SPECIAL FEATURE

Helium in electronics

Enabling leading-edge semiconductor manufacturing

Until 10 years ago, helium usage in electronics manufacturing was relatively low and semiconductor factories, which process thousands of silicon wafers per day, were supplied using helium cylinders or bundles of cylinders. This began to change dramatically as the drive to smaller transistor dimensions below 100 nanometers required the unique properties of helium to achieve specialised plasma reactions and high-throughput from equipment tools that cost millions of dollars.

Electronics usage, which represented less than 1% of total global demand for helium, grew exponentially to constitute more than 15% of the market demand today. The tail of this rapid demand growth coincided with the market tightening earlier in this decade. End-users, suppliers, and equipment manufacturers need to address the supply chain and process demand in order to achieve a market-sustainable usage.

This article reviews the properties of helium that make it essential for leading-edge semiconductor manufacturing, details the specific processes that require helium, and looks at some of the steps recently taken to curb demand growth and balance supply and demand.

Properties of helium

Many of the same superlative properties that make helium indispensable in other manufacturing industries enable semiconductor processes as well.

- **Light:** Helium has a very low molecular weight of four atomic mass units, which is second only to hydrogen.
- **Small size:** Helium is one of the smallest molecular compounds of any gas or liquid fluid and can therefore 'fit' in places that other molecules cannot, including in the porous voids of some solid materials.
- **Chemically inert:** As the atomically simplest of the noble gases, helium is the least reactive material known. No helium-containing compounds have been synthesised.
- **Heat transfer:** Helium is able to convectively remove heat faster than any other molecular compound.
- **Ionisation potential:** Helium requires the most amount of energy to ionise (remove) one of its electrons of any molecule. Ionised helium is therefore a highly reactive material.

These extreme properties have made helium very useful for pushing the limits of semiconductor processing capabilities, and at the same time, difficult to substitute for or engineer around. And often it is a combination of these properties that are employed in a single process, complicating any changes.

Process applications

Semiconductor chips are manufactured on base silicon wafers largely using deposition (additive) and etch (subtractive) chemical reactions in the gas phase to create thin layers of different materials on the wafer surface. Reactions take place in a vacuum chamber on single wafers between 100 and 300 mm in diameter. Generally, several different reactive gases are used at a time, and these are further activated using heat or plasma energy sources.

- **Carrier gas:** Helium or other inert gases can be used as a carrier gas to entrain (entrap) and transport less volatile chemicals – ordinarily liquids at atmospheric pressure and room temperature – into the reaction chamber. The helium is heated and bubbled through the liquid chemicals. Because the mass of helium is very light compared to entrained chemical vapor, specialised mass flow controllers can then be used to sense, measure, and precisely control the amount of chemical vapor dispensed. Typical carrier gas flows are 100s of standard cubic centimeters per minute (sccm).

- **Energy transfer:** Once in the reaction chamber, helium serves to transfer energy to the chemical reactants. Helium can be used as a direct heat transfer medium, because its high heat transfer rate couples the external heat source to the reactants, which is especially challenging at sub-atmospheric pressures. It can also be energised in a plasma, generally along with argon. A plasma is an ionised gas with equal numbers of positive ions and electrons as well as neutral atoms. In this capacity, helium is coupling electric field energy to the reactants.

Although an individual manufacturing step may result in the net addition or removal of a material, the actual chemical process is the simultaneous combination of multiple deposition and etch reactions. Also, while the wafer surface appears visually smooth and shiny, on the molecular level, the topography is highly structured and three-dimensional, with features in the forms of trenches, holes, ridges, and pillars. Deposition and etch rates vary widely depending upon whether the surface is more horizontal or more vertical, and whether it is recessed inside the wafer or highly exposed on a top-most feature.

- **Reaction mediation:** After the activation energy is imparted, helium and other inert gases are not mere spectators. They are present at the reactive surface of the wafer and mediate the competing deposition and etch reactions by removing excess heat from the surface and reaction by-products. This role is essential for achieving the equilibrium of reactions at different regions of the wafer surface to result in the desired net deposition or etch process.

Maintaining a precise temperature of both the gas phase reactants and the solid wafer is critical for achieving the desired ratio of deposition and etch reactions on each type of surface. This is made more challenging because many of the reactions themselves release large amounts of heat energy. Some early process steps require high temperatures greater than 800°C, while other later steps occur at less than 100°C. In addition, transferring wafers between reaction tools often requires changing the temperature of the wafers so that they can be mechanically handled and prepared for the next reaction.

- **Back side wafer cooling:** The wafers are held in position in the reaction chamber to a chuck by electrostatic force. In order to maintain precise temperatures of the wafer, additional helium is flowed in the small gap between the wafer and the chuck to remove excess heat. The amount of helium used is controlled by a combination of temperature and pressure feedback, and is typically in the range of 10s of sccm.

- **Load lock cooling:** Intermediate chambers known as load locks are used as a transition zone between the reaction chambers and the room environment. In this way, wafers can be transferred in and out of the vacuum reaction chamber with a minimum of air ingress (entering). In addition to being a pressure transition zone, the load is also a temperature transition zone. The wafers can be adjusted to the proper reaction temperature for reaction before being loaded into the reaction chamber. Processed wafers can be cooled to an acceptable temperature for further transport. Helium is most often used in load lock for its speed and precision of heat transfer, which prevent bottlenecks in the manufacturing flow.

Features built by the deposition and etch steps are patterned by a lithographic process. UV laser light illuminates a master pattern mask before casting the image on photoreactive chemicals pre-deposited on the wafer. The photolithography tool is the most expensive piece of equipment in the semiconductor factory. State-of-the-art tools can cost more than $50m; a fab may require 25 or more of the most advanced tools.

Inside the photolithography tools are an array of lens elements to properly adjust the image for maximum resolution. Even though the lens materials are very transparent to the UV light, a small amount is absorbed and can lead to thermal aberrations in the final pattern.

- **Photolithography:** A blend of helium and nitrogen used in a slow tool purge facilitates overall cooling, and more targeted flows are used to actively cool the hottest and most critical lens surfaces. Total usage per tool is typically 100s of sccm.

Throughout the manufacturing process, extremely high chemical purity and integrity are maintained. Reactants are typically 99.999+% pure, and in a high vacuum process environment, allowable leak rates are less than 10-9 atm•cm^3 /s.

- **Leak testing:** Mass spectrometric leak testing, both in-board and out-board, are used to certify the leak integrity of almost all piping, process equipment, and chemical packaging. Because of the sensitivity, helium is the preferred leak test reagent. Typical flows are 10s of sccm.

Supply, demand, and conservation

Helium is supplied to end-users in a number of different package sizes, footprints and volumes.

- Individual cylinders
- Skid-mounted multi-cylinder packages, or MCPs
- Tube trailers of compressed gas
- ISO containers of liquid helium, which is vaporized at the customer site.

In each instance, the supply is highly regulated. Delivered helium is typically 99.999% to 99.9999% pure. On-site purifiers are used to further refine the quality to impurity levels less than one part in a billion. Filters are used at the point of distribution, and again at the point of use, to reduce particles to less than one particle greater than 10 nanometers in diameter per cubic meter.

Electronics are associated with the most high-tech and leading-edge portions of industrial design and manufacturing. Somewhat counter-intuitively, semiconductor manufacturing is also

Helium Storage Volumes
Source: Linde Gases

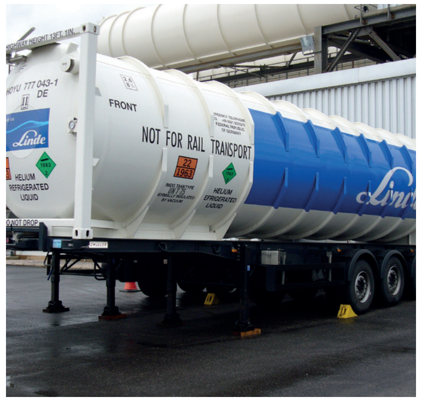
Package	Volume (m^3)
Cylinder	13
MCP (Manifold cylinder pallets – 12 cylinders)	160
Tube trailer	1,000–6,000
ISO container	26,000

one of the most process-conservative fields. This stems from the very high investments required. New factories cost between $5-10bn and process 100,000 or more wafers every month, and each processed wafer represents a finished goods cost of more than $3,000. On each wafer are hundreds to thousands of chips, and each chip has billions of transistor circuits a few nanometers in geometry.

This level of manufacturing excellence has been built from over 50 years of incremental development. Changes to design and process are developed and validated years in advance. Any intermediate changes must be qualified with all of the downstream business supply partners. In the case of foundries, which make chips to other companies' designs, this number can be in the thousands. So while helium demand has grown and expanded quite quickly through natural extensions of key processes, reduction of the helium required to meet supply constraints and contain costs has taken a concerted effort of suppliers, end-users, and tool manufacturers alike.

As outlined above, helium has been increasingly utilised to achieve this precision because of its unique and extensive properties. It is a key material for the transport, activation, and reaction of many of the chemical processes used to manufacture semiconductor transistors. Moreover, its cooling ability further enables the industry by increasing the throughput in costly equipment. Total demand for an individual factory can now exceed 500,000 m^3 per year.

Peak demand per factory occurred several years ago during the most recent supply-constrained market. Supply chain lengths also compound difficulties, as the greatest demand is in East Asia, and most helium is produced in the US and the Middle East. Fortunately, while helium usage is essential for leading-edge semiconductor manufacturing, the variety of applications allowed some latitude for discretionary reduction in less critical applications when required. Suppliers also leveraged available package assets and supply chain efficiencies to maximise supply availability. This created enough time for end-users and tool makers to work together to reduce helium process requirements for existing equipment. Helium conservation is now a part of new tool design and so the demand



"Helium conservation is now a part of new tool design and so the demand growth has slowed to align much more closely with supply growth over the lifecycle of new fabs..."

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Large-scale helium recovery is also feasible for semiconductor factory complexes. Three major development areas need to be addressed, however, for a commercially viable and acceptable scheme. Because of the wide variety and highly reactive nature of the process chemicals used, cleaning of the recovered gas is a multi-faceted challenge, and will require a number of different technologies. Process gas waste is also diluted at several stages from the reaction chamber to the atmospheric exhaust, so that helium is less than 1% by volume, and so re-concentration technology is needed to make the recovery cost-effective. A final, but important, consideration is the integration of the recovered and the make-up helium supplies. Since quality and reliability are paramount to the customer, care must be taken to prevent any out-of-specification material from reaching the resupply line. At the same time, adequate back-up provision must be made to ensure uninterrupted supply.

Conclusion

Leading-edge semiconductor manufacturing pushes the limits of available science, engineering, and material properties. Because of its extreme properties, helium is ideal to enable and extend key processes in the electronics industry, as illustrated by rapid growth in its helium consumption.

Careful conservation in application by end-users and the development of new supplies by producers have allowed for the reliable supply and growth required. And recovery offers a long-term potential for the largest consumers.

The Linde Group provides its customers with the most comprehensive package of helium supply and technology. Linde manages the largest and most diverse portfolio of helium-producing assets, spanning sources across five continents. Linde Kryotechnik designed and built the world's first helium liquefaction plant in 1932, and has supplied over 1,000 cryogenic hydrogen and helium plants globally. Linde Engineering is a leading technology partner for plant engineering and construction, including the separation and purification of helium from natural gas sources. Managed together, Linde offers customers in world-wide locations access to helium products when, where, and how they need them. gw

ABOUT THE AUTHOR

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