

Etching Technologies in Semiconductor Manufacturing: A Short Review

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Abstract

In semiconductor fabrication process etching is a fundamental technology, where it is used to selectively remove material from the surface of a wafer. This step is vital in crafting the intricate patterns and features which form the basis of an integrated circuit. With the ongoing drive in the semiconductor industry towards miniaturization, more compact chips, the need for advanced etching techniques is more crucial than ever. Therefore, this technology must continuously improve and evolve to meet the ever-shrinking feature size requirements. Here, in this review work for EEGR 742 Microelectronics class the history and current state of art of etching technologies will be discussed. With that the major challenges in etching for future nodes, evaluating recent breakthroughs and research, and assessing the impact of these advancements on the industry will also be examined.

Keywords

Etching • Patterns • Ever-shrinking • Microelectronics • Future nodes

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1 Introduction (Etching: The Art of Sculpting Silicon)

The revolution in the silicon industry brought this new world of technology where etching stands as a crucial artist, silently sculpting the intricate landscapes that power our modern world. This seemingly simple act of removing material, however, hides a complex and fascinating world of science and technology. From the towering skyscrapers of CPUs to the microscopic pathways of transistors, etching plays a vital role in shaping the very fabric of our digital age. Etching is an ancient art form, predating the silicon chip by millennia. Today, the tools have become more sophisticated, but the fundamental principle remains the same: to selectively remove material to create a desired pattern. According to Plummer and Griffin [1], machines that have been used in modern etching are among the most sophisticated 2nd tier machines, whereas lithographic tools occupied the first tier. In the silicon industry etching becomes a delicate process between precision and control. In the beginning of the semiconductor industry we started with wet chemical etching which is also known as isotropic etching as well. But now in the modern era of etching, plasma etching plays the role of artist in this art, where a charged gas filled with energetic ions, electrons, free radicals etc. With meticulous precision, these ions or electrons bombard the surface of the wafer, carving away microscopic trenches and pathways. The goal is to create a landscape of valleys and hills, each representing a specific function in the integrated circuit chip. There are numerous challenges on the way of highly precise and controlled etching. Where it is necessary to ensure that the whole etching process is both anisotropic and selective. At the same time it needs to be reproducible and cost effective.

Although silicon industry faces all these challenges, the silicon industry technology has made remarkable advancements and progress over the years. New techniques such as reactive ion etching (RIE) and atomic layer etching

(ALE) have allowed for the creation of nano-scale and more complex features on silicon chips. As we look to the future, etching technology will continue to play a critical role in driving the next wave of research. New breakthroughs in areas like directed self-assembly (DSA) and cryogenic etching offer exciting possibilities for further miniaturization and improved performance. Here in this review work we will discuss the history and current state of the art of etching with major challenges in etching for future nodes, evaluating recent breakthroughs and research, and assessing the impact of these advancements on the industry.

2 History and Current State of the Art of Etching in Microfabrication

The history of etching in microfabrication dates back to the early days of semiconductor manufacturing [2]. Initially, wet chemical etching was used can be observed from Fig. 1, which involved applying liquid chemicals to etch away parts of the substrate. Imagine dipping a silicon wafer into a bath of hydrofluoric acid to etch away its oxide layer, leaving behind the pure silicon for transistor formation. Wet etching, though simple, had limitations. It was difficult to control precisely, often leading to uneven features and rounded edges. Wet etching's roots can be traced back to the early days of microelectronics, dating back to the 1950s and 1960s [2]. Despite of limitation wet etching is still being used because of:

1. **Simplicity and Affordability:** Wet etching setups are generally less complex and expensive than plasma etching equipment.
2. **Versatility:** Different wet etchants can be used for various materials and applications.
3. **Controllability:** By carefully tailoring the etching parameters, desired features and patterns can be achieved.

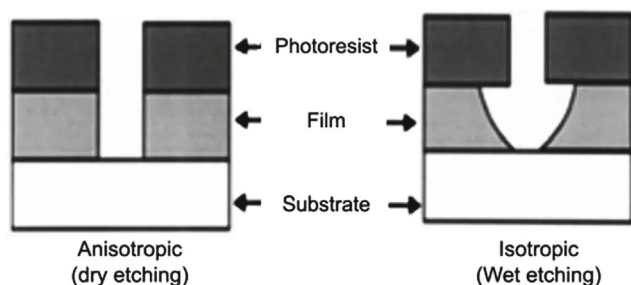


Fig. 1 Anisotropic (dry) and Isotropic (wet) etching [15]

As the need for finer and more precise etching grew, dry etching hence plasma etching techniques were developed around 1980. These techniques allowed for anisotropic (directional) etching, which was a significant improvement over the isotropic etching of chemical methods [3]. By controlling the plasma parameters, etching depth, profile, and pattern can be precisely controlled, enabling the creation of intricate micro and nano-scale features. Plasma generally known as 4th state material is a mixture of Ions, electrons, neutral molecules, excited molecules, and free radicals contained by sheaths that create a positive bias. This bias accelerates ions directionally to the substrate, enabling directional etching. Plasma etching ranges from purely physical to purely chemical processes.

Plasma etching technologies have gained significant advancement over the past few decades. Where researchers and engineers introduced new plasma sources, etching chemistries, and reactor designs. This development has enabled the creation of increasingly smaller and more complex features with greater precision and control [8]. Today, the silicon industry boasts a diverse toolbox for etching:

- **Reactive Ion Etching (RIE):** This technology utilizes reactive gasses like chlorine or fluorine for etching [4]. Then these gasses chemically react with material on a substrate. This reaction causes the material on the substrate to be etched away. It is comparatively a fast-etching technique, while combining this fast speed of etching with its ability to provide good etching control and anisotropy, makes it a popular choice for many semiconductor manufacturing applications. A basic image of this technique can be observed in Fig. 2a.
- **Deep Reactive Ion Etching (DRIE):** This etching system operates on the principle of creating exceptionally deep and narrow trenches in materials. This technique utilizes a cyclic process of alternating etching and passivation steps. The etching phase involves reactive ions that carve out the material. At the same time the passivation phase deposits a protective layer to control the direction and depth of the etch, allowing for the creation of very deep and precisely defined trenches [5]. A basic image of this technique can be observed in Fig. 2b.
- **Cryogenic Etching:** Ultra-low temperature gases have been used for this highly anisotropic etching process. It is an effective etching system for delicate structures. Because while using low temperature it also slows down the chemical kinetics and this slowing down chemical reaction allows us to have more precise and controlled etching. This cryogenic temperature also offers enhancement of reactivity of certain gasses. This enhancement causes more cleaner and more defined etch profiles [6].

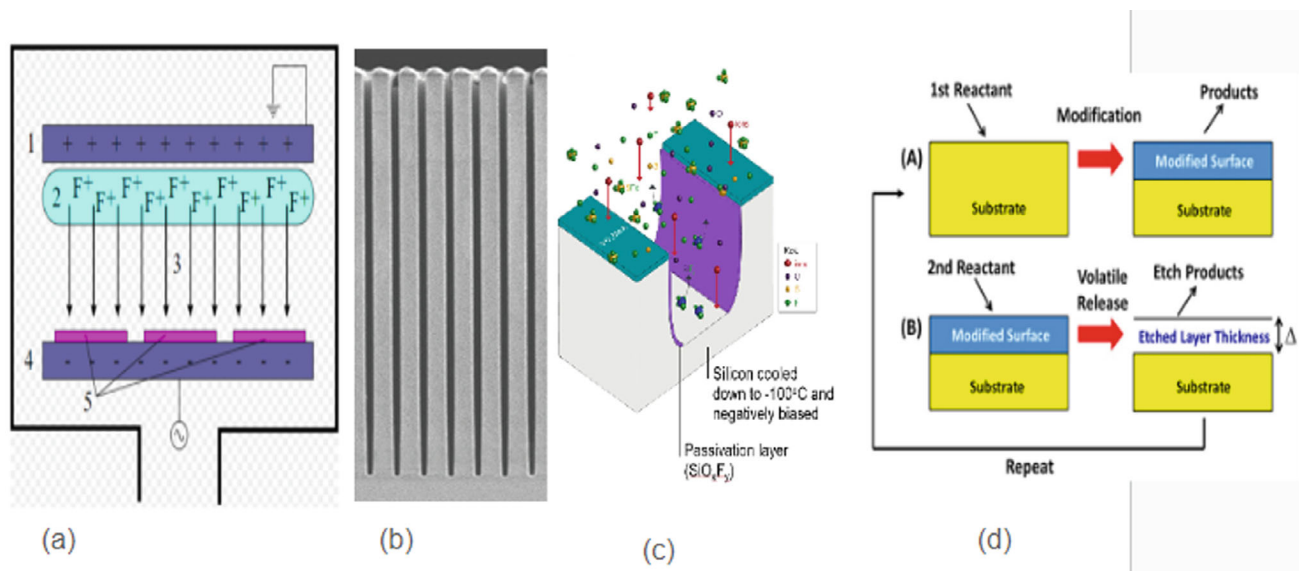


Fig. 2 Different advanced etching techniques in Silicon industry **a** Reactive ion etching (RIE) [15], **b** Deep reactive ion etching (DRIE) [16], **c** Cryogenic etching [17] and **d** Atomic layer etching (ALE) [18]

A basic image of this technique can be observed in Fig. 2c.

- Atomic Layer Etching (ALE): Since the quest for miniaturization and performance enhancement keeps etching technique going on. ALE emerged as a key technique. Especially, where we need atomic-scale accuracy. Atomic Layer Etching (ALE) operates on the principle of removing material from a surface one atomic layer at a time. This precise, controlled method allows for exceptional accuracy in etching, essential for fabricating the ultra-fine features in modern semiconductor devices [7]. A basic image of this technique can be observed in Fig. 2d.

The future of etching technology continues to be a critical area of research and development, driven by the ongoing miniaturization and complexity of electronic devices.

3 Major Problems in Achieving Feature Size Goals

As feature sizes continue to shrink, there are several challenges that must be overcome in etching technology. These include:

- Anisotropy: One of the primary challenges in etching is the trade-off between selectivity and directionality. The ability to etch features with vertical sidewalls is crucial for achieving small critical dimensions (CD). However, most etching processes have some degree of lateral

etching, which can lead to linewidth loss and profile rounding [2].

- Damage: The energetic ions in the plasma can damage the underlying material, leading to reliability issues.
- Selectivity: The etching process must be highly selective for the target material, while minimizing the etching of other materials on the wafer.
- Cost: Etching is a relatively expensive process, especially plasma etching, and the cost per wafer can increase significantly as feature sizes shrink.
- Chemical Mechanical Polishing (CMP) Integration: CMP is a process that combines chemical etching with mechanical polishing to produce a planarized surface. Originally developed for multilevel backend structures, CMP is now also widely used in frontend processing. The integration of CMP is driven by the need for thin, uniform thickness layers of photoresist required by modern DUV and EUV lithography systems to produce high-resolution images. However, CMP modeling is still fairly empirical, and there are ongoing efforts to develop a deeper scientific basis for these models [2].

4 Ability to Meet Future Size Requirements

While etching currently plays a crucial role in enabling miniaturization, its ability to meet future size requirements depends on overcoming existing challenges and continuous advancements in technology. Some of its recent advancement to meet the requirement has been listed below.

4.1 Precision and Control

Recent breakthroughs like 3D integration with deep silicon dry etching (DSDE) enable stacking multiple chips vertically, pushing feature sizes close to 5 nm in leading-edge processors [9]. Another technique, Directed Self-Assembly (DSA) can achieve smaller feature sizes than traditional lithography alone (researcher observed sub-10 nm fabrication), pushing the limits of what can be achieved through conventional techniques [12]. DSA refers to a set of techniques that utilize the intrinsic properties of molecules or nanoparticles to spontaneously assemble into predefined patterns on a surface. Imagine tiny Lego blocks arranging themselves perfectly without needing physical manipulation—that's the underlying principle of DSA. These patterns can then serve as templates for subsequent etching or deposition processes, leading to the creation of highly precise and complex nanostructures. DSA can theoretically achieve feature sizes well below what's currently possible with conventional etching, potentially reaching the atomic scale. This opens doors for next-generation electronics, quantum computing, and other nanotechnologies. Combining DSA with advanced etching techniques holds the key to unlocking a new era of nanotechnology with incredible capabilities. Another 02 advanced technology for etching is shown in Fig. 3.

4.2 Versatility

EUV lithography combined with etching allows for patterning features below 7 nm. For instance, Samsung's 3 nm GAA (Gate-All-Around) transistors rely heavily on EUV and advanced etching techniques [10].

4.3 Continuous Development

Researchers are exploring directed energy deposition techniques like focused electron beam-induced deposition (FEBID) for creating even smaller features, potentially reaching the atomic scale [11].

4.4 Challenges

Material Limitations: Etching some materials like Gallium Nitride (GaN) used in power electronics remains challenging due to its high chemical resistance [13]. Development of novel etch chemistries is crucial for future miniaturization in this area.

Physics and Scalability: As feature sizes approach atomic dimensions, quantum tunneling and other physical limitations can become significant, potentially hindering further miniaturization through traditional etching methods [14].

Etching remains a vital tool for microfabrication miniaturization, but its role in meeting future size requirements will hinge on addressing material limitations, cost-effectiveness, and pushing the boundaries of physics and scalability. The future likely lies in a combination of improved etching techniques, innovative materials, and potentially complementary fabrication methods [20–32].

4.5 Recent Breakthroughs and Research

By pushing the limits of precision and control several recent breakthroughs and research efforts hold promise for improving etching technology. These include- High-aspect-ratio etching: This technique uses a combination of RIE and

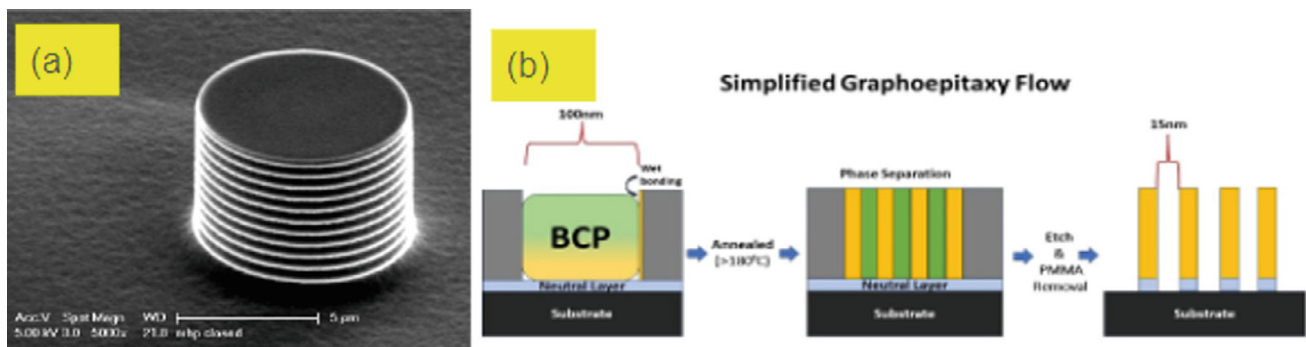


Fig. 3 Another 02 advanced technology for etching **a** A silicon micro-pillar fabricated using DSDE technique [19] and **b** a simplified flow demonstrating graphoepitaxial directed self-assembly [20]

other processes to achieve very high aspect ratios (depth-to-width ratios). Atomic layer etching (ALE): This technique uses self-limiting chemical reactions to etch surfaces one atomic layer at a time, offering excellent control and selectivity. Plasma-based directed self-assembly (DSA): This technique uses plasma to create high-resolution patterns on the wafer surface that can be used as etch masks. Cryogenic etching: This technique uses a cold plasma to etch materials at low temperatures, minimizing damage to the underlying substrate.

4.6 Impact on the Silicon Industry

These advancements in etching technology are expected to have a significant impact on the silicon industry. Which will make it possible to create smaller and more complex features in semiconductor devices. Hence, will help to drive the next generation of semiconductor devices and make them faster, more powerful, and more energy-efficient. All these recent breakthroughs and ongoing research in etching hold immense potential to impact the silicon industry in a significant way, which have been discussed below:

Shrinking Circuits: This improvement will allow us to shrink circuit size. Techniques like 3D integration with DSDE and directed self-assembly (DSA) allow for feature sizes close to 5 nm and even sub-10 nm, respectively. Having this much smaller allows more transistors packed into smaller spaces, leading to faster, more powerful, and energy-efficient chips. **3D Integration Revolution:** Stacking chips vertically with DSDE opens up possibilities for more complex and integrated functionalities within a smaller footprint. This could lead to innovations in areas like artificial intelligence, high-performance computing, and even neuromorphic computing.

Economic Impact: Advancement in etching technology can increase cheap production and lower the cost of production. It will also allow wider accessibility to cutting-edge technologies. This could have a significant impact on various industries and economies.

Environmental Impact: According to Moore's law miniaturization also reduces energy consumption. If we reduce energy consumption, it will cause a lower carbon footprint of electronic devices.

Also, advanced etching techniques can handle materials like gallium arsenide and silicon nitride, enabling diverse applications beyond traditional electronics:

High-efficiency LEDs: Brighter and more energy-efficient lighting for the world.

Microelectromechanical Systems (MEMS): Tiny sensors and actuators for automotive, aerospace, and medical applications.

Biocompatible Devices: Can be used for implantable microfluidic devices for personalized medicine and drug delivery.

5 Conclusion

Etching Technologies: Traditional methods: Wet etching (chemical) and dry etching (plasma-based) offer good control and versatility. Advanced techniques: RIE, DRIE, Cryogenic Etching, FIB provide precise control, high aspect ratio features, and suitability for sensitive materials. **Emerging advancements:** 3D integration with DSDE, DSA, FEBID push the boundaries of miniaturization and open doors for next-generation technologies. **Overall Technology Assessment:** Promising potential: Significant impact on the silicon industry and beyond is highly likely. **Key benefits:** Miniaturization leading to faster, more powerful, and energy-efficient chips; expansion to new materials and applications; 3D integration for complex functionalities. **Challenges:** Material limitations, quantum effects at the atomic scale, cost and scalability of some advanced techniques. **Areas of Impact:** Consumer electronics: Lighter, thinner, and more powerful devices. AI and HPC: More efficient and powerful AI systems. Medical technology: Miniaturized sensors and devices for improved diagnostics and treatments. New materials and applications: LEDs, MEMS, biocompatible devices. **3D integration revolution:** Neuromorphic computing, high-bandwidth memory, heterogeneous integration.

Future Outlook: Continued research and development to address challenges and enhance practicality. Synergies with other technologies like self-assembly and additive manufacturing. Responsible development and deployment considering ethical implications. Etching is a critical technology in the silicon industry, and it will continue to play a vital role in enabling the development of ever-smaller and more complex chips. While there are still challenges that need to be addressed, recent breakthroughs and research offer promising solutions for the future. As the industry continues to push the boundaries of technology, etching is sure to evolve and adapt to meet the ever-changing needs of the silicon roadmap. Overall, etching technology is a mature and well-established field, but it is constantly evolving to meet the demands of the silicon industry. Recent breakthroughs and research suggest that etching will continue to play a critical role in enabling the development of smaller and more complex chips for many years to come. Also, Technology is

advancing at an unprecedented pace across various domains, significantly impacting power generation, machine learning, robotics, and photovoltaics.

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