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To mitigate airborne molecular contamination through ultra-pure air system

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ABSTRACT

Airborne Molecular Contamination (AMC) has become one of the major problems in nano-technology development and manufacturing facilities. To deal with this problem, a prototype Ultra-Pure Air (UPA) system with a targeted air quality level of 10 ppt impurity was experimentally developed.

The prototype UPA system presently composes two process modules; pre-treatment and post-treatment. In order to deal with the hard-to-remove airborne organic molecular substances, $UV_{185+254nm}$ is first used in the pre-treatment module to provide the energy needed for breaking the molecules into smaller transitional compounds. Meanwhile aerosol water droplets are introduced; these combine with the transitional compounds to form hydrophilic substances. After the "Immersing Photochemical Oxidation" reaction, the hydrophilic contaminants go through compression and condensation processes, which comprise the post-treatment module. During the air compression and condensation processes, the collision probability of the contaminants and aerosol water droplets is highly increased. Later, a dehumidification process removes the water droplets within the condensed air; this removes both the water and the dissolved contaminants. These pre and post-treatment processes yield air quality levels of less than 1 ppb of volatile organic compound (VOC); the minimum detection limit for a measuring analyzer.

The purpose of this paper is to introduce the developed UPA system and to present its experimental results.

1. Introduction

Airborne molecular contaminants (AMCs) refer to contaminants within the air that exist as molecules causing airborne molecular contamination (AMC). According to the ISO 14644-8 classification of airborne molecular contamination [1]; "*the product or process can be sensitive to, or can be destroyed by, molecular contamination resulting from airborne molecules due to external, process, or otherwise generated sources.*"

As shown in Fig. 1, AMCs are different from particles, AMCs exist in gaseous or vapor forms with average dimensions of only 0.2 ~ 3.0 nm (nano meter, 10^{-9} m), therefore AMCs can penetrate and pass through ULPA (ultra-low particulate air) filters [2]. In the semiconductor industry, AMCs have long been known to negatively impact process yields by degrading product performance and reliability [3]. Since AMCs severely jeopardize the cleanroom operation, a great deal of research has been performed with the goal of reducing and diminishing problems caused by AMCs, particularly when the feature size of the manufacturing technology node approaches 100 nm or below.

This paper proposes a prototype system, which aims to solve AMC problems occurring during nanotechnology R&D or manufacturing. The prototype system is named Ultra-Pure Air (UPA). The system aspires to produce molecular contaminant free air. This paper will introduce both UPA methodology and functions. Additionally, experimental results will be presented which demonstrate the effectiveness of a UPA system.

1.1. AMC problems and challenges

After the initial problem of airborne chemical contamination was reported by IBM researchers in the early 1990s [4], semiconductor companies began to examine the damage caused by AMCs during manufacturing processes. Later, AMC related studies and preventive measures were introduced. For instance, Sematech [5] projected AMC limits for the 0.25 μm (micro meter, 10^{-6} m) process, ITRS [6] initiated an AMC control roadmap for yield enhancement, Purafil Inc. [7]. introduced AMC control practices, Balazs Nanoanalysis [8] recommended AMC analysis methods and ISO 14644-8 covered the classification of AMC in cleanrooms and associated controlled environments. These studies presented

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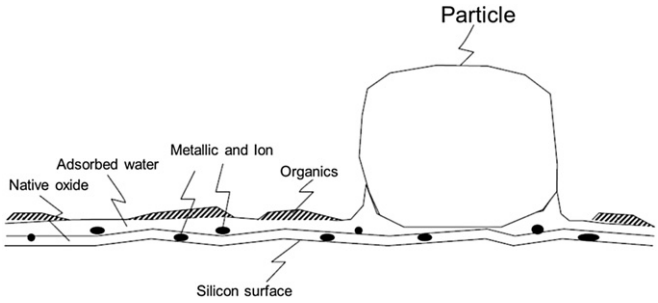

Fig. 1. Schematic of various contaminants on silicon surface [2].

significant discussions and findings regarding AMC damage to manufacturing processes along with detection techniques, control methods, and other related topics.

Grenon [9] examined worldwide AMC incidents from 1997 to 2008. Since Dominion Semiconductor Inc. reported the first AMC incident in 1997, semiconductor plants globally had reported 23 major AMC incidents, the most serious of which resulted in a loss of approximately US$100 million [9]. AMC-free facilities have now become a crucial requirement in semiconductor plants.

Thus, Den et al. [10] proposed chemical filters as the major method for AMC control in semiconductor manufacturing processes with a scale of feature size below 100 nm. Moreover, McIlvaine and Vacura [11] projected sales of AMC control systems to be US$136 million in 2010 along with AMC filters sales of US$67 million.

At the time of writing, chemical filters have been the general choice for reducing AMC concentration levels in cleanroom operations, for over a decade. One major difference between chemical filters and conventional cleanroom particulate filters is end-of-life criteria [12]. A particulate filter increases its efficiency as it loads and will not have any quality impact on cleanroom operations, even when the filter has reached an end-of-life condition whereby the increased pressure drop overtakes a certain energy tolerance. By the same token, while a well-designed chemical filter may start off with over 99% removal efficiency for a particular contaminant; this efficiency will be degraded over time [13]. Consequently, as individual adsorptive materials are deteriorated, the statistical probability of failure increases.

1.2. Emerging clean air techniques

Van Zant [14] initiated the 'Clean Air Strategies (CAS)' which aims to provide contamination-free workspaces through the design of clean workstations, tunnel layout and mini-environments in order to solve AMC problems in cleanroom operations. CAS is a concept, which involves two elements; clean space, and clean air. However, there are only a few clean air studies that use a non-filter approach to AMC control in a semiconductor cleanroom. Wakamatsu et al. [15,16] developed a cooled-type, two-stage air washer in make-up air units to remove high-concentration AMCs from intake-air and also used a pure water showering method to remove water-soluble substances, such as NH_4^+ and amine ions, for cleanroom re-circulation air.

However, even though studies on clean air technology are still rare for cleanroom applications, advanced oxidation processes (AOPs) are regarded as an emerging clean and efficient technology that may be of use in treating AMCs and producing clean air for cleanroom operations. The advantage of AOPs technology is that it can completely, or partially, destroy organics by converting them into various harmless intermediates and end-products, such as carboxylic acids, carbon dioxide, and halide ions [17,18]. Table 1 summarizes the current studies on AOPs that may be applicable to the removal of AMCs classified by ISO 14644-8.

1.2.1. Advanced photochemical oxidation processes

Chou and Chang [19] reported that in a batch mode operation, 1 (one) liter of gas-phase hexamethyldisilazane (HMDS) could be 100% eliminated within 40 s by using 185 nm ultraviolet. Jeong et al. [20] indicated that 100% of NO and 92% of NO_2 could be removed by the process of UV-$C_{254+185\ nm}$/TiO_2 irradiation coupled with an air washer. Chen and Zhang [21] investigated the effects of an ultraviolet photocatalytic oxidation (UV-PCO) device on multiple volatile organic compounds (VOCs) and found that in a 16-VOC mixture experiment, it took almost 6 h to eliminate ethylbenzene. Zhang et al. [22] concluded that an O_3/TiO_2/UV process had better performance in removing trace VOCs from indoor air than O_3/UV and TiO_2/UV processes. Yu and Lee [23] demonstrated that the ozone removal efficiency of a TiO_2/UV/O_3 reaction in the presence and absence of toluene ranged from 61.1 to 99.5% and 38.1–95.1%, respectively.

1.2.2. Advanced non-photochemical oxidation processes

Lee and Chang [24] indicated that, in dielectric barrier discharge (DBD) processes, around 95% of the carbons in p-xylene molecules were transformed into carbon dioxide with water vapor. Li et al. [25] reported that 82% of p-xylene was removed by a positive DC streamer discharged plasma reactor. Schmid et al. [26] found that under realistic conditions and using standard operating air flow rates, degradation efficiencies of $1 \pm 1\%$ for o-xylene, and $3 \pm 0.4\%$ for m-/p-xylene were found in commercial plasma air purifiers. Wu and Lee [27] examined negative air ion (NAI) technology and concluded that oxidation of VOCs by NAI proceeded slowly.

1.3. UPA paradigm

Chuang and Chang [28] addressed an innovative UPA method to mitigate AMC problems in nano-scale processes on 45 nm or below. The objective of the UPA research was to effectively control the

Table 1
AOPs techniques applicable to AMCs.

Category	Method	AMCs/removal rate	References
Advanced photochemical oxidation processes	UV/O_3	HMDS/>90%	Chou and Chang, 2005 [19]
	UV/TiO_2	NO/100%, NO_2/92%	Jeong et al., 2006 [20]
		VOC	Chen and Zhang, 2008 [21]
	UV/TiO_2/O_3	Ozone/96.5–97.8%	Zhang et al., 2003 [22]
		Ozone/38.1–95.1%	Yu and Lee, 2007 [23]
Advanced non-photochemical oxidation processes	Non-Thermal Plasma (NTP)	p-Xylene/95%	Lee and Chang, 2003 [24]
		p-Xylene/82%	Li et al., 2007 [25]
		Xylene/1–3%	Schmid et al., 2010 [26]
	Negative Air Ions (NAI)	VOC	Wu and Lee, 2004 [27]