Cutaneous exposure scenarios for engineered nanoparticles used in semiconductor fabrication: a preliminary investigation of workplace surface contamination

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Background: Numerous studies are ongoing in the fields of nanotoxicology and exposure science; however, gaps remain in identifying and evaluating potential exposures from skin contact with engineered nanoparticles in occupational settings.

Objectives: The aim of this study was to identify potential cutaneous exposure scenarios at a workplace using engineered nanoparticles (alumina, ceria, amorphous silica) and evaluate the presence of these materials on workplace surfaces.

Methods: Process review, workplace observations, and preliminary surface sampling were conducted using microvacuum and wipe sample collection methods and transmission electron microscopy with elemental analysis.

Results: Exposure scenarios were identified with potential for incidental contact. Nanoparticles of silica or silica and/or alumina agglomerates (or aggregates) were identified in surface samples from work areas where engineered nanoparticles were used or handled.

Conclusions: Additional data are needed to evaluate occupational exposures from skin contact with engineered nanoparticles; precautionary measures should be used to minimize potential cutaneous exposures in the workplace.

Keywords: Cutaneous, Dermal, Nanoparticle, Occupational exposure, Skin, Surface sample

Introduction

Engineered nanomaterials are increasingly being used in industrial processes and products, consumer goods, and other applications. Questions have been raised as to whether the size and novel chemical physical properties that allow a particular technological advancement or improvement might result in unintended effects on human health and/or the environment.^{1–5} Studies are being conducted to better understand these risks, including toxicology studies, exposure assessments, and tests of the effectiveness of exposure controls. Challenges exist due to the numerous materials and applications, as well as current uncertainties and limitations in assessment methods.

While much of the exposure assessment and toxicology literature to date has focused on inhalation exposure, the primary pathway of concern in most occupational settings, there is also need to investigate

other potential exposure pathways. Skin (cutaneous) exposure to engineered nanomaterials may occur through intentional use of consumer products (e.g. sunscreen, cosmetics) and therapeutic applications (e.g. drug delivery) or unintentionally, including in workplaces where nanoparticles or nano-enabled products are manufactured, used, or handled. Workers can have potential cutaneous exposure to nanoparticles and agglomerates in a number of forms depending on the material and process characteristics, including powders, colloids, and/or aerosols (e.g. dusts from processing composites). Mechanisms of nanoparticle interactions and potential health outcomes from cutaneous exposures are not fully understood, although much of the current data suggests that healthy, intact skin generally acts as a barrier to nanoscale particles.^{6–15} However, some studies have found that certain nanoparticles could penetrate the dermal barrier, depending on the particle size and other test conditions.^{16–23} Tests of commercial glove materials (e.g. nitrile, latex, neoprene) found they were effective against nanoparticles in aerosol and powder form, except after mechanical

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deformation, or after immersion in colloidal solution; nanoparticle penetration of fabric material depends on particle size and fabric characteristics.^{24–28} The potential risks from skin contact with engineered nanomaterials in the workplace are not well defined with limited data on occupational exposure scenarios.

This paper describes the results of a preliminary study to identify cutaneous exposure scenarios at a workplace using engineered nanoparticles in chemical mechanical planarization (CMP), a highly controlled process for wafer polishing in complementary metal oxide semiconductor fabrication which utilizes nanoscale silica, alumina, and ceria in aqueous slurry as polishing abrasives. Surface contamination screening was conducted using microvacuum and wipe sample collection methods and electron microscopy analysis. Although there is uncertainty in the findings given the current state of knowledge, including incomplete hazard information and limitations in sampling methods, such data help inform toxicology studies as well as provide a frame of reference for worker protection decisions, as these materials have already been introduced in commerce and are being used in a growing number of workplaces.

Schneider *et al.* described a conceptual model for processes leading to dermal uptake with six compartments in the workers' environment: the source, air, surface contaminant layer, outer clothing or protective item layer, inner clothing or protective item layer, and the skin, with the potential for contaminants to move within this environment by emission, deposition, transfer and other processes.^{29,30} At the study site, there was potential for worker contact with engineered nanoparticles in aqueous CMP slurry or process wastewater directly (emission), if aerosolized (deposition), or if on workplace surfaces or equipment (transfer). Aerosol measurements during CMP processes tasks at the site were described by Shepard and Brenner.³¹ Other dermal exposure pathways and characteristics of residue material from CMP slurry or wastewater on workplace surfaces have not been fully described.

Surface sampling

Surface sampling can be used for measurements of the skin, inner and outer clothing or protective item layers, and surface contaminant layer.^{29,30,32–34} This data is useful in identifying material characteristics, calculating exposure point concentrations, and/or evaluating the effectiveness of protective equipment or a decontamination process, housekeeping procedure or other control (depending on the sample collection and analysis methods used). Only limited data are available on surface sampling at workplaces creating or handling engineered nanoparticles. Worker exposure investigations published to date have focused mostly on aerosol measurements and potential inhalation exposure, the

primary pathway of concern in most workplaces. Some evaluations have used semiquantitative models such as applying a modified version of the Dermal Exposure Assessment method to assess the likelihood of dermal exposures to engineered nanomaterials.³⁵ A search of peer-reviewed literature yielded no studies where sampling of workplace surfaces was used in assessing potential cutaneous exposures to nanoparticles in occupational settings. Several unpublished studies conducted by the US National Institute for Occupational Safety and Health (NIOSH) used wipe sampling and elemental analysis to identify surface concentrations by mass for silver and nickel titanium alloy nanoparticles.^{36,37} With the exception of asbestos and other fibers, elemental mass concentration analysis has been used in surface sampling for most occupational contaminants (e.g. lead, beryllium). In workplaces creating or handling engineered nanoparticles, mass concentration analysis may be useful in screening or mapping as it can identify whether materials of interest are present above detectable levels or reference values for removable contamination, and offers the advantages of being relatively inexpensive and commonly conducted at commercial laboratories and numerous research institutions, with validated methods for some bulk materials. However, characteristics such as particle size, agglomeration state, surface area, and other properties may be of particular importance in evaluating risks from engineered nanomaterials.^{38,39} In some occupational exposure scenarios, such data may be necessary in differentiating from incidental sources of nanoparticles. Application of electron microscopy techniques in combination with elemental analysis can be used to provide data on particle size and morphology that cannot be obtained relying solely on traditional elemental methods for mass concentration. While electron microscopy methods have been established for surface sampling of bulk materials (e.g. asbestos), these methods are not currently validated for nanomaterials and require a high degree of resources in time and cost to obtain sufficient samples for statistical analysis. This study demonstrates how best known methods for surface sampling may be challenged by engineered nanomaterials and the need for further research if such methods will be applied in nanoparticle exposure assessment.

Methods

Study site and processes

The study site used engineered nanoparticles of aluminum oxide (alumina), cerium oxide (ceria), and amorphous silicon dioxide (silica) for CMP applications during process research and development and integrated circuit fabrication for complementary metal oxide semiconductors. The engineered nanoparticles were used as an abrasive in wafer polishing to remove excess material

(e.g. copper wiring used to connect transistors) and planarize surfaces for further processing.

Nanoparticles were supplied in colloidal form as aqueous slurries that typically contained an oxidizer, dispersing agents, and other additives depending on the CMP application and material being removed. The CMP processes were conducted in enclosed, automated tools located inside a cleanroom where semiconductor device fabrication occurs (fab). Bulk slurry was supplied from the subfab level directly below and pumped through an automated slurry delivery system to the CMP tools in the fab level above. The CMP tools were also occasionally run using a mobile cart system in the fab to pump batch quantities of slurry to the tools. Wastewater from CMP copper removal processes was treated onsite by filtration prior to pH neutralization and subsequent discharge, with two parallel treatment systems for acidic or basic slurries.

Exposure scenarios

Process review and workplace observations were conducted to identify cutaneous exposure scenarios, including the work area, processes, material characteristics, tasks and exposure controls, and determine sampling locations and plans.^{30,40} Sampling locations on non-porous surfaces in the fab, subfab, and wastewater treatment area were selected based on observed or potential worker contact and/or visible evidence of residue slurry or wastewater material.

Sample collection and analysis

Samples were collected from workplace surfaces using microvacuum and wipe sampling methods and analyzed by transmission electron microscopy and energy dispersive X-ray spectroscopy (TEM/EDX) to identify elements of interest and to evaluate the particle size, morphology, and concentration where detected.

Surface microvacuum samples were collected on filter media using tygon tubing cut at approximately 45° to vacuum a 100 cm² area for approximately 2 minutes and analyzed by TEM/EDX (JEOL 1230; JEOL USA Inc., Peabody, MA, USA) following a method modified from ASTM D5755 'Standard test method for microvacuum sampling and indirect analysis of dust by transmission electron microscopy for asbestos structure number surface loading'. Flow rates for sampling pumps (SKC AirChek 52; SKC Inc., Eighty Four, PA, USA) were set at approximately 2–2.5 l/min. Sampling media included 0.8 µm polycarbonate (PC) filters in 25-mm conductive polypropylene cassettes with extension cowls and 0.8 µm mixed cellulose ester (MCE) filters in 25-mm cassettes (SKC Inc.).

Surface wipe sampling was conducted using commercial wipes (SKC Ghost Wipes; SKC Inc.) and following a method modified from ASTM D6480

'Standard test method for wipe sampling of surfaces, indirect preparation, and analysis for asbestos structure number concentration by transmission electron microscopy' (JEOL 1230; JEOL USA Inc.; Hitachi H600 AB; Hitachi High Technologies America, Dallas, TX, USA).

Vacuum and wipe samples were collected using a 100 cm² template or by estimating the area where it was not feasible to use the template due to the surface being sampled (e.g. on a handle). Where repeated measurements were collected of the same sampling surface, the time between the repeat sampling events was at least two months (site operating 24 hours a day, 7 days a week). Quality control procedures included use of field and media blanks for filters and wipes; pre and post-calibration of air sampling pumps used for vacuum sample collection; and modification of existing ASTM surface sampling methods (i.e. modified from TEM methods for asbestos).

Sampling results were compared to in-house characterization of numerous types and manufacturers of slurry (not reported here) to facilitate identification of materials of interest. Samples of bulk slurry were prepared from a dilution of 0.01–0.1% nanoparticles by mass (based on slurry manufacturer non-proprietary specifications); 2.5 µl aliquot pipetted onto a Formvar coated copper grid, dried for at least 3 hours, and imaged (JOEL 200cx). Figure 1 presents TEM images of bulk slurry for four different formulations used at the study site.

Results

The exposure scenarios identified are summarized in Table 1, including a description of the workplace factors. Engineering and administrative controls (e.g. procedures for wet cleaning methods, HEPA vacuum), gloves and other personal protective equipment were used at the study site; cleanroom apparel was used in the fab and subfab areas. Process review and workplace observations indicated the potential for incidental worker contact with: slurry containing nanoparticles, CMP process wastewaters, or contaminated consumable items (e.g. used polishing pads from CMP, used filters from wastewater treatment) during tasks where process containment and closed systems were opened or accessed for tool set-up or maintenance activities, from non-routine conditions (e.g. if overflow in chemical delivery system or spill from slurry drum in subfab), or residues on workplace surfaces or equipment.

Table 1 also outlines the samples collected to evaluate surface contamination (i.e., the surface contaminant layer as the source for exposure). Surface samples from the workplace were analyzed using TEM/EDX to aid in identifying potential

Figure 1 (A) Bulk slurry containing <20% silica by mass; size: 51.9 ± 16.2 nm; $\times 200\,000$. (B) Bulk slurry containing 6% silica; size: 37.2 ± 6.5 nm; $\times 140\,000$. (C) Bulk slurry containing <2% alumina; size: 87.4 ± 19.0 nm; $\times 200\,000$. (D) Bulk slurry containing <1.5% alumina; size: 84.6 ± 20.0 nm; $\times 200\,000$. (©CNSE) (Note: percent by weight as reported by slurry manufacturer; sizing based on average size from 33 images, plus or minus one standard deviation). Image and particle sizing credit: G. Roth, CNSE (Albany, NY, USA).

source materials and evaluating surface contamination. The results of TEM/EDX analysis in Tables 2 and 3 were included to provide a frame of reference, allow for relative comparisons between areas sampled, and as a means to help illustrate current challenges in exposure assessment and encourage further deliberation and study. Owing to the inherent uncertainties and limitations in the methods used, these preliminary sampling data are not intended to be interpreted or directly applied as quantitative results, but rather used to help inform the qualitative exposure assessment and provide a general idea as to particle composition, size, and number density.

Microvacuum samples

Results from TEM/EDX analysis indicated that all nine of the microvacuum samples collected in the subfab and wastewater treatment area contained silica and/or alumina particles (as Si, Al, AlSi, and with other elements), with nanoparticles of Si and/or Al less than 100 nanometers (nm) identified in five of nine samples. No ceria (as Ce) particles of any size were detected in the samples; however, ceria-containing slurry was used infrequently during the sampling

period. Table 2 summarizes the particle compositions, size distributions, and surface concentrations identified for microvacuum samples. Most of the Si and Al particles detected were less than 500 nm, with the exception of two samples collected of dried slurry residue on the floor where the majority was mixed agglomerates or aggregates greater than 1000 nm. The highest surface concentration of Si particles less than 500 nm was identified in the wastewater treatment area, with the highest concentration for nanoparticles (Si or AlSi <100 nm) in the subfab area for a sample collected from the rim of a silica slurry drum handled by workers operating the CMP bulk chemical delivery system in the subfab. While most results were consistent with the tendency of nanoparticles to agglomerate or aggregate with each other and/or with other materials present, Fig. 2 includes two images from surface vacuum samples collected in the subfab and wastewater treatment area where a single nanoparticle or small chain agglomerate was observed and with a uniformity of shape and size to suggest other than incidental material. The size and morphology of silica particles in Fig. 2

Table 1 Summary of workplace factors and surfaces sampled

Work area	Fab	Subfab	Wastewater treatment area
Processes	Operate and maintain CMP tools	Operate and maintain bulk chemical delivery systems for CMP tools	Operate and maintain wastewater treatment systems for CMP processes
Engineering controls	Class 100 cleanroom; CMP tools enclosed and negatively pressured	Class 1000 cleanroom; automated slurry delivery system	General ventilation
Tasks:	a. Tool set-up; b. tool operation; c. preventive maintenance; d. repairs	a. load slurry delivery system; b. maintain or repair system; c. handle, change slurry drums; d. clean-up overflows, small spills or releases	a. Operate and monitor system; b. change pre-filter; c. change post-filter, carbon or cation tank; d. repair or replace pump
Task frequency and duration:	a. Daily (<0.5 hours); b. daily (varies); c. monthly (1–4 hours); d. as needed	a. Daily to weekly (<0.5 hours per tool); b. as needed (varies); c. as needed (<0.5 hour); d. as needed (<1 hour)	a. 24/7 operation; b. aprox. monthly (<0.5 hour); c. as needed (<0.5 hour); d. infrequent (varies)
Protective equipment and work apparel	Disposable gloves (nitrile or nitrile, neoprene, latex blend), safety glasses, Cleanroom suit, hood, and booties	Disposable gloves (nitrile or nitrile, neoprene, latex blend), safety glasses, and hard hat, Cleanroom suit, booties	Double gloves (15 ml nitrile, latex), faceshield, safety glasses, protective apron, and sleeves when changing filters
Material form for tasks with potential for contact	If opening tools (set-up, maintenance, repairs): nanoparticles in slurry or on contaminated surfaces or items, or if aerosols created (e.g. in removing used polishing pads)	Nanoparticles in slurry if overflow during chemical delivery or accessing system for maintenance or repairs, clean-up of slurry drum releases, or dried residues on surfaces*	Nanoparticles in wastewater if opening system for maintenance or repairs, on contaminated surfaces* or items (used filters), or if aerosols created (e.g. spray when opening valve)
Surface sampling locations	Inside of door to CMP tool polishing module; access hatch to mobile slurry delivery cart used to load non-bulk slurry	Rim of slurry drums; HEPA vacuum handle/buttons; floor by chemical delivery system; door to chemical delivery system cabinet	Access covers to wastewater lift tanks; pre-filter housing; handle of bucket used to drain/transfer wastewater
No. of samples collected	3 (3 wipe)	11 (5 microvacuum, 6 wipe)	9 (4 microvacuum, 5 wipe)

Note: Other parameters: intensity of contact — intermittent contact with liquid or dried residual on contaminated surfaces or items (no immersion, short duration); accidental spray or splash potential (opening wastewater lines, if slurry delivery system overflow or drum release). Amount of substance handled — limited (residual material or small quantity) except if opening wastewater lines or if release from slurry drum.

*where slurry or wastewater contacted surfaces or items and the liquid evaporated, a white residue was observed as a film layer on equipment and tools, as well as a powder form on the floor and certain surfaces in the subfab where bulk slurry was handled.

most closely resembles bulk slurry shown in Fig. 1A (Fig. 2B may possibly contain alumina particles from the slurry shown in Fig. 1C). The isolated observations of single particle and small chain agglomerates may possibly be due to effects of sample preparation or dispersant agents used in the slurry, as those agents are designed specifically to prevent agglomeration. The example images in Fig. 3, from other sampling events in the fab and wastewater treatment area, show agglomerates/aggregates containing the elements of interest where it is more difficult to differentiate from incidental material.

Wipe samples

A total of 14 wipe samples were collected on equipment and surfaces in the fab, subfab, and wastewater treatment area. Silica (as Si) particles with dimensions of 80×80 nm were detected for 10 of the 14 wipe samples collected, with the highest surface concentration detected for a sample collected from the subfab floor where residue material was observed near a slurry drum and slurry delivery system cabinet. Because Si particles less than 100 nm were also detected in the field and media blanks for the wipes, results were blank corrected resulting in Si

Table 2 Summary of surface microvacuum sampling results

#*	Surface sampled	Total surface concentration (all particles)	Size distribution of Si, Al, and/or AlSi particles [†] Percent (%) by size							Surface concentration Si or AlSi <100 nm [‡]
		s/cm ²	% Si and/or Al	% Si	% Al	<100 nm	100–500 nm	500–1000 nm	>1000 nm	s/cm ²
	Wastewater treatment area									
	Access cover to CMP wastewater lift tank									
1	Basic slurry system	117,000,000	98.33	98.33	98.23	0	99.90	0.03	0.06	ND
2	Basic slurry system	7 228 200	100	100	2.05	83.62	14.68	0.34	1.37	6 045 000
3	Acidic slurry system	1 500 000	42.62	42.62	14.75	0	96.15	0	3.85	ND
4	Acidic slurry system	1 134 100	100	100	100	93.48	0	0	6.52	1 060 000
5	Subfab area Rim of slurry drum (alumina)	31 100	83.33	73.81	16.67	54.29	45.71	0	0	14 000
6	Rim of slurry drum (amorphous silica)	27 246 800	99.89	99.89	0	100	0	0	0	27 217 000
7	HEPA vacuum handle/ buttons	5 724 400	100	100	68.73	99.22	0	0	0.78	5 680 000
8	Floor by slurry drum and slurry delivery cabinet	370 000	100	20	80	0	0	20	80	ND
9	Floor by slurry drum and slurry delivery cabinet	1 330 000	100	100	0	0	0	0	100	ND

Note:

*Sample numbers (#) 2, 7, and 8 were collected on MCE filter media; all other microvacuum samples were collected on PC filter media. Sample #s 1, 3, 5, and 6 were collected during surface sampling event 2; sample #s 2, 4, 7, 8, and 9 were collected during surface sampling event 3.

[†]Si, Al, and AlSi particles include some mixed agglomerates with other elements. There were no Si or Al particles detected for 7 of the 11 media and field blanks tested for PC filters. For the other four controls, only one AlSi and/or one Si-containing particle were detected in a size range, based on a counting area of 0.013 mm². For the six media and field blanks tested for the MCE filters, from 0 to 3 Al or Si particles were detected in 0.013 mm² analyzed. No blank corrections were conducted for this evaluation since the average number of structures detected by size was less than one.

[‡]For the MCE filter field and media blanks (*n*=6), no Si or Al structures less than 100 nm were detected. One AlSi structure less than 100 nm (in 0.013 mm² analyzed) was detected for 1 of 11 controls (field and media blanks) tested for the PC filters for a media blank associated with sampling events 1 and 3. However, neither sample from these events contained Si or AlSi particles less than 100 nm so no blank correction was conducted. Surface concentration rounded to nearest thousand; ND=not detected.

^{||}Results based on chemical composition (Si, Al) were adjusted to subtract Si, SiS, and SiCa fibers detected (fibrous morphology not a match for materials of interest).

particles less than 100 nm in 7 of the 14 wipe samples. The surface concentrations estimated for Si particles less than 100 nm are presented in Table 3. Alumina particles (as Al) greater than 100 nm were identified in 12 of the 14 samples. Figure 4 includes two examples of micrographs from wipe samples that illustrate agglomerated (or aggregated) morphology.

Discussion

This study identified cutaneous exposure scenarios at a workplace that used engineered nanoparticles and included preliminary screening of surface contamination using microvacuum and wipe sampling as a means of differentiating from incidental materials and to provide a general idea of particle size,

Table 3 Summary of surface wipe sampling results

#	Surface sampled	Surface concentration Si structures <100 nm	Surface concentration Si structures <100 nm Blank corrected*
		s/cm ²	s/cm ²
1	Wastewater treatment area		
1	Access cover to lift tank, basic slurry system	2 218 760	246 810
2	Access cover to lift tank, basic slurry system	4 785 990	2 814 050
3	Access cover to lift tank, acidic slurry system	4 074 750	2 102 810
4	Handle and rim of bucket used to collect/transfer slurry wastewater	ND	NA
5	Pre-filter housing, basic slurry system	ND	NA
6	Subfab area		
6	Outside surface, door of slurry delivery system cabinet loading amorphous silica slurry	647 860	...
7	Outside surface, door of slurry delivery system cabinet loading alumina slurry	333 270	...
8	Inside surface, door of slurry delivery system cabinet loading amorphous silica slurry	3 277 850	1 305 910
9	HEPA vacuum handle and buttons	ND	NA
10	Rim of slurry drum, amorphous silica slurry	2 407 740	387 555
11	Floor by slurry drum and slurry delivery cabinet	5 028 910	3 008 725
12	Fab area		
12	Outside surface, hatch to slurry cart	1 673 320	...
13	Inside surface, hatch to slurry cart	ND	NA
14	Inside surface, door of CMP tool	2 368 133	347 950

Note: Sample numbers (#) 1, 6–7, and 12–13 were collected during sampling event 1, samples 2–3 and 8–9 during event 2, and samples 4–5, 10–11, and 14 during sampling event 3. ND=not detected; NA=not applicable; '–'=value <0 after blank corrections.

*Surface concentrations for particles less than 100 nm were blank corrected based on an average of 57 Si nanoparticles (0.00065 mm² analyzed) for the field and media blanks (*n*=2) for the wipe media.

agglomeration, and number density. The description of workplace factors and results from evaluating surface contamination can be applied in semiquantitative models for estimating dermal exposure or in risk banding models, along with data on other exposure pathways.

A number density metric was used based on methods adapted from surface sampling for asbestos. While there is no consensus as to the most appropriate exposure metric, and more rigorous methods and statistics would be necessary to improve reliability in particle sizing and number density, these screening-level data provide a frame of reference and allow for relative comparisons. A mass-based metric may be useful as a conservative approach in some

workplaces; however, it provides less value for applications involving ubiquitous materials, such as alumina or silica, which can commonly be found in air, in soil particles tracked indoors, etc. In addition, a mass-based metric does not provide data to evaluate the actual potential dermal exposure or risk (i.e. provides no data on particle size or agglomeration state).

Only a small number of samples (*n*=23 total) were collected due to the preliminary nature of this project and resources required for TEM analysis; results should be regarded as preliminary due to uncertainties with the method application and the small number of samples and controls, particularly the field and media blanks for the commercial wipes

Figure 2 (A) Nanoparticles in surface vacuum sample collected from HEPA vacuum handle/controls in the bulk slurry area of the subfab; EDX: Si (90 wt-%) Ca Cr; size: 79.2×80.6 nm; $\times 40\,000$; (B) Nanoparticles in surface vacuum sample collected from access cover for lift tank in wastewater treatment area (acidic slurry system); EDX: Si Al (90wt-%) Ca Cr Fe; size: 77.7×74.9 nm, 89.5×87.1 nm; $\times 40\,000$ (©CNSE). Image credit: R. Shumate, iATL (Mt Laurel, NJ, USA).

used. Particle counts were determined to estimate surface concentration by number but were calculated based on a counting area of $\leq 0.013\text{ mm}^2$ in conducting TEM analysis and assuming uniform distribution on the grid. Owing to uncertainties and limitations in the methods, the surface sampling results are not intended as quantitative findings but rather a preliminary screening used to inform the

qualitative exposure assessment. While this study could have been expanded to include more robust sampling and analytical methods (e.g. increased samples and grids analyzed, statistical methods in scaling up from the counting area to results reported in square centimeters, etc.), it was determined that the current analysis was adequate for the intended purpose based on the results of the qualitative

Figure 3 (A) Mixed agglomerate/aggregate in surface vacuum sample collected from inside of door to CMP tool in fab during preventive maintenance; EDX: Si (4 wt-%) Mg P S Cl Sn Ca Cr Fe; size: 666×626 nm; $\times 20\,000$; (B) Si Al agglomerate/aggregate in surface vacuum sample collected from access cover for lift tank in wastewater treatment area (acidic slurry system); EDX: Si Al (89 wt-%) Fe; size: 340×414 nm; $\times 40\,000$ (©CNSE). Image credit: R. Shumate, iATL (Mt. Laurel, NJ).

Figure 4 (A) Si Al agglomerate/aggregate in wipe sample collected from access cover for lift tank in wastewater treatment area (basic slurry system); EDX: Si Al (94 wt-%) Ca Fe; size: 1100×700 nm; $\times 50\,000$; (B) Si Al agglomerate/aggregate in wipe sample collected from access cover for mobile slurry delivery cart in fab during CMP tool set-up; EDX: Si Al (97 wt-%) Mg Ca; size: 1300×1200 nm; $\times 40\,000$ (©CNSE). Image credit: R. Shumate, iATL (Mt Laurel, NJ, USA).

assessment and given the inherent uncertainties in these data with the current lack of validated methods for nanoparticles. Optimally, exposure assessments should be tiered with qualitative assessment followed by screening and more robust sampling and analysis methods where warranted; in reality limited sample collection may occur concurrently with the qualitative assessments due to logistical constraints and resources required in conducting workplace field visits and gaining access to restricted areas.

Results from preliminary sampling indicated the potential for single particles or small agglomerates of Si or AlSi less than 100 nm to be present on workplace surfaces or items in areas where CMP slurry or wastewater was handled ($n=5$ of 9 microvacuum samples; seven of fourteen wipe samples). Si- and/or Al-containing particles were detected in all of the surface samples collected ($n=23$); for most samples ($n=18$ of 23), the majority of Si and Al particles were in the less than 100 nm or 100–500 nm size ranges. While Si and Al are ubiquitous, the shape, size, and uniformity of certain particles detected (Fig. 2) appear to match characteristics of materials of interest (nanoparticles in a slurry formulation). In addition, background particle concentrations and potential interferences from incidental materials are expected to be lower in cleanroom areas (fab, subfab). These factors, combined with the sampling strategy and workplace observations, suggest that it is plausible that some Si, Al nanoparticles detected originated from engineered nanoparticles in CMP slurry rather than incidental sources.

In sampling the wastewater lift tank access covers for the copper filtration systems (parallel systems for acidic or basic slurry), no Al and/or Si particles less than 100 nm were detected in either sample collected during the initial sampling event. However, the initial

sample collected from the access cover for the basic slurry system lift tank had the highest total surface concentration by an order of magnitude and contained over 98% Si and Al, with 99.9% in the 100–500 nm size range. In repeat sampling at this location 2 months later, the majority of Si and Al detected (over 80%) was in the less than 100 nm size range. Similarly for the access cover to the acidic slurry system lift tank, Si and Al nanoparticles were detected in the repeat sampling event, with over 90% of the Si and Al detected in the less than 100 nm size range. Not all material and process information was available to evaluate variability, or the impact of previous sampling events in disturbing agglomerates.

Where wipe and microvacuum sample collection methods were used in the same location (i.e. sampling adjacent areas), the surface concentration results from wipe sampling were generally less than those obtained by microvacuum except for the samples of the subfab floor and the access covers to the wastewater lift tank during the second sampling event. The specific impacts of sample collection techniques and TEM sample preparation steps on nanoparticle size and agglomeration state are not currently known. Microvacuum sampling may be a more appropriate collection method if interested in size-resolved measurements (i.e. less disturbance of particles and agglomerates); however, disturbance from wipe sampling protocols may not be dissimilar to cleaning or other workplace contact.

While there are uncertainties and limitations in these methods, the data on elemental composition, size, and morphology were useful in identifying materials of interest and differentiating from incidental nanoparticles, which is particularly important for ubiquitous materials (i.e. Si, Al). For surface concentrations, a relative comparison can be made

among measurements and areas sampled; however, there is currently no direct comparison to what might be considered an acceptable level since surface contamination limits have not been established for nanoparticles (i.e. gaps in data on potential health effects from cutaneous exposure to nanoparticles, etc.). Laboratory and field studies are needed to evaluate and validate methods if surface sampling will be used to assess cutaneous risks from engineered nanomaterials produced or used in occupational environments.

Conclusions

Workers had the potential for incidental contact with slurry containing nanoparticles, CMP process wastewaters, dried residues on workplace surfaces or equipment, or other contaminated items (e.g. used polishing pads from CMP, used filters from wastewater treatment), although the risk of actual skin contact was limited by the use of gloves and other controls at the study site (e.g. HEPA vacuum for wet cleaning). Results from sampling workplace surfaces using microvacuum and wipe collection methods and TEM/EDX analysis indicated the potential for nanoparticles of silica or silica and/or alumina agglomerates to be present on workplace surfaces and equipment where CMP slurry or wastewater was used or processed; however, more rigorous and validated methods are necessary if quantitative results of particle size and number density are desired.

Additional studies are needed to investigate potential adverse health effects from skin contact with nanoparticles, the associated doses, and where such exposures may occur in the workplace, as well as laboratory and field data to evaluate sample collection and analysis methods. Findings from this investigation should be interpreted in the context of emerging research in nanotoxicology and exposure science in order to appropriately evaluate and mitigate risk to workers. While gaps remain in data on workplace exposures and potential health risks, steps to avoid or minimize aerosolization and skin contact continues to be prudent as a precautionary approach.

Disclaimer statements

Contributors MS designed and performed sampling, analyzed and interpreted data, and wrote the paper. SB developed and supervised the project, participated in data collection, and edited the manuscript.

Funding This work was supported by the U.S. Environmental Protection Agency (EPA STAR Fellowship FP-91730701 to MS) and partially funded by the NanoHealth and Safety Center, New York State (to SB).

Conflicts of interest There are no conflicts of interest identified. This paper has not been formally reviewed by the U.S. EPA. The views expressed are the fellow's (MS), and the EPA does not endorse any products or commercial services mentioned in this report.

Ethics approval Not applicable.

Acknowledgements

The authors wish to thank the participating companies at the study site, and acknowledge the contributions of Alan Rossner, Clarkson University, in project discussions and manuscript review. TEM/EDX analysis of surface samples was conducted by iATL (Mt. Laurel, NJ), and bulk slurry characterization by G. Roth, CNSE. Thanks also to Catherine Beaucham and Ken Martinez, formerly on the NIOSH Nanotechnology Field Research Team, for discussions on nanoparticle sampling methods.

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