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Automating RF PA device manufacturing to accelerate 5G wireless rollout

By Limin Zhou, Julius Ortega [MRSI Systems, Mycronic Group]

The successful rollout of 5G wireless depends on the deployment of a significant quantity of base stations with a higher density of radio frequency (RF) power amplifiers (PA) compared to the older 4G technology. Each 5G base station has more channels, and each channel needs one RF PA device. These devices are key components that boost the RF power signals in base stations.

Before the 5G era, silicon-based lateral double-diffused metal oxide semiconductor (Si-LDMOS) was the mainstream solution in the RF PA market for 4G long-term evolution (LTE) technology. Those devices are now regarded as almost commodities with a high level of technical maturity. Traditional Si-LDMOS performs well at 3.5GHz and below, but is unable to meet the higher frequency requirements for 5G applications. The operating frequency of gallium arsenide (GaAs) applications is mainly within 8GHz, suitable for medium- and low-power devices for 5G cell stations. In the high-power RF application, gallium nitride (GaN) has obvious advantages and is a necessary material for 5G macro stations. GaAs and GaN are on the rise to replace silicon as the backbone of power switching technology thanks to better power systems efficiency, performance, and cost, of GaAs and GaN. As wide-bandgap (WBG) semiconductor materials, both GaAs and GaN devices are more efficient than Si. GaAs/GaN devices are replacing Si-LDMOS devices in 5G base stations, radar, and avionics, as well as other broadband applications. In future network designs, GaAs/GaN and other WBG materials will replace most of the existing Si-LDMOS devices due to limitations of their physical properties [1]. Generally speaking, 5G base stations will incorporate GaAs/GaN-based PAs for the higher frequencies, while Si-LDMOS will remain just a part of the mix for lower bands [2]. According to Yole's report [3], the total GaN RF market will increase from $740 million in 2020 to more than $2 billion by 2025, with a compound annual growth rate (CAGR) of 12%. Telecom infrastructure and military radar are the main drivers for RF GaN. The telecom infrastructure market segment for 5G wireless will enjoy a 15% CAGR.

This article discusses an essential element in automating RF power amplifier device manufacturing—a fully automated die bonding solution to support the flexible, high-precision, high-volume manufacturing required for large-scale deployment of RF PA devices in 5G applications.

Manufacturing requirements and challenges

RF PA devices have two major die bonding assembly methods: eutectic and epoxy. The eutectic process, which is the most common die bonding technique for power electronic devices, has historically been the only method for making higher power RF PA devices used in base stations. The eutectic alloy between the die and the heat sink is typically gold-silicon (AuSi) or gold-tin (AuSn), which gives the best thermal conductivity and lowest possible void rate after bonding. On the other hand, the traditional epoxy process may be cheaper, but has lower thermal conductivity and a higher void rate after bonding. This may be sufficient for some low-power/low-reliability devices. In recent years, some new die bonding adhesive materials and processes have been developed to replace AuSi/AuSn solder for cost reduction for high-power devices. For example, the pressureless nanosilver sintering materials are expected to have good thermal conductivity for high-power devices and to be able to adapt the standard epoxy dispensing equipment and process. The materials and processes have not yet matured enough for RF PA devices.

There are five major challenges to achieving a good die bonding process using a fully-automated solution in order to enable multi-process and multi-die manufacturing required for RF PA device production for 5G base stations. The sections below discuss these challenges.

RF PA chip handling. Electrostatic discharge (ESD) is a major factor that can potentially destroy or damage the RF PA chips. To solve this problem, the die bonder should be properly grounded and periodically tested for ESD compliance for all work surfaces that contact the product to minimize or eliminate ESD risk during production.

These RF PA chips have unique characteristics—they may be larger than other chips, with an aspect ratio of more than 10. They are long and thin dies (thickness can be as little as 30µm), with air bridges or sensitive structures on the top that can be damaged if excessive force or stress is applied to the top. These characteristics require delicate handling including placement force control that is only achieved with real-time force feedback. The die pick and place process uses vacuum collets that hold the chip edges. GaAs and GaN are naturally brittle materials. The bonding force ranges from 10g to 100g, which must be tightly controlled to avoid damage and for the best bonds.

GaAs and GaN eutectic processes. Gold-tin (AuSn 80/20) is the alloy most commonly used in the industry for bonding GaAs and GaN chips, because of its compatibility with gold-based components and its long-term stability. The backsides of GaAs and GaN chips are plated with a gold layer to provide a good thermal and electrical interface and allow flexibility in the die attachment method. The solder preforms (12~50µm in thickness) are often used in this process. The solder preform size is determined experimentally. Al_2O_3, Cu-W, Cu-Mo, and Si and SiC, etc., are the common materials for substrates.

The lowest melting point of the AuSn 80/20 alloy is 280°C. A 2% decrease of tin to 18% increases the melting point to 350°C. The eutectic reflow temperature should be 20-40°C higher than the melting point. Because of reliability concerns, a maximum reflow temperature of 320°C for a maximum of 30 seconds is recommended for GaAs and GaN. The temperature profile is dependent on the eutectic stage, the size and number of dies, and the substrate, etc. The first step of the process is to pick and place the solder preform while at a pre-heating temperature. The second step of the process is to pick and place the die. The die are placed on top of the solder preform either at the reflow temperature, or just before reaching it. The die are placed with a force of 10~100g and scrubbed according to some preprogrammed parameters. In some cases, the preform is pre-deposited on either the substrate or the PA chip.

LDMOS eutectic process. AuSi is used for ultra-high thermal demand applications, such as silicon-based LDMOS. The packaging or substrate materials of LDMOS RF PA devices are Cu-W or Cu-Mo. With AuSi bonding, an additional alloy material is not included. Instead, the process relies on the diffusion of gold and silicon that occurs at a high temperature. This process is done in the presence of forming gas with 5-10% hydrogen.

AuSi eutectic bonding occurs at a high melting temperature of 363°C. In order to maintain the LDMOS performance, the bonded chip-on-substrate (CoS) needs to be processed quickly and removed from heat as soon as possible. The bonding force of the eutectic process may be set to 30~100g. Scrubbing must be applied during die attachment to eliminate voids.

Void-free processing. Solvent cleaning of solder preforms and substrates/packages is recommended to remove any existing surface contaminants (from machining, packaging, handling, etc.). GaAs and GaN can be cleaned using an oxygen or plasma cleaning process before the eutectic process. During the eutectic process, an inert gas (nitrogen or nitrogen with 5-10% hydrogen) is used to surround the parts and remove oxygen during reflow, preventing oxidation of the interconnect surface.

Reliable eutectic die attach of high-power/high-frequency devices requires nearly a void-free attachment. A better than 95% void-free attachment is achievable with a scrub assist. An oxygen level >10,000ppm contributes to voiding poor quality solder joints. The oxygen level in the eutectic chamber of <5000ppm is necessary to achieve a low void rate. The oxygen level should be controlled <1000ppm to have a buffer for different eutectic processes. For process control, the amplitude of the scrub cycle, time of scrub, and force, must all be optimized to form a good void-free attachment. Scrub-assisted automatic die attach is a common process that relies on "scrubbing" of the die into the gold or package surface to break up the oxidation layer and have good mixing to form the eutectic alloy. The scrubbing process usually is a 5-10 cycle scrubbing movement under a certain amplitude and frequency in X-Y-Z directions. During the eutectic process, the scrubbing process distributes the solder and removes the gas bubbles that are among the main reasons for void generation.

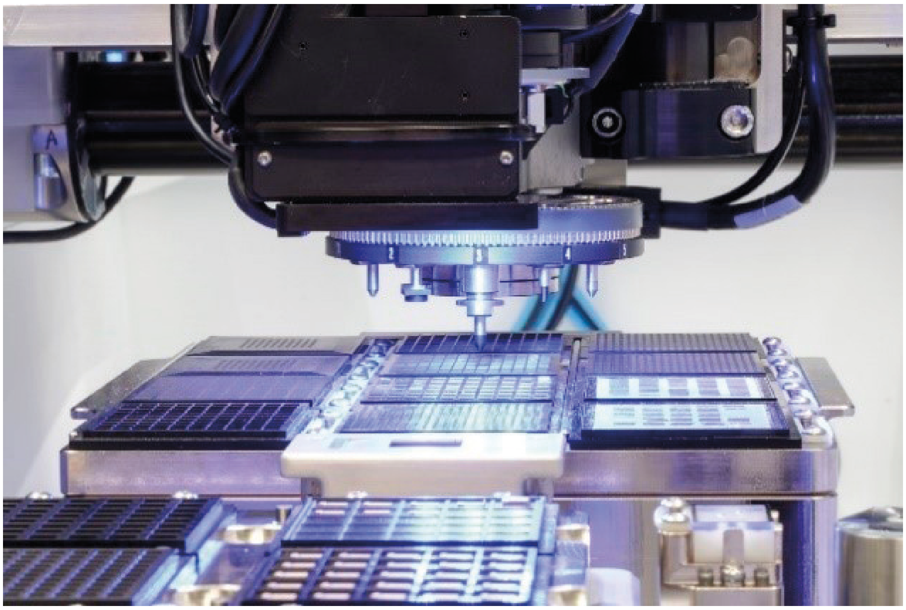


Figure 1: MRSI's "on-the-fly" tool changer.

Epoxy process. The epoxy process has mostly been used for attaching passive components, such as capacitors, but not active components in RF PA devices. In recent years, new adhesive materials have been developed to replace AuSn. Silver micron-particle sintering joining technology developed by Prof. Katsuaki Suganuma of Osaka University has enabled pressureless die bonding in ambient temperature at a low cost. Because this technology showed high reliability at high temperatures over 250°C, its use is spreading as a key next-generation power semiconductor die bonding technology. There is a lot of ongoing research and development work on the pressureless nano Ag sintering materials and sintering processes [4]. Potentially, the new materials will be used for high-power RF PA [5-7].

The thinner the epoxy bond lines, the higher their thermal conductivity. Achieving these thin bond lines requires a careful design of the dispense pattern, die placement and process parameters during the epoxy process. A thicker bond line may help mitigate CTE mismatches between the chip and the substrate, especially for GaN dies (that can handle a slightly higher mismatch), but the resulting increase in thermal resistance may not be an acceptable trade-off. High-performance stamping and dispensing functions, as well as bonding force control, provided by the die bonder are necessary for a satisfactory bond line control.

MRSI automation solution

MRSI has developed fully-automated die bonding solutions to enable multi-process and multi-die manufacturing of RF PA devices for 5G base stations. These systems have the flexibility and high throughput required for this high-mix and high-volume manufacturing environment and solve the challenges outlined above. The sections below summarize the bonding solutions.

Automation solutions for RF PA. Our new assembling solutions have two platforms, the 1.5μm MRSI-H-LDMOS and the traditional 5µm MRSI-705 with horizontal turret. Both platforms support AuSi and AuSn process requirements and have high-performance stamping and dispensing options.

Both of our products come with an integrated turret that can hold up to 12 tips. The turret enables "on-the-fly" tool changing to achieve zero-time between tip changes. **Figure 1** illustrates our "on-the-fly" tool changer. Any version of custom die pick up tip or epoxy stamping tip can be used in the turret. It can flexibly handle multiple dies, multiple processes, and multiple products in one machine. This helps users to create flexible production lines that can be rapidly reconfigured for different products.

Furthermore, high-volume production is aided by the in-line eutectic die bonding system we developed. By utilizing a progressive heat stage system that indexes through heat zones, eutectic die attach can be performed on parts transported in "boats" or carriers that are loaded, processed, and unloaded to cassettes automatically. The in-line eutectic system is a "Universal" Progressive Indexing Conveyor (**Figure 2**). It is a modularly-designed common architecture across multiple machine platforms (MRSI-705, MRSI-M3, MRSI-H), and supports both AuSn and AuSi eutectic processes. This in-line mode is also applicable to the epoxy process.

Temperature profile control. To achieve eutectic bonding, a heating station is typically employed that can ramp up and ramp down the temperature rapidly and precisely to maintain good temperature uniformity on the hotplate. Our eutectic station is a pulsed heating station, with a maximum temperature of 450°C, a temperature control accuracy of <±1°C, a temperature ramp-up speed of up to 40°C/s, and a cool-down speed of 30°C/s.

Oxygen environment control. The eutectic process is performed in an inert environment to prevent oxidation of the bonding surfaces, as the RF PA device is subjected to heat. We used a specially designed gas cover over the eutectic station. The flow of forming gas is carefully managed to create an oxygen-free environment for the eutectic process. The standalone eutectic station can achieve a <100ppm oxygen level environment and the indexing eutectic station can achieve a <500ppm oxygen level environment, using pure nitrogen forming gas. Both cases far exceed the process requirements mentioned earlier.

Scrubbing process. Scrubbing is a critical process step in the formation of a common material (bond) between AuSi and AuSn by forcing out air to reduce voiding. Also, the solder is better distributed across the die and the pressure assists the diffusion process. As a starting point, our software includes a pre-programmed library of scrub patterns to guide users as they quickly develop their process. The scrubbing parameters are completely programmable for customization to the specific process. Scrubbing consists of applying vertical and lateral forces to a chip during its placement. The chip is usually moved in a figure eight pattern that is repeated for several cycles. Movements in alternate directions are also possible. Rotational scrubs are sometimes employed. Scrub parameters consist of amplitude, speed, and frequency in the x, y, and theta directions. Parameters are determined by process requirements, such as the surface area of the chip, and process constraints, such as proximity to adjacent die.

Bond line control for the epoxy process. Our epoxy stamping process uses a rotating stamping-well with multiple epoxy grooves presenting epoxy for stamping. The dispensing process uses time-pressure dispensing units with precision fluid control technology. The substrate surface is measured by a three-point laser height system that maps the plane to ensure that the gap between the needle and surface is maintained at all locations. We also provide an option for a confocal height sensor to measure bond line thickness. Consistent bond lines are achieved through a combination of precision epoxy volume control and closed-loop force control.

RF PA process results

Below, we share the performance results achieved using the MRSI-H-LDMOS. This system included an indexing conveyor for high-volume manufacturing. We used 60 industry standard glass dies to test the machine's pick and place accuracy, the 3σ results of x<1.21µm and y<0.84µm surpassed the machine specification <1.5µm @3σ. The machine oxygen level at the eutectic bonding station was tested by using a Pro OX-100 Digital Oxygen Purge Monitor. The results show the oxygen level at the eutectic bonding area is <100ppm.

The real AuSn process was done for two different size GaN chips bonding on a substrate by using AuSn solder preforms. Chip sizes were about 3 x 1mm and 4 x 1mm. Both chips were 100µm thick. Au-Sn solder preform sizes were slightly smaller than the chips. As the carriers were indexed through the machine, parts were heated to a pre-heat temperature before arriving at the bond station. The bond station was ramped from the preheat to reflow temperature during the processing. Optimal force and scrub parameters were found through process development. Metrology revealed that the bonding process accuracy met the requirements well. The results are shown in **Figure 3**. The left image shows 15 samples, the right image shows the real size sample. These

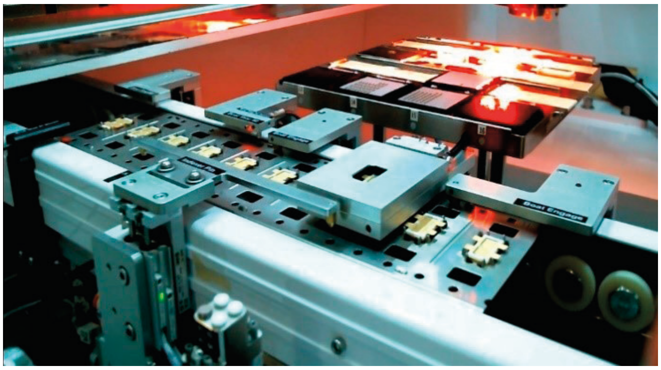


Figure 2: "Universal" progress indexing conveyor.

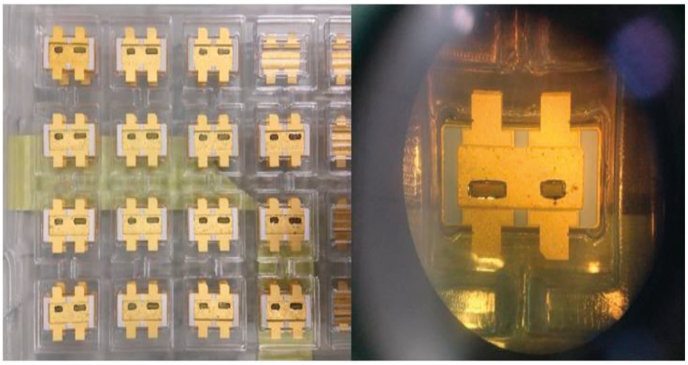
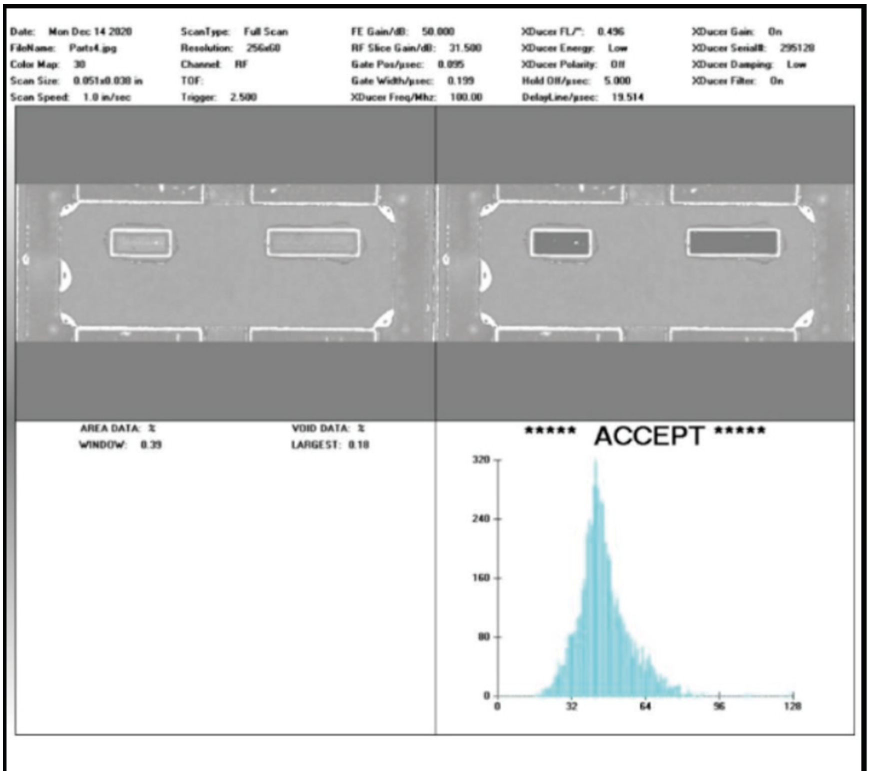


Figure 3: 15 samples show solder flowed evenly without oxidation.



Parameter	MIL-STD 883K Method 2030.2	Typical RF PA specification	Measured	Result
Total voids	<50%	<5%	1.60%	Passed
Single void	<15%	<1%	0.89%	Passed

Figure 4: Voiding results by scanning acoustic microscope results for the five samples.

images show that all of the 15 samples of the solder flowed evenly without oxidation.

After the build, five samples were tested for voiding through the use of a scanning acoustic microscope (SAM). The average total void is 1.6% and the average single void is 0.89%. The results are shown in **Figure 4**.

Summary

We have developed a highly flexible automation solution to support multi-die, multi-process production for RF PA devices for 5G base station applications. The tests show that the machines achieve high die bonding accuracy and very low void percentage with high production throughput to support the GaN AuSn eutectic process. The machines also support the AuSi eutectic process by using different pre-heat and eutectic temperatures and can be configured to add epoxy dispensing and epoxy stamping. Our fully-automated solution for RF power amplifier device manufacturing meets the challenges posed by the accelerated deployment of 5G at an attractive return on investment for users.

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Biographies

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