

# CO<sub>2</sub> Clean Manufacturing Technology for Electronic Device Fabrication

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## Abstract

CO<sub>2</sub> technology offers electronic device manufacturers a robust platform for a variety of precision cleaning and machining applications. Surface and substrate contamination such as flux residues, organics, particulate matter, outgassing residues, ionic residues, and laser and mechanical machining heat can be addressed (uniquely) with this technology. Available CO<sub>2</sub> processes include one or a combination of composite jet sprays, centrifugal liquid immersion, supercritical fluid extraction, and both vacuum and atmospheric plasma surface treatments.

CO<sub>2</sub> technology eliminates or significantly reduces both lean and green waste generation at the production operation level (source) by modifying manufacturing processes such as precision cleaning and machining. Because it is safe and dry, CO<sub>2</sub> technology can integrate directly into manufacturing processes and tools to provide in-situ cleaning and/or thermal control. CO<sub>2</sub> technology can be implemented in a variety of process configurations to meet the constraints of lean production layouts and product flow requirements, including direct integration into existing production lines and equipment where the surface contamination is being generated. CO<sub>2</sub> is a very unique manufacturing agent that affords multiple cost reduction and performance improvement opportunities for electronic device fabrication.

Exemplary applications include silicone contamination removal from a surface using a CO<sub>2</sub> composite spray, hybrid CO<sub>2</sub> particle-plasma pad surface preparation for gold wire bonding, ceramic flip chip defluxing using centrifugal liquid CO<sub>2</sub>, surface residue removal using a CO<sub>2</sub> composite spray following laser processing, particle removal from a CMOS image sensor following wire bonding, and CO<sub>2</sub>-enabled laser machining of organic and ceramic substrates.

## I. Introduction

Over the past 25 years, CO<sub>2</sub> clean manufacturing technology (CO<sub>2</sub> CleanTech) has been used within many high technology, high reliability, and high capacity manufacturing operations. Industries have included aerospace, hard disk drive, microelectronics, and optoelectronics, among many others. CO<sub>2</sub> CleanTech has been used primarily as a means for increasing the cleanliness of components, assemblies, tools and fixtures to increase both capacity and quality. Possibly more significant, CO<sub>2</sub> CleanTech has proven itself to be a means for reducing the cost of manufacturing high reliability products [1].



Figure 1 – Lean and Green Manufacturing

As described under Figure 1, in an environment of escalating manufacturing challenges such as intense global competitiveness, environmental regulation and energy supply issues, material and process engineers must have both lean and green manufacturing (aka “Clean Manufacturing”) technology to identify and eliminate multifaceted manufacturing wastes in their operations that stealthily steal away business profits. CO<sub>2</sub> CleanTech represents a significant business opportunity to adapt production tools and operations to meet the challenges. The merging of green practices such as CO<sub>2</sub> technology into manufacturing is delivering additional value in the form of less chemical, energy, labor, and water usage as well as the elimination of solid wastes, air and water pollution [2].

CO<sub>2</sub> CleanTech offers electronic device manufacturers, component suppliers and assembly equipment OEMs new ways to re-tool their factories and equipment for cleaner production. Assembly tool builders can develop and deliver clean-in-place assembly process-tool combinations to support sustainable manufacturing initiatives. Component suppliers can produce and supply better quality product at lower cost and device manufacturers can adapt dry clean-in-place capability throughout the factory. CO<sub>2</sub> CleanTech can uniquely address the composite opportunity to reduce both lean and green manufacturing waste throughout the production network; tool suppliers, component suppliers, and manufacturers.

## **II. CO<sub>2</sub> is a Unique Manufacturing Solution**

CO<sub>2</sub> is a safe and abundant compound that plays a very important role in many commercial and industrial applications. CO<sub>2</sub> can be used in cleaning, cooling and machining applications. Many companies have implemented CO<sub>2</sub>-based cleaning technology and have realized improved productivity and a lower cost-of-operation of their production operations. CO<sub>2</sub> CleanTech has also served as a strategy for complying with worker safety and environmental regulations. The CO<sub>2</sub> used in cleaning, machining and thermal control processes is the same CO<sub>2</sub> used to charge fire extinguishers, carbonate beverages, weld steel, cast metals, and refrigerate products, among many other important industrial uses. In fact it's the same CO<sub>2</sub> that you are exhaling while reading this paper; about 1 kilogram of it every day.

CO<sub>2</sub> is an abundant (and recyclable) by-product of numerous industrial and natural processes. Recycled CO<sub>2</sub> is a valuable and renewable manufacturing resource that will never run out of supply. Unique benefits derived from using recycled CO<sub>2</sub> include the conservation of water, reduced energy consumption and a reduction in industrial CO<sub>2</sub> emissions. Moreover CO<sub>2</sub>-based process technology is a positive contribution to Hazardous Air Pollutant (HAP), Volatile Organic Compound (VOC), and Greenhouse Gas (GHG) emissions reduction strategies.

Using recycled CO<sub>2</sub> to reduce pollution, conserve energy and eliminate wastes (both environmental and manufacturing) produces numerous tangible and measurable benefits. Major industrial sources of CO<sub>2</sub> emissions include:

1. Electrical power generation and usage,
2. Chemical generation and usage, and
3. Transportation.

The use of recycled CO<sub>2</sub> technology as a chemical/process substitute lowers electrical power usage, reduces manufacturing wastes, increases manufacturing productivity, and decreases the need for chemicals such as lubricants and solvents, among many other positive socioeconomic and environmental benefits. A reduction of manufacturing wastes or elimination of production chemical inputs of any kind decreases industrial CO<sub>2</sub> (carbon) footprint. Following are examples of how this works:

- ✓ Less CO<sub>2</sub> is produced if less electricity is consumed for processing.
- ✓ Less CO<sub>2</sub> is produced if less oil is refined, transported and consumed.
- ✓ Less CO<sub>2</sub> is produced if less cleaning solvents are produced, transported and consumed.
- ✓ Less CO<sub>2</sub> is produced if more products can be manufactured for the same energy, labor and space inputs.
- ✓ Less CO<sub>2</sub> is produced if products don't have to be cleaned using hot deionized water or dried using solvents or other drying agents.

Thus from a GHG emissions perspective, using recycled CO<sub>2</sub> significantly offsets new CO<sub>2</sub> gas production and emission from both the industrial supply and consumption sides of the equation. Pending USEPA CO<sub>2</sub> emissions reporting legislation is intended to impact the "generators" of CO<sub>2</sub>. A user of recycled CO<sub>2</sub> is not considered a generator of CO<sub>2</sub>. The CO<sub>2</sub> used in commercial and industrial processes is already accounted for in the GHG emissions inventory.

With regards to smog generation, CO<sub>2</sub> is not a VOC and is not regulated as such. From a worker health and safety perspective, CO<sub>2</sub> is non-toxic. From a building safety and equipment protection perspective, CO<sub>2</sub> is non-flammable and non-

corrosive. CO<sub>2</sub> is a perfect solution for protecting the environment and improving the health and safety of both workers and communities, while improving the performance and cost-of-operation of high reliability product manufacturing operations.

### III. CO<sub>2</sub> is Many Manufacturing Agents in One



**Figure 2 – Phases of CO<sub>2</sub>**

As shown in Figure 2, CO<sub>2</sub> is a very versatile manufacturing agent; 5 manufacturing agents in 1. It can be used as a solid, liquid, supercritical fluid, and both atmospheric and low-pressure plasma. CO<sub>2</sub> is useful as a spray treatment agent [3], immersion and extraction solvent [4], as well as in the form of many hybrid or combinational substrate processing possibilities. In addition, CO<sub>2</sub> fluids purification and management systems have been developed to support these various capabilities. Manufacturing applications for CO<sub>2</sub> CleanTech are diverse as well. Applications include precision degreasing, departiculation, outgassing, precision drying, disinfection, surface modification and functionalization, cooling and lubrication, among many others.

CO<sub>2</sub> solvent properties are similar to halogenated solvents such as Freon® 113 and HFE-7100. CO<sub>2</sub> possesses a Hildebrand solubility parameter in the adjustable range between 14 MPa<sup>1/2</sup> to 22 MPa<sup>1/2</sup> depending upon phase, temperature and pressure. CO<sub>2</sub> can be compressed to a range of liquid-like densities, yet it will retain the diffusivity of a gas with extremely low viscosity. Supercritical and liquid CO<sub>2</sub> cleaning agent densities may be adjusted between 0.5 g/cm<sup>3</sup> and 0.9 g/cm<sup>3</sup>. Solid phase CO<sub>2</sub> has a density of 1.6 g/cm<sup>3</sup>, identical to Freon® 113. High density provides significant and controllable impact shear stresses of between 10kPa (i.e., using fine CO<sub>2</sub> particles at low velocity) and 300 MPa (i.e., using CO<sub>2</sub> pellets at high velocity) when projected against a non-compliant substrate surface. Surface tensions for CO<sub>2</sub> fluids range from 0 dynes/cm (supercritical) to 5 dynes/cm (liquid). Practical benefits derived from these unique properties include rapid penetration and wetting, hydrocarbon solubility, and energetic cleaning, cooling and dry lubrication effects.

### IV. CO<sub>2</sub> Technology Reduces or Eliminates Manufacturing Waste

CO<sub>2</sub> CleanTech eliminates or significantly reduces waste generation at the production operation level (i.e., at the source) by modifying manufacturing processes, and in particular precision cleaning, assembly processes requiring critical cleaning, and precision machining operations. CO<sub>2</sub> modifies conventional manufacturing processes and tools in several dimensions, described as follows;

1. Physically; shape, size, space, application and configuration;
2. Chemically; solvency, toxicity, and dryness;
3. Quality; defects, rework, scrap; and
4. Time; productivity.

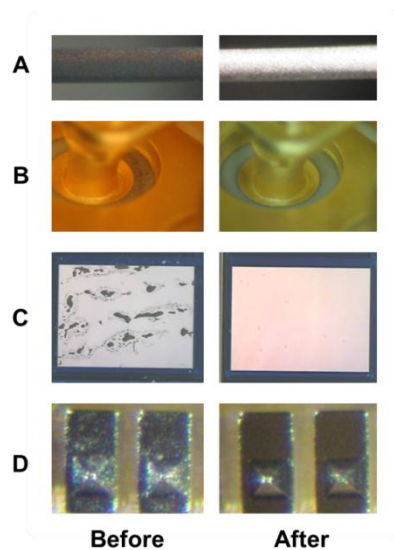
**Table 1 - Examples of CO<sub>2</sub> CleanTech  
Utilization and Benefits**

| <b>Equipment and<br/>Process Configuration</b>                                                                                                                                           | <b>Waste Reduction<br/>Benefits</b>                                                                                  |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|
| Integrate CO <sub>2</sub> CleanTech with automation and environmental control to produce custom stand-alone automated cleaning cells or islands to replace aqueous and solvent cleaners. | Eliminate aqueous cleaning and rinsing fluids, drying equipment and related waste-producing operations.              |
| Integrate CO <sub>2</sub> CleanTech into existing production lines and processes.                                                                                                        | Enables in-line cleaning where none existed and without an increase in floor space.                                  |
| Hybridize CO <sub>2</sub> CleanTech with one or more manufacturing processes such as dispensing, bonding, welding, coating, curing, soldering, machining and inspection.                 | Eliminate the need for separate and additional cleaning equipment, processes and related waste-producing operations. |

CO<sub>2</sub> CleanTech may be implemented in a variety of production equipment and process configurations to meet the needs of lean production schemes and product flow constraints, including both existing and new production line and tool implementations. Examples of unique CO<sub>2</sub>-enabled production configurations and manufacturing waste reduction benefits are summarized in Table 1.

## **V. Applications**

CO<sub>2</sub> CleanTech provides material and process engineers with a robust surface treatment platform and window for challenging substrates having complex or microscopic geometries. As shown in Figure 3, many different types of devices can be processed to address numerous contamination challenges including particulate matter, organic residues, outgassing residues, oxides, ionic residues, as well as process heat during machining processes. Shown in Figure 3: [A] Removal of laser welding oxides (alloys) from titanium neurostimulator electrodes, [B] Removal braze weld debris from electronic package, [C] Removal of fingerprint from CMOS image sensor, and [D] Removal of built-up aluminum and aluminum oxide particles from test probe contact. CO<sub>2</sub> treatment processes include composite jet sprays, centrifugal immersion, supercritical fluid extraction, precision drying (i.e. critical point drying), and vacuum and atmospheric plasma treatments – and hybrid processes using combinations of these.

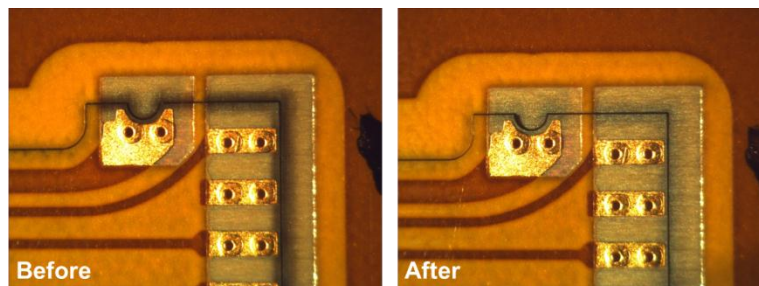


**Figure 3 – CO<sub>2</sub>-Processed Devices**

Many different hybrid processes comprising the various CO<sub>2</sub> treatment processes are possible. Numerous combinations of CO<sub>2</sub> treatments with other advanced substrate processing techniques such as Laser, UV, micromachining, ozone, microabrasives, plasma, robotics, among many others are uniquely possible. The inherent compatibilities and synergies generated between these systems create numerous and varying manufacturing benefits, including the creation of new intellectual property.

CO<sub>2</sub> CleanTech is used in a variety of microelectronic device manufacturing and assembly processes, and in manual, mobile, and automated production configurations. Examples include:

- Adhesive Bonding,
- Functional Coating
- Encapsulation/Sealing

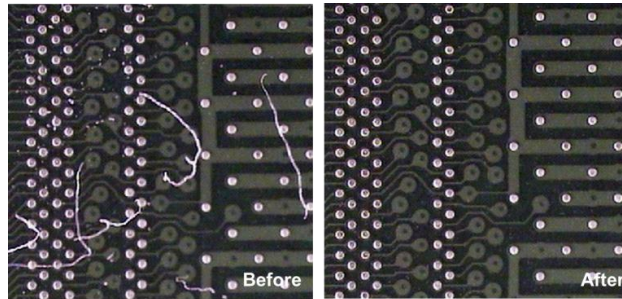


**Figure 4 – Removing Laser Cutting Residues**

- Wire Bonding
- Welding
- Ceramic, Glass and Crystal Polishing
- Optical Device Assembly (and Test)
- Laser and Diamond Machining
- Microfluidic Device Fabrication
- Precision Device Assembly

CO<sub>2</sub> CleanTech applications have included many types of passive, electro-mechanical and electro-optical substrates with varying end-product performance requirements, and for many different markets including Biomedical, Military, HDD, and Aerospace. Examples of materials and applications relevant to microelectronic device manufacturing are summarized in Table 2.

Microelectronic assemblies require high-volume and cost-effective cleaning during various stages of assembly or rework operations. Due to component compatibility problems and drying challenges, partially assembled devices cannot be immersed in or sprayed with aqueous cleaners or solvents. CO<sub>2</sub> CleanTech overcomes these constraints by providing high capacity, dry solvent-like spray cleaning capability [5]. In many electronic device fabrication applications, selective cleaning of the surface is needed to remove localized contamination generated by processes such as pad preparation, cutting, and drilling. Figure 4 shows an example of selective removal of laser residues from a portion of a polyimide flexible circuit following cutting using a CO<sub>2</sub> Composite Spray cleaning process. This process can be further enhanced using combinational or hybrid processes such as CO<sub>2</sub> particle-plasma treatments, described under the case study below.



**Figure 5 – Removing Particles and Fibers**

CO<sub>2</sub> CleanTech can remove microscopic thin film residues, particles and fibers from the functional surfaces of electronic devices, including sub-micron particles. For example, this is evidenced by electronic performance changes noted during the treatment of quartz crystal resonators [6]. Figure 5 shows the removal of typical airborne manufacturing debris such as fibers and particles from a circuit board.

**Table 2 – Materials and Applications**

| <b>Material</b>                | <b>Application</b>                                                                          |
|--------------------------------|---------------------------------------------------------------------------------------------|
| Quartz Crystal Resonator       | Drive-Level-Dependence (DLD) reduction                                                      |
| Fiber Optical Device           | Removal of polishing residues                                                               |
| Optoelectronic Device          | Build clean protocol                                                                        |
| Ceramic Substrate              | Removal of Laser and diamond cutting residues during or following machining (clean cutting) |
| Polymeric Substrate            | Removal of residues during or following machining                                           |
| Metallic Bond Pads             | Bond pad preparation for wire bonding                                                       |
| Low-Energy Polymer             | Improved adhesion                                                                           |
| Flexible Printed Circuit Board | Removal of residues from laser-processed devices                                            |
| Acrylic Polymer                | Improved adhesion for Light-cure acrylic bond                                               |
| RF/Microwave Packages          | Particle and residue removal following brazing                                              |
| Ceramic-Metal Composites       | Improved adhesion                                                                           |
| Patterned Wafer                | Photoresist and processing residue removal                                                  |

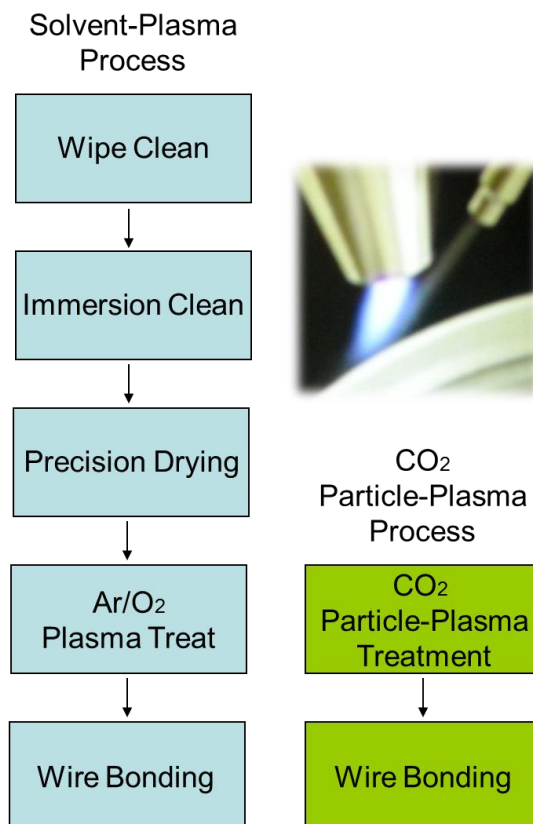
## VI. Case Study

### Bond Pad Surface Preparation for Wire Bonding

## **Background**

A statistically significant study was performed to determine the effectiveness of a dry, selective CO<sub>2</sub> particle-plasma surface treatment process for preparing bond pads for gold wire bonding operations [7]. The study compared and contrasted the performance of the CO<sub>2</sub> surface treatment method with that of a conventional solvent-plasma method. The two treatment methods were used to prepare the surface of a metalized ceramic wafer that simulated bond pad surfaces and treatment areas representative of the actual high-reliability electronic board. Robust surface treatment of bond pads is required in this particular application to insure complete removal of a variety of possible surface contaminants for strong and reliable wire bonds following gold ribbon bonding operations.

As shown in Figure 6, the conventional solvent-plasma method used in this study comprised four sequential steps (proprietary processing parameters), as follows: 1) manual solvent wipe cleaning (i.e., acetone) to remove any thick films and gross manufacturing debris, 2) ultrasonic immersion cleaning (i.e., aqueous) and deionized water rinsing to remove thin film and inorganic contamination, 3) precision drying to remove residual rinsate, and 4) Ar/O<sub>2</sub> low pressure plasma treatment to precision clean, micro-etch, and activate surfaces. Issues associated with the solvent-plasma method include surface contaminant smearing and re-deposition of residues, contamination accumulation within the treatment solvents, and an inability of low-pressure plasma treatment to reliably remove various inorganic residues and particulate matter from the bonding pads. Contaminant transfer, solvent-contaminant build-up, and manual cleaning operations are known to introduce cleaning process variability that result in wire bonding defects. Another constraint associated with the solvent-plasma process is a lack of selectivity. The entire electronic assembly must be immersed into cleaning solvents and plasma, which can introduce contamination or compatibility issues with other electronic components and materials co-located on the electronic assembly. Finally, the solvent-plasma process prevents the implementation of a lean and continuous high-capacity cleaning in this application.



**Figure 6 – Solvent-Plasma compared to CO<sub>2</sub> Particle-Plasma Process**

The CO<sub>2</sub> particle-plasma process used in this study involved a patented and patents-pending hybrid CO<sub>2</sub> particle-plasma spray process called CO<sub>2</sub> particle-plasma cleaning [8]. The CO<sub>2</sub> particle-plasma process is a single-step process derived by mixing CO<sub>2</sub> particles and CO<sub>2</sub> plasma into a composite atmospheric treatment stream. A blown ion spray (Plasma Component) is directed into the CO<sub>2</sub> Composite Spray (Particle Component); the composition of which is directed against the

surface as shown in the picture under Figure 6. Using this hybrid spray composition, the CO<sub>2</sub> particles (and propellant) are doped with beneficial ions, radicals, UV light, and ozone from the blown ion plasma stream through both fluid shearing and vortical mixing actions. The CO<sub>2</sub> Composite Spray further serves as a chemical and physical cleaning and cooling barrier stream, transmitting and transporting beneficial UV radiation and reactants (i.e., ozone, oxygen radical, nitrate ions, hydroxyl, heat, etc.), respectively, to the surface – simultaneously removing plasma-surface reaction by-products including excess heat and ablated, oxidized, or decomposed contaminants.

Metalized ceramic surfaces were doped with thick layers of various common contaminants as well as a mixture of same. An example of a doped test coupon is shown in Figure 7. Gold ribbon wire bonding was performed following surface cleaning operations. The CO<sub>2</sub> particle-plasma cleaning process was developed and performed under the direction of the author. Solvent-plasma cleaning and treated-coupon wire bonding, pull testing and statistical analysis were performed by the co-investigator. The experimental testing and results are summarized and discussed below.

### **Experimental**

106 ceramic wafers (Al<sub>2</sub>O<sub>3</sub>), designated as sample numbers SN1-SN106, each containing a surface layer comprising vapor-deposited TiW, Ni, and Au, were divided into 5 test groups. These composite substrates represented the bonding pad



**Figure 7 – Example of Contaminated Test Sample**

characteristics (surface chemistry and area) of the actual hybrid electronic board and bond pads in various states of cleanliness, described as follows:

#### **Solvent-Plasma Cleaning Process Test Group (SN1-5, SN16-20, SN31-35, SN45-50 and SN85-89)**

25 samples, designated as SN1-5, SN16-20, SN31-35, SN45-50 and SN85-89, were subdivided into 5 sample sets, contaminated as described below and cleaned using the proprietary solvent-plasma process described above.

#### **CO<sub>2</sub> Particle-Plasma Cleaning Process Test Group (SN6-15, SN21-30, SN36-45, SN51-60, and SN90-99)**

25 samples, designated as SN6-15, SN21-30, SN36-45, SN51-60 and SN90-99, were subdivided into 5 sample sets, contaminated as described below and cleaned using the CO<sub>2</sub> Particle-Plasma cleaning process described below.

#### **OSEE Inspection Baseline Test Group (SN61–65)**

5 samples (SN61-65) were retained for establishing a baseline photocurrent using a non-contact surface inspection method called Optically Stimulated Electron Emission (OSEE). The OSEE photocurrent of the OSEE baseline testing group was compared to the contaminated and CO<sub>2</sub> cleaned coupons.

#### **Bonding Parameter Test Group (SN101, SN102, SN101-105)**

7 samples, SN101, SN102, SN101-SN105, were used to establish the ribbon bonding and pull test criteria for all test groups.

#### **Control Test Group (SN66-84, SN106, SN100)**

A total of 21 samples, designated as SN66-84, SN106 and SN 100, were retained as sample controls. Following wafer metalization processes, control samples were vacuum plasma treated (Ar/O<sub>2</sub>), gold ribbon bonded, and pull tested to establish clean surface baseline bond strength.

#### Surface Contamination Challenge

Both the solvent-plasma and CO<sub>2</sub> particle-plasma process test groups (50 sample coupons total) were doped using a brush with a particular contaminant type, described as follows:

- Tape Adhesive (SN1-15)
- Finger Oils (SN16-30)
- Flux (SN31-45)
- Silicone Oil (SN46-60)
- Combination of adhesive, finger oils, flux and silicone oil (SN85-99)

Each type of contamination was brushed onto the metalized wafer surfaces using an acetone solvent carrier and dried.

**Note:** The simulated surface contamination produced was a very thick film. This level of contamination is not a normal manufacturing surface contamination level and thus represented a worst-case challenge test for both treatment processes.

#### CO<sub>2</sub> Particle-Plasma Cleaning Test Apparatus

Shown in Figure 8, the CO<sub>2</sub> Particle-Plasma treatment test apparatus comprised a programmable Cartesian robot with moveable x, y and z axes. An end-of-arm tool (EOAT) connected to the z-axis comprised a CO<sub>2</sub> Composite Spray nozzle (45 degree angle), and CO<sub>2</sub> Plasma nozzle (shown with OSEE surface inspection probe in 90 degree position). Doped wafers were affixed to the x axis using double-sided tape, whereupon the same (optimized) CO<sub>2</sub> Particle-Plasma surface cleaning and treatment recipe was executed for each test sample.



**Figure 8 – Experimental Cleaning Test Apparatus**

#### Optimized CO<sub>2</sub> Particle-Plasma Cleaning Process Variables

##### *Propellant Gas:*

|              |                  |
|--------------|------------------|
| Type:        | Nitrogen Gas     |
| Pressure:    | 80 psi (552 kPa) |
| Temperature: | 120° C (393 K)   |

##### *CO<sub>2</sub> Particle Generator:*

|                            |                      |
|----------------------------|----------------------|
| Condenser Diameter (I.D.): | 0.030 inches (8 mm)  |
| Condenser Length:          | 8 feet (244 cm)      |
| Spray Nozzle:              | Coaxial 2:2 Straight |
| Spray Angle:               | 45 Degrees           |

#### *CO<sub>2</sub> Plasma:*

Treatment Gas: Carbon Dioxide  
Plasma Type: Blown Ion  
Spray Pressure: 80 psi (552 kPa)  
Spray Angle: 90 Degrees

#### *Robot/EOAT:*

Robot Type: Cartesian, 3-axis  
Treatment Scan rate: 10 mm/sec  
Treatment Sequence: X-Y Scan, 10 mm Step  
EOAT distance from surface: 1.27 cm

#### CO<sub>2</sub> Particle-Plasma Treatment Process Description

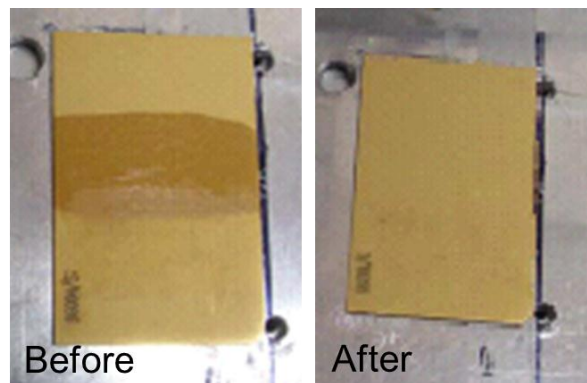
CO<sub>2</sub> Particle-Plasma is sprayed over the entire topside surface of the test sample, which simulated the actual surface area of the electronic board bonding pad strips. The treated surface area was 2 inch x 1 inch (5 cm x 2.5 cm) portion of a 2 inch x 3 inch (5 cm x 8 cm) test substrate. A total of three (3) treatment passes were performed on each strip.

#### CO<sub>2</sub> Cleaning Method and Packaging

1. Test sample was mounted to robot fixture using tack tape (un-treated side).
2. CO<sub>2</sub> Particle-Plasma spray was projected at test sample surface using optimized treatment spray and robotic scan cleaning parameters described above.
3. Treated test substrates removed from the mounting fixture and heat-sealed in clean nylon packaging.

An example of surface condition before and after CO<sub>2</sub> treatment is shown in Figure 9.

#### Gold Ribbon Bonding Process



**Figure 9 – Before and After CO<sub>2</sub> Cleaning (Coupon SN096)**

The gold wire bonding equipment and process parameters used are described as follows:

Ribbon Bonder: Westbond Model Number 4630E  
Au Ribbon: 0.005” x 0.007”  
Ribbon Bonding Tool: Deweyl MRCSVD-1/16-1-52-CG-.5X7-M

Gold ribbon bonding was performed with tool heat and work holder temperature at 150° C. Following wire bonding, all wire bonds were pull-tested using a procedure detailed in MIL-STD-883E [8].

#### Results and Discussion

##### *Bond Pull Failure Modes; Number of Bond Lifts*

Control Group: 0  
Solvent-Plasma: 10  
CO<sub>2</sub> Particle-Plasma: 6

As shown in Figure 10, the CO<sub>2</sub> particle-plasma process showed a lower aggregate number of bond lifts as compared to the solvent-plasma cleaning group. Within the variance of the process, the CO<sub>2</sub> particle-plasma cleaning process performance was equivalent to the solvent-plasma cleaning process for finger oils, flux, and silicone oil and for contaminant mix coupons.

### Average Bond Pull Strength

Control Group: 58 g

Shown in the Figure 11, all ribbon bond pull strength test measurements for both solvent-plasma and CO<sub>2</sub> particle-plasma cleaning for each type of contaminant were a magnitude higher than the 6.8 g minimum pull strength per MIL-STD-883,

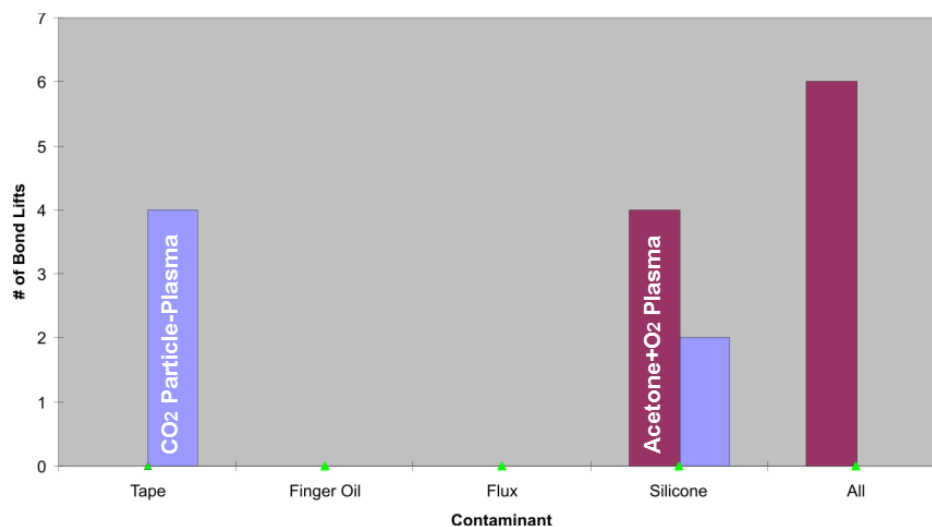


Figure 10 – Number of Bond Lifts

Method 2011.7.

### Bond Pull Defects; Calculated Defects per Million (DPM)

Control Group: 233 DPM

The solvent-plasma treatment group showed a higher aggregate DPM compared to the CO<sub>2</sub> particle-plasma treatment group.

Solvent-Plasma: 117664.7 DPM

CO<sub>2</sub> Particle-Plasma: 17051.8 DPM

Shown in Figure 12, the data also showed that CO<sub>2</sub> particle-plasma treatment represents only 2% of the DPM as compared to

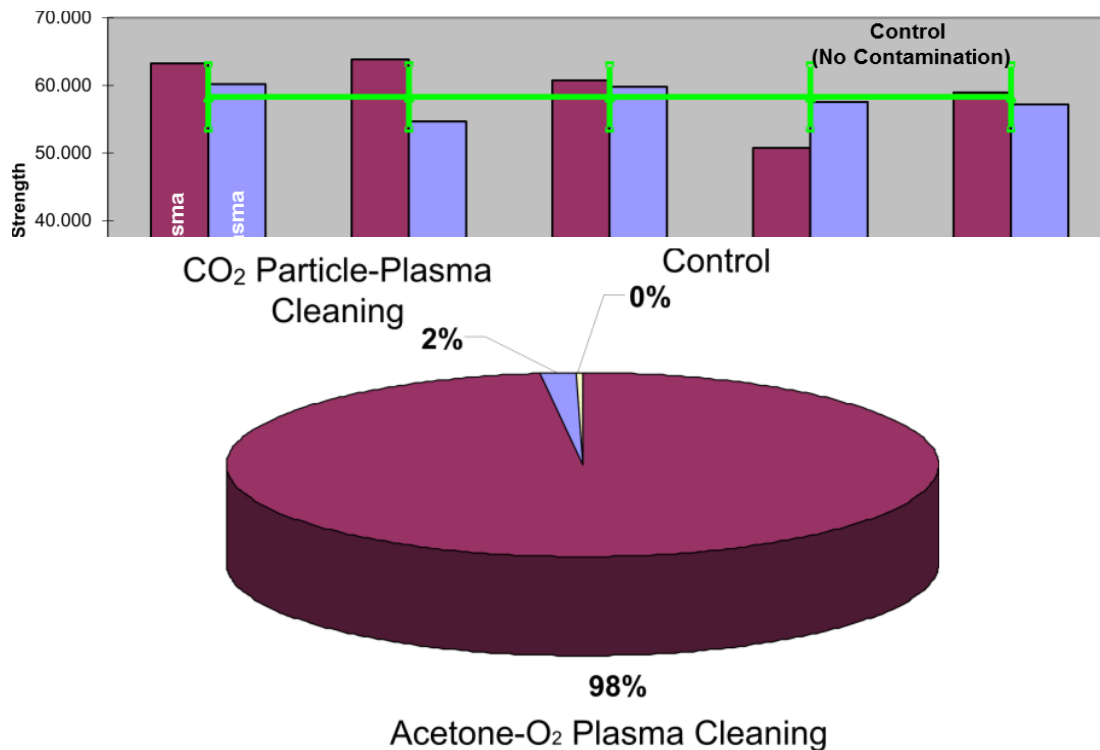


Figure 12 – Defects-Per-Million (DPM)

solvent-plasma cleaning which represents 98% of the DPM.

*Bond Pull Strength Variance; Coefficient of Variance (CpK)*

Shown in Figure 13, the CO<sub>2</sub> particle-plasma cleaned coupons showed a tighter distribution within the established control limits as compared to the solvent-plasma treatment group. The CpK data for silicone contamination indicated that the CO<sub>2</sub> particle-plasma cleaning process is slightly more effective, with the solvent-plasma CpK data falling below the Lower Safety Limit (LSL).

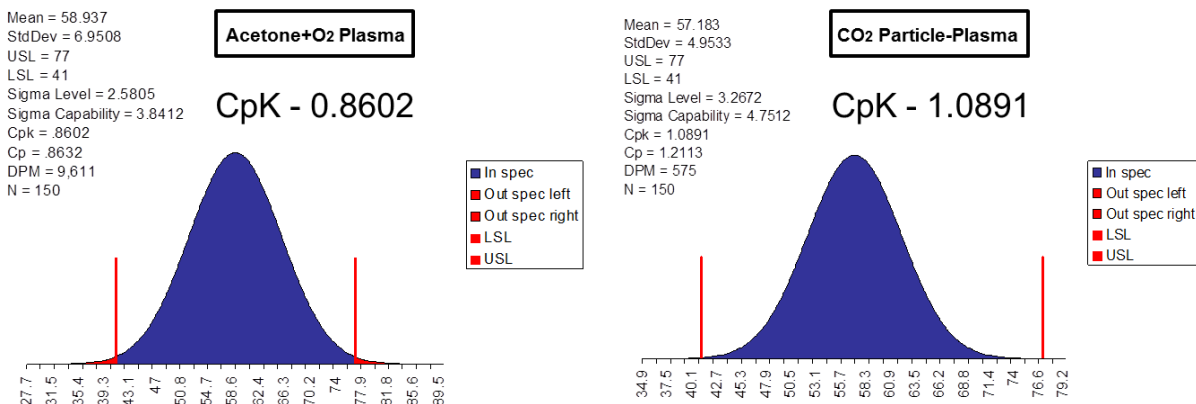


Figure 13 – CpK Analysis

## Conclusion

The test results of this evaluation demonstrated that the CO<sub>2</sub> particle-plasma surface treatment process is statistically similar to or sometimes better than the solvent-plasma cleaning process. CO<sub>2</sub> cleaning was determined to be better for some types of contaminants as well – and in particular the more relevant mixed-contaminant challenge tests. The CO<sub>2</sub> cleaning process demonstrates a lower defect-per-million (DPM) level and an improved CpK.

Compared to the solvent-plasma process, the CO<sub>2</sub> cleaning process does not produce waste by-products such as spent cleaning solvents, wipers and associated cleaning residues. The CO<sub>2</sub> cleaning process is easily automated and can be integrated into existing fabrication lines. CO<sub>2</sub> cleaning process is robust, less susceptible to cleaning process (i.e., chemistry) variation, selective, and more efficient - requiring much less labor. Moreover, the CO<sub>2</sub> cleaning process is a lean and green operation, producing a dry and clean surface in a single-step without cleaning waste by-products.

## VII. Conclusion

CO<sub>2</sub> CleanTech transforms electronic device manufacturing operations in a variety of unique ways. CO<sub>2</sub> CleanTech addresses challenging contamination constraints with cleaner production solutions and a lower cost-of-operation (CoO). CO<sub>2</sub> CleanTech serves as an alternative to conventional immersion, extraction, spray and plasma treatment processes. CO<sub>2</sub> CleanTech is uniquely versatile and adaptable to the production of a diverse array of high-reliability products including flexible and hybrid printed circuit boards, CMOS image sensors, optoelectronic devices, microfluidic devices, guidance systems, fuel injection devices, spacecraft components, and disk drive assemblies, among many other examples. Finally, CO<sub>2</sub> CleanTech is proving to be a superior option in material cleaning and modification processes such as the preparation of bond pads for wire bonding operations. CO<sub>2</sub> cleaning processes produce as good as or better wire bond strength with fewer defects as compared to conventional methods – and without the labor, space, chemical, and energy waste constraints associated with same.

## VIII. References

- [1] D. Jackson, "CO<sub>2</sub> Clean Technology: A Business Sustainability Strategy", Metal Finishing, July/August 2012.
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