

Much Concern but Little Research on Semiconductor Occupational Health Issues

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Emerging occupational and environmental issues in the semiconductor industry

We humans have experienced historical lessons on the dangers of introducing new techniques and chemicals expecting benefits, while ignoring unexpected harmful side effects. Examples include untreatable diseases (mesothelioma, lung cancer, and asbestosis) caused by asbestos use, human nervous system defects due to pesticides used to increase crop yields, severe health issues due to DDT used to kill malaria-causing mosquitos, and the depletion of the ozone due to Freon use for refrigeration.

The semiconductor industry, a microelectronics industry, emerged in the late twentieth century as a brilliant contributor to industrial development, the development of new techniques, increased scientific knowledge, and an advance in human life styles throughout the world. The dark side of this prosperous industry has become apparent in both environmental and occupational health issues since the 1980s in the US and the 1990s in the UK, and in Asian countries including Taiwan, Singapore, and Korea in the 2000s.

Environmental health issues occurred in the 1980s in Silicon Valley, where Fairchild and IBM were blamed for contaminating ground water with the organic solvents, 1,1,1-trichloroethane and 1,1-dichloroethane. A similar series of events occurred in Japan in the 1980s and 1990s and in Taiwan in the 2000s that provoked resident outrage. In all cases, the companies initially denied that they had caused environmental pollution, and governments refused to release the results to the public.

Occupational health issues have emerged since the 1980s in the Silicon Valley in the US and at National Semiconductor in Greenock in the UK, where retired workers filed lawsuits against IBM, National Semiconductor, and other companies due to increased incidences of cancers, birth defects, and other chronic diseases. The first data that highlighted the unexpected high illness rates in the semiconductor industry, four times higher than that in other industries, were drawn from the Silicon Valley in California in the early 1980s. There were no data on a definitive medical diagnosis, but about 47% of cases were attributed to "systemic poisoning", which indicated a poor work environment (1).

Because of the number of lawsuits and concerns, several epidemiological studies were performed, most of which were inconclusive. In 2001, the US Semiconductor Industry Association and the UK government published separate reports on cancer risk among chip production workers, raising concerns about the chemically rich working environment, but no conclusive proof was forthcoming.

The large companies responded in two ways. First, they tried to produce scientific evidence that proved a lack of causal relationship between the hundreds of cases of cancer and the work environment. Second, they sponsored several epidemiological studies and sometimes blocked the publication of reports that were unfavorable to the companies (2). For example, in 2004, the so-called Clapp-Johnson paper, which presented an analysis of mortality records for 32,000 IBM employees over 32 yr that showed significantly higher death rates due to several different types of cancer, was scheduled to be published in the journal *Clinics in Occupational and Environmental Medicine*, but the publisher, Elsevier, refused to publish it. At that time, a guest editor and many contributors said that Elsevier had bowed to pressure from IBM not to publish the report. Seven of nine contributors to the next volume boycotted the journal and refused to allow it to publish their research (3). On the other hand, the large companies tried to improve the work environment continuously by adapting global standards, replacing chemicals, installing real-time monitoring instruments in the workplace, and developing safe working procedures, all of which could be used as counter-evidence that the former working environments were unsafe.

A huge controversy still surrounds environmental and occupational health issues in the semiconductor industry throughout the world because of the lack of sufficient hard data. The semiconductor industry has several characteristics that make it difficult to identify imminent occupational health issues. First, the semiconductor industry can hide the occupational health issues under the secrecy umbrella in the name of protecting state-of-the-art technology. Second, the technology of the semiconductor industry moves so rapidly that new materials and pro-

cesses replace old ones before sufficient information is obtained on health hazards (1). Third, the rate of change toward new techniques and applications is so fast that legal enforcement cannot ensure that both the outdoor environment and the workplace are kept safe. Fourth, as critics say, the huge semiconductor industry has power over the government and society to manipulate inconvenient truths.

Overview of the chip-making process and health hazard-producing agents

The semiconductor manufacturing process begins with sand, which will generate the final product, chips. This process can be explained as three individual steps: wafer manufacturing (ingot process), wafer fabrication (fab process), and packaging and testing (package process). The first ingot process is relatively safe (except when gallium arsenide is used) compared with the second and third process, but few data are available. The fab process consists of hundreds of sub-processes. To create the altered electrical conductivity with pre-designed nano-sized circuits in high-purity silicon, various chemicals, high-energy sources, and equipment are used. The four main steps in the fab process include material deposition, photolithography, etching, and doping, with cleaning between steps. Photolithography uses many chemicals, and ion implantation equipment emits X-rays and arsenic.

Then, each chip on a given wafer must be cut and tested in the packaging process, where many chemicals are also used. Workers can be categorized into two types. The operators, who handle the wafers, are exposed to relatively low concentrations these days. The maintenance workers, however, are responsible for the process and the equipment, so they frequently take apart the equipment and clean the inner parts. Thus, they are likely to be exposed to high concentrations of the various chemicals. Most occupational experts in the semiconductor industry believe that maintenance workers are increasingly exposed and have more health risks, but this does not mean that the operators are safe. Many depositions from former operators indicated that they were heavily exposed because of overwork and equipment breakdown.

In 2009, the present author had an opportunity to investigate several semiconductor companies in Korea and found that, of the 424 chemical ingredients in 509 chemicals used by one company, only 10% were monitored. Besides the raw materials, many unexpected by-products could be emitted because of high-energy plasma, hot temperatures, UV, and ion sources. Particularly plasma, a very high-energy source that can break down a chemical to every possible constituent variable, could cause high exposure to unexpected chemicals. Formaldehyde from novorak resin involved in the photo process, arsenic from ion implantation, and ethylene oxide gas from ethylene glycol are known carcinogens that are emitted as by-products. Besides the sever-

al hundred chemicals, nano-material exposure, ionizing radiations such as radiography, and extremely low-frequency radiation could affect workers' health.

The public has misinterpreted the semiconductor industry as a clean occupation because workers appear on TV with white coveralls. The word 'clean' in a clean room has to do with the chip products, not the workers. In the semiconductor industry, "clean" has been defined in terms of the number of small (0.5 μm) particles per cubic foot of air, as these are detrimental to microchips. Workers wear white coveralls and masks to protect the chips from human body products. These coveralls and masks were not designed to protect workers from hazardous material exposure. In the clean rooms, gaseous materials including volatile organic compounds (VOCs) may not be controlled and may even be re-circulated continuously if they are evaporated in the photo-register process or other processes. Workers in clean rooms may be exposed to multiple hazardous agents, which could cause potential adverse health effects. In my view, workers in the Korean semiconductor industry in the 1980s, 1990s, and early 2000s were frequently exposed to higher levels of various kinds of hazardous chemicals, because of frequent leaks and breakdowns in the facilities, compared with workers today.

Major health concerns

Reproductive defects including spontaneous abortions are well-established health effects in the semiconductor industry; ethylene glycol ether (EGE) use in the photolithography process has a dose-response relationship with reproductive defects. This chemical has been blamed for reduced fertility and irregular or increased menstrual cycles among female workers in the US in the 1990s and in Taiwan in the 2000s (4, 5). After these studies, ethylene glycol ether was replaced with propylene glycol monomethyl ether (PGMEA), which is suspected to cause neurotoxicity. Also, maintenance workers involved in the fabrication process suffered from a high risk of restrictive lung abnormality and significantly lower white blood cell counts (6), and the frequency of urinary tract infections was also significantly increased.

The most important health concern in the semiconductor industry is cancer. The incidence (or prevalence) rate and causality of cancer have been hot issues in the semiconductor industry throughout the world since the 1980s. In the semiconductor industry in the Silicon Valley, Taiwan, and the UK, numerous cancer clusters have been found among workers or retired workers. When it was published in 2006, the Clapp-Johnson paper revealed that the proportional mortality ratios (PMR) for all cancers were elevated in both male (PMR = 107; 95% confidence interval = 105-109) and female (PMR = 115; 95% confidence interval = 110-119) workers in the semiconductor industry. The incidence of several specific cancers including brain cancer and other central nervous system cancers, kidney cancer, melanoma of the skin, and pancreatic cancer in male work-

ers and cancer of all lymphatic and hematopoietic tissues in female workers was significantly elevated, but lack of individual exposure information made it difficult to associate the cancer with particular agents (7). After that study, an IBM-supported study reported that cancer mortality was 22% lower in this group than in the general population (8), but some researchers argued this was due to healthy worker effects. The US Semiconductor Industry Association contracted with Vanderbilt University for a study in 2005, and a final report published in 2010 showed that the standardized mortality ratios (SMR) were similar and significantly lower among fabrication and non-fabrication workers due to all causes (0.54 and 0.54) and all cancers (0.74 and 0.72) compared with the general population. However, due to the young average age of this cohort and the associated relatively low numbers of deaths, the authors argued that updates of the comparison between mortality rates in the general population and those in this semiconductor worker cohort were necessary (9).

The UK government conducted two epidemiological studies of National Semiconductor employees in Scotland. The first study found that the incidence of four types of cancer (brain, stomach, breast, and lung cancer) was elevated compared with that in the general population, but only the difference in lung cancer incidence was significant. This study has been criticized due to the small sample size, the possibility of misclassification, and the absence of adjustment for smoking in the case of lung cancer. A later study published in 2010, also with a restricted the sample size, reported similar conclusions (10).

Regarding cancer risk, after reviewing related epidemiological cancer studies most researchers agree that definite conclusions are unclear because of the study designs, data accessibility, and the need for future detailed studies in which the job classification and job exposure are presented in greater detail.

Cases in Korea

A retrospective cohort study was conducted by the Korean Occupational Safety and Health Research Institute from 2009 to 2011. A total of 113,343 workers who died from cancer and 108,443 workers who had cancer were included; all were employed between 1998 and 2008. Most cancer SMRs were low compared with the general population (for example, SMR of leukemia was 0.39 (95% CI, 0.08-1.14) in males, 1.37 (95% CI, 0.55-2.81) in females), but the standardized incidence rate (SIR) of non-Hodgkin's lymphoma (NHL) in female workers (2.31, 95% CI, 1.23-3.95) and thyroid cancer in male workers (2.11, 95% CI, 1.49-2.89) was significantly increased. Considering the very low SMR (0.25 for male (95% CI 0.21-0.29) and 0.66 for female workers (95% CI, 0.55-0.80)), which may reflect healthy worker effects and the short observation period of 7-8 yr, data on other non-significant cancer types such as leukemia should be interpreted very carefully (11).

As in the US and UK, the possibility of occupation-related cancer in Korea emerged because of retired workers' lawsuits. The Korean Workers Compensation & Welfare Service has denied compensation to all 18 applicants since 2007. In 2011, despite this previous denial of compensation by the government, five plaintiffs sued the court to vacate the disposition for the denial of occupational disease approval, and two cases won. However, this is only a very small portion of this huge issue in Korea. A total of 155 cases of various cancers and rare diseases were reported to the Korean NGO group SHARPS (Supporters for Health And Rights of People in the Semiconductor Industry) by microelectronics retired workers and employees over several years. In the semiconductor industry, a total of 96 cases were reported in recent years, and 34 of them were died. Most of the cancers (15 of 32 cases) were hematopoietic cancers, including leukemia and lymphoma. But all the semiconductor industries in Korea have denied any causal relationship between the working environment and the diseases (12).

It is clear that the current working environment has improved compared with the conditions in the 1980s or 1990s. However, maintenance workers should be considered as a high-risk group and operators as a vulnerable group because they include young females. The semiconductor industry in Korea should keep in mind that workers' health could be affected adversely by the many hazardous chemical and physical agents in the fabrication and packaging process.

Unacknowledged sick workers in the semiconductor industry

Until now, most research conducted in many countries has not drawn definitive conclusions about the causal relationship between occupational exposure and the various types of cancer, and arguments still continue. As seen with IBM and Korea, there has been a high incidence of disease including cancers and reproductive defects (in Korea, reproductive issues are not well reported), although we do not know enough about the levels of exposure and the specific agent(s) involved. The first common response of manufacturers regarding the cancer outbreaks in the semiconductor industry has been to follow every legal requirement and ensure that the concentration of chemicals was lower than the occupational exposure limits. They have overlooked, or have tried to hide, the fact that short-term exposure could increase during maintenance work or breakdowns and that many by-products could be emitted during both the fabrication and packaging processes. Because of secrecy, rapid change, and the relatively short history, even experts do not know exactly how dangerous these conditions are. All epidemiological studies highlight the shortcoming of insufficient information about exposure.

SUGGESTION

The semiconductor industry is a new industry that developed in the late twentieth century, and the paucity of scientific evidence on occupational health and environmental issues exists in part because of the short history. The effects of many unknown constituents in chemicals have not been investigated yet due to the protective umbrella of corporate secrecy.

The Korean semiconductor industries have been confronted with several occupational issues. The first was the outbreak of cancer due to past exposure, though the companies deny a causal relationship between exposure and disease. Individual cases were considered unrelated to working conditions, but over 150 clustered cases have been reported from retired and current workers to an NGO group. The second issue is to identify the risks and protect workers' health in the face of numerous potentially hazardous conditions and agents.

We must distinguish among various occupational diseases in the semiconductor industry. To prevent cancer in both operators and maintenance workers and reproductive toxicity in female operators, more research and sophisticated preventive controls should be implemented. As we all know, the semiconductor industry stands on the cutting edge of technology, science, and knowledge. This cutting edge should also apply to protect workers' health and their environment. I hope that the semiconductor industry, government, researchers, NGOs, and workers will cooperate to generate sounder and more sustainable working conditions.

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Received: 7 March 2012

Accepted: 12 April 2012

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