Batch Microwave Plasma Cleaning for Robustification of Automotive Devices

An Alternative to Strip-type Radiofrequency Plasma

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Abstract—This study attempts to explore Batch-type Microwave (B-MW) plasma cleaning as a potential alternative to the conventional Strip-type Radiofrequency (S-RF) plasma; for application prior molding to improve adhesion along the mold-lead frame interface. Performance of B-MW was evaluated in terms of improvement in surface wettability, quantified via Contact Angle (CA) measurements. Mix of typical industrial plasma gases (Ar, H\textsubscript{2} and O\textsubscript{2}) were assessed. Constant flow pattern was observed to significantly improve surface wettability and uniformity compared to its pulsed counterpart; and also affect the effect of other factors on the over-all cleaning performance of B-MW. Proceeding with constant flow pattern, surface wetting was found to improve with increasing power and cleaning time. The combination of O\textsubscript{2} and H\textsubscript{2} plasma was found to be more effective compared to utilizing them separately. Both cleaning time and flow rate increased the amount of reactive species that come in contact with the contaminants. With optimized parameters, both techniques are effective in addressing delamination; but B-MW was confirmed to be a more efficient method than S-RF i.e. better uniformity, 12% more effective in and improving surface wettability and at least 28% higher throughput.

Keywords—batch plasma cleaning, delamination, microwave, package reliability

I. INTRODUCTION

Higher standards on emission and fuel consumption continually challenge automotive makers, compelling them to rely on smarter electronics. Considering the vast market for smart electronics, it is certainly not just limited to upgraded user experience; but an even more important aspect to emphasize is their reliability and robustness. One of the most challenging defects encountered in IC packaging is interfacial delamination, a defect which often precedes other package failures [1]. According to Djennas et al., interfacial delamination is the consequence of package exposure to thermal gradients. These thermal gradients cause the formation of thermomechanical stresses on different contacting materials within the package [2]. Interfaces in any composite assembly such as the IC are considered general weak spots since these regions are easily weakened by CTE mismatch, moisture attack and contamination. The interface between mold and lead frame is one of the regions that is most susceptible to delamination due to build-up of high stresses and pressure (i.e. due to CTE mismatch and moisture release, respectively). Hence, it is also most susceptible to crack formation during reflow soldering [3]. The lead frame surface is also prone to acquiring contamination from preceding processes such as wire bond and die-attach. Any contaminant on the leads and flag surface would reduce the interfacial strength making it easy to delaminate.

Various cleaning techniques have been explored to address contamination-induced defects in the IC packaging industry. The cleaning performance of these techniques are often evaluated based on surface wettability, which is quantified by measuring the contact angle (CA) of water on the sample surface. A large contact angle means the surface energy is lower than the surface tension of water; a good indicator of potential delamination later on. Therefore, smaller contact angles are desirable. The most widely used cleaning technique within the past decade is plasma cleaning, mainly because of its solvent-free approach and fast processing rate [4]. Summarized on Fig. 1 are the various types of plasma sources; two of the most common types are microwave (MW) and radiofrequency (RF), dominated by chemical and physical mechanisms, respectively. Related literatures have enumerated several advantages and disadvantages of both MW and RF. However, actual performance would have to depend on the application and the nature of materials involved in the plasma process.
**Fig. 1. Diagrammatical Overview of Plasma Cleaning Sources.** Both MW and RF sources can be used in low pressure and atmospheric environments.

Based on the author’s survey of industrial plasma use in the local semiconductor industry, RF plasma is more widely used both prior wire bond and prior mold processes. This study features a Batch-type Microwave (B-MW) plasma cleaning technique as a solution to addressing delamination between NiPdAu-plated lead frames and a mold compound with hybrid epoxy chemistry. The study attempts to define and optimize factors that are significant to the efficiency of the abovementioned plasma technique. Results based on optimized parameters are further compared with the performance of a conventional Strip-type RF (S-RF) plasma machine in terms of surface wetting, uniformity and throughput.

## II. REVIEW OF RELATED WORK

Plasma cleaning offers a wide variety of options in terms of machine configuration and excitation source. The succeeding paragraphs contain a comparative summary of available options in the semiconductor industry.

### A. Strip-type vs. Batch-type Plasma Cleaning

Conventional plasma cleaning machines have a strip-type set-up which allows a direct application of plasma onto lead frame strips [5]. This configuration allows maximum concentration of reactive ions to contact the lead frame surface; and has good uniformity results. However, this poses a risk of over-etching package parts (e.g. wires and die) especially if the plasma process is dominated by physical reactions. Direct plasma systems using physical cleaning mechanisms promote ion bombardment that can knock off metal by-products onto the silicon substrate [1]. To address this, several manufacturers install an optional fixture to induce indirect plasma flow. Nevertheless, the strip-type set-up still promotes frequent handling of strips, only cleans one side of lead frame strips per plasma shot and has low throughput. In terms of high-volume cleaning, batch-type set-up is preferred. Instead of loading one strip after another, strips are loaded onto slotted magazines which are then loaded onto the plasma machine chamber. One plasma shot in batch-type takes longer cleaning time but allows up to a hundred strips per shot. It also does not require frequent conversion of fixtures every time a different lead frame size is to be loaded. However, uniformity is typically not as good as in strip-type.

### B. Physical vs. Chemical Plasma Cleaning

Plasma cleaning involves a combination of physical and chemical reactions; although, parameters can be adjusted to make either type more dominant. Physical cleaning involves bombardment of the surface with ions. The process involves pulling of ionized atoms (i.e. via electrical attraction) to an oppositely charged electrode plate where the sample is placed. The impact of ions on the sample surface dislodges contaminants that are then removed from the chamber through vacuum. In chemical cleaning, the effluent is a by-product of the ionized species and contaminant from the sample surface. In general, the efficiency of both mechanisms are dependent on the sample surface. Physical cleaning is most suitable for removing layers of oxidation or contaminants that have settled on the surface forming a film. However, this mechanism risks damage due to impact, overheating and sputtering. On the other hand, chemical cleaning are best for samples which require selective cleaning, which is often the case for composite assemblies. However, O<sub>2</sub> is a common gas used for this type of cleaning and oxidation of surfaces is detrimental to the integrity of IC packages [5],[6].

### C. Microwave vs. Radiofrequency Plasma

Microwave (MW) and Radiofrequency (RF) are two common types of electromagnetic radiation used to excite gas molecules to form plasma. Physical reactions are typically more dominant in RF while chemical reactions are more dominant in MW. Previous studies have demonstrated that MW generates more electrons than RF and also has a faster cleaning rate [7],[8]. This is attributed to the fact that MW plasma is produced at higher frequencies than RF plasma (i.e. 2.45 GHz and 13.56 MHz, respectively). In solid state physics, the maximum electron density (N<sub>e</sub>) is directly proportional to the square of frequency f as in Equation (1), where m is the electron mass, ε is free space permittivity and e is electron charge [8]. Furthermore, the amount of electrons formed is expected to be proportional to the amount of ions produced.

\[
N_e = \frac{f^2 4\pi e m e_0}{\varepsilon^2}
\]  

Based on one of De Broglie’s equations and the concept of work function as in Equations (2)-(4), a wave of higher frequency will produce electrons with higher energy (therefore, also higher velocity) thus explaining the faster cleaning rate of MW plasma [9].

\[
f = \frac{E}{h}
\]  

\[
KE = hf - \text{work function}
\]  

\[
KE = \frac{1}{2}mv^2
\]

## III. MATERIALS & METHODS

Discussed in this section are the materials and equipment used throughout the study and a general description of the methods involved.

### A. Materials & Equipment

The study is done using 63mm x 210mm roughened NiPdAu-plated lead frame strips.

For B-MW cleaning, strips were mounted onto 215mm x 6 mm x 144mm (LxWxH) magazines with 3 mm slots on top, sides and bottom faces. Six of these magazines were loaded onto the Electron Cyclotron Resonance (ECR) tray in a batch-type machine with plasma source on the side as shown on Fig. 2. Twenty lead frame strips are loaded onto each magazine.

Previous studies have used O<sub>2</sub> for removal of organic contaminants and H<sub>2</sub> for removing oxides. Since contaminants often found in this case are organic, the ff. types of gas mix were evaluated:

1. Ar (95%)/ H<sub>2</sub> and O<sub>2</sub>
A. Pulsed vs. Constant Flow

Among all the factors listed on Table I, flow type had the most interesting effect on the response and on other factors. In this study, flow type is defined as the manner in which gases are introduced into the chamber. Based on ANOVA, flow type has a significant effect on surface wettability (p<0.0001, at 95% CL).

**Pulsed flow** - the reactive and inert gases are introduced alternately into the chamber; the former at very high flow rates within a short time (e.g. 1-2 seconds) and the latter at low flow rates for longer periods (e.g. 10 seconds). The introduction of a reactive gas at high flow rate is done to create a wave-like pressure to dislodge contaminants from the lead frame surface; but only at a short period to avoid either too much oxidation or etching. Constant flow - The reactive and inert gases are introduced simultaneously into the chamber at fixed flow rates. The effects of power, gas mix and cleaning time on surface wetting were observed to be different for pulsed and constant flow as summarized on Table II.

| TABLE II. SUMMARY OF VARIATION IN X-Y RELATIONSHIPS FOR PULSED & CONSTANT FLOW TYPE |
|---------------------------------------------|-------------------|
| **PULSED** | **CONSTANT** |
| POWER | lower power, better surface wetting |
| GAS MIX | no significant effect on wetting |
| TIME | 20 minutes is optimum |
| | longer cleaning time, better surface wetting |

Constant flow was also observed to contribute several advantages over pulsed flow:

1. **Improved surface wetting.** The average contact angle values obtained with pulsed and constant flow (i.e. with all other factors set at optimum) are 40° and 20°, respectively. Surface wetting is twice better using constant flow. When reactive and inert gases are introduced at fixed flow rates, the reactive species are given enough time to react with the contaminants.
2. **Improved Uniformity.** With pulsed flow, non-uniformity was observed across the height of a magazine and the distance from the plasma source. But for constant flow, better uniformity is achieved as confirmed via ANOVA (i.e. p values greater than 0.05, 95% CL). Because of the improved surface wetting and uniformity attained with constant flow, it was used in succeeding experiments of this study.

B. Significant Factors and their Effects

All factors enumerated below have been confirmed via ANOVA (i.e. at 95% confidence level) to have significant effects on the cleaning performance of B-MW plasma technique. Conclusions on the optimum parameter settings were made based on results of Tukey’s test, to distinguish relationships between factors and responses.
which settings have the most significant improvement on surface wetting.

(a) **Power.** Power has been found to have a significant interaction with flow rate \( (p=9.77E-04, 95\% \text{ CL}) \), thus affecting surface wetting. Three power settings were studied: 100 W, 200 W and 300 W. Fig. 3 shows that the lowest contact angle values were achieved with 300 W setting. The higher the power settings used, the lower the contact angle and the better the surface wetting. According to Sapieha et al., this observed improvement in surface wetting can be correlated with the *degree of treatment*, \( D_{\text{treatment}} \) \( (J/cm^2) \), or the discharge energy delivered per unit area of the treated surface. Based on Equation (5), \( D_{\text{treatment}} \) is directly proportional to power \( (P) \) and cleaning time \( (t) \) but inversely proportional to the sample surface area \( (SA) \) [9]. This relationship between power & surface wetting is in agreement with the power balance considerations in the breakdown of a neutral gas using microwave [11].

\[
D_{\text{treatment}} = \frac{P \times t}{SA} 
\]  

(5)

(b) **Gas Mix.** The type of gas/es used also has significant effect on surface wetting \( (p=3.33E-16, 95\% \text{ CL}) \). Among the three types of gas mix used, the lowest contact angle values were achieved with the combination of pure \( O_2 \) and pre-mixed \( Ar/H_2 \) (see Fig. 4). Previous studies claim that Argon gas does not promote plasma cleaning with microwave frequencies [12, 13]. However, it is often found in plasma cleaning applications for safety purposes since Argon is inert. In this case, \( O_2 \) and \( H_2 \) are considered as reactive gases since both contribute to the cleaning process. During the plasma cleaning process, species excited \( O_2 \) states react with organic contaminant molecules to form \( CO_2 \) and \( H_2O \) [14]. However, \( O_2 \) promotes oxidation of the metal surface which can counter improvements on surface wetting; especially considering that the topmost layer of the NiPdAu lead frame plating is composed of gold approximately 0.2-2.5 microns in thickness. The incorporation of \( H_2 \) acts as a counter-measure to this undesirable formation of oxides. A study by Fuchs confirmed via XPS the formation of \( Au_2O_3 \) during \( O_2 \) plasma applications but a succeeding \( H_2 \) plasma cleaning step is able to remove the oxide [15].

(c) **Oxygen-to-Premix Gas Flow Rate.** The ratio of oxygen flow rate to that of the pre-mixed gas also has significant effect on surface wetting \( (p=1.31E-08, 95\% \text{ CL}) \). Since one of the reactive gases is introduced at fixed amounts (i.e. pre-mixed gas has 95% \( Ar \) and 5% \( H_2 \)), the ratio of oxygen-to-premix gas flow rate was varied. Fig. 5 shows that the best contact angle settings were achieved with the 5:1 \( O_2:Ar/H_2 \) ratio (i.e. 500 sccm \( O_2 \) and 100 sccm \( Ar/H_2 \)). The higher the flow rate of \( O_2 \), the more amount of excited \( O_2 \) states are introduced onto the surface sample; thus the higher the contamination removal rate and the better the surface wetting. A similar correlation has been observed by Ono et al. using atmospheric pressure microwave plasma for cleaning metal surfaces with organic contamination. The amount of oxygen radical density and contact angle were measured separately with increasing distance from the plasma central part. The oxygen radical density decreases with increasing distance from the center; and correspondingly, the contact angle increases [12]. Based on the results shown in Fig. 5 and those published by Ono et al., the cleaning performance of microwave plasma (both in vacuum and atmospheric pressure) is driven by the amount of reactive \( O_2 \) species introduced onto the sample surface.
(d) Cleaning Time. Cleaning time, the length of sample’s exposure to plasma, also has significant effect on surface wetting (p<0.001, 95% CL). Experiments were done with three settings for plasma cleaning time: 10 mins, 15 mins and 20 mins. Fig. 6 shows that the lowest contact angle values were achieved after 20 mins cleaning time. The longer the cleaning time, the lower the contact angle measured and the better the surface wetting. Aside from the prolonged time for contaminant removal, this is attributed to the presence of H₂ which (1) controls oxide formation from O₂ and (2) has no etching effect.

C. Validation of Effectiveness: Delamination Response

To confirm if both techniques are effective in addressing delamination, units cleaned via B-MW (with 10, 15 and 20 mins cleaning time) and units cleaned with S-RF (i.e. using optimized parameters) were molded using the same mold compound and equipment to check for delamination. These molded units were also subjected to MSL 1 conditioning (i.e. 85°C, 85% relative humidity for 168 hours). None of the units exhibited delamination, prior and after temperature-humidity conditioning.

D. Comparison of Efficiency

The efficiency of these two plasma methods can be compared in terms of three criteria: surface wetting, uniformity and throughput.

Surface Wetting. The surface wetting induced by B-MW was also compared with that of conventional S-RF and strips without plasma clean (control lot). S-RF cleaning was done using previously optimized parameters shown on Table III.

Based on ANOVA, both plasma applications have significantly improved surface wetting (p<0.001, 95% CL). However, B-MW is significantly better than S-RF as shown on Fig. 7 and as confirmed by Tukey’s test. B-MW improved surface wetting by 80%; while S-RF only improved wetting by 68%. The spread of boxplots on Fig. 7 signify that better uniformity is achieved in B-MW. While this is not an expected result, this can be attributed to the use of constant flow in addition to other optimized parameters. This improvement in uniformity is further confirmed through a separate study.

| TABLE III. SUMMARY OF STEPS & OPTIMIZED PARAMETERS FOR STRIP-TYPE RF PLASMA CLEANING |
|----------------------------------|------------------|
| **STEP 1**                        | **STEP 2**       |
| **GAS MIX**                       |                  |
| Ar(96%) / H₂                      | Ar(85%) / H₂     |
| **POWER**                         |                  |
| 300 W                             | 200 W            |
| **TIME**                          |                  |
| 20 sec                            | 10 sec           |
| **FLOW RATE**                     |                  |
| 160 sccm                          | 160 sccm         |

on the sample [15]. Samples were staged in a clean room environment for 24 hours to evaluate recontamination after plasma treatment. % Recontamination was the least on samples cleaned for 20 minutes (i.e. 15.2% increase in contact angle). According to a study by Fuchs, H₂ reduces the rate of recontamination by 50% [15]. The longer the cleaning time, the longer the exposure to H₂ plasma, hence the lower the risk of recontamination.
Uniformity. Aside from surface wetting, uniformity is another measure of cleaning performance. Cleaning uniformity in B-MW (i.e. with constant flow pattern) was evaluated using three criteria (shown in Table IV). An illustration of these three are shown on Fig. 8 for visual reference.

Based on a three-way ANOVA, none of the three criteria exhibited p-values greater than 0.05; thus complete uniformity was achieved in all of these three directions using constant flow pattern. This could not be achieved when pulsed flow pattern was used, two areas of non-uniformity were confirmed – across the height of a magazine and along the perpendicular distance from the plasma source. This further confirms that constant flow is a better setting than pulsed flow.

For comparison, cleaning uniformity of conventional S-RF was also characterized. The equipment used can only accommodate four strips per plasma shot, thus uniformity evaluation was only done across these four strips. Based on ANOVA, the position of strips in S-RF have a significant effect on surface wetting (p<1.05E-06, 95% CL). Two of the four strips have significantly better wettability than the rest as confirmed by Tukey’s test. This further confirms the observed difference in variability of B-MW & S-RF data on Fig. 7.

Throughput. Aside from surface wetting and uniformity, the throughput is also a measure of performance. This can be quantified by the number of units cleaned per hour (UPH). For both B-MW and S-RF, this is calculated as in Equation (6).

\[
UPH = \frac{\text{strip density} \times \text{no. of strips per plasma shot}}{\text{cleaning time} \times \text{index time}}
\]

By converting from S-RF to B-MW, UPH can be improved by almost 28% using the optimum cleaning parameters (i.e. 20 mins cleaning time). If a higher increase in UPH is desired, a compromise in surface wetting is necessary (i.e. up to 68% and 144% UPH improvement for 15 mins and 10 mins cleaning time, respectively).

V. CONCLUSION

Discussed in Section IV-A is the first noteworthy finding in this study; the conversion to constant flow imposed a statistically significant improvement in wettability and uniformity. Both can be further improved with increasing power, time and \(O_2\) flow rate. The combination of \(O_2\) and \(H_2\) plasma (i.e. \(Ar/H_2 + O_2\)) resulted to desirable wettability and reduced rates of recontamination. With optimized parameters, both techniques are effective in addressing delamination; but B-MW is confirmed to be a more efficient method than S-RF i.e. better uniformity, 12% more effective in and improving surface wettability and at least 28% higher throughput. From the results obtained from this study, the authors conclude that the Batch-type Microwave plasma technology is a competitive alternative to conventional Strip-type RF plasma machines.

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