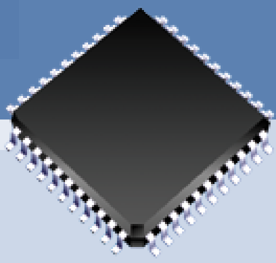
THE EUROPEAN SEMICONDUCTOR INDUSTRY'S VOLUNTARY AGREEMENT TO REDUCE 'PERFLUOROCOMPOUND' EMISSIONS



EECA ESIA

European Semiconductor Industry Association

European Semiconductor Industry Association
PFC Voluntary Agreement Final Report

Introduction

Semiconductor (microchip)[1] manufacturing is not considered a significant contributor to global warming gases. However, the industry does emit some greenhouse gases in the course of the manufacturing process. Based on the European Union's annual greenhouse gas emissions total for 2008[2] (4,560 million tonnes of CO_2 equivalents), the European semiconductor industry sector emitted less than 0.025% of the total CO_2 equivalent emissions in Europe in 2008. Despite being a small piece of the overall emissions picture, European semiconductor companies have long recognised the need to be proactive in addressing their sustainability responsibilities. In the 1990s, the industry agreed to a voluntary commitment to reduce, by 2010, the absolute basket of all perfluorocompounds (PFCs) (including NF_3, SF_6 and HFC-23) emissions of the European industry by 10% below the baseline year of emissions in 1995.

This final report of the European Semiconductor Industry Association (ESIA) will detail the industry's voluntary actions from 1995 to 2010 to reduce emissions of PFCs[3] and present 2010 data for the voluntary reduction programme. The use of PFCs presents a dilemma for the semiconductor industry; the gases themselves have significant global warming potential, however, there are no viable alternatives to their use in manufacturing leading edge semiconductor devices.

1 More commonly known as a Microchip, Silicon chip or an Integrated circuit (IC). An IC is a miniaturised electronic circuit (consisting mainly of semiconductor devices, as well as passive components) that has been manufactured in the surface of a thin substrate of semiconductor material. Integrated circuits are used in almost all electronic equipment in use today and have revolutionized the world of electronics.

2 European Environment Agency – Annual EU greenhouse gas inventory 1990-2009 and inventory report 2011 - submission to the UNFCCC Secretariat page 11 (2008 data gives a pre-economic crisis figure of EU 27 emissions and 2010 EU level data is not publicly available at time of print)

3 (*Perfluorocompounds - for the purposes of the voluntary agreement the European industry has included all greenhouse gases used, the perfluorinated carbon compounds including HFC-23, NF_3 and SF_6 in the basket of gases used and monitored collected as part of the agreement that are used in the industry. Hence the reference to 'perfluorocompounds' which is broader than the traditional categorisation of PFC's)

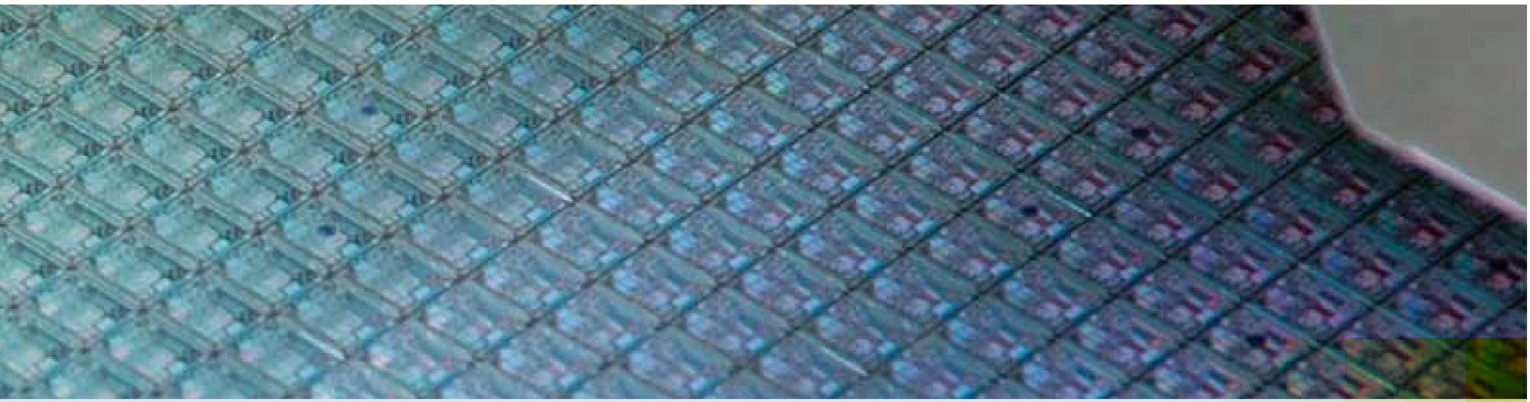
1. Results of 2010 Voluntary Agreement

The European semiconductor industry has met and surpassed its voluntary reduction goal by reducing absolute PFC emissions by 41% from the 1995 baseline to 2010. If no progressive action and investments had been undertaken by industry to reduce these emissions, they would have increased significantly above 1995 levels under a business as usual scenario. Figure 2 outlines the European semiconductor emission data from 1995 to 2010. Figure 1 shows the complete EU 27 wide picture for greenhouse gas emissions in 2008[4]. The ESIA reduction has been achieved through the aggressive implementation of process optimisation and more efficient alternative processes, use of alternative chemistries and through the installation of abatement equipment. The industry has notably continued to make efforts to further reduce emission even after the 10% goal had been achieved.

"The European semiconductor industry sector emitted less than 0.025% of the total CO_2 equivalent emissions in Europe in 2008."

EU 27 Greenhouse gas emissions in CO2 equivalents

Figure 1
Source - European Environment Agency - Annual EU greenhouse gas inventory 1990-2009 and inventory report 2011 - submission to the UNFCCC Secretariat page 11.



ESIA PFC emission data from 1995 to 2010

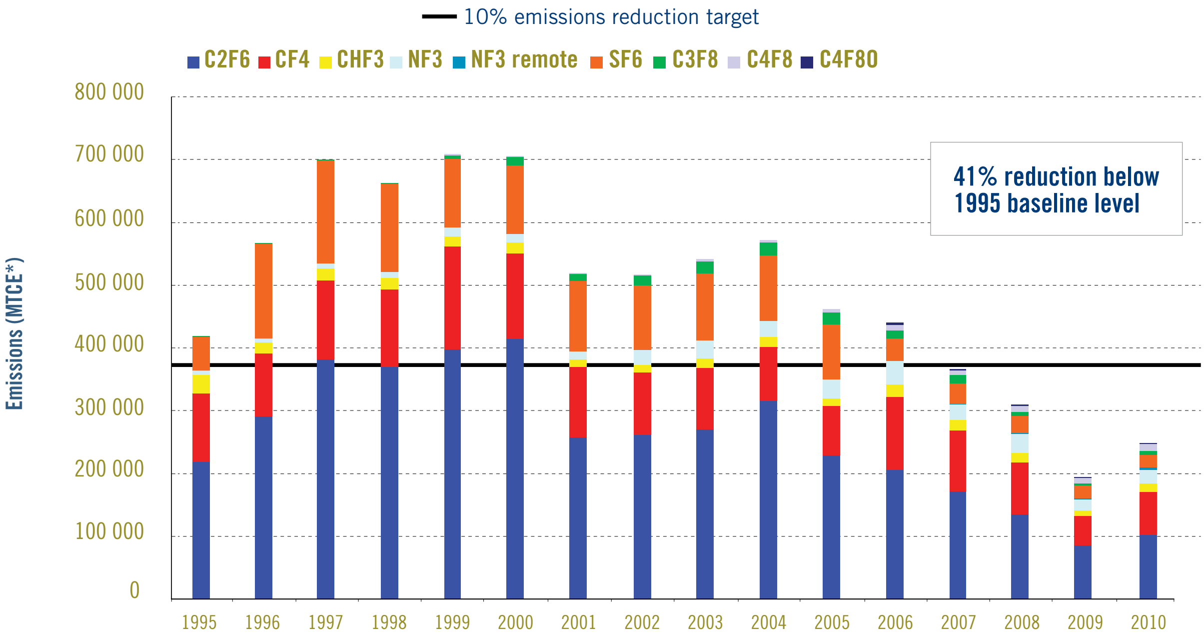


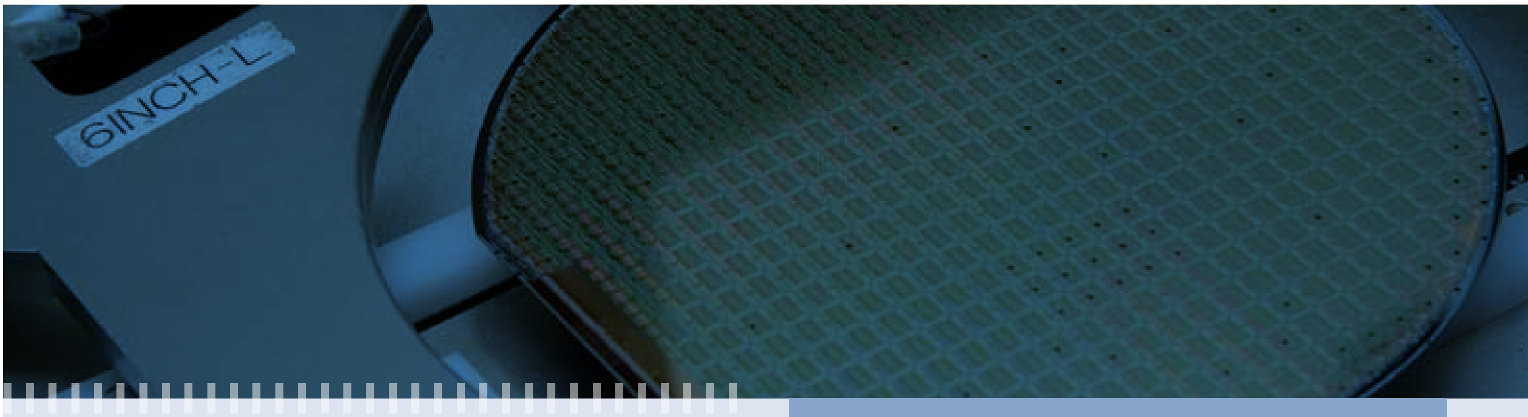
Figure 2
*MTCE - metric tonnes carbon equivalent
Data and 1995 baseline updated and recalculated with the 2006 IPCC formula and the 4th assessment report.

This European goal has formed part of the overall global semiconductor industry's proactive response to reduce PFC emissions on a worldwide basis by 10% by 2010. The global PFC reduction goal is coordinated through an organisation called the World Semiconductor Council (WSC), consisting of regional semiconductor trade associations in Europe (ESIA), China, Japan, Korea, United States and Taiwan who contribute to this worldwide reduction effort[5]. It is important to outline that – through the WSC - the semiconductor industry was the first industry to align globally and establish a worldwide greenhouse gas emission goal which goes beyond the targets established by the Kyoto protocol for Annex 1 countries.

"The European semiconductor industry has surpassed the voluntary PFC goal by reducing absolute emissions by 41% below the 1995 baseline level"

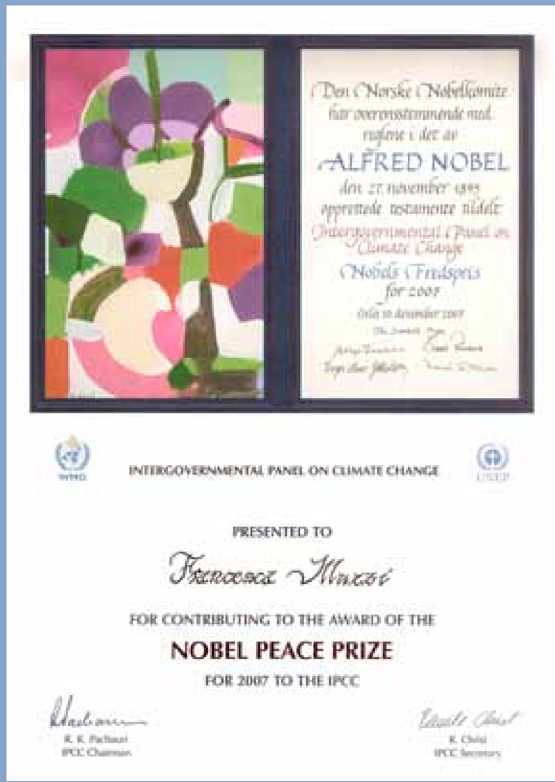
4 Data is based on EU greenhouse gas inventory of EEA. 2008 data gives a more realistic picture of the data pre-economic crisis than 2009 data. 2010 data not yet available.

5 The Chinese semiconductor industry association, CSIA, was not a member of the WSC until 2006 and was not part of the 2010 WSC PFC agreement



By 2010, global emissions were reduced 32% below the baseline, surpassing the 10% reduction target. This is a significant achievement for the semiconductor industry due to the level of production growth that occurred over the 15 year period from 1995-2010. Semiconductor industry production increased roughly six fold over this time period. The main centres of production and, therefore also, of PFC emissions remain in Europe, Japan, Korea, Taiwan, USA, and increasingly China. Of these six regions the European industry emissions in recent years have accounted for typically 7-8% of the total global emissions. Other countries in the Asian region such as Singapore, Malaysia, and the Philippines have also in recent years increased the level of semiconductor device production.

" ...the use of PFC gases is crucial to the production of semiconductor devices, as there are no effective substitutes that can be utilised. "



▲ **Picture 1 -** Award presented to Dr Francesca Illuzzi (ESIA PFC chairperson) for her work on the IPCC

For these reasons, to be an effective vehicle for reducing and monitoring global emissions of PFC gases from the semiconductor sector, only a global level approach by the semiconductor industry now and in the future can be a truly comprehensive solution for the global climate. This global perspective is necessary to ensure that the countries with increasing growth in production in the future years can also be integrated to achieve a balanced effort to reduce emissions worldwide. This can be done by considering the process optimisation and substitution of a lower emitting gas as first possible priorities followed by point of use (POU) abatement systems installation.

Several representatives of the WSC's PFC Working Group were involved with the Intergovernmental Panel on Climate Change's (IPCC) work and the Nobel Peace Prize Award in 2007. Dr. Francesca Illuzzi, ESIA's PFC Group chairperson attended the peace prize ceremony for her expert collaborative work representing the sector on the guidelines of the IPCC since 2000. (▲ Picture 1)

Another very positive outcome achieved by the European companies is a continued decrease in the normalised emissions rate (NER) (MTCE/square meter of silicon wafer) as outlined in Figure 3. ▸

This reduction in normalised emissions means that the industry has consistently reduced PFC emissions (per production unit) per square metre of silicon since 2001. This decrease in the NER is despite the fact that semiconductor devices have become more and more complex over time requiring additional manufacturing process steps and therefore more PFCs to be utilised in production. The NER figures do not account for this increased complexity of the semiconductor devices.

To ensure that the most up-to-date information is used in its reports, the European semiconductor industry has always updated the sector's complete reporting data based on the most recent IPCC scientific assessments and the calculations for the GWP (global warming potential) and emission factors when available. For the complete basket of all gases, the most recent update is based on 2007 IPCC methodology in combination with the GWP100 values of the IPCC 4th assessment report. This may not be the case with all national inventories. In addition, the IPCC methodologies overestimate the actual data values.

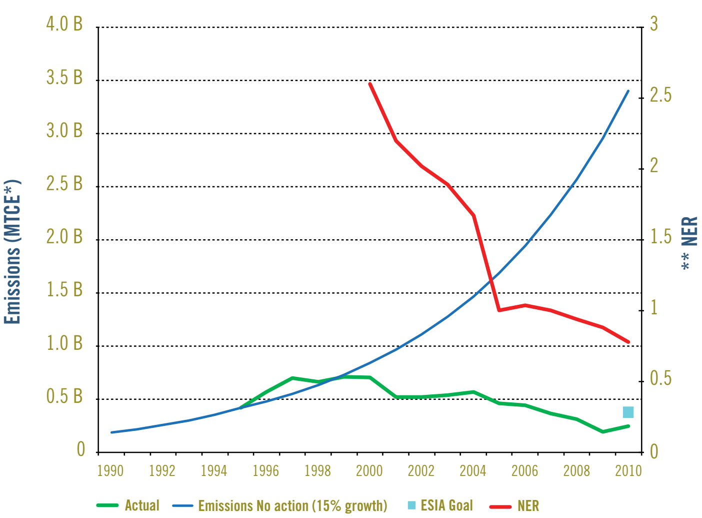


Figure 3 - The European Normalised emissions rate (NER) has continued to decrease throughout the Voluntary Agreement - this shows that the industry has consistently reduced the amount of PFCs used per square metre of silicon.

* MTCE - metric tonnes carbon equivalent — ** NER = MTCE/M² of silicon wafer

2. The use of perfluorocompounds (PFCs) in semiconductor manufacturing processes

To produce semiconductor devices, the semiconductor industry requires gaseous fluorinated compounds, silanes, doping and other inorganic gases. Wafers consist of high-purity silicon are the basic building blocks for all semiconductor components. The basket of PFCs used in semiconductor manufacturing process are: tetrafluoromethane (CF_4), hexafluoroethane (C_2F_6), octofluoropropane (C_3F_8), octofluorocyclobutane (c-C_4F_8), nitrogen trifluoride (NF_3), sulphur hexafluoride (SF_6) and hydrofluorocarbons such as trifluoromethane (CHF_3).

Essentially, these high-purity gases are used in a number of different process steps.

a. PFCs are used as etching gases for plasma etching. The gases etch the submicron patterns on silicon and dielectric layers of advanced integrated circuits. In addition, SF6 decomposed by the plasma allows the etching chambers to be cleaned.

b. The fluorinated compounds are also used to accurately perform a rapid chemical cleaning of Chemical Vapor Deposition (CVD) tool chambers. When the silicon and silicon based dielectric layers are being applied, a deposit remains in the CVD chamber. To ensure that the wafers are not contaminated by these deposits, the chambers are cleaned at defined intervals, thereby avoiding frequent mechanical wet cleanings.

c. In the wafer testing process stage, SF_6 is used as an insulator for power device testing. Power devices are used for automotive applications to simulate the real device working conditions which are essential to prove device reliability. The SF_6 reuse concept can allow SF_6 to be used in an environmentally friendly manner and to be kept in a closed cycle.

The criticality of the process technologies in semiconductor manufacturing and the use of PFCs, relate to the complete basket of the PFC compounds used. PFCs have been used in semiconductor fabrication plants because they provide a uniquely effective process performance as echants. PFCs are a safer, more reliable source of fluorine, which is required for cleaning certain deposition process chambers. Manufacturers of semiconductor devices have been able to reduce PFC emissions by taking a number of actions including process optimisation, use of alternative chemicals, employment of alternative manufacturing processes and improved abatement systems. However, the use of the basket of PFC gases in these processes is crucial to the production of semiconductor devices, as there are no effective substitutes that can be utilised. Production processes which use gases in combination with other gases have been specifically tuned by supplier engineers and process engineers to create the right chemistry mix and right process conditions to produce working semiconductor devices. The criticality of the process technologies in semiconductor manufacture and the use of PFCs relate to the complete basket of the PFC compounds used.

Table 1 - Greenhouse gases: GWPs of gases used by ESIA as specified by IPCC 2007

Gas Compound	Chemical Formula	CAS number	GWP_{100}[7]
Tetrafluoromethane	CF_4	75-73-0	7,390
Hexafluoroethane	C_2F_6	76-16-4	12,200
Octofluoropropane	C_3F_8	76-19-7	8,830
Octofluorocyclobutane	$c\text{-}C_4F_8$	115-25-3	10,300
Nitrogen Trifluoride	NF_3	7783-54-2	17,200
Sulphur Hexafluoride	SF_6	2551-62-4	22,800
Trifluoromethane	CHF_3	75-46-7	14,800

GWP-Global Warming Potential of the gas relative to carbon dioxide, for a time horizon of 100 years.

These global warming potential values come from the physical science basis- contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change 2007; section 2.10.2 (Cambridge, UK: Cambridge University Press, 2007). These are the current values used for calculating the semiconductor reporting in Europe.

◂ **Picture 2** - Semiconductor manufacturing clean room

3. Emission reduction technology development

The semiconductor industry employs a hierarchy in the development of PFC emission reduction technology. This is structured around the pollution prevention concepts of reduce, replace, re-use/recycle, and abate. These development areas are:

1. **Process optimisation/alternative processing - reduces the amount of PFCs that are used and emitted;**
2. **Alternative processing chemistries – reduces or eliminates emissions;**
3. **Capture/recovery – re-uses or recycles PFCs;**
4. **Abatement – reduces or eliminates PFCs emissions.**

3.1 Process optimisation

Process optimisation continues to focus on CVD chamber cleans because they have historically been the largest source of PFC emissions. Furthermore, they occur in the absence of wafers and can be optimised without negatively affecting product yield. The PFC gases used in CVD chamber cleans include CF_4 and C_2F_6 in older (pre-1999) manufacturing equipment, as well as C_3F_8, C_4F_8, C_4F_8O (octafluorotetrahydrofuran) and NF_3 that are lower emitting C_2F_6 replacement chemistries. These last substances have become more common in recent years.

Based on 2010 emission data collection, C_2F_6 continues to be the primary chamber clean gas and currently makes up the majority of semiconductor PFC emissions. However, in terms of amounts purchased, NF_3 is continuing to replace C_2F_6 and is now the largest purchased gas. In process optimisation, endpoint detection or extractive metrology are used to monitor emissions and provide clean end point times that are minimised by adjusting process parameters such as chamber pressure, temperature, plasma power, cleaning gas flow rates, and gas ratios in the case of mixtures. Cleans are optimised to minimise gas consumption, thereby resulting in lower cost of ownership (COO) due to decreased gas usage. Process optimisation can yield emissions reductions of 10-56%[6] compared with non optimised processes. Moreover, it is a low cost emission reduction option with so-called potential process throughput benefit. Process optimisation effectively reduces emissions in older fabs and ensures that new chamber clean processes minimise gas consumption and operate efficiently.

▲ **Picture 3** - STMicroelectronics semiconductor fab, Crolles, France (courtesy of Artechnique & STM)

6 C. Allgood, S. Hsu, B. Birmingham, and J. Soucy, Proceedings of the SEMICON Southwest 'A Partnership for PFC Emissions Reductions' Seminar, paper #9 (2000).

3.2 Alternative processing chemistries

Replacement of the original process with a new and lower emitting process is a technology area which has undergone significant development in recent years. The industry has developed NF_3 remote plasma clean technologies to replace in-situ CF_4 and C_2F_6 chamber cleans. Remote cleans dissociate NF_3 into fluorine ions or atoms in a remote plasma and then feed the F ions/atoms into the process chamber to remove silicon-based residues. Remote cleans convert NF_3 at 95-99% utilisation efficiency and semiconductor companies have adopted remote plasma technology for chamber cleans across their advanced 200mm and 300mm CVD equipment line[7]. Some companies have developed remote plasma technologies utilising NF_3 or other PFC chemistries that can be retrofitted to certain older CVD chambers. When compared to the original carbon based PFC chamber cleans that they replace, retrofitted remote cleans result in more than 95% PFC emissions reduction and improved tool utilisation throughput; reduced clean times, reduced wet clean frequency, improved mean time between failures (MTBF), reduced chamber parts costs and improved yield through reduced defects. NF_3 is used as a substitute for other PFC process gases due to this superior efficiency. Despite the NF_3 high GWP100 value, NF_3 remote plasma clean technologies have been developed to replace some other process gases and have a superior utilisation efficiency (which means most of the gas utilised is not emitted to the environment). The use of NF_3 in processes is continuously being optimised and made more efficient by the semiconductor industry and its suppliers.

▲ **Picture 4** - Infineon Technologies fab, Dresden, Germany (courtesy of Infineon)

While replacement of high GWP gases with lower or non-GWP gases is generally preferable, it has not proven to be feasible in most plasma etch applications. Processing requirements for high aspect ratio plasma etching continue to become more stringent, requiring both fluorine to etch and the right carbon to fluorine ratio to ensure anisotropic etching. While a significant amount of research has been done on alternative etchants such as iodofluorocarbons, hydrofluorocarbons, and unsaturated fluorocarbons, many of these chemicals are not viable alternative etchants in a manufacturing environment due to excess polymerisation, lack of etch selectivity, difficulties in delivering gases to the process chamber, and potential increased employee exposure risks. An exception is hexafluoro-1,3-butadiene (C_4F_6) for oxide and low-k etching where high selectivity for silicon is required in the presence of nitride or other films with high aspect ratios, thinner resists and less etch resistant resists. In these cases, C_4F_6 replaces CF_4, CHF_3, and C_4F_8[8]. By using C_4F_6 characterised by an atmospheric lifetime of less than 1 year and a utilisation efficiency of more than 95%, PFC emission reductions of more than 90% compared to conventional gases can be achieved.

7 200 or 300mm refers to the size of the silicon wafer used to produce semiconductor devices

8 F. Fracassi, R. d'Agostino, E. Fornelli, F. Illuzzi, T. Shirafuji, Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films, Volume 21, Issue 3, pp. 638-642, May 2003.

9 Reduction of perfluorocompound (PFC) emissions: 2005 State-of-the- Technology Report, Technology Transfer #05104693A-ENG, International SEMATECH, (2005)

10 Final Report on the European Climate Change programme prepared on behalf of the European Commission by Jochen Harnisch and Ray Gluckman, 2001, page 43

"Process optimisation is the only cost-effective method of emissions reduction."

3.3 Capture / Recovery

Several semiconductor manufacturers and suppliers conducted alpha and beta evaluations of PFC capture/recovery systems which could be installed as a central, building-wide means for handling PFC emissions. No evaluation resulted in successful re-use of PFC; all were deemed to be too costly to implement. As NF_3 based cleans proliferate, large building-wide capture/recovery systems become less cost effective due to the reduced volume of PFCs available for recovery. To date, no semiconductor facility has implemented centralised capture/recovery technology.

3.4 Abatement

Significant developments have occurred in the area of PFC abatements, with the development of new technologies and the commercialisation of many new abatement systems[9]. The industry has favoured point-of-use abatement over centralised end-of-pipe (EOP) abatement for PFCs, believing that it is more effective to abate close to the source and, thus, prior to dilution. Most abatement technologies can be applied to PFC emissions from both etch and CVD processes, although several companies have developed plasma abatement systems specifically for etch chamber emissions. These are typically installed prior to the vacuum pump (i.e., the foreline) to avoid dilution of the stream with pump-purge N_2.

4. Cost effectiveness of emission reduction investments

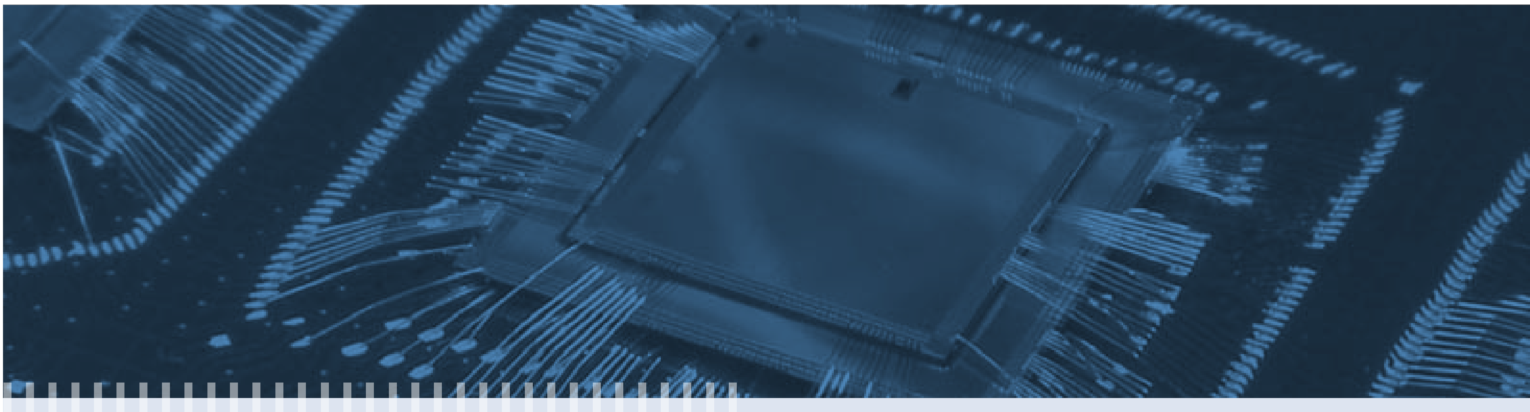
The ESIA PFC emissions reduction agreement has come with significant cost implications for all companies involved[10]. In comparison with many other industry sectors, the European semiconductor industry is often confronted with high marginal costs to reduce a small amount of emissions. The costs are high in respect of the absolute reductions achieved, since the PFC emissions by the semiconductor industry are only a very minor portion of overall industry GHG emissions.

▲ **Picture 5** - NXP Semiconductors fab, Nijmegen, The Netherlands (courtesy of NXP)

Process optimisation is the only cost-effective method of emissions reduction. It affords lower gas consumption, and therefore, lower emissions and may lead to throughput benefits.

However, to achieve this, the processes must be optimised and (partly) re-qualified and this requires significant engineering resources. The implementation of alternative processes and, in particular, of abatement measures has involved significant investments by the European semiconductor industry. These investment costs include:

- Qualification costs for alternative processes (every process must be released from production).
- Hardware and installation costs (dedicated process tool configurations, abatement tools).
- Infrastructure costs (gas supply, energy supply, downstream effluent treatment). Space requirements and special safety precautions may significantly enhance these costs.
- Running costs (abatement systems, etc.).



There may be a very large variation in the costs of emission reduction. In the case of a new fab, the cost impact will be less than in the case of an already existing fab. This is because new production facilities can be built according to the newest insights, whereas for older fabs, the implementation of reduction measures and retrofits interferes with running production, and sometimes the existing infrastructure space poses problems leading to disproportionate costs.

For the future it is worth noting that the most significant absolute reductions of emissions have already been achieved by the European industry over the past number of years though the investment in alternative processes, continued process optimisation and the purchase and installation of abatement technology. Whilst the industry will continue to strive to manage emissions responsibly into the future, due to the aggressive past investments, factory infrastructure and nature (age profile of the fabs) it can be forecast that continued significant future reductions in absolute emissions from the European industry in line with the past achievements of the last decade will not occur. The abatement costs for any additional small amount of emissions reduction will remain completely disproportionate. On a conservative estimation, emissions from the European industry will flatten out in the years following 2010. In addition, as fabs come to the end of their natural and technological life, some of them will close down.

5. The enabling benefits of semiconductors

The European semiconductor industry has been recognised in Europe and the US for its proactive approach. Viewing the emission reduction efforts of the industry should not be done in isolation, as by far the biggest benefit for the en-

SEMICONDUCTORS - At the origin of sustainable lifestyles

Figure 4

"Semiconductors are indispensable for the delivery of smart, sustainable and inclusive European growth."

vironment and society comes from semiconductor devices themselves. Semiconductor devices provide solutions that help people and the planet reduce energy and power consumption by increasing energy efficiency and improved functionality in many end user products. A broad approach to greenhouse gases related to the semiconductor industry in Europe should also consider the clear socio-economic benefits and enabling capabilities that semiconductor devices provide for the sustainability of Europe and the attainment of Europe's climate and energy efficiency policy goals. PFCs (including HFCs, SF_6, NF_3) are key to the manufacture of semiconductor devices. There are no proven alternatives and without access to these gases the semiconductor industry cannot manufacture devices. As acknowledged by the European Commission (EU 'KETS' - COM 2009 - 512) the semiconductor industry provides the key enabling technologies to enable a more energy efficient and sustainable European society. The High Level Expert Group on Key Enabling Technologies (KETs) final report declared that semiconductors are 'indispensable for the delivery of smart, sustainable and inclusive growth'[11]. Energy-smart semiconductors are ensuring the more efficient use of energy in the home, in LCD TV's, in industrial manufacturing systems, in public transport, in lighting, in personal computing and in data storage centres. Semiconductor technology also enables positive developments in automotive fuel efficiency, automotive safety, reduced automotive emissions and improved innovations in medical devices and the realisation of integrated smart grid energy systems across Europe.

6. Conclusion

The European semiconductor industry - although being a minor contributor to overall emissions and in spite of the high costs associated with emission reduction in the sector - continues to make its contribution to reduce global warming by voluntarily reducing its PFC gases emissions. As the first industry to coordinate globally and establish a voluntary greenhouse gas emissions reduction goal, the semiconductor industry has established itself as a leader and model for other industrial sectors. The semiconductor industry has already achieved far beyond the voluntary agreement goal and its continued actions have resulted in a 41% reduction based on 1995 baseline levels. This figure goes beyond the voluntary goal and the European Unions recent 2020 goals its represents the clear commitment of the industry to fulfilling its environmental responsibilities. The industry in Europe remains strongly committed to continue its proactive management of PFC emissions of the sector through a post-2010 global level voluntary agreement that addresses the entirety of the global emissions from semiconductor manufacturing in 2010 and going forward towards 2020. This new voluntary programme has been agreed by all members of the World Semiconductor Council and continues the proactive track record of the semiconductor industry towards greenhouse gases.[12]

"The industry remains strongly committed to continue its management of PFC gases … a new global voluntary programme on PFCs emissions has been agreed by all members of the World Semiconductor Council up to 2020."

11 High Level Expert Group on KETS, Final Report, June 2011

12 The details of the Post 2010 World Semiconductor Council global voluntary agreement on PFCs can be found in the Joint Statement of the WSC, from Fukuoka Meeting, Japan May 26th 2011 at http://www.eeca.eu/data/File/WSC_2011_Joint_Statement_Final_(formated)(Normal_Font)1.pdf

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