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Original article

Assessment of Occupational Health Risks for Maintenance Work in Fabrication Facilities: Brief Review and Recommendations

Dong-Uk Park [1,*], Kyung Ehi Zoh [2,3,#], Eun Kyo Jeong [4], Dong-Hee Koh [5], Kyong-Hui Lee [6], Naroo Lee [7], Kwonchul Ha [8]

[1] *Department of Environmental Health, Korea National Open University, Seoul, Republic of Korea*
[2] *Department of Environmental Health, Graduate School of Public Health, Seoul National University, Seoul, Republic of Korea*
[3] *National Cancer Control Institute, National Cancer Center, Goyang, Republic of Korea*
[4] *Department of Industrial Safety and Health, Osan University, Osan, Republic of Korea*
[5] *Department of Occupational and Environmental Medicine, International St. Mary's Hospital, Catholic Kwandong University, Republic of Korea*
[6] *US Army 65th Medical Brigade, Force Health Protection and Preventive Medicine Unit, USA*
[7] *Occupational Safety & Health Research Institute, KOSHA, Ulsan, Republic of Korea*
[8] *Changwon National University, Changwon, Republic of Korea*

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ABSTRACT

Background: This study focuses on assessing occupational risk for the health hazards encountered during maintenance works (MW) in semiconductor fabrication (FAB) facilities.
Objectives: The objectives of this study include: 1) identifying the primary health hazards during MW in semiconductor FAB facilities; 2) reviewing the methods used in evaluating the likelihood and severity of health hazards through occupational health risk assessment (OHRA); and 3) suggesting variables for the categorization of likelihood of exposures to health hazards and the severity of health effects associated with MW in FAB facilities.
Methods: A literature review was undertaken on OHRA methodology and health hazards resulting from MW in FAB facilities. Based on this review, approaches for categorizing the exposure to health hazards and the severity of health effects related to MW were recommended.
Results: Maintenance workers in FAB facilities face exposure to hazards such as debris, machinery entanglement, and airborne particles laden with various chemical components. The level of engineering and administrative control measures is suggested to assess the likelihood of simultaneous chemical and dust exposure. Qualitative key factors for mixed exposure estimation during MW include the presence of safe operational protocols, the use of air-jet machines, the presence and effectiveness of local exhaust ventilation system, chamber post-purge and cooling, and proper respirator use. Using the risk (R) and hazard (H) codes of the Globally Harmonized System alongside carcinogenic, mutagenic, or reprotoxic classifications aid in categorizing health effect severity for OHRA.
Conclusion: Further research is needed to apply our proposed variables in OHRA for MW in FAB facilities and subsequently validate the findings.

1. Introduction

The Republic of Korea Occupational Safety and Health Act mandates that employers and self-employed individuals assess health and safety risks in their workplaces [1]. While occupational risk assessment helps companies adhere to this legal obligation by identifying risks and supporting the safety of workers, the concept primarily addresses the probability of harm or injury from work-related activities and conditions [2]. Occupational health and safety risk is simply a combination of the likelihood of the

Dong-Uk Park: https://orcid.org/0000-0003-3847-7392; Kyung Ehi Zoh: https://orcid.org/0000-0002-2821-070X
* Corresponding author. Department of Environmental Health, Korea National Open University, 86 Daehak-ro, Jongnogu, Seoul 03087, Republic of Korea.
E-mail address: pdw545@gmail.com (D.-U. Park).
# The authors contributed equally to this work as the first author.

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occurrence of a work-related hazardous event or exposure(s) and the severity of injury or illness that could be caused by the event or exposure(s) [3].

Although the foundational principles for occupational risk assessment are well-documented, there is a noticeable absence of specific methodologies tailored for particular operational processes or roles [4]. Specifically, Occupational health risk assessment (OHRA) focuses on acute or long-term exposure to health hazards that could result in chronic illnesses. Exposure to hazardous factors generated in work processes may cause various types of health effects from immediate sensory irritation to chronic diseases, including cancer, in workers many years after exposure [5].

Semiconductor manufacturing (FAB) covers a range of tasks, from maintenance work (MW) including preventive, breakdown, and corrective maintenance in different processes to infrastructure facilities and each task presents unique safety and health risks. Given the diversity of these risks, selecting the most appropriate methods and factors for assessment is a complex undertaking. The Semiconductor Equipment and Materials International (SEMI) standards were developed to provide technical standards for the semiconductor, microelectronics, and related industries. These standards cover a wide range of subjects, including equipment specifications, safety, and best practices specifically tailored for safety risk assessment [6]. Currently, specific guidance for OHRA in semiconductor operations is limited.

This study aims to identify the health hazards faced by maintenance workers in FAB operation facilities through a literature review, to review the methods used in evaluating the likelihood and severity of health hazards through OHRA recommended; and to suggest variables for likelihood of exposures to health hazards and the severity of health effects associated with MW in FAB facilities. Findings from this research can guide general risk assessment (GRA) practices for MW.

2. Methods

2.1. The range and extent of the study

This study focuses on evaluating health hazards tied to MW in FAB facilities. The primary areas covered include the following.

- Focusing on MW in FAB facilities, taking into account that maintenance workers often face greater hazards compared to operators, especially in automated semiconductor setups. The study excludes OHRA pertaining to the cleaning of various parts and machinery that have been detached within the FAB facilities.
- A brief review of potential health hazards maintenance workers might encounter during MW in FAB facilities based on a literature review. To identify health hazards associated with MW in semiconductor fab facilities, search terms like 'health hazards,' 'chemicals,' and 'semiconductor industry' were used both individually and in combination. Of the 35 articles initially found, eight were thoroughly reviewed and summarized [7–14].
- Suggesting factors to estimate the likelihood of exposure to health hazards and the potential harm from MW in the FAB facilities. This study recommends elements for qualitative GRA that can be used to prioritize health risk among MWs in FAB facilities and to select specific MW for site-specific risk assessment. GRAs assess prevalent workplace risks and are ideal for evaluating uniform risks across different tasks or sites [7]. In order to explore suitable OHRA methodologies for MW in FAB facilities, keywords such as 'occupational health risk assessment' and 'manufacturing industry' were employed. An initial screening yielded 20,592 entries. Exclusions were made for OHRA cases specific to workplace scenarios and manuscripts focused solely on occupational safety risk assessment (OSRA) methods. The study was limited to manuscripts that provide guidance or recommendations on OHRA either recommended or developed by governmental or professional organizations. These were then compared based on key attributes of OHRA, such as health hazard and estimation methods.

2.2. Overview of fundamental processes in semiconductor FAB operations

The FAB operations in the semiconductor sector revolve around crafting integrated circuits on silicon wafers. This intricate process involves repeating four main stages: (1) patterning: oxidation, photolithography, etching, and stripping; (2) junction formation: diffusion and ion implantation; (3) deposition: epitaxial or chemical vapor deposition for thin film layering; (4) metallization: sputtering and evaporation [8,9,11,15]. Repeated multiple times, these steps systematically add and remove materials from wafer surfaces to produce integrated circuits [16]. According to the Samsung Economic Research Institute, the trend in Republic of Korea since 2003 has been leaning toward automated 12-inch wafer manufacturing [17]. However, MW within these facilities remains hands-on work and poses distinct health risks.

2.3. Health hazards associated with MW in semiconductor FAB facilities

Based on an extensive review of the literature up to August 2023 focusing on maintenance tasks in such facilities, several key health hazards were identified. Three primary health hazards associated with MW in FAB processes emerged.

- Exposure to dust composed of diverse chemical components: this primarily arises from MW during the removal of residues and debris from machinery and facilities.
- Exposure to chemicals with various components: from hazardous chemicals and gases used in FAB operations or during MW.
- Thermal hazards: found when maintaining high-temperature facilities, like deposition, diffusion, and dry etching chambers.

Maintenance workers in FAB facilities are exposed to a diverse range of health hazards, including a wide array of chemical components associated with their work. While other potential safety risks exist, such as from machinery, electrical issues, and fire hazards, they are generally well-addressed by stringent safety protocols in semiconductor facilities [6]. Semiconductor plants employ comprehensive measures, including process safety management systems and automated controls. Additionally, certain hazards related to ergonomics, mental stress, and working conditions, extremely low frequency-magnetic fields were deemed uniform across all FAB facility MW and thus not detailed further in this study.

2.4. Exploring factors for suitable OHRA methodologies for MW in FAB facilities

Based on an extensive review of the literature, relevant official guidelines, academic articles, and research reports were collected and summarized. Our findings highlighted the review of key factors used in various OHRA methods—ranging from quantitative to semi-quantitative and qualitative—and detailed their unique role of categorization of exposure probability and severity of health effects.

Table 1
Characteristics of fabrication (fab) process and the major health hazards associated with the maintenance tasks for fab facilities.

Major fab process	Fab process characteristics		Health hazards associated with MW for fab facility		
	Process principle	Major chemicals used in the process [6,8,9,11–14,19]	Dust exposure*	Cleaning chemicals	Thermal conditions
Oxidation	Forming a thin, insulating layer of silicon dioxide on a wafer surface at high temperatures (800–1200°C)	Hydrochloric acid, hydrogen, ammonia, boron tribromide, dichloro silane, fluorine, hydrogen chloride, hydrogen fluoride, nitric oxide, nitrogen trifluoride, phosphorus oxychloride, and silane	Yes	Yes	Yes
Photo	Exposing a photosensitive chemical layer (photoresist) on a silicon wafer to UV light	Aliphatic hydrocarbon, gamma-butyrolactone; solvents (acetone and isopropyl alcohol), n-butyl acetate, cresol, cyclohexanone, ethanol, 2-ethoxyethanol, ethyl benzene, ethyl lactate, 2-heptanone (methyl-n-amyl ketone), 1-methoxy-2-propanol (PGME), and 1-methoxy-2-propyl acetate or propylene glycol monomethyl ether acetate	Yes	Yes	No
Dry etching	Removing material from a silicon wafer to create patterns defined by the photoresist mask	Chlorine, boron trichloride, carbon tetrafluoride or sulfur hexafluoride, argon and oxygen, carbon monoxide, carbonyl sulfide, difluoro methane, ethylene, ethylene glycol, hexafluoro-1,3-butadiene, hexafluoroethane, hydrogen bromide, methane, octafluoro cyclobutane, octafluoro cyclopentene, octafluoro propane, and trifluoro methane	Yes	Yes	Yes
Wet etching	Using chemical solutions at room temperature to selectively dissolve material from a silicon wafer	Hydrofluoric acid, potassium hydroxide, phosphoric acid, acetic acid, nitric acid, mixtures of hydrogen peroxide and sulfuric acid, ammonium fluoride, dichloro methane, ethanolamine, and polyethylene glycol	Yes	Yes	No
Chemical mechanical planarization (CMP)	Combined use of chemical reactions and mechanical forces to remove material and achieve a smooth, defect-free surface on a silicon wafer.	Alumina or silica, hydrogen peroxide, potassium hydroxide, ammonium hydroxide, citric acid, surfactants, diborane, dibutyl ether, heavy aromatic solvent, hydrogen, hydrogen chloride, nitrous oxide, propylene, silane, silicon tetrachloride, triethyl borate, trimethyl borate, trimethyl phosphate, tungsten hexafluoride, and tetraethyl orthosilicate	Yes	Yes	No
Diffusion	Introducing impurity atoms into a silicon wafer at elevated temperatures (typically around 900 to 1200°C)	Common dopants; boron, gallium, indium, phosphorus, arsenic, antimony, arsine, boron trifluoride, ethylene glycol, phosphine, and sulfur hexafluoride	Yes	Yes	Yes
Ion implantation	Bombarding a silicon wafer with a beam of desired dopant ions at high energy levels		Yes	Yes	Yes
Metal deposition	Depositing thin layers of metal such as aluminum or copper onto a silicon wafer to form interconnections, typically at elevated temperatures	Variety of precursor gases and the specific metals (Al, Cu, Ti, W, etc.), ammonia, chlorine trifluoride, nitrogen trifluoride, hydrogen fluoride, tetrakis (dimethylamino) titanium (TDMAT), and titanium tetrachloride	Yes	Yes	Yes

* Dust consisting of a diverse range of chemical components.

Table 2
Review of key factors for assessing exposure probability and evaluation of maintenance work application for fabrication (FAB) facilities in OHRA.

Authors	Health hazards covered	Estimation method	Factors to represent exposure potential	Exposure classification	Factors considered for maintenance tasks in FAB facility	References
COSHH (UK, 1998)	Chemicals and dust	Control banding	Physical properties (the dustiness of solids and volatility of liquids)		Dustiness	[23]
			Amount used in an operation or batch process	Three levels (small, medium, and large)	Yes[*]	
			Control approaches	Four levels (general ventilation	Yes	
Crop life (Belgium, 2019)	Chemicals with OES[‡]	Semi-quantitative based on control banding	Exposure level and OES	Four levels (<10% OES, 10−50 % OES, 50−100% OES, >OES)	Applicable to hazards with OES	[27]
	Chemicals without OES		Tentative limit values	Five levels	Applicable to hazards with quantification level	
				Solids in mg/m^3 (1−10, 0.1−1, 0.01−0.1, <0.01 and expert advice		
				Liquids in pMW (5−100, 5−50, 0.5−5, <0.5 & expert advice)		
University of Queensland (Australia, 2011)	Carcinogens, electricity, manual handling, and infected blood	Qualitative	Frequency of interaction with hazards. No further detailed information to classify the frequency	Five levels (very rare, rare, infrequent, frequent, and continuous)	No[†]	[28]
National Research Ins. for Labour Protection (Romania, 1998)	Chemicals, biological, thermal effect, etc.	Semi-quantitative	Probability of consequences/year	Six levels based on quantitative injury occurrence of consequences.	No	[29]
Ministry of Manpower (Singapore, 13)	Chemicals and dust	Semi-quantitative	Exposure rating with weekly exposure level (E) and PEL	Five levels (E/PEL, <0.1, 0.1−<0.5, 0.5−<1.0, 1.0−2.0 and ≥2.0)	Applicable to hazards with OES	[2]
			Exposure index using vapor pressure or particle size, ratio of odor threshold/PEL, hazard control measures, amount used/week and duration of work/week	Five levels categorized semi-quantitatively by factor	Both amounts used and the level of hazard control in MW	
NIOSH (US, 2020)	Chemicals without OES[§]	Semi-quantitative based on control banding	Occupational exposure bands (OEB) or tentative limit values.	Solids in mg/m^3 (>10, >1−10, >0.1−1, >0.01−0.1 and ≤0.01)		[30]
				Liquids in ppm (>100, >10−100, >1−10, >0.1−1 and ≤0.1)	Yes	
Int. Council on Mining & Metals (ICMM, 2009)	Chemicals and dust	Qualitative	OEL exposure band.	Three levels (<0.5 × OES, >0.5−1 × OES, >OES)	Hazards with OES	[31]
KOSHA (Korea, 2012)	Chemicals and dust	Qualitative	If measurements with OEL are available.	Four levels (<10 % OES, 10−50 % OES, 50−100 % OES, >OES)	Hazards with OES	[10]
			If measurements are not available regardless of the presence of OES.	Combination of volatility, dustiness and the amount used per day	Dustiness	
ECETOC TRA (EU, 2012)	Individual chemicals	Semi-quantitative	Concentration (no mixture), PROC, physical Form of the substance, volatility, amount used, work duration and frequency of use, LEV[††], use of personal protective equipment, room size and general ventilation, and dermal exposure controls	Quantitative	Yes	[18]

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Stoffenmanager exposure model (Netherlands, 2008)	Individual chemicals	Semi-quantitative algorithm	Concentration (no mixture), type of activity (mixing, spraying, etc.), product characteristics, dustiness, volatility), amount used, work duration and frequency of use, local exhaust ventilation, and use of personal protective equipment	Quantitative	Yes	[19]
SEMI (2023)	Semiconductor process and equipment	Qualitative	Number of occurrences of harm No specific factors to assess exposure to health hazards	Six levels (frequent, likely, possible, rare, unlikely, and not reasonably foreseeable)	No	[6]

Abbreviations. OHRA: Occupational health risk assessment; COSHH: Control of substances hazardous to health; OES: Occupational exposure standard; MW: Maintenance Work; NIOSH: National Institute for Occupational Safety and Health; KOSHA: Republic of Korea Occupational Safety and Health Agency; ECETOC TRA: European Center for Ecotoxicology and Toxicology of Chemicals Targeted Risk Assessment; LEV: Local exhaust ventilation; SEMI: Semiconductor Equipment and Materials International.

* Yes = Certain factors can be used to assess the likelihood of exposure associated with maintenance work in FAB facilities.

† No = Not applicable for MW exposed to mixed hazards. Specifically tailored for safety risk assessment.

Based on this research, we have proposed specific variables tailored to OHRA methodologies best suited for MW in FAB facilities.

3. Results

3.1. Health hazard identification in MW for FAB facilities: a literature review

Table 1 categorizes the primary health hazards faced by maintenance workers during MW in FAB facilities. During these tasks, workers often encounter exposure to debris, byproducts, and potential machinery entanglements. Standard MW procedures such as brushing, vacuum ventilation, and air jetting aim to remove facility residues. Consequently, workers may be exposed to airborne fine particulate matter consisting of diverse chemical components. In high-temperature processes such as dry etching, diffusion, ion implantation, thin film transistor, and deposition processing, the primary hazards emanate from various fine particulate matters and reactive fumes. Meanwhile, during wet FAB tasks that involve wet etching, chemical mechanical planarization, and photo processing, workers may come into contact with airborne mists and chemical gases. Additionally, workers may occasionally face exposure to isopropyl alcohol or acetone vapors during cleaning activities.

3.2. Characteristics of OHRA: a literature review

While there are quantitative methods that use numeric scales and tools to estimate risks, they are rarely used in occupational health risk evaluations. The European Center for Ecotoxicology and Toxicology of Chemicals Targeted Risk Assessment (ECETOC TRA) and Stoffenmanager exposure models for workers are principally formulated to quantitatively estimate exposure to individual substances [18,19]. These models predict potential worker exposure to airborne chemicals based on physical properties, usage amount, the extent of engineering control, and various task and situational parameters of the substances. Quantitative evaluations weigh factors like exposure duration and health standards [20]. On the other hand, qualitative assessments, which are widely used in workplaces, rely on descriptors or ranking scales and subjective judgment of experts (Table 2) [21,22]. The UK's Health and Safety Executive (HSE) has developed a simple GRA system for identifying suitable control strategies. It is accompanied by guidance sheets demonstrating examples of good practices [23]. Most OHRA focuses on individual chemicals, including dust, yet there are no recommended approaches to assess exposure to mixed hazardous substances.

3.3. Assessing the probability of exposure to health hazards

Table 2 presents variables used for both semi-quantitative and qualitative assessments of the likelihood of exposure to workplace chemicals, including dust, for OHRA. The methods encompass qualitative and semi-quantitative exposure assessments, which measure both exposure levels and chemical quantities. A predominant approach in OHRA involves using quantitative exposure data categorized based on the percentage of levels exceeding the occupational exposure limit to determine health effect probabilities. Factors like engineering controls and physicochemical properties, including vapor pressure, volatility, and dustiness, are suggested to assess the potential exposure to chemicals and dust.

3.4. Assessing severity of health effects from exposure to health hazards

Typically, standard risk (R) phrases and hazard (H) phrases coded under the Globally Harmonized System of Classification and

Labelling of Chemicals (GHS) were used to categorize the severity of health effects from chemical exposures (Table 3). Specifically, chemicals presenting carcinogenic, mutagenic, and reproductive (CMR) hazards are assigned the highest severity level, irrespective of exposure duration or concentration [10,23]. Severity levels of health effects are generally differentiated into the categories of minor (slight health effects), harmful (short-term adverse or reversible health effects), toxic (major, irreversible health effects), and very toxic (major, irreversible health effects, compounded by evidence of CMR). For instance, during MW in diffusion and ion implantation facilities, maintenance workers were reported to be exposed to arsenic [24].

3.5. *Approaches for conducting OHRA in MW at a FAB facility*

Various factors for evaluating the likelihood of exposure to significant health hazards during maintenance work in FAB facilities are summarized (Table 4). The level of engineering and administrative control can be qualitatively assessed by experts to determine exposure probability. The presence and effectiveness of ventilation systems, including movable local exhaust ventilation (LEV), as well as the frequency of air jet use to remove fine dust from FAB facilities and machinery can be qualitatively evaluated. In addition, the average frequency of MW across all FAB processes can help estimate the relative likelihood of exposure to these hazards in

Table 3

Review of essential criteria for evaluating severity categories of health effects and analysis of maintenance work application in fabrication (FAB) facilities for OHRA.[*]

Authors	Health hazards covered	Type of estimation method	Factors representing health effect	Hazard classification	Consideration for maintenance works in FAB facility[*]	Reference
COSHH[‡] (UK, 1998)	Chemicals	Qualitative	Risk (R) phrases[‡]	Six levels (band, A-E & S); A-D: Inhalation of dust and vapor, E: Substances presenting the most serious health effects, including cancer, and S: Harmful by contact with skin and eyes	Yes[*]	[23]
Crop life (Belgium, 2019)	Chemicals	Semi-quantitative	Hazard (H) phrases[‡]	Four levels based on hazard bands (A, B, C, D, and E)	Yes	[27]
University of Queensland (Australia, 2011)	Carcinogens, electricity, manual handling, and infected blood	Qualitative	Outcome of an incident such as human injury, financial cost, work, and environment	Six levels (catastrophic, disastrous, very serious, serious, substantial, and minor)	No[†]	[28]
National Research Ins. For Labour Protection (Romania, 1998)	Chemicals, biological, thermal effect, etc.	Qualitative	Consequences of the action of risk factors on the human body: the level of degree invalidity	Seven levels based on the injury	No	[29]
Ministry of Manpower (Singapore, 13)	Chemicals	Qualitative	Level of carcinogenicity	Five levels of carcinogenicity classification based on organizations like ACGIH, IARC, and NTP (possible, probable, and known)	Yes[*]	[2]
			Hazard rating based on LC_{50}, LD_{50} by acute toxicity	Four levels based on LD_{50} and LC_{50}	Yes[*]	
NIOSH (US, 2020)	Chemicals	Quantitative	Factors supporting quantification of the dose-risk relationships. Point of Departure	Conceptual model that identifies the hazard (source, stressor, and pathways)		[30]
Int. Council on Mining & Metals (ICMM, 2016)	Chemicals	Qualitative	Hazard (H) phrases[†]	Four levels based on hazard or health effect rating (minor, reversible, adverse, and significant and severe)	Yes	[31]
KOSHA (Republic of Korea, 2012)	Chemicals and dust	Qualitative	Hazard (H)/Risk (R) phrases[‡]	Four levels based on hazard or risk phrases		[10]
			OEL and health effect	Four levels based on the combination of OEL and health effect	Yes	
			Classification of CMR	Highest level of severity		
SEMI (2023)	Semiconductor process and	Qualitative	Level of people and equipment/ facility severity group	Four levels (catastrophe, severe, moderate, and minor)	No	[6]

Abbreviations. OHRA: Occupational health risk assessment; COSHH: Control of Substances Hazardous to Health; ACGIH: American Conference of Governmental Industrial Hygienists; IARC: The International Agency for Research on Cancer; NTP: National Toxicology Program, NIOSH: National Institute for Occupational Safety and Health, SEMI: Semiconductor Equipment and Materials International; OEL: Occupational Exposure Limit; CMR: carcinogenic, mutagenic and reprotoxic.

* Yes = Certain factors can be used to assess the likelihood of exposure associated with maintenance work in FAB facilities.

† No = Not applicable for MW exposed to mixed hazards.

‡ Codes used under the Globally Harmonized System of Classification and Labelling of Chemicals (GHS).

Table 4
Various factors * for evaluating the likelihood of exposure to significant health hazards during maintenance work in fabrication(FAB) facilities.

Major health hazards	FAB applied	Factors for semi-quantitative or qualitative exposure assessment
Wet cleaning chemicals	All FAB process	Percentage of exposure level exceeding the occupational exposure standard
		Quantity of cleaning chemicals utilized in each maintenance work.
Airborne dust (mg/m^3)	All FAB process	If gravimetric results are available; tentative level in mg/m^3: <0.01, 0.01−<0.1, 0.1−<1, and >1.
		Subjective observation
Airborne arsenic ($\mu g/m^3$)	Etching, diffusion, deposition, and ion implantation	Exposure level and occupational exposure standard
All chemical and dust hazards	All FAB process	Level of engineering controls: e.g., well controlled, sufficiently controlled, unclear, and no control.
		Level of administrative controls: e.g., well implemented, sufficiently implemented, unclear, and no implementation.
		Exposure probability by subjective assessment: e.g., very low, low, medium, and high.
Extremely low frequency-magnetic field	Etching, diffusion, and ion implantation	Exposure banding with tentative limit values.

specific operations. MW frequency in a particular process is compared to the average MW frequency across different semiconductor processes. Recommended qualitative key factors for mixed exposure estimation during MW include the presence and effectiveness of LEV, chamber post-purge & cooling, and proper respirator use (Table 5). Not only the R and H phrases, but also CMR hazards were recommended for categorizing the severity of health effects from chemical exposures.

4. Discussion

MW in a semiconductor FAB process involves various activities, including maintenance, cleaning, equipment calibration, repair, and sometimes replacement. Given the complexity of semiconductor FAB operations, which employ a wide range of hazardous materials (Table 1) and the high-powered equipment requiring periodic and breakdown MW for operational efficiency and safety, maintenance workers are generally exposed to a range of different hazards rather than a single risk factor. It is challenging in prioritizing the health risks among MW for FAB facilities through the combined impact of these hazards on the likelihood of exposure and severity of health effect. This study discusses the challenges encountered when we assess various factors to estimate the exposure probability and the potential severity of health effects from MW in FAB facilities.

Firstly, an approach for identifying and assessing health risks from combined exposure to major hazards associated with MW across various FAB facilities should be explored. Typically, such methods are utilized to estimate health risks during MW operations within FAB facilities. When performing MW in FAB facilities, which typically operate with a variety of chemicals at high temperatures within enclosed chambers, workers can face several potential health hazards. These include exposure to cleaning chemicals used for MW, thermal burns from hot surfaces or equipment like process chambers, inhalation of fine particulate matter, and residues and reaction byproducts from precursor materials persisting in the FAB facilities (Table 1). Additionally, there is the risk of extremely low frequency-magnetic fields exposure near electric installations and equipment [25]. After identifying health hazards associated with MW for each FAB facility, it is essential to evaluate the level of risk, including estimating the likelihood and severity of potential exposures.

Secondly, several occupational factors for estimating likelihood of exposure to health hazards during MW in FAB facilities should be determined. There are general occupational factors related to the estimation of exposure level, such as the level of airborne measurements, the level of engineering and administrative control measures, working hours, frequency of MW, the volume of chemicals used, workload, etc. (Table 2). Ideally, quantitative exposure measurement can provide one of the best means for estimating exposure levels, if reliable data can be recorded and provided. In many cases, there might be limited or even non-existent exposure levels for specific occupational hazards. Quantitative measurements for health hazards cannot be considered an effective variable for estimating exposure levels, not only due to limited access to FAB cleanrooms, irregular tasks, and unwillingness on the part of the employer, but also to the presence of unknown gaseous and particulate matter without OELs and to sampling and analytical feasibility. Most of the safety and health hazards found in FAB processes do not have OELs and have been found to be below the

Table 5
Examples of factors influencing the level of engineering and administrative controls.

Factors for engineering and administrative controls	Evaluation (score)*
Is the chamber or space opened for maintenance work after undergoing a comprehensive purge process or once the temperature has adequately cooled down?	Yes (1), No (0)
Has local exhaust ventilation been installed?	Yes (1), No (0)
Has the local exhaust ventilation been functioning effectively?	Yes (1), No (0)
Are air jet machines utilized to clear entanglements or dust in FAB facilities?	Yes (1), No (0)
Is a protocol for safe operational procedures available?	Yes (1), No (0)
Are maintenance workers familiar with the safe operational procedures?	Yes (1), No (0)
Are maintenance workers wearing proper respirators?	Yes (1), No (0)
Total	Score

* A qualitative or semi-quantitative assessment (score). The number of qualitative categorization and semi-quantitative score can be determined by evaluators.

limit of detection. In addition, the use of physical properties (dustiness, volatility, molecular weight, etc.) and amount used in an operation can generally not be used not only for MW in FAB facilities where a variety of chemicals with a wide range of properties (solid, liquid, gaseous) are mixed and generated simultaneously [23]. The benefit of estimating exposure probability based on the level of engineering, administrative control, and average MW frequency can be applied to assess exposure to all hazards. It's crucial to establish specific criteria related to the extent of engineering and administrative control measures when estimating exposure probability, either qualitatively or semi-quantitatively (Table 5).

Thirdly, the R and H phrases as categorized by the GHS in conjunction with the health risks of CMR can serve as common metrics to categorize the severity of health effects. Many health hazards encountered by MW workers are associated with chronic health effects. This means that signs of harm may not be immediately apparent and can remain undetected for prolonged periods after exposure. Health hazards from MW can vary based on the type of MW and the specific fabrication facility. Factors contributing to these variations include the specific health hazards, inclusive of chemicals (as detailed in Table 1), their concentrations, handling techniques, compliance with safety protocols, and the use of personal protective equipment. Health risks attributed to potential CMRs can be categorized as the most severe level based on toxicity evaluations.

Finally, our recommended approach for conducting qualitative or semi-quantitative OHRA for MW in FAB facilities (Table 5) facilitates clear communication between management and employees about the risks and corresponding controls related to their work. The types of health hazards generated during MW in fab facilities may differ by type of specific FAB processes and chemicals used (Table 1). The severity of these hazards is assessed by their intrinsic properties. Furthermore, it is recommended that the level of exposure to these hazards be determined based on the level and scope of the engineering and administrative controls the company has in place. This study recommends that the risk associated with MW in a FAB facility can be effectively estimated by jointly considering the severity of the hazards—as categorized in Table 4—and the level of engineering and administrative controls, as recommended in Table 5. It emphasizes straightforward and accessible workplace assessments while ensuring consistency, reliability, and ease of understanding for stakeholders such as employers, employees, and regulatory authorities. Given the similar MW carried out across different FAB process sites within the cleanrooms of semiconductor operations, this study suggests the general application of GRA for assessing health risks from MW in FAB facilities. This encompasses all common hazards in a unified assessment. Our GRA approach for MW in FAB facilities could assist numerous companies, regardless of size, in identifying hazardous agents, assessing associated health risks, and managing them [26].

While this study offers straightforward variables to assess the likelihood of exposure and the severity of health effects related to MW in FAB facilities, it does have some limitations. The assessment of exposure likelihood is based on a semi-quantitative and qualitative evaluation, which may not be as accurate as a fully quantitative assessment. The study also assumes that the frequency of MW and level of control measures are directly proportional to the exposure probability and health risk, which may not always hold true. The determination of the effectiveness of control measures can be subjective and may vary widely across different workplaces, impacting the validity of the conclusions. Nonetheless, this study offers critical factors to consider when conducting OHRA for MW in FAB facilities, providing a guide for OHRA in similar maintenance work environments.

5. Conclusion

This study determines that the likelihood of exposure to hazards associated with MW in FAB facilities can be assessed both semi-quantitatively and qualitatively. Such assessment takes into account the exposure measurements, the existing level of engineering controls, and the quantity of cleaning materials used. The severity of health impacts can be categorized from minor to highly toxic using GHS R and H hazard phrases, with particular emphasis on substances containing CMR hazards. Further research is needed to apply our proposed variables in OHRA for MW in FAB facilities and subsequently validate the findings.

Conflicts of interest

All authors have no conflicts of interest to declare.

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