NIST Advanced Manufacturing Technology (MfgTech) Roadmap

5G/6G mmWave Materials and Electrical Test Technology Roadmap (5G/6G MAESTRO)

Market Assessment Report
TechSearch International, Inc.
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Introduction
The iNEMI team was awarded a grant in May of 2022 to develop a comprehensive NIST Advanced Manufacturing Technology (MfgTech) Roadmap on the topic of 5G/6G mmWave Materials and Electrical Test Technology (5G/6G MAESTRO). The goal of this roadmap is to create a foundation of knowledge and expertise in the U.S. to support the development and manufacturing of leading edge 5G and 6G products. Higher levels of performance directly translate into better range, coverage, and penetration for next-generation U.S. wireless networks. The secondary impact will be the generation of high-skill, high-paying jobs with significant employment multiplier effects across regional economies.

Project Goals and Objectives
The goal of this technology roadmap is to create in the U.S. a world-leading knowledge base and technical know-how in mmWave material selection, characterization and test – the first necessary foundation for the development and manufacturing of leading edge 5G and 6G products with the highest radio performance. That performance directly translates, through lower losses and higher linearity, into better range, coverage, and penetration for next-generation U.S. wireless networks, reaching more of the U.S. population and businesses more quickly and economically. The project has four primary objectives:

- Develop a comprehensive 10-year hardware roadmap for mmWave materials characterization and testing, out to 2033
- Develop and detail an implementation strategy for the above roadmap
- Build a national consortium of a technically strong, diverse and resilient supply chain team to execute the vision of the roadmap by creating an appropriate U.S. manufacturing base in RF materials and testing (referenced as an “RF cluster”).
- Promote the growth of a strong and diverse U.S. workforce in RF communication technologies by proposing a post-project plan of university curricula development, as well as other workforce development training, and other dissemination activities.

The above objectives address one key component for a strong national 5G/6G competitive positioning: mmWave materials technology and know-how are a necessary condition for the U.S. to become a 5G/6G leader, both in terms of manufacturing 5G solutions and in terms of unlocking major societal, economic and environmental benefits that arise from a rapid and extensive rollout of 5G/6G infrastructure. Other regions such as the EU, Japan and China have already demonstrated the ability to conduct pre-competitive research with industry through public-private institutes such as IMEC\(^1\) (Belgium), Fraunhofer-Gesellschaft (Germany)\(^2\), ITRI (Taiwan)\(^3\) and others. With the recently funded CHIPS and Science Act, the U.S is in an excellent position to create similar institutes for multiple market sectors, including telecommunications and sensing.

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\(^1\) [https://www.imec-int.com/en](https://www.imec-int.com/en)
\(^3\) [https://www.itri.org.tw/english/](https://www.itri.org.tw/english/)
The plan outlined for the defined objectives were divided into four work packages as shown in Figure 1.

Figure 1. Project work packages

WP1 Technology and Market Updates

The Work Package 1 (WP1) team, consisting of TechSearch International, Florida International University and Georgia Institute of Technology, was formed in early May of 2022. The specific “tasks” identified are:

- Market Survey and Analysis: TechSearch International
- System Design Analysis for mmWave Hardware: Florida International University
- Identification of Next-Generation Materials and Testing Needs – Georgia Institute of Technology

This report delivers the details of the market survey and analysis and serves as a key input to the WP2 roadmap generation workgroup.
Overview of Market Assessment Report

A survey questionnaire was generated and sent to a broad sampling of industry OEMs, foundries, OSATs, and material and equipment suppliers. The survey was divided into the following categories:

- Device materials (ICs)
- Package materials (substrates)
- PCB materials
- Thermal challenges
- Test challenges
- Reliability and operational specs

The recipients were provided a table (Table 1) to fill out.

Table 1. Industry Survey Template

<table>
<thead>
<tr>
<th>Year of Production</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
<th>2026</th>
<th>2028</th>
<th>2030</th>
<th>2032</th>
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<tr>
<td>Mobile RF Front-End Modules</td>
<td></td>
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<tr>
<td>Mobile Power Amplifier</td>
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<tr>
<td>Consumer premises equipment</td>
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<tr>
<td>Small cells</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infrastructure (base stations)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Automotive radar</td>
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<tr>
<td>Defense radar systems</td>
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</tr>
</tbody>
</table>

Unfortunately, the survey return rate was limited. Hence, one-on-one interviews and forums such as workshops were used to gather information. The feedback is summarized below, with overall progress areas (current status and roadmap) and challenges highlighted.

Discussions for standards for 6G will begin in 2023 with anticipated commercialization around 2027. Future speed could be up to 1 TB/s (8,000 times faster than 5G). Download speeds are also expected to be fast. For example, 50 4K-quality movies could be downloaded to a mobile device in a second. The complete roll-out of 6G is projected to occur in 10 to 15 years, based on experience with the 5G roll-out. 5G developments started in 2008 and the roll-out of 5G is just underway. 5G mmWave capable handsets were introduced ahead of the infrastructure roll-out. The U.S. 5G mmWave infrastructure is expected to roll out in 2024 (2X current levels) with the peak in 2027 for U.S., Japan, South Korea, Australia, and Thailand. This is slower than expected because of CAPEX and OPEX spending plans. The introduction of the less expensive C-band delayed 5G mmWave deployment in the U.S.

6G is at the concept phase with a massive technological foundation that is not fully laid out and is a work in progress. More hardware at higher frequencies will be required for 6G. D-band covers a
spectrum at 140 GHz. While 5G has been focused on ~30 GHz for many applications, 6G is projected between 100 to 300 GHz.

For ICs, GaN on silicon is common, but GaN on SiC can handle higher power. Continued use of SiGe is projected. New 3D structures to decrease signal loss have been proposed, including the use of SiC. For dielectric materials, organics have been used up to 66 GHz and higher, pushing the frequency range further than expected. However, new lower loss materials may be needed for new devices. With 5G, the skin effect issue has been a challenge with 77 GHz. Fan-out redistribution layers (FO RDL) may help in improving attenuation. Different solutions may be needed for higher frequency. Antenna-on-board is used for some 5G designs, but with higher frequencies, the antenna needs to be closer to the die. The antenna design needs to be smaller. Higher Dk mold compounds may be needed. LTCC has been mentioned but seems to be seeing limited adoption. LCP has lower conductor loss, but there are concerns that LCP may not be extendable for 6G bands. For package layers, several RDL structures have been proposed, but it may not be possible to stack vias. Dielectric thickness is important and tight lines are desirable. Glass core substrates are seen as a reasonably good homogeneous material for RF signals by some companies. The glass core materials are believed to have stiffness and flatness for fine-line lithography on subsequent build-up layers. The CTE can be tailored to address reliability between die-to-substrate and substrate-to-board interconnects. Glass substrates can also be used to embed die. It is available in large panel sizes. Some see advantages with the use of silicon or glass for higher frequencies, but cost is important. Glass fused silicon offers the potential for lower loss, but it is important to consider cost reduction. At 100 to 300 GHz, new thermal solutions may be needed.

The transmission distance of 6G base stations is expected to be 200 meters or less, requiring 100 million base stations worldwide. Japan has 600,000 base stations today and has projected a need of one billion for 6G. Globally, the investment is under way, despite the fact that frequencies have not been fixed and the spectrum is not set. Frequency selection is a slow process. More timely spectrum auctions will provide greater efficiency in the development of packages, materials and testing. Companies such as Samsung and LG Electronics have established research centers, other companies may follow suit. The South Korean government is considering spending $800 million for 6G developments.
Mobile Phones

RF FEM

Use of CMOS silicon devices is projected though 2032 for the RF front-end module (FEM). Laminate substrates such as embedded trace substrate (ETS), molded interconnect substrate (MIS), and build-up film are all projected to see continued use, with an increased use of wafer level packages (WLP) projected in 2030 to 2032. PCB layer counts are projected to increase from 8-12 layers for 2023-24, 16-20 layers for 2026-28, and >20 layers in 2030-32; however, layer counts add thickness and cost so there is some debate about the higher layer counts.

In the 28/39 GHz range the build-up film material requires a flatter Cu surface (less roughness) to minimize transmission loss. There is a need to balance between low insertion loss (Cu flatness with low Dk/Df substrate) and delamination (minimum Cu roughness).

A Skyworks Sky5™ 3838-17 FEM in the iPhone 13 Pro uses a double-sided FBGA with 13 die, one is flip chip, two are wire bond the remaining die are SAW and FBAR filters. The logic die is stacked on a dual III-V PA chip.

Some consideration is being given to glass substrate with embedded die.

Power Amplifier

Power amplifiers (PAs) are expected to use CMOS and GaAs in 2022-23, plus GaN in 2024-23. Laminate substrates such as ETS, MIS, and build-up film, as well as WLP are all projected to see continued use. PCBs with 4-8 layers are expected to be used from 2022-28, with >8 layers expected from 2030-32.

The Broadcom AFEM-8214 PAM in the iPhone 13 Pro uses a laminate substrate with 9 ICs, and 21 FBAR filter devices.

Smartphone Antennas

The iPhone 13 Pro smartphone uses an antenna-in-package (AiP) for the 5G mmWave transceiver and antenna module. The 3.7 mm x 21.8 mm AiP module contains a transceiver + PMIC + antenna. The transceiver + PMIC module is 7 mm x 9.6 mm. A 6.6 mm x 21.3 mm passive 5G array antenna package is located on the opposite side of the board. The use of AiP modules is expected to be ubiquitous in the future.

Infrastructure

Base stations are expected to use GaAs and GaN through 2032, with the possibility of SiGe for lower power. Laminate substrates are used today, and increased use of system-in-package (SiP) is anticipated. In one example, a 60 mm x 37.5 mm package uses a 400 µm laminate core substrate. There are 23 different part numbers (195 on the top side and 247 on the bottom side). The module features high component density with limited spacing. A special lid covers the center of the package to provide improved thermal dissipation.

In an AiP example for a Gen-1 28/39 GHz range, a 0.910 mm thick laminate substrate is fabricated with 10-layer build-up layers with a 4-2-4 construction. The 200 µm thick core material is copper...
clad laminate (CCL) HL972LF Type LD and the prepreg thickness is 60 µm using GHPL-970LF Type LD. The package has a 23 mm x 23 mm body size.

Low-cost AiP phase array modules have been demonstrated in 47.5 mm x 47.5 mm with two structures, one with a coupled patch antenna in a two-laminate structure, and the other a magneto-electric dipole antenna array with a laminate substrate. The laminate stacks demonstrated unique designs and IC functionality integration without an embedded air cavity. Flip chip interconnection was used for the die.

A Gen-2 28 GHz range module example is in a package-on-package (PoP) structure. The antenna is in the top package. 4.1 mm x 4.6 mm SiGe die with a thickness of 100 µm are mounted in the package using flip chip interconnect. The bump is Cu pillar with a 200 µm bump pitch and each die has 161 bumps. The 65 µm high bump has 40 µm Cu + 25 µm SnAg. A Ni barrier metal is used. The 0.286 mm bottom substrate with four layers with 35 µm L/S traces. It is fabricated with a 60 µm thick core (HL832NX-LC) and 500 µm thick HL0972LF material. The solder resist is a fully open design with 30 µm BOL. The 1.252 mm thick top antenna package substrate has five layers with 100 µm L/S traces. The antenna pad solder resist is 0.4 mm x 1.13 mm.

Researchers at Georgia Institute of Technology have provided data on the properties of glass substrates for high frequency applications (see Antenna, Material, and Test Concerns section of this report). Work at Corning and SCHOTT also discussed the properties of glass substrates for RF applications.

IME A*STAR has developed a FO-WLP AiP for SATCOM On the Move (SOTM) beam steering application.

Research on embedding III-V chips using FO-WLP SiP for RF based 5G transmission stations was published by a group from Grenoble University Alps. A high-power amplifier (GaN on SiC) and a low-noise amplifier/driver (GaAs) were embedded using patterned molding compound in a FOWLP on a 200 mm wafer. This package is to be incorporated into an active antenna array operating at 28 GHz. Thermal dissipation was improved by adding a Cu-liner as a heat spreader directly contacting the high-power amplifier. Signal loss was measured 0.1 dB/mm at 30 GHz. There is still work to be performed to establish electrical and reliability performance. The final product process cross-section images indicate good process control. This technology demonstrates a promising concept for being able to embed different III-V technologies in the same package improving overall packaging and system performance.

Fraunhofer and the University of Berlin published a paper that showed the concept of 6G AiP antenna arrays for MIMO D-band applications that could be developed in a double molded FOWLP. A 1x5 series feed antenna array was made on a 150µm molded substrate to be used at 140GHz. Researchers anticipated high side lobe radiation and incorporated amplitude tapering to reduce this affect from 1 dBi to –1 dBi while maintaining a constant gain of 12.5dB. This was accomplished by adjusting the width between the center and the edge of the array. The bandwidth was measured as

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10.7 GHz at 137 GHz. The researchers showed good agreement between measured values and simulated model values\(^5\).

Development of a molded RDL package structure for a 150 GHz frequency is underway by a company in Asia.

**Consumer Premises Equipment**

Mobile RF FEM, PA, consumer premise equipment, and small cells are roughly based on the same technology, with the exception of more advanced small cells in some specific designs. Both CMOS and GaN will be used through 2032 for consumer premises equipment (CPE). Laminate substrates with ETS, MIS, or buildup material or lead frames are used.

An example of a CPE power amplifier module that supports the lower frequency C-band n78 (3.3 to 3.8 GHz) and n77 (3.3 to 4.2 GHz) has 37 IC packages on the main board including QFN, FBGA, FLGA, WLP, and FO-WLP packages.

AiP for a 16-element, 37-40 GHz scalable to form large arrays has been demonstrated by MixComm and Globalfoundries. It is a 15.2 mm x 15.2 mm PoP with a two-metal layer top package for antenna elements and a 10-metal layer bottom package for SOI RF, digital, and DC signal routing. Solder balls are used to maintain the air gap between the top and bottom package. The air gap mitigates surface waves and increases bandwidth of antenna. The flip chip bump uses 75 µm diameter SnAg solder. A patch antenna is used.

**Small Cells**

In most cases, the same technology as found in mobile RF FEM and PA will be used. Some more advanced small cells are in development with higher power and higher performance requirements. More RF SiPs are anticipated, and increased use of GaAs is projected. There are some expectations of 60-90 GHz or up to THz in 2032.

DuPont has proposed LTCC with Ag paste for <20 GHz RF device packages and 9K7 with Ag for up to 100 GHz with Df <0.0015 for high performance components or highly integrated modules such as PAM, heterogeneous integration, RF FEM, SiP, and AiP. 951 has a Dk of 7.5 and 0.006 @ 3 GHz. 9K7 has a Dk of 7.1 and 0.001@10 GHz and maintains this level up to 100 GHz and possibly beyond. There is active work to develop lower Dk than 9K7 with the same or better loss. LTCC is fully isotropic and has a CTE between 4 to 6 ppm/K. LTCC can be made with an open cavity with a cap manufactured in parallel that may have circuitry or other activities. Each piece is assembled with ICs and then two pieces are combined through solder, braze, or other.

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Automotive Radar

Automotive radar modules are in production with FC-CSP using laminate substrates and FO-WLP for 79-81 GHz mmWave. FO-WLP has been selected for automotive radar modules with both single and multiple die. Advantages for FO-WLP include:

- Improved system performance due to lower electrical parasitics (R, L, and C), attenuation, and insertion losses
- Smooth conductor
- Material set conducive to high speed
- Controlled impedance achievable with embedded ground plane or multilayer RDL
- Excellent RF isolation
- Ability to achieve AEC-Q100 Grade 1 reliability performance (operation from -40°C to 125°C) at moisture sensitivity of MSL 1

The radar modules are mounted on PCBs with 8-10 layers. The antenna is typically on the board. MmWave modules that support 94 to 100 GHz are anticipated in the future.

Defense

Device options include Si, SiGe, GaAs, and GaN. Si CMOS (SOI and bulk Si) is an important choice with the move to 6G. GaN fabricated on Si is a lower cost option, but GaN on SiC is suitable for higher performance. There is also some consideration of InP HBT transferred to AlN. A wafer transfer process increases thermal capability.

There are several concerns for the package material. The challenge is the integration of InP and Si together. Is this best on the wafer, package, or wafer-to-wafer bonding? There is some discussion the SHIP-RF of a rigid core interposer with glass using through glass vias (TGVs).

Design is important in improving thermal management. Advanced thermal interface materials are needed. There is ongoing investigation of diamond substrates. Micro-fluidic channels for cooling are under investigation. DuPont and others have developed sintered silver die attach process. LTCC is reported to provide higher reliability due to CTE matching and higher thermal dissipation of 3-5 W/mK.

Higher frequency materials are needed for PCBs with the move to 6G. Embedded antennas and filters may be required. Improved thermal capability is needed. Tighter widths and spacing will be needed.

Defense final test needs differ from commercial test needs. Commercial requires faster test times (seconds) at low cost. Defense requires extremely low defect rates, so much higher test coverage.

Antenna, Material, and Test Concerns

Most companies have not seen 6G antenna designs. Antennas for 5G are integrated on low loss laminate substrate packages and PCBs (for two-piece antennas). Antenna designs are Si-based. Some companies have LCP-based combinations with filters.

Antenna sizes are typically small. For 30 GHz the antenna element size is 5 mm x 5 mm, for 300 GHz it is expected to be 0.5 mm x 0.5 mm. For 6G antennas most implementations will be larger arrays
of these – perhaps 10’s of array elements, such that the actual antenna array is significantly larger than 0.5mmx0.5mm.

The main issue is material properties at high frequency. There are concerns that laminates may not be able to support frequencies at 90 GHz and higher. Thin materials are hard to characterize and reliability properties at elevated frequencies are required. Material suppliers and users agree that the industry needs standard mmWave test coupons and specified test metrics for package development. The test coupons need to include microstrip lines to get insertion loss, ring resonators for Dk, reference power dividers and antenna arrays to test devices. Operating temperature range varies. The Dk measurements will vary depending on the temperature. Attenuation is another factor in material selection. Low dielectric constant materials are sought and dielectric constants of 3 or 4 may be too high.

Glass has been proposed as a substrate for high frequency applications and is reported to have excellent thermal stability up to 600°C. Some companies indicated the CTE for glass is tailorable from zero to 14 ppm/°C through the use of compositional changes. Dielectric constant ranges from 3.8 to >10. Dielectric loss (10 GHz) as low as 0.00014 for fused silica and 0.006 for a widely used alkali-free Corning glass have been reported. Alumina borosilicate glass (SG3) and high purity fused silica (HPFS) are provided by Mosaic. SG3 is used below 10 GHz, HPFS is used above 30 GHz. Lower Dk and Df properties for substrates are desirable. The Dk depends on the application. SG3 is CTE matched to silicon, has a Df of 0.006 at 30 GHz and increases with frequency. HPFS has a CTE of ~0.5 x 106 ppm/C. HPFS has a Df of <0.002 below 100 GHz. Surface roughness impacts RF performance, especially at higher frequencies. Skin effect of Cu is a concern. Additional improvements are desired in Df for glass, especially with substrates that have higher CTE in the range of 5 to 9 ppm/°C.

Researchers at Georgia Institute of Technology have provided the results of transmission lines on polymer films laminated to glass substrates up to 170 GHz. Low dielectric constant (4.6) and loss tangent (0.004 to 0.008) was reported from 75 GHz to 110 GHz. The average insertion loss for 40 GHz, 110 GHz, and 170 GHz was measured to be 0.085dB/mm, 0.21dB/mm and 0.275dB/mm respectively.⁶

Some companies are focused on the use of a glass core because it provides a reasonably good homogeneous material for RF signals. It is available in large panels and may be a good medium for embedded die. The promise of a tailored CTE is especially attractive and there is a desire to have it tailored to address the reliability between die-to-substrate and substrate-to-board interconnects. The perception is that a glass core has stiffness and flatness needed for fine-line lithography on subsequent build-up layers. Improvement in the Dk to <3 and Df <0.004 is desirable. Processability and mechanical properties at elevated temperatures are increasingly important.

For glass, the surface roughness of the dielectric (glass) is determined by the starting glass roughness, which can be <1 nm. In this respect, glass can be considered superior to laminates. In addition, the smooth surface of glass allows for finer geometries. The L/S for glass is limited by lithography technology, glass and silicon are essentially the same. The minimum via diameter for glass today is about 15 µm, with the minimum via pitch still being determined. Glass interposers are used in production for 300 mm diameter wafers, and work on RDL on glass is underway. The conductors are Cu and Au. Integrated passives are under development. Both spiral and helical

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inductors have been demonstrated. Companies are concentrating on AiP or antenna-in-module or a separate antenna without any active devices. For Ka band at 30 GHz an 8x8 array is ~50 mm x 50 mm. Some 5G infrastructure and satellite communication applications require these 8x8 modules.

For standard PCB technology, surface roughness of the dielectric is determined by surface roughness of the copper foil. For ED copper, roughness is about 1.4 µm and for rolled copper it is ~0.4 µm. This is on the order of the skin depth or greater. There will be excess loss for some transmission line structures.

Filters are a concern with high frequency and bulk acoustic wave (BAW) filters are considered a replacement for surface acoustic wave (SAW) filters. Broadcom film bulk acoustic resonator (FBAR) filters are a form of BAW filter that have superior performance with steeper rejection curves compared to surface acoustic wave (SAW) filters. FBAR filters also feature 0.3 to 0.5 dB less insertion loss, resulting in up to 50mA less current consumption, thereby improving battery life and talk time. Qorvo supplies BAW filters up to 9 GHz. M/A-COM offers BAW filters up to 6 GHz. Resonant, recently acquired by Murata, offers a filter using a piezoelectric monocrystal thin film technology that can handle high frequencies and has high power resistance. It has a reported performance of up to 40 GHz. Resonant developed the proprietary XBAR™ high-frequency filter technology. XBAR stands for “laterally excited bulk acoustic wave resonator.”

Electrical testing is a significant challenge for 5G and 6G frequencies. Small deviations in phased array antennas can cause unacceptable performance issues. Testing may be necessary at multiple levels, including module and complete terminal. For some applications, testing can exceed cost of fabrication.

There are concerns that RF probe data will not be sufficient. The tolerance area is smaller. Progress is being made by several probe and test tool companies. Rohde & Schwarz has provided front-end extensions for signal generation and analysis solutions to allow D band application test. High-end test instruments will be able to cover frequency ranges between 110 GHz and 170 GHz. Test sockets to support 100 GHz testing are available from two or three vendors.

Over the Air (OTA) is technologically viable, but many customers do not want to use OTA for cost reasons. OTA is considered best for development, not high-volume manufacturing. In some cases, OTA will be used alongside typical conductive testing of constituent elements. Increased use of wafer-level test as well as use of self-test is expected (receiver, transceiver). Increased use of AI is anticipated. Traditional probe is possible, but at higher frequencies, some companies plan to test the antenna separately. The AiP antenna is small in size for mobile. For most companies, current designs are centered on 28 GHz. They are tested electrically with BIST features, with some limited OTA. OSATs are typically not geared for OTA, and those that are doing limited OTA are not geared to test above 50 GHz. Typically designs are not hermetic. The mmWave RF modules contain both silicon and directional antennas in a package that fits into a standard IC handler, the remaining question is how common it will be to do OTA testing on ATE instead of doing a separate module test insertion using more focused equipment, as is done for lower frequency devices today.

Non-destructive metrology tools are needed, such as 3D x-ray with the use of AI to analyze data. Small cells are expected to have a 10-year life. Base stations are similar. Mobile devices are expected to have a two-year to 18-month replacement cycle. Operation temperature environments for SiC and GaN are reported to be 160-180°C and are expected to be >200°C in the future.
Operating humidity is reported to be 85 percent or higher. Materials such as LTCC do not have water uptake and are naturally hermetic.

Team Members and Contributors

Contributors

<table>
<thead>
<tr>
<th>Name</th>
<th>Organization</th>
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<tr>
<td>E. Jan Vardaman</td>
<td>TechSearch International</td>
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<td>Susan Bagen</td>
<td>Consultant</td>
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<td>Urmi Ray</td>
<td>iNEMI</td>
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Maestro Team Members

AMD, Applied Materials, Binghamton University, Dell, Dow, Dupont Ectron Corporation, Florida International University, Georgia Tech, IBM, iNEMI, Intel, Keysight, ITRI, liloTree, Mosaic Microsystems, NIST, Nantero, NIST, Nokia, Penn State University, Qorvo, QWED, TechSearch International, 3DGS, 3M and others.

Acronyms/Abbreviations

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<td>BAW</td>
<td>Bulk acoustic wave</td>
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<td>CAPE</td>
<td>Capital expenditure</td>
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<td>CCL</td>
<td>Copper clad laminate</td>
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<td>CPE</td>
<td>Consumer premises equipment</td>
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<td>Coefficient of thermal expansion</td>
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<td>Coplanar waveguide</td>
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<td>Integrated circuit</td>
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<td>IEC</td>
<td>International Electrotechnical Commission</td>
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<tr>
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<td>-------------</td>
</tr>
<tr>
<td>InP</td>
<td>Indium phosphide</td>
</tr>
<tr>
<td>LCP</td>
<td>Liquid crystal polymer</td>
</tr>
<tr>
<td>LTCC</td>
<td>Low temperature cofired ceramic</td>
</tr>
<tr>
<td>MIS</td>
<td>Molded interconnect substrate</td>
</tr>
<tr>
<td>OTA</td>
<td>Over the air</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed circuit board</td>
</tr>
<tr>
<td>PA</td>
<td>Power amplifier</td>
</tr>
<tr>
<td>PMIC</td>
<td>Power management integrated circuit</td>
</tr>
<tr>
<td>PoP</td>
<td>Package on package</td>
</tr>
<tr>
<td>SAW</td>
<td>Surface acoustic wave</td>
</tr>
<tr>
<td>SiC/SiGe</td>
<td>Silicon carbide/germanium</td>
</tr>
<tr>
<td>SnAg</td>
<td>Tin silver</td>
</tr>
<tr>
<td>WLP</td>
<td>Wafer level package</td>
</tr>
</tbody>
</table>

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