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The Future of Semiconductor Packaging

Volume 24, Number 2

March • April 2020

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Antenna in package (AiP) technology for 5G growth

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Antenna in package (AiP) or antenna on package (AoP) simplify challenges associated with mmWave applications and expedites system design. Today's AiP technologies can be implemented through standard or custom system in package (SiP) modules. This article provides an in-depth look at the different AiP options, shielding, material selection, and best use cases in emerging 5G applications.

5G applications and projected growth

The driving forces for implementing 5th generation new radio 5G (NR) or simply 5G technology, include the transmission of large data rates as well as the need for more reliable connections, quicker response time (low latency) and better coverage. In mmWave applications, signal loss becomes critical and design challenges increase in complexity. In addition to emerging 5G smartphones, other applications that operate at very high frequencies and demand a small size include wearables, small cells, security cameras, radar units in autonomous vehicles and numerous Internet of Things (IoT) appliances.

By 2023, over 1 billion mmWave units will be produced annually according to Gartner, Inc. market research. With AiP technology, the antenna is no longer a separate component within the wireless device but is integrated in a SiP with radio frequency (RF) switches, filters and amplifiers. According to consulting firm Yole Développement, the total RF front-end (RFFE) module SiP market is projected to reach US $5.3 billion by 2023, representing an 11.3% compound annual growth rate (CAGR) (Figure 1).

Another market forecast projects the 5G mmWave market to increase tenfold by 2025 [1]. The supporting base station and small cell infrastructure will require a tremendous amount of semiconductor packaging and system integration support. Outsourced semiconductor assembly and test (OSAT) suppliers are typically best suited to invest in the package development and production scaling for such applications by leveraging their broad customer and supply base.

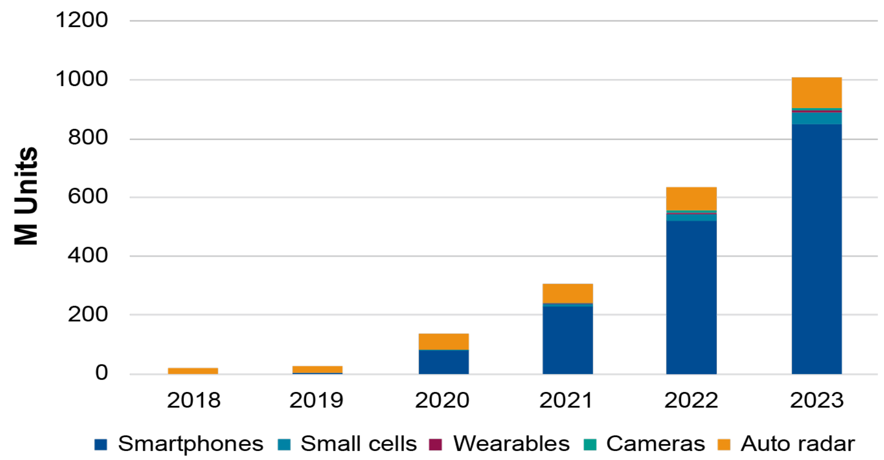


Figure 1: The market for mmWave devices is expected to grow to 1 billion units by 2023. SOURCE: Gartner, Small cells market status report, December 2018

5G AiP technology

Instead of separate power amplifiers (PA), low-noise amplifiers (LNA), switches, transceivers, filters and a discrete antenna, today's fully-integrated RFFE module is completely achieved with AiP technology in a SiP. The integration is accomplished using SiP technologies, including double-sided assembly, advanced wafer-level redistribution layers (RDL), passive component integration and sophisticated RF shielding techniques to provide the most advanced 5G package solutions available today.

In addition to the reduced size required for handheld and other small mmWave devices, AiP provides improved signal integrity with reduced signal attenuation and addresses the range and propagation challenges that occur at higher frequencies. Among the changes occurring with the transition from 4G long-term evolution (LTE) to the 6 to 60GHz of 5G are increased RF switch and band complexity (from 40 bands x3 carrier aggregations [CAs] to 50 bands x5 CAs) and increased antenna design and tuning complexity (from 8x8 multiple input and multiple output [MIMO] to 68x4 MIMO). To achieve the promised improvements of 5G (see Figure 2), many of the technical challenges must be addressed at the package level.

	3G	4G	5G
Deployment	2004-05	2006-10	2020
Bandwidth	2 mbps	200 mbps	>1 gbps
Latency	100-500 milliseconds	20-30 milliseconds	<10 milliseconds
Average Speed	144 kbps	25 mbps	200-400 mbps

Figure 2: The use of 5G technology provides significant advantages over previous generations. SOURCE: Raconteur

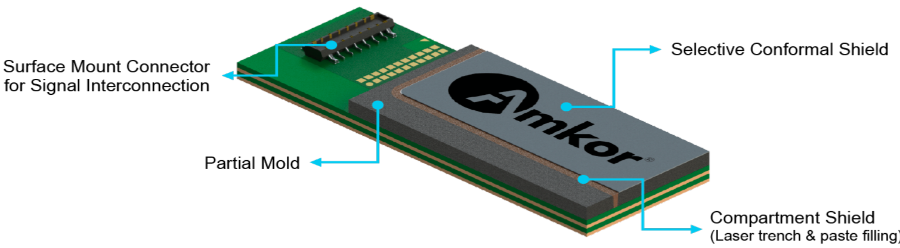


Figure 3: With an AiP design, the antenna is not a separate device, but is integrated in the device package.

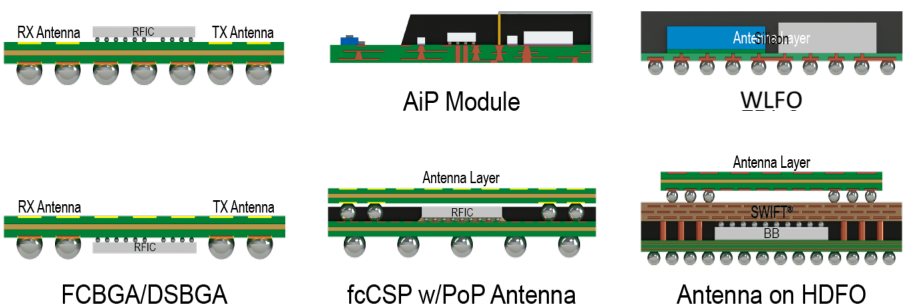


Figure 4: A technology toolbox for integrated antenna includes several different package platforms.

Implementing AiP technology

The type of integrated antenna or specific AiP platform designed into a specific application involves several factors. In addition to the antenna structures, an AiP package may also include a power amplifier (PA), low-noise amplifier (LNA), switch and transceiver integrated circuits (ICs). Depending on the frequency range, different platforms are used for both the antenna and the IC package. The integrated antenna can be mounted on the package, on a substrate, or in a SiP mmWave antenna module. The AiP approach itself can also vary from package to package. **Figure 3** shows an example of an AiP implemented with a SiP approach.

For some cost-sensitive applications, a flip-chip ball grid array (FCBGA) or double-sided ball grid array (DSBGA) are two AiP possibilities. **Figure 4** illustrates the extensive technology toolbox for integrated antennas. For mobile and infrastructure applications, the design options include:

- Antenna in substrate;
- Antenna module;
- Dual-side die mount packages (DSBGA);
- Wafer level fan-out (WLFO) with integrated antenna layer substrate;
- High-density fan-out (HDFO) with antenna on package; and
- Antenna on mold.

For other applications, the antenna could be an SiP module antenna or a flip-chip chip-scale package (fcCSP) with package on package (PoP) antenna. The different design options include: 1) SiP mmWave antenna module; 2) partial molding; 3) passive/filter integration; 4) array antenna design; and 5) small form factor.

Shielding

For higher levels of system integration, advanced SiP and RF shielding technologies are employed. RF SiPs can contain the complete RF to base-band system functionality with an integrated antenna and antenna matching circuitry. The result is a fully-integrated AiP where all the elements of at least one complete RF system is included in the format of a single semiconductor package.

RF shielding techniques include dual-side mold, conformal shield, compartment shield using laser trench and paste filling technology, partial molding, selective conformal shielding, and hybrid SiP designs. These techniques implement a variety of materials including conductive lids, cored, coreless and low coefficient of thermal expansion (CTE) substrates and innovative conformal shielding materials. **Figure 5** shows key technologies to implement different shielding techniques.

The type of shielding in the AiP can have a significant impact on performance. **Figure 6** shows how a SiP with a sputtered conformal shield outperforms an unshielded SiP, thereby substantially improving the electromagnetic compatibility/electromagnetic interference (EMC/EMI) performance.

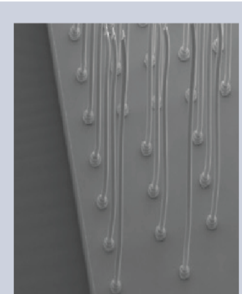
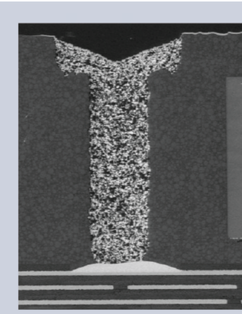
	Wire Fence	Wire Cage	Vertical Wire	Trench and Filling
Fixture				
Key Technology	High loop wire bonding	High loop wire bonding	Vertical wire bonding and wire reveal	Laser trench and paste filling

Figure 5: A variety of SiP RF shielding techniques address different design requirements.

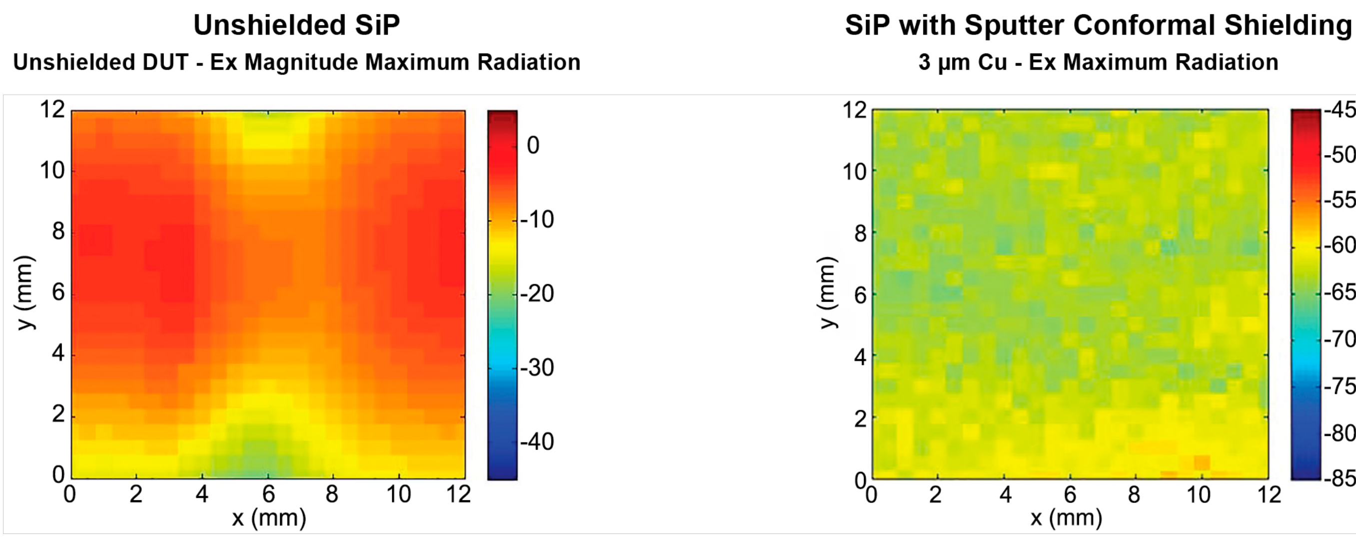


Figure 6: Near-field conformal shielding performance measurements from 100MHz to 6GHz.

Materials

Similar to shielding, material selection also has a significant impact on AiP design and performance—a variety of materials provide design options to meet different performance levels. In addition to materials for mmWave shielding, an antenna substrate can have:

- Asymmetrical stack-up;
- <3.3 dielectric constant (Dk) materials;
- <0.005 dissipation factor (Df) materials;
- Ra >300nm (Cu trace surface roughness); and
- Low Dk/Df solder resist.

Wafer-level processing and WLFO packages include:

- Low Dk/Df passivation and mold/electromagnetic compatibility (EMC);
- Thick passivation development;
- Multi-layer RDL for T-line/waveguide; and
- Wafer-level magnetic shield.

Advanced, high-frequency discrete antenna/transceiver applications employ wafer-level package technologies, where the metal RDLs that form the antennas' elements are high precision, repeatable, and easily tuned for the application. Specific AiP platform implementations include: 1) Top layer assembly; 2) Double-side assembly; 3) Double-side molded assembly; and 4) Double-side molded assembly with exposed die.

Choosing the right package platform for a specific design typically involves discussions between OSAT package designers and original equipment manufacturer (OEM) system designers. Design considerations for 5G substrates must account for different package-level signal losses including: conductor, dielectric loss, leakage and radiation losses. Conductor losses must address plating, skin depth, surface roughness, and via (structure, pitch and placement). Key elements affecting dielectric loss include the substrate materials' dissipation factor and dielectric constant. The substrate materials' thickness stack-up also has a direct effect on signal integrity (e.g., core, prepreg and solder mask thickness). The epoxy mold compound may also come into play for structures where the mold compound is used as a dielectric. Leakage losses can occur within the plane due to under-etched seed layers and between substrate layers because of RDL and via patterning defects. Radiation losses can occur because of:

- Circuit configuration: stripline, complainer and microstrip;
- Via stub (radiation and reflection);
- Impedance transition and discontinuities; and
- Spurious resonance frequency spectra.

Another design factor that can improve antenna performance is to optimize the substrate stack-up (see Figure 7). Direct connection with receive/transmit (RX/TX) signals reduces signal mismatches that can negatively impact the receiver signal sensitivity and increase power consumption at the transmitter.

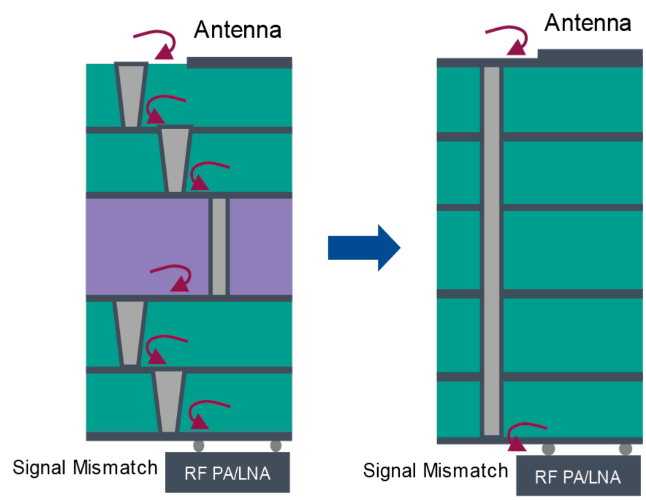


Figure 7: Optimized substrate stack-up and RDL/via routing can improve antenna performance by reducing signal mismatch.

Specific implementations of different design aspects in a variety of packaging technologies for AiP include:

- Body sizes up to 23.0mm with several form factor options;
- Up to 14 substrate layers; and
- Thin-film RDLs and dielectrics for 77GHz and higher applications.

For mmWave applications, the right AiP design provides several essential system advantages. With AiP technologies, system designers get:

- A smaller footprint-phased antenna array design to minimize space;
- Reduced signal attenuation for mmWave products;
- Lower power consumption;
- Improved range for devices; and
- A design proven and qualified by the supplier.

As signal loss to the antenna is reduced, this may help reduce the power requirements compared to the conventional antenna. In addition, AiP reduces the engineering effort and required resources for the OEMs because the design and product are qualified by the supplier. With this qualification, OEMs can feel confident about introducing a robust product in the market much quicker with the integrated antenna. In fact, with proven materials up to 77GHz, Amkor's AiP packaging technologies are shipping products today with over 60GHz operation.

AiP use cases

A variety of AiP use cases exist today, including:

Smartphones. 1) High speed 5G connectivity to mobile phones; 2) Samsung Galaxy S10 contains 3 AiP products; and 3) Several new phones coming to market in 2020 with 5G enabled (sub-6GHz).

Small cells. 1) Antenna arrays for small cells for indoor and outdoor applications; 2) Last-mile connectivity to bring high-speed networks to homes; and 3) High-speed connectivity in office buildings; and 4) Connectivity in public spaces like stadiums, airports, etc.

Security camera. 1) Connecting 5G-enabled security cameras to a network; 2) Reduced form factor benefits because of AiP.

Autonomous vehicle. 1) Cars will require multiple connectivity modes for Infotainment, advanced driver-assistance systems (ADAS) and over-the-air (OTA) updates; 2) High-bandwidth 5G connection for infotainment; and 3) Navigation with 3D images and rich content.

AiP design services/design capabilities

Addressing all AiP technologies calls for an extensive toolset to maximize circuit density and support the sophisticated packaging formats required for high-volume production of 5G and any mmWave design. Based on the appliation requirements, whether 5G or low-power wide-area network (LPWAN) or other connectivity, customers should be able to select low dissipation factor/dielectric constant substrates, thermal interface materials (TIMs) for heat dissipation, and a wide array of different package architectures to provide high levels of system and sub-system integration. These design options require sophisticated models for electrical, thermal and mechanical simulations for customers, as well as services for design, signal integrity simulations, test and characterization.

In addition to an advanced multi-die integration toolbox and RF SiP design and simulation know-how, other capabilities should include:

- Extensive fcCSP, WLCSP, WLFO and HDFO portfolios for multi-die designs;
- An established and reliable supply chain; and
- Global assembly scale and system test investments.

Finally, a complete set of design guidelines for system designers allows them to confidently engage the OSAT that will fully meet their needs.

5G in the palm of your hand

There are many package options to incorporate AiP in next-generation designs. For the quickest and easiest implementation, the OSAT's package or SiP must have high-volume production capacity to support design of next-generation mmWave products.

With many of the discussed packages already in production, we have been supporting 5G mmWave AiP applications in high-volume manufacturing for over five years. This includes both conventional and advanced packaging techniques that integrate a laminate substrate-based antenna element with a transceiver and the associated components and circuitry to address both sub-6Ghz and true mmWave products.

Summary

Amkor has developed an extensive toolset to maximize circuit density and address the sophisticated packaging formats required to enable 5G applications – such as double-sided assembly, embedded die in substrate, thin-film RDL and dielectrics and various types of RF shielding techniques. This toolset, combined with expertise in RF and antenna package design enables partnering with customers who want to outsource the challenges and high investment associated with combining multiple ICs with advanced package assembly and test technologies for 5G networks. As demand for packages that support 5G starts to ramp up, we are already well underway with the successful implementation of AiP technology.

Reference

1. "Millimeter Wave (MMW) Technology Market, Industry Report 2018-2025," Grand View Research; https://www.grandviewresearch.com/industry-analysis/millimeter-wave-mmw-technology-market

Biographies

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