Occupational Exposure to Nanomaterials: Assessing the Potential for Cutaneous Exposure to Metal Oxide Nanoparticles in a Semiconductor Facility

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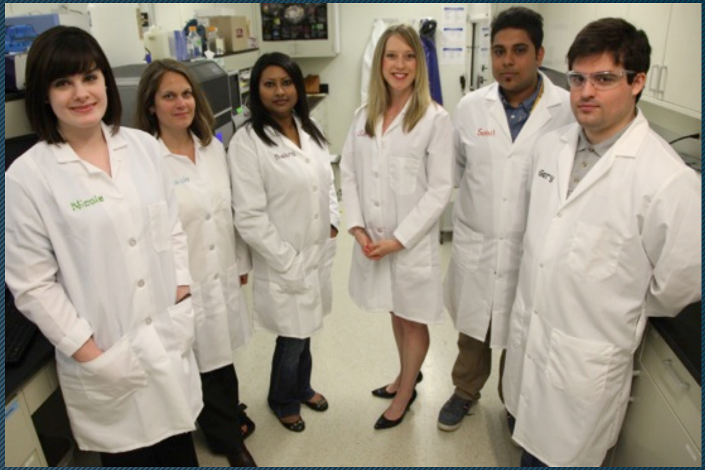
Occupational and Environmental Health & Safety of Engineered Nanomaterials

Scope: The integration of occupational and environmental medicine, exposure science, industrial hygiene, materials science, and metrology to investigate the human health and safety implications of exposure to engineered nanomaterials

Goal: To proactively address the emerging needs of health and safety research related to engineered nanomaterials, seeking to develop in real-time the innovative technologies and methodologies needed to assess, monitor, and safely accelerate nanotechnology R&D worldwide

Challenge: Nanomaterials present new challenges to understanding, predicting, and managing potential health risks to workers, consumers, and the environment because the characteristics of nanoparticles may be different from those of larger particles with the same chemical composition.



Proactive Assessment of Potential Health & Safety Risks

While moving forward to develop and incorporate engineered nanomaterials into product pipelines, one common challenge shared by all stakeholders is how to address emerging health and safety implications.

Engineered nanomaterials produced and handled in industrial and academic settings present new challenges to understanding, predicting, and managing potential health risks to workers, consumers, and the environment.

The rapid growth and projected acceleration of nanotechnology creates urgency in understanding, predicting, and managing the health risks associated with occupational, environmental, and consumer exposures to nanomaterials.

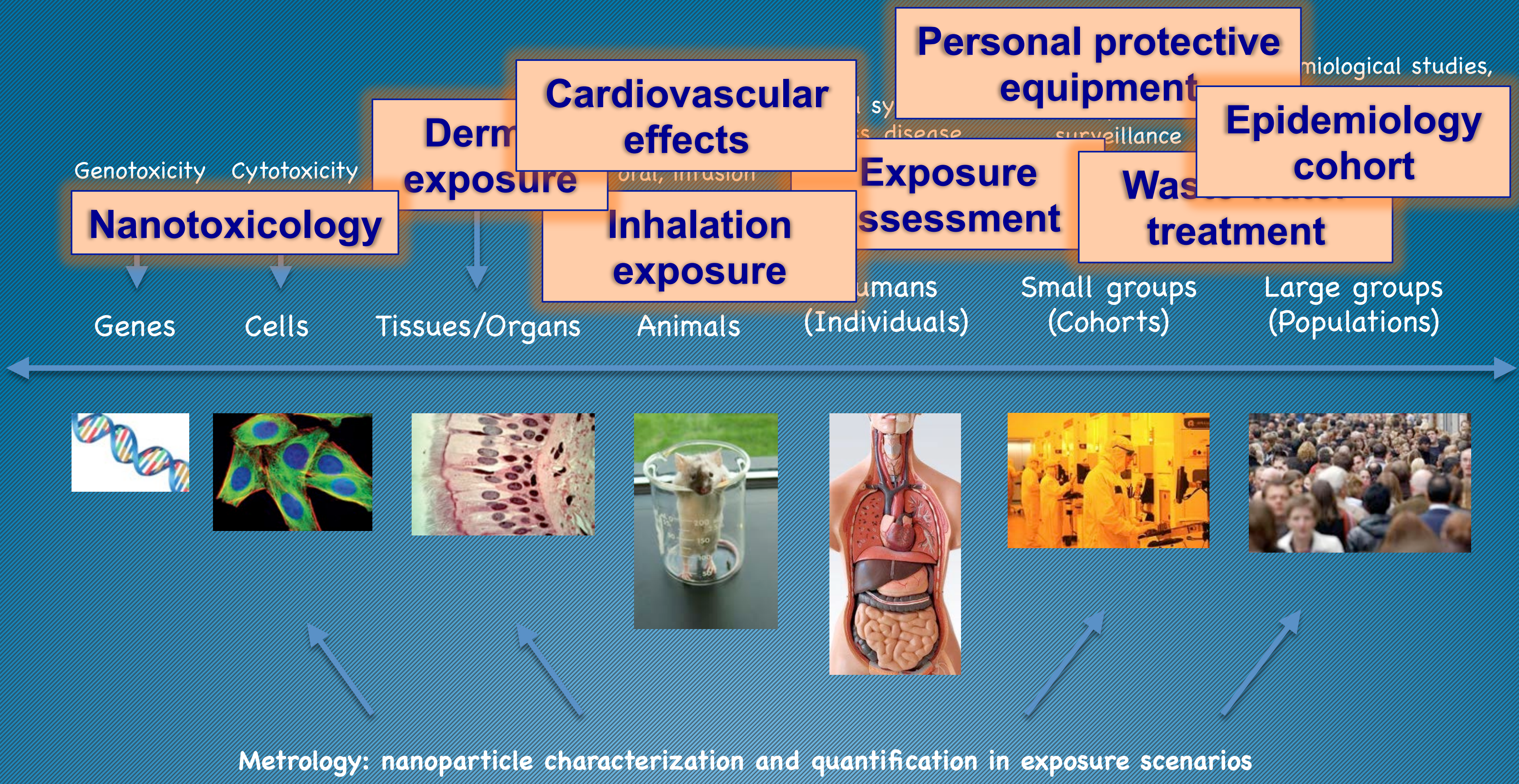
NIOSH Top 10 Nanotechnology Research Needs

1. Exposure Assessment
2. Toxicity and Internal Dose
3. Epidemiology and Surveillance
4. Risk Assessment
5. Measurement Methods
6. Engineering Controls and Personal Protective Equipment
7. Fire and Explosion Safety
8. Recommendations and Guidance
9. Communication and Information
10. Applications

CDC
CENTERS FOR DISEASE CONTROL AND PREVENTION

National Institute for Occupational Safety and Health
NIOSH

NanoHealth & Safety Research



Stebounova, L, Morgan H, Grassian V, Brenner S. (2011). Occupational Health & Safety Implications of Exposure to Engineered Nanomaterials. WIREs Nanomedicine & Nanobiotechnology, in press.

Risk = Hazard x Exposure

In order to characterize the potential risks to human and environmental health, we must evaluate both exposures and hazards.

Hazard → inherent properties of a substance with the potential to cause adverse, or harmful, effects

Exposure → quantitative measurement of the extent to which a given hazard is present

Risk → probability that an adverse effect will occur to someone if exposed to the hazard

Project Relationships

Risk = Hazard x Exposure

Exposure assessment projects help to define exposures in real world scenarios…

"CMP"
Nanoparticle Exposure Assessment during Chemical Mechanical Planarization (CMP) Operation and Maintenance

"WWT"
Identification and Determination of Fate of SiO_2 and Metal Oxide Nanoparticles During Conventional Wastewater Treatment

"PPE"
Efficacy of Personal Protective Equipment in Preventing Dermal Exposure to Engineered Nanoparticles

Exposure assessment projects inform realistic dosing regimens for nanotoxicology projects…

Nanotoxicology projects help to define hazards using cell and animal models…

"CV Effects"
Fundamental investigation of cardiovascular/microvascular effects of exposure to nanoparticles in mouse and hamster models

"Neurological Effects"
Neurological effects of inhalation exposure to engineered metal oxide nanoparticles in a mouse model

"Inhalation Exposure"
Acute vs. subchronic health effects of inhalation exposure to engineered metal oxide nanoparticles in a rat model

"Dermal Penetration"
Dermal penetration of nano-sized SiO_2, Al_2O_3 and CeO_2 in a porcine model

"Epi Cohort"
Cross-sectional study of an occupational cohort employed in the semiconductor industry: Early investigation of potential health effects from occupational exposure to nanoparticles

Long term epidemiologic studies monitor human health outcomes over time and ultimately provide the most convincing data on what health effects may result from exposures…

Occupational Health & Safety: Nanoelectronics Workforce

Work <u>proactively</u> with industry partners and collaborators to monitor, assess, and document the exposure to and potential health effects associated with nanomaterials prior to commercialization and introduction to market.

Exposure Assessment Sampling Approach

- Qualitative Assessments
  - Air Sampling
    - Direct-Reading Instruments
      - Condensation Particle Counter
      - Optical Particle Counter
      - Nanoparticle Sizer (SMPS)
    - Filter-Based Samples
      - Mass Concentration
      - Electron Microscopy
      - CytoViva® Hyperspectral Imaging
  - Surface Sampling
    - Filter-Based Samples

Air Sampling Approach

Instrument/Device	Type	Size Range	Metric
Condensation particle counter (CPC)	Size integrated, time resolved	10 - ~1000 nm	Number conc.
Optical particle counter (OPC)	Size and time resolved	300nm-20μm	Number size dist.
Aerosol photometers	Size integrated, time resolved	250nm-20μm	Mass conc.
Filter collection and off-line analysis (gravimetric, ICP, XRD)	Off-line analysis; Size and time integrated	Depends on method	Mass conc., chem
Electron microscopy (ESEM, SEM, TEM) *EDX/EDS –chem composition	Off-line analysis; Size and time integrated	Depends on device	Morph, size, number

Slide credit: Michele Shepard, PhD, MS, CIH

Surface Sampling Approach

- Wipe samples
- Vacuum samples
  - MCE filters
  - PC filters
- Used modified approaches to identify nanoparticles of interest (as Si, Al, or Ce):
  - ASTM D5755 Standard Test Method for Microvacuum Sampling and Indirect Analysis of Dust by Transmission Electron Microscopy for Asbestos Structure Number Surface Loading
  - ASTM D6480 Standard Test Method for Wipe Sampling of Surfaces, Indirect Preparation, and Analysis for Asbestos Structure Number Concentration by Transmission Electron Microscopy

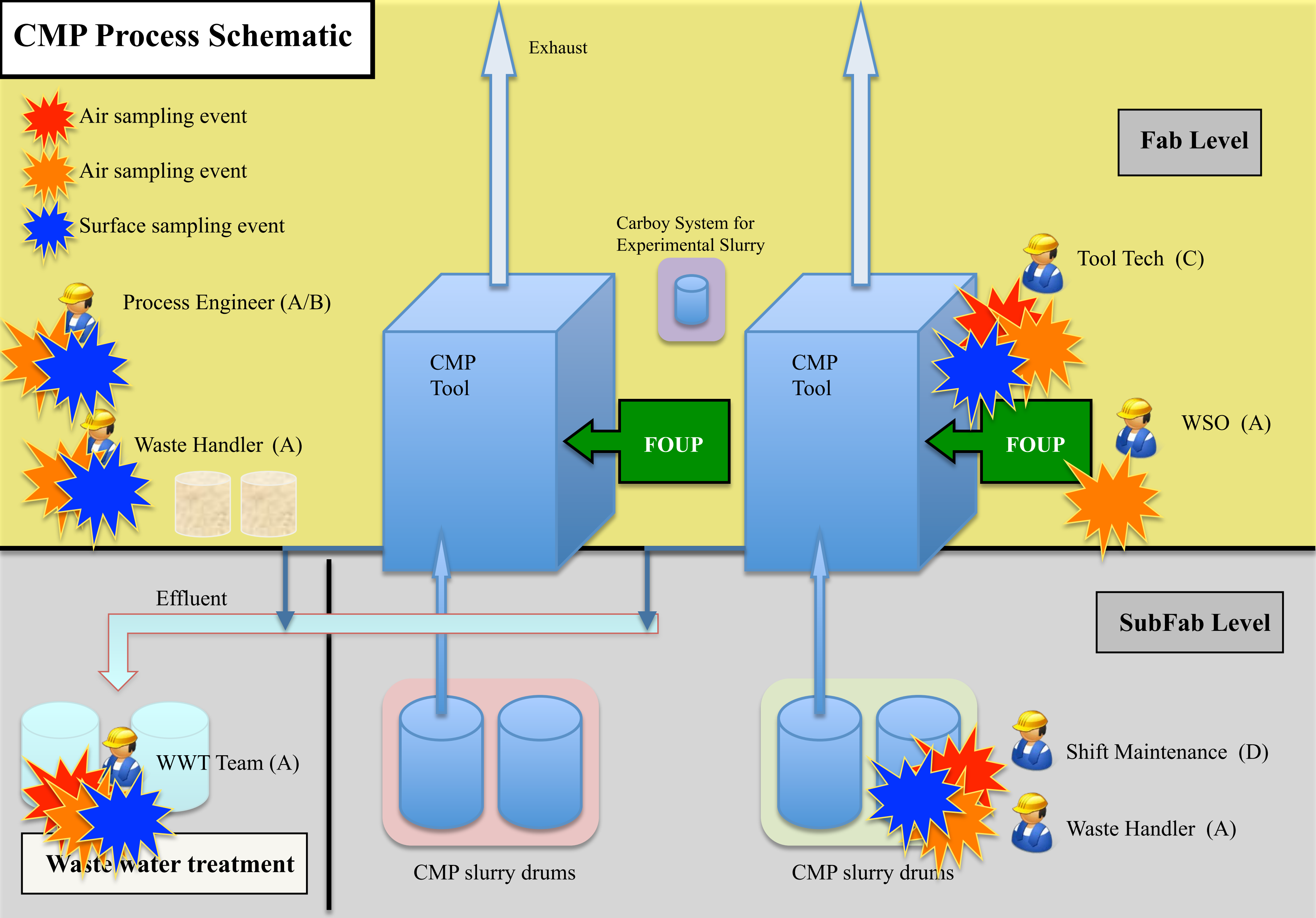
Slide credit: Michele Shepard, PhD, MS, CIH

Job Tasks and Exposures

*selected examples for illustrative purposes

Job Title	Task(s)/Location	Airborne Exposure Potential (Monitoring Priority Based on Qualitative Risk Assessment)
Workstation operator	Operate CMP Tool/Fab	Low – Normal operations
Tool technician	Maintain CMP Tool/Fab	Low – Set-up Moderate – Change-out of consumables Moderate to High – Entry into tool for PM
Process engineer	Mixing experimental slurries/ Chem Mix Room	Moderate to High – Prepare slurry formulations for experimental use
Shift maintenance	Operate and maintain slurry distribution system/Subfab	Low – Routine operations Moderate to High – Overflows, drum washout, slurry delivery system cleanout
Waste handler	Remove waste for offsite shipment/Subfab to Storage	Low to moderate – Periodic waste pick-ups
Wastewater treatment operator	Treat and manage process wastewater/Subfab to Mech-WWT1	Low - Routine operations Moderate – PM to change copper filter

Slide credit: Michele Shepard, PhD, MS, CIH



Brenner, S. A., Neu-Baker, N. M., Caglayan, C., & Zurbenko, I.G. Occupational Exposure to Airborne Nanomaterials: An Assessment of Worker Exposure to Aerosolized Metal Oxide Nanoparticles in Semiconductor Wastewater Treatment. *Journal of Occupational and Environmental Hygiene*. Accepted January 2015. Article in press.

Microvacuum surface samples containing materials of interest identified by EM

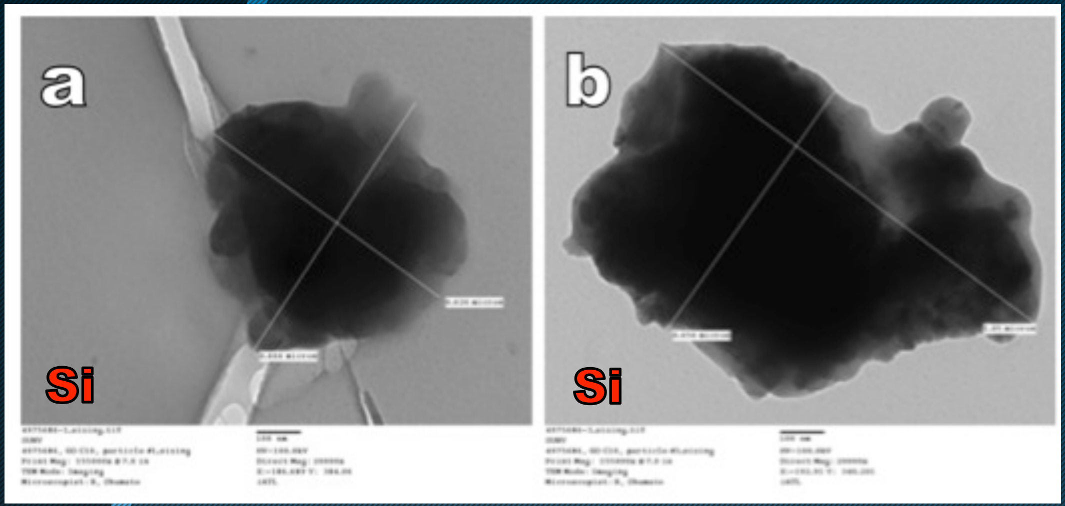
Date of Capture	Sampling Location	Microvacuum Sample	Imaging Modality		Materials of Interest			Samples Containing Si/Al/Ce			
			TEM	SEM	Si	Al	Ce	<100nm	100nm-500nm	500nm-1,000nm	>1,000nm
2/5/2013	WWT	Hatch to acid filter tank	✓		✓	✓			✓	✓	✓
		Field blank	✓		✓	✓			✓		✓
2/6/2013	Subfab	Outside of door hatch to slurry dispenser A	✓		✓	✓			✓	✓	✓
		Outside of door hatch to slurry dispenser B	✓		✓	✓			✓	✓	
		Field blank	✓		✓	✓					✓
2/7/2013	Fab	Below door of CMP tool	✓		✓						✓
		Field blank	✓		✓	✓					✓
2/2013	N/A	Media blank	✓		✓	✓				✓	✓
10/8/2013	WWT	Hatch to acid filter tank*	✓	✓							
		Floor next to acid filter tank*	✓	✓	✓				✓	✓	✓
		Hatch to base filter tank*	✓	✓							
		Floor next to base filter tank*	✓	✓	✓	✓			✓	✓	✓
		Plastic wall covering next to sump pump valve^	✓	✓	✓	✓			✓	✓	✓
		Field blank	✓	✓							
10/25/2013	Subfab	Outside door to filter box to CMP tool 1	✓		✓	✓	✓		✓	✓	✓
		Outside door to filter box to CMP tool 2	✓		✓	✓				✓	✓
		Field blank	✓	✓							
10/2013	N/A	Media blank	✓	✓							
10/2013	N/A	Media blank	✓	✓							
TOTAL number of samples			19	9							
Number of samples containing material of interest/total samples					13/19	11/19	1/19	0/19	8/19	9/19	12/19

*Materials of interest identified by SEM but not TEM; all others identified by TEM only.
^Materials of interest identified by both imaging modalities (TEM and SEM).

Brenner SA, Neu-Baker NM. Occupational exposure to nanomaterials: assessing the potential for cutaneous exposure to metal oxide nanoparticles in a semiconductor facility. *Journal of Chemical Health and Safety.* Available online 15 November 2014. Article in press. doi:10.1016/j.jchas.2014.11.001.

Fab sampling

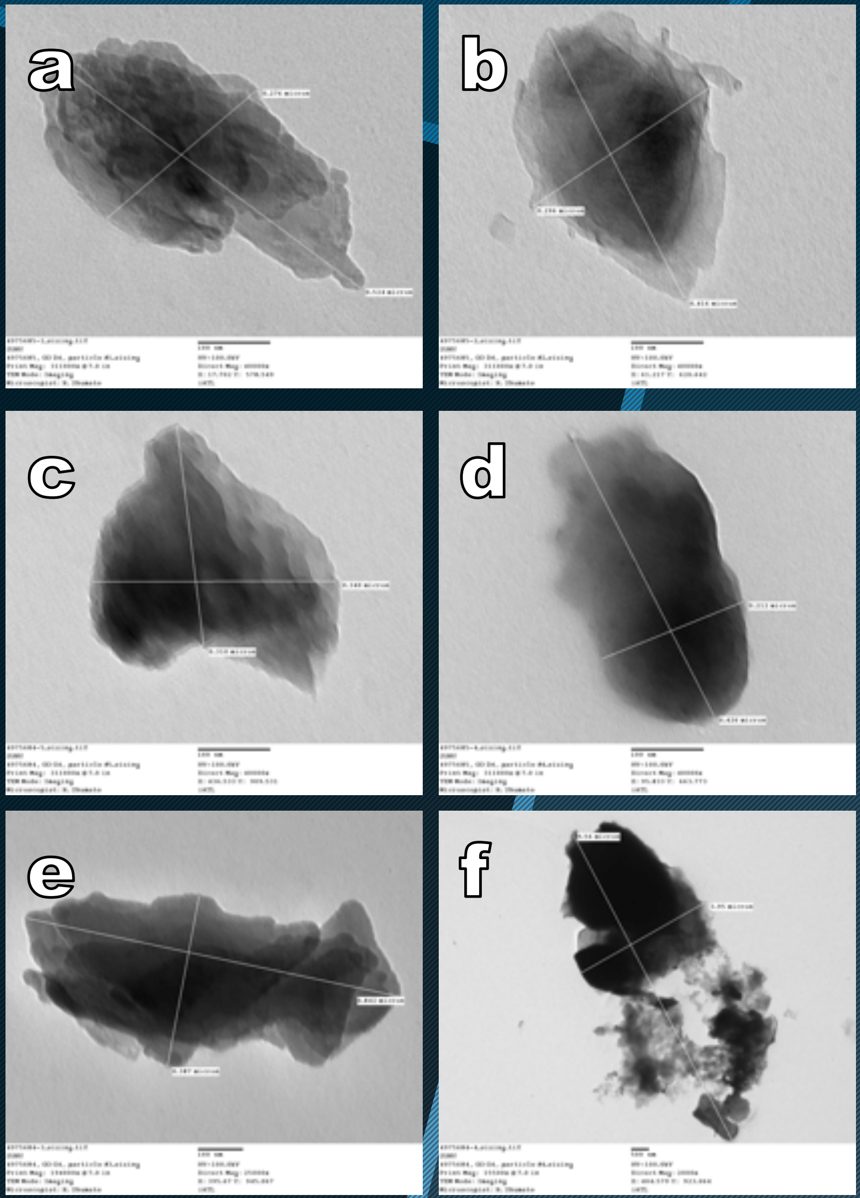
Selected TEM images of surface samples obtained in the fab (February 2013)



Microvacuum surface samples from below the CMP tool door were acquired during preventive maintenance tasks in the fab (February 2013). a) Particulate containing **Si**. Size: 666nm×626nm. EDS: **Si**, Mg, P, S, Cl, Sn, Ca, Cr, Fe. b) Particulate containing **Si**. Size: 656nm×1,050nm. EDS: **Si**, Cl, Sn, Cr, Fe. Both imaged at iATL (Mt. Laurel, NJ) by R. Shumate.

Brenner SA, Neu-Baker NM. Occupational exposure to nanomaterials: assessing the potential for cutaneous exposure to metal oxide nanoparticles in a semiconductor facility. *Journal of Chemical Health and Safety.* Available online 15 November 2014. Article in press. doi: 10.1016/j.jchas.2014.11.001.

Subfab sampling

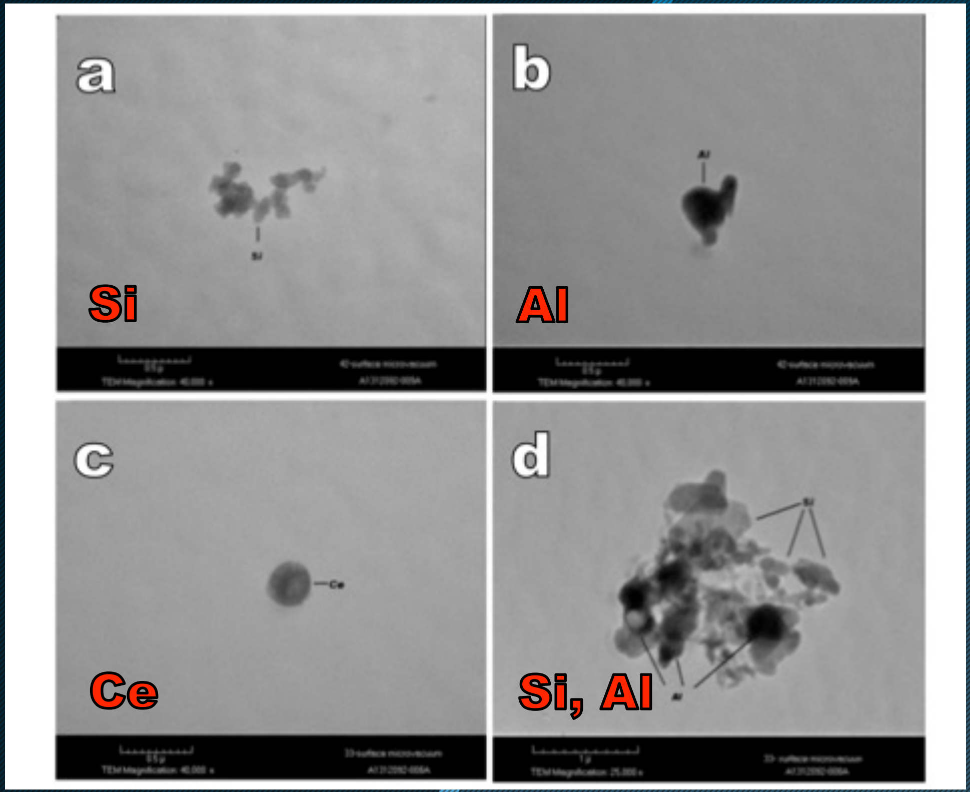


Selected TEM images of surface samples obtained in the subfab (February 2013)

Microvacuum surface samples from the door hatch to a slurry loading tool were acquired during preventive maintenance and quality control tasks in the subfab (February 2013). a) Particulate containing Si. Size: 276nm×524nm. EDS: **Si**, Cr. b) Particulate containing Si and Al. Size: 276nm×524nm. EDS: Mg, **Si**, **Al**, P, Cr. c) Particulate containing Si only. Size: 310nm×340nm. EDS: **Si**. d) Particulate containing Si. Size: 276nm×524nm. EDS: **Si**, P, Ca. e) Particulate containing Si and Al. Size: 387nm×842nm. EDS: **Si**, **Al**, Cr. f) Particulate containing Si and Al. Size: 9,560nm×3,950nm. EDS: Mg, **Si**, **Al**, K, Fe. a) – f) imaged at iATL (Mt. Laurel, NJ) by R. Shumate.

Brenner SA, Neu-Baker NM. Occupational exposure to nanomaterials: assessing the potential for cutaneous exposure to metal oxide nanoparticles in a semiconductor facility. *Journal of Chemical Health and Safety.* Available online 15 November 2014. Article in press. doi: 10.1016/j.jchas.2014.11.001.

Subfab sampling

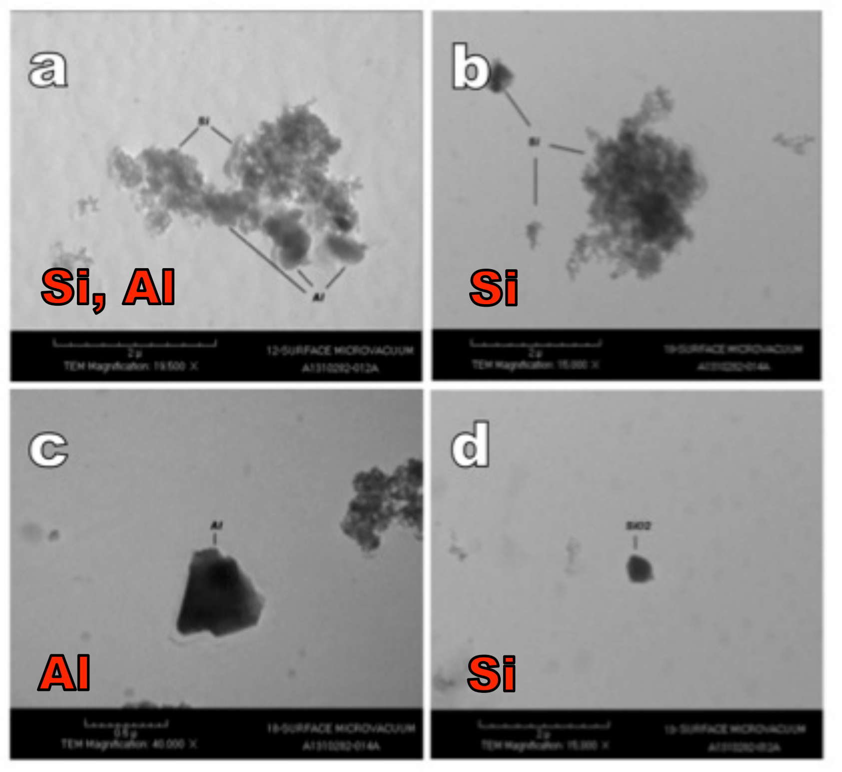


Selected TEM images of surface samples obtained in the subfab (October 2013)

Microvacuum surface samples were acquired during preventive maintenance and quality control tasks in the subfab (October 2013). All samples were acquired from the outside door to filter boxes that load slurry. a) Agglomerate containing **Si**. b) Particulate containing **Al**. c) **Ce** particle. d) Agglomerate containing **Si** and **Al**. a) – d) imaged at BVNA (Kennesaw, GA) by N. Gapon.

Brenner SA, Neu-Baker NM. Occupational exposure to nanomaterials: assessing the potential for cutaneous exposure to metal oxide nanoparticles in a semiconductor facility. *Journal of Chemical Health and Safety.* Available online 15 November 2014. Article in press. doi: 10.1016/j.jchas.2014.11.001.

WWT sampling

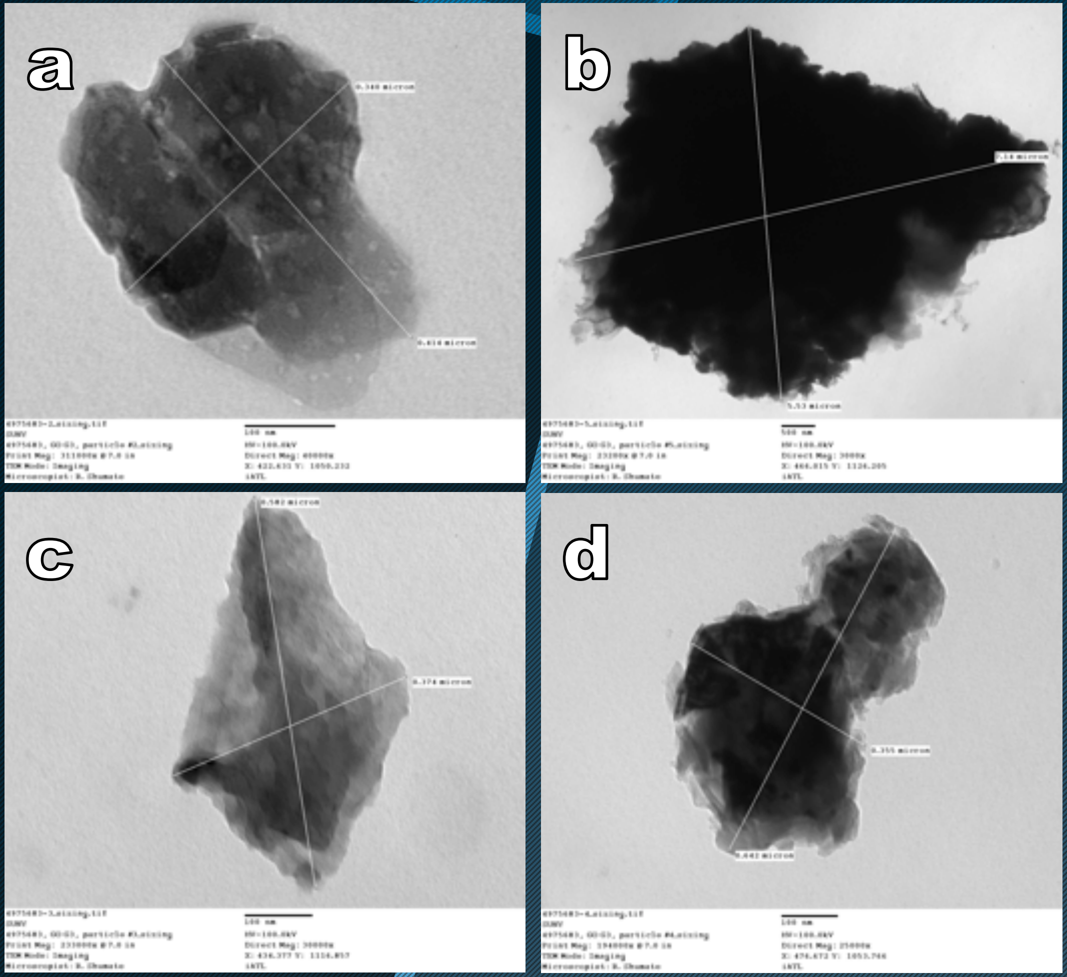


Selected TEM images of surface samples obtained in WWT (February 2013)

Microvacuum surface samples from WWT during filter changes and sump pump clean-out (October 2013). a) Agglomerate containing **Si** and **Al** from the plastic wall covering next to the sump pump valve during a pump clean-out. b) Particulate containing **Si** from the floor next to the base filter tank. c) Particulate containing **Al** only from the floor next to the base filter tank. d) Particulate containing **SiO_2** from the floor next to the acid filter tank. a) – d) imaged at BVNA (Kennesaw, GA) by N. Gapon.

Brenner SA, Neu-Baker NM. Occupational exposure to nanomaterials: assessing the potential for cutaneous exposure to metal oxide nanoparticles in a semiconductor facility. *Journal of Chemical Health and Safety.* Available online 15 November 2014. Article in press. doi: 10.1016/j.jchas.2014.11.001.

WWT sampling



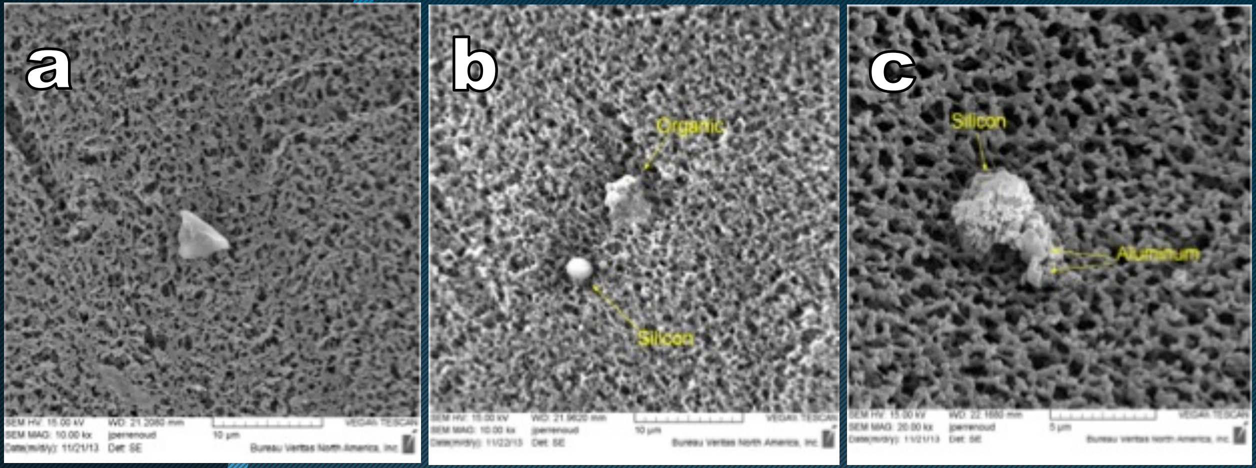
Selected TEM images of surface samples obtained in WWT (February 2013)

Microvacuum surface samples from the hatch to the acid filter tank in WWT (February 2013). a) Particulate containing Al and Si. Size: 340nm×414nm. EDS: **Si**, **Al**, Fe. b) Particulate containing Si and Al. Size: 5,530nm×7,140nm. EDS: Mg, **Si**, **Al**, K, Ti, Cr. c) Particulate containing Si only. Size: 374nm×582nm. EDS: **Si**. d) Particulate containing Si only. Size: 642nm×355nm. EDS: **Si**. a) – d) imaged at iATL (Mt. Laurel, NJ) by R. Shumate.

Brenner SA, Neu-Baker NM. Occupational exposure to nanomaterials: assessing the potential for cutaneous exposure to metal oxide nanoparticles in a semiconductor facility. *Journal of Chemical Health and Safety.* Available online 15 November 2014. Article in press. doi: 10.1016/j.jchas.2014.11.001.

WWT sampling

Selected SEM images of surface samples obtained in WWT (October 2013)



Microvacuum surface samples from WWT during filter changes and sump pump clean-out (October 2013). a) **Si** particle from the floor next to the acid filter tank. b) Particulate containing **Si** (bottom particle) and organic material (top particle) from the floor next to the base filter tank. c) Particulate containing **Si** and **Al** from the plastic wall covering next to the sump pump valve during a pump clean-out. a) – d) imaged at BVNA (Kennesaw, GA) by J. Perrenoud.

Brenner SA, Neu-Baker NM. Occupational exposure to nanomaterials: assessing the potential for cutaneous exposure to metal oxide nanoparticles in a semiconductor facility. *Journal of Chemical Health and Safety.* Available online 15 November 2014. Article in press. doi: 10.1016/j.jchas.2014.11.001.

Conclusions to date

- This study identified the presence of metal oxide particulates and agglomerates on surfaces frequently contacted by workers associated with the CMP process
- Since the effectiveness of current PPE in protecting workers from ENMs is not yet fully understood, research is needed to investigate their efficacy under conditions that simulate occupational use
- It is critical to interpret exposure assessment data alongside data from toxicology studies (hazard assessment) in order to accurately and appropriately assess risk to workers
- This builds on prior surface sampling work by Shepard and Brenner (Shepard, M.; Brenner, S. Cutaneous exposure scenarios for engineered nanoparticles used in semiconductor fabrication: a preliminary investigation of workplace surface contamination. *Int J Occ Environ Health* 2014a, *20*(3), 247-257.)
- Air (inhalation) exposure assessment is underway, and research is ongoing concurrently, but was not reported in this presentation due to time
- Toxicology research investigating these real-world exposures is also ongoing concurrently, but was not reported in this presentation due to time

Nano Regulation

The need for NanoEHS research and evidence-based policy

National Institutes of Health

CDC
Centers for Disease Control and Prevention

United States Environmental Protection Agency

National Institute for Occupational Safety and Health
NIOSH

OSHA®

USDA

National Cancer Institute®

nanoEHS

National Nanotechnology Initiative

us eu
bridging nanoEHS research efforts

NIEHS
National Institute of Environmental Health Sciences

FDA

"The Obama Administration is committed to supporting significant research into the potential environmental, health, and safety (EHS) impacts of nanotechnology . . ."
-- *National Nanotechnology Initiative*

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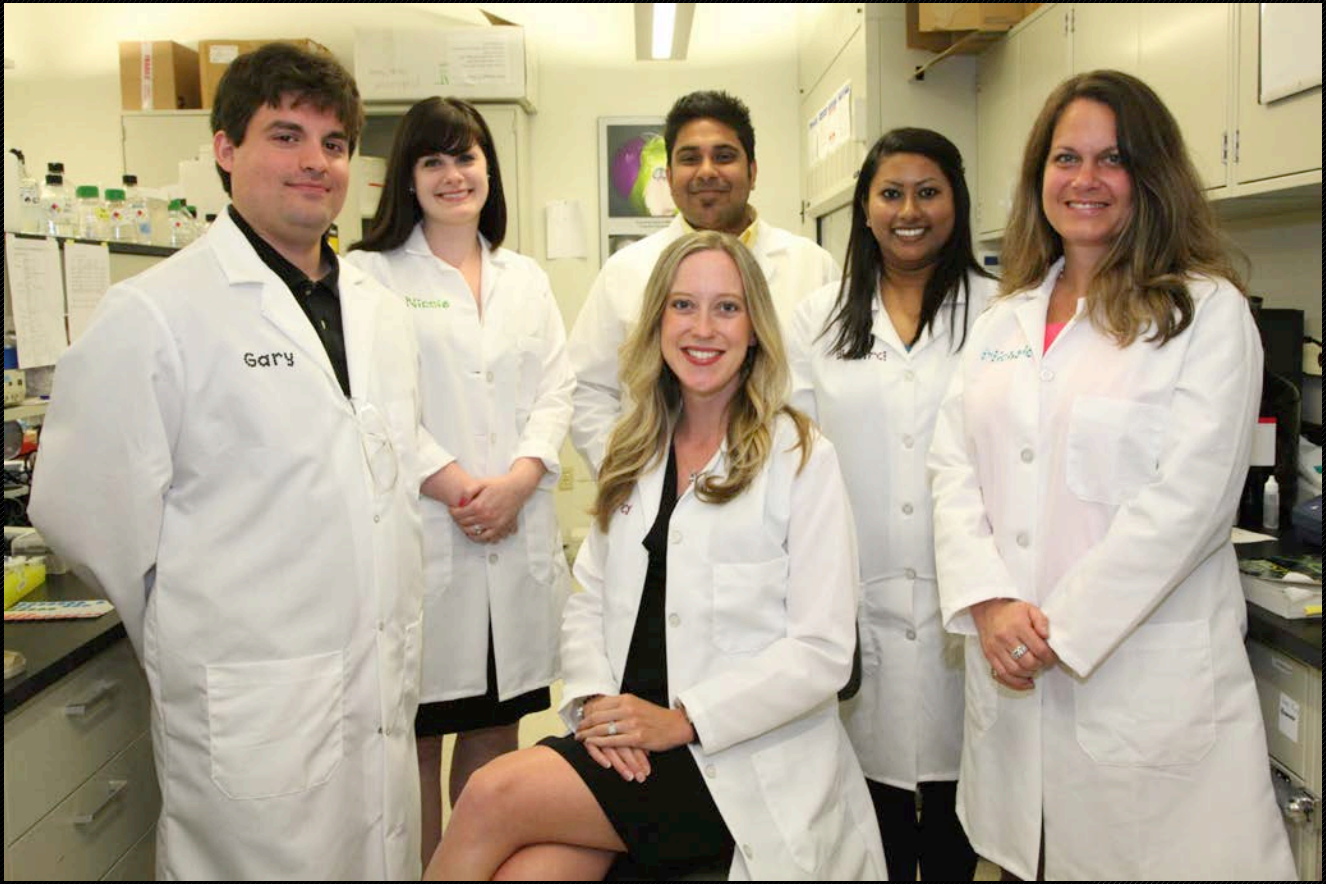

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Current Support

- Nanoparticle Exposure Assessment during CMP Operation and Maintenance (CDC-NIOSH)
- EPA STAR Fellowship-Risk Assessment and Life Cycle Analysis of Nanoscale Metal Oxides used in Semiconductor Wafer Fabrication (U.S. Environmental Protection Agency [EPA])
- Nanoparticle Exposure Assessment during CMP Operation and Maintenance Phase IV (SEMATECH/NYS)
- Identification and Determination of Fate of SiO_2 Nanoparticles in Conventional Wastewater Treatment Phase III (SEMATECH/NYS)
- Efficacy of Personal Protective Equipment (PPE) in Preventing Dermal and iNhalation Exposure to Nanoparticles and Nanoagglomerates Phase III (SEMATECH/NYS)
- Acute vs. Subchronic Health Effects of Inhalation Exposure to Engineered Metal Oxide Nanoparticles in a Rat Model Phase III (SEMATECH/NYS)
- Development of Advanced Imaging and Analytical Techniques for Occupational Exposure to Nanomaterials (CDC-NIOSH)

Former Staff & Students

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