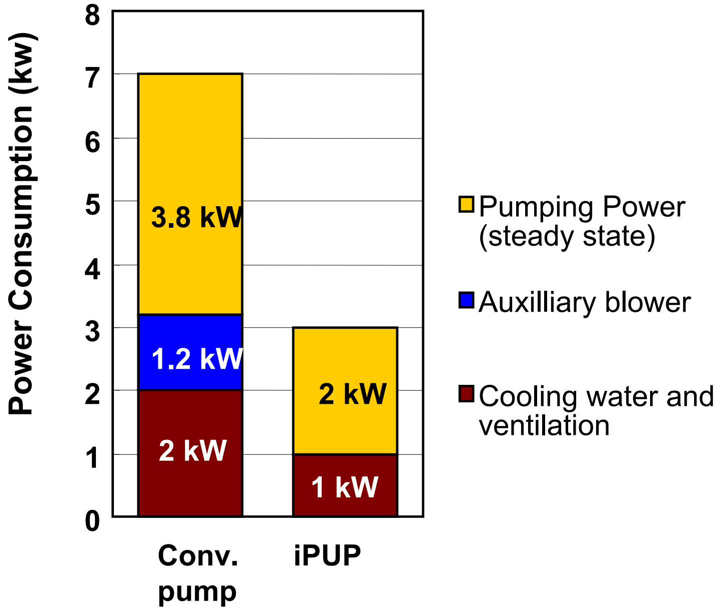
- Water injection as sole source of reactant
- Formation of CO_2, CO, COF_2, HF as byproducts of PFC decomposition

Performance

- > 95% DRE on most demanding 300mm PFC gas flows
- Power management (interface with Applied Materials etchers)

Energy Consumption Reduction

- SIA Roadmap for energy consumption reduction
  - 1.2 kWh/cm^2 of Si in 2000
  - 0.9 kWh/cm^2 of Si in 2005
  - 0.7 kWh/cm^2 of Si in 2011
- Applied Materials developed a power measurement protocol and proposed it for inclusion in the SEMI E6 revision



- Energy consumption can be reduced through:
  - Inefficiency identification, measurement
  - Optimization, point-of-use (POU) solutions
  - Idle power reduction (non value-added energy)
- Use of next generation vacuum pumps could save up to:
  - 200,000 kWh per system per year (6 pumps)
  - 150,000 kg CE per system per year

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Abatement Solutions Gap Analysis

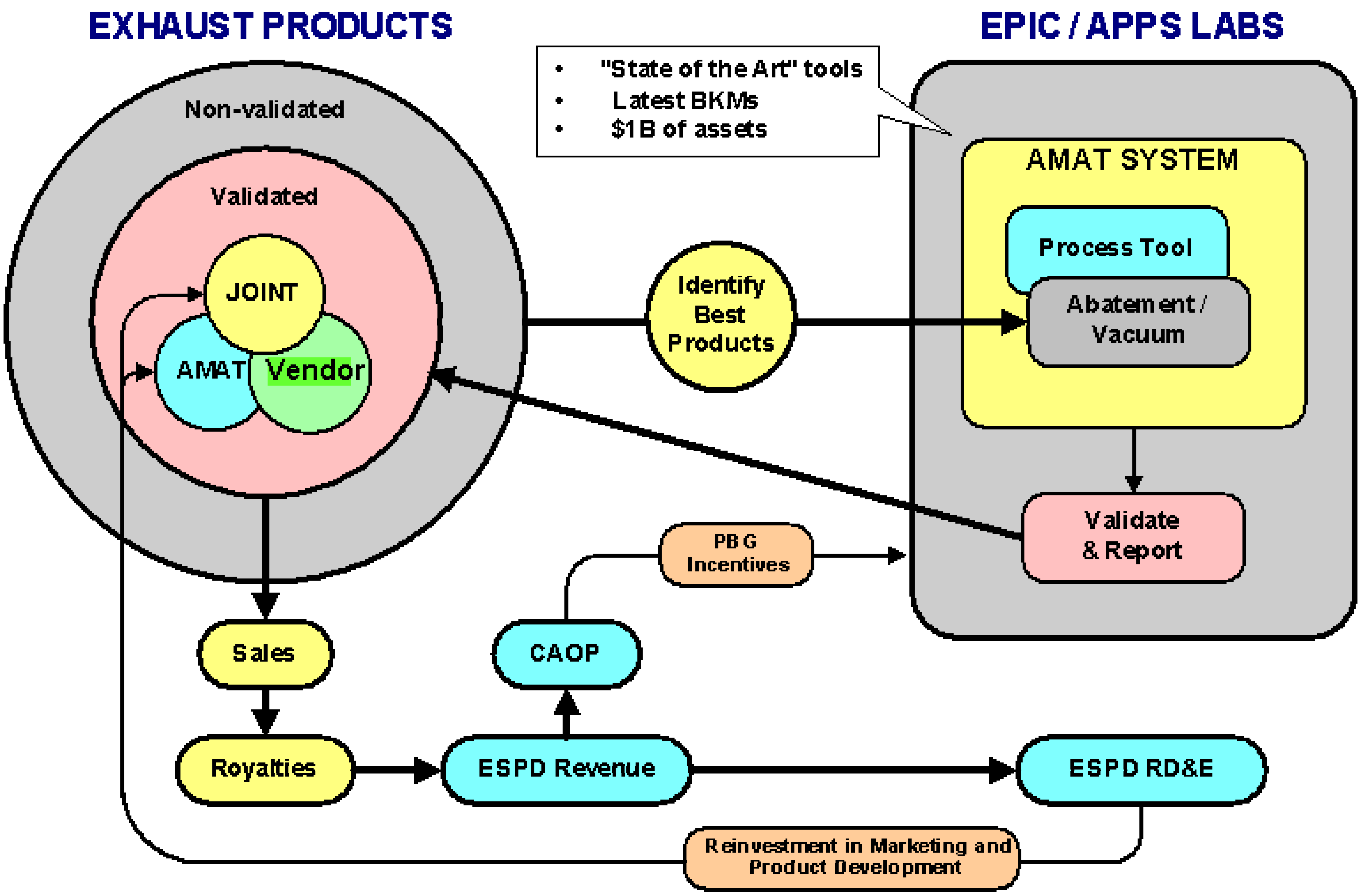
🟩 Good treatment solution 🟨 Require improvements 🟥 Inadequate

Key Product Unit	Process	Emission Byproducts
PECVD	🟩 USG	SiF4, F2, HF, COF2, CO, NF3, CO2, TEOS, C2H5OH, CH4
	🟩 SiNx	SiF4, F2, HF, NF3, N2O, SiH4, NH3
	🟩 FSG	SiF4, F2, HF, COF2, CO, NF3, CO2, TEOS, C2H5OH, CH4
	🟩 PSG	SiF4, F2, HF, COF2, CO, NF3, CO2, TEOS, TEPO, C2H5OH, CH4
Low-k	🟥 BD	SiF4, F2, HF, COF2, NH3, NF3, CF4, CO2, TMS, CH4
	🟥 BLOk	SiF4, F2, HF, COF2, NH3, NF3, CF4, CO2, TMS, CH4
HDP-CVD	🟩 USG	SiF4, F2, HF, NF3, SiH4
	🟩 FSG	SiF4, F2, HF, NF3, SiH4
	🟩 PSG	SiF4, F2, HF, NF3, SiH4, PH3
SACVD	🟨 BPSG	SiF4, F2, HF, COF2, CO, NF3, CO2, TEOS, TEPO, TEB, C2H5OH, HCOOH, CH4
	🟨 BSG	SiF4, F2, HF, COF2, CO, NF3, CO2, TEOS, TEB, C2H5OH, HCOOH, CH4
LPCVD	🟨 SinGen	SiF4, F2, HF, NF3, SiH4, NH3
	🟨 PolyGen	SiF4, F2, HF, NF3, SiH4, PH3, N2O
	🟨 OxyGen	SiF4, F2, HF, NF3, SiH4, N2O
	🟨 WSix	SiF4, F2, HF, NF3, SiH4, WF6, DCS, HCl, Cl2, SiCl4

Key Product Unit	Process	Emission Byproducts
RTP	ISSG	H2, O2,
	🟩 EISSG	N2O, H2
	🟩 RTN	H2, NH3
Epi	🟥 Standard Epi SiGe Blanket	HCl, DCS, SiH4, SiCl4, Cl2, H2, GeH4
High-k	🟩 TaOx	SiF4, F2, HF, COF2, NF3, CF4, CO2
	🟩 HfOx	DEA, NH3, CO, C2H4, Cl2
MCVD	🟨 W-CVD	SiF4, F2, HF, NF3, SiH4, WF6, B2H6
	🟨 TiCl4/TiN	TiCl4, NH3, Cl2, HCl, NH4Cl
	🟩 TiCl4/Ti	TiCl4, Cl2, HCl
	🟩 TDMAT/TiN	TDMAT, CH4, NH3, DMA
	🟩 TDMAT/TiSiN	TDMAT, CH4, NH3, DMA, SiH4, H2
Etch	🟩 Dielectric Etch	COF2, SiF4, C4F8, CF4, CHF3, C2F6, C4F6, C2F4
	🟨 Metal Etch	BCl3, Cl2, HCl, F2, AlCl3, CF4, CHF3, SF6
	🟨 Silicon Etch	SiF4, C4F8, CF4, CHF3, C2F6, Cl2, H2, C2F4, SF6
	🟩 Low-k Etch	COF2, F2, HF, CO, SiF4, C4F6, CF4, CHF3, C2F4, C2F6
	🟩 Photomask Etch	COF2, HF, CO, SiF4, CF4, CO2, Cl2, SO2, SF6, C2F6
Implant	🟩 Quantum	AsH3, BF3, PH3, SiF4, CO, CO2
	🟩 Swift	AsH3, BF3, PH3, SiF4, CO, CO2
CMP	🟥 Copper	Cu++, copper salts, organics
	Oxide	HF, NH4OH, IPA

- **30% of the applications require improvement of the abatement systems**
- **Some abatement applications currently do not have acceptable performance**

Simplified Business Model



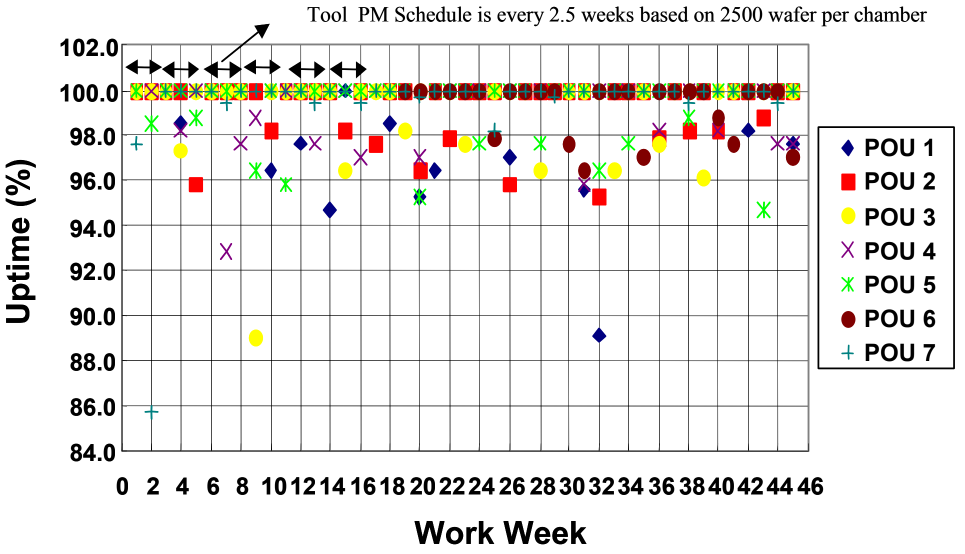
Abatement Validation Report Contents

- Summary of Findings
  - Purpose, value, key data, conclusions
- Gaseous Emission Analysis
  - Deposition process
  - Clean/seasoning process
  - Mixed process
  - Abatement recipe and process window
- Liquid & Solid Byproducts
  - Liquid byproducts analysis
  - Solid byproducts analysis
  - Phase change data (condensation curve)
  - Material capability
- Process Transparency & Reliability
  - Particle data, uniformity
  - Abatement uptime information
- EnV-S Analysis
  - Extended CoO analysis
  - EHS indicator
  - Performance indicator
  - TLV, IDLH
- Analytical Methodology and Calibration
  - QMS
  - FTIR
  - Calibration curve
  - Dilution factor calculation
  - PFC calculation
  - Breakdown efficiency and F closure
- Appendix
  - Installation procedure
  - Maintenance schedule and procedure
  - Safety and regulatory information

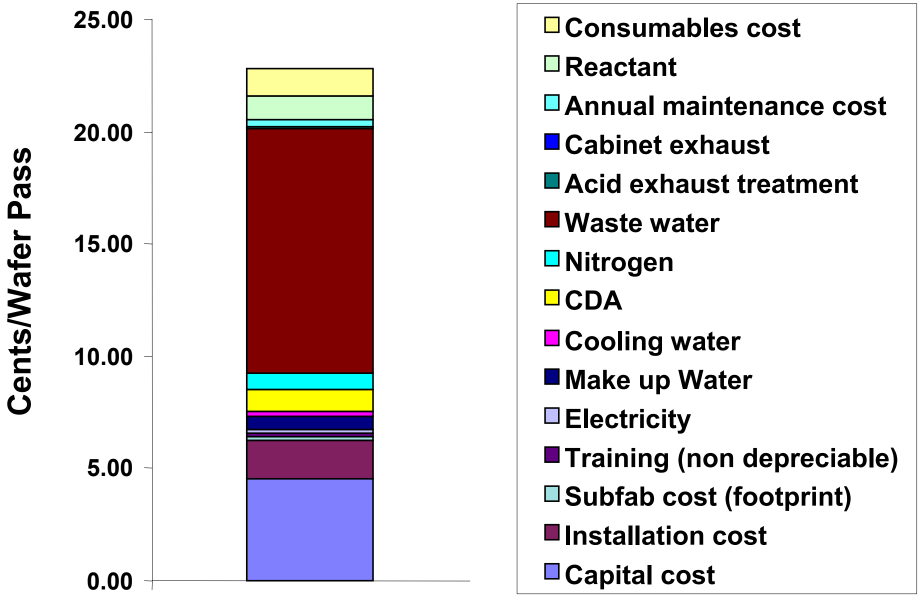
Aligned to industry standard:
“Equipment Environmental Characterization Guidelines - Rev 3.0”

Example POU Abatement Validation Results

- Point of use abatement systems are rigorously characterized for:
  - destruction removal efficiencies (DREs)
  - environmental cost of ownership
  - reliability



Emission Component / Category		POU In (g/wafer)	POU out (g/wafer)	DRE
HAPs	F_2	0.296	0.013	95.50%
	HF	0.4	< 0.012	> 96.88%
	SiF_4	5.927	< 0.013	> 99.78%
PFCs	NF_3	0.095	0.022	77.05%
	CF_4	0.179	0.026	85.60%
CO	CO	0.218	0.32	-
GWG	CH_4	0.005	0.052	-
	N_2O	10.728	2.624	75.54%
NOx	NO	-	0.197	-
Flammable	SiH_4	0.065	< 0.002	> 97.45%
	B_2H_6	0.02	<0.001	> 92.82%



POU Abatement Costs

Drivers of Green Manufacturing Technologies

The development of environmentally-friendly technologies must take into account:

- Cost of ownership
  - Capital cost
  - Treatment cost
  - Operation cost
- Process performance
  - Process repeatability
  - Tool productivity
  - Utilization / abatement efficiency
- EHS impact
  - Human health impact
  - Environmental impact
  - Regulatory compliance

- What are the drivers for change?
  - Moore’s law
    - Cost reduction ($/bit)
    - Performance improvement (bit/cm^2)
  - Awareness
    - Public, government, industry
    - Investors, shareholders
    - Local vs. global environmental impact
  - Sustainable development

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