In Situ Hydrogen Plasma – A New Paradigm for Advanced Packaging

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Introduction

Two- and three-dimensional stacking of integrated circuits is at the forefront of semiconductor advanced packaging. These advanced packages are required across the spectrum of semiconductor devices, including memory, microprocessors and communication devices. Tremendous demand for these devices is being driven by applications in artificial intelligence, data storage in the cloud, high-performance computing, autonomous vehicles on land and in the air, and 5G communications.

Critical to stacking chips is the bonding together of a two-dimensional array of interconnects in a flip chip design. The pitch between interconnects should be 50 microns or less in order to achieve required I/O densities, and at the same time, provide communication speeds in the gigahertz range without significant signal loss. John H. Lau's book on *Semiconductor Advanced Packaging (Springer, Singapore, 2021)* is an excellent guide to the many types of 2D and 3D packages that have been developed. The two architectures that have emerged as viable candidates for flip chip interconnects are micro-bumps and hybrid bonds.

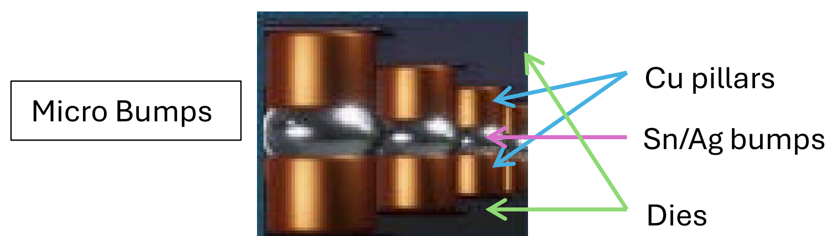


Figure 1: Micro-bump structure after thermocompression bonding.

Micro-bumps consist of an array of copper pillars with tin/silver solder caps, as shown in Figure 1. In the packaging process, the oxide layer is removed from the solder caps, and the interconnects are joined by thermocompression bonding (TCB). After the TCB step, the interconnects are protected by injection of underfill. Due to the extremely small pitch sizes, it is not practical to clean between the interconnects. Therefore, flux

cannot be used because there is no way to remove the flux residue from between the soldered micro-bumps. As an alternative to flux, an atmospheric pressure hydrogen plasma may be employed to remove the oxide via the example reaction: $CuO + 2H = Cu + H_2O$ vapor. No organic residues are generated in this case. However, the hydrogen plasma process must be carried out *in situ*, i.e., inside the TCB machine in an inert gas environment, otherwise the tin/silver solder may reoxidize before bonding. The TCB process can be configured for die-to-die or die-to-wafer bonding.

Hybrid bonding is an alternative approach that takes advantage of the ability to fuse glass-like dielectric layers together by a hydrolysis reaction. The interconnects are an array of copper vias distributed throughout the dielectric layer. A suitable dielectric is silicon dioxide (SiO_2) that has been deposited on the integrated circuit by plasma-enhanced chemical vapor deposition. Both substrates to be joined are carefully polished to produce an extremely smooth surface with the copper pads slightly recessed relative to the dielectric film. Then the surfaces are joined together in a TCB machine. A post annealing step causes the glass-like A and B surfaces to fuse together by the reaction: $Si_A\text{-OH-OH-}Si_B = Si_A\text{-O-}Si_B + H_2O$ vapor. During annealing the copper vias expand and fuse together across the joint making a pure copper interconnect. A schematic of this structure is illustrated in Figure 2. Hybrid bonding can be configured for joining dies to dies, dies to wafers, and wafers to wafers.

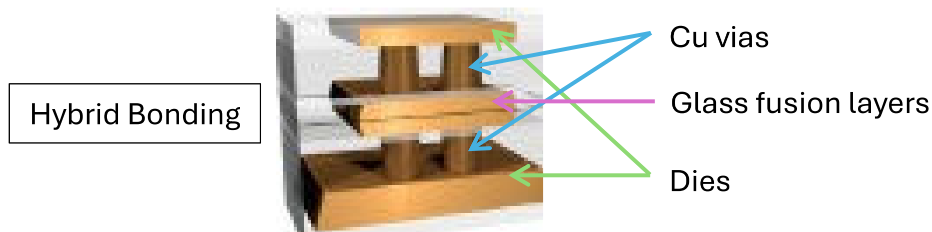


Figure 2: Hybrid bond structure.

In hybrid bonding, a critical surface clean is essential prior to thermocompression bonding. This surface clean can be performed by a weakly ionized vacuum plasma, or a weakly ionized atmospheric pressure plasma. The purpose of this process is to remove any organic contamination on the dielectric surface and to maximize the population of Si-OH

groups for the hydrolysis reaction. The plasma cleaning process does not have to be *in situ,* inside the TCB, because the activated dielectric surface is stable in the cleanroom environment for many hours.

Atmospheric Pressure Plasma

An atmospheric pressure plasma suitable for use in advanced packaging must meet several requirements. It must be low temperature, so that the dies are not heated above 200 °C during processing, thereby eliminating the potential for thermal damage of the integrated circuits. It must not produce particles which can settle on the interconnect surfaces and block the formation of a solid metal-metal joint. It must generate a beam of hydrogen radicals that uniformly removes the metal oxide from the solder micro-bumps both on die and wafer surfaces. And lastly, it must not generate any electrostatic discharge that could damage the integrated circuits.

A picture of an atmospheric pressure plasma that meets the requirements for advanced packaging applications is shown in Figure 3. The plasma head contains powered and grounded electrodes that are driven by radio frequency power at 27.12 MHz. Gas containing argon and about 1.0% hydrogen, nitrogen or oxygen is fed into the head to generate the appropriate reactive gas species required for the intended process. The energetic electrons generated in the plasma inside the head cause the molecules to dissociate into neutral radicals, for example: $e^- + H_2 = H + H + e^-$. As shown in the picture, the hydrogen radicals flow out of the head and down onto the substrate where they convert the metal oxide into metal and water vapor. By contrast, the energetic electrons remain inside the head where their presence is stabilized by the RF circuit formed between the electrodes and the ionized gas in the gap.

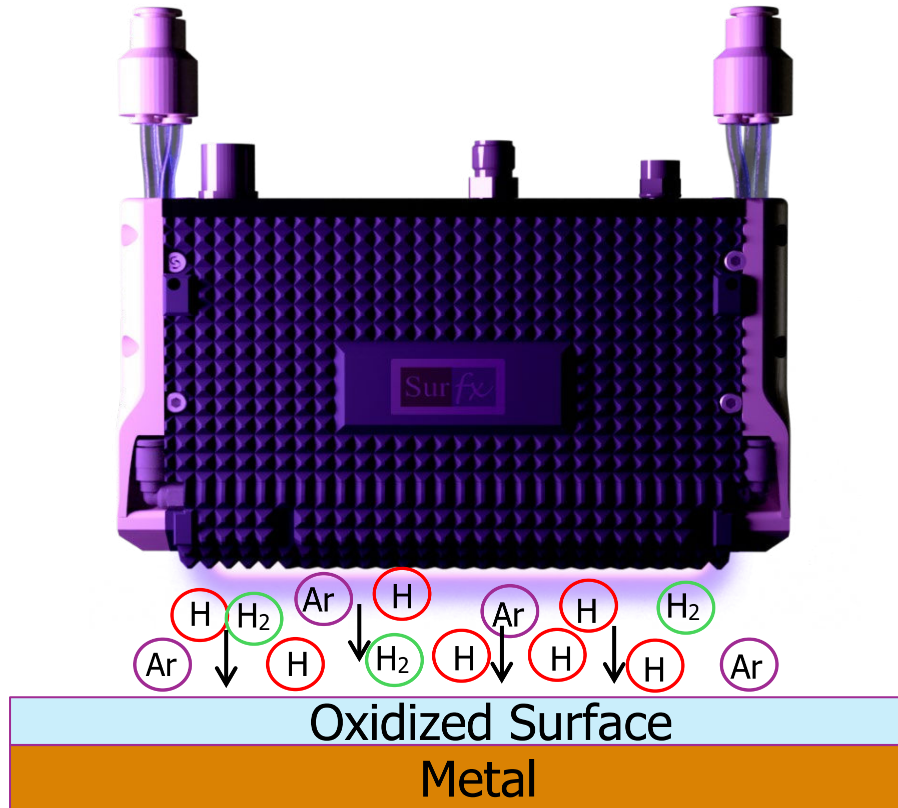


Figure 3: Atmospheric pressure plasma for advanced packaging applications.

For semiconductor processing, the plasma must be weakly ionized, so that it is uniformly distributed as a “glow discharge” between the electrodes, and so that the gas temperature stays low. The easiest way to generate a weakly ionized plasma is to carry out the process in vacuum. Hence, vacuum plasmas are ubiquitous in semiconductor fabs. Generating a stable, weakly ionized plasma at atmospheric pressure is much more challenging. This fact is best explained in reference to the Paschen curve shown in Figure 4. The y-axis is the breakdown voltage of the gas and the x-axis is the gas pressure times the gap spacing between the electrodes, p*d (Torr*cm). Vacuum plasmas are operated at pressure between 50 and 200 milliTorr with gaps in the range of 1 to 100 centimeters. At atmospheric pressure, the gap must be on the order of a few millimeters.

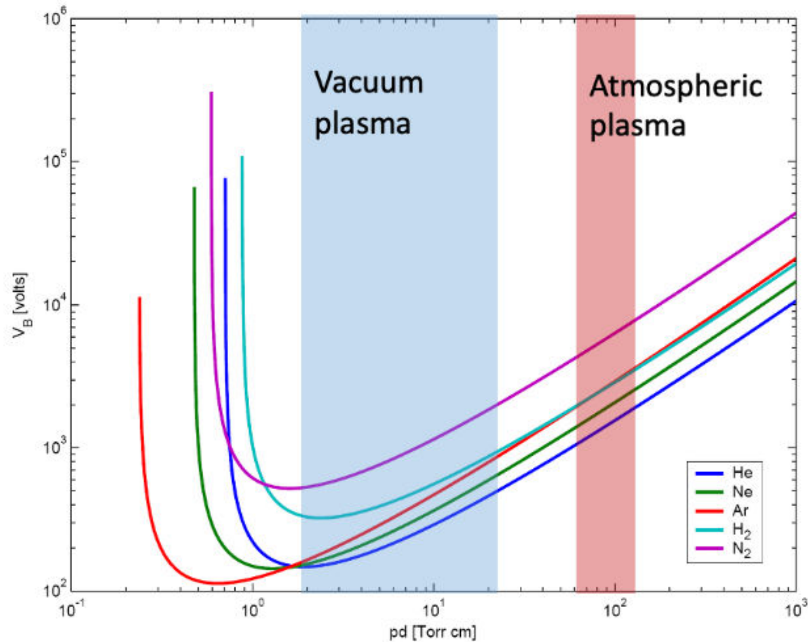


Figure 4: Paschen curves of breakdown voltage versus the pressure times electrode gap for different gases.

At atmospheric pressure, the breakdown voltage is strongly affected by the type of gas used. Air requires a V_B of 2 to 10 kilovolts, which requires a lot of power to be delivered to the electrodes to strike the plasma, and inevitably leads to an arc. By contrast, argon and helium have low V_B values, approximately 600 and 180 V, respectively, using radio-frequency power. In this case, the plasma may strike and run in the weakly ionized state.

In order to prevent the plasma from transitioning into an arc, the ionization rate, i.e., the rate of free electron generation, must be less than the termination rate, i.e., the rate of electron loss at the walls. For all practical purposes, only two gases may be used to generate weakly ionized plasmas at atmospheric pressure, helium and argon. This is because these two gases have the twin benefits of low breakdown voltage and low ionization rate constant. A current/voltage graph is presented in Figure 5.

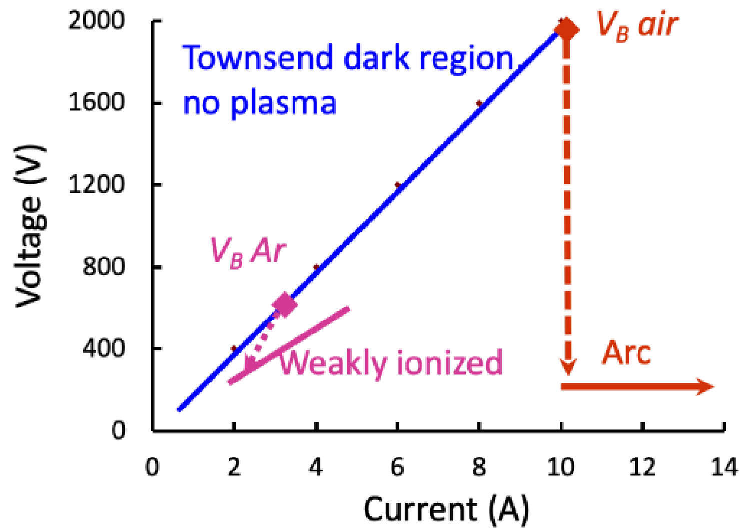
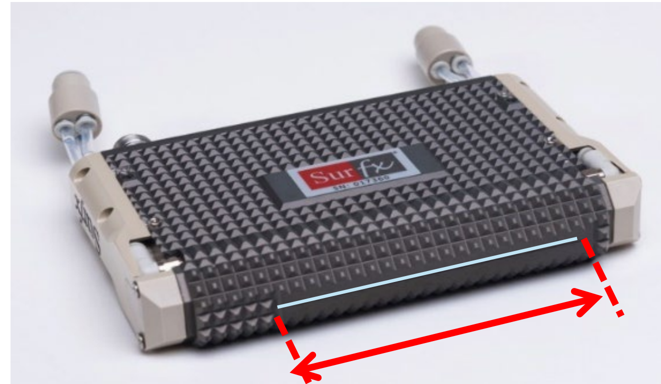


Figure 5: Dependence of voltage on current for the operation of argon and air plasmas at atmospheric pressure.

When electrical power is supplied to the electrodes the voltage and current increase linearly along the blue line until breakdown occurs and the gas becomes ionized. Argon with its low breakdown voltage and low ionization rate can be stabilized in the weakly ionized state (pink line). By contrast, air (N_2+O_2) has a very high breakdown voltage. This combined with the large ionization rate constant inevitably leads to arc formation at atmospheric pressure.

<u>Atomflo™ Atmospheric Pressure Plasma</u>

Shown in Figure 6 is the Atomflo atmospheric pressure plasma offered by Surfx Technologies, LLC. It comes in three widths, 25-, 50- and 100-mm wide beams, that are driven with RF power at 27.12 MHz. The plasma is fed with argon and about 1.0% hydrogen, nitrogen or oxygen. The atmospheric pressure plasma fed with about 7.5 Torr hydrogen generates 20,000 times more H radicals than a typical vacuum plasma.



25-, 50- & 100-mm widths

Figure 6: Picture of atmospheric pressure argon plasma source offered by Surfx Technologies, LLC.

The plasma head is operated from a controller that houses the RF power train, gas flow system, and computer control board, plus a coolant control module that circulates warm water through the plasma head. This equipment is shown in Figure 7. The computer monitors and stores all the plasma process parameters in real time, including gas flow rates, water circulation temperature, forward and reflected power, and phase and magnitude of the RF signal. In addition, a sensor monitors the glow generated by the plasma to guarantee the "process on" state when materials are being treated.

Figure 7: Controller for atmospheric pressure argon plasma source.

Metal Oxide Removal

The metal oxide removal process with the hydrogen plasma is temperature sensitive. Presented in Figure 8 is the dependence of the copper oxide removal rate on inverse temperature (see J. Lee, T.S. Williams, and R.F. Hicks, "*Atmospheric pressure plasma reduction of copper oxide to copper metal,*" J. Vac. Sci. Technol. A, **39**, 023001 (2021)). From the slope of the line, an activation energy of 3.7 kcal/mole is calculated. It is expected that activation energies will be different for the removal of other metal oxides, such as tin oxide and indium oxide. Depending on the temperature chosen for the oxide removal process the micro-bumps may reflow during treatment.

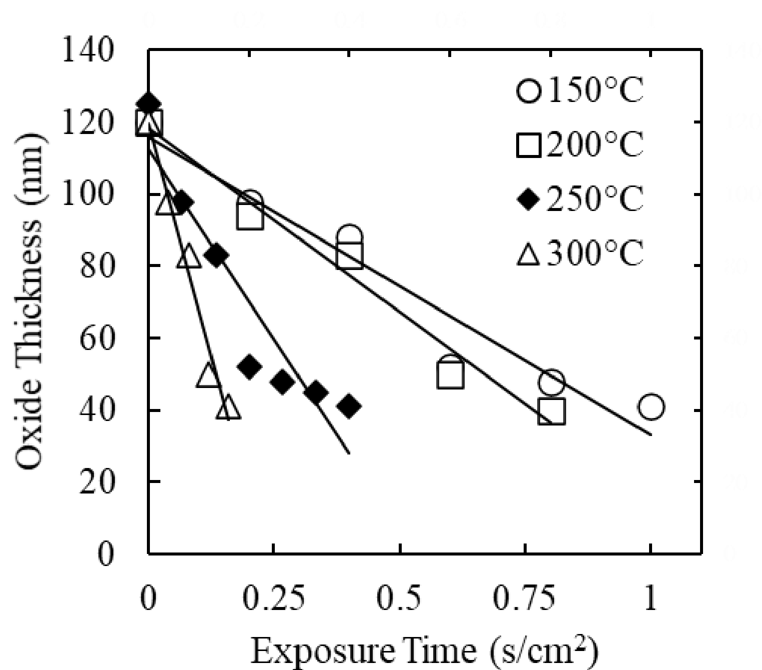


Figure 8: Effect of temperature on copper oxide reduction rate.

Deoxidation of micro-bumps on a die can be accomplished in one scan of the linear H_2 plasma beam at process times in as little as one second. On the other hand, a 300mm wafer requires a step and scan program to complete the process. This procedure is illustrated with a 100mm plasma beam in Figure 9. A wafer chuck is suspended below a purge cover that provides a means of flowing inert gas through the chamber and reducing the oxygen concentration below 100 parts per million. This design has been implemented

in the STW wafer processing tools. The plasma is turned on with the head positioned in the upper left corner a few centimeters off the edge of the wafer. Then, it scans down the left one third of the wafer, steps to the right 100 mm, scans back up the middle one third of the wafer, steps to the right 100 mm, and scans down the right one third of the wafer. The total scan path is 1,100 mm. The throughput depends on the plasma head scan speed. For example, at a speed of 10 mm/s, the process is completed in 110 seconds.

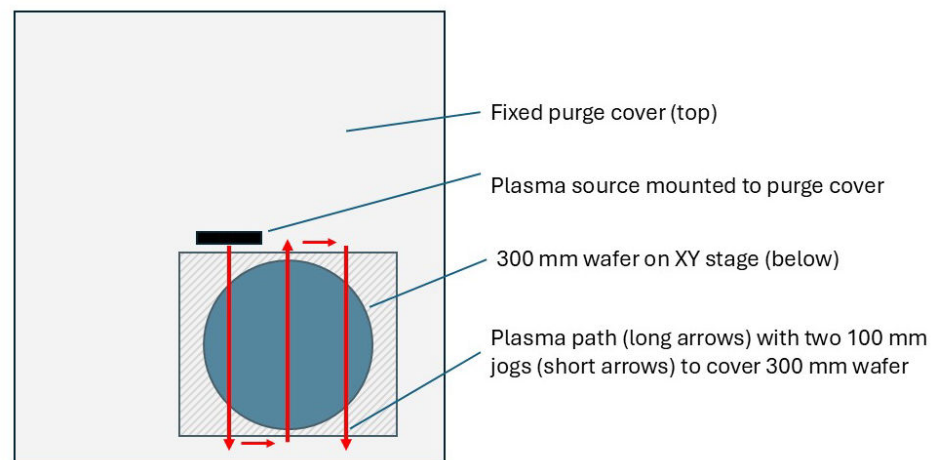
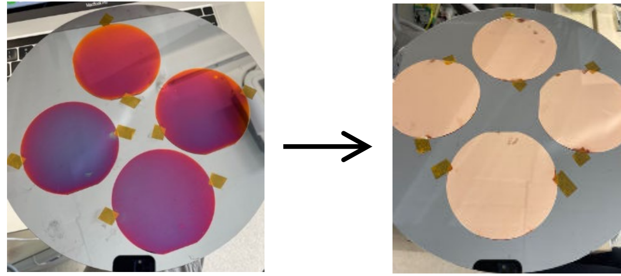


Figure 9: Step and scan path for processing a 300 mm wafer with 100mm atmospheric pressure plasma source.

Shown in Figure 10 are pictures of four 100mm wafers of copper coated silicon wafers taped onto a 300m wafer. In (a), the copper is covered with a CuO film 45nm thick giving it a purple color. In (b), the wafer has been treated with the atmospheric pressure hydrogen plasma at 150 °C. All the oxide has been removed as evidenced by the characteristic copper color. Proprietary recipes have been developed for the micro-bump structures employed in 2D and 3D packaging.



(a) Cu-coated wafers with 40 nm CuO before plasma treatment.

(b) Cu-coated wafers after plasma treatment.

Figure 10: Copper-coated silicon wafers with thick oxide layer before treatment and no oxide layer after treatment with atmospheric pressure argon and hydrogen plasma.

Conclusions

In situ hydrogen plasmas have an important role to play in realizing 3D chips with interconnect densities approaching 1 million per centimeter squared, and at signal speeds of 5 GHz and higher. The weakly ionized, atmospheric pressure hydrogen plasma has proven itself to be a robust alternative for flux-free oxide removal prior to thermocompression bonding of Cu/Sn/Ag micro-bumps. It will be exciting to see this technology built out in high volume manufacturing over the next few years.