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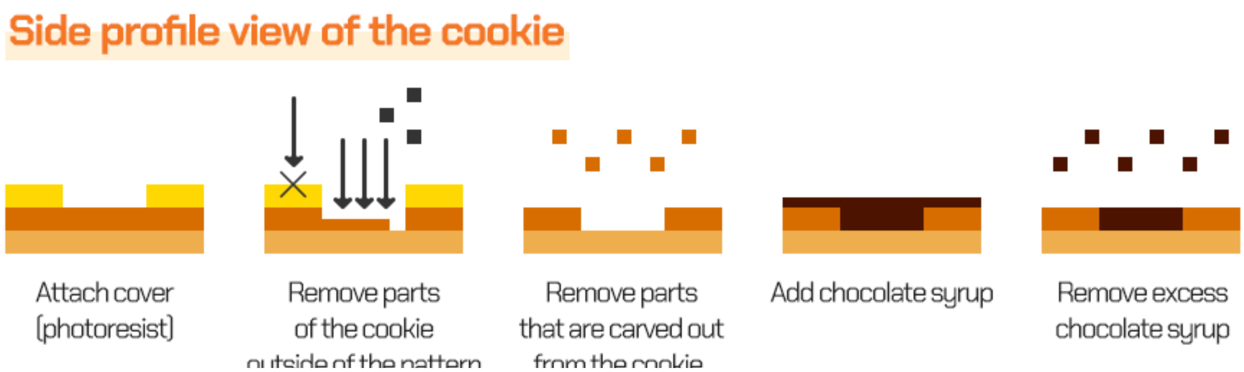
Semiconductor Front-End Process Episode 4: Etching Fine and Identical Wafer Patterns

February 21, 2023

In the previous episode, we explained how semiconductor manufacturers use photolithography to create the desired pattern on the wafer's surface. While this process can be said to "print" the required pattern, a subsequent process known as etching is required to remove unwanted materials to carve the pattern on the wafer. This article will provide an overview of the etching process and introduce the key methods of chemical and physical etching.



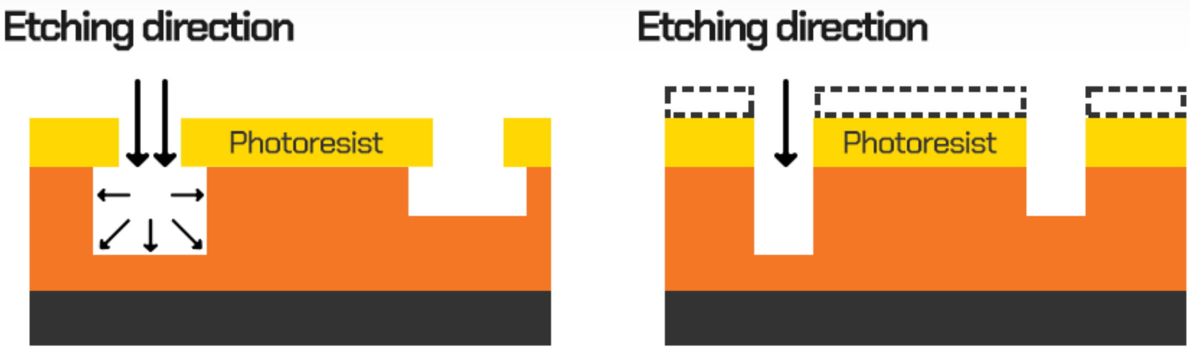
▲ Figure 1. Steps to carving out the center of a cookie to fill it with chocolate syrup

Returning to the cookie analogy in the previous episode, how can chocolate syrup be added to the middle layer of the cookies shaped like the SK hynix logo, the Wings of Happiness? The easiest way that comes to mind is to remove the middle part of the cookie to pour the chocolate syrup into it. The process of carving out the part where the chocolate syrup needs to go is equivalent to "etching" in semiconductor manufacturing. When making cookies, it involves placing a cover (acting as a photomask) with holes on top of the cookie and applying a solvent that removes the uncovered areas. Afterwards, the cover is removed from the cookie so the chocolate can be poured in. Removing the excess chocolate syrup and making another layer of the cookie on top of it will allow chocolate syrup to fill the crack in the cookie.

Going back to semiconductors, there are various types of processes used to remove materials on the wafer including rinsing and etching. Rinsing refers to washing the entire wafer to remove unwanted impurities, while etching is a process that uses a photomask to carve out the desired fine pattern.

Etching Characteristics: From Selectivity to Uniformity

As etching has many important properties, the figure below will help explain many of



Isotropic Etching	Anisotropic Etching
High selectivity	Low selectivity
Fast speed	Slow speed
High uniformity	Low uniformity

▲ Figure 2: Characteristics of isotropic and anisotropic etching

The first term to know is “selectivity,” which is the measure of how well an etching process removes only the targeted materials. During etching, some materials which are supposed to remain on the wafer such as the photoresist can also be slowly dissolved. Therefore, high selectivity means efficiently removing only the targeted materials and minimizing the removal of the areas which are to remain.

“Directionality” refers to the direction of the etching, and this can be divided into isotropic etching and anisotropic etching. Isotropic etching occurs in all directions with the exposed part of the photoresist as the starting point, while anisotropic

Therefore, there needs to be a balancing act between accuracy and speed during the etching process. For example, the pressure of the gas must be lowered to increase the anisotropy of etching, but lowering the pressure leads to reducing the amount of gas that is reacted and, eventually, to the slowing down of the etching.

"Uniformity" measures how evenly etching occurs on the entire surface of the wafer. Unlike photolithography, etching exposes an entire wafer to gas. For etching to proceed, substances must be circulated by injecting reactant gas and removing by-products. However, applying this evenly to the entire wafer is a difficult task, which is why different areas on the wafer have varying etch rates.

Dry and Wet Etching

Like oxidation, etching is also divided into wet and dry. While wet oxidation involves using steam as the reactant gas, wet etching dips the wafer in a reactant liquid. This method of etching has the advantages of being fast and having a high selectivity as a chemical process. However, the nature of this method leads to the etching being strongly isotropic. The liquid moves freely and reacts with the substances when the wafer is dipped in it. This leads to low precision as parts on the back of the photoresist that are not meant to be removed are taken off quickly. Moreover, due to surface tension, the etching liquid can't pass through the gap between the photoresist and the wafer if the gap is too small. Even if a stepper draws a fine pattern, it proves to be useless if the circuit cannot be made according to the blueprint. As a result, wet etching can't be used in core layers of modern semiconductors.

▲ Figure 3: Liquid moving freely inside a gap during wet etching

Dry etching is a process in which a wafer applied with a photomask is exposed to gas. Some examples of this type of etching include plasma etching, sputtering, and reactive ion etching (RIE). Unlike wet etching, these processes remove materials in a variety of ways, so the anisotropic and isotropic properties cannot be clearly explained. For instance, dry etching that's performed chemically will be isotropic and physical etching will be anisotropic. Nevertheless, as RIE became a prominent dry etching method, its properties of being highly anisotropic and reasonably quick resulted in dry etching being considered as anisotropic. The exact parameters of RIE's mechanism to remove materials will be further explained in the next section.

Chemical and Physical Etching

In addition to dry and wet etching, the etching process can also be categorized into chemical and physical etching. The chemical method uses a substance that reacts well with the material to be removed. There are various materials on the bottom of the photoresist that need to be removed such as an oxide film formed in the oxidation process or other materials applied in the deposition process. These materials are successfully taken off with the spraying of a substance that only reacts well with these

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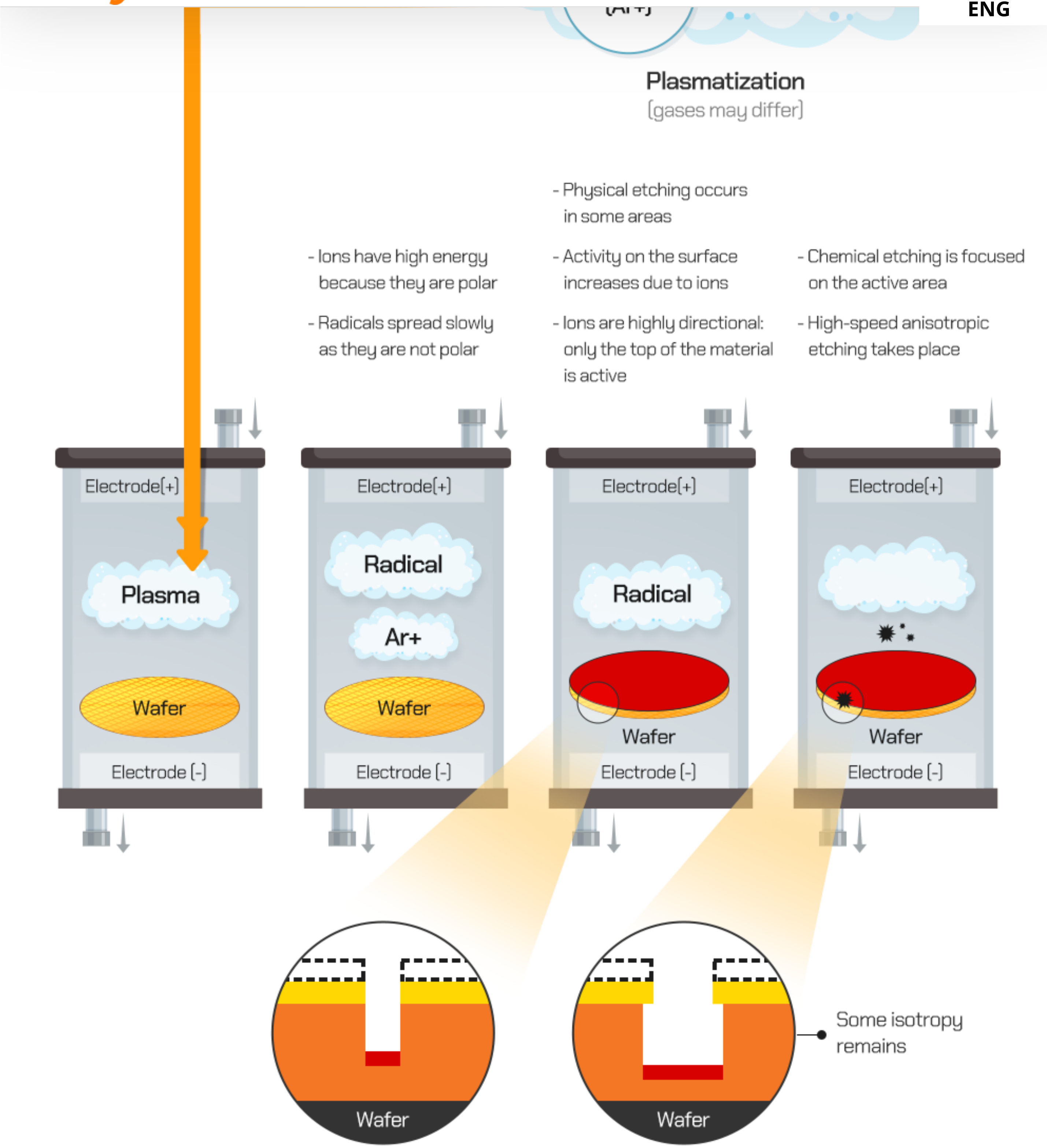
etching. As a chemical reaction is the main mechanism of this process, it has high selectivity.

The other method is physical etching, also referred to as sputtering. This process involves high-energy particles colliding with the wafer's surface and removing the surface of materials. When the pressure of gas–usually inert gas–is lowered and high energy is applied to it, the gas separates into positive atoms and negative electrons. After the electric field is applied towards the direction of the wafer, the atoms accelerate and collide with the wafer.

Although physical etching is quite a simple process, it does have its limitations. As low pressure equates to low amounts of gas, the etch rate is slow. Additionally, physical etching removes a large proportion of materials that should remain on the wafer as it relies on force–which doesn't distinguish between materials. The most important method that's used in practice is RIE which combines the two methods mentioned above. As a type of dry etching, RIE converts the gas used in etching into plasma. When strong energy is applied after injecting mixed gas–formed with substances such as reactant gas and inert gas–into the equipment, the etching gas separates into electrons, positive ions, and radicals[1)]. Electrons are lightweight and don't have a big impact, but positive ions can perform physical etching if they accelerate toward the direction of the wafer's surface with an electric field. Since positive ions carry an electric charge, they are highly directional when accelerated in an electric field. Up to this point, there aren't too many differences between RIE and physical etching.

*[1)]**Radical**: A highly reactive atom, molecule or ion that has at least one unpaired electron.*


(Ar+)
Plasmatization
(gases may differ)
- Physical etching occurs in some areas
- Ions have high energy because they are polar
- Radicals spread slowly as they are not polar
- Activity on the surface increases due to ions
- Ions are highly directional: only the top of the material is active
- Chemical etching is focused on the active area
- High-speed anisotropic etching takes place
Electrode(+)
Plasma
Wafer
Electrode (-)
Electrode(+)
Radical
Ar+
Wafer
Electrode (-)
Electrode(+)
Radical
Wafer
Electrode (-)
Electrode(+)
Wafer
Electrode (-)
Wafer
Wafer
Some isotropy remains

However, positive ions produce an additional effect. They weaken the bond between the collided materials as they are highly directional due to the electric field. Consequently, they tend to collide in the red area shown in Figure 4. This causes the side area to remain strongly bonded, while the bond at the front becomes weaker. When the radicals that are highly reactive come into contact later on, the front part of the surface is etched even quicker. In the end, this increases the anisotropy of the etching.

Plasma etching technology achieves three different feats. In addition to physically etching by producing positive ions, the method weakens the material to be etched while increasing the reactivity of the gas being used in the etching. Therefore, it possesses both the advantages of high selectivity and anisotropy found in chemical and physical etching, respectively. Nevertheless, even if RIE is used, etching alone cannot create all of the intended patterns.

Etchants and Etching Gases

It becomes clear by now that the gases used in etching are crucial and that the key to etching is chemical reactions. Therefore, etchants must be picked according to the material that is meant to be removed. Major factors to consider when choosing the gas include seeing whether the resulting by-products are easily removable and knowing how fine the selectivity and reaction rates are. Compounds of the halogen family that have high reactivity rates–including fluorine, chlorine, and bromine–are commonly used.

Types of gases for plasma etching

			concentration
Example	See table below	O_2, N_2, He, etc.	He, Ar, Xe, etc.

Target of etching	Etchant	By-products from etching	Usage
Si	NF_3, SF_6, CF_4, etc., Cl_2, CCl_4, HBr	SIF_4(-86℃), $SICl_4$(58℃), $SiBr_4$(154℃)	(For insulation) trench barrier, gate
SiO_2 (Si_3N_4, SiON)	CF_4, C_4F_6, C_4F_8, etc., CHF_3, CH_2F_2, CH_3F, etc.	SIF_4(-86℃) CO(-191℃), CO_2(-57℃), HCN(26℃)	Contact area of the device or metal
Al	Cl_2, BCl_3	$AlCl_3$(180℃, Subl.)	Metal wiring
Ti, TiN	Cl_2, CCl_4	$TiCl_3$(136℃)	
W	NF_3, SF_6, CF_4, etc., Cl_2	WF_6(19℃), WCl_4(337℃)	
PR(α -Carbon)	O_2, N_2, etc.	CO(-191℃), CO_2(-57℃), HCN(26℃)	Mask
Cu, Fe, Ni, Co, Pt, etc.	Difficult to etch	Cu_2Cl_2(1,490℃), Cu_2F_2(1,100℃)	Metal

▲ Figure 5: Types of gases for plasma etching (Source: The Understanding of the Semiconductor Manufacturing Technology, p. 443)

Large numbers of materials can be applied to the top of a wafer and etched. This next section will look at several of these important materials. Generally, silicon-based materials can be easily removed with fluorine gas. When silicon comes into contact

Silicon dioxide, which is commonly used as an insulating or protective mate[...] also be easily removed by gas containing fluorine. But unlike pure silicon, silicon dioxide is in a stable state as it is bonded with oxygen and, thus, needs to be used with gas that produces heat. So, gases that have carbon atoms bonded to fluorine are usually used for etching. The silicon atom is taken from oxygen by the thermogenic action of the gas.

In the HKMG[2)] and BEOL[3)] processes, it's necessary to etch metallic materials. While metals generally react with halogen-based gases like chlorine and fluorine, it's notable that metals generally have by-products with high evaporation points. Therefore, it's more difficult to remove them. For copper, the evaporation point of its by-products from reacting with gas is over 1,000 degrees Celsius. This means that copper adheres like rust. However, if the temperature of the wafer is raised to 1,000 degrees Celsius to remove these by-products, the heat can damage important devices. As a result, copper–regardless of its exceptional electrical properties–could be introduced with a new method of construction called Damascene[4)] only after the electrical properties of aluminum have reached their limit. It's important to bear in mind that a new material is not valuable in and of itself, but that it's only valuable when a new process capable of mass production is introduced and harmonizes with existing processes.

[2)]***HKMG (High-K Metal Gate)****: A new MOSFET gate developed to effectively reduce leakage current. A transistor where metal replaces the gate that was polysilicon and high-K replaces the insulation film that was silicon dioxide.*

[3)]***BEOL (Back End of Line)****: A process of creating extremely fine wiring to connect billions of unit devices together.*

[4)]***Damascene****: A process used to create copper wiring. After etching the metal space, the metal goes under deposition and its excesses are physically removed.*

Note that the above reactions are not perfectly controlled according to the type of substance. For example, gases that efficiently remove silicon can also tend to remove

Additive gases are also critical, as adding various gases like oxygen, nitrogen, and hydrogen to the etching gas can bring about desired properties. In the case of hydrogen, it generates a lining that increases anisotropy if added during the process of removing silicon. Inert gases are also added partially. Neon gas is a prime example as it can control the concentration of the etching gas or provide the effects of physical etching.

Another Factor to Raising Density

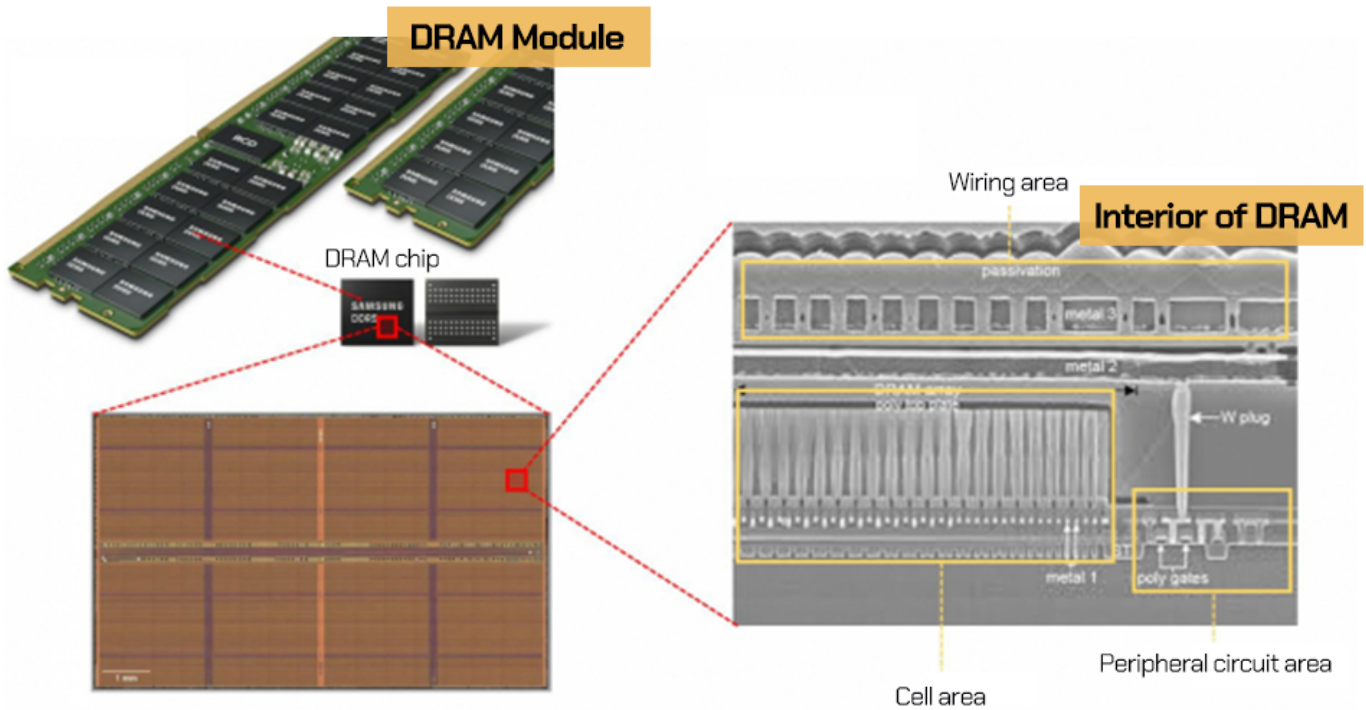
Etching is a key step in the semiconductor manufacturing process that combines physical and chemical methods to create desired fine patterns on a wafer. Although it does not directly draw a precise pattern like a stepper, it is a very important task that helps hundreds of billions of transistors across the wafer to have nearly identical shapes. It adjusts various factors such as the gas ratio, temperature, the intensity of the electric field and pressure.

The importance of etching has grown even greater recently as the increase of density through the development of steppers has reached its limit. FinFET[5)] from products such as CPUs and APs is an example of this occurrence.

DRAM and NAND, the two core products of SK hynix, rely heavily on etching. For DRAM, it has the problem of having to gradually make the capacitor higher to store more data, while more than 100 layers need to be etched to upgrade to 3D NAND memory.

These products require a very high aspect ratio[6)] and, in order to ensure high reliability, there are innumerable factors that etching must solve such as having the

the removal.



▲ Figure 6: The internal structure of DRAM. Numerous thin and deep structures in the cell area are capacitors.

As explained in this episode, silicon and silicon dioxide are very easy to remove because they vaporize and disappear immediately when they come into contact with fluorine. With this in mind, it is possible to anticipate what happens after a silicon wafer changes to germanium or another material. Germanium is of no use if it can't be manufactured through processes like etching or deposition, regardless of how strong its properties are.

precise pattern needs to be etched to ensure the chip functions correctly.

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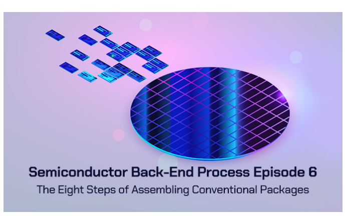

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