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Experimental Wafer Carrier Contamination Analysis and Monitoring in Fully Automated 300 mm Power Production Lines

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Abstract. Contamination control is essential in semiconductor manufacturing to ensure high yield and product quality. Latest power electronic devices are manufactured in fully automated 300 mm production lines, which utilize closed wafer containers called Front Opening Unified Pods (FOUPs). It has been observed, that FOUPs capture airborne molecular contaminants (AMCs) outgassing from processed wafers or being transferred from the equipment minienvironment. These AMCs might be released afterwards and can lead to defects causing yield and/or reliability issues of the power devices. Specific FOUP cleaning and exchange rules are already being utilized in the fab. But so far, these rules are not validated or adapted by actual concentration values in the FOUPs. In this paper, contamination levels in FOUPs are investigated to identify the sources of different AMCs. The contamination data is analysed together with FOUP logistics data in order to establish an optimized FOUP management strategy. In the first part, in-line carrier contamination control is explained and a general overview of the AMCs detected is given. In the second part, the data-driven FOUP-monitoring is described using the example of the root cause analysis of hydrofluoric acid (HF) contamination.

Introduction

Yield enhancement and decrease of defectivity are of highest importance in high volume manufacturing. In power electronics manufacturing, the wafer environment has a significant impact on the wafer yield. Wafer containers can capture AMCs outgassing from just-processed wafers or being transferred from the equipment minienvironment and release them afterwards, eventually damaging wafers sensitive to AMC compounds later on [1-6]. Different contamination profiles can be found in the FOUPs depending on the process steps passed by the wafers beforehand [7, 8]. The cross-contamination chains from wafer to FOUP and from process tool to FOUP are shown in Figure 1.

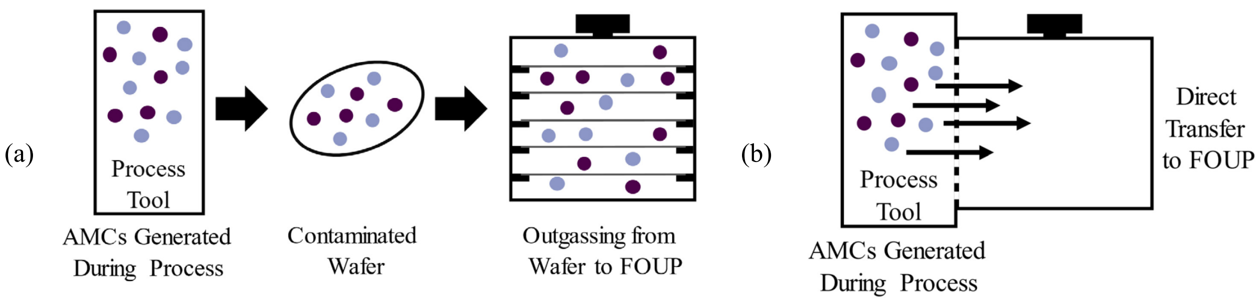

Figure 1: Cross-contamination chain from wafers to FOUP (a) and from process tool to FOUP (b)

So far, FOUPs are cleaned in specific equipment after a certain number of process steps or a certain time, without taking account of the kind of process steps passed and the possible prevalent AMC concentration. In addition, it is necessary to define contamination areas to avoid cross-contamination due to the transport of wafers between fabrication areas. If a lot crosses areas with different contamination specifications, the FOUP must be exchanged. For this purpose, specific transfer stations are used to exchange the wafers, resulting in a high logistic effort.

An optimized cleaning and contamination monitoring strategy for wafer containers is therefore needed and will rely on advanced metrology and data-driven analysis capabilities. Traditional methods for analysing wafer carrier contamination are offline analytics. In this case, the FOUPs were taken out of the production line and water was poured into them. Then they were shaken manually and a sample of the water was extracted and analysed with ion chromatography (IC) or inductively coupled plasma mass spectrometry (ICP/MS).

Improved analysis methods for wafer carrier contamination were already presented in [10]. However, these methods are complex and not automated. Therefore, an in-line, fully automated contamination monitoring method for FOUPs was established using a specific FOUP contamination control tool - the APA-Tool (Advanced Pod Analyzer) from Pfeiffer Vacuum, which was integrated in the fabrication line. This way, the concentration of selected contaminants in the FOUPs can be monitored automatically during the active process flow. The platform is equipped with an optical laser spectroscopy measurement system using cavity ring-down spectroscopy (CRDS) with a detection limit of 0.01 ppbv (parts per billion by volume*)* to determine the most critical acid and basic AMC components.

Recently, a standard procedure for FOUP cleaning validation was developed. The FOUPs are sent to clean after certain attributes have been met. After cleaning, the AMC concentration is measured with the APA-Tool. Depending on the results, the FOUP is cleaned again or is sent back into production. Figure 2 shows the concept for advanced wafer carrier cleaning validation.

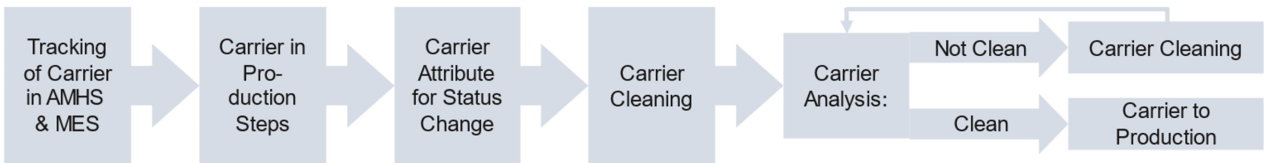

Figure 2: Concept for the development of an advanced cleaning strategy for wafer carriers in power device manufacturing

Furthermore, a data-driven approach for wafer carrier contamination monitoring shall be established. The FOUPs are tracked throughout the fab whereby every step is stored in a dedicated FOUP database, in the material flow control and in the manufacturing execution system (MES).

The tracking and the contamination data can be used to detect dependencies between operations and tools in the production line and FOUP contamination. For this purpose, the concentration in FOUPs was measured after several relevant process steps (e. g. dry etching) in one production line. This will lead to an enhanced strategy for wafer container monitoring and decision support in power device manufacturing.

The present work consists of two parts. In the first part, in-line wafer carrier contamination monitoring using the APA-Tool is explained. A summary of first results for AMC levels throughout one product line is given. In the second part, a data driven approach for FOUP contamination monitoring is demonstrated. Wafer carrier logistics are explained and information about the available data is given and visualized. Finally, first results for a root cause analysis of HF contamination are shown.

InLine Analysis of Wafer Carrier Contamination

As explained above, FOUP contamination monitoring is critical to ensure high yield and quality of the product. To measure the contamination in FOUPs in an automated way, Pfeiffer Vacuum developed an equipment capable of measuring the concentration of AMCs in a FOUP’s atmosphere, the APA-Tool. The APA-Tool pumps the air out of the FOUP and the air is being analyzed by a state-of-the-art sensor system, e.g. an optical laser spectroscopy measurement unit with high sensitivity. The system can be utilized for the analysis of the most critical acids and bases. The sampling takes only two minutes with a flow of 2,700 cm³ and a detection limit of 0.01 ppbv. The compounds measured are hydrofluoric acid (HF), hydrochloric acid (HCl) and ammonia (NH_3). Before each measurement, the gas concentration in the ambient cleanroom air is analyzed, to be able to differentiate the values found in the cleanroom from those found in the FOUPs.

With the integration of the APA-Tool, the AMC analysis of FOUPs can be implemented in-line with the process flow without the need of additional manual handling and manual transportation steps. To measure FOUPs with just processed wafers along the production line though, it is necessary to stop active lots in the process flow and redirect them to the APA-Tool. Therefore, for this investigation, the FOUPs were stopped before and after selected process steps, redirected towards the nearest stocker and then put on the APA-Tool manually with the wafers still inside. The results for the AMC levels in the FOUPs along one product line will be reported elsewhere [10]. Here, an overall summary of the collected data shall be given and a concept for data-driven FOUP management will be shown. First, the distribution of the measured values in the cleanroom ambient and in the FOUPs will be shown and compared using histograms, which can be seen in Figure 3. These graphs show how many of the measured values fall into the respective concentration bins. The concentration range is given in arbitrary units.

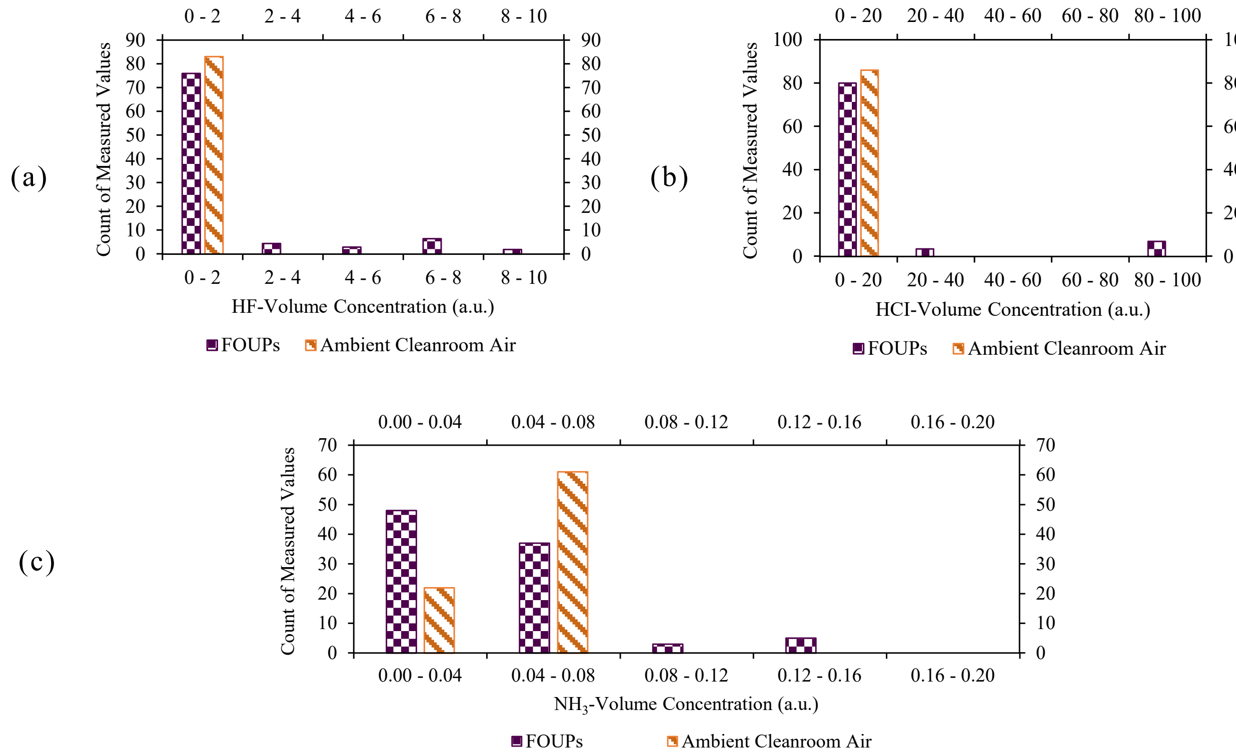

Figure 3: Histogram of the contamination concentration in the FOUPs (purple) and in the ambient cleanroom air (light-blue) - a) HF; b) HCl; c) NH3

A relatively low concentration of HF could be detected in most of the FOUPs; only in some cases, higher levels were detected. The HF concentration in the ambient cleanroom air was always in the lowest concentration range and is therefore no source of cross-contamination. The higher concentration levels of HF contamination in the FOUPs can be explained by the outgassing of processed wafers, which are transported in the FOUPs. The chemical is widely used in semiconductor manufacturing and typical areas of application are etch and cleaning processes.

Again, most values of HCl are very low; the ambient concentration was always in the lowest bin. Only a few concentration levels measured inside the FOUPs were higher. Thus, the processed wafers, rather than the ambient air, cause high HCl levels. Generally, possible sources of HCl contamination are etching processes, leaking of exhaust and pump lines and the outdoor air [11]. The NH_3 concentration measured in the ambient air and the FOUPs was constantly in a very low range.

The concentration of NH_3 in the FOUPs was mostly even lower, which indicates that this compound's source is the cleanroom environment. NH_3 can be derived from the outdoors (industry, agriculture), from process chemicals in the cleanroom or from the construction material of the cleanroom building itself [12]. HF proved to be the most variable compound in the observation, with the highest differences from the cleanroom air. In addition, HF contamination in the FOUPs can lead to corrosion effects, for example of metallic interconnects [2] and crystal growth [7] and is therefore very important to monitor. This is the reason why the following investigation and root cause analysis will focus on this compound. Figure 4 shows a SEM image of corrosion effects on aluminum interconnects.

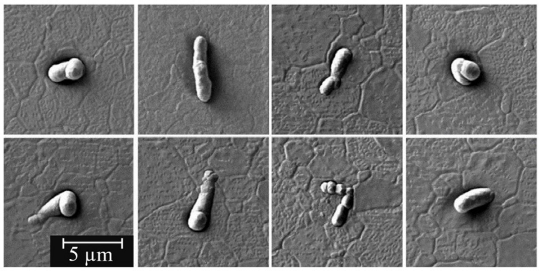

Figure 4: Figure 4: SEM image of corrosion effects on aluminum interconnects

With the possibility to measure FOUPs in-line, data about FOUP contamination in the process flow can be gathered. This information can be used to link contamination to certain process steps or events during the transportation. In the following, FOUP logistics and the available data will be explained. The results of the data analysis of the concentration and the transportation data will be shown.

Data-Driven Wafer Carrier Contamination Monitoring

At first, a short introduction in the logistics of fully automated 300 mm semiconductor manufacturing shall be given. In these production lines, the lots are transported in wafer containers using automated material handling systems (AMHS) between the equipment and the different stockers. Typically, the storage and transport take around 80 % of the total manufacturing time of a lot [13]. This means the investigation of the cross contamination, which can occur during transport and storage, is most important. Cleaning of the FOUPs happens after a certain timespan or a certain amount of process steps is passed. Both parameters were fixed with the knowledge of domain experts, to ensure the high quality of the product and minimize the effort of the FOUP cleaning. Exchanging of FOUPs at exchange stations occurs after specific process steps assumed to be critical for contamination. Contamination areas are defined in a way that FOUPs cannot cross these areas uncleaned. Figure 5 shows the time distribution at the different FOUP locations of 1 month.

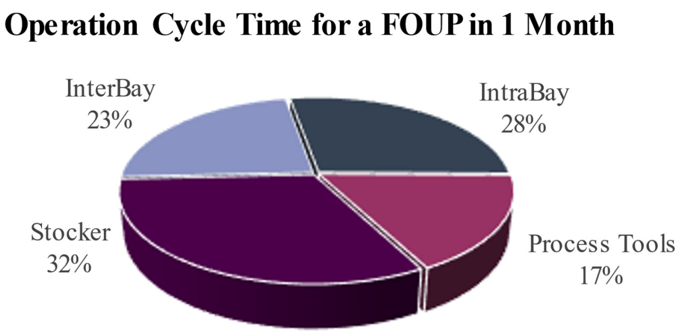

Figure 5: Sum of operation cycle time at different process tool types, stockers, intrabay and interbay for a FOUP (1 month)

The chart shows that a FOUP spends most of the time in stockers and in the intrabay and interbay. During this time, cross-contamination from wafers to FOUPs and vice versa can occur, but the FOUP

atmosphere is also in exchange with the cleanroom air, which decreases the AMC concentration. No further investigation of adsorbtion and outgasing mechanism were performed in this work, because the final goal was a better FOUP exchange and cleaning procedure, respectivly.
With the contamination values from the APA-Tool, dependencies between FOUP properties, logistics and the contamination can be investigated. One assumption was, that FOUPs with a longer operating lifetime show higher AMC concentrations than newer ones and should therefore be replaced. The operating lifetime is defined as the time between the first use in the fab and the measure date. The HF contamination value for approximetly 100 FOUPs depending on the operating lifetime in the manufacturing line is shown in Figure 6. No relation between the entry date and the measured contamination was detected.

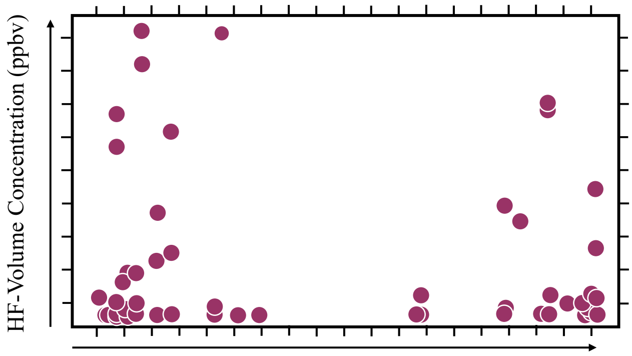

Figure 6: HF concentration levels in FOUPs plotted over the operating lifetime of the FOUPs

As only gases in the FOUP atmosphere are measured with the APA-Tool, it is also possible that substances are adsorbed deep into the FOUP material and are only released when heated or when they can diffuse directly from the plastic onto the wafer. It can be assumed, that older FOUPs store these contaminants, which cannot be detected with the APA-Tool [14]. Therefore, it is still worthwhile to replace FOUPs after some years.
As explained above, FOUPs are cleaned after a certain time of use or after a certain amount of door open cycles, corresponding to the number of process steps passed. Figure 7 and Figure 8 show the HF concentration in the FOUP plotted over the time since the last cleaning step and the number of door open cycles since the last clean.

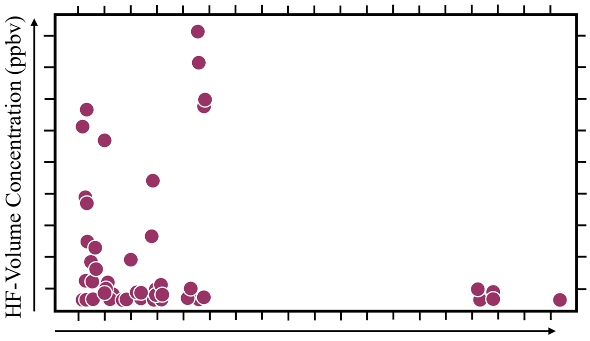

Figure 7: HF concentration levels in FOUPs plotted over the time since the last cleaning step

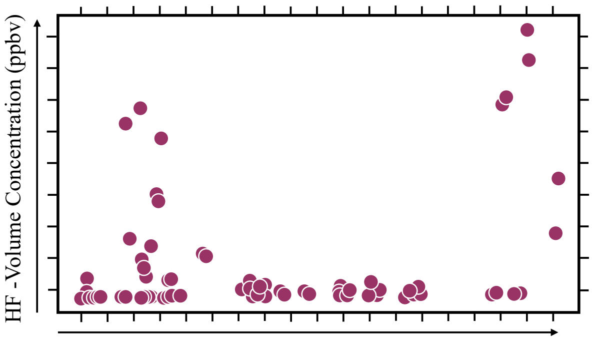

Figure 8: HF concentration levels in FOUPs plotted over the number of door open cycles after cleaning

No influence of the time the FOUP was used after the last cleaning or the number of processes passed since the last cleaning on the HF concentration was observed. Again, the contamination level in the FOUPs depends rather on the process steps before the measurement. To confirm this, in Figure 9 a swarm plot of different process types before measurement and the resulting HF concentration measured in the FOUP is presented. It can be shown that the process type with the highest impact on the HF concentration in the FOUP is dry etching. This was expected, as the wafers are in contact with fluorine ions in these tools, depending on the process recipe. The scattering of the measurement values after the etch processes is very high, which indicates further influences. Further investigation on the process steps the wafers passed at these tools were carried out. We observed that the HF contamination was high when the wafers passed a process step using CF_4 or C_2F_8 plasma. Figure 9 shows the HF concentration levels measured in FOUPs after dry etching steps. The use of CF_4 or C_2F_8 in the process before the measurement is indicated with dark orange colour (see box in Figure 9).

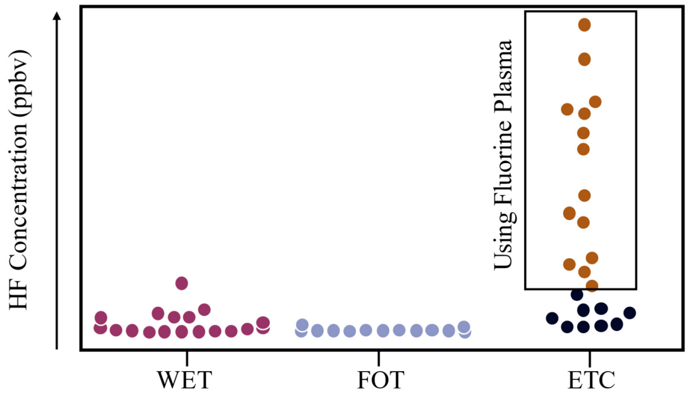

Figure 9: Swarm plot of HF concentration values after wet chemistry (WET), photolithography (FOT) and dry etching (ETC) processes

Fontaine et al. [7] also reported HF contamination in FOUPs after a dry etching and dry stripping step using C_2F_8, CF_4, O_2 and N_2 gases. They propose the following reaction mechanism: HF can directly be formed out of the plasma of H· and F· radicals. Additionally, F· radicals can react to form F_2. Volatile SiF_4 is formed with any Si-containing material, stored in porous materials or in the resist residues and can then react with F_2 and humidity to HF, which leads to the outgassing of the wafers.
In the previous analysis, it could be shown that the current FOUP cleaning and management rules are not based on the real level of AMCs inside the FOUP. The operating lifetime, the time since the last cleaning step and the number of door open cycles since the last cleaning step, did not show any relation with the FOUP contamination. The highest influence observed was the type of process the FOUP passed before. Especially the dry etching processes using CF_4 and C_2F_8 proved to be sources of HF contamination. This shows that by using logistic data from FOUPs and in-line contamination analysis methods, a root cause analysis for carrier contamination can be performed.
Further analysis will be carried out when more data is collected and available, which will increase the reliability of the results. Nevertheless, a possible concept for data-driven FOUP monitoring was shown and proven suitable. The results will lead to improvement in carrier monitoring and logistics management based on valid analysis in the future. For example, if a process step with high influence on the contamination is detected, a FOUP exchange and a cleaning step using a standardizes DIW cleaning procedure can be implemented afterwards, in particular after the wafers have been cleaned. This will lead to a data-driven FOUP monitoring approach, which provides the information after which or after how many operations the FOUP should be cleaned or exchanged.

Conclusion

Advanced wafer container contamination control methods and enhanced cleaning strategies are developed to meet the challenging requirements for power device manufacturing. A data-driven approach for FOUP contamination monitoring was presented. This will enable a decision support for smart wafer container logistics as well as advanced cleaning procedures. The data used is the wafer container tracking data and contamination analysis data, which is being collected by in-line, fully automated trace-gas measurement system. Relevant process steps for contamination can be identified and targeted measures can be derived. The final goal is to build a tool for data-driven decision making in order to optimize the container logistics and the required cleaning procedures, with regard to the given requirements of the individual process steps in power device manufacturing.

Acknowledgement

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