REVOLUTIONIZING MICROELECTRONICS: AN INNOVATIVE HYBRID EVALUATION OF PURE ARGON PLASMA IN ADVANCING WIRE BOND PERFORMANCE AND MANUFACTURING EFFICIENCY

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ABSTRACT

Wire bonding in microelectronic packaging requires exceptionally clean surfaces, as even minor contamination can compromise bond integrity and device performance. This study evaluates pure Argon plasma cleaning as a cleaner, more controlled alternative to the conventional Argon-Nitrogen gas mixture. This study presents a first-of-its-kind hybrid evaluation approach that uniquely integrates established metrologies to assess pure argon plasma treatment. Rapid diagnostic tools—Plazmark™ plasma indicators and the Konica Minolta® FD-5 spectro-densitometer—were synergistically combined with advanced surface characterization techniques, including Time-of-Flight Secondary Ion Mass Spectrometry (ToF-SIMS) and Atomic Force Microscopy (AFM). This novel integration enables a comprehensive, multi-dimensional analysis of plasma effects, bridging rapid process feedback with in-depth surface insights. A Design of Experiment (DOE) identified RF Power and Step Time as key parameters influencing cleaning performance.

Results showed that pure Argon plasma significantly reduced surface contaminants, improved surface roughness, and enhanced metallurgical bonding. Ball Shear Tests (BST) confirmed stronger bonds, and Intermetallic Compound (IMC) analysis revealed more uniform coverage. While the Wire Pull Test (WPT) and Stitch Pull Test (SPT) remained consistent, a 21% increase in Wire Bond Units Per Hour (UPH) was achieved due to faster bonding after performing wire bond parameter optimization. Reliability testing, including TC and HTSL, confirmed the durability of pure Argon plasma-treated samples. Evaluations showed higher shear strength, thicker IMC layers, and stable failure modes. No electrical failures were observed after uHAST, validating performance under thermal and humidity stress. These findings support pure Argon plasma as a superior, scalable, data-driven, and cost-effective solution for high-throughput semiconductor packaging.

1. 0 INTRODUCTION

As microelectronic devices shrink in size and complexity, ensuring wire bond reliability becomes critical. Surface contamination, even at trace levels, can compromise bond integrity, yield, and long-term performance.

1.1 Plasma Cleaning in Microelectronics

Plasma cleaning is a standard process in semiconductor packaging for non-contact contaminant removal. While Argon-Nitrogen plasmas are common, pure Argon offers a cleaner alternative by minimizing chemical reactions and oxidation (see Fig. 1). However, conventional evaluation techniques like ToF-SIMS, AFM, and Contact Angle Measurement are time-consuming, costly, and unsuitable for high-throughput environments (see Appendix A). This underscores the need for a faster, cost-effective, and reliable assessment method.

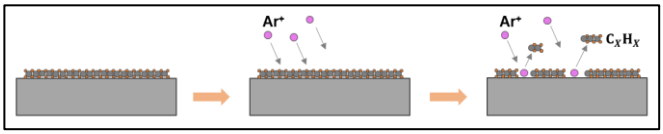

Fig. 1. Working Principle of Pure Argon Plasma. Surface cleaning is achieved through physical reactions, avoiding unwanted chemical reactions or oxidation.

1.2 Alternate Methodology in Assessing Plasma Effectiveness

To overcome these limitations, this study introduces a hybrid approach using Plazmark and FD-5 (see Fig. 2). Plazmark provides a visual indication of plasma exposure, while FD-5 quantifies color change (⊿E*ab), enabling rapid, non-destructive assessment of plasma intensity and uniformity—ideal for real-time process control[1,2].

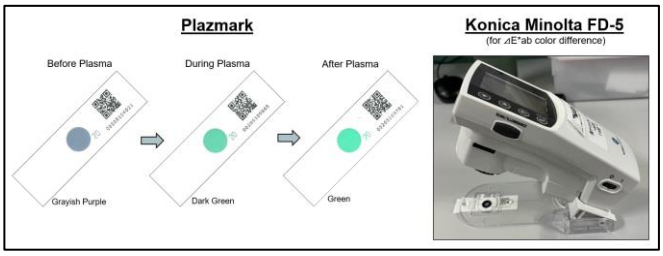

Fig. 2. Plazmark Color Transitions. Visual indicator changes before, during, and after plasma treatment, with ⊿E*ab quantified using FD-5.

1.3 Wire Bond Improvements through Optimized Plasma Process

The effectiveness of plasma cleaning directly influences the quality and reliability of wire bonding, especially in advanced semiconductor packaging where surface contamination can lead to weak bonds or long-term failures. This study focused on optimizing pure Argon plasma parameters to improve surface activation and cleanliness prior to bonding. Unlike conventional Argon-Nitrogen mixtures, pure Argon plasma offers a purely physical cleaning mechanism that minimizes chemical reactions and oxidation, making it ideal for various products.

To evaluate the impact of this optimization, a structured experimental approach was implemented, supported by both rapid diagnostics and high-resolution surface analysis. The goal was to determine whether improved plasma exposure could enable faster bonding cycles and lower bonding parameters without compromising mechanical integrity. This approach aims to enhance not only bond strength and IMC formation but also production efficiency. The detailed outcomes of this optimization are presented in the following sections, where the relationship between plasma conditions and wire bond performance is explored in depth.

2. 0 REVIEW OF RELATED WORK

Wire bonding remains the dominant interconnect method in microelectronics due to its cost-effectiveness and material compatibility. However, its performance is highly sensitive to surface cleanliness. Even minimal contamination can weaken bond strength and compromise long-term reliability, highlighting the need for effective surface preparation.

2.1 Plasma Cleaning in Semiconductor Packaging

Plasma cleaning is a preferred method for surface preparation in semiconductor assembly, offering non-contact removal of organic and inorganic contaminants. Traditional systems often use gas mixtures like Argon-Nitrogen, which combine physical and chemical cleaning mechanisms. However, these mixtures can introduce unwanted oxidation or residues that may compromise bond integrity. Recent studies highlight pure Argon plasma as a cleaner alternative, relying solely on physical sputtering to remove contaminants while minimizing chemical alterations, making it ideal for sensitive materials[3].

In practice, the effectiveness of plasma cleaning is influenced by key process parameters: RF power, step time, and gas flow rate—commonly recommended by equipment suppliers for process optimization[4]. Despite the advantages of pure Argon plasma, real-time evaluation of its cleaning performance in high-throughput production environments remains a challenge[5,6]. Additionally, based on the current procurement data, the cost of Argon-Nitrogen mixtures is approximately 430% more expensive than pure Argon gas. This substantial difference highlights the importance of evaluating not only the cleaning effectiveness but also the economic implications of plasma gas selection in high-volume manufacturing environments.

2.2 Surface Characterization Techniques

To evaluate plasma cleaning effectiveness, high-resolution surface analysis techniques such as ToF-SIMS and AFM are widely used. These methods provide detailed insights into surface composition and morphology, but they are often time-consuming, require specialized equipment, and are not conducive to in-line process monitoring[7].

Contact Angle Measurement is another common technique used to assess surface energy and wettability. While more accessible, it still requires dedicated instrumentation and may not provide sufficient sensitivity to subtle changes in surface chemistry or morphology.

2.3 Innovations in Plasma Diagnostics

To address the limitations of conventional plasma diagnostics, recent innovations have introduced real-time and user-friendly tools such as Plazmark, which visually respond to plasma exposure through color change. These indicators utilize a combination of two organic colorants—one highly reactive (Red) and one hardly reactive (Green) to plasma-generated radicals. During plasma treatment, the highly reactive component fades, leaving only the hardly reactive colorant visible. This transformation provides a clear visual cue of plasma activity (see Fig. 3).

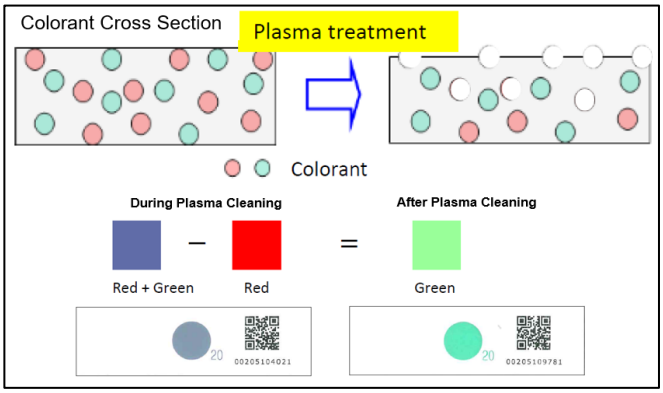

Fig. 3. Plazmark Mechanism. Highly reactive red colorants are bleached by plasma radicals, leaving only the stable green colorants.

The color change can be quantified using FD-5, which measures ⊿E*ab values based on the CIE L*a*b* color space

to assess plasma-induced variations in surface color, which correlate with plasma uniformity and treatment intensity[8].
It captures three key parameters such as L^* (lightness), a^* (green to red), and b^* (blue to yellow) to evaluate surface color variations. These values are used to calculate the color difference between a reference and a treated sample using the Euclidean distance formula.

$$\Delta E^*_{ab} = \sqrt{(L^*_2 - L^*_1)^2 + (a^*_2 - a^*_1)^2 + (b^*_2 - b^*_1)^2}$$

This method enables fast, in-line assessment of plasma uniformity and treatment intensity, supporting real-time process control in Plazmark applications.

Building on recent advancements, this study integrates Plazmark and ⊿E*ab analysis with conventional surface characterization to develop a hybrid method for evaluating pure argon plasma cleaning. This approach enhances accuracy, supports real-time process control, and links plasma conditions to wire bonding performance, offering a comprehensive framework for optimizing surface preparation and improving manufacturing efficiency.

3.0 METHODOLOGY

This study aims to evaluate and optimize the effectiveness of pure Argon plasma cleaning for microelectronic wire bonding, with the goal of enhancing surface cleanliness, improving bond quality, and increasing production efficiency. A four-phase approach was employed: (1) defining the operational characteristics of pure Argon plasma, (2) conducting a comparative analysis between pure Argon and Argon-Nitrogen mixture using diagnostic tools and bonding metrics, and (3) validating the effectiveness of the optimized pure Argon process through analysis of Wire Bond output responses, and production throughput (UPH). (4) subjecting both plasma-treated sample sets to industry-standard reliability tests—HTSL, TC, and uHAST—to assess bond durability under accelerated aging conditions.

3.1 Experimental Design

A 3-factor, 2-level full factorial Design of Experiment (DOE) with two center points was implemented to explore the operational envelope of pure Argon plasma cleaning. The three key process parameters—RF power, step time, and gas flow rate—were selected based on supplier recommendations and their known influence on plasma behavior and surface interaction. The DOE matrix (see Table 1) was designed to evaluate extreme and intermediate values of each parameter, enabling the exploration of optimal settings and potential interactions. This approach was designed to systematically evaluate the plasma system's cleaning process and parameter sensitivity. Due to resource limitations, this study focused on evaluating the linear effects of the factors on the responses. Refer to Appendix B for detailed DOE plan.

Table 1. Pure Argon Plasma DOE Runs

Process Step		Step Time	Gas Flow	RF Power
Maximum Allowed		900 sec	250 sccm	600 Watts
Run 1	- + -	40	250	400
Run 2	- - -	40	150	400
Run 3	+ + +	200	250	600
Run 4	- - +	40	150	600
Run 5	+ - +	200	150	600
Run 6	+ + -	200	250	400
Run 7	+ - -	200	150	400
Run 8	- + +	40	250	600
Run 9	0 0 0	120	200	500
Run 10	0 0 0	120	200	500

To characterize plasma performance, Plazmark and FD-5 were used as rapid, quantitative diagnostic tools, providing real-time feedback on plasma exposure, uniformity, and intensity. These tools served as practical alternatives to traditional surface analysis methods such as Contact Angle, ToF-SIMS, and AFM. The results from this phase established a baseline understanding of pure Argon plasma's cleaning behavior and its potential for process optimization.

3.2 Materials and Equipment

Plasma cleaning experiments were conducted using Strip Plasma X. Real-time plasma diagnostics were performed using Plazmark (Argon card type) and FD-5 which has successfully passed calibration and Measurement System Analysis (MSA), including Bias, Linearity, Stability, and Gauge Repeatability and Reproducibility (GR&R). These evaluations were conducted with reference to Lucideon BCRA Color Standard Tile Sets[9], ensuring high confidence in measurement accuracy and consistency (see Appendix C). Surface characterization was conducted using ToF-SIMS-X for chemical analysis and AFM-X for topographical assessment. Wire bonding was executed using the WB-X bonder, and bond quality was evaluated through BST, WPT, SPT, and IMC coverage analysis.

3.3 Comparative Analysis of Pure Argon and Argon-Nitrogen Plasma

To benchmark the performance of pure Argon plasma, a comparative analysis was conducted against the conventional Argon-Nitrogen mixture (See Appendix D). Identical diagnostic tools and evaluation procedures were applied to both gas chemistries to ensure consistency. Plasma exposure and intensity were measured using Plazmark and FD-5, while surface cleanliness was assessed through ToF-SIMS and AFM. Wire bonding was then performed, and bond quality was evaluated.

Statistical analysis was conducted to compare the two plasma treatments across key performance indicators, including bond strength, IMC formation. The relationship between ⊿E*ab values and bonding outcomes was also explored to determine diagnostic thresholds for effective plasma treatment. This phase provided a data-driven comparison of cleaning effectiveness between the two plasma chemistries, laying the groundwork for potential wire bond improvements.

3.4 Validation of Optimized Pure Argon Plasma

This phase explores the application of the optimized pure Argon plasma settings in a production-relevant environment. The objective is to examine whether the defined parameters can support enhanced process efficiency while maintaining surface cleanliness and bond quality. In parallel, wire bond parameter optimization is carried out to enable faster bonding cycles, with the intent of improving unit-per-hour (UPH) throughput. The scope of this study was restricted to linear factor-response relationships due to resource limitations. Refer to Appendix E for detailed DOE plan. Bonding trials are conducted using these adjusted parameters, and wire bond output responses are evaluated. This setup allows for the investigation of the interplay between plasma treatment, bonding speed, and bond integrity under optimized conditions.

3.4 Reliability Testing

To assess the long-term durability of wire bonds formed after plasma cleaning, reliability testing was conducted on SSOP-36 samples treated with both pure Argon and Argon-Nitrogen plasma. This ensured a fair comparison of their performance under accelerated aging conditions. The following industry-standard tests were performed:

- High Temperature Storage Life (HTSL): 175°C for 2016 hours
- Temperature Cycling (TC): −55°C to 150°C for 1000 cycles
- Unbiased Highly Accelerated Stress Test (uHAST): MSL1, 260°C reflow, Ta = 110°C / 85% RH; 528 Hours

Post-stress evaluations included WPT and BST, accompanied by corresponding cross-sectional SEM inspections. These tests were conducted to validate the mechanical integrity and reliability of the bonds formed after each plasma treatment, providing critical insights into their suitability for high-reliability semiconductor applications.

4.0 RESULTS AND DISCUSSION

This section presents the outcomes of the study, beginning with the parameter definition of pure Argon plasma, followed by a comparative analysis with the existing Argon-Nitrogen gas mixture. The results are discussed in terms of plasma effectiveness, surface cleanliness, wire bond quality, and process efficiency.

4.1 Pure Argon Plasma Parameter Definition

A dedicated phase was conducted to define the optimal operating parameters for pure Argon plasma. This involved validating extreme values of RF Power, Gas Flow, and Step Time to assess the range of plasma cleaning capability. Plasma intensity was quantified using ⊿E*ab values from Plazmark indicators and FD-5, where higher values indicated stronger plasma exposure (see Fig. 4).

Run	Pattern	Plazmark	⊿E*ab	Run	Pattern	Plazmark	⊿E*ab
1	- + -		42.85	6	+ + -		50.88
2	- - -		43.02	7	+ - -		50.82
3	+ + +		52.37	8	- + +		46.02
4	- - +		44.27	9	0 0 0		50.56
5	+ - +		52.31	10	0 0 0		50.35

Reference (Before Plasma): 

Fig. 4. ⊿E*ab per Plasma Parameter Set. Plazmark color changes illustrate plasma intensity across parameter sets, with higher ⊿E*ab values indicating stronger exposure.

To identify a safe and effective operating window, Prediction and Contour Profilers were used. These tools revealed that Step Time and RF Power significantly influence plasma performance (see Fig. 5).

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Step Time(40,200)	1	1	574.41241	399.2765	**<.0001***
Gas Flow (Argon)(150,250)	1	1	1.33956	0.9311	0.3400
RF Power(400,600)	1	1	37.09476	25.7847	**<.0001***
Step Time*Gas Flow (Argon)	1	1	1.17649	0.8178	0.3709
Step Time*RF Power	1	1	1.68921	1.1742	0.2846
Gas Flow (Argon)*RF Power	1	1	2.80900	1.9525	0.1695

Fig. 5. Effect Test of Plasma Parameter. Step Time and RF Power significantly influence plasma performance.

The optimal range was defined as the region producing high ⊿E*ab values with shorter cleaning time and lower power—favorable for manufacturability and equipment longevity (highlighted in blue in Fig. 6). In contrast, the existing Argon-Nitrogen settings fell outside this optimal range, indicating lower plasma intensity.

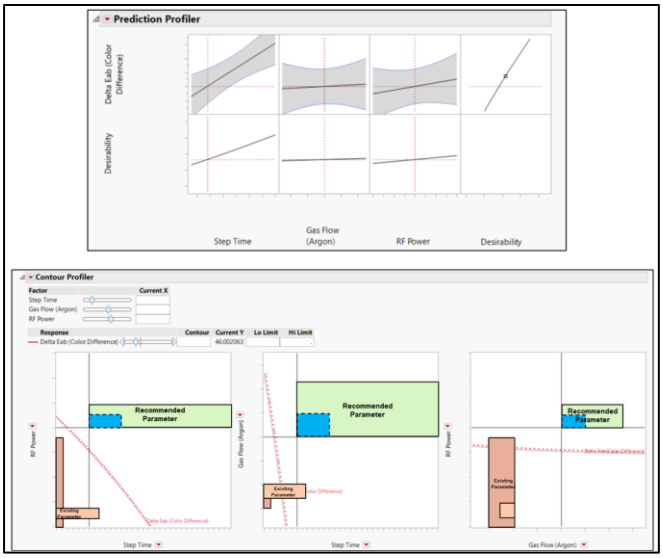

Fig. 6. Prediction and Contour Profilers for Process Optimization. The blue box indicates the suggested operating window for pure Argon plasma based on ⊿E*ab values.

This phase established the operational envelope of pure Argon plasma and demonstrated the utility of Plazmark and FD-5 as efficient, real-time diagnostic tools, offering a practical alternative to traditional surface analysis methods. Further details are provided in Appendix F.

4.2 Comparative Analysis of Pure Argon and Argon-Nitrogen Plasma

To benchmark the performance of pure Argon plasma, a comparative analysis was conducted against the conventional Argon-Nitrogen mixture. Identical diagnostic tools and evaluation procedures were applied to both gas chemistries to ensure consistency. This section presents the results across three key areas:

4.2.1 Plasma Exposure and Uniformity

Results showed that pure Argon-treated samples exhibited significantly higher and more consistent ⊿E*ab values compared to the Argon-Nitrogen gas mixtures, indicating stronger and more uniform plasma activity with p-value < 0.001 (see Fig. 7).

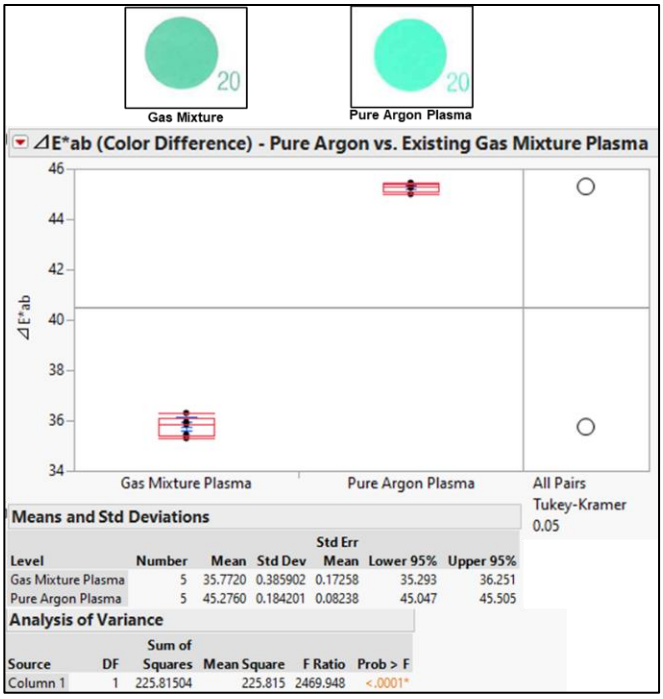

Fig. 7. ⊿E*ab Comparison of Different Plasma Condition. Pure Argon showed the brightest, most consistent green, while Argon-Nitrogen mixtures had lower, more varied results.

4.2.2 Surface Cleanliness and Morphology

To evaluate the cleaning effectiveness of pure Argon plasma, ToF-SIMS and AFM analyses were conducted on both treated and untreated samples (see Fig. 8). The untreated samples provided a baseline for comparison against surfaces treated with defined pure Argon plasma and Argon-Nitrogen plasma.

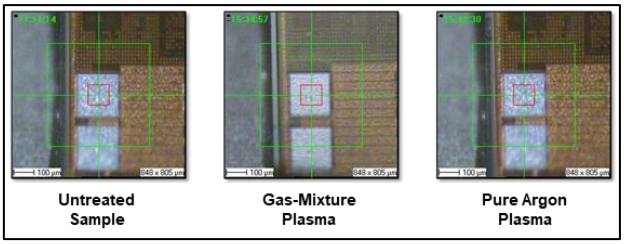

Fig. 8. ToF-SIMS and AFM Bond Pad Locations. Bond pad sites of untreated and plasma-treated SSOP-36 devices are analyzed.

ToF-SIMS results showed that untreated samples had the highest levels of surface contamination, particularly hydrocarbons and oxides. Samples treated with Argon-Nitrogen plasma showed moderate contaminant reduction, while those treated with pure Argon exhibited the lowest contamination levels, confirming superior cleaning performance. A summary of ToF-SIMS results is presented in Table 2, with full spectra available in Appendix G.

Table 2. ToF-SIMS Results of untreated and plasma-treated samples.

Peak Label	Atomic Mass	Normalized By Total Ion Intensity		
		Untreated Sample	Gas-Mixture Plasma	Pure Argon Plasma
C^-	12.00	0.01760	0.00408	0.00316
CH^-	13.01	0.06140	0.00886	0.00762
CH_2^-	14.02	0.00923	0.00124	0.00113
O^-	15.99	0.13800	0.11300	0.07230
OH^-	17.00	0.09640	0.04020	0.02800
C_2^-	24.00	0.00982	0.00290	0.00239
C_2H^-	25.01	0.02450	0.00624	0.00551
S^-	31.97	0.00118	0.00101	0.00081
Cl^-	34.97	0.00330	0.00259	0.00235
CNF^-	45.00	0.00017	0.00047	0.00018
CF_3^-	69.00	0.00009	0.00009	0.00005
C_2H_2	26.01	0.00434	0.00407	0.00350
Al^+	26.98	0.19500	0.20100	0.19800
C_2H_3	27.02	0.03800	0.01990	0.01970
C_2H_5	29.04	0.03890	0.01300	0.01660
CF^+	31.00	0.00040	0.00042	0.00031
C_4H_5	53.04	0.01110	0.00474	0.00576
$C_3H_3O^+$	55.02	0.00513	0.00227	0.00207

AFM measurements of surface roughness (Ra) were conducted to further investigate the effects of plasma treatment on bond pad morphology. Untreated samples exhibited relatively smooth surfaces with minimal roughness. Samples treated with the Argon-Nitrogen mixture showed a slight increase in roughness, while those treated with pure Argon plasma demonstrated a controlled and more pronounced increase in Ra. This increase is hypothesized to enhance mechanical interlocking during wire bonding without inducing surface damage (see Fig. 9).

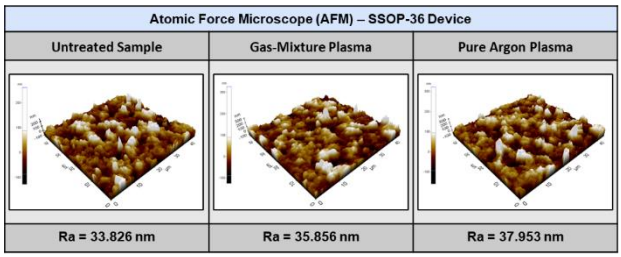

Fig. 9. AFM Results of Untreated and Plasma-Treated Samples. Pure Argon plasma yields the highest surface roughness, followed by Argon-Nitrogen plasma, compared to the untreated sample.

This progression in surface morphology supports the observed improvements in surface cleanliness and suggests that pure Argon plasma provides more favorable surface conditions for high-quality wire bonding.

4.2.3 Wire Bond Quality

To isolate the effects of plasma cleaning, all wire bonding tests were conducted using identical parameters on both pure Argon and Argon-Nitrogen treated samples. This controlled approach ensures that any observed differences in bond quality are directly attributable to the plasma cleaning process.

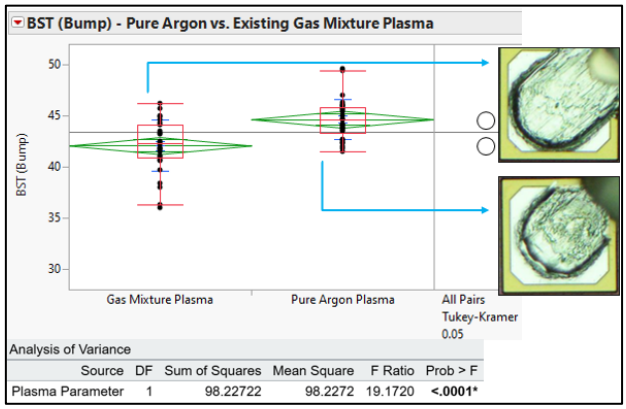

Fig. 10. BST Results of Pure Argon vs. Gas Mixture Plasma. Pure Argon samples exhibit stronger interfacial bonding and higher mechanical values compared to Argon-Nitrogen mixtures ($p < 0.0001$), with corresponding differences in failure modes.

BST revealed significantly higher shear strength in pure Argon-treated samples, indicating improved surface activation and cleaner bonding interfaces. Failure mode analysis confirmed stronger interfacial bonding in these samples (see Fig. 10). IMC coverage was also more uniform and complete in the pure Argon group, suggesting enhanced atomic diffusion during bonding. In contrast, Argon-Nitrogen samples showed lower and less consistent IMC coverage, particularly at the bond periphery (see Fig. 11).

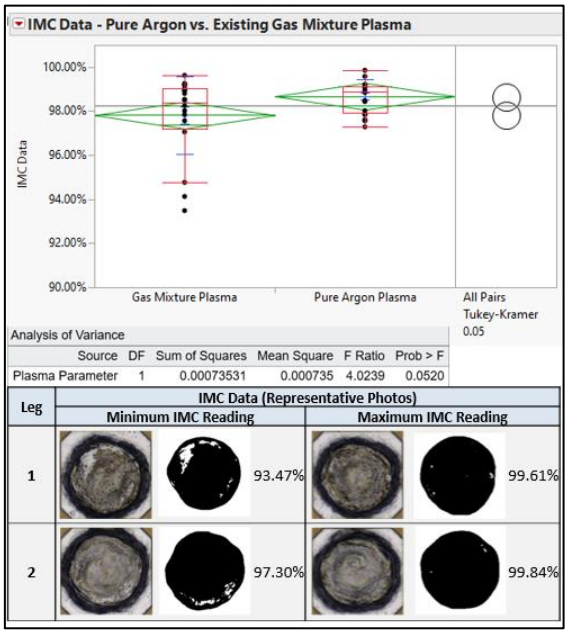

Fig. 11. IMC Comparison of Pure Argon vs. Gas Mixture Plasma. Pure Argon samples exhibit more uniform IMC coverage than those treated with the gas mixture, with a near-significant difference ($p = 0.0520$).

WPT and SPT results showed no statistically significant differences between the two plasma conditions, indicating that wire loop integrity remained stable regardless of plasma chemistry (see Fig. 12).

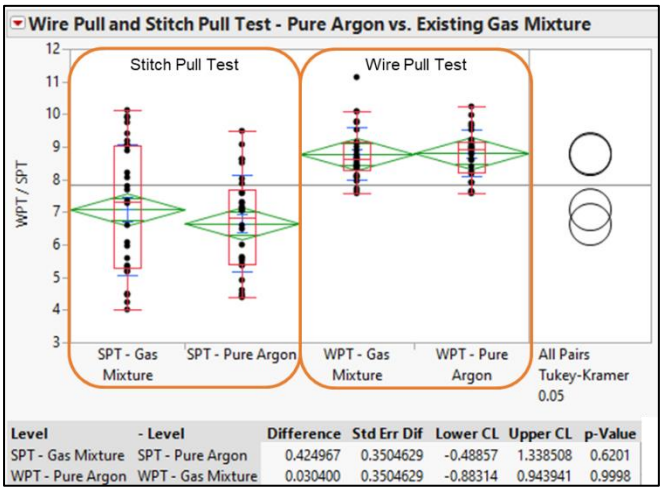

Fig. 12. WPT and SPT Results of Pure Argon vs. Gas Mixture Plasma. No statistically significant differences were observed in either test, with p-values of 0.9998 for WPT and 0.6201 for SPT.

4.3 Process Efficiency and Operational Gains with Pure Argon Plasma

To explore the impact of plasma cleaning on production efficiency, wire bond parameter optimization was performed using the defined pure Argon plasma settings. The goal was to enable faster bonding cycles while maintaining bond quality. This optimization resulted in a 21% increase in Wire Bond UPH compared to the Argon-Nitrogen process (see Table 3). The improvement is attributed to cleaner surfaces that allowed for reduced bonding time and lower parameter input.

Table 3. Wire Bond UPH calculation of Existing Gas Mixture vs. Pure Argon gas plasma.

Plasma Parameter	Wire Bond Parameter	Remarks
Argon-Nitrogen (Existing)	Existing (Production)	Baseline UPH for XDFN-4 Device
Pure Argon (Optimized)	Improved (faster bonding)	Wire Bond Optimization + Pure Argon plasma ***21% UPH Gain*** as compared to production device

To validate this gain, BST was conducted using the reduced bonding time enabled by pure Argon plasma. The results showed no statistically significant difference in bond strength compared to the baseline process, confirming that mechanical integrity was maintained (see Fig. 13).

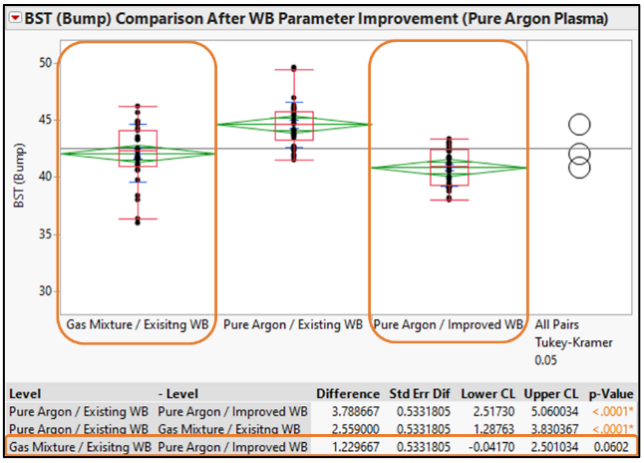

Fig. 13. BST Comparison After Wire Bond Improvement. Statistical analysis revealed no significant change relative to the baseline process (p = 0.0602).

These findings highlight a key advantage of pure Argon plasma: its superior cleaning capability enables faster, lower-energy bonding without compromising quality. This supports its suitability for high-throughput, high-reliability semiconductor manufacturing.

4.4 Reliability Results

Reliability testing was conducted on SSOP-36 samples treated with both pure Argon and Argon-Nitrogen plasma to evaluate long-term bond durability. Post-reliability evaluations included BST, WPT, IMC inspection, and failure mode analysis. Pure Argon plasma-treated samples consistently showed higher shear strength (see Fig. 14) and thicker IMC layers as confirmed through cross-section (see Fig. 15), indicating stronger and more stable interfacial bonding. WPT results remained consistent across both plasma chemistries, confirming wire loop integrity (see Fig. 16).

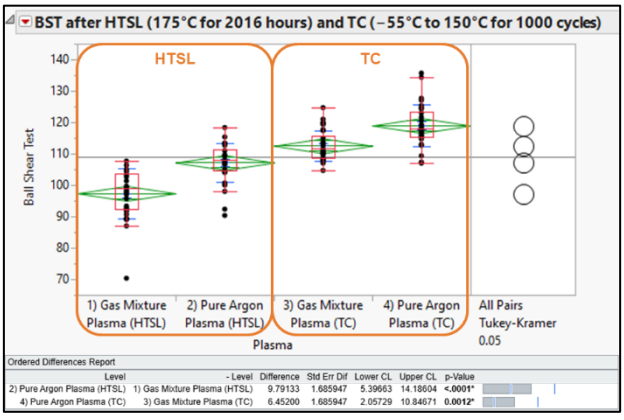

Fig. 14. BST Comparison After Reliability Testing (HTSL and TC). Pure Argon samples show higher shear strength and stronger bonding than Argon-Nitrogen under both stress conditions.

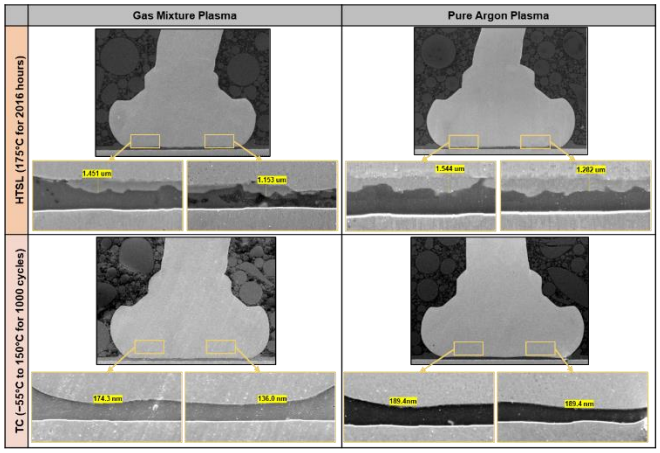

Fig. 1. SEM Cross Section Inspection. Thicker IMC layers observed in pure Argon samples under both HTSL and TC conditions.

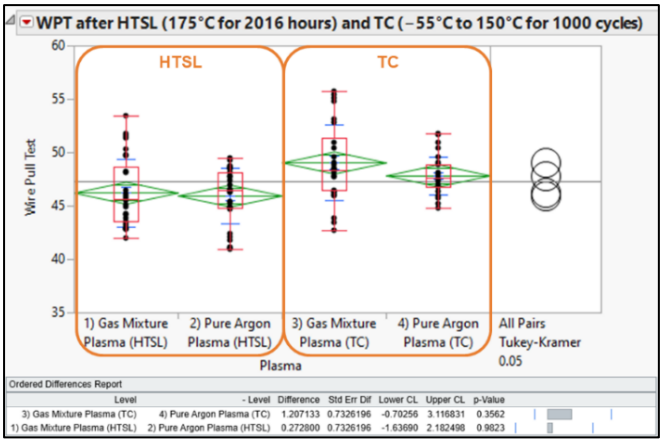

Fig. 14. WPT Comparison After Reliability Testing (HTSL and TC). No statistically significant differences were observed in either test, with p-values of 0.9823 (HTSL) and 0.3561 (TC).

Failure modes were typical and stable, occurring at the ball neck and wire span (WPT) and within the bond shear (BST). No abnormal degradation was observed, validating the mechanical reliability of both treatments. Furthermore, no electrical failures were detected after uHAST exposure, confirming robustness under thermal and humidity stress as shown in Table 4.

Table 3. Unbiased Highly Accelerated Stress Test Result

uHAST Condition	Plasma Parameter	Electrical Test Results
MSL1, 260°C reflow, Ta = 110°C / 85% RH; 528 Hours	Argon-Nitrogen (Existing)	80/80 units passed
	Pure Argon (Optimized)	80/80 units passed

These results confirm that pure Argon plasma not only enhances initial bond quality but also maintains performance under thermal and humidity stress, supporting its use in high-reliability semiconductor applications.

5.0 CONCLUSION

This study demonstrates that pure Argon plasma is a highly effective surface preparation method for microelectronic wire bonding. By integrating real-time diagnostics (Plazmark and FD-5) with high-resolution surface analysis (ToF-SIMS and AFM), a robust and practical framework was established for evaluating plasma performance in a production-relevant context. The use of ⊿E*ab as a quantitative, non-destructive indicator showed strong correlation with surface cleanliness and bond quality, enabling rapid process feedback and control.

Compared to the conventional Argon-Nitrogen mixture, pure Argon plasma yielded superior outcomes in terms of surface morphology, bond strength, IMC uniformity, and plasma exposure consistency. Following wire bond parameter optimization, a 21% increase in Wire Bond UPH was achieved, attributed to cleaner surfaces that enabled faster bonding with reduced parameter input. Reliability testing including HTSL, TC, and uHAST confirmed that pure Argon plasma-treated samples maintained higher shear strength and thicker IMC layers after stress, validating their long-term durability. The optimized process also supported gentler bonding conditions, minimizing stress on sensitive devices and contributing to improved yield. Overall, pure Argon plasma cleaning offers a technically superior, scalable, and cost-effective solution for high-throughput semiconductor manufacturing, with strong potential for broader adoption in advanced packaging technologies.

6.0 RECOMMENDATIONS

Although this study confirmed the effectiveness of pure Argon plasma for wire bonding, further research is recommended to address its limitations and broaden its applicability. The DOE conducted were limited to linear effects; future work should explore higher-order interactions for more comprehensive process optimization. Expanding the study to advanced packaging technologies (e.g., flip-chip, wafer-level) and emerging materials like low-k dielectrics and flexible substrates would provide valuable insights. Additionally, integrating AI-driven plasma control and assessing scalability across manufacturing environments could support wider industry adoption.

7.0 ACKNOWLEDGMENT

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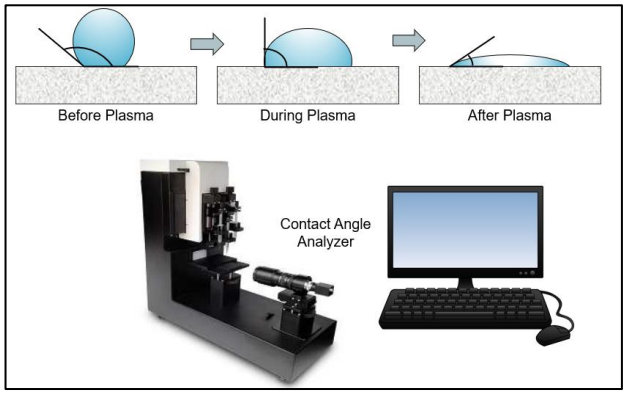
9.0 ABOUT THE AUTHOR

Jorell D. Pelingo earned his undergraduate degree in Manufacturing Engineering from the Mapúa Institute of Technology – Intramuros (now Mapúa University). Currently, he is furthering his academic credentials by pursuing a Master of Science in Materials Science and Engineering at the same university. With over a decade of combined experience in semiconductor assembly, focusing on plasma process and wire bond process. Currently, he holds a position as Package Development Engineer (Process Development) under Central Engineering.

10.0 APPENDIX

Appendix A:

Contact Angle Measurement using Contact Angle Analyzer. The top sequence shows a water droplet transitioning from high to low contact angles after plasma exposure, indicating increased surface energy. The bottom section highlights the requirement of complex instrumentation, including low accuracy and time-consuming manual processes.



Appendix B:

DOE plan utilizing Plazmark and Konica Minolta FD-5.

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Design of Experiment PLAN

Experimental Objective/s	
	Comparison
x	Characterization
x	Optimization
Date	1-Jun-24

Background / Problem Statement

Plasma cleaning is essential for ensuring surface cleanliness in wire bonding, directly impacting bond strength and reliability. While Argon-Nitrogen mixtures are commonly used, they may introduce variability in cleaning performance. This study explores pure Argon plasma as a potential alternative, aiming to optimize process parameters and evaluate its effectiveness in improving bond quality and production efficiency.

Objective Details

- To define optimum and efficient Plasma Prior Wirebond parameter utilizing Plazmark and Konica Minolta FD-5
- Demonstrate and identify different techniques / methodologies on how to measure the effectiveness of plasma process

Variables Under Study

Dependent Variable/s (Response/s)	Continuous or Categorical?	Number of Replicates	Specification	Unit of Measurement
⊿E*ab (Plazmark)	Continuous	1 (5 strips / run)	> 45 ⊿E*ab	⊿E*ab (Color Difference)

Independent Variable/s (Input Factor/s)	Continuous or Categorical?	Number of Factor Levels	Values of Factor Levels	Unit of Measurement
RF Power	Continuous	2	400, 600	Watts
Gas Flow Rate	Continuous	2	150, 250	sccm
Step Time	Contiuous	2	40, 200	seconds

Experimental Design Used	**3-factor, 2-level full factorial Design of Experiment (DOE)**
# of Center Points Used	**2 center points**
Process/es Under Study	Plasma Prior Wire Bond Process
Equipment/s Used	Strip Plasma X
Fixed Factors and their Levels Used	Plazmark - Argon Card Type
	Konica Minolta FD-5
	Pure Argon Gas (99.99% Purity)
	Argon-Nitrogen Gas Mixture (Baseline Process) - Using Existing Parameter
Assumptions & Limitations (if any)	- Explore only on the linear effects of the factors on the responses for Pure Argon Plasma

Appendix C:

Calibration was performed in accordance with IATF 16949, ISO 17025, and onsemi internal requirements. The Konica Minolta FD-5 passed Measurement System Analysis (MSA), including Bias, Linearity, Stability, and GR&R, referenced against known standards calibrated to 0°:45° geometry using Lucideon BCRA Color Standard Tile Sets.

Appendix D:

Comparative Analysis Plan for Pure Argon and Argon-Nitrogen Gas mixtures:

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Design of Experiment PLAN

Experimental Objective/s	
x	Comparison
	Characterization
	Optimization
Date	15-Jul-24

Background / Problem Statement

To evaluate the relative performance of pure Argon plasma, a comparative analysis will be conducted against the conventional Argon-Nitrogen mixture.

Objective Details

- The objective was to assess differences in plasma exposure, surface cleanliness, and bond quality using diagnostics and evaluation methods.
-This phase aimed to establish data-driven insights into the cleaning effectiveness of each gas chemistry and explore correlations between ⊿E*ab values and bonding outcomes.

Variables Under Study

Dependent Variable/s (Response/s)	Continuous or Categorical?	Number of Replicates	Specification	Unit of Measurement
Ball Shear Test (Bump)	Continuous	1 (30 readings / run)	> 20.0 grams; No Lifted Ball	grams (g)
Stitch Pull Test	Continuous	1 (30 readings / run)	> 3.0 grams; No Lifted Stitch	grams (g)
Wire Pull Test	Continuous	1 (30 readings / run)	> 3.0 grams; No Lifted Ball	grams (g)
IMC Coverage	Continuous	1 (30 readings / run)	> 80.0%	Percent (%)
⊿E*ab (Plazmark)	Continuous	1 (5 strips / run)	> 35 ⊿E*ab	⊿E*ab (Color Difference)
AFM (Surface Roughness)	Categorical	1 (1 unit / run)	Roughness	Ra
ToF-SIMS (Surface Analysis)	Categorical	1 (1 unit / run)	Surface Analysis	-

Independent Variable/s (Input Factor/s)	Continuous or Categorical?	Number of Factor Levels	Values of Factor Levels	Unit of Measurement
Plasma Cleaning Type	Categorical	2	Pure Argon vs. Argon-Nitrogen	-

Experimental Design Used	**Simple Comparative Experiment**
# of Center Points Used	-
Process/es Under Study	Wire Bond Process
Equipment/s Used	Strip Plasma X, WB-X
Fixed Factors and their Levels Used	Pure Argon Gas (99.99% Purity)
	Argon-Nitrogen Gas Mixture (Baseline Process) - Using Existing Parameter
	NiAuPd Leadframe (XDFN - 4)
	1.0 mil PCC Wire
	Plazmark and Konica Minolta FD-5
Assumptions & Limitations (if any)	None

Appendix E:

Wire Bond optimization Plan using defined Pure Argon:

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Design of Experiment PLAN

Experimental Objective/s	
	Comparison
	Characterization
x	Optimization
Date	10-Aug-24

Background / Problem Statement

Pure Argon plasma has demonstrated improved wire bond performance compared to conventional Argon-Nitrogen mixtures. By optimizing key parameters such as RF power, gas flow, and step time, the process enhances surface activation, enabling stronger bonds, better IMC formation, and more consistent output. These improvements also support faster bonding speeds and the use of lower bonding parameters, contributing to increased throughput and process efficiency in high-volume manufacturing.

Objective Details

- To validate if defined Pure Argon gas can improved wire bond output responses on existing devices running in production.
- Use of pure argon gas plasma for Wire bond parameter improvement (Yield, Bondability, UPH improvement)

Variables Under Study

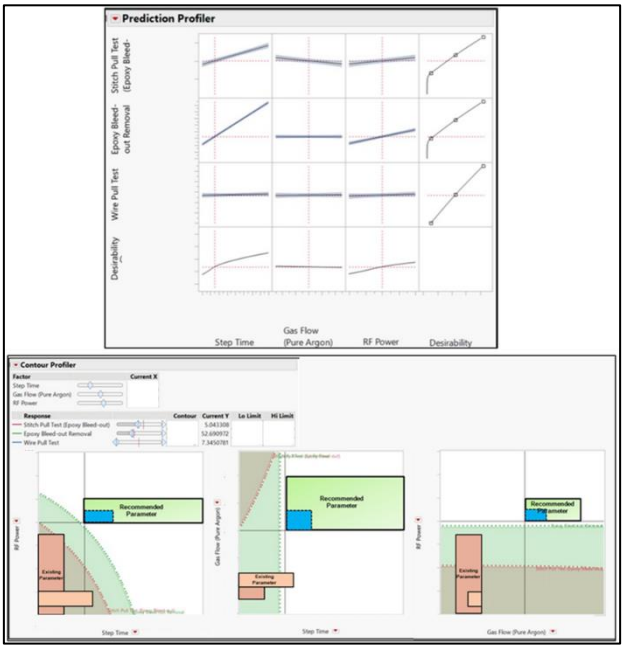
Dependent Variable/s (Response/s)	Continuous or Categorical?	Number of Replicates	Specification	Unit of Measurement
Ball Shear Test (Bump)	Continuous	1 (30 readings / run)	> 20.0 grams; No Lifted Ball	grams (g)
Stitch Pull Test	Continuous	1 (30 readings / run)	> 3.0 grams; No Lifted Stitch	grams (g)
Wire Pull Test	Continuous	1 (30 readings / run)	> 3.0 grams; No Lifted Ball	grams (g)
IMC Coverage	Continuous	1 (30 readings / run)	> 80.0%	Percent (%)

Independent Variable/s (Input Factor/s)	Continuous or Categorical?	Number of Factor Levels	Values of Factor Levels	Unit of Measurement
Bond Time	Continuous	2	4 - 6	milliseconds
Bond Force	Continuous	2	18 - 40	gram-force
US Power	Contiuous	2	420 - 600	-

Experimental Design Used	**3-factor, 2-level full factorial Design of Experiment (DOE)**
# of Center Points Used	**2 center points**
Process/es Under Study	Wire Bond Process
Equipment/s Used	Strip Plasma X, WB-X
Fixed Factors and their Levels Used	Pure Argon Gas (99.99% Purity)
	Argon-Nitrogen Gas Mixture (Baseline Process) - Using Existing Parameter
	NiAuPd Leadframe (XDFN - 4)
	1.0 mil PCC Wire
Assumptions & Limitations (if any)	- Explore only on the linear effects of the factors on the responses for Pure Argon Plasma

Appendix F:

Prediction Profiler and Contour Profiler (Traditional and Complex Analysis)



Both profilers show consistent parameter recommendations for pure Argon plasma, confirming the alternative method is faster and more efficient than traditional surface analysis.

Appendix G:

ToF-SIMS (Positive and Negative Spectra) Results of untreated and plasma-treated samples.