

What lies beneath? 50 years of enabling Moore's Law

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Vacuum technology trends can be seen over the period of innovation defined by Moore's Law, particularly in the areas of increasing shaft speed, management of pumping power, and the use computer modeling.

The sub-fab lies beneath. And down there in that thicket of pipes amidst the hum of vacuum pumps, the sentinel of gas combustors and the pulse of muscular machinery doing real work -- innovation has also played a crucial role in enabling Moore's Law. Without it the glamor boys up top with their bunny suits and FOUPS would not have achieved the marvelous feats of engineering derring-do for which they are so deservedly celebrated.

Vacuum and abatement are two of the most critical functions of the sub-fab. Many process tools require vacuum in the process chamber to permit the process to function. Vacuum pumps not only provide the required vacuum, they also remove unused process gases and by-products. Abatement systems then treat those gasses so they are safe to release or dispose. Vacuum and abatement systems in the sub-fab have had to innovate just as dramatically as the exposure, deposition and etch tools of the fab. In many cases, new processes would not have been possible without new vacuum pumps that could handle new materials and new abatement systems that could make those materials safe for release or disposal.

Moore's Law

Moore's Law originated in a paper published in 1965 and titled "Cramming More Components onto Integrated Circuits", written by Gordon Moore, then director of research and engineering at Fairchild Semiconductor [1]. In it Moore observed that the economics of the integrated circuit manufacturing process defined a minimum cost at a certain number of components per circuit and that this number had been doubling every two years as the

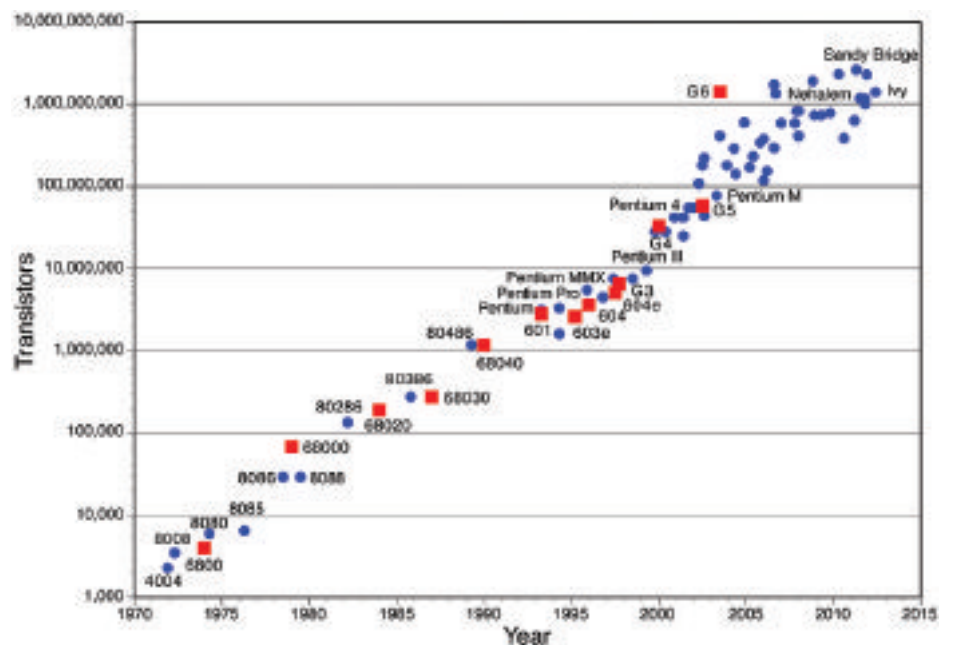


FIGURE 1. A plot of the increasing number of transistors per CPU confirms the accuracy of Moore's prediction. Note that the vertical axis is log scale.

manufacturing technology evolved. He believed that the trend would continue for at least the short term, and perhaps as long as ten years. His observation became a mantra for the industry, soon to be known as Moore's Law (**FIGURE 1**).

More an astute observation than a law, Moore's Law is remarkable in several respects. First, the rate of improvement it predicts, doubling every two years, is unheard in any other major industry. In "Moore's Curse" (IEEE, March 2015) Vaclav Smil calculated historical rates of improvement for a variety of essential industries over the last couple of centuries and found typical rates of a few percent, and order of magnitude less than Moore's rate [2]. Second, is its longevity. Moore thought it was good for the short term, perhaps as long as ten years. This is perhaps due, at least partly, to the unique role Moore's Law has assumed within the semiconductor industry where it has become both a guide to and driver of the pace of innovation. The Law has become a guiding principle – you shall introduce a new generation with double the performance every two years. It is a rule to live by, enshrined in the industry's roadmap, and violated only at great peril. Only painfully did Intel recently admit that the doubling period for its latest generation appeared to have stretched to something more like two and a half years [3]. To an extent the Law is a self-fulfilling prophecy, which some have argued works to the detriment of the industry when it forces the release of new processes before they are fully optimized. Whatever you might think of it, the Law's persistence is remarkable. The literature is full of dire predictions of its demise, all of which, at least so far, have proven premature.

Finally we must ask, what is meant by the names assigned to each new node? What exactly does 14 nm, the current state of the art, mean? Although Moore originally described the number of components per integrated circuit, the Law was soon interpreted to apply to the density of transistors in a circuit. This was variously construed. Some measured it as the size of the smallest feature that could be created, which determined the length of the transistor gate. Others pointed to the spacing between the lines of the first layer of metal conductors connecting the transistors, the metal-1 half-pitch. These may have been a fairly accurate measures twenty years ago at the 0.35 μm node, but node names have since steadily lost their connection to physical features of the device. It would be difficult to point to any physical dimension at the 14 nm node that is actually

14 nm. For instance, the FinFET transistor in a 22 nm chip is 35 nm long and the fin is 8 nm wide.

What remains true is that in each successive generation the transistors are smaller and more densely packed and performance is significantly increased. Each generation seems to be named with a smaller number that is approximately 70% of the previous generation, reflecting the fact that a 70% shrink in linear dimension equates to a 50% reduction in area and therefore a nominal doubling in transistor density.

Enabling Moore's Law in the sub-fab: A brief chronology

In the 1980s new semiconductor processes and increasing gas flows associated with larger diameter wafers led to problems with aggressive chemicals and solids collecting in the oil used in oil-lubricated "wet" pumps, resulting in short service intervals and high cost of ownership. These were resolved by the development and introduction of oil-free "dry pumps" which have subsequently become the semiconductor industry standard.

Dry rotary pumps require extremely tight running clearances and multiple stages to achieve a practical level of vacuum. Additional cost of these machines, however was more than offset by the benefits offered to semiconductor manufacturing. Dry pumps use a variety of pumping mechanisms -- roots, claw, screw and scroll (**FIGURE 2**).

Many of these are new concepts, but modern machining capabilities made it possible to produce them at a realistic cost, the most notable being Edwards' introduction of the first oil-free dry pump in the 1980's. Each pumping mechanism has been successfully deployed and each has its own advantages and disadvantages in a given application. The scroll pump, for example, is unique in its ability to economically scale down to much smaller sizes.

In the early 1990s it became apparent that with the introduction of dry pumps, the pump oil no longer acted as a "wet scrubber" to collect process by-product gases, which therefore passed into the exhaust system. The solution was the development of the Gas Reactor Column (GRC) to chemically capture process exhaust gases in a disposable/recyclable cartridge, minimizing exhaust emissions to the atmosphere.

At about the same, new, more aggressive process gases being used in leading-edge semiconductor processes posed significant challenges for turbo molecular pumps (TMPs) due to the damage they caused to the

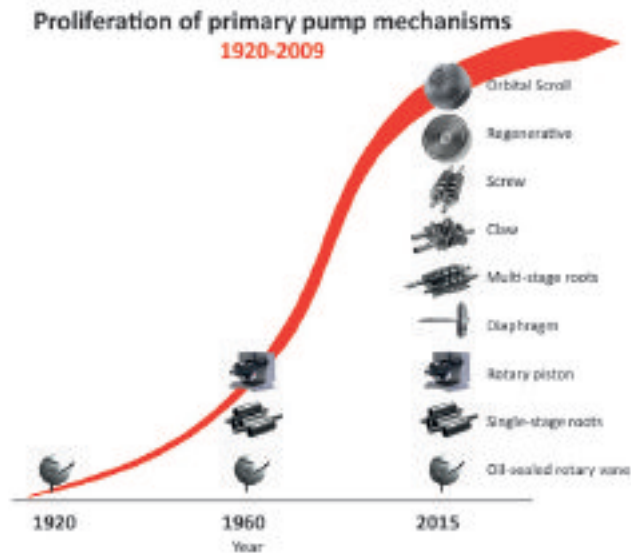


FIGURE 2. Innovation in vacuum technology, inspired by innovation in semiconductor manufacturing process, led to a proliferation of pumping mechanisms, each best suited for particular applications.

mechanical bearings used to support their high-speed rotating shafts (typically ~40,000 rpm). Turbo pumps use rapidly spinning blades to impart direction to gas molecules, propelling them through multiple stages of increasing pressure. Early turbo pumps used oil- or grease-lubricated bearings. Similar to the problems encountered with oil sealed rotary pumps, the new process chemicals tended to degrade the oil, frequently causing pumping failures in as little as a few weeks. This problem was solved by introducing magnetic bearings to levitate the pump drive shaft and eliminate the need for lubricating oil.

In the mid-1990s the semiconductor industry started to use perfluorinated compounds (PFC's) as a convenient source of chamber cleaning and etch gases. However, since only ~30% of the input gas was consumed in the process chamber, there were considerable PFC emissions to the atmosphere. Of particular concern was CF_4 due to its half-life of 50,000 years. The solution was the Thermal Processor Unit which offered the first system with proven destruction reaction efficiency (DRE) of 90% or more for CF_4 .

In the 2000's safety concerns regarding the increasing use of toxic gases led to increasing concerns about the abatement of these materials before they were released to the environment and the safety of personnel within the fab. Integrated vacuum and abatement systems, where everything is contained in a sealed and extracted enclosure, offer a significant improvement

in safety. Integrated systems have since been refined with improvements such as a common control system, reduced footprint and installation costs, and shorter pipelines to reduce operating and maintenance costs.

Abatement systems have continued to evolve. New processes using new materials often require a different approach the abatement. For example, new technologies were developed for high hydrogen processes, copper interconnects and low k dielectrics.

Trends and prospects

Certain vacuum technology trends can be seen over this history of innovation, particularly in the areas of increasing shaft speed, management of pumping power, and the use computer modeling to monitor performance and predict when maintenance will be required so that it can be synchronized with other activities in the fab.

Shaft Speed

When dry pumps were first introduced, they typically operated at around 3,000 to 3,600 rpm. Today's dry pumps use electric drives to run considerably faster, typically 6,000 rpm for claw, screw, and multi-stage roots pumps (**FIGURE 3**).

Increasing a pump's rotational speed delivers a number of advantages. It makes it possible to build more compact pumps and motors, with less internal leakage, which in turn, enables a reduction in the number of pump stages required. It also allows the speed to be reduced when wafers are not being processed, thereby saving energy. Combined, these benefits help reduce the overall pump cost.

Each type of pumping mechanism has different characteristics in the size and shape of volume to fill. A scroll mechanism, with a narrow, ported inlet and long, thin volume space, is one of the slowest pumping mechanisms to fill, so its performance does not increase in proportion to increasing shaft speed. Most scroll pumps operate at just 1500 rpm. A roots mechanism, by contrast, has a very large opening and a short volume length, enabling it to fill quickly allowing efficient use of higher shaft speeds.

The conductance ceiling for roots and screw pumps is probably ~15,000 rpm. Achieving this speed, will require incremental improvements in materials, bearings, and drives. It is likely that we will reach the conductance ceiling for most of the current primary pumping mechanisms within the next decade, although some, such as roots and screw mechanisms, may prove more durable than others.

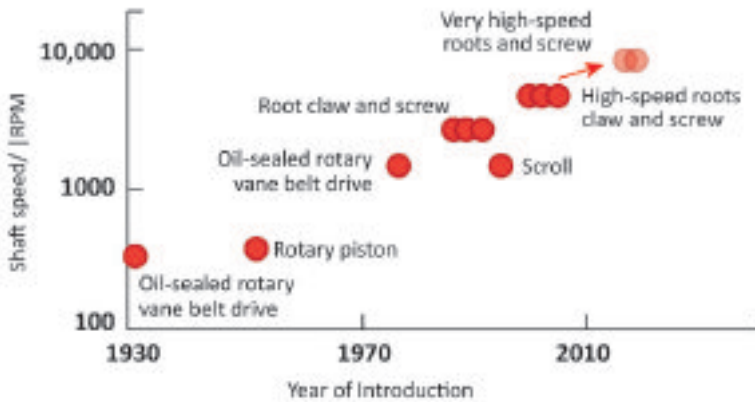


FIGURE 3. Vacuum pump shaft speed has also increased at an exponential rate during the 50 years of Moore’s Law.

Turbomolecular pump conductance is governed by blade speed and molecular velocities. Turbo performance has been limited primarily by the maximum speed the bearings and rotor can withstand. The industry is looking for new materials that are lighter and stronger to enable increased speed. While this pump type may be reaching its conductive limit on heavier gases, it is far from reaching it for lighter gases, such as hydrogen. This may take a much longer time to achieve.

Power management

Significant advances have been made in improving the energy efficiency of both vacuum pumps and abatement systems. Improvements in pump design have increased energy efficiency. Variable speed motors and controllers allow better matching of the motor speed to varying pump requirements. Idle mode allows both pumps and abatement systems to go into a low power mode when not in use. Improvements in burner design have reduced the fuel consumption of combustion based abatement. With the increase in concern about environmental impact and carbon foot print continued improvement in this area can be expected.

Modeling

Computer modeling has been applied extensively to all stages of pump performance. Such variables as stage size, running clearance, leakage, and conductance can all be modeled quite effectively. This allows design simulation and the optimization of performance, such as the shape of the power and speed curve. In this way, a pump can be designed for specific duties, such as load lock pumping or processing high hydrogen flows (**FIGURE 4**).

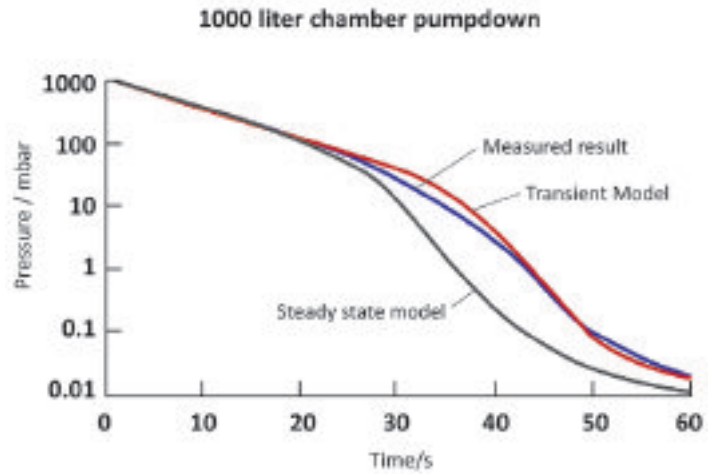


FIGURE 4. Computer modeling allows engineers to experiment with changes the design of vacuum and abatement systems without actually building to system. The plot compares modeled performance to actual performance in pumping down a 1000 liter chamber.

Vacuum pumps of the future will be more reliable and capable of operating for longer periods of time before requiring maintenance. They will be safer to operate, will occupy less fab space, run cleaner and require less power, as well as generate less noise, vibration, and heat. They will also have improved corrosion resistance and the ability to run hotter when required.

As a result, vacuum pumps will be more environmentally friendly, running cleaner and using less power to help reduce their carbon footprint. In addition, they will likely make much greater use of recycled materials and use fewer consumables, thereby helping to reduce overall pump costs. The pumps will be easier to clean, repair, and rebuild for reuse.

Likely technical developments will also include higher shaft speeds, a growing proliferation of pump mechanisms and combinations of mechanisms to increase performance. Finally, vacuum pumps will incorporate new materials and improved modelling to further sharpen performance and reduce system and operating costs.

References

1. G. Moore, "Cramming more Components onto Integrated Circuits" in Electronics, April 19, 1965.
2. V. Smil, "Moore's Curse" in IEEE Spectrum, March 19, 2015.
3. R. Courtland, "The Status of Moore's Law: It's Complicated" in IEEE Spectrum October 28, 2013. ◀