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Balancing Throughput and Process Control for Manufacturing of RF Power Amplifier Assemblies

Author: Kyle Schaefer, Palomar Product Marketing Manager

Introduction: RF Power Amplifier Market

Figure 1: The overall market for RF Power Amplifiers.

The RF power amplifier market is expected to increase substantially in the next five years, primarily as a result of the 5G rollout which depends heavily on new power amplifier assemblies in the base stations. The estimated CAGR for the general RF power amplifier market is 5-6% from 2020-2025[1]. This anticipated demand translates into a subsequent necessity for RF power amplifier manufacturers to increase their volume of production. Yet, a simple ramp up will be insufficient as with this growth in volume also comes new challenges and processes to develop and refine. The market suppliers must simultaneously churn out considerably more devices while dealing with design, material, and process faults. In addition, these companies need also maintain the integrity of their assemblies as they represent the pillars for the foundation of a new commercial initiative and therefore require high reliability and performance in order to convince the public of their acclaimed abilities.

The goals of robust development and rapid ramp-up of production result in two conflicting methodologies of maximizing throughput and implementing process control. These objectives naturally counteract each other and yet need to be focused on in tandem to achieve the highest yield of quality product. While maximizing throughput has its own intricacies, the available options for process control are vast and present ample variations for implementation into a process. Using RF Power Amplifier assemblies as a framework, the numerous process control steps which exist for these devices will be explored in depth. These optional build techniques will be evaluated in terms of impact on both their ability to regulate the key application metrics and their corresponding effect on cycle time. In order to bring this discussion into as literal of an example as possible, we will narrow our focus from the general term of RF power amplifier to one of its key components, RF power transistors. We will similarity limit our conversation to the realm of die bonding to further refine the many process control topics present in the RF power amplifier manufacturing ecosystem.

Key Metrics of RF Power Transistor Manufacturing

When it comes to the die bonding process for the assembly of RF power transistors, the most important metric is good thermal management. Ensuring high thermal conductivity of the bond between the chips and the transistor package is paramount to the longevity and performance of the device. Beyond that, the build requirements vary based on assembly approach and materials used.

There are two major divisions in the RF power transistor designs as seen in Figure 2. The first separation is between transistors that use laterally diffused metal-oxide semiconductor (LDMOS) die and those that use Gallium Nitride (GaN) on Silicon Carbide (SiC) die. GaN based transistors are able to operate much more efficiently at higher frequencies (3.5GHz level and above) but are generally more costly than their LDMOS based counterparts, which are a much more mature and therefor cheaper option. The 5G infrastructure does require these high frequency compatible transistors and will thus primarily necessitate GaN based solutions but LDMOS will certainly be implemented where able, due to its advantages of being a legacy product.

The primary differences between GaN and LDMOS transistors from an automated assembly perspective are the thermal management requirements, die fragility, and die cost. As GaN technology is younger than LDMOS, the operating efficiencies are lower and thus require better dumping of heat to the package when in operation. This means that the thermal conductivity of the bond for GaN based transistors is extremely important and factors like voiding, solder quality, and bond line thickness play a large part in the overall performance of the device. The higher cost of GaN chips means that percent yield will likely take a higher precedence over sheer volume of production in comparison to LDMOS assemblies. Finally, the GaN die themselves are generally more fragile and susceptible to surface damage, which calls for greater care when handling and bonding.

SiC on GaN	VS.	LDMOS
Characteristics: • Better operating efficiency at higher frequencies • Best choice at 3.5GHz frequency range • Higher material cost *Applications:* • 5G Base Stations • Radar Systems in Defense Market		*Characteristics:* • Operates well in the lower frequency rangess • Well developed assembly processes • Lower material cost *Applications:* • 5G Base Stations (lesser extent) • Radar Systems in Defense Market

Figure 2: General overall differences between GaN and LDMOS transistors.

Figure 3: Wide array of RF Power Transistors on the market

The second most important division in transistor designs with respect to assembly of the devices is the die attach material used. Since high thermal conductivity is a strict requirement, eutectic bonding with alloys such as AuSn has been as staple for transistor builds. Pressure-less silver sintered paste is a strong alternative that boasts similar thermal conductivity of the bond with an offline “cure” cycle instead of the in situ reflow for eutectic bonding. The silver sintered solution generally leads to higher throughput but can introduce other potential issues.

In general, the eutectic bonding method for RF power transistors depends on several factors. Good solder quality is important as any oxides that are introduced into the bond or are present at bonding can inhibit the full thermal conductivity potential of the AuSn solder. Oxides form when either the solder – usually present as a preform or deposited on the back of the die – is exposed to oxygen in the air over a long period of time or when the solder is exposed to oxygen during the reflow step of bonding. These oxides not only limit thermal conductivity but can also lead to voiding, which is caused by gaps in the solder layer between the die and substrate. Voiding also greatly diminishes the thermal conductivity of the bond. Another important metric that comes into play with eutectic bonds is die surface quality after bonding. When using a die bonder to attach components with eutectic solders, it is preferable to “scrub” the component by commanding the bonder to move repeatedly in lateral directions while apply slight pressure in order to both break up oxides and spread the solder out in an effort to eliminate voids. However, due to the nature of eutectic alloys, there is a potential that the scrubbing can occur too early or too late in the reflow process thereby damaging the edges of the sensitive die. This is an even greater risk for GaN die where the surface is extremely fragile.

With pressure-less silver sintering, there is less concern with die damage but the emphasis on voiding remains paramount though the elements that result in voiding are instead centered on adhesive volume control, along with bonding force and bonding height repeatability. Adhesive volume control is necessary as inconsistent dispensing can lead to voids caused by an uneven bond line. Any gaps caused by poor dispensing control will also severely impact thermal conductivity. Bonding force control ensures consistent squeeze out as long as the adhesive volume is constant. Even more effective at producing quality silver sintered bonds is varying force, while ensuring bond height is repeatable. With the aid of extremely repeatable height measurement of the surface, the bond line can be set as the target instead of a force value, and the quality of the bond can be more tightly regulated.

Available Process Control Options

In order to ensure the aforementioned key metrics for RF Power transistors are properly maintained in an automated assembly environment, process control steps are required. When reviewing the options for monitoring and controlling process variations, there are two separate approaches; *passive and active control techniques.*

Passive Control Methods:

Passive control steps usually consist of changes to the base process that reduce variation or improve overall build quality. These alterations can be in the form of using different hardware or substituting one assembly material for another. One such example would be switching from a Time Pressure dispense unit to a Jetting Pump for dispensing adhesive. The Jetting Pump is expected to have greater volume control and be less sensitive to surface irregularities, but will change the assembly sequence for every build.

In regards to specific control steps available for RF power amplifier transistors, we will look at regulating dispense, bond line consistency, solder quality, and die placement. The tools available for dispense control include both passive and active control steps. For passive, there are various dispensing options that can be outfitted to a Palomar die bonder. A standard time pressure system is the simplest but does not offer much in the realm of control. An auger pump uses a volume controlled method for dispensing but is still susceptible to surface variations and fluctuations in fluid temperature. A jetting pump has both temperature and volume control systems with its onboard heater block and precise valve controlled adhesive chamber. The jetting pump is also not susceptible to any valleys or peaks found on a surface which would otherwise cause a break in the pattern for other dispense systems. The cause for inconsistent dispense is due to the capillary action and surface tension that helps pull the adhesive from the needle for time pressure andauger solutions; when the adhesive loses contact with the surface, it will build up at the needle instead of being deposited. Since the jetting unit can dispense from as high as 150mils, because of its mechanism which is to rapidly eject small balls of adhesive onto a substrate, the surface quality of the package makes little difference to the overall volume control and pattern consistency for a jetting pump solution.

Active Control Methods:

Active control steps include a separate process statement to visually check the dispense pattern on the surface of the substrate before die placement. This step would verify volume control and pattern quality but would add extra cycle time. The active step could be amortized across several assemblies if it is set to execute only once every x runs, which is not an option for passive control steps. The flexibility of active control steps make them an attractive option during the maturation of a new process or device.

Active control tools for regulating dispense consist primarily of vision based checking to verify dispense volume and pattern uniformity. These steps are possible with the usage of the VisionPilot® tools in the Palomar 3880 Die Bonder. These pattern recognition algorithms alert the operator or halt the program if the actual dispense deviates too much from the expected pattern. For instance, if a clean star pattern was the intention, but one or two of the 'legs' of the star are missing or have gaps, then the vision system picks this up and takes action. In addition, the bonder also sets limits on overall pattern width/volume and can fail adhesive deposits that have too much or too little volume. These checks are placed anywhere within the program and at any desired frequency. It is also possible to create a 'diagnostic' dispense step to execute every 'x' builds where a more complex (or simple) pattern can be used to verify dispense/ adhesive quality.

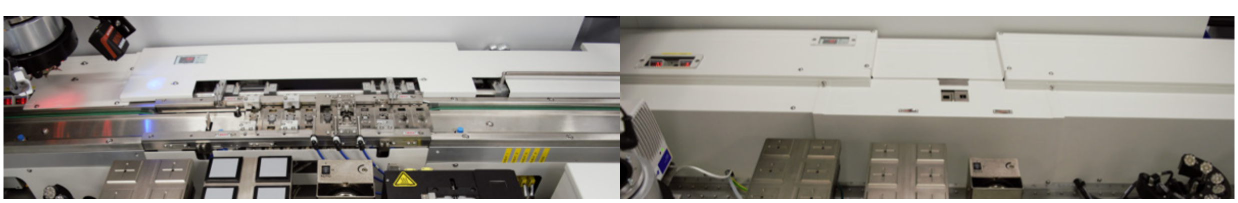

Figure 4/5: Various hot rail handler options are examples of passive controls used to ensure proper temperature for regulating solder quality. The monitoring capabilities of the software used to run the handler is an example of an active control.

When trying to maintain bond line consistency, the primary issues to deal with are adhesive irregularities and surface variations. As controlling adhesive dispensing was just discussed, surface quality will be the topic of the discussion for the challenges of bond line repeatability. Conventional placement techniques rely on a 'force controlled' approach – that is the pick and place operation is driven by applying a set amount of force once contact is made with a surface. When placing a die into adhesive on a rough surface, that contact point and the required force can vary, especially if there are any high points in the package relative to the average surface height. Thus, when aiming for a set bond line thickness, being able to drive to specific heights, independent of force is more important. This poses an issue however if the taught surface height is not repeatable – from varying overall package thickness, for instance. Even a few microns difference can impact bond line consistency, thus it is advised to first measure the height of the surface with micron level accuracy. On the die bonder this is done through touchdown or with a contactless method such as a confocal sensor. This sensor is extremely fast and repeatable, allowing for multiple measurements quite quickly for the most accurate understanding of the package surface. This passive method can be employed to ensure bond line repeatability for every assembly. The same confocal sensor can even be used to check the die height after placement for verifying bond line thickness and tilt of the die in respect to the surface measurements from earlier.

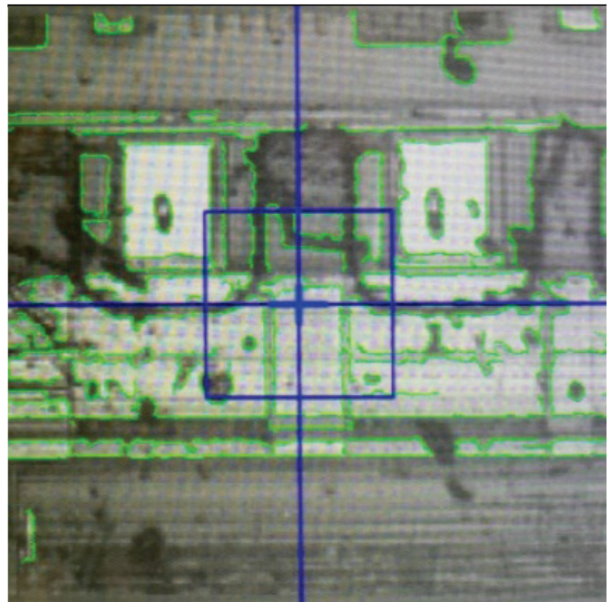

Figure 6: VisionPilot® Radar referencing of a damaged die surface. Using this information to sort die before picking is an example of a passive control step, while using it for an after-process step is an example of active control.

For eutectic assemblies, ensuring high solder quality is done through careful monitoring and control of the environment. Both usage of high flowrates of inert cover gas and tight enclosures can keep Oxygen levels as low as possible during bonding to prevent oxides forming. In high volume scenarios, a heated handler (Figure 4/5) is generally used to ensure the minimum downtime between assemblies; however, these handlers generally have poorer enclosure abilities. To remedy this, a new version of the heated handler was designed with a more tightly sealed bonding area. Switching from the standard heated handler to this enclosed variant lead to improved solder quality after bonding. In terms of more active control steps, the heater control software on the die bonder can keep close track of cover and cooling gas flowrate along with the temperature of the heater surface. This monitoring can be utilized in determining the best time to execute scrubbing motions and for preventing any bonding when conditions are not optimal. Additionally, force feedback can be used to monitor the exact moment the eutectic solder liquefies and use that event as a trigger for scrubbing – essentially preventing die damage during every bond, regardless of substrate thermal path irregularities.

For preventing component damage in general, or even simply just monitoring die placement, the die bonder vision system can be used to great effect. Often a simple active process control step consisting of a single reference can be enough to prevent repeated misplacement or consecutive component damage. This can be achieved by using a unique feature of the VisionPilot® referencing system (Figure 6), referred to as the ability to 'score clutter'. Essentially, the pattern recognition algorithms can use excess data (i.e. clutter) which comes from debris, chips, and scratches, to lower the given 'score' for a reference. This allows rejection of die based on damage or cleanliness. Using this technique before beginning any assembly allows for die sorting during the actual build process to prevent any waste of material. It is also possible to use this same 'chip damage check' after placement to avoid any instances where damage was done through any debris collected on the vacuum tool – a situation, where when left unchecked could result in consecutive device destruction until noticed much later down the line. This control step can also simultaneously check for die placement repeatability in terms of X, Y, and Theta, further adding to the complete control options available.

Balancing Process Control and Throughput

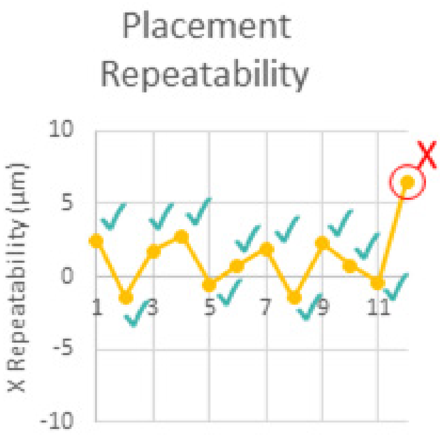

Figure 7: VisionPilot can check placement repeatability.

Each of the above process control techniques can lead to increased cycle time and a reduction in overall production volume. For instance, the dispense check can take several seconds if you were to check every dispense pattern on a package with several die; the verification of bond line thickness could add another 200-500ms for every potential measurement; each placement repeatability and damage check yet another 900ms per check. When aiming for high volume, every second literally counts. As such, it is important to find ways to balance these methods that are focused on high device quality and yield percent with ways to maximize throughput. The best ways to do this will be to first automate every control step and resulting action as much as possible, then begin to disperse these control processes between the appropriate numbers of assemblies in relation to the device design maturity, and finally look for ways to solve the issues that are necessitating these control schemes.

When aiming to automate process control steps it is important to utilize every tool available to produce a robust and complete automated routine. Several of these means will be walked through with the subject of tool cleanliness used as an example for a potentially automated control step. As mentioned earlier, debris on the tool can lead to damage on the die during manipulation of components, and as a result, is something that should be checked for and removed if found. In the most manual sense, this would be performed by an operator using the upwards facing camera on the bonder to check the tool quality and proceed to manually clean or replace the tool if necessary. One of the first ways to can increase the automation of this step is by using the flexible programming environment combined with the VisionPilot® referencing software to set up an operator-independent tool quality check. This can be achieved through using the same 'clutter scoring' as mentioned prior to look for debris on a tool with a 'look-up' reference that is taught as a clean surface. With the programming, you can also que up several tools to be automatically checked at once. In addition to this programmed sequence alerting the operator of failed tools and saving images of tool surfaces for quality tracking, the process can be further automated by using a system to trigger these tool checks.

A trigger event for this can either be a failed post placement reference that is looking for debris or damage, or it can be prompted sooner through some bond monitoring software. Bond Counter is a feature that tracks the number of times a tool has been used in a pick and place sequence, as well as many other events, such as pick failures. By using Bond Counter to observe the total number of actions a pick tool has taken and the amount of times it has failed to manipulate a component, it is possible to preventatively run the tool check routine. With the SECS/GEM (SEMI Equipment Communications Standard) / (Generic Equipment Model), software capability on the bonder, it is possible to automate even further by using a host application that sets thresholds for particular counts or behavior from the bonder and automatically switches the program from the production process to the tool check process. Using an automated procedure for tool cleaning, such as a simple program to run the tool through a tool cleaning brush or scrubbing on a coarse cleaning surface, it is possible to also set up the host application to automatically clean the tool based on the tool check results. By embracing high levels of automation, a regular maintenance step can be executed more efficiently and at optimal frequencies.

In general, implementing control or maintenance steps at ideal intervals will lead to the greatest effects for maximizing throughput while simultaneously preserving a high device yield. This is the value in using active control steps, as they lend themselves well to amortization across multiple builds. A simple example of an Ag sintered paste attach application with four die can be used to show the effectiveness of spreading control steps out between assemblies. In this example, we will implement an adhesive dispense check on the actual assembly pattern for each die. The base cycle time for this case would be 16 seconds with the active control step taking 3 additional seconds. If this control measure were to be taken for every assembly, roughly 16% of the maximum production would be lost. However, even just slightly spreading out the check to every 5 assemblies drastically improves production back up to 96% of the maximum volume. This frequency can be easily set in the programming for the bonder and can be reduced as confidence is gained in the assembly process, material quality, and device design. Eventually, the effect can essentially be negated by sufficiently increasing the interval between each check.

# Assemblies Before Check	UPH	Time Before Checks (min)	% of Max Production
1	189	0.3	84.2%
5	217	1.3	96.4%
10	221	2.7	98.2%
25	223	6.7	99.3%
50	224	13.3	99.6%
-	225	-	100.0%

Figure 8: Balancing checks vs UPH will help deliver the highest throughput.

At a certain point, the assembly process should ideally mature to provide the option for resolving an issue entirely, such that the corresponding control steps are not needed. While process control is meant to ensure device quality, it is also a fantastic tool to learn about the shortcomings of a particular material choice or design. This learning can lead to optimizing production volume through something as simple as changing material. In a rudimentary case, this can be changing the syringe barrel size for the adhesive used from 5cc to 3cc to better synchronize adhesive working life with consumption rate. This change could be all that is needed to solve any irregularities in dispense consistency – thereby removing the need for dispense checks. Another example would be to change the AuSn preform thickness (while maintaining volume) to achieve higher and more reliable solder quality. Many of these actions to take will be situational and highly dependent on the device design and operating circumstances, but will generally all come from learning as the build process matures and feedback is received from implementing process control steps.

Conclusion

The importance of process control in markets that require both high demand and high reliability cannot be understated. These steps not only ensure the required device performance but also significantly accelerate the learning and maturing process for the design and assembly sequence. In the early stages of a product, it is wise and likely necessary to implement several high frequency active process control measures. As time goes on, transitioning to more passive control schemes and finally discovering solutions to reduce the need for process control will be the goal. Process control and throughput will always be a delicate balance in any process, but understanding the tools on hand and using them intelligently and collectively will certainly guarantee an optimal path to maximum production volume without sacrificing quality or performance.

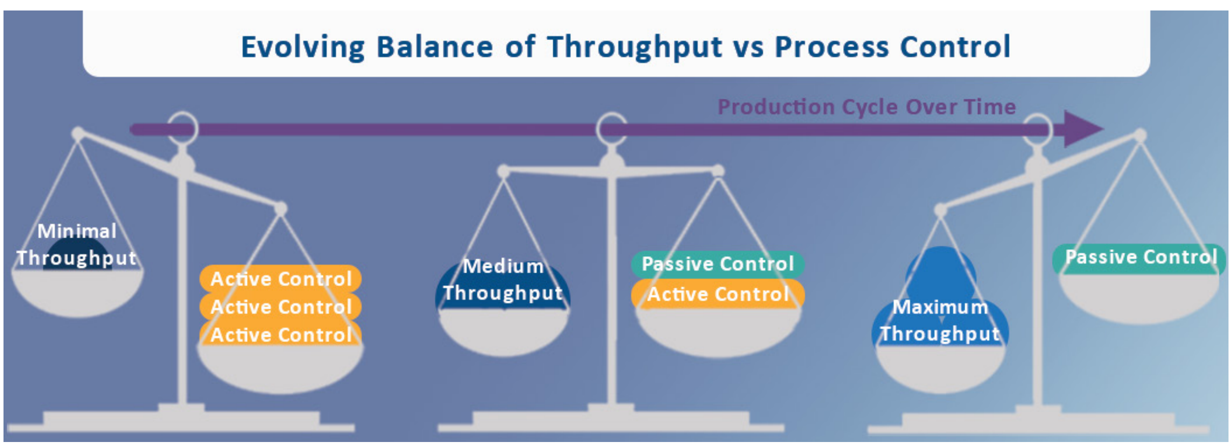

Figure 9: The level of process control decreased over production time as throughput is maximized.