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Original Article

Chemical Use and Associated Health Concerns in the Semiconductor Manufacturing Industry

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ABSTRACT

Background: Research on the status of many chemicals used in the semiconductor industry is needed. The purpose of this study was to describe the overall status of chemical use in the semiconductor industry in Korea and to examine it from a health perspective.
Methods: Data on the status of chemical use and safety data sheets at 11 of 12 major semiconductor workplaces in Korea were collected. The number of chemical products and chemical constituents, quantities of chemicals, and trade secret ingredients used, as well as the health hazards were examined.
Results: On average, 210 chemical products and 135 chemical constituents were used at the surveyed workplaces. Among all chemical products, 33% (range: 16–56%) contained at least one trade secret ingredient. Most of the trade secret ingredients were used in the photolithography process. Several carcinogens, including sulfuric acid, chromic acid, ethylene oxide, crystalline silica, potassium dichromate, and formaldehyde were also used. Only 29% (39 of 135) of the chemical constituents had occupational exposure limits, and more than 60% had no National Fire Protection Association health, safety, and reactivity ratings. Based on the aforementioned results, this study revealed the following. First, many chemical products and constituents are being used in the semiconductor industry and many products contained trade secret ingredients. Second, many products contained significant amounts of carcinogenic, mutagenic, and reproductive toxicant materials.
Conclusion: We conclude that protecting workers in the semiconductor industry against harm from chemical substances will be difficult, due to widespread use of trade secret ingredients and a lack of hazard information. The findings of the status of chemical use and the health and safety risks in semiconductor industry will contribute to epidemiological studies, safe workplace, and worker health protection.

1. Introduction

The semiconductor industry is considered the most high-tech of all industries, and modern life depends greatly on its products. After the invention of the integrated circuit in 1959, the first commercial silicon-based integrated circuit chips were launched in the early 1960s and their sales grew every year [1]. Their rapid development was explained well by Moore's law and Whang's law which state that chip-computing capability doubles about every 2 years and memory density doubles every year, respectively [2–4]. This high-tech–based industry originated in developed countries such as the United states, Japan, and Europe, migrated globally, and then found a niche in Korea, Taiwan, the Philippines, Malaysia, Vietnam, China, and other Asian countries because of the low wage rate, highly skilled workers, and limited regulations pertaining to the environment and occupational health [5,6].

The semiconductor industry is characterized by very complex processes, several hundred of which are repeat processes, and by

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rapid technological innovation, high secrecy, and large-scale investment to support innovation and mass production, as well as massive chemical use [6–8]. It is clear that this rapidly expanding industry could have detrimental environmental effects, including pollution by manufacturing plants, depletion of raw materials, high electricity consumption, and e-waste [9]. Environmental issues stemming from groundwater contamination by a variety of organic solvents, such as 1,1,1,-trichloroethane and 1,1-dichloroethane, first emerged in Silicon Valley in the USA, followed by in Japan in the 1980s and in Taiwan after the 1990s [9].

In 2015, a Taiwan district court ordered the current owner of RCA Corporation (General Electric, Ltd.) to pay US $18 million to its previous workers and their families because of polluted groundwater [10].

However, although several large epidemiological studies have been carried out, there is no conclusive proof of any health hazards to workers associated with chemical use. Although the necessity for a larger, systemic study of this industry was suggested by the US National Institute for Occupational Safety and Health after its investigation of chemical exposure in a small-scale study in 1979 [11], and a report of worker exposure to a variety of carcinogens and reproductive toxic chemicals by the California Department of Industrial Relations in the US in 1980 [12], no in-depth study was conducted until the late 1990s. Several large-scale epidemiological studies on the relationship between cancers and job history in the US [12–14], as well as investigations by the UK government [15–18] and the Korean government [19], raised concerns but resulted in no clear proof and thus led to calls for more research [8,20].

Occupational health hazard issues include various types of cancer, negative effects on the reproductive system, and systemic poisoning [5,10,21]. Reproductive abnormalities including spontaneous abortion, congenital malformation, and reduced fertility were suggested to have a causal relationship with chemical use, but detailed data are limited. In addition, elevated risks of non-Hodgkin's lymphoma, leukemia, brain tumor, and breast cancer have been reported [8]. A cancer epidemiologic study conducted by the Occupational Safety and Health Research Institute in 2019, followed by 18-year follow-up of six major semiconductor companies in Korea, reported new findings. Female operators employed before 2010 had a significantly higher risk of leukemia, whereas male engineers tended to be higher. Non-Hodgkin's lymphoma was also significantly higher for female operators, especially in the 20-24 age group, employed before 2010. Thyroid cancer, stomach cancer, breast cancer, brain and central nervous system cancer, and kidney cancer also showed an increased relative risk ratio [22].

It is clear that large amounts of chemicals have been used, replaced, and introduced continuously for more efficient and improved production of semiconductors [1,5,6,21,23], such that the cliché “the cleanroom is not clean” may be appropriate for chemical use and the related issue of environmental and occupational disease [20]. Although hundreds of chemical products are used in the workplace, the true extent has yet to be revealed [5]. The semiconductor industry itself also has concerns, leading to the introduction of key environmental priority indicators [24,25], but data about chemical use are very limited. In 2018, the use of chemicals at the one semiconductor industry was reported by our research group, and in 2019, a more detailed description of chemical uses in the photolithography process [23,26] The first study reported that more than 150 chemical constituents were used in more than 450 chemical products, more than 40% of which contained trade secrets and that safety and health information was very limited. In second study, we found that more than 90% of the chemicals in the photolithography process contain trade secrets, safety data sheets (SDSs) provides inadequate safety and health information, and has found that by-products such as benzene and formaldehyde may be produced at the photolithography process; however, no comprehensive study on the use of chemical products in the workplace exists.

In summary, there are many articles, reports, and books on worker health, workplace monitoring, and environmental issues in the semiconductor industry, but no data reflecting real status of chemical use in the industry are available, despite most of the occupational and environmental issues associated with this industry being related to use of chemicals.

Thus, this study aimed to describe the overall status of chemical use in the semiconductor industry. In detail, the goals of this study were to (1) determine the number of chemical products and chemical constituents in use, (2) evaluate the current status of use of trade secret ingredients, and (3) evaluate the high-risk carcinogenic, mutagenic, and reproductive toxicant (CMR) chemicals used in the semiconductor manufacturing industry.

2. Materials and methods

In Korea, there are seven different semiconductor manufacturing companies and five of these have two separate worksites; thus, there are twelve worksites in all. Each workplace has its own environmental health and safety (EHS) team, which is in charge of the health and safety of the workplace, ensured by adhering to EHS policy.

In 2015, on behalf of the Occupational Safety and Health Research Institute Project, we distributed a chemical use survey, in the form of an Excel document (Microsoft Corp., Redmond, WA, USA) for recording product serial numbers and content, chemical names, chemical constituents (name, CAS No., and any trade secret ingredients), chemical physical status, amounts used annually, the manufacturers and vendors of products, and chemical use processes. However, the process information provided was inconsistent among companies and thus was not analyzed in this study. The reason why the classification of chemicals by process is difficult is that companies have different names for the processes and their categories are different. For example, in the fab process, the deposition process is called by various names, for example, chemical vapor deposition, thin film, diffusion, metal, and so on. In package factories, process names are more diverse because of the different packaging styles or large technical gap. In addition, one company did not submit data by process.

Among the twelve workplaces surveyed, one did not submit any information, so the data of only eleven workplaces (92%) were analyzed. For certain chemicals, including liquefied natural gas and gas oil (used as fuel) and detergents (used in an on-site restaurant), some workplaces provided no information, and thus these chemicals are not covered in this study. The research team communicated several times with the EHS team within each company to ascertain the accuracy of the lists of chemicals. The final lists were analyzed, with hazard information including CMR designations first being added.

We classified products as solids, liquids (including paste-type products, such as the many adhesives used in the die-attach process in packaging plants), and gases. The annual amount of chemicals used was calculated based on the product unit (e.g., kg, g, and so on) and yearly usage statistics. If there was no density information available, we assumed that the density was 1, so 1 L was assumed to be 1 kg.

After checking the list and adding the hazard information to the Excel spreadsheet, the characteristics of the chemical products, including the number of products used and their constituents, the number of products containing trade secret ingredients, and amounts of these ingredients, were calculated.

Data were not submitted by the largest semiconductor fabrication worksite in Korea, but data from that company's package factory were available.

3. Results

3.1. Outline of chemical use

The characteristics of the eleven workplaces surveyed in this study are summarized in Table 1. Six of the eleven workplaces were the sites of fabrication processes, where hundreds of steps are involved in the building of electrical structures for conducting electrical signals in small chips. Two workplaces consisted only of an assembly line, where prepatterned chips were singulated, mounted to the board, and tested. At three workplaces, both fabrication and assembly processes were performed.

The overall chemical use data for the semiconductor industry are summarized in Table 2. On average, 210 chemical products were used at the workplaces surveyed in this study. Workplaces that involved both fabrication and assembly processes used the most chemical products (345 ± 147), followed by fabrication-only workplaces (176 ± 74) and assembly-only workplaces (109).

The average number of mixed-material products used was 128 ± 78, whereas the average number of single-material products used was 82 ± 55. One company used 135 ± 35 different chemical constituents. The total amount of chemicals used by Korean semiconductor companies was 247,600 tons per year, with an average of 22,511 ± 27,363 tons used per company per year. Large companies, such as those of workplaces G, H, and J, which produce large numbers of chips, used more than 45,000 tons of chemicals per year.

3.1.1. Trade secrets

As shown in Table 2, chemical products containing at least one trade secret ingredient on average comprised 33 ± 16% of all products used by each workplace (range: 16% to 56%). For example, at workplaces I and K, more than half of the chemical products contained trade secret ingredients, whereas the proportion was less than 20% at workplaces A, E, and F. For workplaces G, H, and J, which are the three largest workplaces, 44%, 39%, and 46%, respectively, of the chemical products used contained trade secrets.

The average proportion of trade secret chemicals, relative to all constituents listed in the SDSs of the chemical products, was 25 ± 8%. For example, company H, which used the largest number of chemical constituents (1,160, counting duplicates) used 363 (31%) trade secret ingredients.

The proportion of chemicals used per year classified as trade secrets varied widely, from 0.02% to 44.2%, but was typically less than 0.7%; this value was exceeded only by workplace I (44.2%) and workplace K (10.8%). Although the proportion was low in most of the workplaces, the average amount of products used containing trade secret ingredients was 175 ± 344 tons per year. As shown in Table 2, the mean number of trade secret ingredients per trade secret-containing product was 2.02 ± 0.23 (range: 1.5 to 2.3). The number of trade secret ingredients per trade secret-containing product varied widely among the workplaces. For example, in workplaces G and H, the highest proportion of trade secret ingredients in a single product was 5 of 7 constituents, whereas in workplace J it was 7 of 8 constituents (data not shown). Some chemical products consisted entirely of trade secret ingredients. For example, at workplace I, 9 of 175 products consisted entirely of trade secret ingredients, followed by 3 products in workplace B, 2 products in workplace G, and 1 product each in workplaces A, C, E, F, and J.

Fig. 1 shows the number of products containing trade secret ingredients by workplace, and Fig. 2 shows the number of trade secret ingredients in products by workplace. As shown in Table 1 and Fig. 1, the larger worksites (G and H) used more chemical products and chemical constituents, including trade secret ingredients. Although there were differences among the companies, the most well-represented trade secret ingredient proportion category was 10–30%, followed by 1–10% (Fig. 1). I addition, at worksites G, I, and J, more than 25% of products containing trade secret ingredients included such ingredients in proportions exceeding 50%. In total, across all workplaces, 102 of 796 products containing at least one trade secret ingredient (12.8%) contained such ingredients in proportions exceeding 50%.

Fig. 2 shows a similar pattern of results to Fig. 1, albeit that the x-axis scale was larger. As shown in Fig. 2, trade secret ingredients were typically present in proportions of 1–10% or 10–30% but also in proportions <1% and >50%. For example, in workplace G, 182 of 345 trade secret ingredients (52.8%) were present in products in proportions of 1–10%, whereas 105 (30.4%) were present in proportions of 10–30%, 23 (6.7%) in proportions of less than 1%, and 11 (3.2%) in proportions of more than 50%.

The major categories of trade secret substances used in the semiconductor industry are summarized in Table 3. The most well-represented category of trade secret ingredient was resins (29.5%), followed by the “trade secret” category (12.8%), photo-related

Table 1
Characteristics of the surveyed semiconductor workplaces

Workplace	Main process	No. of workers	Main products
A	Fab	1,190	CMOS image sensor, RF-COMOS, etc.
B	Fab	743	Mixed signal, CMOS image sensor, RF-COMOS, ASIC, etc.
C	Fab	770	LDI, Timing controller
D	Fab	2,300	LDI, Timing controller
E	Fab	1,488	Power MOSFET[5)]
F	Fab	606	Power MOSFET, IGBT[6)]
G	Fab/assembly	12,975	DRAM[1)], NAND flash memory, etc.
H	Fab/assembly	6,800	LDI[2)], CMOS[3)] image sensor, etc.
I	Fab/assembly	3,521	Bumping, Packaging, etc.
J	Assembly	4,500	Saw, Attach, Bond, etc.
K	Assembly	1,681	Saw, Attach, Bond, etc.

1 Fab, fabrication; DRAM, dynamic random access memory; LDI, LCD driver IC; CMOS, complementary metal-oxide semiconductor; ASIC, application-specific integrated circuit; MOSFET, metal-oxide semiconductor FET; IGBT, insulated gate bipolar transistor; IC, integrated circuit.

Table 2
Numbers and amounts of chemical products used, and use of trade secret ingredients, in the surveyed workplaces

Workplace	Main process	No. of chemical products used					Amount of chemical used, tons/y	No. of products containing trade secrets (%)[§]	No. of trade secrets[‖] (%)[¶]	Amount of trade secret products used, ton/y (%)[#]
		Total	Single-substance products[*]	Mixed products[†]	Constituent chemicals (duplicates included)	Constituent chemicals (duplicates removed)[‡]				
A	Fab	206	133	73	357	120	5,037	28 (14)	53 (15)	9.3 (0.18)
B	Fab	302	126	176	730	198	6148	95 (31)	196 (27)	26.0 (0.42)
C	Fab	104	46	58	238	104	31,119	23 (22)	48 (20)	7.5 (0.02)
D	Fab	163	79	84	356	99	7,858	47 (29)	92 (26)	51.6 (0.66)
E	Fab	106	45	61	240	99	4,310	17 (16)	35 (15)	23.3 (0.54)
F	Fab	177	68	109	390	152	10,702	28 (16)	40 (10)	20.3 (019)
G	Fab/assembly	428	158	270	1136	189	46,850	186 (43)	345 (30)	126.0 (0.27)
H	Fab/assembly	432	169	263	1160	157	45,628	168 (39)	363 (31)	122.9 (0.27)
I	Fab/Assembly	175	32	142	622	147	2,659	97 (55)	223 (36)	1,174.5 (44.17)
J	Assembly	144	29	115	504	142	86,895	66 (46)	150 (30)	324.6 (0.37)
K	Assembly	73	14	59	265	74	412	41 (56)	82 (31)	44.3 (10.77)
Mean ± SD		210 ± 124	82 ± 55	128 ± 78	545 ± 336	135 ± 39	22,511±27,363	72 ± 59 (33 ± 16)	148 ± 120 (25 ± 8)	175.5 ± 344.0 (5.26 ± 13.28)

* Single-substance products: chemical products consisting of only a single constituent.
† Mixed products: chemical products consisting of two or more constituents.
‡ Chemical constituents contained in several products, counted only once.
§ Percentage of chemical products containing at least one trade secret ingredient among the constituent chemicals.
‖ Number of trade secret ingredients listed in the material safety data sheets of chemical products.
¶ Percentage of constituent chemicals classed as trade secrets.
\# Percentage of all products used containing trade secret ingredients.

compounds (11.3%), additives (10.7%), polymers (5.6%), and surfactants (4.1%). In some categories, subcategories could be derived.

3.1.2. Classification of chemicals as solids, liquids, and gases

Table 4 shows the number of products, number of chemical constituents (including duplicates), and annual usage amounts for solids, liquids, and gases by workplace. As shown in the table, liquids were used most frequently, followed by gases and solids. The workplaces used an average of 10,495 ± 16,862 tons (range: 241–44,371 tons) of liquids, in 130 ± 75 products (range: 52–280 products). A mean of 60 ± 57 and 20 ± 18 gas and solid products were used, respectively. As stated in the footnote of Table 4, the data varied in accordance with whether or not nitrogen gas was included in the reported gas use amounts.

3.1.3. Carcinogenic, mutagenic, and reprotoxic substances

Table 5 shows the number of products including CMRs, and the number of constituents in each CMR category used by the surveyed workplaces. As shown in Table 5, the most well-represented category with respect to both products and constituents was carcinogens, followed by reproductive toxins and mutagens. Typically, carcinogen-containing products were classified into Korean Ministry of Employment and Labor (KMOEL) carcinogen group 1 or 2B, but not 2A. Only a few products containing mutagenic substances were listed; none were classified into KMOEL mutagen group 1A, and only a small number belonged to group 1B or 2, across five workplaces. There were fewer reproductive toxicants than carcinogenic substances, but more reproductive toxicants than mutagenic substances; KMOEL reproductive toxicant groups 1A, 1B, and 2 were all represented.

3.1.4. Listed chemicals with occupational exposure limits and National Fire Protection Association (NFPA) ratings

Fig. 3 presents the number of constituents with occupational exposure limits (OELs) among the chemical constituents used in each workplace. On average, only 29% of the chemical substances listed by the workplaces had OELs, indicating that many chemical substances without OELs are being used. For example, in workplace A, 82 of 206 chemical products (40%) contained at least one chemical constituent having OELs, whereas only 39 of the 120 chemical constituents (33%) had OELs.

Fig. 4 shows the number of chemical products having a National Fire Protection Association (NFPA) classification. As shown in Fig. 4, a number of the substances used in the surveyed workplaces have no hazard rating for the health and inflammability categories, whereas in the reactivity category considerably fewer substances had a rating versus those who did not. In the health category, an average of 62 ± 8% of the chemical constituents used by the workplaces did not have a rating, versus 77 ± 6% and 87 ± 4% in the safety and reactivity categories, respectively.

4. Discussion

The purpose of this study, which describes the status chemical use and its safety and health information in semiconductor companies, was well achieved by analyzing the data provided by eleven Korean semiconductor workplaces. This is the first article to review the use of chemicals at various semiconductor companies, although there are limitations as described later in the discussion.

The workers detailed in Table 1 are employees on the company payroll; numerous contract workers were not included in our analysis due to a lack of information. Most of the companies hired numerous contract workers. The products and numbers of employees detailed in Table 1 could change due to the rapid evolution

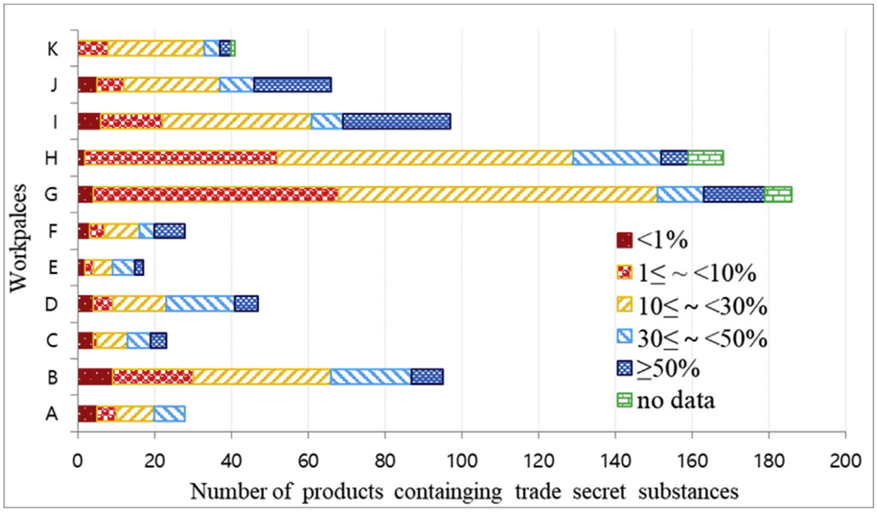

Fig. 1. Number of products containing trade secret ingredients by workplace and the proportions (%) in which trade secret ingredients are presents.

of technology and market demand. As shown in Table 2 and its explanation in the result, the semiconductor companies were more likely to use chemicals as part of a mixture rather than as single materials. The SDS of these chemical mixtures is likely to be less accurate than the SDS of a single substance. The SDS of these chemical mixture products is likely to be less accurate than the SDS of a single substance. The reason is that when the chemical constituents are mixed, the information on the mixing chemicals characteristics might be varied, whereas most of the SDS of the composite material is made mainly by the safety and health information of a single chemical substance.

It is unclear why the percentage of products containing trade secrets varied from company to company (14~56%). However, in Table 2, the percentages of trade secrets of small companies (A, C, D, E, F) which have fewer chemicals are generally lower (average 19.4%) than those with large Fab processes (B, 31%). We assume that small companies produce lower graded chips rather than the state of the art chips. In other words, in the fab process, most trade secrets are used in the photolithography process, but low-grade chips do not need lots of trade secrets. On the other hand, the companies with both Fab and assembly (G, H, I) are large and produce state of the art chips with high percentage of trade secrets (average 46%). It is presumed that the companies with only an assembly process (J, K) has a molding process that uses chemicals with a lot of trade secrets (average 51%).

The exact chemical names of trade secret substances were not provided; categories or generic names were given. For example, in the resin category, ingredients labeled as "phenol resin" were most common, followed by the labels of "resin," "acrylic resin," "epoxy resin," "novolac resin," "polyhydroxystyrene resin," and "polyester resin." Likewise, ingredients related to the photolithography process could be subclassified into photoactive, photogenerator, photosensitizer, and thermal acid generator ingredients, as shown in Table 3. In the category of polymers, the subcategories were polymer, acrylic monomer, aromatic polymer, styrene-vinyl phenol copolymer, and polyamine polymer. Epoxy resin is a solid used mainly as an epoxy molding compound pellet during the molding process in packaging plants. Novolac resin and acrylic resin are classified as liquids, and are mainly used for photolithography, and in small amounts for etching. Phenol resin, was used in liquid form by some workplaces, in the molding and photolithography processes.

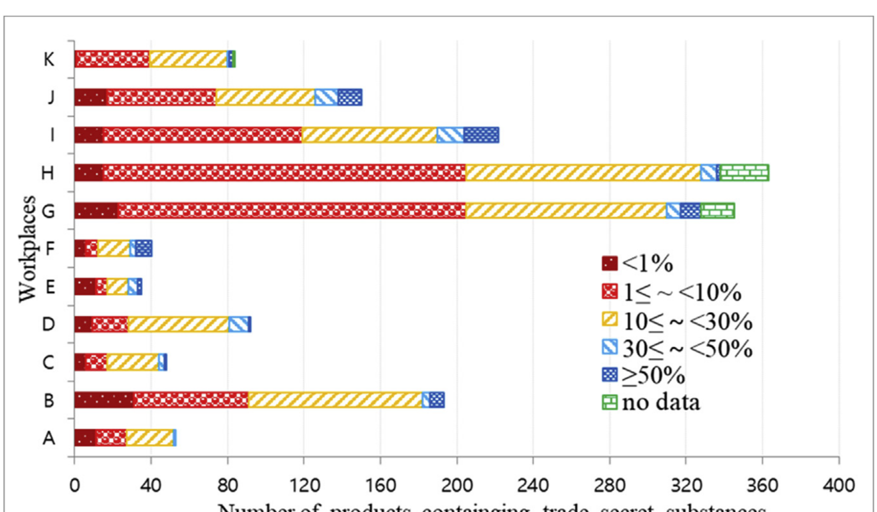

Fig. 2. Number of trade secret ingredients in chemical products by workplace and the proportions (%) in which individual trade secret substances are present.

Table 3
Frequently listed trade secret ingredients in the surveyed workplaces

Trade secret ingredient	Number	Trade secret ingredient	Number
Resins	480 (29.5%)	Polymer	91 (5.6%)
Phenol resin	(113)	Polymer	(41)
Resin	(107)	Acrylic monomer	(19)
Acrylic resin	(94)	Aromatic polymer	(18)
Epoxy resin	(85)	Styrene-vinylphenol copolymer	(8)
Novolac resin	(52)	Polyamine polymer	(5)
Polyhydroxystryrene resin	(20)	Surfactant	66 (4.1%)
Polyester resin	(9)	Organic acid	30
Trade secret	209 (12.8%)	Pigment	24
Photo-related compound	185 (11.3%)	Aromatic sulfur compound	18
Photoactive compound	(73)	Amine	17
Photogenerator	(64)	Aluminum compound	12
Photosensitizer	(36)	Organic compound	11
Thermal acid generator	(12)	Amidomethyl ether cross-linker	10
Additive	4 (10.7%)	Hardener	10
		Trisphenol derivative	10
		Others	282
Total			1,629

The number of trade secret ingredients in each category in Table 2 could be underestimated; for example, most ingredients classified as polymers seemed to be types of resins, whereas the opposite could also be true because synthetic resins are mostly polymers. In addition, trade secret ingredients listed as photo-related compounds might also have been polymers. Underestimation of the number of trade secret ingredients in a given category could also have occurred because many such ingredients were simply classified as a “trade secret” (12.8%) or “additive” (10.7%). In addition, some ingredients could be included in more than one category. For example, many amidomethyl ether cross-linker, hardener, and trisphenol derivative ingredients could also be included in the polymer, resin, and photo-related compound categories. However, in this study, we only categorized the trade secret ingredients in accordance with their names as listed in the SDSs.

Describing a constituent as a “trade secret” or “additive” is not illegal, but by doing so no health and safety information can be obtained, while categorizing constituents as polymers, resins, or surfactants allows basic health and safety information to be derived. In Korea, the Occupational Safety and Health Act requires that hazard information be provided in SDSs even for trade secret ingredients. Nevertheless, in this study it was not always straightforward to determine whether hazard information for such ingredients was included in the SDSs. Until now, even if a manufacturer or importer falsified information about trade secrets, there was no effective way for the government to impose sanctions or for the user to verify whether information on SDS was true or not. In Korea, however, two large semiconductors have self-verified whether several CMR constituents were contained in some chemical products which were listed in the SDSs. The revised Korean Occupational Safety and Health Act, which was effected from January 1, 2020, has introduced a preapproval system to overcome the incompleteness of safety and health information on trade secrets. Therefore, a chemical manufacturer or importer should submit to the Ministry of Employment and Labor the hazards of the constituents to keep the constituent of the chemical product a trade secret. If it is determined that there is no hazard, the alternative name and alternative content of that constituent could be used. In the past, trade secrets could be assigned by the manufacturer or importer without any examination or preparation.

In Table 5, the reproductive toxicant and mutagen classifications of Korean Ministry of Employment and Labor are used, where these are very similar to those of the classification, labeling and packaging of substances and mixtures of EU Registration, Evaluation, Authorization and Restriction of Chemicals.

As shown in the third column of Table 5, several carcinogens were used in the surveyed workplaces. Among the group 1 carcinogens, as classified by the International Agency for Research on Cancer, sulfuric acid was used in all workplaces, chromic acid (CAS No. 1330-82-0) in three workplaces, ethylene oxide (CAS No.75-21-8) and silica (crystalline quartz, 14808-60-7) in two workplaces, and potassium dichromate (CAS No. 7778-50-9) and formaldehyde (CAS No. 50-00-0) in one workplace. Among the group 2B carcinogens, diborane (19287-45-7) was used in eight workplaces, followed by carbon black (1333-86-4) in seven workplaces, 1,4-dioxane (123-91-1) and pyrocatechol (120-80-9) in six workplaces, antimony trioxide (1309-64-4) and methyl isobutyl ketone (108-10-1) in four workplaces, ethylbenzene (100-41-4), diethanolamine (111-42-2) and titanium dioxide (13463-67-7) in three workplaces, lead (7439-92-1), dichloromethane (75-09-2), and naphthalene (91-20-3) in two workplaces, and alpha-methyl styrene (98-83-9), 1,2-benzenediol (120-80-9), nitrilotriacetic acid (139-13-9), and cumene (98-82-8) in one workplace.

Chemicals classified by Korean Ministry of Employment and Labor as mutagenic to reproductive cells included ethylene oxide (CAS No, 75-21-8) in group 1B, and hydroquinone (CAS No. 123-31-9), phenol (CAS No. 108-95-2), and N-butyl glycidyl ether (CAS No. 2426-08-6) in group 2.

The group 1A reproductive toxicants included carbon monoxide (CAS No. 600-08-0) and lead (CAS No. 7439-92-1), and the group 1B reproductive toxicants were 2-ethoxyethanol (CAS No, 110-80-5), 2-methoxyethanol (CAS No, 109-86-4), ethyl cellosolve acetate (CAS No. 111-15-9), N,N-dimethylacetamide (CAS No, 127-19-5), and sodium tetraborate (CAS No. 1303-96-4); the group 2 reproductive toxicants included toluene (CAS No. 108-88-3), cyclohexylamine (CAS No. 108-91-8), and hexane (CAS No. 110-54-3).

OELs were established to protect workers from chemical exposure. Without OELs, it would be difficult to assess exposure levels. Therefore, OELs are very important for safe management of chemicals in the workplace. The first OELs in Korea was introduced

Table 4
Classification of chemical products used by the surveyed workplaces: solids, liquids, and gases

Workplace	Solid phase			Liquid phase			Gas phase			Total		
	No. of products	No. of constituents including duplicates	Use/year (tons)	No. of products	No. of constituents including duplicates	Use/year (tons)	No. of products	No. of constituents including duplicates	Use/year (tons)*	No. of products	No. of constituents including duplicates	Amount use/year (ton)
A	7	7	8	125	254	4,755	74	96	274	206	357	5,037
B	43	45	1,465	206	613	4,681	53	72	2	302	730	6,148
C	4	8	<1	62	181	1,148	38	49	29,971	104	238	31,119
D	3	3	<1	98	275	7,631	62	78	227	163	356	7,858
E	0	0	0	63	180	3,405	43	60	905	106	240	4,310
FI	19	51	292	105	266	1,132	53	73	9,277	177	390	10,702
G	25	119	1,163	221	781	44,371	182	236	1,317	428	1,136	46,850
H	11	49	40	280	931	44,284	141	180	1,303	432	1,160	45,628
I	35	166	145	140	456	2,514	0	0	0	175	622	2,659
J	55	164	6,891	80	327	1,281	9	13	78,724	144	504	86,895
K	21	90	170	52	175	241	0	0	0	73	265	412
Sum	223	702	10,174	1,432	4,439	115,443	655	857	122,001	2,310	5,998	247,618
Mean	20	64	925	130	404	10,495	60	78	11,091	210	545	22,511
SD	18	63	2,042	75	261	16,862	57	73	24,152	124	336	27,363

* The amount of gaseous material used varied depending on whether or not nitrogen was included in the reported gas use amounts. For example, worksites A, C, F, and J reported using 145, 27,429, 8,957, and 78,716 tons of nitrogen, respectively, whereas sites G and H reported using only 0.3 tons of nitrogen. Workplaces I and K, belonging to the same company, did not report any use of gaseous substances.

in 1986, which was similar to the American Conference of Governmental Industrial Hygienists (ACGIH) TLV. Since then, it has been revised 16 times, most recently in January 2020, with about 700 chemical OELs and three physical agents (noise, heat stress, and radon). However, unlike ACGIH, notice of intended change is not made in advance systematically, but if there is a need for revision, a professional review, notification of revision, and final notice are made. In Korea, workplace exposure is assessed twice a year in accordance with OELs.

As shown in Fig. 3, the absence of OELs means that management is difficult. This exacerbates the difficulties associated with chemical management in the semiconductor industry.

The NFPA classification is displayed as a diamond symbol, to facilitate rapid responses in an emergency, where the diamond is composed of health, inflammability, reactivity, and “other” categories rated from 0 (no danger) to 4 (very dangerous). Similar to the OELs, the percentage of those without the NFPA index was very high as shown in Fig. 4. In the absence of NFPA data, a facility may not be able to cope with emergency situations. This suggests that responding adequately to chemical spills or other accidents will be difficult in the semiconductor industry.

Although this article provides useful information by analyzing chemicals and safety and health information used in Korea's important semiconductor sites, the following limitations are inevitable. The first is the accuracy of the information provided by each company. The researcher could not confirm the accuracy of the information provided by each individual workplace. The research group, however, has conducted separate chemical database studies at two of these sites, and experience has shown that the data are reliable. Second, the EHS team may not have the most up-to-date information. Owing to the competitiveness of the semiconductor industry, some of the chemicals used can change rapidly. Therefore, the chemical data used at the production site may not match the data of the EHS team. In particular, we guess that the amount of chemicals used might be less accurate due to the difficulty in storage and used chemicals. However, we requested data at the

Table 5
Summary of carcinogens, in accordance with the International Agency for Research on Cancer (IARC), and of mutagens and reproductive toxic chemicals in accordance with the Korean Ministry of Employment and Labor (KMOEL), used in the surveyed workplaces

Workplaces	Number of carcinogens (Groups 1/2A/2B)[a]		Number of mutagens (Groups 1A/1B/2)[b]		Number of reproductive toxic chemicals (Groups 1A/1B/2)[c]	
	In products	Constituents without duplicates	In products	Constituents without duplicates	In products	Constituents without duplicates
A	4/0/9	1/0/5	0/0/1	0/0/1	1/4/2	1/1/1
B	16/0/15	4/0/7	0/0/0	0/0/0	1/5/2	1/2/2
C	3/0/7	2/0/5	0/0/0	0/0/0	0/0/2	0/0/1
D	1/0/14	1/0/5	0/0/0	0/0/0	1/3/2	1/2/1
E	5/0/6	1/0/4	0/0/1	0/0/1	1/0/0	1/0/0
F	10/0/22	4/0/9	0/1/0	0/1/0	3/4/0	1/3/0
G	18/0/29	1/0/4	0/0/0	0/0/0	2/9/3	1/3/1
H	5/0/23	1/0/5	0/0/0	0/0/0	1/10/1	1/2/1
I	7/0/25	2/0/6	0/0/0	0/0/0	2/0/0	1/0/0
J	2/0/22	2/0/3	0/0/2	0/0/2	0/0/0	0/0/0
K	4/0/15	2/0/1	0/1/0	0/1/0	0/0/0	0/0/0

[a], [c]: IARC classification, [b]: Korean Ministry of Labor and Employment (KMOEL) classification.

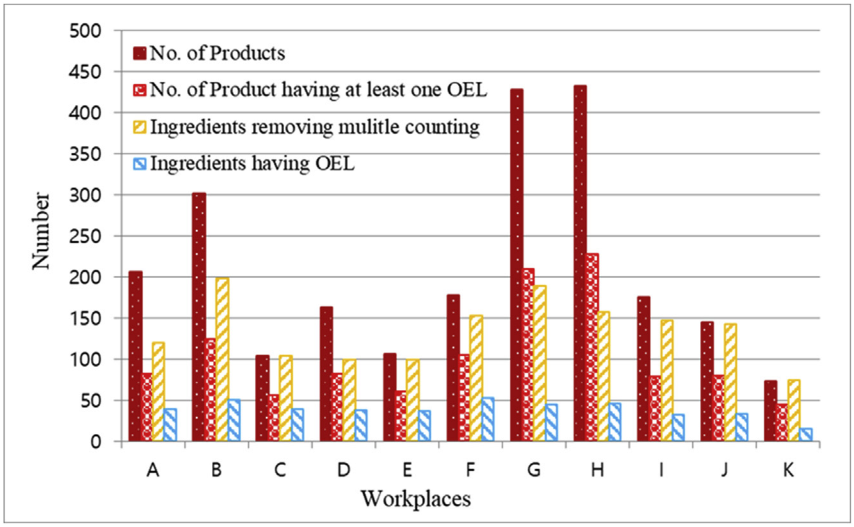

Fig. 3. Number of chemical products and constituents having occupational exposure limits (OELs), as set by the American Conference of Governmental Industrial Hygienists (ACGIH).

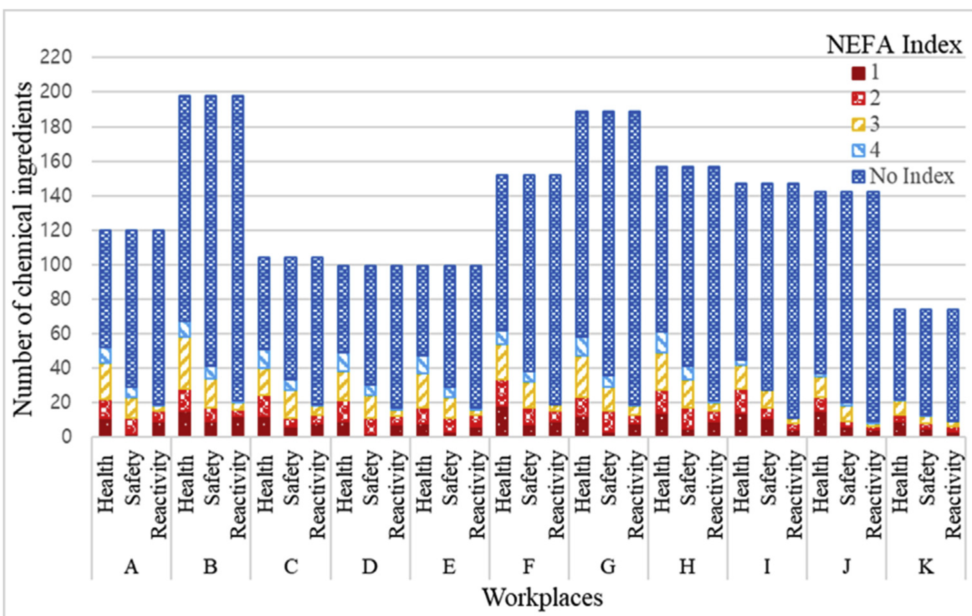

Fig. 4. The National Fire Protection Association (NFPA) health, safety, and reactivity ratings of the chemical constituents used by the surveyed workplaces.

same time in 2015 and received the latest information available at the same time. Finally, one of Korea's largest semiconductor companies did not submit chemical database and was not included in this study. We received one of the company's workplaces but did not get another one. Despite these shortcomings, it is valuable to know the status of chemical use and safety and health information, including most of the workplaces in Korea, an advanced semiconductor country.

In summary, this study found that many chemical products and constituents are used by the semiconductor industry, and further that it is will difficult to ensure the health of workers owing to widespread use of trade secret ingredients and a lack of hazard information. The abundance of CMR toxicants and absence of OELs and NFPA ratings are further barriers to the safe use of chemicals. The semiconductor industry is expected to continue to thrive but damage to the health of workers and the environment should be prevented. Therefore, efforts to reduce the risks associated with use of chemical substances in the semiconductor industry must be applied continuously. In this study, the use of chemicals in almost semiconductor workplaces in Korea has been identified. In addition, analyzing the safety and health risks of chemicals can contribute to a healthier and safer semiconductor industry in the future.

Conflict of interest

The authors declare they have no actual or potential competing financial interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.shaw.2020.04.005.

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