How Plasma-Enhanced Surface Modification Improves the Production of Microelectronics and Optoelectronics

ABSTRACT

Over the past 30 years, plasma, the fourth state of matter, has become a very useful method for surface modification and deposition of various materials. In IC packaging applications, plasma is employed to prepare surfaces for die attach, wirebonding and mold/encapsulation.

Moreover, plasma-enhanced contamination removal and surface activation processes improve the reliability and yield, and also enhance the manufacture of advanced technology products. In many optoelectronic devices, plasma-enhanced contamination removal is used to prepare surfaces prior to eutectic die attach and wirebonding. This article examines examples of plasma surface modification in both the microelectronic and optoelectronic industries.

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Substrate materials and the adhesives employed for attachment often do not possess the needed physical or chemical properties to allow for good adhesion, and require surface modification.[1]

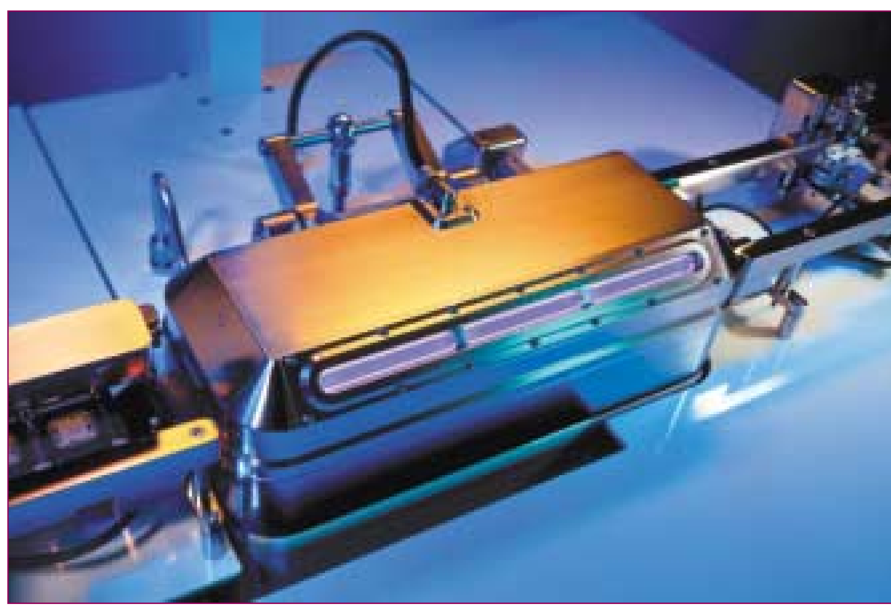
Plasma surface modification involves the interaction of the plasma-generated excited species with a solid interface. The plasma process results in a physical and/or chemical modification of the first few molecular layers of the surface, while maintaining the properties of the bulk.

Typical materials employed in the microelectronics and optoelectronics industries include ceramics, glass, polymers and metals—such as gold, copper, aluminum, nickel, palladium, tungsten, and silver. The effectiveness of the plasma on these complex interfaces is determined by the plasma source gases, the configuration of the plasma system and the plasma operating parameters.

Surface modification processes can be classified into four categories:

- Contamination Removal
- Surface Activation
- Etch
- Cross Linking

Selection of a specific process is determined by the physical and chemical composition of the material to be processed, as well as by the ensuing process required. The plasma process and the subsequent processing steps must also be considered.



This single strip, compact plasma chamber processes BGA-type substrates with argon plasma.

Surface modification is often sensitive to time and environmental exposure, where the surface may lose its plasma-induced physical and chemical properties.

Automated in-line plasma systems (Figure 1), which allow the surface modification process to be performed individually—immediately prior to the next step in the assembly process—have gained popularity due to the consistency they offer.

The lead photo displays the single strip, compact plasma chamber, which processes BGA-type substrates with argon plasma. The characteristic photon emission of the argon plasma can be seen through the chamber window. (Process applications are shown in the table.)

Contamination Removal

Surface contamination removal involves the use of the plasma's physical and/or

Process Applications for Plasma Surface Enhancements

Plasma Source Gas	Surface Modification Processes	Advanced Technology Application
Argon (Ar)	Contamination Removal–Ablation	Wirebond Die Attach
	Cross Linking	Substrate Polymer–Metal Adhesion
Oxygen (O_2)	Contamination Removal–Chemical Oxidation Process (Organic Removal) Surface Activation Etch	Wirebond Die Attach Mold and Encapsulant Adhesion Photoresist Removal
Nitrogen (N_2)	Surface Activation	Mold and Encapsulant Adhesion
Hydrogen (H_2)	Contamination Removal–Chemical Reduction Process (Metal Oxide Removal)	Wirebond Eutectic Die Attach
Carbon Tetrafluoride (CF_4) and Oxygen (O_2) or Sulfur Hexafluoride (SF_6) and Oxygen (O_2)	Etch	Polymer Etch–Fiber Stripping Photoresist Removal Thin Film Etch–Oxides, Nitrides

Figure 1. This automated, in-line plasma tool is designed for surface modification processes. The upstream and downstream transfer mechanisms and the compact high-density plasma chamber are contained within a single enclosure.

chemical energy to remove micron-level contamination.

This process employs ablation, where the positive ions bombard the surface. The ablation process can dislodge contamination from the surface, and can roughen the surface on an atomic scale, as revealed by atomic force microscopy.[2]

The chemical process is widely employed to remove residual materials, typically less than a few microns, such as organic films, and oxidation. The chemical process employs either reduction or oxidation chemistry via the gas-phase radicals.

Specific contamination issues in microelectronic and optoelectronic package reliability are poor wirebond pull strength and voiding, due to insufficient solder reflow in eutectic die attach.

Wirebond pad contamination can be a by-product from previous processing steps such as die attach epoxy bleed or environmental exposure (i.e., bond pad metal oxidation).

A physical, chemical or combined physical-chemical process using argon and oxygen source gases can be employed to prepare the bond pads. An oxygen-based plasma will take advantage of the oxygen radicals to chemically react with the epoxy, producing volatile gas-phase by-products that can be pumped from the vacuum chamber.

The success of an oxygen plasma for removal of die bond epoxy bleed has been widely demonstrated.[3]

In cases where oxidation is of concern, a physical process can be employed to prepare the bond pad surfaces. An argon plasma treatment of PBGA strips has been shown to improve the wirebond pull strength by as much as 24.3 percent.[4]

Metal oxidation can act as a physical barrier for both wirebonding and solder reflow. A combined physical and chemical process using argon and hydrogen can reduce the metal oxides. For example, reduction of copper oxide to copper is achieved in a hydrogen plasma via the reaction of the hydrogen radicals with the metal oxide.

$$CuO + 2H\bullet \rightarrow Cu + H_2O$$

Even in the absence of a contamination source, ablation will roughen the surface and provide a larger surface area for wirebonding, resulting in improved wirebond uniformity bond to bond.[4]

Surface Activation

Plasma surface activation employs gases, such as oxygen, nitrogen, hydrogen, and ammonia, which, when exposed to the plasma, will dissociate and react with the surface, creating different chemical functional groups on the surface.

The different functional groups modify the chemical activity of the surface. The new functional groups have strong chemical bonds with the bulk material and have the capability to further bond with adhesives to promote better adhesion. The functional groups also increase the surface area available for the adhesive and thus will distribute the load over a larger area resulting in improved adhesive strength. Gas selection and surface type determine the functional group that will be substituted on the surface.[4]

In microelectronic applications, plasma surface activation prior to die attach provides better contact, improved heat transfer and minimal voiding.

The purpose of the mold/encapsulant material for semiconductor applications is to provide adequate mechanical strength, adhesion to various package components, good corrosion and chemical resistance, matched CTE to the materials it interfaces with, high thermal conductivity and high moisture resistance in the temperature range used.

Figure 2. Illustration displays a fiber with the buffer material removed, and the glass cladding and core exposed.

The ability to form good adhesion with package components and to remain bonded is of paramount importance, since delamination along the interfaces is a major reliability issue for plastic-encapsulated microcircuits.

Plasma treatment has been demonstrated to improve the bond strength at the plastic encapsulant, gold-plated copper leadframe interface via an enhanced chemical compatibility with the molding compound.[2] Initial studies have also indicated that plasma treatment of nickel surfaces with water-based plasma improves the adhesion of the mold compound to the nickel surface.

Etch

Plasma etch is characterized by the chemical reactivity of the discharge. The etching process utilizes source gases that dissociate within the plasma, creating a mixture of highly reactive species. The advantage of this chemical plasma is its chemical selectivity.

The process chemistry can be optimized so that one material can be selectively etched in the presence of other materials. For example, the dissociation of carbon tetrafluoride (CF_4) and oxygen in the appropriate concentrations produces highly reactive oxy, oxyfluoro, and fluoro radicals that rapidly break carbon-carbon bonds within numerous materials.

The reaction at the solid interface produces volatile by-products, which are pumped from the vacuum system. Plasma etch has many applications specific to semiconductor and optoelectronic processing, including photoresist removal, thin film etch, and polymer etch.

In optoelectronic manufacturing, plasma etch has been employed to produce stripped fibers through the controlled removal of the urethane acrylate buffer coating.

Conventional optic fibers are composed of a cylindrical core covered by a cladding material and a buffer material that encases the cladding. The core is the light-carrying element, and the cladding promotes the total internal reflection in the fiber.

Stripping the buffer is required for various applications, including hermetic sealing, pigtailing of laser diodes, fiber arrays, fiber Bragg gratings, and amplifier seeding.

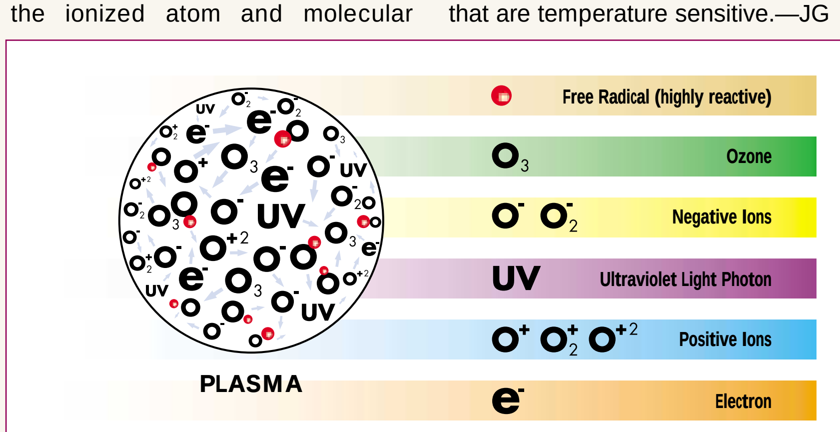
Fiber Bragg gratings, for example, are widely used in the fabrication of devices for dense wavelength division multiplexing (DWDM).

Figure 2 displays a fiber with the buffer material removed and the glass cladding and core exposed. A critical requirement in the removal of the fiber buffer is to completely remove the urethane acrylate polymer while maintaining the intrinsic

The Fourth State of Matter

Gas phase plasma is an electrically neutral mixture of electrons, ions, radicals, photons, recombination products and neutrals created by the application of energy, such as radio frequency (RF), to a source gas contained within a vacuum chamber. (The figure summarizes the active species that are present in an oxygen plasma.) Free electrons initiate the process; exposure of the free electrons to the external energy source allows the electrons to gain sufficient kinetic energy, so that a collision with another atom or molecule will result in the formation of ions and radicals. The reactive radical species are capable of chemical work where the ionized atom and molecular species are capable of physical work through sputtering.

Photon emission within a plasma is a result of the excited neutrals, ions and free radicals formed in the plasma losing their excess energy. The wavelength of the emission is sufficient to break chemical bonds, and can be useful when treating polymeric materials. Though non-equilibrium plasma has electron energies in excess of 10,000°C, critical for sustaining the plasma through atomic and molecular ionization and dissociation processes, it maintains a gas stream temperature that is less than 100°C. The low process temperature is important to products that are temperature sensitive.—JG



This illustration summarizes the active species that are present in an oxygen plasma.

strength of the glass core. Therefore, tight control of the buffer removal process is required to minimize the plasma etch of the glass core.

Cross Linking

Plasma-induced cross linking employs inert gases such as argon or helium to remove some atomic species from the surface, and generates reactive surface radicals.

These radicals react within the surface forming chemical bonds, which results in cross-linked surface. This approach is employed on polymeric substrates, such as those used for PBGA packages.

Argon plasma effectively sputters nanometers of material from the sample surface, literally roughening the surface on the nanometer scale. The cross linking that results improves the adhesion of metal layers to the plasma-treated polymer laminate.

Conclusions

Surface modification employing gas phase plasma technology has wide applications in both the microelectronic and optoelectronic industries.

Often substrate materials and the adhesives do not have the required physical or chemical properties to allow for good adhesion, and require surface modification.

Plasma surface modification involves the interaction of the plasma-generated excited species with a solid interface. The plasma process results in a physical and/or chemical modification of the first few molecular layers of the surface while maintaining the properties of the bulk.

Plasma treatment has been demonstrated to improve the bond strength at the plastic encapsulant, gold-plated copper leadframe interface via enhanced chemical compatibility with the molding compound.

Surface modification can be classified into four categories: contamination removal, surface activation, etch and cross linking, with selection of a specific process determined by the subsequent process requirement.

References

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