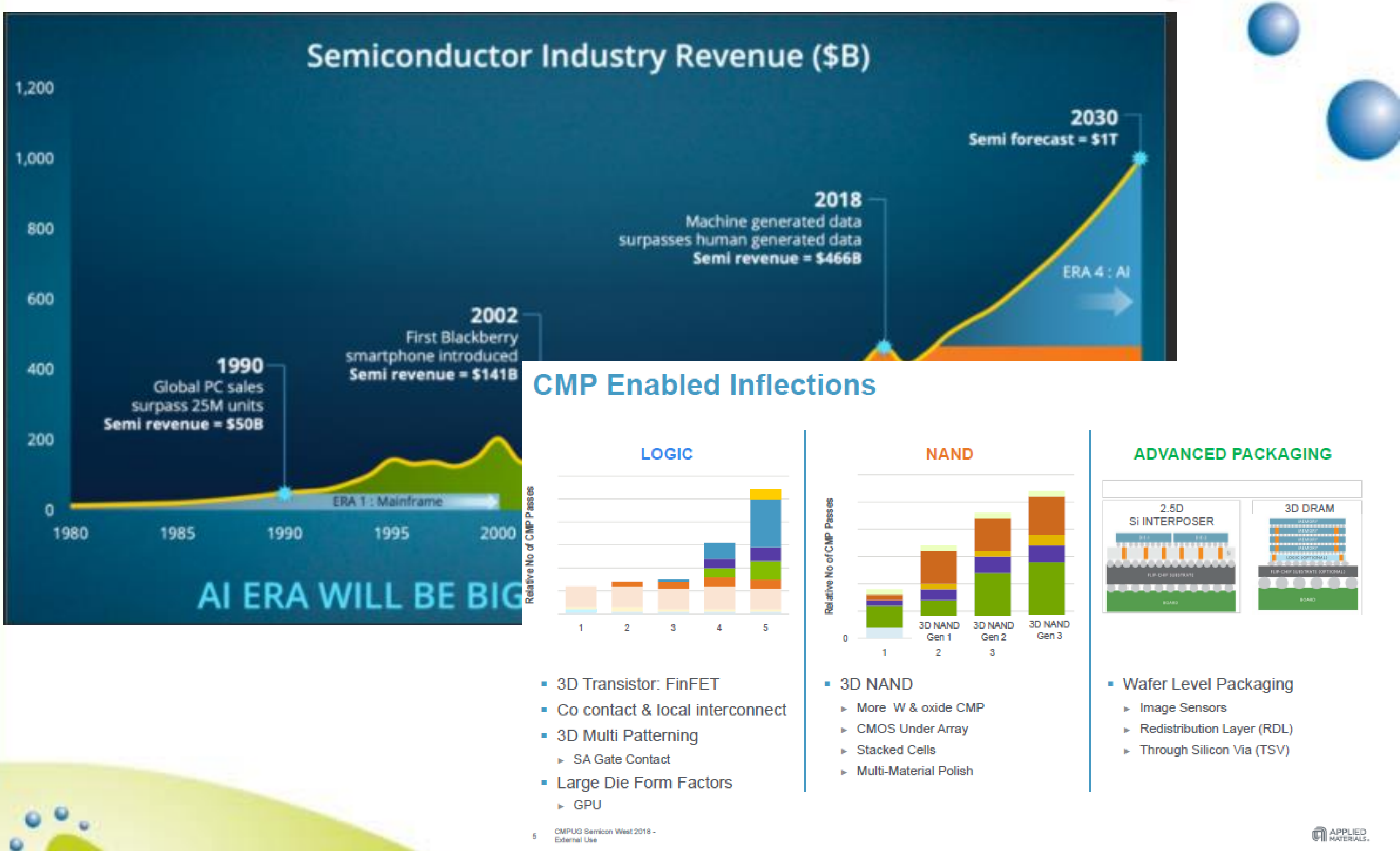
Reducing CMP Process Mass Intensity

sjbenner@confluense.com

Unprecedented Demand for Semiconductors - CMP



Semiconductor Industry Revenue ($B)

AI ERA WILL BE BIG

CMP Enabled Inflections

LOGIC

- 3D Transistor: FinFET
- Co contact & local interconnect
- 3D Multi Patterning
  - SA Gate Contact
- Large Die Form Factors
  - GPU

NAND

- 3D NAND
  - More W & oxide CMP
  - CMOS Under Array
  - Stacked Cells
  - Multi-Material Polish

ADVANCED PACKAGING

- Wafer Level Packaging
  - Image Sensors
  - Redistribution Layer (RDL)
  - Through Silicon Via (TSV)

5 CMPUG Semicon West 2018 - External Use

APPLIED MATERIALS.

‘The Chip Industry Has a Problem With Its Giant Carbon Footprint’

Bloomberg, 2021-04-08

- The total mass of liquid input is **3487 kg/wafer including UPW** and city water (not circulated PCW) and **210kg/wafer excluding water**.
- Technology scaling continues to bring benefits in transistor density and higher speed. In parallel, for the assumptions made in this work, the PPACE analysis shows **a significant increase in** electricity (x3.46) and **ultrapure water consumption (x2.3),** and in greenhouse gas emissions (x2.5) per wafer from the 28nm to the 2nm node. “The Environmental Footprint of Logic CMPS Technologies”, Imec, 12/20
- **The higher number of CMP and wet steps led to an increase of UPW consumption from 6 l/cm2 at iN28 to 14 l/cm2 at iN3 in our analysis (Fig.14).** “The Environmental Footprint of Logic CMPS Technologies”, Imec, 12/20

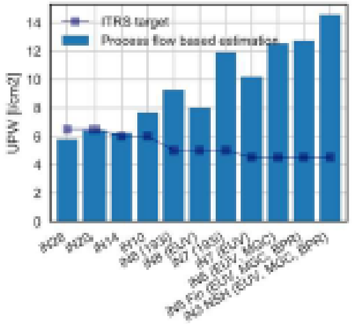
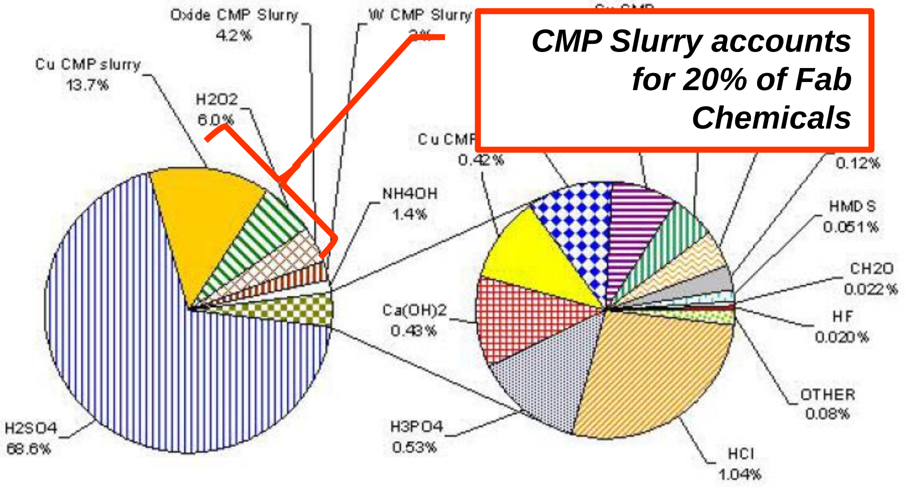


Fig.14- Total Ultra Pure Water (UPW) usage in liters per cm^2 for full process flows from iN28 to iN3 for 300mm wafer equivalent. ITRS guidelines shown as reference.



CMP Slurry accounts for 20% of Fab Chemicals

- From an [CMP] environmental sustainability point of view, reducing slurry consumption is more significant than saving electric energy Evaluation of environmental impacts during chemical mechanical polishing (CMP) for sustainable manufacturing, Hyunseop Lee*, Sunjoon Park and Haedo Jeong, Journal of Mechanical Science and Technology 27 (2) (2013) 511~518

Estimating CMP Process Mass Intensity

THE SEMICONDUCTOR INDUSTRY – PART OF THE PROBLEM AND THE SOLUTION

The Problem

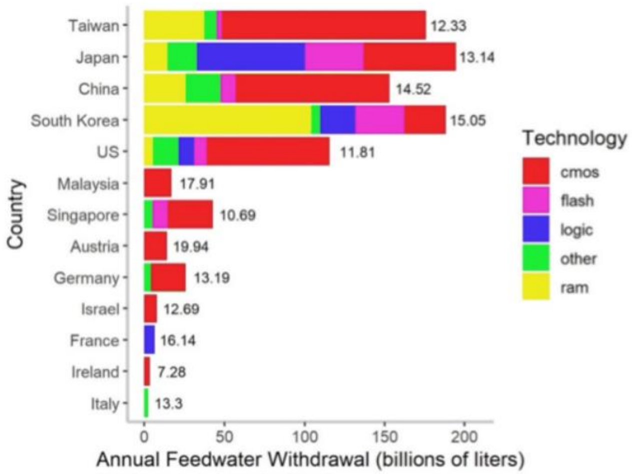
- Large semiconductor fabs can consume electricity at 100 MW / hour – enough to power 50K houses
- A single fab can use up to 9 million gallons of water / day
- 70+ new fabs coming online over the next few years

Enabling The Solutions

- Advancements in semiconductors are critical to enabling:
  - Industry 4.0 Smart Manufacturing – improved efficiency, less waste
  - Technologies that conserve energy and water and reduce carbon footprint

billion liters per year. The numbers at the right end of each country show the consumption per square centimeter of product. Various types of product are represented in the color key.

Water used by fabs



Annual Feedwater Withdrawal (billions of liters)

Water Resources and Industry 22 (2019) 100115

CMP Process Mass Intensity; **40% Fab Water is CMP** [1]

- **((4.62 l/cm2 * 700 cm2/wafer) + (0.3l slurry / wafer pass * 41 wafer passes)) ÷ (41 layers/wafer * (0.3 micron film removal / layer * 0.00000579 kg/cm3**) = PMI**
- **3246 KG + 12.4 KG / (41 * 0.00000012) = PMI**

- **3246 KG/ 0.00000502 KG = *647,257,000 :1* *Mass input : Mass removed***

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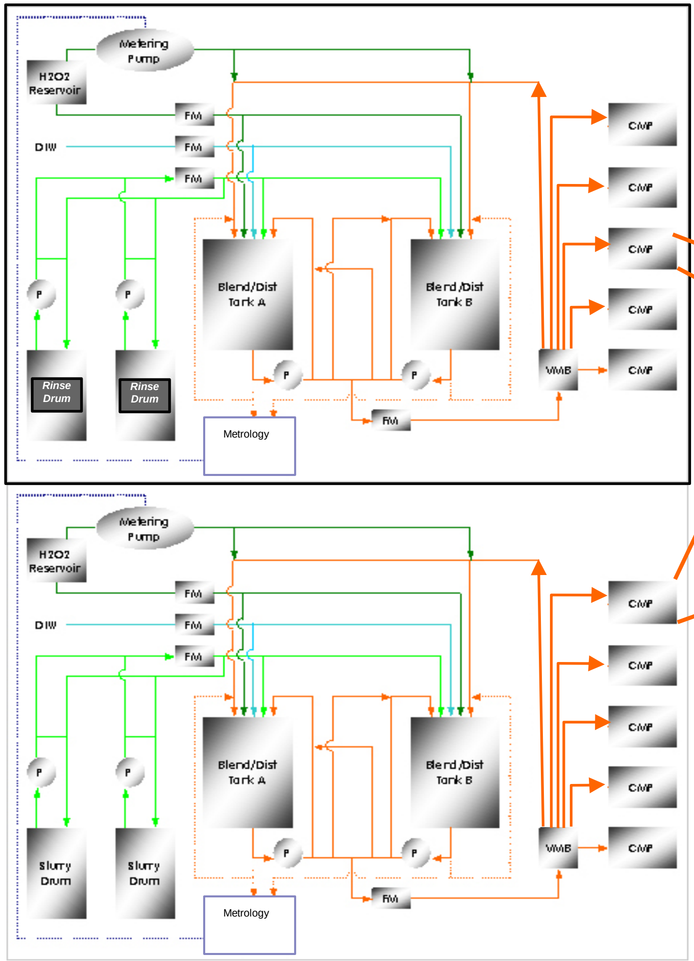
[1] Gordon C.C.YangInstitute of Environmental Engineering, National Sun Yat-Sen University, Kaohsiung 804, Taiwan, R.O.C.

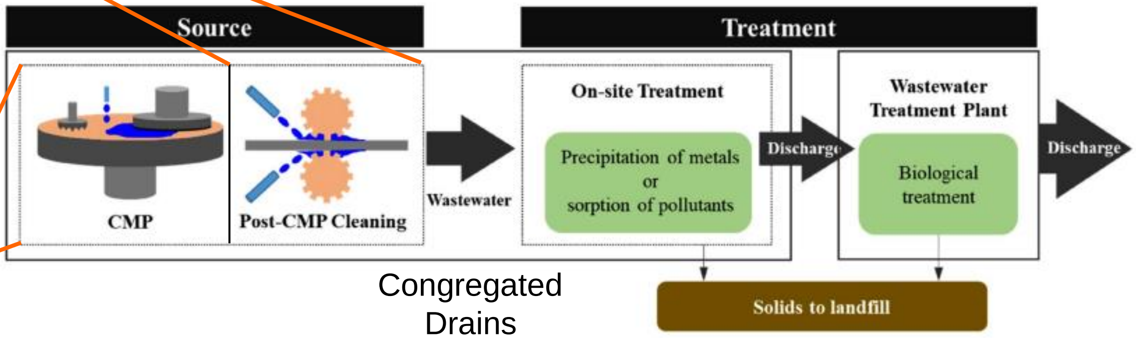
Context - Opportunities

- Although chemical mechanical planarization (CMP) is widely applied in integrated circuit fabrication, it is still a process of significant trial and error.
- Most systems aim to maintain a consistent global average of materials properties, concentrations, particle size distribution, and stability, throughout the delivery lifecycle, the polishing and cleaning operation cycles, and within the effluent/waste stream.
- Process mass intensity for CMP is estimated to be 650 – 1100 KT / gram of film removal. This measure could be readily compiled and used as a benchmark for new materials development and process intensity improvement.
- POU Infeed materials are ‘oversupplied’ to maintain interfacial chemistry ‘global average’; 90% never touches wafer.
- CMP efficiency can be dramatically improved using flow chemistry principals

‘Global Average’ Chemistry

Blend Formulation to Drain





Congregated Drains

Work In Process Volume ~150 liter – 1000 liter

Bulk 100 liter-800 liter Per Process (pp)

Loop 100 liter-300 liter (pp)

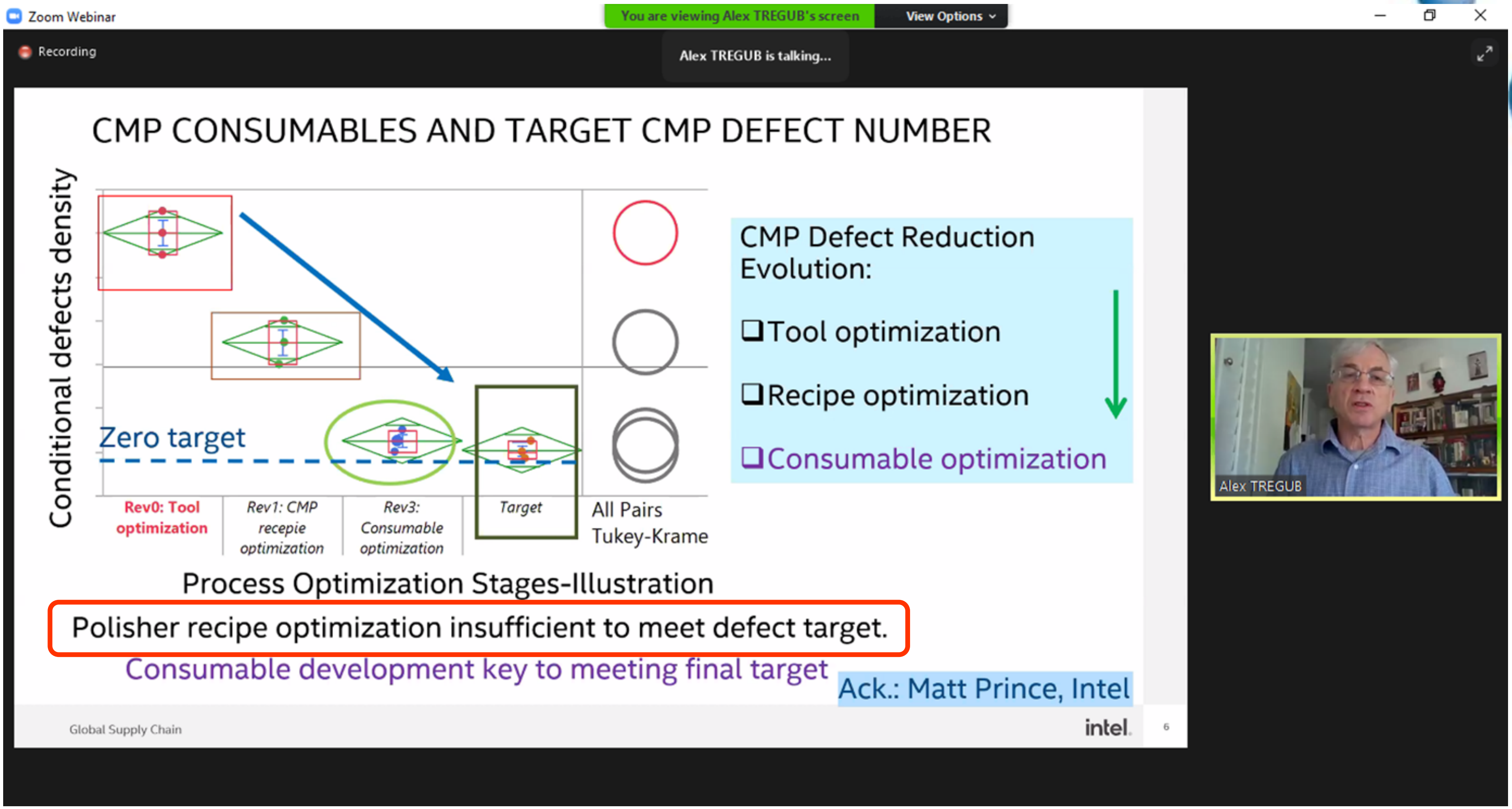
POU 100 ml/min-300 ml/min

50 hrs – 2 hrs ‘Batch Inventory’ (pp)

1,700,000 GPD – 3,000,000 GPD All CMP

1) https://www.toyokokagaku.co.jp/en/product/cmp/slurry.html
2) International Journal of Precision Engineering and Manufacturing-Green Technology (2022) 9:349–367

Limited improvement levers



CMP CONSUMABLES AND TARGET CMP DEFECT NUMBER

CMP Defect Reduction Evolution:

- ☐ Tool optimization
- ☐ Recipe optimization
- ☐ Consumable optimization

Process Optimization Stages-Illustration

Polisher recipe optimization insufficient to meet defect target.

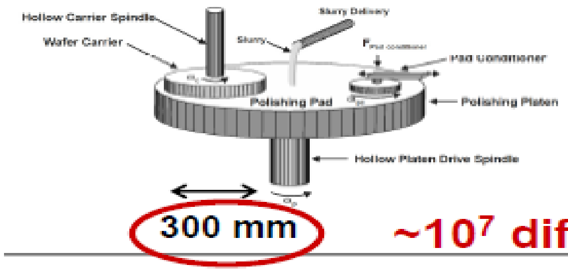
Consumable development key to meeting final target

Ack.: Matt Prince, Intel

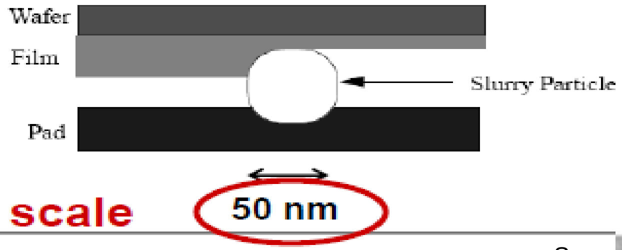
Pad Residence → Source of material variation

Oversupply required to counteract process induced slip-stream variations

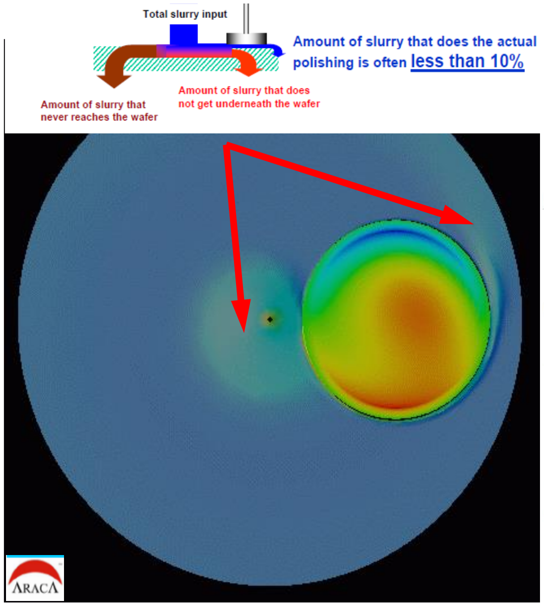
Macroscopic Control

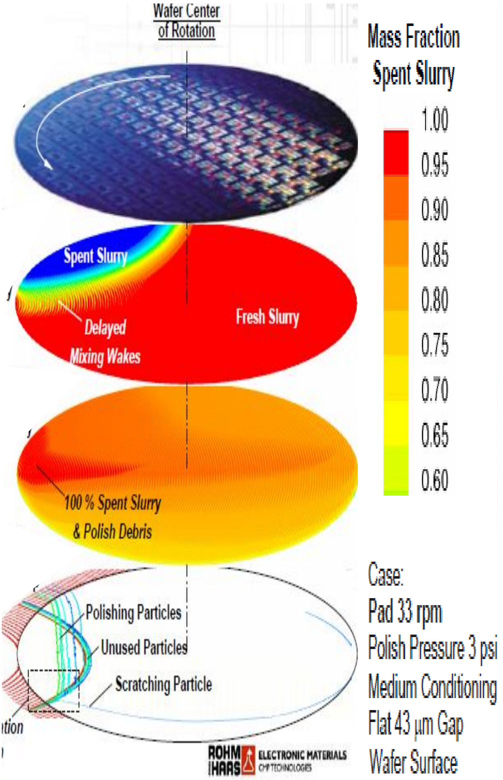


Microscopic Phenomenon



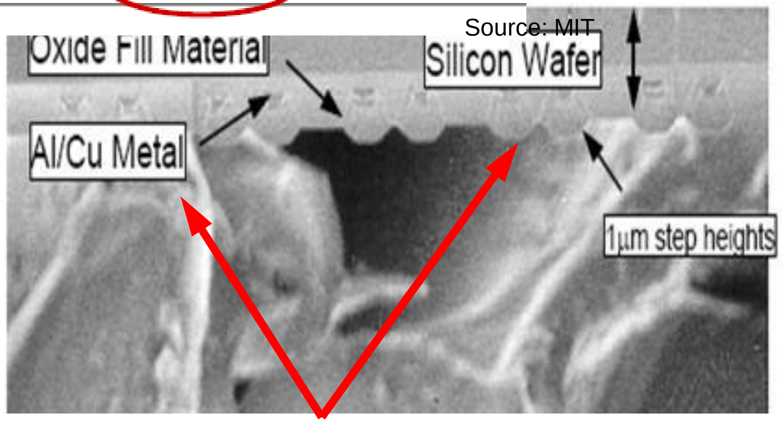
~10^7 difference in scale



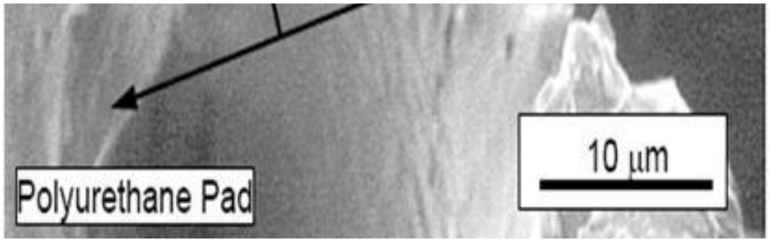


Case:
Pad 33 rpm
Polish Pressure 3 psi
Medium Conditioning
Flat 43 µm Gap
Wafer Surface

Source: MIT



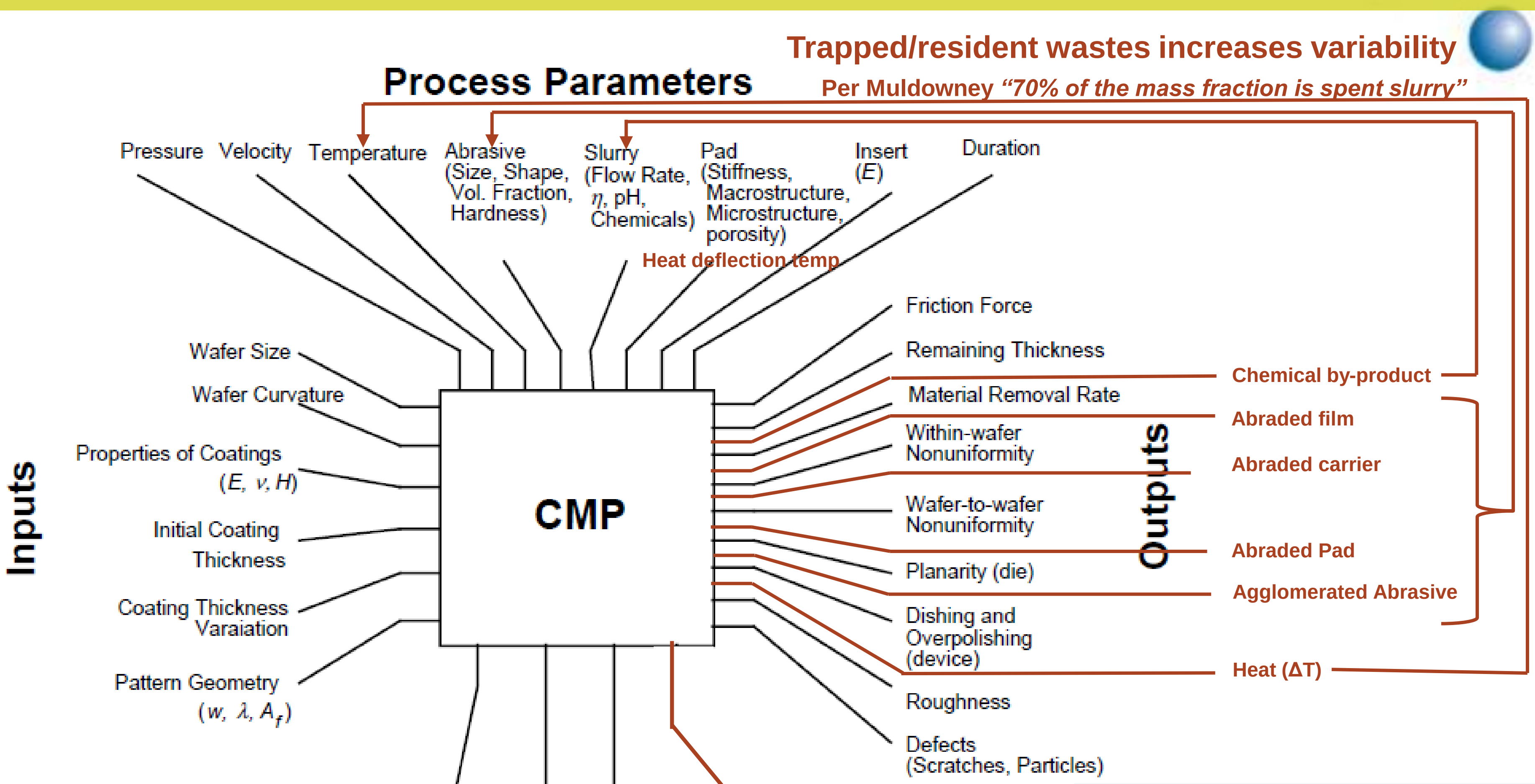
Pad: Hardness,Glazing,Temp range, Roughness, Debris
Slurry: pH, Concentration, Temp. Rise, Electrochemistry
Abrasive: Size Distribution,Agglomeration,Concentration



- Average slipstream residence time 30 seconds [2]
- 90% of fresh slurry carried away by bow wave [1]
- 70% of steady state mass fraction is 'spent' slurry [3]

1 Slurry Utilization Efficiency Studies in Chemical Mechanical PlanarizationAra Philipossian and Erin Mitchell
2 Investigating Slurry Transport beneath a Wafer during Chemical Mechanical Polishing Processes;Coppeta,J.,Rogers,C.,Racz,L., Philipossian,A.,Kaufman,F.B.
3 Muldowney; http://www.avsusergroups.org/cmpug_pdfs/CMP2007_4_Lawing.pdf

FIX your inputs; variation IN = variation OUT



Trapped/resident wastes increases variability

Per Muldowney *"70% of the mass fraction is spent slurry"*

Process Parameters

Pressure
Velocity
Temperature
Abrasive (Size, Shape, Vol. Fraction, Hardness)
Slurry (Flow Rate, *η*, pH, Chemicals)
Pad (Stiffness, Macrostructure, Microstructure, porosity)
Insert (*E*)
Duration

Heat deflection temp

Inputs

Wafer Size
Wafer Curvature
Properties of Coatings (*E*, *ν*, *H*)
Initial Coating Thickness
Coating Thickness Varaiation
Pattern Geometry (w, λ, A_f)

CMP

Outputs

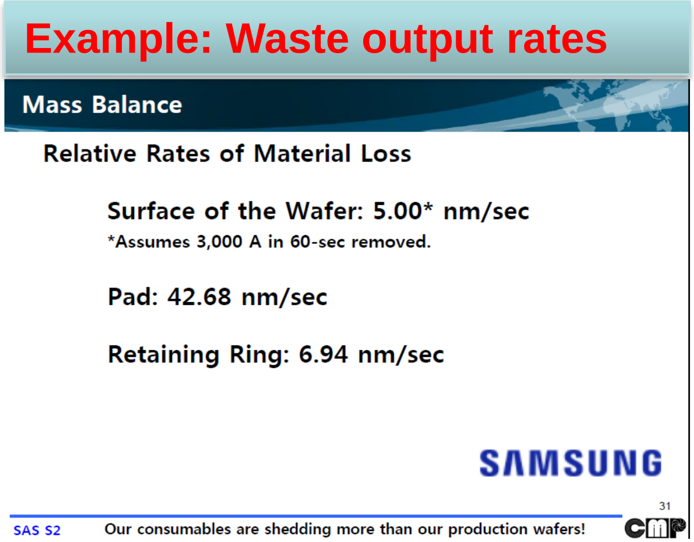
Friction Force
Remaining Thickness
Material Removal Rate
Within-wafer Nonuniformity
Wafer-to-wafer Nonuniformity
Planarity (die)
Dishing and Overpolishing (device)
Roughness
Defects (Scratches, Particles)

Chemical by-product
Abraded film
Abraded carrier
Abraded Pad
Agglomerated Abrasive
Heat (ΔT)

ISRM
End Point
Zone Press

Controls

Opportunity:
Controlled Fluid Residence



Example: Waste output rates

Mass Balance

Relative Rates of Material Loss

Surface of the Wafer: 5.00* nm/sec
*Assumes 3,000 A in 60-sec removed.

Pad: 42.68 nm/sec

Retaining Ring: 6.94 nm/sec

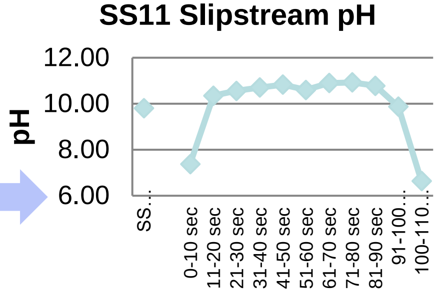
SAMSUNG

31

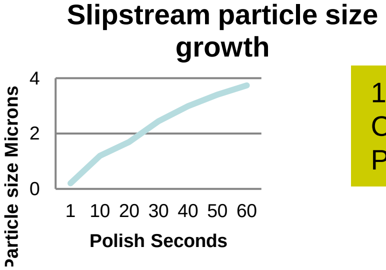
SAS S2 Our consumables are shedding more than our production wafers!

Characteristic slip stream variation; 60 sec polish

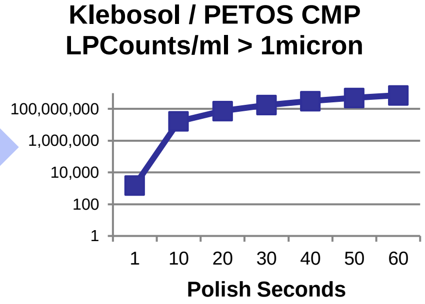
Dynamic State variable	Control	Conventional Equipment
Slurry Concentration (pH)	Incoming	>50%
Conditioning Debris	Rinse	>4000% dia
Large Particle count (>1μ)	Incoming	>5x10^6 #/ml
Temperature	Friction / Chemical reaction / Platen HT	0.3º-0.5º/sec



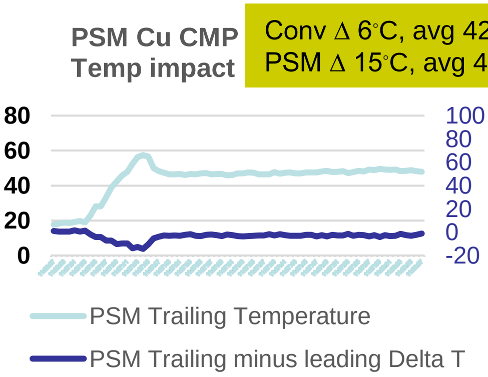
Control 9.8
Process 7.0 – 11.0



1501-50
Control 0.05μ
Process 2.3μ → 3.5μ



Control 1.5 * 10^3
Process 5.8 * 10^6



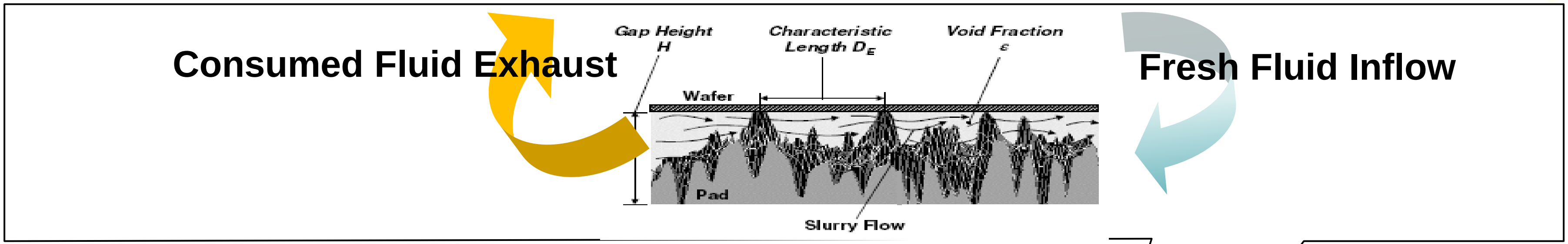
Conv Δ 6°C, avg 42.9C, σ 2.2C
PSM Δ 15°C, avg 47.9C, σ 0.96C

Our Solution - Controlled Fluid Residence

Vacuum extract spent slurry, products, debris, and rinse water in-situ to reduce σ

Reduce CMP PMI 24% …..

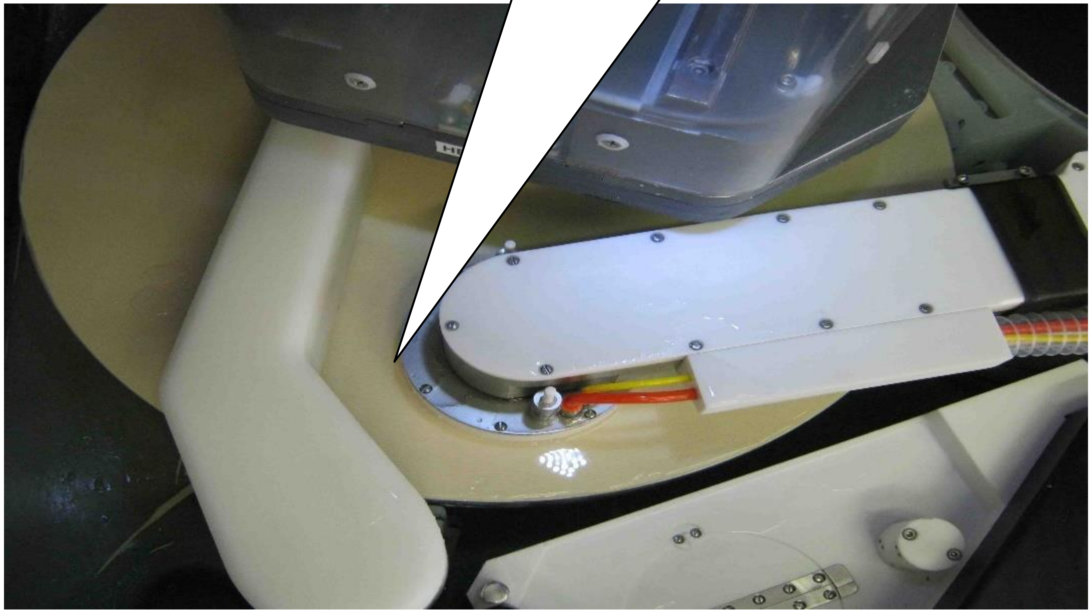
- Consumption savings are enabled by *controlling* slip stream properties



Consumed Fluid Exhaust

Fresh Fluid Inflow

- **Variable Exhaust Attributes**
  - **Volume, Location, Timing, Routing**
- **Efficient slurry replenishment**
- **Localized high pressure rinse**
- **Independent of Abrasive Downforce**
  - **Supports any conditioning abrasive**
- **Effluent instrumentation for AI / analytics**



…..Dramatic DD improvements are enabled by controlling the slurry 'quality' in 'slipstream'

Findings: Rinse Water

- UPW is used in great quantities to rinse both tooling and wafers

  Pad Rinsing
  - 4 l/min / HPR nozzle, 6-8 nozzles per platen
  - 9-12 sec HPR per wafer-platen
  - Average: 20 l/wafer pass

  Ex-Situ Conditioning
  - 4 l/min / HPR nozzle, 6-8 nozzles per platen
  - 9-12 sec HPR per platen
  - Average: 20 l/wafer pass

  Typical total = *23 liters pwp*

- Localized Pad Cleaning
  - 0.2 l/min / HPR nozzle, 36 – 56 nozzles per platen
  - 9 sec total
  - Result: *4 liters pwp*

Conventional UHPW Consumption, 23 liters pwp
Mean UHPW Saving opportunity 19 liters pwp

Findings: Slurry Utilization Efficiency

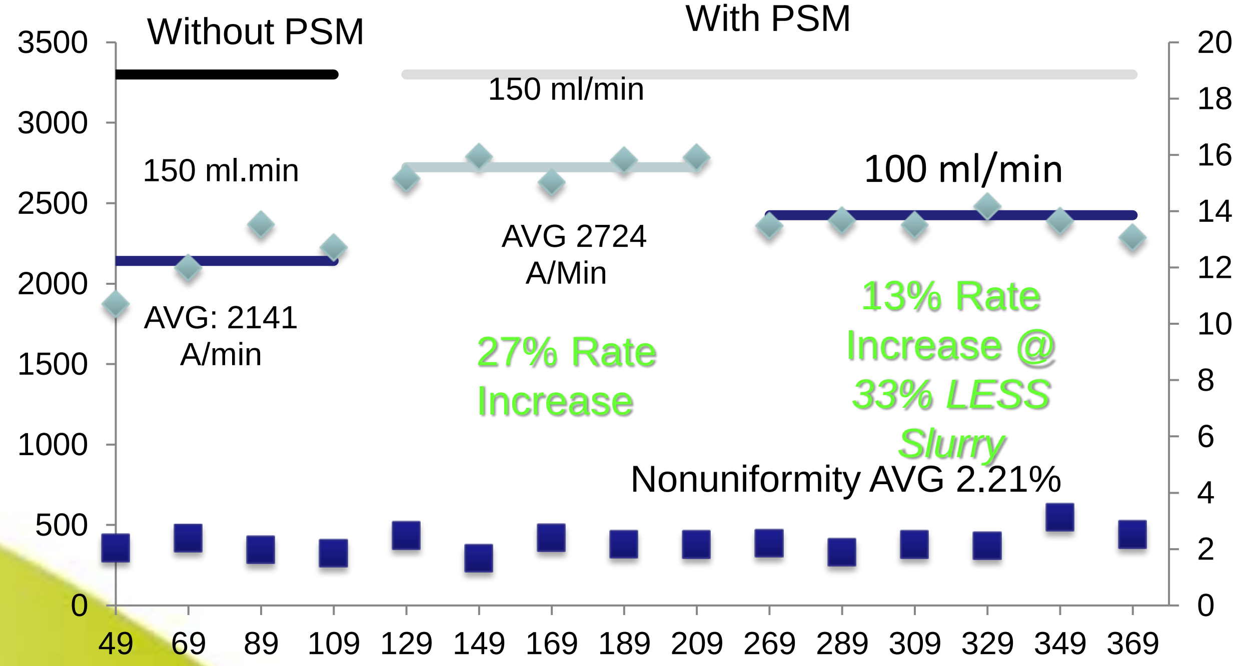
Wafers / Film Type:	25KA TOX
Main Polish Slurry / Pad Type:	**Ferro SRS 2092, Ceria / DOW IC1010 K**
Pad Conditioner End Effector:	TBW Grid Abrade for PSM
CMP Process Tool:	200mm Mirra running Titan II Heads

369 wafers were run with a test wafer placed after every 20 TOX dummies. All test wafers were run on the same head. Process was a customer Oxide POR polishing for 60 sec on Platen 1 with PSM Conditioner and 30 sec buff on platen 3. Platen 2 was not used. For baseline, PSM was used without Vacuum. The first data point is wafer #49 after 49 min of polish and 69 min of conditioning (20 min Cond Break in). **Test wafers 389 and beyond were patterned test wafers for alternate interest, rather than TOX dummies .

Average Rate w/o PSM™ :	@150ml flow rate – 2141 Å/Min
Average Rate with PSM™ :	@150ml flow rate - 2724 Å/Min
Average Rate with PSM™ :	@100ml flow rate – 2426 Å/Min

Improvement of 27%

Improvement of 13% *using 33% LESS Slurry*



Findings: Defectivity

Wafers / Film Type:	Novellus 40KA PeTeos
Slurry / Pad Type:	**DOW Klebosol 1501-50, Colloidal Silica IC-1010**
Pad Conditioner:	TBW Grid Abrade for PSM
CMP Process Tool:	200mm Mirra running Titan II Heads

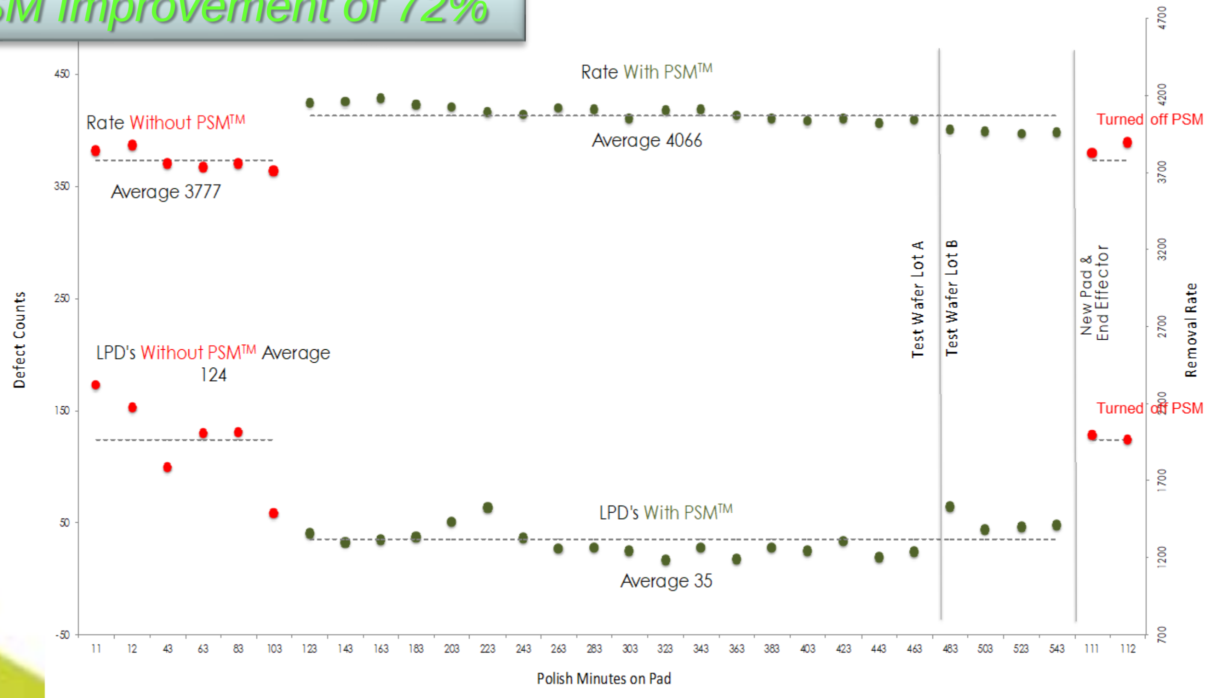
544 wafers were run with a test wafer placed after every 20 PeTeos dummies. All test wafers were run on the same head. Process was a customer Oxide POR polishing for 60 seconds on Platen 2 with PSM™ Conditioner followed by 60 sec buff on platen 3 with water. Platen 1 was not used. For baseline, PSM™ was used without Vacuum for first 100 wafers. The first data point is wafer #11 after 11 min of polish and 41 min of conditioning (30 min Cond Break in). A Control Set of test wafers were repeated at the end without the PSM™. Light Point Defects measured with SP1

Average Rate w/o PSM™ : 3777 Å/Min
Average Rate with PSM™ : 4066 Å/Min

PSM Improvement of 7%

Average LPD's w/o PSM™ : 124 LPD
Average LPD's With PSM™ : 35 LPD

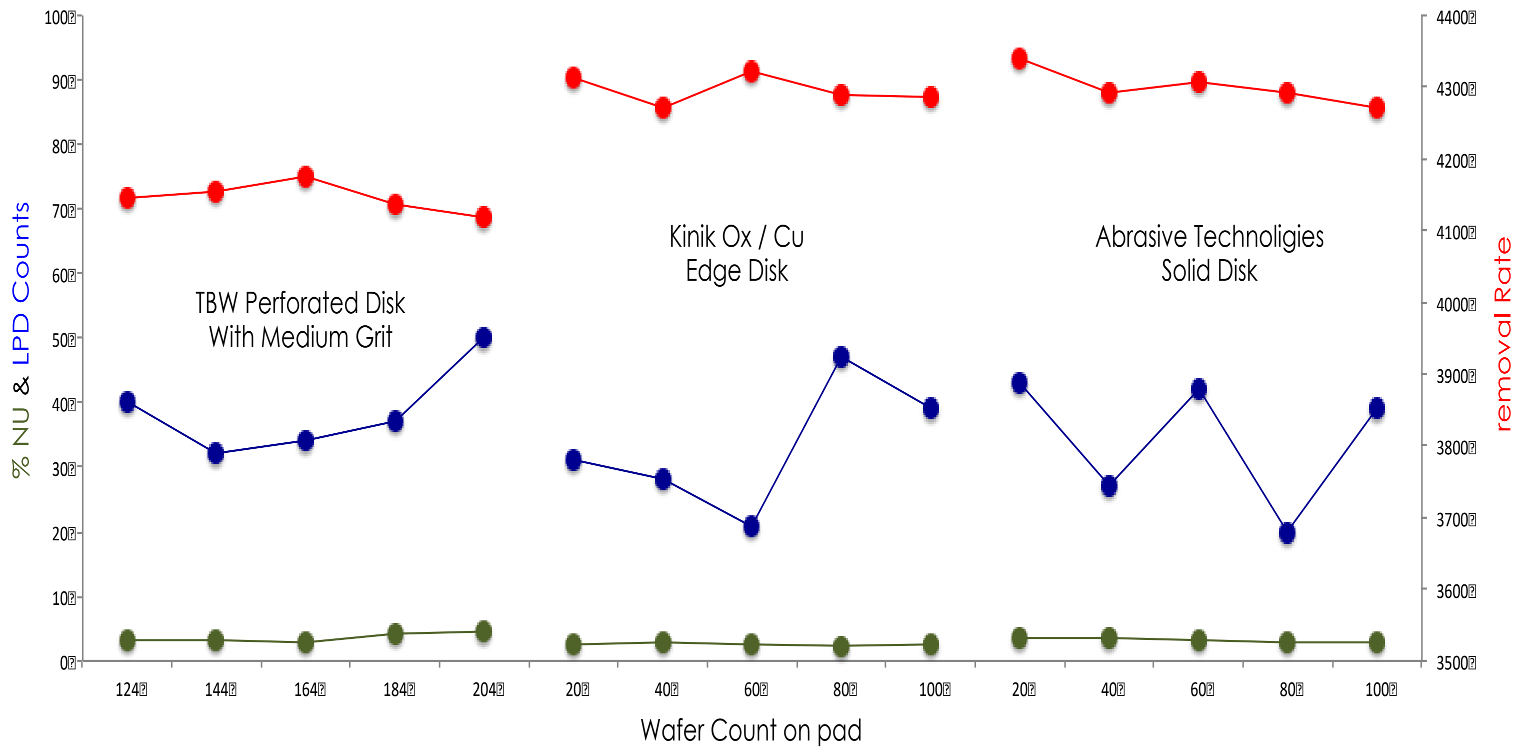
PSM Improvement of 72%



Non-uniformity (not shown) was stable and unchanged across the run which averaged 3.65 @ 3mm

Independent of Conditioner

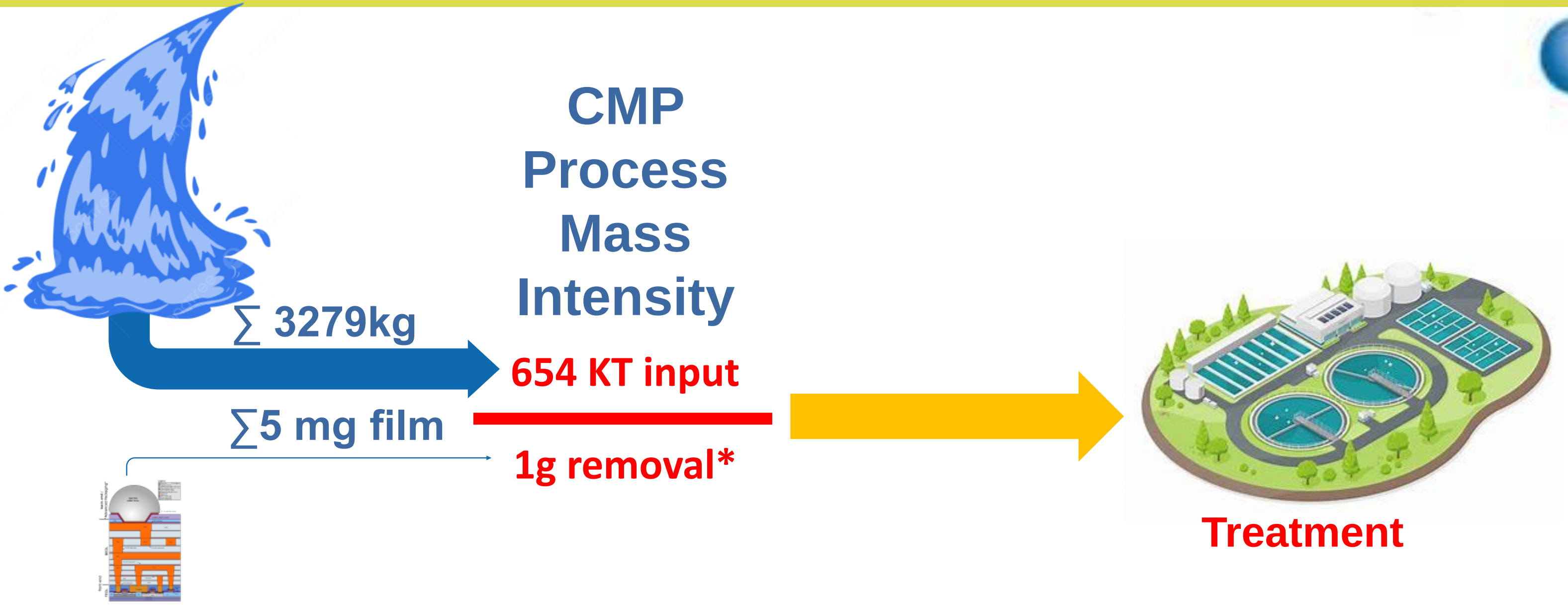
- **Universally improved defect performance**



PSM Summary

- *647,257,000:1 PMI* CMP has "disproportionate consumption" of high cost consumables, and excessive variation
- Confluense improves utilization and input variation.
  - 30% slurry reduction, increase utilization efficiency by removing spent materials
  - 40% rinse water reduction, addn'l savings via reduced post CMP cleaning burden
  - 70% reduction in defects, in-situ control of PSD, chemistry, convection coefficient (T), pad profile.
  - 10%+ throughput increase, in-situ conditioning, RR increase
- System can retrofit over 50% of existing polishers in the field. Extensible to ANY polisher.
- High ROI
- *Enabler for kinetic inference, predictive analytics, continuous process improvement, materials simplification, CMP waste reduction / segregation / recycle*

Call to action?



∑ 3279kg

∑5 mg film

CMP Process Mass Intensity

654 KT input

1g removal*

Treatment

UHP Water requirements have grown 2.5X between iN28nm to iN3nm (5.8 l/cm^2 → 14.5 l/cm^2)[1]

Customer	Water Sustainability Initiatives
Intel (2030)	Onsite water reclamation plants (>$300MM) Net water conservation of 60 billion gal
TSMC (2030)	Onsite water reclamation plants (>$600MM) Unit water consumption 30% reduction >60% replacement with reclaimed water
Samsung	Zero increase for Device Solutions (DS) water intake by 2030, Treat water to natural level quality by 2040
Micron (2030)	75% water conservation

*For standard iN3 Cu CMP

1. **DTCO including Sustainability: Power-Performance-Area-Cost-Environmental score (PPACE) Analysis for Logic Technologies**: M. Garcia Bardon1, P. Wuytens1, L.-Å. Ragnarsson1, G. Mirabelli1, D. Jang1,

Interesting or Imperative?

Observed Savings opportunity **- 200mm POI testing** **- Baseline comparisons, Non-optimzed**	**Saving per Wafer**	**PMI Saving %**
30% Slurry savings	4.2 Kg / wafer	0.1%
19 liters CMP Rinse water savings	780 Kg/wafer	24%
Reduced process defects	~1.5% die yield/wafer??	
10% Cycle time reduction	0.2KW/pwp	
Totals	**784 KG/wafer**	**24%**

Thank you

sjbenner@confluense.com