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Plasma cleaning prior to wire bonding, flip-chip bonding and device packaging.

Summary:

Plasma cleaning prior to wire bonding and chip packaging removes organic, oxide and fluoride contaminations on the surface, promotes better interfacial adhesion for wire bond and chip packaging, reduces non-stick-on-pad (NSOP), bond lifting and underfill void problems.

Introduction to IC chip packaging.

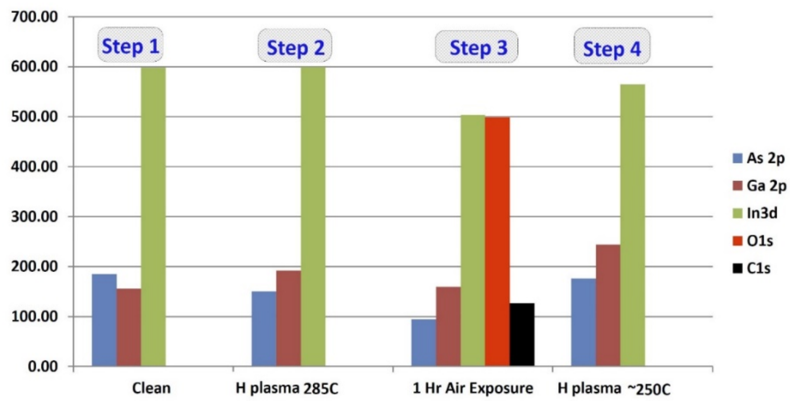
Semiconductor packaging can bridge the gap in dimensions between the silicon die and the PCB. The metal pads on the silicon die are usually too small to be directly connected to PCB. Packaging can also help the silicon chip to conduct the heated more effectively to the heat sink. In the past half a century, from 1970s to 2020, semiconductor chip packaging has evolved significantly from DIP (dual in-line package) to 3D IC, as shown in the graph below. Many of the traditional chip packaging technologies are still widely used today, such as wire bond BGA and flip-chip BGA technology. Plasma cleaning has been widely used to clean chips, die, and lead frames before bonding to improve the reliability and reduce the failure rate.

Contaminations in IC chip packaging

To achieve a reliable chip package, the surface of all the internal interface must be clean to ensure good adhesion. Contaminations on IC chips and packaging can be organic or inorganic. The inorganic contamination can be metal oxide formed on bonding pads or fluoride. There are many sources of contamination on IC packaging.

1) Contamination can come from many organic materials existed on handling tape, plastic storage bag, solder flux, and adhesive bleed-out from the die attach process. Organic compounds may have a higher outgas rate. The organic vapor can directly coat the fresh surface.
2) Fluorine containing gases are often used in semiconductor fab as a strong etchant. Fluorine slightly reacts with Al and forms $[AlF_x]^{(x-3)-}$ (e.g. $[AlF_6]^{3-}$) or compounds $Al_xF_yO_z$ on the surface of bonding pads. Those compounds can't be easily washed away from EKC & DI water cleaning processes. Therefore, it's normal that some percentage of fluorine can be detected on bonding pads.
3) Some levels of contamination can also be created during the manufacturing and assembly process, such as unetched glass, the residual photoresist on the silicon chip, silicon sawdust, or tape residual during back grinding or die-cut.
4) Abundant hydrocarbon contamination exists in the ambient air. Once the bonding pads or lead-frames are exposed to ambient air, it will soon be coated with a layer of organic hydrocarbon. For reactive metals, a thin layer of metal oxide will form on the surface. The contamination induced by ambient air can be explained in the data shown below. In step 1, an XPS system measured the composition of a clean InGaAs sample surface. In step 2, the sample was cleaned by a 2-second remote hydrogen plasma. Then the surface was analyzed by the XPS system again. There is no contamination added to the surface by the hydrogen plasma cleaning step. In step 3, the cleaned

InGaAs sample was exposed to ambient air for 1 hour. The subsequent XPS measurement indicated that the surface had been contaminated by carbon and oxygen. In step 4, the contaminated InGaAs sample was cleaned by 2-second hydrogen plasma again. It means ambient air can easily contaminate a clean sample surface. Hydrogen plasma can successfully remove the carbon contamination and reduce the metal oxide on InGaAs samples.



Impact of contaminations on the wire bonding process

Thermasonic wire bonding is one of the critical packaging processes, especially for aerospace and automotive industry, where the bonding joint can be stressed under extreme conditions. As mentioned in the previous section, contaminants like fluoride, oxide, organic hydrocarbon can reduce the interface quality for the bond. For the wire bond process, it can cause issues such as non-stick-on-pad (NSOP) and bond lifting. Non-stick-on-pad refers to the issue that surface contamination reduced surface bondability so that wire won't adhere to the bond pads. Bond lifting refers to the issue that wire bond detached from its position, resulting in loss or degradation of electrical and mechanical connections between the bond wire and the pads. Contaminants on the surface of the bonding pads can act as barriers and prevent the formation of strong intermetallics. As a result, the bond can often fail the pull force test. Fluoride contamination can cause long term corrosion issues.

How to use plasma cleaning to improve wire bonding and flip-chip bonding reliability and success rate

Plasma is an ionized gas phase substance that consists of ions, electrons, neutral atoms, or molecules that maintain charge neutrality. To ignite a plasma, free-moving electrons will be accelerated by an external electric field and acquire enough energy to ionize the neutral atoms or molecules along the path. If oxygen or hydrogen gas is used to generate the plasma, the high energy electron can dissociate oxygen/hydrogen molecules and generate atomic oxygen/hydrogen, ozone, or other types of reactive radicals. Besides the reactive radicals, plasma can also generate high energy ions. There are two major mechanisms for plasma to interact with the samples. The first one is the chemical reaction with the reactive radicals. The second one is the physical high-energy ion sputtering. Both mechanisms play important roles in removing surface contaminations for wire bonding and flip-chip bonding process. Here is how plasma cleaning can benefit wire bonding and flip-chip bonding process.

Tergeo and Tergeo-plus tabletop plasma system from PIE Scientific LLC

Plasma cleaning removes organic contaminations for wire bonding and flip-chip bonding process.

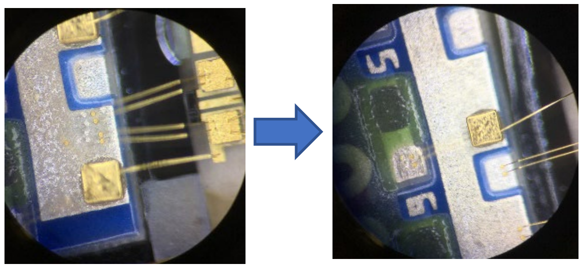
Organic contaminations are the major source of contaminations in many wire bonding and flip-chip bonding process. Fortunately, reactive oxygen or hydrogen radicals can quickly react with the surface organic contaminations, such as hydrocarbon, photoresist residual, solder flux residual, tape adhesive residual, etc. Plasma etching has been widely used in the IC fabrication process because it can precisely remove materials on the nanometer scale. The scale of the components in the bonding and packaging process is usually much bigger. So if the thickness of the organic contamination is more than tens of microns, the plasma cleaning process alone may not be very effective. The thickness for most of the contaminations on the surface of the bonding pads is in the order of nanometer-scale to several microns. Those contaminations can be quickly removed by the plasma cleaning process within a couple of minutes. If the residual of solder flux, tape, and adhesive is thicker than several microns, a solvent cleaning process should be carried out first before the plasma cleaning steps.

If the thickness of the organic contamination is on the order of several nanometers, pure argon plasma cleaning process can also remove the surface contamination effectively through the physical argon ion sputtering process. If the chip, PCB, or the lead frame contains reactive metals, such as silver, copper, or aluminum, that can be easily oxidized, oxygen plasma shouldn't be used. For those samples, pure argon plasma or argon mixed with hydrogen should be used instead. For gold pads, argon, oxygen, or hydrogen plasma can all achieve good results. In most cases, the etching speed of oxygen plasma is significantly higher for organic materials.

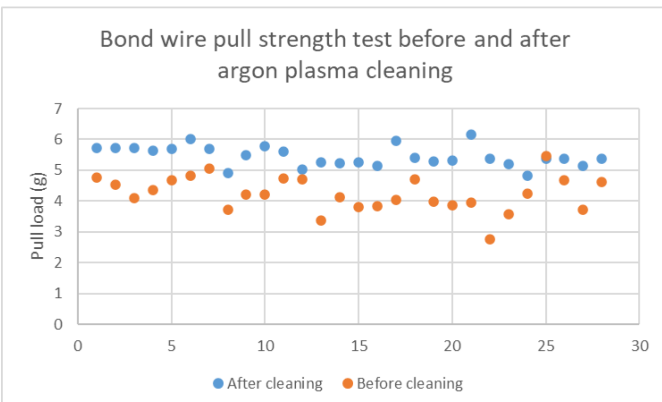
Argon or argon+hydrogen plasma can remove surface oxide and fluoride on the bonding pads.

Many metal pads can be easily oxidized when the chips, lead frames are stored in the ambient environment. It's a common issue that silver pads can be easily tarnished. Of course, fluoride corrosion is another major cause of many premature bond failures. Argon ion sputtering can effectively remove a thin layer of the oxide and fluoride on the surface of the metal pads. Mixing argon with hydrogen to generate the plasma can also remove the oxide through hydrogen reduction reactions. But not all metal oxide can be reduced by atomic hydrogen at the room temperature. For example, hydrogen plasma can't reduce aluminum oxide chemically at the room temperature. Hydrogen ions are not heavy enough to sputter away the surface oxide or fluoride. It is important to add heavier argon gas to the plasma so that high-energy argon ions can remove the surface oxide and nitride through the physical ion sputtering process. Plasma cleaning is only a surface process, so it can't remove fluorine diffused into the bulk of the metals.

Old contaminated chip | Argon plasma cleaned



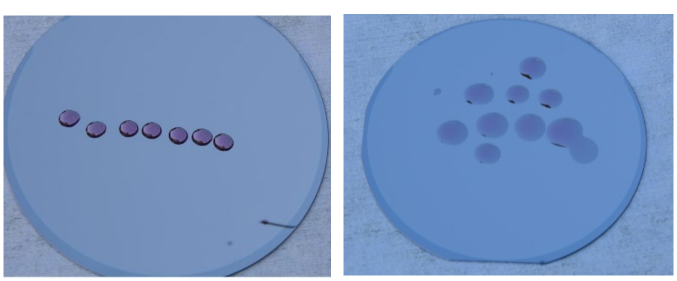
In the photos above, argon plasma cleaning makes the tarnished silver pads look brighter and shiner after the surface organic contamination and silver oxide layer are removed. The data below shows that the pull force for the wire bonds significantly improved after 3 minutes of pure argon plasma cleaning.



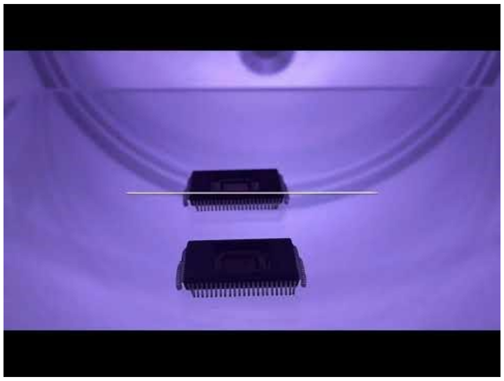
Plasma cleaning can increase surface energy and reduce the underfill void.

Water droplet contact angle measurement method has been widely used as a low-cost method to evaluate the thickness of organic contaminations on the surface of the samples. Organic contamination can repel the waters, thus increase the contact angle. A clean surface will significantly reduce the contact angle. Of course, a low contact angle means higher surface energy. For flip-chip underfill application, high surface energy can substantially increase the wicking speed, reduce the underfill voids, and create homogeneous fillet height.

Water droplet on silicon wafer with metal coating before and after plasma cleaning

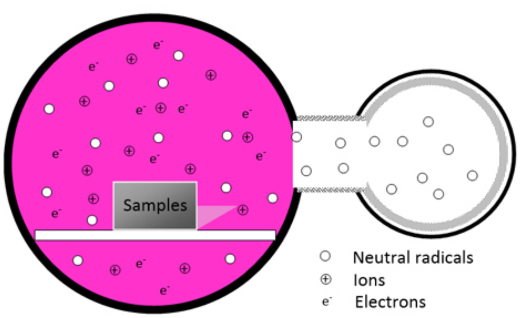


Water droplet contact angle on chip package before and after argon plasma cleaning (external link to a youtube video)

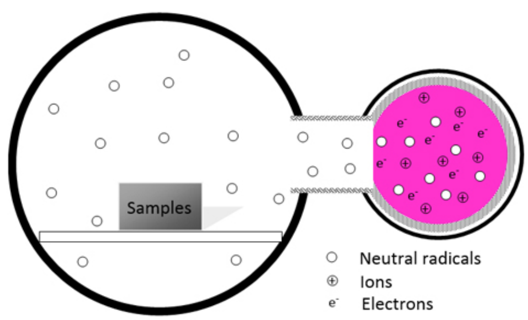


Direct mode vs. downstream mode plasma cleaning

In the direct mode of plasma cleaning, the sample is directly immersed in the plasma. The sample will experience high energy ion sputtering and surface chemical reaction with oxygen or hydrogen radicals. Plasma can also generate infrared, visible, and UV photons. Some specialized chips are extremely sensitive to surface ion sputtering, UV photon radiation, or electrical charge. In this case, a more gentle downstream mode of plasma cleaning could be used. In the downstream mode of plasma cleaning on the Tergeo plasma system, plasma is not generated in the sample chamber directly. It's generated in a separate plasma source attached to the sample chamber. Since the sample is not immersed in the plasma, the surface ion sputtering, UV photon radiation, and electrical charging can be minimized. The downstream mode sample cleaning is mostly surface chemical reaction with the neutral radicals diffused out of the remote plasma source. Direct mode plasma cleaning is usually faster than the downstream mode plasma cleaning. The downstream mode is more gentle than the direct mode. Since the physical ion sputtering is mostly absent in the downstream mode plasma cleaning, pure argon plasma will not be very effective. Usually, oxygen or hydrogen gas should be added to the process gas for downstream mode plasma cleaning.



Direct mode plasma cleaning



Downstream mode plasma cleaning

Limitation of plasma cleaning

Plasma cleaning is effective in removing organic contamination with a thickness of less than several microns. Even though it's possible to ash a thicker layer of organic contaminations with oxygen plasma, the time could be longer than the solvent cleaning method. In some cases, oxygen plasma can't be used because reactive metals such as copper and silver can be easily oxidized by the oxygen plasma. Pure argon ion-spttering cleaning method is not very effective in removing a thick layer of organic contaminations. If the chip has a thick layer of solder, adhesive, or tape residuals, it's better to remove the bulk of the residuals with the solvent cleaning method, then followed by a plasma cleaning process to achieve the pristine surface cleanliness.

For surface oxide or nitride, the thickness should be on tens of nanometer or less for plasma cleaning to be effective with argon or argon+hydroen plasma. It can't remove oxide or nitride deep below the surface layers at the normal room temperature.

Plasma cleaning may not be very effective in removing the big sawdust or particles/debris generated by the wafer dicing process because those contaminations are usually big inorganic particles or deposition that can’t be easily etched or sputtered away by the argon, argon+oxygen, or argon+hydrogen plasma.