CHAPTER 39

EUV

Apple isn't the only company in the semiconductor business with a bewilderingly complex supply chain. By the late-2010s, ASML, the Dutch lithography company, had spent nearly two decades trying to make extreme-ultraviolet lithography work. Doing so required scouring the world for the most advanced components, the purest metals, the most powerful lasers, and the most precise sensors. EUV was one of the biggest technological gambles of our time. In 2012, years before ASML had produced a functional EUV tool, Intel, Samsung, and TSMC had each invested directly in ASML to ensure the company had the funding needed to continue developing EUV tools that their future chipmaking capabilities would require. Intel alone invested $4 billion in ASML in 2012, one of the highest-stakes bets the company ever made, an investment that followed billions of dollars of previous grants and investments Intel had spent on EUV, dating back to the era of Andy Grove.

The idea behind EUV lithography tools was little changed from when Intel and a consortium of other chip firms had given several of America's national labs "what felt like infinite money for solving an impossible problem," as one of the scientists who worked on the project put it. The concept remained much the same as Jay Lathrop's upside-down microscope: create a pattern of light waves by using a "mask" to block some of the light, then project the light onto photoresist chemicals applied to a silicon wafer. The light reacts with photoresists, making it possible to deposit material or etch it away in perfectly formed shapes, producing a working chip.

Lathrop had used simple visible light and off-the-shelf photoresists produced by Kodak. Using more complex lenses and chemicals, it eventually became possible to print shapes as small as a couple hundred nanometers on silicon wafers. The wavelength of visible light is itself several hundred nanometers, depending on the color, so it eventually faced limits as transistors were made ever smaller. The industry later moved to different types of ultraviolet light with wavelengths of 248 and 193 nanometers. These wavelengths could carve shapes more precise than visible light, but they, too, had limits, so the industry placed its hope on extreme ultraviolet light with a wavelength of 13.5 nanometers.

Using EUV light introduced new difficulties that proved almost impossible to resolve. Where Lathrop used a microscope, visible light, and photoresists produced by Kodak, all the key EUV components had to be specially created. You can't simply buy an EUV lightbulb. Producing enough EUV light requires pulverizing a small ball of tin with a laser. Cymer, a company founded by two laser experts from the University of California, San Diego, had been a major player in lithographic light sources since the 1980s. The company's engineers realized the best approach was to shoot a tiny ball of tin measuring thirty-millionths of a meter wide moving through a vacuum at a speed of around two hundred miles per hour. The tin is then struck twice with a laser, the first pulse to warm it up, the second to blast it into a plasma with a temperature around half a million degrees, many times hotter than the surface of the sun. This process of blasting tin is then repeated fifty thousand times per second to produce EUV light in the quantities necessary to fabricate chips. Jay Lathrop's lithography process had relied on a simple bulb for a light source. The increase in complexity since then was mind-boggling.

Cymer's light source only worked, though, thanks to a new laser that could pulverize the tin droplets with sufficient power. This required a carbon dioxide–based laser more powerful than any that previously existed. In summer 2005, two engineers at Cymer approached a German precision tooling company called Trumpf to see if it could build such a laser. Trumpf already made the world's best carbon dioxide–based lasers for industrial uses like precision cutting. These lasers were monuments of machining in the best German industrial tradition. Because around 80 percent of the energy a carbon dioxide laser produces is heat and only 20 percent light, extracting heat from the machine is a key challenge. Trumpf had previously devised a system of blowers with fans that turned a thousand times a second, too fast to rely on physical bearings. Instead, the company learned to use magnets, so the fans floated in air, sucking heat out of the laser system without grinding against other components and imperiling reliability.

Trumpf had a reputation and a track record for delivering the precision and reliability Cymer needed. Could it deliver the power? Lasers for EUV needed to be substantially more powerful than the lasers Trumpf already produced. Moreover, the precision Cymer demanded was more exacting than anything Trumpf had previously dealt with. The company proposed a laser with four components: two "seed" lasers that are low power but accurately time each pulse so that the laser can hit 50 million tin drops a second; four resonators that increase the beam's power; an ultra-accurate "beam transport system" that directs the beam over thirty meters toward the tin droplet chamber; and a final focusing device to ensure the laser scores a direct hit, millions of times a second.

Every step required new innovations. Specialized gases in the laser chamber had to be kept at constant densities. The tin droplets themselves reflected light, which threatened to shine back into the laser and interfere with the system; to prevent this, special optics were required. The company needed industrial diamonds to provide the "windows" through which the laser exited the chamber, and had to work with partners to develop new, ultra-pure diamonds. It took Trumpf a decade to master these challenges and produce lasers with sufficient power and reliability. Each one required exactly 457,329 component parts.

After Cymer and Trumpf found a way to blast tin so it emits sufficient EUV light, the next step was to create mirrors that collected the light and directed it toward a silicon chip. Zeiss, the German company that builds the world's most advanced optical systems, had built mirrors and lenses for lithography systems since the days of Perkin Elmer and GCA. The difference between the optics used in the past and those required by EUV, however, was about as vast as the contrast between Lathrop's lightbulb and Cymer's system of blasting tin droplets.

Zeiss's primary challenge was that EUV is difficult to reflect. The 13.5nm wavelength of EUV is closer to X-rays than to visible light, and as is the case with X-rays, many materials absorb EUV rather than reflect it. Zeiss began developing mirrors made of one hundred alternating layers of molybdenum and silicon, each layer a couple nanometers thick. Researchers in Lawrence Livermore National Lab had identified this as an optimal EUV mirror in a paper published in 1998, but building such a mirror with nanoscale precision proved almost impossible. Ultimately, Zeiss created mirrors that were the smoothest objects ever made, with impurities that were almost imperceptibly small. If the mirrors in an EUV system were scaled to the size of Germany, the company said, their biggest irregularities would be a tenth of a millimeter. To direct EUV light with precision, they must be held perfectly still, requiring mechanics and sensors so exact that Zeiss boasted they could be used to aim a laser to hit a golf ball as far away as the moon.

For Frits van Houts, who took over leadership of ASML's EUV business in 2013, the most crucial input into an EUV lithography system wasn't any individual component, but the company's own skill in supply chain management. ASML engineered this network of business relationships "like a machine," van Houts explained, producing a finely tuned system of several thousand companies capable of meeting ASML's exacting requirements. ASML itself only produced 15 percent of an EUV tool's components, he estimated, buying the rest from other firms. This let it access the world's most finely engineered goods, but it also required constant surveillance.

The company had no choice but to rely on a single source for the key components of an EUV system. To manage this, ASML drilled down into its suppliers' suppliers to understand the risks. ASML rewarded certain suppliers with investment, like the $1 billion it paid Zeiss in 2016 to fund that company's R&D process. It held all of them, however, to exacting standards. "If you don't behave, we're going to buy you," ASML's CEO Peter Wennink told one supplier. It wasn't a joke: ASML ended up buying several suppliers, including Cymer, after concluding it could better manage them itself.

The result was a machine with hundreds of thousands of components that took tens of billions of dollars and several decades to develop. The miracle isn't simply that EUV lithography works, but that it does so reliably enough to produce chips cost-effectively. Extreme reliability was crucial for any component that would be put in the EUV system. ASML had set a target for each component to last on average for at least thirty thousand hours—around four years—before needing repair. In practice, repairs would be needed more often, because not every part breaks at the same time. EUV machines cost over $100 million each, so every hour one is offline costs chipmakers thousands of dollars in lost production.

EUV tools work in part because their software works. ASML uses predictive maintenance algorithms to guess when components need to be replaced before they break, for example. It also uses software for a process called computational lithography to print patterns more exactly. The atomic-level unpredictability in light waves' reaction with photoresist chemicals created new problems with EUV that barely existed with larger-wavelength lithography. To adjust for anomalies in the way light refracts, ASML's tools project light in a pattern that differs from what chipmakers want imprinted on a chip. Printing an "X" requires using a pattern with a very different shape but which ends up creating an "X" when the light waves hit the silicon wafer.

The final product—chips—work so reliably because they only have a single component: a block of silicon topped with other metals. There are no moving parts in a chip, unless you count the electrons zipping around inside. Producing advanced semiconductors, however, has relied on some of the most complex machinery ever made. ASML's EUV lithography tool is the most expensive mass-produced machine tool in history, so complex it's impossible to use without extensive training from ASML personnel, who remain on-site for the tool's entire life span. Each EUV scanner has an ASML logo on its side. But ASML's expertise, the company readily admits, was its ability to orchestrate a far-flung network of optics experts, software designers, laser companies, and many others whose capabilities were needed to make the dream of EUV a reality.

It's easy to lament the offshoring of manufacturing, as Andy Grove did during the final years of his life. That a Dutch company, ASML, had commercialized a technology pioneered in America's National Labs and largely funded by Intel would undoubtedly have rankled America's economic nationalists, had any been aware of the history of lithography or of EUV technology. Yet ASML's EUV tools weren't really Dutch, though they were largely assembled in the Netherlands. Crucial components came from Cymer in California and Zeiss and Trumpf in Germany. And even these German firms relied on critical pieces of U.S.-produced equipment. The point is that, rather than a single country being able to claim pride of ownership regarding these miraculous tools, they are the product of many countries. A tool with hundreds of thousands of parts has many fathers.

"Will it work?" Andy Grove had asked John Carruthers, before investing his first $200 million in EUV. After three decades of investment, billions of dollars, a series of technological innovations, and the establishment of one of the world's most complex supply chains, by the mid-2010s, ASML's EUV tools were finally ready to be deployed in the world's most advanced chip fabs.