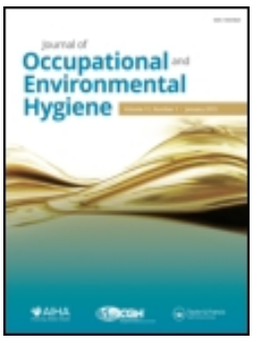

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Case Study
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Occupational exposure to airborne nanomaterials: An assessment of worker exposure to aerosolized metal oxide nanoparticles in a semiconductor fab and subfab

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ABSTRACT

This occupational exposure assessment study characterized potential inhalation exposures of workers to engineered nanomaterials associated with chemical mechanical planarization wafer polishing processes in a semiconductor research and development facility. Air sampling methodology was designed to capture airborne metal oxide nanoparticles for characterization. The research team obtained air samples in the fab and subfab areas using a combination of filter-based capture methods to determine particle morphology and elemental composition and real-time direct-reading instruments to determine airborne particle counts. Filter-based samples were analyzed by electron microscopy and energy-dispersive x-ray spectroscopy while real-time particle counting data underwent statistical analysis. Sampling was conducted during worker tasks associated with preventive maintenance and quality control that were identified as having medium to high potential for inhalation exposure based on qualitative assessments. For each sampling event, data was collected for comparison between the background, task area, and personal breathing zone. Sampling conducted over nine months included five discrete sampling series events in coordination with on-site employees under real working conditions. The number of filter-based samples captured was: eight from worker personal breathing zones; seven from task areas; and five from backgrounds. A complementary suite of direct-reading instruments collected data for seven sample collection periods in the task area and six in the background. Engineered nanomaterials of interest (Si, Al, Ce) were identified in filter-based samples from all areas of collection, existing as agglomerates (>500 nm) and nanoparticles (100–500 nm). Particle counts showed an increase in number concentration above background during a subset of the job tasks, but particle counts in the task areas were otherwise not significantly higher than background. Additional data is needed to support further statistical analysis and determine trends; however, this initial investigation suggests that nanoparticles used or generated by the wafer polishing process become aerosolized and may be accessible for inhalation exposures by workers performing tasks in the subfab and fab. Additional research is needed to further quantify the degree of exposure and link these findings to related hazard research.

KEYWORDS
Chemical mechanical planarization; engineered nanomaterials; inhalation; metal oxide nanoparticles; occupational exposure assessment; semiconductor fabrication

Introduction

The nanotechnology workforce represents one of the first populations exposed to ENMs due to their involvement in the research, development, manufacturing, and disposal processes of emerging materials and technologies.[1] Proactive health and safety research and occupational exposure assessments are urgently needed in order to: (1)

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characterize real-world exposures of workers to ENMs; (2) elucidate the potential health and safety consequences of exposures; and (3) establish evidence-based guidelines and recommendations to protect worker health. These needs have been defined and broadcasted by agencies such as NIOSH and NIEHS; however, aside from a limited number of site visits performed by the NIOSH Field Research Team, very few research studies involving occupational exposure assessment with workers in industrial settings have been reported. This study focuses specifically on detailed characterization of potential inhalation exposures of workers to airborne metal oxide nanoparticles (NPs) associated with the chemical mechanical planarization (CMP) process in the fab (cleanroom) and subfab spaces of a semiconductor research and development facility. CMP is a polishing process that maintains planarity of multiple dielectric and metal layers on the silicon wafer during integrated circuit (IC) fabrication.[2–7] The ENMs of interest for this study were the most common metal oxide NPs found in commercial CMP slurries currently in use by the semiconductor industry: fumed or colloidal silicon dioxide (SiO_2; silica), aluminum oxide (Al_2O_3; alumina), and cerium oxide (CeO_2; ceria).

This study aims to address critical knowledge gaps and achieve the following goals: (1) provide a baseline assessment for a population of workers handling ENMs in a real-world industrial setting; (2) reveal the current limitations in best-known occupational exposure assessment methodology regarding tools, techniques, and state-of-the-science for ENMs; (3) identify hurdles and challenges that organizations may face in trying to implement occupational exposure assessment strategies in their facilities (e.g., time, logistics, interpretation of results, translation to best practice recommendations); and (4) provide a proactive case example of how such assessments could be performed or adapted in other industries or workforces handling ENMs.

Methods

Sampling locations: Fab (cleanroom) and subfab

An initial series of qualitative assessments identified workers for exposure assessment sampling in job tasks with risk for exposure to ENMs associated with the CMP process and established a sampling methodology that uses a task-based approach.[7,8] In this study, air sampling was conducted during preventive maintenance (PM) and quality control (QC) tasks at the semiconductor ENM user facility that were identified as having medium to high potential for inhalation exposure based on qualitative assessments. Variables considered in ranking the priority of tasks for sampling included: type and volume of materials handled; material hazards (if known); frequency and duration of the task; likelihood of the task to result in aerosolization of ENMs; engineering controls and administrative controls in place; and use of personal protective equipment (PPE). Areas in the facility where workers handle CMP slurries, waste, or associated processes include a chemical mix room for making batches of experimental or alternate slurry, on-site wastewater treatment (WWT; reported previously[2]), areas for storage of materials and waste, the fab, and the subfab (depicted in Figure 1S[2]). This study investigated potential inhalation exposures of workers in the fab, where the CMP tools are housed, and in the subfab level below, where the bulk chemical delivery systems are located.

The fab operates at an average ISO 5 (Class 100; <100 particles/ft^3 size 0.5 μm and larger and <300 particles/ft^3 size 0.3 μm and larger). Exposure assessment in this area focused on workers including tool technicians, workstation operators, and process engineers who operate and maintain the CMP tools and perform PM tasks on a scheduled or as-needed basis, including consumable change-outs and cleaning of the CMP tool polisher module. Process engineers also prepare slurry batches in the chemical mix room, a separate non-cleanroom space outfitted with a mixing apparatus and chemical fume hoods, and then transport the slurries to the CMP tool by carboy. While the entire CMP process itself occurs within a fully enclosed and exhausted CMP tool in the fab, PM tasks and slurry preparation and transport occur outside of standard equipment controls, and therefore represent medium to high risk activities for worker inhalation exposure to CMP slurry NPs.

The subfab, located one level below the fab, is an average of ISO 6 (Class 1,000) space with intermittent episodes of over ISO 7 due to being part of the air return and its location directly below the ISO 5 fab. It is not a cleanroom, but some cleanroom procedures, such as gowning and gloving, are required. The subfab houses bulk slurry delivery systems that feed the four CMP tools located in the fab level above and also houses other chemical delivery systems and machinery. Subfab workers operate and maintain the slurry delivery systems and perform PM tasks on a scheduled or as-needed basis. Other job tasks include cleaning dried slurry off machinery via chemical dissolution followed by manual scraping and vacuuming; cleaning overflow or spilled slurry during chemical loading; sampling slurries for QC; purging and loading slurries into the delivery systems; washing empty slurry barrels; and manually mixing and transporting slurry drums via carboy to the CMP tools in the fab.

Sampling approach

The sampling methodology for airborne exposures has been described in detail[2,3,6,7] and is described again in the Supplemental Materials. It follows guidelines for distinguishing ENMs from incidental sources and determining particle number concentration[8,9] and applies exposure monitoring protocols set forth by the American Industrial Hygiene Association (AIHA)[10] and the Nanoparticle Emission Assessment Technique (NEAT) established by NIOSH.[11,12]

Direct-reading instruments (DRIs)

Direct-reading instruments (DRIs) utilized for air sampling in the fab and subfab included an optical particle counter (OPC; HHPC-6 MET ONE HACH Ultra Analytics/ART Instruments; Grants Pass, OR); a condensation particle counter (CPC; TSI Model 2007; TSI, Inc., Shoreview, MN); and a scanning mobility particle sizer (SMPS; TSI NanoScan Nanoparticle Sizer, Model 3901; TSI, Inc., Shoreview, MN). For each sampling event, including each task in each area, background data was obtained prior to the start of tasks over a minimum collection of 15 min at a location at least 30 m from the task area and away from any other known ongoing tasks. Data from the task area was obtained for the duration of each task as close to the worker as possible (within 0.9–1.5 m), for comparison to background.

Statistical analysis

Data from DRIs are first summarized graphically and descriptively. Each sample was examined graphically as a time series in order to qualitatively assess trends and for comparison with descriptions of activities recorded during the sampling event. Descriptive statistics that were compiled include: minimum and maximum number concentration values, mean and median, the difference between task and background mean, and task mean divided by background mean (see Supplementary Materials). In the case of multi-channel instruments (OPC and SMPS), all values were given for each size channel individually. For sample collection periods that have background and task measurements, the background and task means were tested to determine whether task particle concentration levels were significantly higher than those for the background. First, the task and background data series were assessed for autocorrelation and a time lag was determined that brought autocorrelation within a 95% confidence interval of zero. The time lag was then used to re-sample each series to produce uncorrelated series. The means were compared using Welch's t-test because of unequal sample sizes and unequal variances. Results were assessed at the $\alpha = 0.05$ level. All statistical analyses were completed using R statistical software (version 3.0.1).

Filter-based sampling for transmission electron microscopy (TEM) with elemental analysis by energy-dispersive x-ray spectroscopy (EDS)

Air samples were obtained from workers' personal breathing zones (PBZ) and from the task area while a job task of interest was ongoing. Workers wore personal sampling pumps, which capture airborne particulate onto polycarbonate (PC) filters (0.8 µm pore size in 25 mm diameter conductive polypropylene cassettes with extension cowls; SKC, Inc.) attached to the pumps and taped near the workers' collars within their PBZs (approximately 15–30 cm from mouth/nose). Initial filter-based samples (February 2013) were collected using AirChek52 personal sampling pumps (SKC, Inc., Eighty Four, PA) and subsequent samples (October 2013) were collected using AirChek XR5000 personal sampling pumps (SKC, Inc., Eighty Four, PA). Flow rates were set between 1.6–2.2 L/min. Field blanks served as controls for the sampling location; media blanks served as true negative controls.[2]

Filter-based samples collected from February 2013–October 2013 were analyzed via TEM for size and basic morphology and EDS for compositional analysis, conducted by iATL (nanoTEM, Mt. Laurel, NJ; February 2013 samples) and by Bureau Veritas North America (BVNA; Kennesaw, GA; October 2013 samples) following modified NIOSH 7402[13] method for analysis of asbestos, the current best method for TEM analysis of ENMs. Briefly, filters were transferred to TEM grids and grid openings were examined at ≥15,000x magnification for particle sizing and morphology. Up to 40 TEM grid openings (0.013 mm^2) were analyzed per filter sample; results assume uniform deposition onto the grid surface, providing reasonable confidence that each portion of the filter is representative of the whole for each particular sample. Visualized particles were then analyzed via EDS to determine elemental composition.

Filter-based sampling for gravimetric analysis for mass concentration

Filter-based samples for gravimetric analysis for mass concentration were collected (February 2013) using Leland Legacy sampling pumps (SKC Inc., Eighty Four, PA). Pump flow rates were set between 3.3–3.5 L/min. Gravimetric analysis was conducted by Galson Laboratories (East Syracuse, NY), with cerium oxide mass

Table 1. Number and type of samples captured in each location and area.

			Filter-Based Capture					Direct-Reading Instruments	
Sampling Location	Date (Sampling Event)	Task	PBZ	Task Area	Background	Field Blank	Media Blank	Task Area	Background
Subfab	02/06/2013 (#1)	Slurry sampling for QC	√	√	√	√	√[c]	√[a,b]	√[a]
	10/25/2013 (#2)	Slurry filter box clean-out to CMP tool A	√	√	√	√	√[c]	√	√
		Slurry filter box clean-out to CMP tool B	√	√					
Fab	02/07/2013 (#1)	Monthly preventive maintenance (full-shift observed)	√	√	√	√		√[a] (morning)	√[a]
								√[a] (afternoon	
	02/08/2013 (#2)	Monthly preventive maintenance (morning shift observed)	√	√	√			√	√
	10/30/2013 (#3)	Slurry mixing (in chemical mix room)	√	√	√	√		√	
		Slurry loading and consumables change-outs	√	√	√	√		√[a]	√[a]
Total # of samples or collection periods			7	7	6	5	2	7	5

[a]CPC data not obtained (battery died in field and data not logged).
[b]SMPS data only obtained for last 30 min of task.
[c]One media blank per sampling period (February or October 2013) was analyzed. All filters captured in February were analyzed as a batch, regardless of sampling location; the same is true for filters captured in October.

concentration analysis subcontracted to BVNA (Novi, MI), following modified Occupational Safety and Health Administration (OSHA) method 125G[14] or NIOSH 0500.[15]

Results

Size, morphology, and composition

Sampling was conducted over nine months (February 2013–October 2013), which included six discrete sampling series events: three in coordination with subfab employees and three in coordination with fab employees. Table 1 shows the total number and types of samples collected by location, area, and task. Filter-based samples captured during tasks from the workers' PBZ, task area, and background were analyzed by TEM/EDS for identification and characterization of NPs and agglomerates containing materials of interest (Si, Al, Ce). The expected results of sampling based on the frequency and volume of CMP slurry types used in the facility (which reflects those used in manufacturing) was to detect Si>Al>Ce, which was indeed the case. Table 2 shows the results of filter-based air samples; a check mark indicates that an element of interest (Al, Si, Ce) was confirmed by EDS in the particles/agglomerates captured and imaged by TEM. In the subfab, most filters (nine of 12) analyzed contained materials of interest (Si/Al/Ce) in the >1,000 nm size range and most filters (nine of 12) contained Si. No particles <100 nm containing elements of interest were found for any of the observed tasks. In the fab, most filters (7 of 15) analyzed contained materials of interest (Si/Al/Ce) in the >1,000 nm size range and most filters (10 of 15) contained Si. No particles <100nm containing elements of interest were found for any of the observed tasks. Representative TEM images of filter-based PBZ, task area, and background samples containing materials of interest (SI, Al, Ce) are shown in Figure 1 and in the Supplementary Materials. While most materials of interest captured in air samples were irregularly shaped, some did resemble the spherical morphology of the pristine ENM slurry abrasives in the original polishing product.

Number concentration

There were two collection events using DRIs in the subfab in 2013. For sampling event #1 taken in the subfab taken during slurry sampling, the magnitude of the particle concentration measurements was small (<2 particles/cm^3 in any channel on the SMPS) but higher for the OPC, which, overall, represents larger particle sizes. For the SMPS, the task measured significantly higher than the background only in the 20.5 nm, 115.5 nm, and 154 nm size channels. For the OPC, the task measured significantly higher in the 300–500 nm, 500–700 nm, 1000–2000 nm, 2000–5000 nm, and the >5000 nm size channels.

For sampling event #2 in the subfab taken during the slurry filter box cleaning task in the subfab on 10/25 (Figure 2 and Figure 4S), very high particle counts corresponded to the worker using a wet/dry vacuum on

Table 2. Filter-based air sample results (materials of interest identified by EM with EDS).

Location	Date (Sampling Event)	Sample and Sampling Duration	Si	Al	Ce	Samples Containing Si/Al/Ce <100 nm	100–500 nm	500–1,000 nm	>1,000 nm
Subfab	02/06/2013 (#1)	PBZ (QC slurry sampling) (1 hr 41 min)	√				√	√	√
		Area (QC slurry sampling) (1 hr 41 min)	√				√	√	√
		Background (18 min)	√	√			√	√	√
		Field blank (0 min)	√	√					√
		Media blank (0 min)	√	√				√	√
	10/25/2013 (#2)	PBZ (slurry filter box clean-out to CMP tool A) (19 min)	√						√
		Area (slurry filter box clean-out to CMP tool A) (19 min)	√				√	√	√
		PBZ (slurry filter box clean-out to CMP tool B) (30 min)	√		√		√	√	√
		Area (slurry filter box clean-out to CMP tool B) (30 min)	√		√		√	√	√
		Background (19 min)							
		Field blank (0 min)							
		Media blank (0 min)							
Total # of samples (subfab)			9/12	3/12	2/12	0/12	6/12	7/12	9/12
Fab	02/07/2013 (#1)	PBZ (monthly PM, morning shift) (2 hr 18 min)	√				√		
		PBZ (monthly PM, afternoon shift) (2 hr 22 min)	√						√
		Area (monthly PM, full-shift) (4 hr 40 min)	√						√
		Background (16 min)	√				√	√	
		Field blank (0 min)	√	√					√
	02/08/2013 (#2)	PBZ (monthly PM, morning shift) (2 hr 9 min)	√					√	√
		Area (monthly PM, morning shift) (2 hr 10 min)	√				√	√	√
		Background (14 min)	√	√			√	√	√
	10/30/2013 (#3)	PBZ (slurry loading; consumables change-outs) (1 hr 45 min)	√				√		
		Area (slurry loading; consumables change-outs) (1 hr 55 min)							
		Background (fab) (15 min)							
		PBZ (slurry mixing in chemical mix room) (14 min)	√	√	√		√		√
		Area (slurry mixing in chemical mix room) (14 min)							
		Field blank (fab) (0 min)							
		Field blank (chemical mix room) (0min)							
Total # of samples (fab)			10/15	3/15	1/15	0/15	6/15	4/15	7/15
Grand total # of samples (subfab + fab)			19/27	6/27	3/27	0/27	12/27	11/27	16/27

dried slurry. Correlation between the particle counts during vacuuming ranged from approximately 2–2000 times higher than the background measurements for the SMPS, approximately 200–500 times higher for the OPC, and 59 times higher for the CPC. For the SMPS, the task measured significantly higher than the background only in the 64.9 nm size channel. For the OPC, the task measured significantly higher than the background in all channels except for the 300–500 nm channel. For the CPC, the task did not test as significantly higher than background. Thus, for the entire task duration, the task particle number concentration levels did not test as significantly higher than background in most size channels; however, the specific vacuuming subtask had the highest

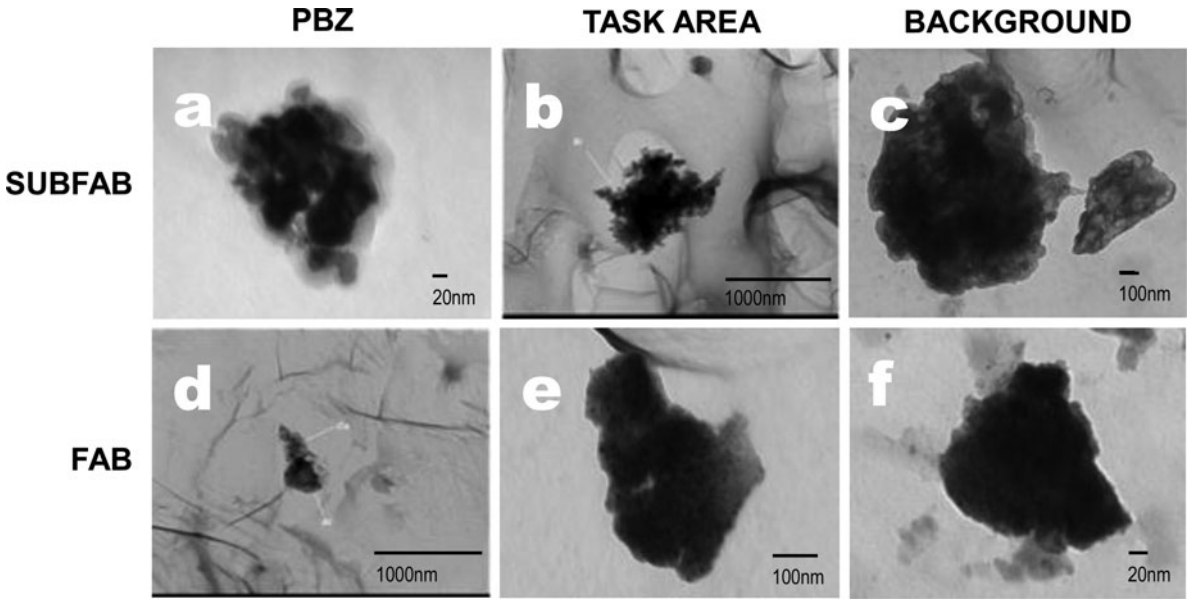

Figure 1. Selected TEM images from filter samples obtained in the subfab and fab during preventive maintenance and quality control tasks. Selected TEM images from worker PBZ, task area, and background filter samples obtained in the subfab (a–c) and the fab (d–f) during PM and QC tasks. (a) Mixed agglomerate containing **Si** collected during a slurry sampling task. 0.189 μm × 0.278 μm; EDS: **Si**, Cr, Fe. (b) **Si** agglomerate during a clean-out of a slurry filter box to CMP tool A. (c) Mixed agglomerates containing **Si**. 1,600 nm × 1,370 nm; 816 nm × 446 nm; EDS: **Si**, Na, Mg, P, S, Cl, Ca, Cr, Fe. (d) Agglomerate containing **Al** during slurry mixing in the chemical mix room. 350 nm × 280 nm; EDS: **Al**, Ca. (e) Mixed agglomerate containing **Si**, collected during monthly PM. 370 nm × 531 nm; EDS: **Si**, Fe, Cr, Ni. (f) Mixed agglomerate containing **Si**. 194 nm × 234 nm; EDS: **Si**, P, Sn, Ca, Cr, Fe. (a, c, e, f) collected during February 2013 sampling event and imaged at iATL (Mount Laurel, NJ) by R. Shumate, May 2013. (b, d) collected during October 2013 sampling event and imaged at BVNA (Kennesaw, GA) by K. Parikh, December 2013.

measurements observed for any of the tasks in the fab and subfab.

There were five collection events in the fab in 2013. Particle concentration levels in the fab were the lowest levels observed in any sampling space. For the SMPS and the three measured PM tasks from February, only the 205.4 nm channel on fab sampling event #1 and the 11.5 nm and 27.4 nm channels on fab sampling event #2 measured significantly higher than the background. For the OPC, only the PM task during fab sampling event #2 in the 300–500 nm, 500–700 nm, 700–1000 nm, and 1000–2000 nm channels had task measurements test higher than the background. No task measurements tested higher on any equipment for the fab sampling event #3 slurry sampling task. The overall magnitudes for these collection events were very small.

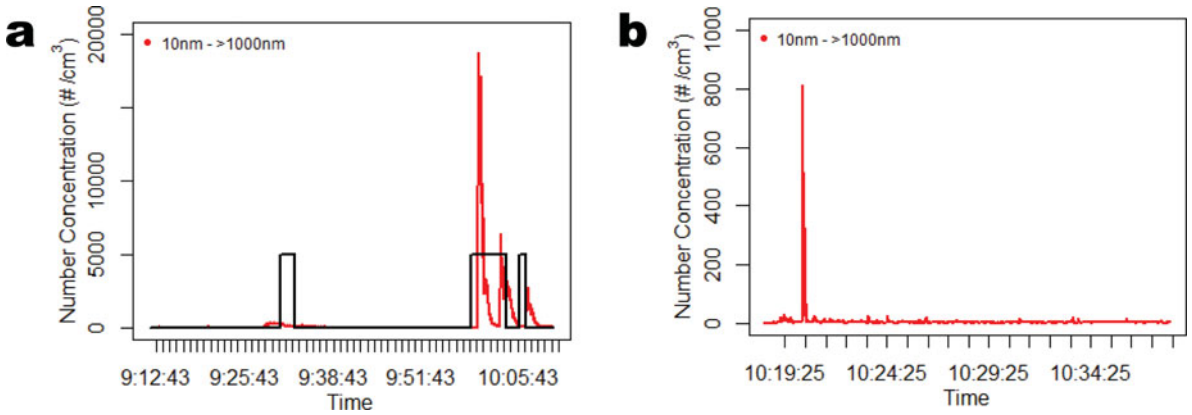

Figure 2. Plots of particle number concentration over time (October 2013). Plots of particle number concentration (number of particles/cm^3) over time during the subfab sampling event #2: slurry filter box cleaning (10/25/13). (a) Particle number concentrations for slurry filter box clean-out task. Particle number concentration during slurry filter box clean-out, as recorded by the CPC. The black line indicates when the vacuum was turned on (arbitrary amplitude of 5,000/cm^3) or off (flat line at 0). Spikes in particle number concentration correspond to vacuuming of dried slurry. (b) Particle number concentrations for the background. Particle number concentration from the background, obtained with the CPC following slurry filter box clean-out.

The task observed in the chemical mix room during the fab sampling event #3 did have measured levels several orders of magnitude higher than that in the cleanroom. Without a background measurement, it is not yet possible to suggest whether this is due to specific worker tasks or due to an overall less clean environment in the chemical mix room. Specific summary statistics and hypothesis test results for all collection events can be found in Tables 1S, 2S, and 3S in Supplemental Materials.

Mass concentration

For the February 2013 sampling events, one sample was collected from the subfab and three samples were collected from the fab for mass concentration analysis for alumina (as Al) and one sample was collected in the subfab and three samples were collected from the fab for mass concentration analysis for ceria (as Ce). Mass concentration results for all eight samples were below the limits of detection for the samples collected (February 2013), based on the analytical limits of quantitation (LOQ) of 14 μg/sample for alumina and 2 μg/sample for ceria. Since previously collected samples were also consistently below the LOQ,[2,7] mass concentration analysis was not conducted for filter samples collected in October 2013.

Discussion

The results of this study indicate that NPs used or generated by CMP become aerosolized during certain tasks and may be accessible for inhalation exposures by workers in fab and subfab facilities. Samples were captured that contained single elements of interest, while other samples contained multiple elements of interest (mixed composition). Overall, in both spaces investigated, Si was most frequently found (80% of all filter-captured air samples analyzed by TEM), followed by Al (15%) and Ce (15%). This was not surprising given that the most common slurry compositions used at the sampling location are Si>Al>Ce (additionally, semiconductor wafers are silicon-based). In terms of proximity to task, PBZ samples contained Si (100%; eight of eight samples), Ce (25%; two of eight samples), and Al (12.5%; one of eight samples). PBZ samples also contained both Si+Ce (12.5%; one of eight samples) and Si+Al+Ce (12.5%; one of eight samples). Area samples contained Si (71.4%; five of seven samples), Ce (14.3%; one of seven samples), and background samples contained Si (60%; three of five samples), Al (40%; two of five samples), and both Si+Al (40%; two of five samples). This indicates that while PBZ samples are most likely to include materials of interest, dissipation to the area and/or the background does occur. These findings also suggest that materials of interest originating from slurries of different compositions that were run on the tools prior to the sampling period could have dissipated beyond the task or area and remained in the background. This could explain differences observed in samples collected from different areas at the same time.

Captured airborne particulate included NPs (100–500 nm) as well as aggregates, agglomerates, and larger single particles (>1000 nm). No single nanoparticles <100 nm were identified. For slurry sampling and slurry filter box clean-out tasks in the subfab, filter-captured air samples contained particles of interest ranging in size from 100 nm to >1000 nm. For PM tasks in the fab and for slurry mixing in the chemical mix room, filter-captured air samples also contained particles of interest ranging in size from 100 nm to >1000 nm. Based on TEM results, the morphologies and compositions of particles captured indicate agglomeration of NPs in most samples collected. Some appear to be aggregates or agglomerates of a single type of NP. Rarely, a single NP made of a material of interest or a mixed agglomerate containing a material of interest and organic material was found.

For the majority of the collection events in the fab space, observed particle concentration levels were low, as would be expected in a cleanroom environment. Higher particle concentration levels were observed in the subfab and in the chemical mix room, as would also be expected. A marked increase in particle counts in all size bins was observed in the subfab collection event, which was well correlated in time with the use of a vacuum. This suggests that particles in relevant size ranges may be aerosolized as a result of PM activities and may agglomerate as they migrate through the workspace and/or move at different rates. The corresponding filter-based samples (PBZ and task area) during this task showed Si and Ce particles (100–500 nm) and agglomerates (500–1000 nm and >1000 nm), suggesting that the particles aerosolized by vacuuming likely originated from slurry, which likely dried as particles and agglomerates that were then physically liberated by the PM vacuuming task. Of the DRIs, the SMPS allows for greater size resolution for particles <500 nm than the other DRIs (OPC, six channels from 300–2000 nm; CPC, one channel measuring all particles between 10–1000 nm); therefore, it may prove the most informative DRI of the three where size resolution in the nanoscale range is desired. In both spaces, additional samples for each specific work task are needed to detect a potential non-random difference between background and task. This study serves to initiate further methodology development for the detailed quantitative and statistical analysis of particle number concentration measurements, both in time and space.

A key finding was that field and media blanks contained elements of interest, which was unexpected. Si and Al structures were found in the February 2013 field blanks (>1000 nm) and a media blank (500 nm to >1000 nm), which might bias results high for those size ranges from the February 2013 sample collection. It is therefore extremely important for investigators using filter media for nanomaterial exposure assessment to investigate any potential contamination issues with specific materials of interest prior to selecting media for testing. Further discussion regarding filter contamination is included in the Supplementary Materials.

Ongoing research by the investigators includes exposure assessment with workers along the entire lifecycle of the CMP slurries on site.[2,3,6,7] The investigators first developed a comprehensive sampling methodology in coordination with the NIOSH Nanotechnology Field Research Team in 2011,[16] and have since continued collecting data and tailoring the assessment approach for specific tasks and on-site locations based on evolving best-known methods. Data collected prior to the sampling period reported in this article has been reported,[2,3,6,7] which include data and EM images from air sampling events (66 total TEM and scanning electron microscopy (SEM) samples) and from surface sampling events (22 total TEM/SEM samples) collected since 2011. An in-depth analysis of potential inhalation exposure scenarios in the on-site WWT facility was described in Brenner et al. (2015),[2] identifying ENMs of interest (Si, Al, Ce) at levels higher than background that are potentially accessible for inhalation exposures by WWT workers. In addition to air sampling, surface sampling in these workspaces is ongoing in order to assess potential for cutaneous (skin) exposure.[3,6]

Current nanotoxicology literature indicates that physicochemical parameters and number concentration of ENMs may confer different toxicological implications compared to their bulk counterparts. Overall, there is a lack of scientific consensus regarding which ENM properties are the leading determinants of toxicity for different classes of ENMs: size[17] or fiber length,[18] surface area,[17,19,20] surface coating,[21,22] crystal phase,[17] and agglomeration state[23] have all been implicated as factors relevant to toxicity. The exposure assessment methods and data reported in this study yield critical characterization data for the ENMs captured, which includes potential determinants of toxicity—elemental composition, size, size distribution, shape/morphology, aspect ratio, degree of agglomeration, specificsurface area, and surface composition. Therefore, these findings will inform toxicology studies and contribute to the comprehensive risk assessment picture (Risk = Exposure × Hazard). The investigators are currently linking exposure assessment data, including ENM characterization results, to ongoing animal toxicology collaborations to investigate the biological and health implications of cutaneous (skin) and inhalation (lung) exposure to real-world CMP-related ENMs.

Limitations

Known limitations of current instrumentation and sampling approaches for ENMs have been reviewed in the literature.[24–27] Due to their size, mass concentration may not be an appropriate metric for evaluation of exposure to nanoscale materials or for setting occupational exposure limits (OELs). Furthermore, the nanotoxicology literature suggests parameters and physiochemical properties other than mass concentration may be more important for determining toxicity of ENMs.[28,29] Limitations are discussed in more detail in Supplementary Materials.

Conclusions

This study represents one of only a few such workplace assessments published to date regarding metal oxide NP exposures in the workplace.[7,11,30–33] Findings suggest the following main themes: (1) particle concentrations in sampling areas were very low, and even for those tasks generating a rise in particle concentration above background, total concentrations remained appreciably low; (2) ENMs of interest were consistently identified in filter-based samples captured in all areas (PBZ, task area, background) with corresponding decreasing frequency; (3) NPs captured on filter media from all areas tended to be aggregated or agglomerated (and visualized as micron-sized non-uniform structures), as opposed to single particles; and (4) NPs captured on filter media from all areas tended to be of mixed composition as opposed to comprised of a single element. While the ENMs of interest in CMP slurries before use in polishing began as single, largely uniform particles comprised of one element, the particles aerosolized during CMP-related tasks tended to be larger and comprised of multiple elements of interest. In other words, the potential inhalation exposures do not match what might be expected if one were to look at the original ENM-containing product alone. It is possible that the CMP process itself mechanically, chemically, or in some other ways alters the morphology of the original NP abrasives. Additionally, ENMs from different slurries (comprised of different elements) appear to linger in the tools and/or the environment such that aerosolized particles captured tend to contain multiple elements, even though one type of slurry is processed through the system at a time. While some micron-sized particles captured appeared to be

clusters of NPs originating from slurry (based on morphology), other micron-sized particles had little to no uniformity, making their origins much more difficult to identify. The cause of NP agglomeration or aggregation in aerosolized samples is not known; this finding could be an accurate reflection of how the particles exist during CMP processes or could reflect physicochemical changes or tendencies of the particles as they move through air.

Although this work targets ENMs employed in the semiconductor industry, the knowledge gained from this study can be extrapolated to improve the health and safety environment for workers in other industries that utilize ENMs. Significant progress must be made in developing and field-testing methods for measurement of airborne ENMs in work environments as well as in developing evaluation systems for comparing and validating sampling instruments.[34] Despite the current limitations and challenges, a proactive approach to exposure assessment for the nanotechnology workforce is particularly important given the knowledge gaps both in sampling methodology and toxicology. By building on these initial findings, the research community can work together to address challenges and limitations in an effort to collectively help advance the state of the science for ENM exposure assessment.

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