Hydrogen Recovery in EUV Lithography

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70% to 80% of hydrogen used in EUV lithography tools can be recovered, deduces operating cost, supply risk, energy consumption and carbon footprint.

EDWARDS VACUUM HAS DEVELOPED A Hydrogen Recovery System (HRS) that can recover and reuse approximately 80% of the hydrogen used by extreme ultraviolet (EUV) lithography tools. The system reduces net hydrogen consumption and cost, reduces the financial and process risks posed by supply disruption and the safety risks of hydrogen transport and distribution, and reduces the total energy consumption and carbon footprint of EUV lithography.

EUV lithography is essential in all advanced node manufacturing. It has proven to be production-worthy at high volume, the economic benefit of its ability to reduce the number of process cycles is now clearly established, and the number of systems in operation is increasing steadily. EUV tools use large flows of hydrogen, currently around 600 standard liters per minute with further increases likely. Recovering and recycling hydrogen allows manufacturers to cut their supply requirements dramatically.

Edwards' HRS is the result of a ten-year development program conducted in collaboration with imec (Leuven, Belgium). A system is currently operating in the 300mm pilot line there and has been validated within the framework of their Sustainable Semiconductor Technologies and Systems program. It has successfully demonstrated its ability to recover hydrogen and reduce the net energy consumption and scope 3 emissions of the EUV process.

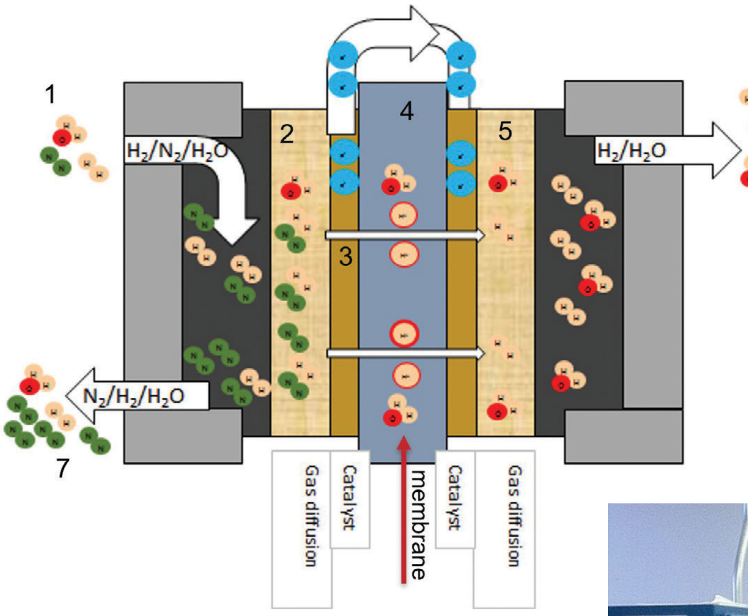

Figure 1. (left) operating principles of the electrochemical cell and (right) a stack of cells assembled to handle larger gas flow.

EUV lithography and hydrogen

EUV systems use high flows of hydrogen at low pressures to remove heat and to prevent particulate contaminants, primarily tin from the EUV source, from depositing on the critical surfaces of mirrors used to shape and focus the illumination. Hydrogen was chosen for this application because it has low absorption at the 13.5nm wavelength used in EUV systems and has high heat transfer capacity. The HRS integrates with the lithography tool's vacuum and abatement systems. It directs gas from the EUV source module to the hydrogen recovery stack and routes gas from the scanner module (a much smaller flow likely to contain contaminants outgassed by the photoresist) to the abatement system. In the recovery stack, extracted gas is purified using a process that combines electrochemical pumping and membrane filtration to recover high-purity hydrogen. The HRS confirms the purity of the gas before returning it to the EUV system and includes failsafe rerouting of gas flows to accommodate changes in the status of the HRS, the lithography tool, or the vacuum and abatement systems.

Although hydrogen is the most abundant element in the universe, most commercially supplied hydrogen is currently produced by steam reformation of natural gas, a process that consumes large amounts of energy and emits carbon dioxide – both directly, from the reformation and subsequent water-gas shift reactions, and indirectly, when non-renewable power is used to generate high-temperature/high-pressure steam. Reducing the amount of hydrogen consumed reduces the overall carbon footprint of the EUV process. Furthermore, by also reducing the amount of hydrogen that must be abated, recovery and reuse reduces the energy consumed and carbon emitted by the abatement process.

The potential value of hydrogen recovery emerged from concerns expressed by a customer as the need for large amounts of ultrapure hydrogen became apparent with the development and deployment of the first EUV lithography systems. In this customer's case, there were no local hydrogen suppliers, and the customer was concerned about the cost of hydrogen and the safety and financial risks associated with transport and supply-chain disruption.

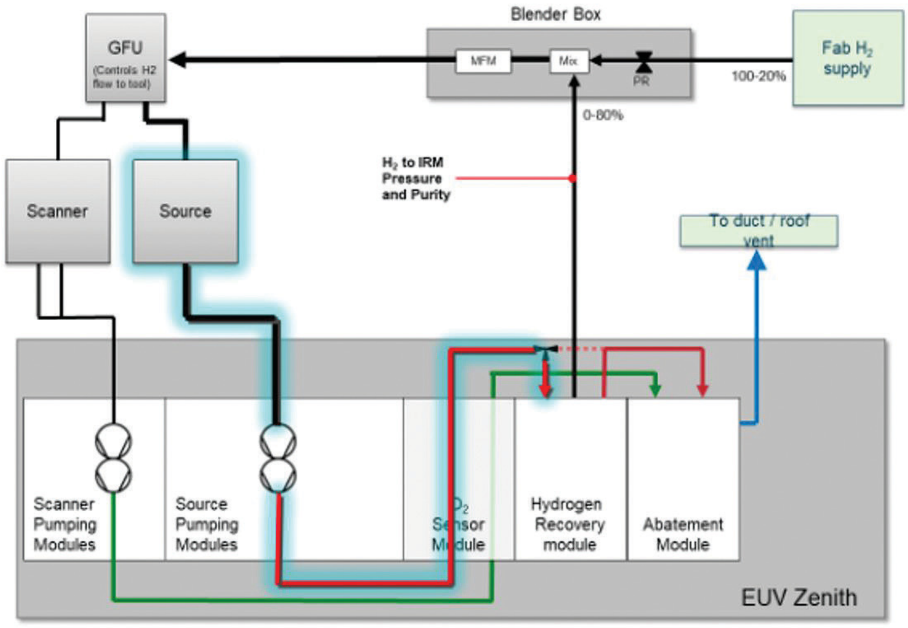

Figure 2. Schematic view of gas flows through the HRS.

Hydrogen recovery

The core technology of the HRS, an electrochemical cell, is well proven using the same principles used in a fuel cell (**FIGURE 1**). Gas from the EUV tool, (primarily nitrogen, hydrogen) and water (introduced for humidification) flows into the cell ①. Hydrogen and water diffuse through a gas diffusion layer ②. A catalyst anode oxidizes the hydrogen to form protons ③. The protons migrate under an electrochemical potential from the anode to the cathode through a proton selective membrane ④. The membrane also passes the water molecules but not most other gases. At the cathode the protons recombine with electrons to form H_2 ⑤. The final purification stage removes the water ⑥. Waste gas from the input stage goes to abatement ⑦.

One of the design goals of the program was to develop a system that could easily scale. EUV systems currently use about 600 slm of hydrogen, but that rate is expected to increase. A single electrochemical cell is not practical for large scale pumping; however, multiple cells can be stacked to increase capacity. Fig. 1 shows a stack of 80 cells with a pumping capacity of 750slm. Stacking allows increases in capacity to handle any desired flow rate.

FIGURE 2 is a schematic diagram of gas flow through the HRS. The EUV system uses separate hydrogen circuits through the Source and the Scanner. Flow through the Source is much greater than flow through the Scanner. Hydrogen flowing through the Source remains relatively pure compared to that which passes through the Scanner module, where it can pick up contaminants outgassed by the photoresist. Source hydrogen goes to the HRS, while Scanner hydrogen is routed directly to the abatement system. Hydrogen leaving the HRS goes to a blender box, where it is supplemented with new hydrogen and routed back to the lithography system.

The HRS will automatically accommodate planned or unplanned shutdowns of various systems. Should the HRS go off-line, hydrogen from Source and Scanner, and waste-hydrogen from the HRS all go to abatement.

FIGURE 3 shows a more detailed view of the overall process flow. Critical components shown here include the humidifier and dehumidifier. The humidifier adds water vapor to the hydrogen flowing from the EUV system. The electrochemical cell requires water vapor to function. After purification in the cell, the water vapor is removed by pressure swing absorption (PSA). A purifier following the PSA provides a final check on the purity of the hydrogen before it is sent to the blender box and recycled through the EUV system.

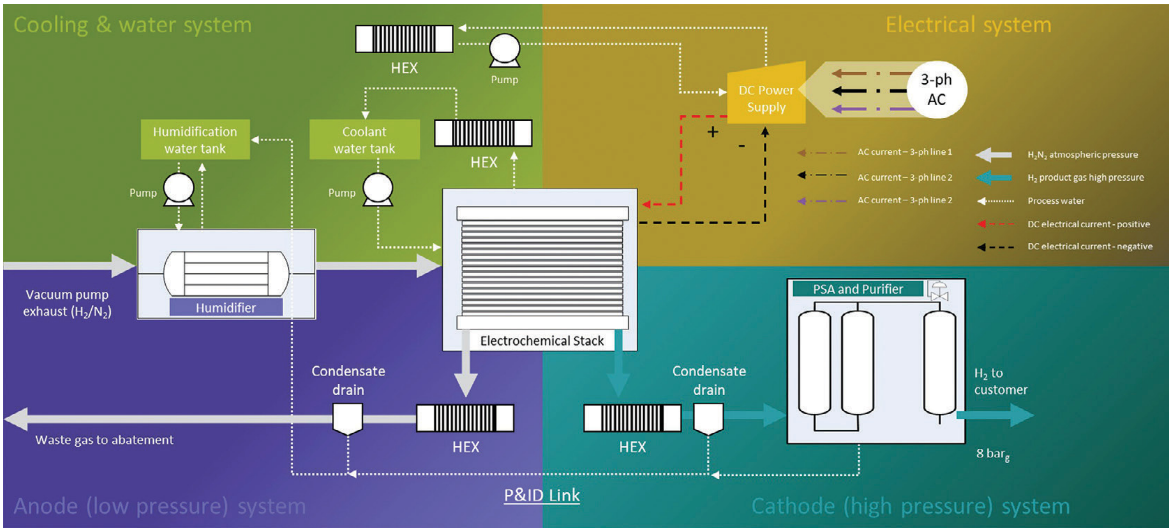

Figure 3. Schematic view of the hydrogen recovery process.

FIGURE 4 illustrates the integration of the HRS with sub-fab vacuum and abatement systems.

HRS can recover more than 70% of hydrogen. It acts as both a purifier and a compressor, delivering pure H_2 at a pressure greater than 100 psi and eliminating the need for a separate compression stage. The process is well suited to steady state continuous flow applications like EUV lithography.

Results

Interuniversity Microelectronics Center (imec), an international research and development organization headquartered in Belgium, is a world-leader in nanoelectronic technologies. Under its Sustainable Semiconductor Technologies and Systems program (SSTS), imec works with material and equipment suppliers, IDMs, and foundries to develop industry-relevant solutions that reduce the negative environmental impact of semiconductor manufacturing processes while preserving process performance. Through pilot practical projects in imec's fab, tool and process experts representing multiple stakeholders develop real world hardware and/or process solutions. HRS is the result of one such collaboration.

TABLE 1 shows the requirements established for the HRS development project.

FIGURE 5 shows results of purity monitoring over a 24-hour period. Small peaks and valleys are associated with regeneration of the water removal system.

Table 1 HRS performance requirements

	REQUIREMENTS
Total nominal flow [Nl/min][a]	660
Pressure range [kPag]	400-999
Temperature range [°C]	cleanroom ±5
Cleanliness grade[b] [c]	9 N or better
Additional ASML requirements [ppbv]:	< 0.2
C_xH_y (45 - 100 amu)	< 0.002
C_xH_y (> 100 amu)	< 0.001
Refractory Compounds	< 0.25
O_2	< 1
H_2O	< 1
CO	< 0.25
Σ all others (incl. C_xH_y (<45 amu)	< 1
Cleanliness particles (IS) 14644-1:2015	class 3 or better

Imec also evaluated the energy consumption and emissions attributable to the use of HRS, concluding, "The HRS installed in our 300mm pilot line process was validated within the framework of our Sustainable Semiconductor Technologies and Systems program. Its ability to recover hydrogen was demonstrated, as well as its ability to reduce the net energy consumption and scope 3 emissions of the EUV process." One of the primary benefits of collaborative development in the

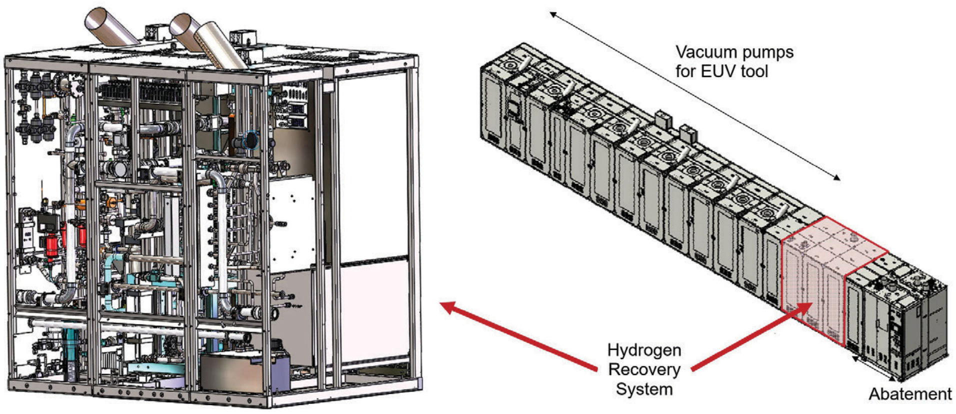

Figure 4. Integration of HRS with sub-fab vacuum and abatement systems.

real-world, in-fab environment of imec is the elimination of first-adopter risk. No one else has to be first.

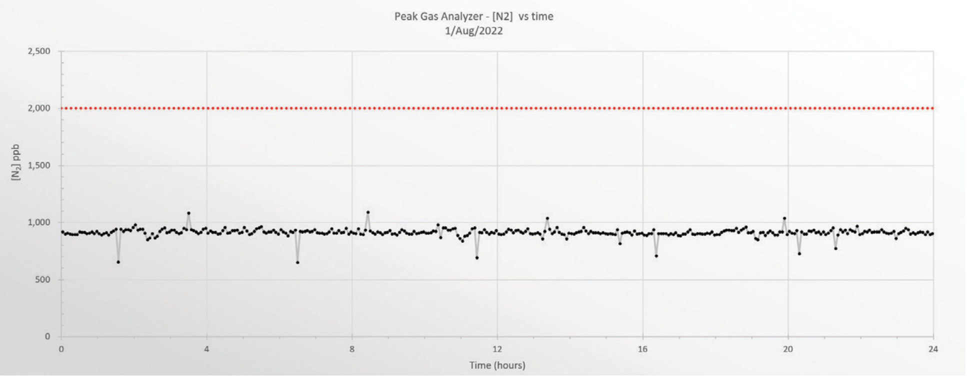

Figure 5. Measured purity of recovered hydrogen over a 24-hour period.

Outlook

There may be substantial value in recovering and recycling other gases used in semiconductor manufacturing, among them noble gases krypton and xenon. New device designs, such as 3D NAND memory, already incorporate very high aspect ratio (HAR) features. As it becomes more difficult shrink features in X and Y, up is the only way to go and the use of HAR features will likely continue to increase. The etch process used to create these features must be highly directional. Etch processes that accelerate ions of a noble gas, such as argon, toward the substrate are frequently chosen. Because argon is a noble gas, the ions do not interact chemically with the bombarded material and the etching proceeds only in the direction of acceleration. The use of heavier noble gases, krypton and xenon, increases the ability of these processes to create taller/deeper features.

While use of krypton and xenon in semiconductor manufacturing processes is expected to grow, their use in other applications is also driving increasing demand. As propellants for satellites, their higher masses increase efficiency, allowing longer lifetimes or greater payloads, and their lack of chemical reactivity reduces corrosion. They are also finding increasing use as gas fill for double and triple glazed windows, where their weight and viscosity reduce convection and thermal conductivity. Both applications are likely to grow significantly in the foreseeable future.

In the short term, supply may also be constrained. Krypton and xenon are currently produced as byproducts of liquid oxygen separation for the steel industry, a significant portion of which takes place in regions (Ukraine) disrupted by military conflict.

Table 2 Concentration and embodied energy of separation for noble gases in air

Gas	Concentration in air	Embodied energy (MJ / std litre)
Argon	0.9%	0.7
Krypton	1 ppm	38
Xenon	0.09 ppm	500

Both krypton and xenon are air gases that are normally separated from air and discharged back into the air. The embodied energies required to separate them from air are inversely proportional to their concentrations – 1ppm for krypton and 0.09 ppm for xenon. For comparison, Argon is present at 0.9%. Growing demand and disrupted supply predicts that we will move from production as by-products to production by air separation specifically for semiconductor applications with increasing prices and environmental costs likely due to their high embodied energy (**TABLE 2**).

As a result, Edwards is looking carefully at the possibility of recovering and recycling krypton and xenon. Because they are present at much higher concentrations in process exhaust gas than in air, they require only 270 kilojoules per standard liter to recover, less than 1% of the megajoule costs of separation from air. Assuming a 90% recovery rate, recycling krypton could save around 10,600 tons of CO_2e per chamber per year, and xenon about 140,000 tons.

Summary

The recently released HRS can recover 70% to 80% of hydrogen used in EUV lithography tools. The system integrates with the tool's vacuum and abatement systems and the recovered hydrogen is pure and pressurized and ready to return to the lithography tool. The system greatly reduces hydrogen consumption and mitigates risks associated with transport and supply-chain disruption. Cost and availability of hydrogen vary widely from place to place, but best estimates, based on average costs, put the payback period for the HRS somewhere more than a year and well below ten years. The system was developed in collaboration with imec and is currently installed and meeting performance targets in their 300mm fab. Edwards is actively exploring other opportunities for recovery and recycling, first among them noble gases.