Semiconductor Front-End Process Episode 3: Forming Patterns on Wafers Through Photolithography

January 5, 2023

If the process of oxidation plays the crucial role of protecting semiconductor components as highlighted in the previous article, photolithography is another vital process as it prints patterns on the wafer's surface. As the wafer's pattern largely determines its function, it is clear that photolithography is an essential step of semiconductor manufacturing which needs to be conducted with the utmost precision. In this article, we will look at the various steps of the photolithography process from applying the photoresist to the develop process.

Just Like Baking Cookies

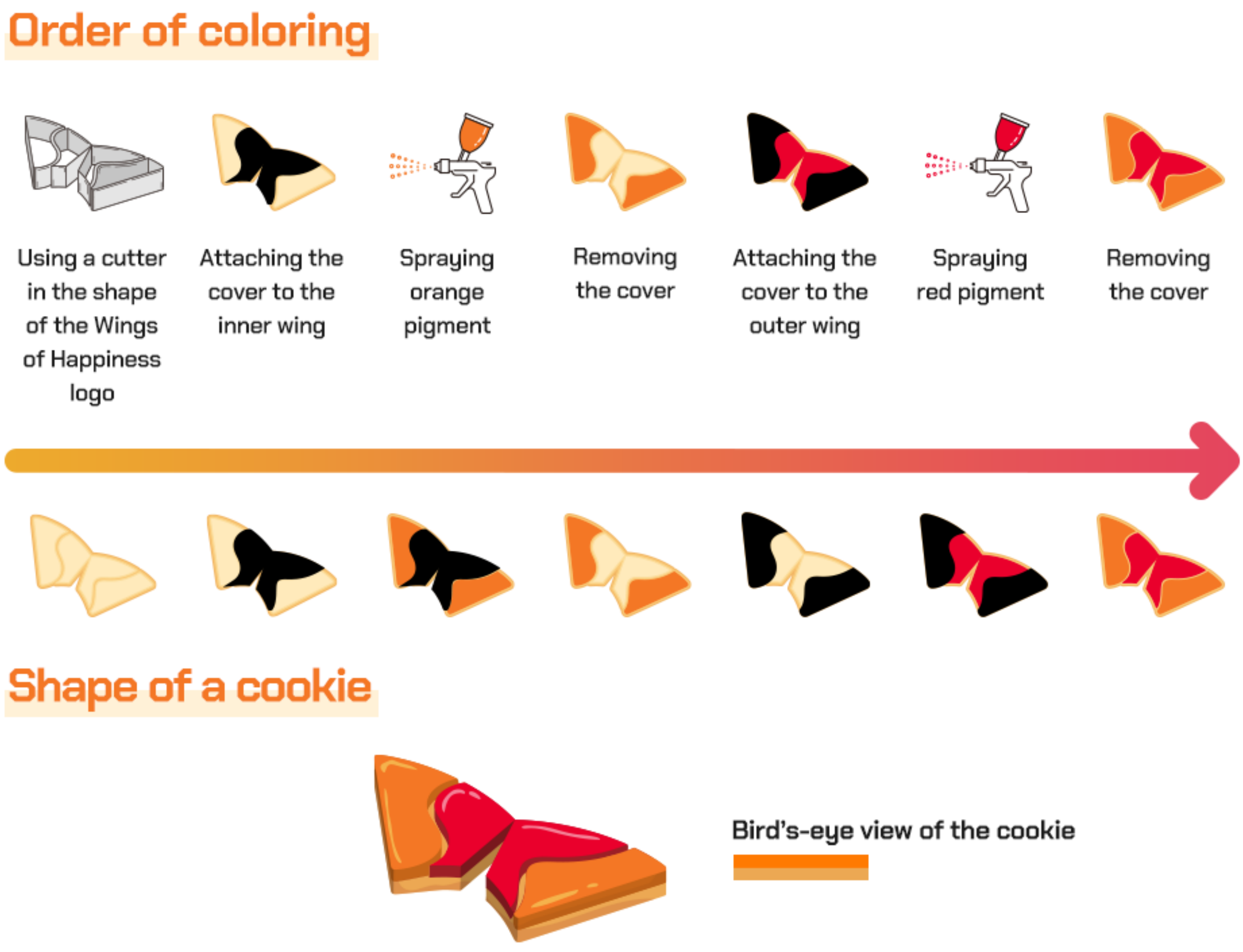
The emergence of the MOSFET (Metal Oxide Semiconductor Field Effect Transistor) allowed more transistors to be packed into a fixed space. As MOSFETs became smaller, they were able to use less power while obtaining more functions as the number of transistors increased. Consequently, making MOSFETs smaller is

The process for manufacturing semiconductors shares similarities with baking cookies. Imagine making a batch of cookies in the shape of SK hynix's "Wings of Happiness" logo. It would take a very long time to make hundreds of these cookies by hand. So, what are the alternative options?

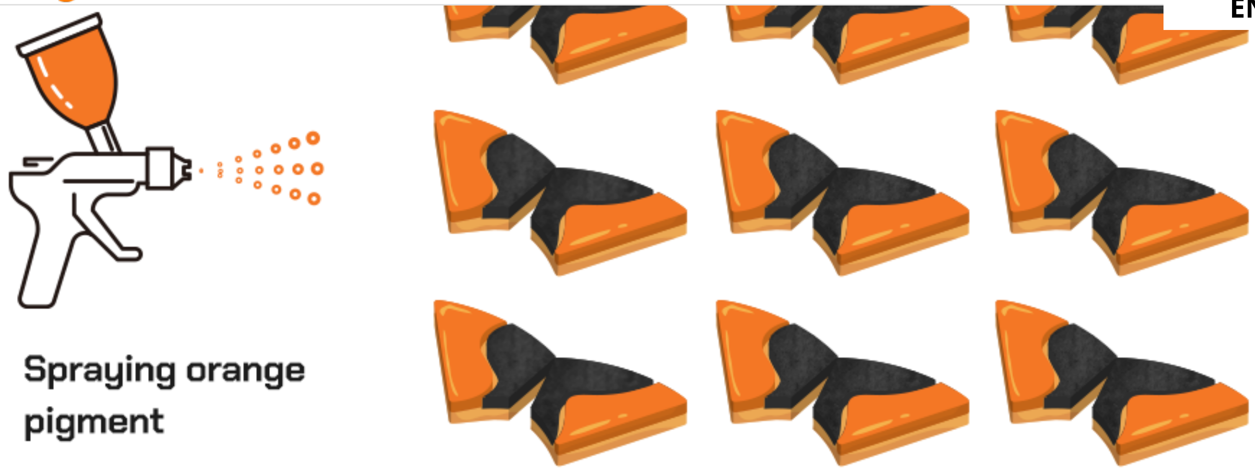
▲ Figure 1: How to swiftly make cookies in the same shape

The best solution would be to use a cookie cutter on the dough. This makes baking 100 cookies relatively simple. But what if the cookies needed to be made smaller? Then, a cookie cutter with a smaller shape could be used to create the cookies. The as having two small MOSFETs is much more useful than having one large one.

The process of producing semiconductors is similar to the steps described above. However, the process becomes more complex when the wing-shaped cookies need to be colored.



▲ Figure 2: The order of coloring the wing-shaped cookies

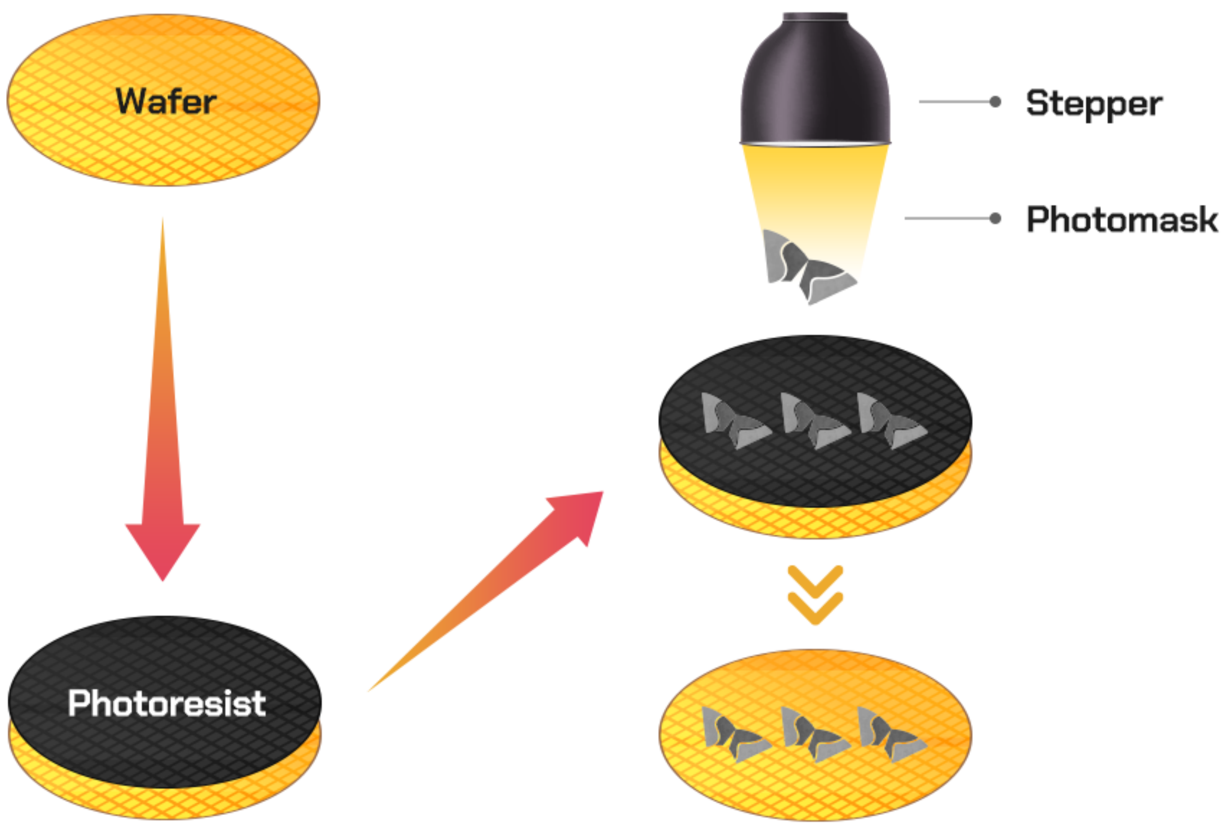


▲ Figure 3: Cookies can be quickly sprayed with color when they are bunched together

By following the steps shown in Figures 2 and 3, color can be added to the cookies. After cutting the cookies into the desired shape, the areas that don't need to be colored are covered before the whole surface is sprayed with pigment. This method allows one to bake cookies with a specific shape or color in a short amount of time. But this still doesn't explain how the black cover in the above image is made. This is, in fact, the main function of the process called "exposure." While the cookies in the images above only have two layers of color, semiconductors require dozens of layers that begin from the device layer to multiple metal line layers. This is why exposure becomes such an essential process.

Photolithography: The Process of Making Semiconductor Patterns

light sensitive solution called a "photoresist" which changes properties whe
to light. After applying the photoresist, light (laser) is shot at the wafer so the areas covered in the photoresist can be printed with the required pattern.



▲ Figure 4: The general sequence of photolithography

To ensure that only the desired areas of the wafer are exposed to the light, a disc with the required pattern is placed in front of the light. This disc is called a "photomask." The intended pattern is printed on top of the wafer by shining light through the photomask and onto the wafer.

SK hynix NEWSROOM

ENG

Selecting Positive or Negative Photoresists

There are two types of photoresist used in the photolithography process: positive or negative photoresist. A positive photoresist softens when it is exposed to light making it more soluble when the solvent is applied, while a negative photoresist will harden when exposed to light and remain on the wafer. With a positive photoresist, the areas exposed to light are removed during the develop process. Conversely, the areas not exposed to light are protected by the photoresist and are not removed during the develop process or the subsequent processes of etching and deposition.

Semiconductor manufacturers choose the type of photoresist according to the purpose of the process. For example, a negative photoresist is not suitable for making fine patterns because the hardened areas that were exposed to light will absorb some of the solution during the develop process and start to swell up. That's why a positive photoresist is usually used when making fine patterns. On the other hand, a negative photoresist holds the advantage of being cheaper and yielding a higher resistance to processes like etching.

▲ Figure 5: Positive and negative photoresists

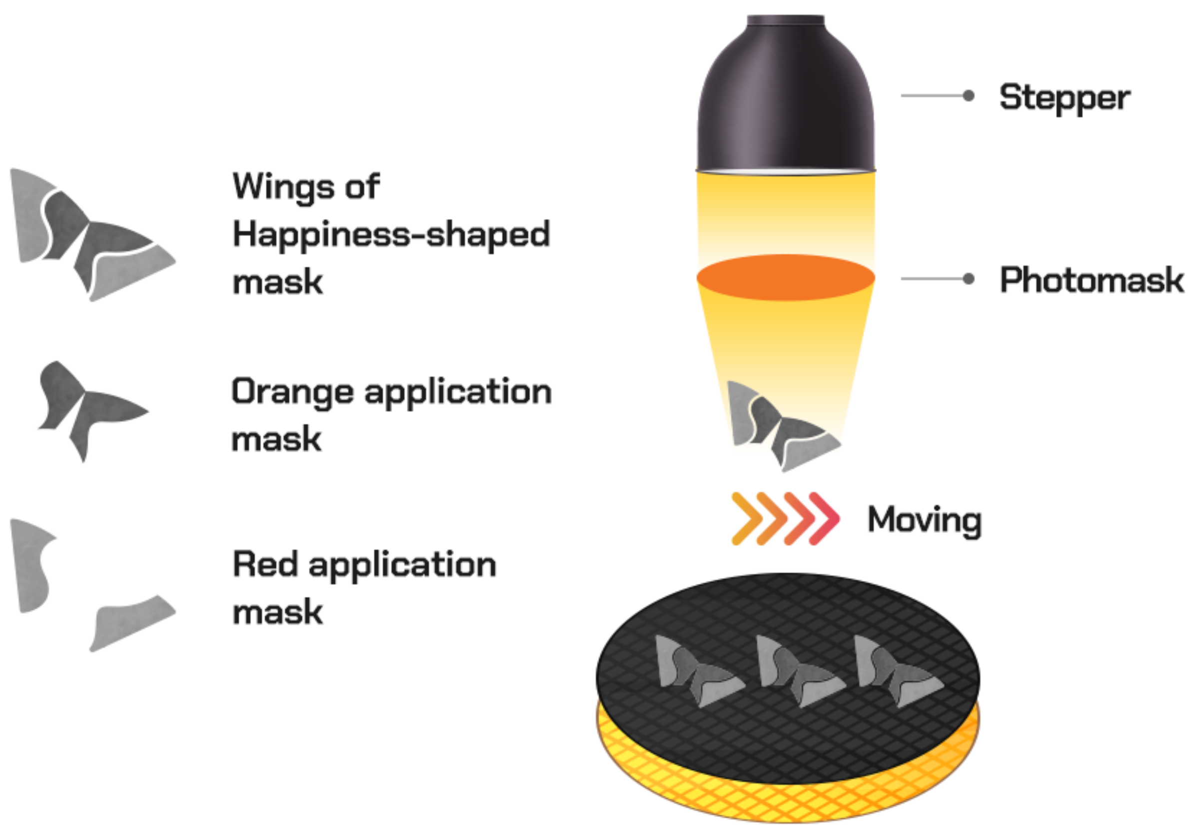
After choosing which photoresist method to use, a device called a "coater" is used. When drops of photoresist fall on the wafer, the coater spins rapidly and spreads the photoresist evenly. After applying the photoresist, manufacturers remove excess photoresist found on the back or edges of the wafer. They also evaporate excessive soluble components by heating them inside an oven, all the while preparing for the next stage of the process.

Over time, the structure of photoresists has become more complex. Photoresists usually consist of multiple layers, and one of these layers is called the bottom anti-reflective coating (BARC). It was developed as the need for miniaturization grew and as light from the stepper started to reflect off the wafer and affected the formation of patterns. The BARC is a substance that is applied to the wafer's surface before applying the photoresist to prevent the reflection of light (hence the name "bottom," as it's located under the photoresist). Additionally, with the development of lithography systems that use water (ArF immersion[1]), a waterproof coating called the top anti-reflective coating (TARC) was developed to repel water droplets and prevent damage.

Rather than memorizing every structural detail of a photoresist, it's more helpful to examine how the industry has addressed new challenges it has faced when new contamination of the photomask. The problem was only solved with research on photoresist materials and by introducing a protective film on photomasks called a pellicle.

[1]ArF immersion: An argon fluoride (ArF) immersion stepper that uses water instead of air as the medium for light, improving its performance.
[2]EUV stepper: A machine that makes ultra-fine patterns using extreme ultraviolet rays.

Creating the Pattern Outline with Photomasks



▲ Figure 6: Operation of a stepper

photomask is needed. The photomask is largely opaque with some transparent areas to allow light to pass through. As the name suggests, the photomask is placed between the light source and the wafer to create the required pattern. The pattern on the photomask is designed taking into account possible issues such as light interference, so it might look different from the pattern that the manufacturer originally intended to make.

The pattern on the photomask is essentially the design of the semiconductor and, consequently, determines its usage. Photomasks used in semiconductor memories such as DRAM and NAND flash have very regular and repetitive patterns that are hard to see with the naked eye. On the other hand, photomasks used for making logic semiconductors such as CPUs and GPUs have very complex patterns.

Additionally, semiconductor manufacturing requires multiple photomasks. After using a photomask for exposure, various processes like etching, deposition, and oxidation are performed. Then, the above processes are repeated to build up the next layers. Ultimately, the design process involves creating photomasks for each layer of a semiconductor in order to provide the semiconductor chip with the desired function of the manufacturer.

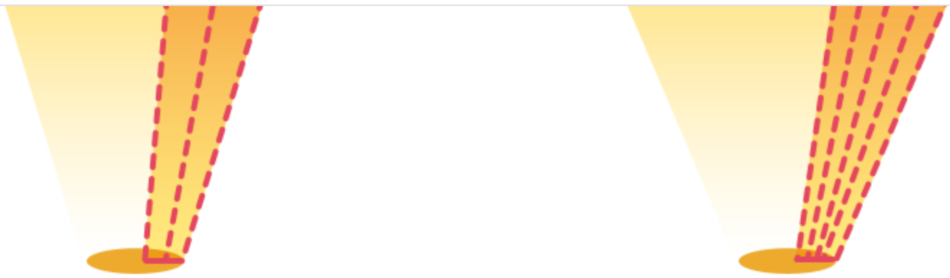
Since the photomasks are prepared in advance, the next step is to accurately find the starting position for exposure. This operation is called alignment. As for exposure, it can be performed multiple times in semiconductor manufacturing. And since the patterns on a semiconductor are only tens of nanometers apart, small errors can accumulate and, thus, cause large defects. Such problems can be prevented before carrying out exposure by precisely adjusting the array according to the alignment mark produced in the previous process.

The stage where light is actually shone onto the wafer is called exposure. Li laser, is shone onto a small area of the wafer that's the size of a chip. After a certain amount of time, the stepper moves slightly to the side of the wafer and repeats the process.

The capability of the stepper to distinguish between two objects and analyze them is called "resolution." Resolution is conveyed by the following formula: d=λ/(2NA) (where λ is the wavelength of light and NA is the numerical aperture). If the resolution is high, two nearby objects may seem as one. So, no matter how fine the pattern on a photomask is, the pattern is not etched accurately on the wafer's surface.

Therefore, the key is to reduce resolution, and the light's wavelength is the most important factor when reducing resolution. As the energy of the laser increases, the wavelength of the light decreases. The EUV stepper is a machine that can draw finer patterns than a deep ultraviolet (DUV) laser by reducing the wavelength by 1/14, or increasing the energy of the light. Another way to improve resolution is to increase the numerical aperture (NA). The NA can be increased by making the lens of the light source larger or by using a medium with a high refractive index. An example of the former is High NA EUV while DUV (ArF immersion), which is still commonly used, is an example of the latter.

The NA is a measure that may be difficult to understand initially. This concept can be clarified by referring to Figure 7 below, which shows that resolution improves, or decreases, when the lens of the light source becomes larger.



▲ Figure 7: Numerical aperture and resolution

Finding a suitable light source for the stepper is very difficult. In the early 2000s, researchers were able to discover a better light source, but it took over 10 years to commercialize a 13.5nm light source for EUV after developing the argon fluoride (ArF) 193nm laser. This is due to shorter wavelengths of light being less refracted and more likely to be absorbed when they hit a material. This is why the development of EUV steppers has been the subject of intense debate among semiconductor manufacturers.

Exposure is also critical for achieving high yields in semiconductor manufacturing. As explained earlier, exposure cannot be performed on multiple wafers at once—unlike oxidation. Thus, it's impossible to create a uniform light source that can process a wafer with a 300mm-wide diameter. The latest steppers are very expensive, costing over 76.8 million US dollars per unit. Nevertheless, they can only process about 100 wafers per hour. The money invested in exposure itself is 12 times as much as the money spent on oxidation. For EUV, it was much harder to achieve commercially

Once exposure is complete, overlay may be performed. Overlays are small marks placed on the wafer during the exposure process. If an overlay mark is engraved in a shape that shares the center and varies in size at every exposure, it becomes possible to measure how misaligned the exposure is or whether the wafer is slightly rotated. However, unlike the alignment process, overlay measurements are not performed on all wafers.

The Develop Process and Finalizing the Pattern

After light is shone on the photoresist, the areas that were exposed to the light either soften or harden depending on if a positive or negative photoresist was used, respectively. This process is called develop, and it involves removing the parts of the wafer that were exposed to the light.

Before this process, the wafer is heated again in an oven during a process called post-exposure bake (PEB). This helps to further intensify the changes in the photoresist that was exposed to the light.

Once the develop process is complete, a chemical agent known as a developer is applied to remove the areas of the photoresist that were affected by the light. Depending on the material used for the photoresist, the area may be rinsed. The solution used for rinsing differs according to the substance used for the photoresist. The rinsing equipment can also vary, and the choice of equipment often has a trade-off relationship between the processing speed and the rate of defects.

After the photoresist has been properly processed, the semiconductor frame is finally ready to be used. Transistors and wires can then be made by applying photomask on

The photolithography process illustrates how important it is to have a deep understanding of the underlying technology rather than merely memorizing specific details. When the ArF laser's light source reached its limit at 193nm, EUV technology wasn't ready yet. But since microfabrication had to continue, industry professionals developed ArF immersion equipment to reduce the wavelength of the same light source. This allowed the semiconductor industry to approach processes below 100nm. Achieving this feat required contributions from other sectors.

▲ Figure 8: New technology added for the ArF immersion equipment process is so advanced that even small errors can cause problems. Impurities in the liquid can cause defects in the semiconductor or photoresist and can even dissolve the photoresist over time. To address these issues, it's necessary to develop technologies that produce high-purity water and to apply a protective coating that can be easily removed from the photoresist. Since the coating changes the properties of the photoresist, changes are also required in the develop process.

These challenges are something that the semiconductor industry and its professionals will have to work together to solve. Recently, SK hynix collaborated with a materials company to develop a dry photolithography process.

As explained in the previous article that focused on the process of oxidation, a dry process is a process that doesn't involve water. Unlike the immersion method described above, the dry process involves attaching the photoresist directly to the wafer and not rinsing it during the develop process. Among the numerous reasons for developing these new technologies, the most important is that miniaturization has advanced to the extent that fine patterns are damaged in the process of applying and cleaning the photoresist even when the stepper shines light with a small photomask. Such challenges will continue to appear down the road, but the semiconductor industry will keep coming up with innovative solutions to combat them.

Photolithography is Just One Step

After a pattern has been successfully created using photolithography, the next step is to fill or carve off the insides of the pattern. While photolithography is one of the crucial processes of semiconductor manufacturing, it's not the only important one. Creating a fine pattern through photolithography is only one step, as utilizing it for a specific purpose is a completely different story.

Semiconductors

Semiconductor Front-End Process Episode 2: Protecting Key Components Through Oxidation

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

Semiconductor Front-End Process Episode 5: Supporting Wafer Miniaturization Through Deposition

Semiconductor Front-End Process Episode 6: Metallization Provides the Connections That Bring Semiconductors to Life

Semiconductor Back-End Process Episode 1: Understanding Semiconductor Testing

Semiconductor Back-End Process, Episode 2: The Roles, Process, and Evolution of Semiconductor Packaging

Semiconductor Back-End Process Episode 3: Understanding the Different Types of Semiconductor Packages

Semiconductor Back-End Process Episode 4: Understanding the Different Types of Semiconductor Packages, Part 2

Semiconductor Back-End Process Episode 5: Package Design and Analysis

TAG #semiconductor #front-end process #Photolithography

RELATED POSTS

Semiconductor Back-End Process Episode 6: The Eight Steps of Assembling Conventional Packages

Open Communication, Creative Research, and Agile Problem-Solving: The Keys to RTC's Advances in Semiconductor Research

The Story Behind SK hynix's AAA-Rated Global Compliance Program

[Tech Pathfinder] Small Size, Big Impact: Unveiling the Latest Advances in Semiconductor Packaging and Miniaturization

SK hynix NEWSROOM

in ENG