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Improved Bond Strength in Au Wire Bonding Through Process Parameter Optimization and Argon Plasma Cleaning

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Keywords

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Abstract

This article reports on the optimization of Au wire bonding for GaAs chips. The effects of bonding parameters on ball size were evaluated by measuring both the average diameter and its standard deviation. Using the parameter set with the smallest deviation, argon plasma cleaning was applied to the pads while maintaining the unchanged bonding conditions. Although the average pull strength remained nearly constant, the standard deviation decreased from 1.1 to 0.61, indicating an improvement in process consistency. These results demonstrate that plasma-assisted surface treatment provides a more consistent and reliable wire bonding process in GaAs packaging applications.

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1. INTRODUCTION

Wire bonding has remained the most widely adopted first-level interconnection technology in microelectronic packaging for more than five decades, accounting for over 80% of semiconductor packages owing to its cost-effectiveness, flexibility, and mature manufacturing ecosystem (Gan & Hashim, 2015; Zhou et al., 2023a). Despite the rapid development of alternative interconnect technologies such as flip-chip and through-silicon vias (TSVs), wire bonding continues to be indispensable in a broad range of applications including automotive electronics, RF modules, power devices, and optoelectronic packaging, where process robustness and long-term reliability are critical (Alim et al., 2021). Comprehensive studies have consistently reported that a significant fraction of package-level failures up to 25–30% originate from wire bonding-related issues, emphasizing the necessity of continued process optimization and mechanistic understanding (Zhou et al., 2023a).

Among available bonding wire materials, gold (Au) wire has long been the industry standard due to its excellent chemical stability, high ductility, and wide process window (Gan & Hashim, 2015). However, the increasing cost of Au and the demand for higher integration density and harsher operating conditions have

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stimulated extensive research into alternative materials such as copper (Cu), silver (Ag), and their alloyed counterparts (Gan & Hashim, 2015; Zhou et al., 2023a; Fan et al., 2025). While Cu wire offers advantages in terms of electrical and thermal conductivity and reduced material cost, its higher hardness, oxidation sensitivity, and narrower process window significantly increase the risk of bond-pad damage and process instability (Papadopoulos et al., 2020; Khajehvand et al., 2024). Ag-based and alloyed wires have emerged as promising alternatives, particularly for high-frequency and power applications, yet unresolved reliability issues such as electromigration and interfacial degradation continue to limit their widespread industrial adoption (Zhou et al., 2023b; Fan et al., 2025). As a result, Au wire bonding remains dominant in high-reliability applications where bonding consistency and yield are critical.

Thermosonic wire bonding is a complex solid-state joining process governed by a strong coupling between ultrasonic energy, bonding force, bonding time, and interfacial temperature evolution (Xu et al., 2010; Mostafavi et al., 2018). Numerous experimental and analytical studies have demonstrated that ultrasonic vibration plays a decisive role in disrupting surface contamination layers, activating dislocation motion, and promoting metallurgical bonding at the wire–pad interface (Xu et al., 2010; Long et al., 2017). Early macroscopic sliding and fretting models have gradually been replaced by microslip-based bonding theories, in which bonding initiates at the periphery of the contact area and propagates inward with increasing ultrasonic energy (Xu et al., 2010; Long et al., 2017). Detailed footprint and lift-off analyses have revealed that the spatial distribution of bonded and non-bonded regions is highly sensitive to ultrasonic power and bonding force, directly affecting bond strength and failure mode (Xu et al., 2010).

In parallel, extensive efforts have been devoted to understanding the influence of process parameters on bond integrity and reliability. Optimization strategies ranging from empirical trial-and-error approaches to full-factorial design of experiments and response surface methodologies have been proposed to identify robust bonding windows (Gomes et al., 2015). These studies consistently indicate that excessive ultrasonic energy or bonding force can induce pad cratering, interfacial micro cracking, and substrate damage, whereas insufficient energy results in incomplete intermetallic formation and weak bonding (Mostafavi et al., 2018; Khajehvand et al., 2024). Recent studies employing high-resolution surface profiling and molecular dynamics simulations have further demonstrated that bond-pad damage is intrinsically linked to plastic deformation mechanisms at the atomic scale, highlighting the narrow margin between optimal bonding and latent reliability risks (Khajehvand et al., 2024).

Beyond bonding parameters, the surface condition of the bond pad has been identified as one of the most critical factors governing wire bondability. Native oxides, organic residues, and process-induced contaminants can significantly inhibit interfacial diffusion and reduce effective ultrasonic energy transfer (Knotter et al., 2011; Sammut, 2025). Consequently, plasma-based surface treatments using oxygen, argon, or hydrogen plasmas have become widely adopted to restore bond pad surface energy and enhance wire bonding process windows (Chan et al., 2005; Peng et al., 2015). Comparative studies have shown that plasma cleaning can

significantly improve wire pull and shear strength while enabling lower bonding forces and ultrasonic power, thereby reducing pad damage and improving manufacturing yield (Chan et al., 2005; Peng et al., 2015). However, the effectiveness of plasma treatment strongly depends on plasma type, exposure conditions, and post-treatment shelf life, and reported results vary across metallization schemes and bonding environments (Peng et al., 2015; Sammut, 2025).

Despite the extensive literature on bonding wire materials, surface treatments, and bonding mechanisms, several critical gaps remain. In particular, the coupled influence of ultrasonic energy and bonding force treated not as independent parameters but as combined contributors to interfacial energy input has not been systematically clarified for Au wire bonding on plasma-treated surfaces. Moreover, many existing studies focus on average bond strength values, without addressing bond strength distribution and variability, which are key indicators of process robustness in high-volume manufacturing (Papadopoulos et al., 2020).

Previous studies have demonstrated that the mechanical reliability of wire bonds is fundamentally governed by interfacial shear stresses rather than solely by monotonic tensile strength. Accelerated mechanical fatigue investigations have shown that bond lift-off and heel cracking are driven by cyclic shear loading at the bond interface, and that lifetime behavior is controlled by the local stress state and metallurgical integrity of the interface (Czerny & Khatibi, 2022). In high-temperature packaging systems, such as 3-D stacked SiC interconnects, die shear and wire pull tests further confirm that interfacial stability strongly depends on the metallization scheme and the evolution of intermetallic compounds under thermal exposure (Li, 2022). Moreover, comprehensive reviews on alternative bonding materials, particularly silver-based systems, have highlighted that the type, morphology, and growth kinetics of intermetallic phases critically influence shear strength and interfacial cracking behavior (An et al., 2023).

While plasma-assisted surface treatments have been widely reported to enhance wire bond performance, most prior studies predominantly focus on improvements in average pull or shear strength. However, in practical manufacturing environments, process robustness is determined not only by the absolute strength level but also by bond-to-bond variability and statistical consistency. Despite the extensive literature on plasma cleaning and bonding parameter optimization, statistically validated investigations of pull-strength dispersion, particularly for GaAs metallization systems, remain limited.

The present study addresses this gap by integrating bonding parameter window optimization based on ball-diameter stability with a variance-centered statistical evaluation of pull strength following argon plasma treatment. By applying independent-samples t-tests and F-tests to quantitatively assess both mean strength and variance reduction, this work demonstrates that argon plasma cleaning significantly enhances bond consistency on GaAs pads. Rather than merely reporting absolute strength enhancement, the study establishes statistical dispersion as a primary metric for bonding optimization, thereby providing a reliability-oriented framework directly applicable to high-frequency GaAs microelectronic packaging.

2. MATERIAL AND METHOD

The wire bonding experiments were carried out on GaAs source pads with lateral dimensions of 80 × 80 µm, metallized with a Ti/Au stack of 3 µm total thickness. These pads were bonded to ENEPIG-finished destination pads on a PCB substrate, selected to ensure good wettability and compatibility with Au wire bonding. All GaAs chips used in the bonding experiments were selected from the same diced wafer to eliminate wafer-to-wafer process variability.

Prior to bonding, all samples were handled and processed in an ISO Class 6 cleanroom environment to minimize airborne particulate contamination. The ambient temperature was maintained at 21 ± 1 °C and the relative humidity at 45% ± 5% throughout the experiments. These environmental conditions were carefully controlled to ensure stable thermosonic bonding behavior and to reduce potential variability associated with moisture adsorption or surface oxidation. Immediately before bonding or plasma treatment, the samples were transferred under cleanroom conditions to prevent unintended surface contamination.

Gold bonding wire with a purity of 99.99% and a diameter of 1 mil (25.4 µm) was used throughout the study. All wire bonds were formed using a standard thermosonic ball–wedge bonding process on an F&S Bondtec 5610 Wire Bonder equipped with a ceramic capillary suitable for fine-pitch applications. The ball diameters were measured using a Nikon LV150N Optical Microscope and Nikon NIS-Elements imaging software. The bonding temperature was kept constant during all experiments. Mechanical characterization of the wire bonds was performed using an F&S Bondtec 5600 Pull Tester in accordance with standard wire pull testing procedures.

Following the pull tests, the failed samples were systematically inspected to identify the dominant failure modes, which were categorized as ball lift, neck break, wire break, heel break, or wedge bond lift. Among these, ball lift and wedge bond lift are generally considered undesirable failure mechanisms, as they indicate inadequate interfacial integrity between the wire and the metallized pad due to insufficient metallurgical bonding or poor interfacial adhesion. In contrast, heel break and wire break are typically associated with stronger interfacial integrity, as fracture occurs within the wire material rather than at the bond interface, indicating that the bond interface is mechanically stronger than the wire itself. This classification was used to evaluate the interfacial integrity and the effectiveness of the plasma cleaning process.

To systematically evaluate the influence of bonding parameters on free air ball formation and bond quality, a total of 30 distinct parameter combinations were investigated. The study focused on three primary process variables: ultrasonic (US) power, bonding force, and electronic flame-off (EFO) current. The bonding temperature was maintained at 120 °C throughout all experiments to ensure consistent thermosonic conditions. The bonding time was fixed at 25 ms for all experiments in order to isolate the effects of the selected parameters. Preliminary trials indicated that 25 ms provided sufficient ultrasonic energy input to initiate stable interfacial metallurgical bonding without inducing excessive pad deformation or over-bonding. Increasing the

bonding time beyond 25 ms led to excessive ball deformation and noticeable pad surface imprinting, whereas shorter durations increased the risk of insufficient interfacial formation. Therefore, 25 ms was selected as an optimized and manufacturing-relevant bonding duration. The US power was varied between 40 and 60 machine units, corresponding to approximately 16–24% of the ultrasonic generator's maximum output power. The bonding force was adjusted in the range of 25 to 50 cN, and the EFO current was varied between 70 and 90 mA. These ranges were selected based on preliminary trials and manufacturer recommendations to cover both under-bonded and over-bonded regimes.

Each unique parameter set was applied to fabricate 50 wire bonds from the GaAs source pads to the PCB destination pads. The resulting free air ball and bonded ball geometries were examined, and the bonded ball diameters were measured to assess process repeatability and geometric stability. The statistical distribution of ball diameters was used as a primary indicator for identifying a stable bonding window with minimal variation.

Following the identification of the most stable bonding parameter window, additional experiments were conducted to investigate the effect of surface plasma cleaning on bond strength and process consistency. Plasma treatments were performed using the Tergeo Plus plasma system manufactured by PIE Scientific, operating with argon radio-frequency (RF) plasma. High purity (6N) argon gas was used during plasma treatments to minimize the influence of residual contaminants. Prior to plasma ignition, a 2-minute gas stabilization period was applied to ensure a stable chamber atmosphere and uniform gas flow conditions before initiating RF power. The plasma power was varied at 50, 75, and 100 W, while the argon gas flow rate was adjusted to 5, 7, 9, and 11 sccm. The corresponding chamber pressures were measured as 90, 114, 133, and 150 mTorr, respectively. The plasma exposure time was kept constant at 2 minutes for all experimental conditions. After the plasma treatment, the samples were transferred to the wire bonder and the bonding process was initiated within 60 seconds to minimize surface recontamination effects.

For each plasma treatment condition, 50 consecutive wire bonds were performed using the previously optimized bonding parameters. The bonded samples were subsequently evaluated by wire pull testing to quantify bond strength and assess the influence of plasma power and gas flow on bonding performance. Pull force distributions were analyzed to compare both average bond strength and bond-to-bond variability across different plasma conditions.

3. RESULTS AND DISCUSSION

The influence of bonding parameters on free-air-ball (FAB) deformation is shown in Figure 1. Ball diameter increased systematically with ultrasonic (US) power and bonding force, while the dependence on flame-off (EFO) current remained comparatively weak. As clearly observed in the figure, ultrasonic energy exhibits a significantly more dominant effect on ball diameter compared to bonding force. This behavior can be attributed to the fact that ultrasonic vibration directly governs interfacial microslip, frictional heating, and acoustic softening, thereby controlling the extent of plastic flow within the Au ball. The strong sensitivity to US power

is consistent with the established bonding mechanisms in thermosonic Au ball bonding, where interfacial microslip and localized plastic deformation dominate bond formation, as extensively described by Xu et al. (2010) and further supported by metallurgical interface analyses.

In contrast, although increasing the EFO current enlarges the initial FAB volume, excessively large balls can partially compensate or dampen the effective transmission of ultrasonic energy and bonding force into the pad interface. When the FAB diameter becomes excessively large, the contact stress distribution changes and the effective acoustic energy density at the interface decreases, thereby masking the otherwise dramatic influence of ultrasonic power in this region. This compensatory behavior explains why the US effect appears less pronounced at higher EFO currents in Figure 1. A similar relationship between FAB geometry, interfacial stress distribution, and bonding parameter sensitivity has also been discussed in silver and Au-based bonding systems, where ball morphology strongly influences stress localization and shear strength development (An et al., 2023). Therefore, while EFO primarily determines the initial ball volume, ultrasonic energy remains the primary driving factor governing final ball deformation and interfacial plasticity.

Process stability was assessed by analyzing the standard deviation of ball diameters across 30 parameter combinations, as shown in Figure 2. The results revealed that variations in ball size were strongly dependent on the combination of bonding parameters. Among all 30 configurations, the minimum variation was obtained at an ultrasonic power of 40, a bonding force of 25 cN, and a flame-off current corresponding to 80 mA. This condition yielded the most stable and repeatable bonding performance, and was therefore selected as the optimized parameter window for the subsequent plasma cleaning experiments.

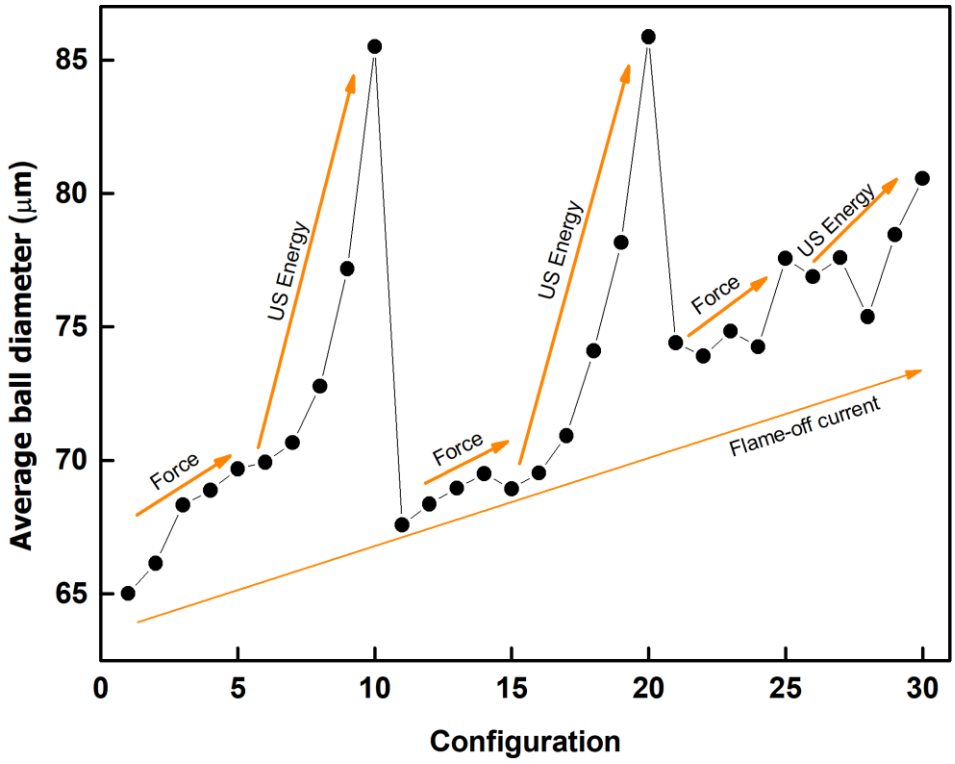


Figure 1. *Influence of bonding force, ultrasonic power, and flame-off energy on the ball diameter*

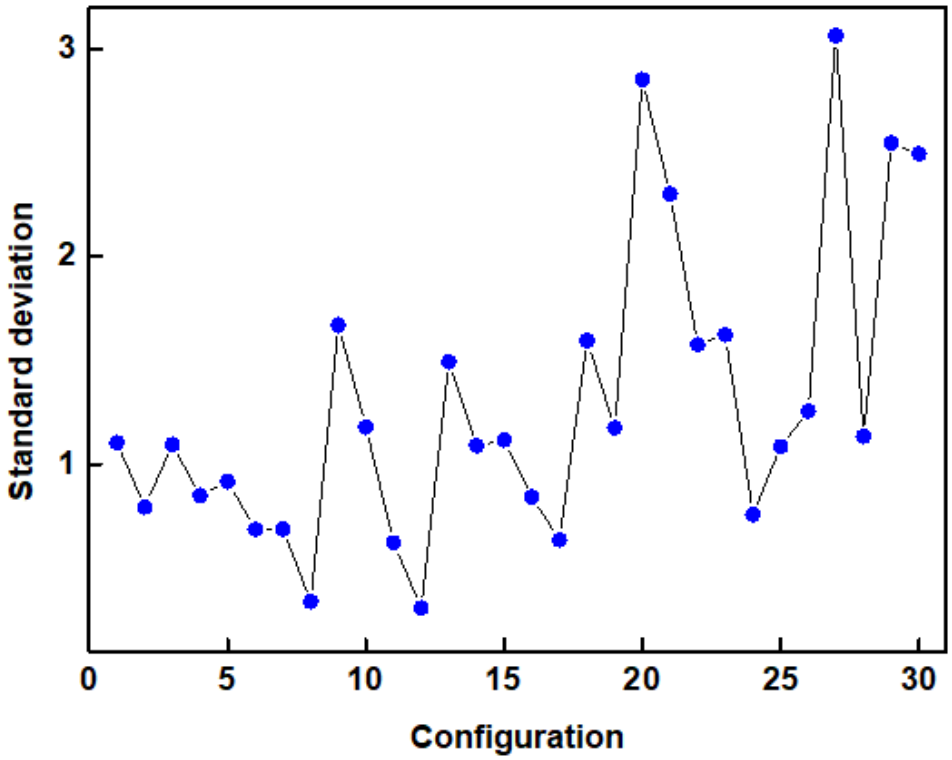


Figure 2. *Standard deviation of ball diameters across 30 bonding parameter configurations.*

The effect of plasma power on pad integrity revealed a critical sensitivity to ion bombardment. At ≥75 W plasma power, the GaAs pads exhibited progressive metallization damage, which is consistent with inadequate treatment may fail to remove contaminants while excessive exposure can lead to surface re-oxidation (Amri et al., 2020). Oxygen and argon based plasma studies also show that excessive plasma energy roughens the Au surface and can expose underlying metals, severely degrading bondability (Sammut, 2025). As summarized in Table 1, the number of unsuccessful bonds increased sharply with rising plasma power across all Ar flow rates. Therefore, 50 W was determined to be the maximum safe plasma power ensuring complete bond yield without pad degradation.

Table 1*. Number of unsuccessful bonded wires as a function of plasma power*

Plasma power (W)	Number of bonding failures for all flow rates
50	0
75	47
100	143

Plasma treatments were applied at 50 W with Ar flow rates of 5, 7, 9, and 11 sccm. For each condition, 50 wires were bonded and tested as shown in Figure 3.

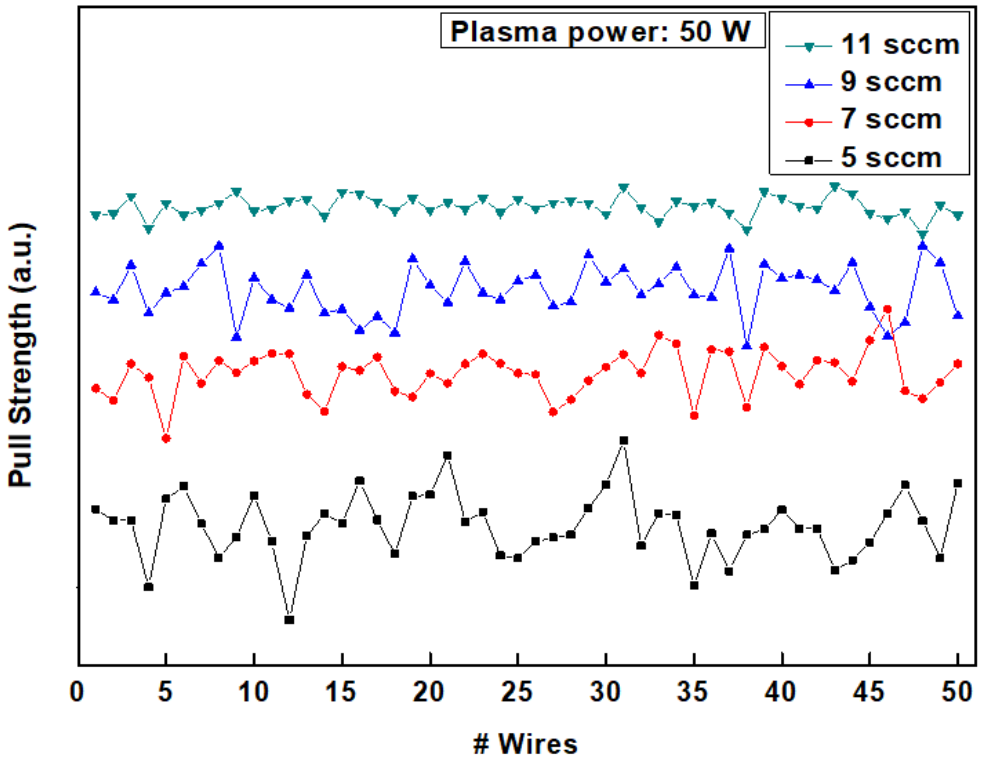


Figure 3. *Pull strength measurements of 50 consecutive wire bonds processed at different Ar plasma flow rates at 50 W plasma power (5, 7, 9, and 11 sccm). Results are presented in arbitrary units (a.u.) to highlight relative variations in bond strength*

At this fixed plasma power (50 W), the argon flow rate had a pronounced influence on pull strength dispersion, as shown in Figure. 4. Although the mean pull strength remained within a relatively narrow range (8.8–9.1 g) for all flow rates, the statistical spread of the data exhibited a clear monotonic decrease with increasing Ar flow, reaching a minimum standard deviation at 11 sccm. This indicates that the dominant effect of increasing gas flow is not a substantial enhancement of absolute bond strength, but rather a stabilization of interfacial conditions across consecutive bonds.

The observed trend can be attributed to improved plasma uniformity and more effective removal of surface contaminants at higher argon flow rates. Increasing the gas flow enhances ion density homogeneity and reduces localized stagnation zones within the plasma chamber, leading to more consistent ion bombardment across the pad surface. As a result, organic residues, weakly bonded surface thin films, and adsorbed species are more uniformly removed. This promotes a more homogeneous surface energy distribution prior to bonding. This result agrees with reports that higher Ar flow enhances plasma uniformity, removes contaminants more effectively, and reduces re-deposition of hydrocarbons or oxides factors shown to directly affect bond adhesion variability in Au–Ni–Cu and LED chip pads (Chan et al., 2005; Peng et al., 2015). Furthermore, the importance of optimizing plasma exposure and flow conditions to achieve surface homogeneity without inducing over-processing aligns with the findings of Amri et al. (2020) on leadframe surface conditioning. In this study, the primary failure mode observed during pull testing was the heel break, while a limited number of samples exhibited wire break failures, particularly at higher pull strength values. The prevalence of heel breaks is

predominantly attributed to the asymmetric nature of the ball-wedge interconnect, while the ball bond provides a robust and large-area interfacial contact on the chip side, the wedge bond on the PCB side creates a reduced cross-sectional area at the heel of the bond, and making it the most vulnerable point for stress concentration during pull testing. Furthermore, the superior quality of the 3 µm Au metallization on the GaAs chip pads compared to the PCB metallization further ensures that the chip-side interface remains intact, thereby consistently directing the failure towards the weaker heel region of the wedge bond. This finding shows that heel break constitutes a desirable fracture mode, serving as an indicator of high bond integrity and overall connection quality (Zhou et al., 2023b). Plasma-cleaned Au pads in these studies also demonstrated more uniform surface energy distributions and improved wetting behavior, correlating with reduced scatter in bond strength.

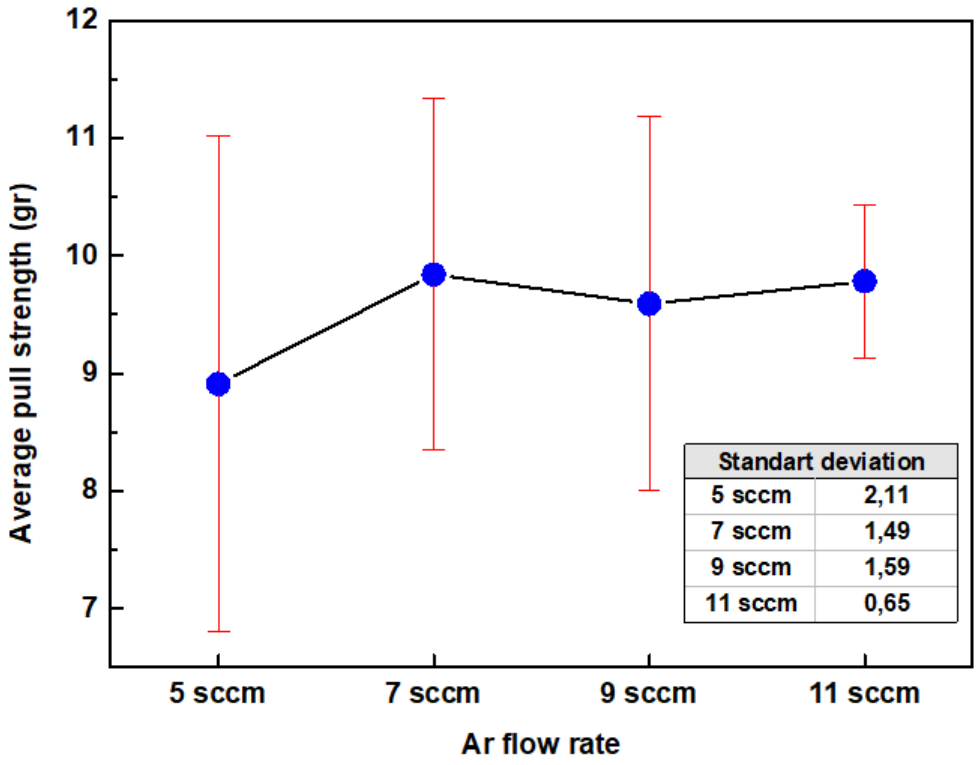


Figure. 4 *Average pull strength values of wire bonds processed at various Ar plasma flow rates at 50 W plasma power (5, 7, 9, and 11 sccm). Error bars represent standard deviations*

Finally, Figure 5 compares untreated GaAs pads with those cleaned under the optimal plasma condition (50 W, 11 sccm). Although the average pull strength exhibited a slight increase after plasma treatment (from 8.72 g to 9.44 g), the most notable observation was the pronounced reduction in variability. The standard deviation decreased from 1.10 g (untreated) to 0.61 g (cleaned), indicating a substantial improvement in process consistency. Statistical significance was assessed using an independent-samples t-test ($n = 50$ per group) to compare the mean pull strength values, while an F-test was performed to evaluate differences in variance between the untreated and plasma cleaned samples. Statistical analysis revealed that although the increase in mean pull strength was relatively modest, it was highly significant ($p < 0.001$). In addition, the reduction in variance was also statistically highly significant ($p < 0.001$), demonstrating that

plasma treatment substantially improves the consistency of bond strength. These findings suggest that argon plasma treatment enhances the bonding process both by improving the average bond strength and by significantly reducing data dispersion, which is consistent with prior reports emphasizing the role of surface conditioning in enhancing process reproducibility. For example, plasma cleaning improves interfacial reliability primarily through two complementary mechanisms: physical sputtering of native oxide layers via ion bombardment and enhancement of surface energy by removal of organic contaminants (Sammut, 2025). In addition, leadframe investigations have shown that argon plasma significantly reduces oxide thickness and improves surface wettability, as confirmed by contact angle measurements and TEM analysis of oxide layer (Amri et al., 2020). The physical mechanism underlying this plasma treatment is attributed to the removal of microscopic organic residues and native oxides, which typically act as barriers to efficient atomic diffusion. By exposing the Au surfaces on the wire bonding pads of both GaAs and the PCB to high-energy argon ions, a more uniform nucleation of the intermetallic bond across the entire contact area is achieved. This homogenization of the bonding interface effectively eliminates localized weak spots that contribute to high pull-strength variability. The consistency of this effect is supported by the observation that heel break was the predominant failure mode, which is generally preferred over interfacial separation as it indicates a stronger bond interface. The reduced scatter observed in pull strength further indicates that the plasma treatment establishes a more uniform and mechanically robust interfacial condition, enabling more consistent ultrasonic energy transfer and stable interdiffusion during bond formation.

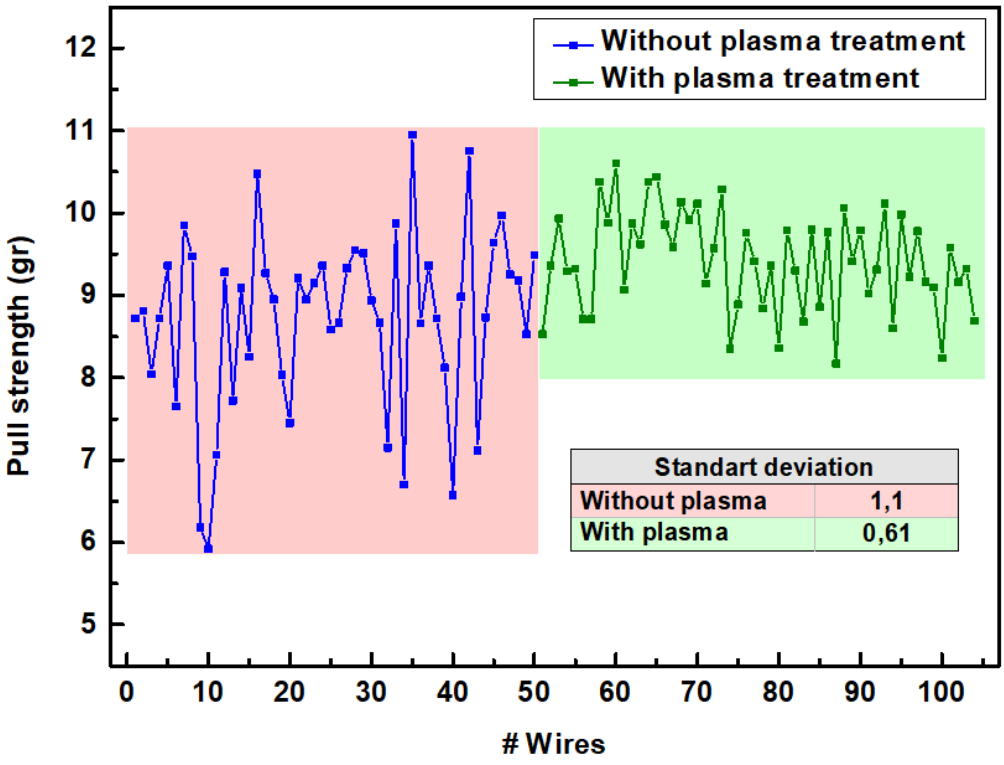


Figure 5. *Pull strength distributions of 50 bonds fabricated without plasma treatment and 50 bonds treated with 50 W, 11 sccm Ar plasma*

4. CONCLUSION

This study systematically investigated the combined effects of ultrasonic power, bonding force, and flame-off current on free-air-ball formation and bond reliability in thermosonic Au wire bonding on GaAs metallization. By decoupling key process parameters while maintaining controlled bonding conditions, a stable bonding window was identified in which ball diameter exhibited minimal dispersion, indicating improved process controllability and geometric stability.

Within this optimized bonding regime, argon plasma surface treatment was introduced and evaluated using a variance-centered statistical framework. Although the average pull strength increased only moderately (from 8.72 g to 9.44 g), the most significant outcome was the statistically validated reduction in pull-strength dispersion. The standard deviation decreased from 1.10 g to 0.61 g, and both mean improvement and variance reduction were confirmed to be highly significant ($p < 0.001$). These findings demonstrate that plasma cleaning primarily enhances statistical robustness and bond-to-bond reproducibility rather than merely increasing absolute bond strength.

Mechanistically, the improvement is attributed to plasma-induced homogenization of the Au pad surface through removal of organic residues and native oxides, leading to more uniform ultrasonic energy transfer and more consistent interfacial intermetallic nucleation. The predominance of heel-break failure further confirms that the interfacial integrity exceeds the tensile strength of the wire, supporting the interpretation that plasma treatment stabilizes interfacial conditions rather than altering failure mechanisms.

Importantly, this work establishes statistical dispersion as a primary optimization metric for thermosonic wire bonding on GaAs pads, providing a reliability-oriented framework directly applicable to high-frequency and compound semiconductor packaging technologies, where yield and long-term performance are strongly influenced by distribution tails rather than average strength values alone. In this context, focusing solely on mean pull strength may not fully capture process stability, whereas considering bond-to-bond variability provides a more comprehensive evaluation of bonding robustness.

The present investigation was limited to monotonic pull testing under as-bonded conditions. No accelerated aging, cyclic fatigue, or shear testing was performed to evaluate long-term interfacial durability. In addition, direct surface analytical techniques such as XPS, SEM, or AFM were not employed to quantitatively characterize plasma-induced chemical and morphological modifications. Future studies incorporating surface characterization and extended reliability testing would provide deeper insight into the plasma–interface interaction mechanisms and further validate the variance-centered optimization strategy proposed in this work.

AUTHOR CONTRIBUTIONS

Conceptualization, A.M.Y. and S.A.; methodology, A.M.Y. and S.A; validation, A.M.Y. and S.A.; laboratory work, A.M.Y.; formal analysis, A.M.Y. and S.A.; data curation, A.M.Y. and S.A.; manuscript-original draft,

A.M.Y.; manuscript-review and editing, S.A.; visualization, A.M.Y. and S.A..; supervision, S.A. All authors have read and legally accepted the final version of the article published in the journal. All human authors have read and legally accepted the final version under the CC BY-SA 4.0 framework.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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