The life-cycle environmental impacts of etching silicon wafers and (PE)CVD chamber cleaning

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Abstract

Fluorinated gases are used by the semiconductor and photovoltaic industry for etching silicon wafers and (PE)CVD chamber cleaning. The desired result is due to F atoms and other reactive species, but the emission of the undecomposed PFC (perfluorinated) gases is unwanted because they have a high global warming effect and high atmospheric life-time. In this study a full life-cycle assessment is used in order to (1) compare the environmental impacts of the different technologies and (2) to indicate improvement options.
The steps in the life cycle are the following: synthesis of the compounds, transportation, distribution in the fab (connection of cylinders), use in the process, abatement to destroy the unreacted gases and take-back of cylinders. Emissions from each step can be direct (from emission of the fluorinated gases) or indirect (from energy use).
Results, partly based on best guesses, indicate that fugitive emissions of the fluorinated gases during synthesis, downtime of abatement system and cleaning of the not completely empty cylinders dominate the life-cycle global warming effect. This means that the global warming effect of the gas itself determines the effect being the highest for SF6. F2 turns out to be clearly in advantage over the other fluorinated compounds because it has a global warming potential of zero with moderate efforts for synthesis.
Possible improvement options to minimize the use and emission of fluorinated gas are (1) strict procedure for connection of cylinders, (2) complete usage or reliable abatement of the gas from the bottle, (3) the recovery or reliable abatement of unused gases from the process and (4) end-point detection of the process.

1 Introduction

The total GWP emissions related to the industrial use of CF4, SF6, and NF3, respectively, have been presented in [1].

- efforts and unfiltered emission during synthesis
- efforts and unfiltered emission during transport and distribution
- unfiltered emissions during use in production, including reduction by the process step, the abatement, and efforts for abatement [2]
- unfiltered emissions during cylinder take back and efforts for abatement.

The results have been compared with F2, generated onsite. They were used in a format "kg CO2 equivalent emissions / kg PFC". We present here the results of the investigation of the stability of the resulting conclusions, as well as an application example for a comparison CF4/NF3/F2 in a chamber clean process.

2 Questions and scenarios

Fig 1 shows the standard scenario giving the overall CO2 equivalent emissions. It shows a decreasing GWP effect in the order SF6 > CF4 > NF3 >> F2 onsite. However, unfiltered emissions during synthesis and cylinder take-back have been estimated very conservatively, whereas the contribution of the unfiltered emissions during the use in production could be assessed with higher precision.

So a second scenario is prepared, using less conservative assumptions on unfiltered emissions during synthesis and cylinder return.

To anticipate future improvements, a trend is supposed to strongly increase the abated fraction of PFC in future production and by retrofit of existing facilities.

Then, the derived values are applied to a comparison between a CF4, NF3, and F2 chamber clean recipe based on flow data given in [3]

3 Results

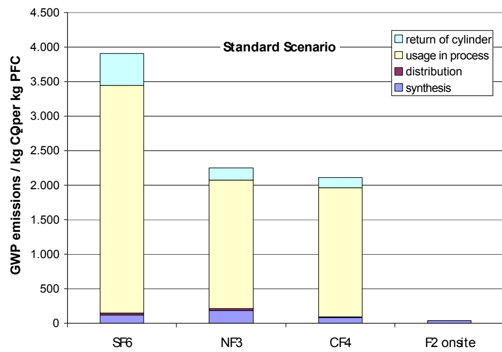

Fig 1: Cumulated efforts of PFC use

The scenario using the standard assumptions shows a dominating effect of the use in production. This effect is due to unfiltered release because of two major reasons: first of all, a significant fraction of fabs is not equipped with PFC abatements, second the standard abatements installed have a significant downtime, leading to a slip of PFC during downtime. Since these figures were based on installation experience [2] they can be regarded as representative. The data quality concerning chemical synthesis and cylinder return are less precise, so the standard scenario is based on conservative figures. Going to a scenario with assumption of more emissions (by a factor of 3) from the last two sources, the following picture is obtained.

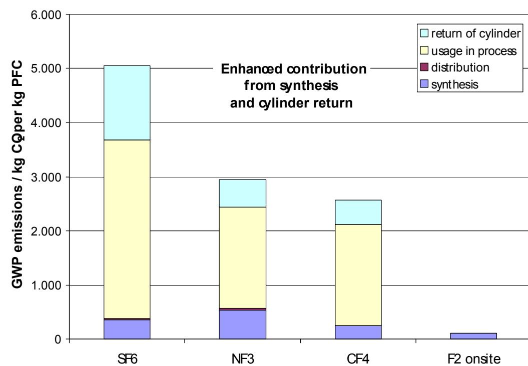

Fig. 2: Modified scenario

It is observed that the overall emissions increase by 20% and the distribution is still dominated by the unfiltered emission during usage in production.

To estimate the minimum emission which may be obtained by future developments, the standard scenario was modified by reducing the emissions from the usage in process. The number of fabs without abatement was assumed to be reduced by a factor 10, the unfiltered emissions after abatement cut by a factor of 5, whereas the effort for abatement, leading to CO2 equivalent emissions by use of resources was increased by a factor of 5. The other contributions remained unchanged. This set of assumptions is definitely optimistic.

It reduces the overall emissions significantly, and the weight of the relative contributions to the overall emission is changed.

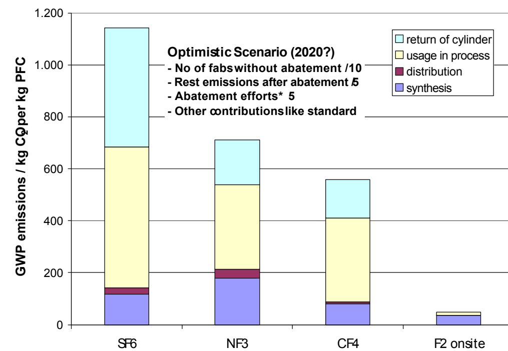

Fig 3: Possible future development

Independent of all these assumptions the F2 onsite generation is by far the most ecological solution.

Additionally to the consideration based on kg CO2 per kg PFC basis, the cleaning step which uses the gases CF4, NF3, and F2, respectively require also different amounts (flow and time) of the respective gas. Based on the data given in [3], the following comparison was made. It was assumed that overetch is moderate (<10%) or an endpoint detection is used to avoid even higher emissions from the process. The fact that in the cited investigation the fluorine/inert gas mixture was taken from a bottle, is not significant for the process results and consumptions. It can as well be used to assess the environmental impact when providing the fluorine in question by onsite generation.

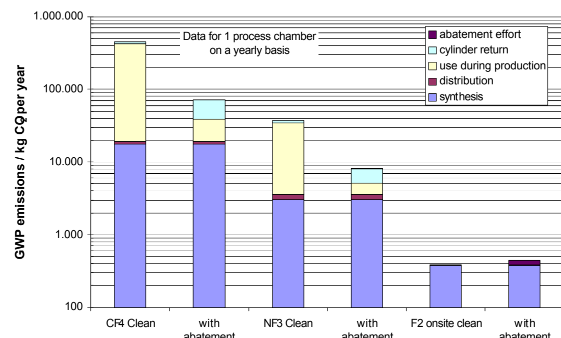

Fig. 4 Comparison of different cleaning recipes

The flow rates for CF4 and NF3 used were as given by the tool manufacturer, and the F2 mixture was op-

timized by the investigators. Not included in the evaluation is the fact, that under these circumstances and flows, the F2 mixture shows the highest etch rate, and the CF4 gas the lowest. So, if applicable, the flow of F2 could be reduced or the flow of CF4 must be enhanced to come to same performance results. Taking this into account, the distance would be even larger. Because this change would be a deviation from manufacturers recipes, it had not been multiplied on top of the emissions.

It is clearly visible (logarithmic scale) that compared on a basis with abatement, the F2 clean is a factor of 20 better than the next best scenario, the NF3 clean. Without abatement of PFC, the difference is even higher. Although CF4 as a PFC is even slightly better than NF3 on a kg basis, the required higher flow in the cited recipe [3] makes the overall GWP balance of the CF4 clean worse than the NF3 clean. This has to be checked from one application to another, case by case.

The recipe used in the cited example is a typical one, with an older equipment on 200-mm-wafers. The outcome looks typical, but not necessarily similar to other potential applications. So the relative consumptions of the respective chamber clean gases have to be checked for each intended application. However, the advantage for F2 is substantial, and will allow to improve a high number of applications.

4 Discussion

Although not all underlying data for the GWP emission estimation are precisely available, the most stable data on abatements and their properties allow to determine the major part of the GWP emissions associated with the usage of PFC in solar and semiconductor industry.

Although SF6 carries the highest impact, the impact of CF4, long time in use, is not higher than that of NF3 on a kg-per-kg basis. As long as less NF3 is used for a comparable process, there is an advantage for NF3, then.

A correct design of abatements with high uptime, and covering all PFC sources in a fab is the today's key to reduce emissions significantly. For the next step of reduction in future, synthesis and cylinder return have to be reviewed and equipped with better precautions against unfiltered release.

However, also a projection to the future under optimistic assumptions shows significant GWP emissions from the PFC use although substantially reduced compared to today.

F2 onsite generation beats all other alternatives, but is not a suitable or at least not a proven replacement for all applications today. A broad replacement of traditional PFC applications by F2 onsite generation would have the highest benefit for GWP emission reduction.

5 Acknowledgements

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6 Literature

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