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USING MACHINE LEARNING IMAGE PROCESSING ALGORITHMS TO CHARACTERIZE MULTIMODAL PARTICLE SIZE DISTRIBUTIONS OF CHEMICAL MECHANICAL PLANARIZATION SLURRIES

Using Machine Learning Image Processing Algorithms to Characterize Multimodal Particle Size Distributions of Chemical Mechanical Planarization Slurries

Chemical Mechanical Planarization Consumables (CMP-C) Task Force

Liquid Chemicals North America Technical Committee

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Goal

- Identify and describe novel Machine Learning - based image analysis to reliably characterize mono- and/or multimodal PSD of abrasives of CMP slurries.

Acronyms

- AFM Atomic Force Microscopy
- BET Brunauer-Emmett-Teller
- BSPD Back Side Power Delivery
- CFET Complimentary Field Effect Transistor
- CHDF Capillary Hydrodynamic Fractionation
- CoWoS Chip on Wafer on Substrate
- DIA Dynamic Image Analysis
- DLS Dynamic Light Scattering
- DMA Differential Mobility Analyzer
- EMIB Embedded Multi-Die Interconnect Bridge
- EUV Extreme Ultraviolet
- FinFET Fin Field Effect Transistor
- GAA Gate All Around
- MA DLS Multi Angle Dynamic Light Scattering
- MANTA Multispectral Advanced Nanoparticle Tracking Analysis

Acronyms (continued)

ML	Machine Learning
MPS	Mean Particle Size
MRR	Material Removal Rate
n-DMA	Nano Dynamic Mechanical Analysis
NMR	Nuclear Magnetic Resonance
OES	Optical Emission Spectroscopy
OM	Optical Microscopy
PSD	Particle Size Distribution
SAXS	Small Angle X-ray Scattering
SEM	Scanning Electron Microscopy
SLS	Static Light Scattering
SMPS	Scanning Mobility Particle Sizer
TEM	Transmission Electron Microscopy
THC	Total Holographic Characterization
WLP	Wafer Level Packaging

Need for New Metrology Capable of Measuring Fine Abrasives of Less than 2 nm

- Development and implementing the latest technology nodes for semiconductor manufacturing were influenced by several significant trends in IC design and manufacturing.
  - ✓ Shrinking of transistor critical dimensions, enabled by quadrupole exposure in 193 nm immersion lithography and implementing EUV lithography.
  - ✓ Design and architecture advances, from planar transistors to FinFET to GAA FET to CFET.
  - ✓ Advances in monolithic integration and packaging, such as WLP, Hybrid bonding, Foveros, EMIB, CoWoS, BSPD and other.
- These developments introduced new requirements for CMP processes, for example, need to polish new types of materials, including organic layers, and/or features with high aspect ratio, while maintaining target zero defect rates.
- These developments also introduced new stricter requirements for materials and chemicals used in CMP processing and post CMP cleaning, such as CMP slurries.

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Need for New Metrology Capable of Measuring Fine Abrasives of Less than 2 nm

- It has been widely recognized by the fab process engineers that CMP process major parameters, such as MRR, planarity, defectivity and other are mostly influenced by the fine abrasive on the low size tale of PSD.
- Most current metrologies to report PSD are not capable of:
  - ✓ Reliably measuring fine particles below 2-3 nm
  - ✓ Reliably resolving closely located peaks in bi- or multimodal PSD*
  - ✓ Recognizing particles' agglomerates
  - We suggest using ML image analysis for:
    - ✓ Identifying peaks and distribution of fine particles at the low size tales of full PSD for any type of PSD (mono-, bi-, or multimodal).
    - ✓ Reliably separate peaks in bi-modal or multimodal PSD
    - ✓ Recognizing and excluding fine particle aggregates from PSD analysis

**Bi- or multimodal abrasive PSD can be designed by slurry manufacturers or can be an unexpected result of slurry manufacturing process, storage, shipping, or delivery in the fabs.*

Major Metrologies to Measure Slurry Abrasive Size in PSD

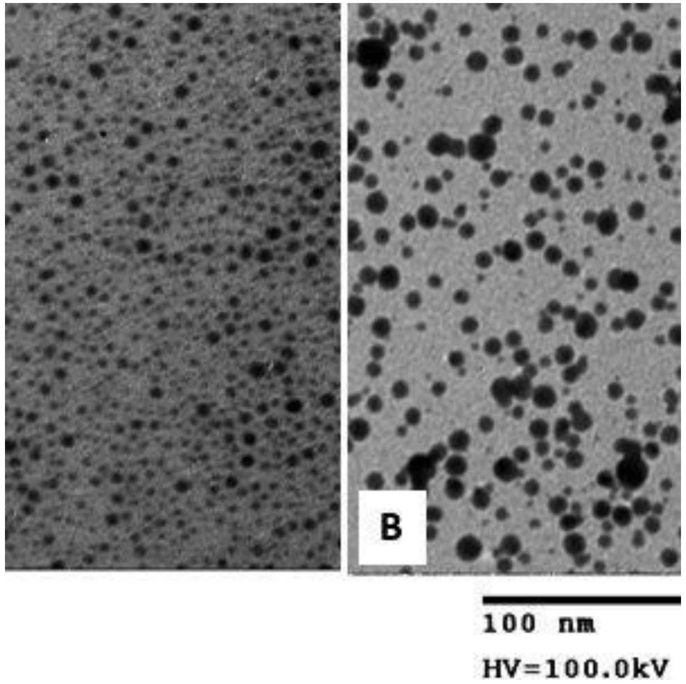
Operating Principle	Activation Source	Measured Signal	Reported Parameter/s	Dilution	Bi- or multi-modal PSD	Estimated Parameter Range, nm	Image Producing
DLS	Brownian movement	Laser Beam Intensity	Total av. Size,	Not required*	Yes	4-1,000	No
MA DLS	Brownian movement	Laser Beam Intensity	Total av. Size, or peak sizes	Not required*	Yes	4-1,000	No
SLS	Flow	Laser Beam Intensity	MPS	Medium	No	20-20,000	No
Sedimentation	Disk centrifuge	Time	MPS	High	Yes	10-75,000	No
Stroboscopic imaging	Flow	Optical Images geometries	Equivalent diameter	High	No	800-20,000	Yes
CHDF	Eluant flow	Time	Particle Size	High	Yes	10->500	No
DMA (SMPS)	Electrostatic Charge	Electrical Mobility	Particle Size	High	Yes	>1-1,000	No

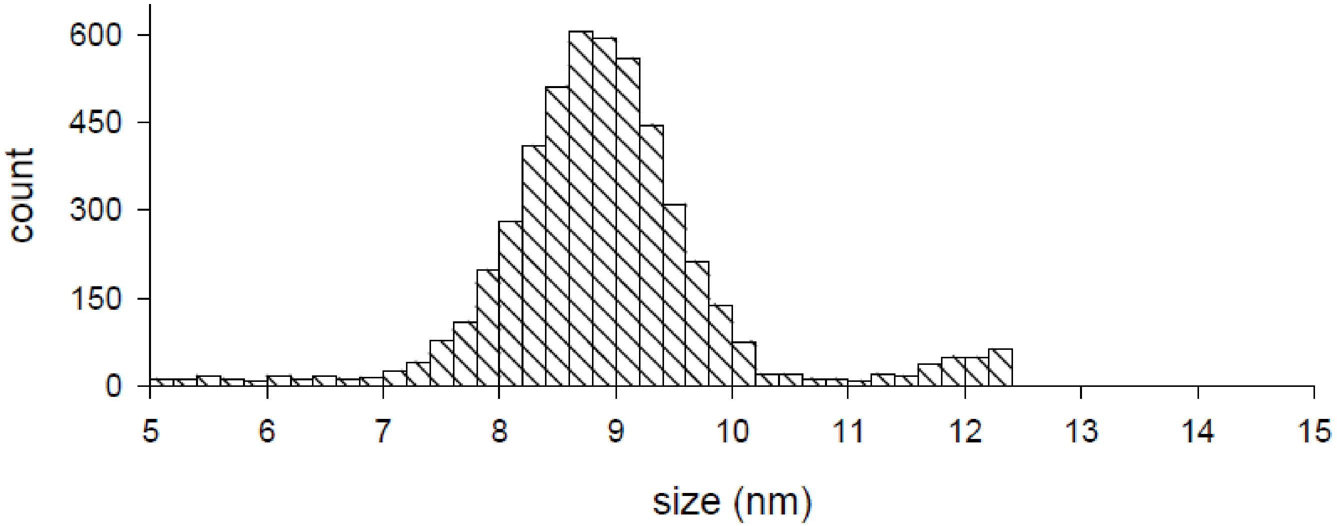
** DLS, MA DLS provides relative concentration; can be diluted to control concentration levels.*

Major Metrologies to Measure Slurry Abrasive Sizes

Operating Principle	Activation Source	Measured Signal	Reported Parameter/s	Dilution	Bi- or multi-modal PSD	Estimated Parameter Range, nm	Image Producing
MANTA	Brownian movement	Scattered light images	Particle Size	High	Not known	10-15,000	No
NMR	Oscillating magnetic field	NMR relaxation Times	Surface Area	Not required	Yes	>5	No
DIA	Stream/flow	Image	Particle images	Not required	NA	>20,000	No
SAXS	X rays	Scattered X ray intensity	Particle diameter	Not required	NA	1-300	No
BET	Gas adsorption	Adsorbed amount vs pressure	Specific Surface Area	Not required	Not known	Surface area > 0.01 m^2	No
AFM-contact & tapping; n-DMA	Mechanical interaction	Tip height	Size; Hardness; Indentation; Adhesion	Not required	Yes	5-15 nm, lateral	Yes
AFM- non-contact	Long-range attractive forces	Force	Size	Not required	Yes	5-15 nm, lateral	Yes
SEM	Electron beam	Particle images	NA: manual assessment	Not always required	Yes	Minimum range: 1-5	Yes
TEM	Electron beam	Particle images	NA: manual assessment	Not always required	Yes	Minimum range: 0.1-5	Yes

Example of TEM Image and PSD

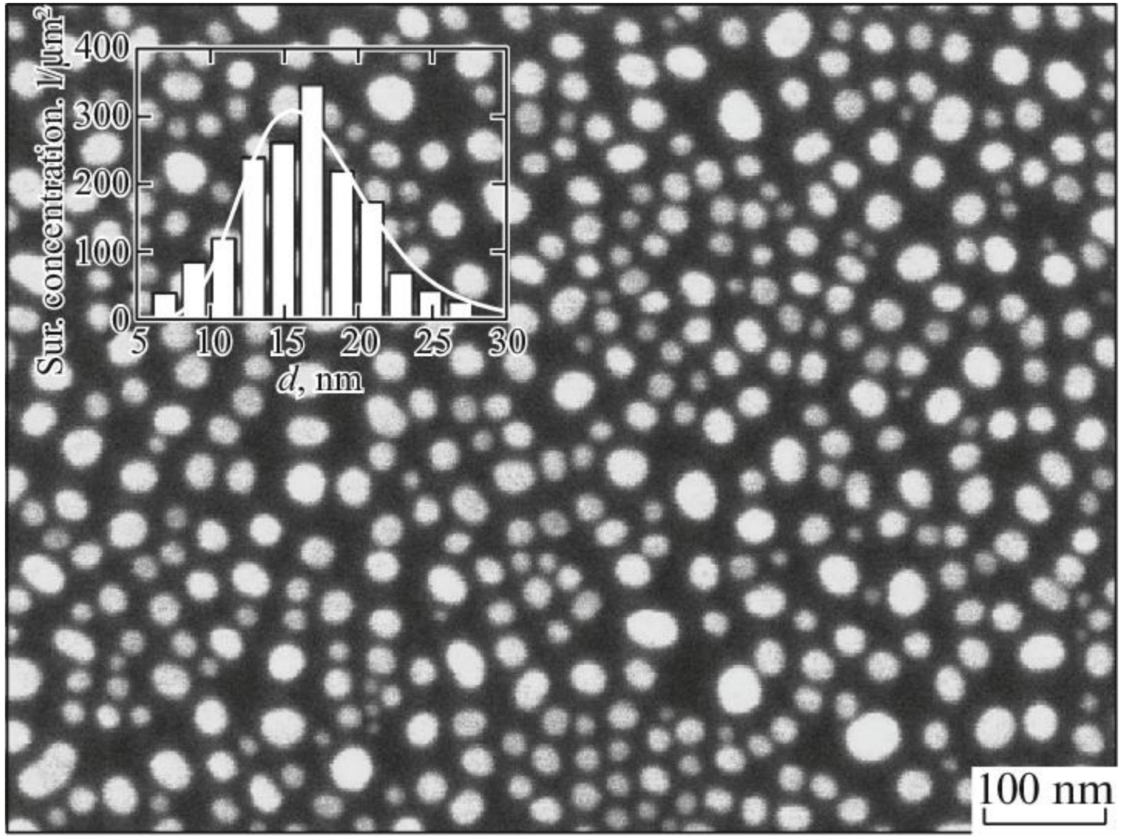




TEM image (left) and size histogram (right) for golden particles

Source: NIST, Reference Material 8011

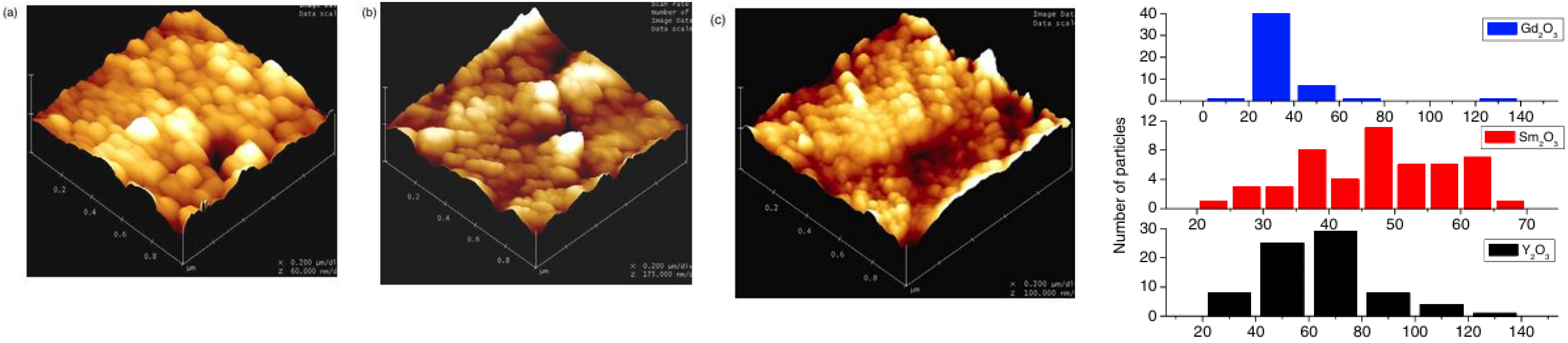
Example of SEM Image and PSD



SEM image and histogram (insert) of gold nanoparticles on a silicon substrate

Source: Baranov et. al. **Technical Physics Letters,** March 2017, 43(3):244-246

Example of AFM Image and PSD

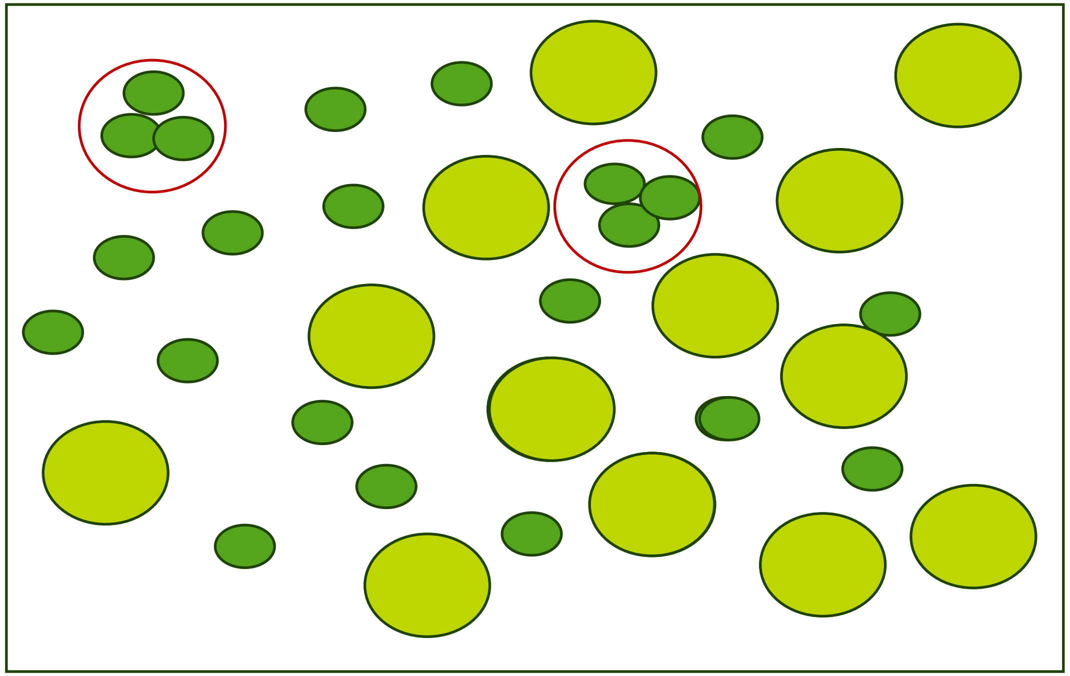


AFM micrographs (left) and size histogram (right) for: (a) Y2O3, (b) Sm2O3 and (c) Gd2O3.

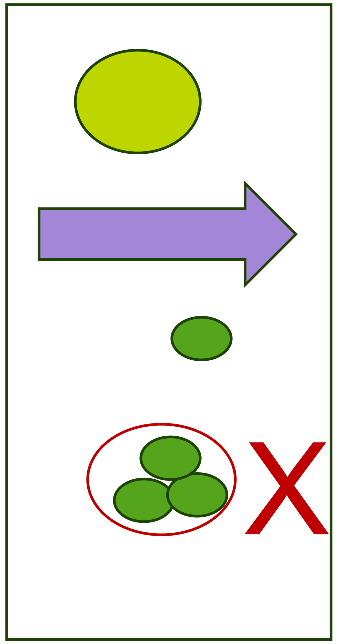
Source: N. Dilawar et al. Anomalous high-pressure behavior in nanosized rare earth sesquioxides, Nanotechnology 19 (2008)

Using ML Analysis to Calculate Accurate PSD for a Slurry: Explanation

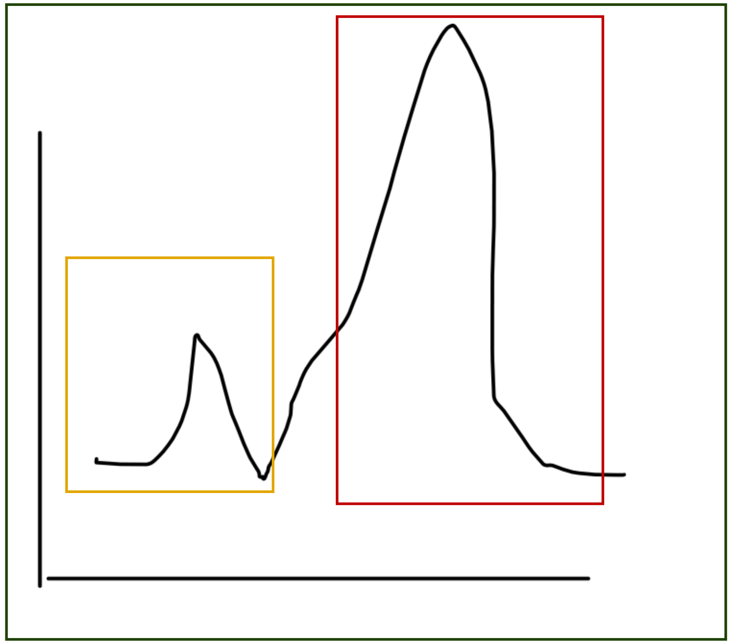
SEM/TEM/AFM Image



ML analysis



Calculated PS



Step 1. Obtain SEM/TEM/AFM images of slurry abrasives deposited on a substrate

Step 2. Use ML analysis to:

- Separate larger particles form fine particles in two different group sizes
- Exclude particle agglomerates from the analysis

Step 3. Generate PSD. Report peak sizes for fine particles in a bimodal PSD, if appropriate

Factors and Parameters to be Specified for Reporting ML Analysis of Abrasive SEM/TEM/AFM images

Factors	Parameters	Parameters	Parameters
Slurry	1. Dilution degree 2. Dispersion	1. RPM of a spinning substrate with slurry sample, is applicable 2. Slurry sample location on the wafer, i.e. center, edge, mid radius	Time & conditions of slurry sample drying out
Substrate	1. TEM grid 2. SEM stub	Wafer 1. Type: Oxide, metal, polySi, other 2. Size: coupon, 100mm, 150mm, 200mm, 300mm)	Filter 1. Filter material 2. Filter size

Factors related to the processing of ML analysis: Examples
Used algorithms and ML/AI models
Number of the analyzed images
Locations on the substrate of the analyzed images
Specifics of ML /AI training
Specifics of AI interference

Conclusions

- Most of the known major metrologies to measure sizes of slurry abrasives do not provide reliable measurements for abrasives below 2nm and accurate separation of the closely located peaks.
- SEM, TEM and AFM show potential to accurately measure abrasives sizes below 2 nm if major development in analysis of SEM, TEM and AFM images is made
- Using ML analysis of SEM/TEM/AFM images will allow to reliably characterize abrasive sizes below 2 nm and accurately separate closely located peaks for monomodal and multimodal PSD of CMP slurries