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OSAT perspective: automotive semiconductor market & manufacturing challenges

By Asif R. Chowdhury [UTAC Group]

The automotive semiconductor segment has consistently grown during the last ten years showing no sign of slowing down. Primarily driven by adoption of electronics in almost all aspects of vehicle management, the growth has become even more secured by acceleration of safety standards and the growth of semi-to-full autonomous electric vehicles. **Figure 1** shows that the automotive electronic content is forecasted to rise from $199B in 2016 to $289B in 2022 — an increase of 45% — despite a 13% growth in vehicle production during the same period. **Figure 1** also shows that hockey-stick style growth of electronic content dollar per vehicle – from a little over $2,000/vehicle in 2016, to an estimated $2,700/vehicle in 2022.

Figure 2 shows the estimated growth of the number of radars, camera (CMOS image sensor [CIS]) and light detection and ranging (LIDAR) sensor modules per the level of vehicle automation. Most of the high-end vehicles today are at Level 2, whereas Level 5 is a fully autonomous vehicle. As the figure shows, the number of each of these sensor modules is predicted to grow significantly at Levels 4/5 [1].

All the electronic content growths areas noted above are utilizing various kinds of semiconductor products. **Table 1** shows the semiconductor revenue growth by end application from 2013 through 2018, as well as the forecast from 2019 through 2023. In the last five years (2013-2018), the automotive market had grown by 7.3% compound annual growth rate (CAGR) and in the next five years, from 2019 through 2023, it is predicted to grow by another 6.3% CAGR, the highest semiconductor market segment growth.

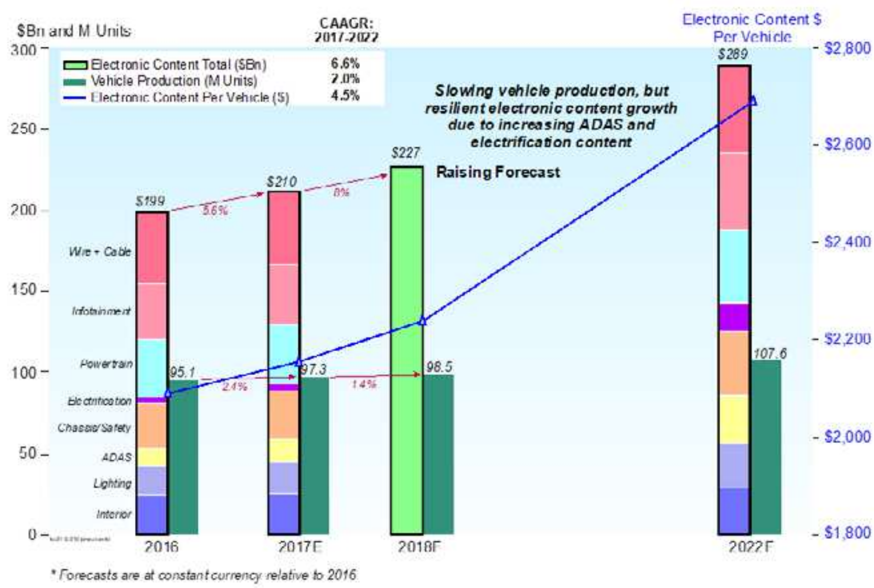


Figure 1: Automotive electronic market 2016-2022. SOURCE: Prismark Oct'18

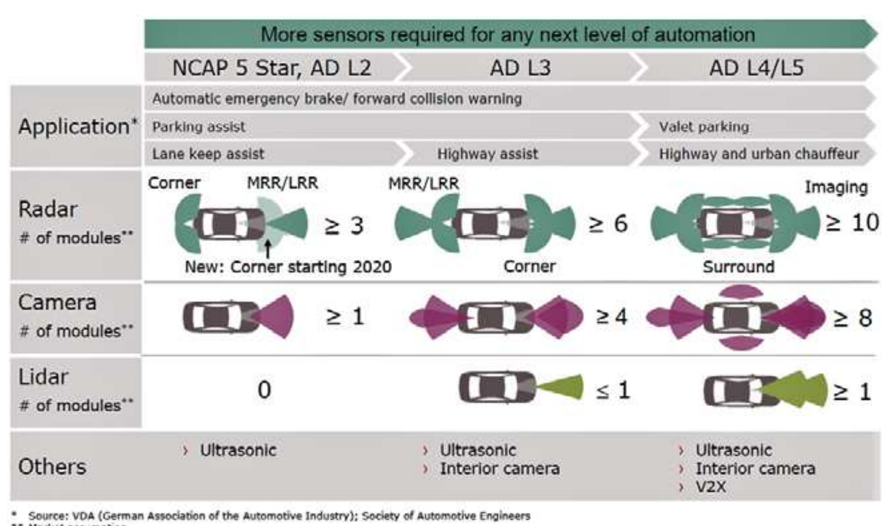
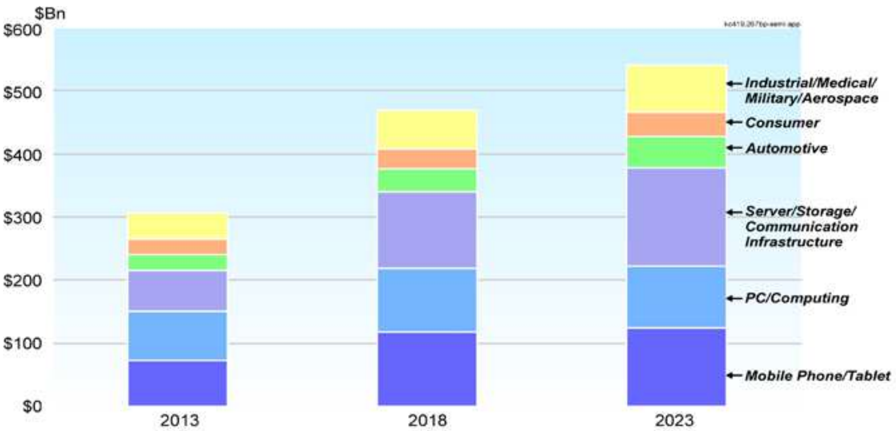


Figure 2: Number of radar, camera and LIDAR modules per vehicle per level of automation. SOURCE: © Infineon Technologies AG.

The automotive supply chain and key players

Table 2 summarizes the automotive semiconductor supply chain and the top players within each of these supply chain industries. Unlike most other markets and industries, the semiconductor integrated device manufacturers (IDMs) typically do not supply their products directly to the automotive original equipment manufacturers (OEMs). Instead, they supply their products to a different group of companies known as "Tier 1" suppliers, such as Bosch and Continental in Europe, Denso and Aisin in Japan, or Mobis in



	CAAGR 2013-2018	CAAGR 2018-2023
Mobile Phone/Tablet	10%	1.0%
PC/Computing	5.6%	-0.6%
Server/Storage/Communication Infrastructure	13%	5.1%
Automotive	7.3%	6.3%
Consumer	5.3%	4.2%
Industrial/Medical/Military/Aerospace	8.3%	4.0%
Total	**8.9%**	**2.9%**

Table 1: Semiconductor revenue by end application 2013-2022F. SOURCE: Prismark

operations in order to have better control over these manufacturing processes. This is primarily because of the stringent quality requirements for automotive applications. Perhaps for the same reason, there are only a handful of outsourced semiconductor and test suppliers (OSATS) participating in the automotive assembly and test market. The top three OSATS providing automotive assembly and test services are Amkor, ASE and UTAC with a combined market share of 95% [2]. The challenges of automotive assembly, as outlined in the later sections, are not trivial and the barrier to entry is relatively high – it requires specially trained manufacturing personnel with a "continuous improvement leading towards a zero defect" type of mindset. Additionally, it may take up to four years to realize any meaningful revenue from a lot of hard work and effort by a lot of valuable resources. It must be mentioned that some fabless design houses (such as Qualcomm)

Korea. These Tier 1 suppliers produce various electronic and sensor modules and components for the automotive OEMs. For example, the Tier 1 suppliers produce brake or transmission modules, oil pressure or level sensor modules, and air bag sensor modules. Semiconductor components are an integral part of these modules manufactured by Tier 1 suppliers. Most of these top semiconductor IDMs such as NXP, Renesas or Analog Devices, have their own internal wafer fabs, assembly and test facilities. However, the outsourcing trend has been on the rise with outsourcing of assembly leading the path. The IDMs typically prefer not to outsource the wafer fabrication, nor the wafer probe and test

OEM ⟷ Tier 1 ⟷ IDMs ⟷ OSATS

Y2017 Rank #	Y2018 Rank #	OEM
1	1	Volkswagen Group
2	2	Toyoto Group
3	3	Renault Nissan Alliance
4	4	General Motors
5	5	Hyundai-Kia
6	6	Ford Group
7	7	Honda Motor
8	8	F.C.A
9	9	P.S.A
10	10	Suzuki

Source: Focus2Move

Y2017 Rank #	Tier 1
1	Robert Bosch
2	Denso
3	Magna International
4	Continental
5	ZF Friedrichshafen
6	Aisin Seiki
7	Hyundai Mobis
8	Lear Corp
9	Valeo
10	Faurecia

Source: Automotive News sponsored by Federal-Mogul Powertrain

Y2017 Rank #	IDMs / Fabless
1	NXP
2	Infineon
3	Renesas
4	TI
5	STM
6	Robert Bosch
7	ON
8	Toshiba
9	Rohm
10	ADI

Source: Statista

Y2017 Rank #	OSATS	Market Share
1	Amkor	56%
2	ASE	25%
3	UTAC	9%
4	STATS ChipPAC	5%

Source: Yole

Table 2: The automotive semiconductor supply chain and the top players.

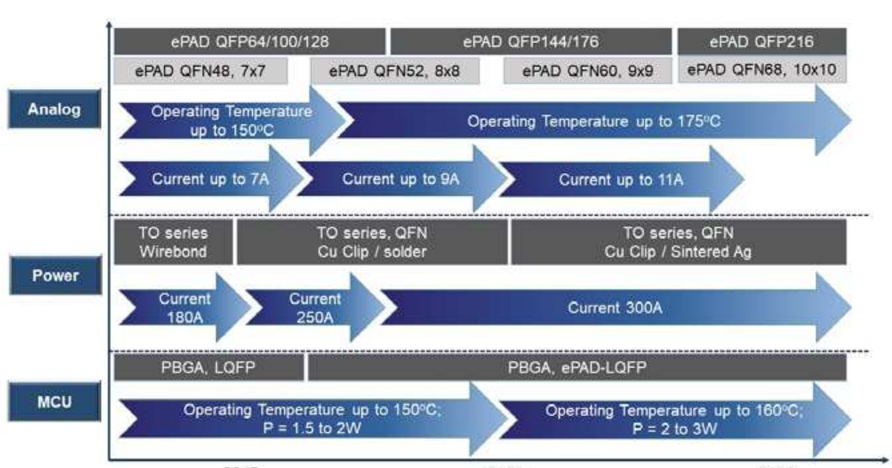


Figure 3: Automotive packaging technology roadmap based on technical requirement for MCU, power and analog products [3].

also provide semiconductor components to the Tier 1 automotive suppliers. Of course, they outsource all their manufacturing to foundries and OSATS.

Package technology in automotive applications

With respect to package types, automotive Tier 1s and OEMs are now using advanced packaging solutions along with the traditional lead frame-based packages. The trend is driven by technology requirements, package size, and cost reduction. For example, 8-bit automotive microcontrollers used to be in thin shrink small outline package (TSSOP) and quad flat package (QFP)-

type packages and have mostly migrated to quad flat package no-leads (QFNs), which have smaller form factor and lower cost. However, going to 16-bit and to 32-bit microcontrollers, flip-chip ball grid array (FCBGA) package solution is utilized due to higher I/O density. **Figure 3** shows a high-level roadmap for automotive microcontroller units (MCUs), analog, and power products based on operating temperature and current/power requirements [3].

The roadmap shows the significant use of lead frame based packages through 2025. However, with high-power and current or high-temperature applications, advanced lead frame packaging solutions such as exposed pad, Cu-clip interconnect technology, and Ag-sintering process are utilized. **Figure 4** shows modules from various Tier 1 suppliers showing the heavy use of lead frame-based packages. Within the lead frame family, driven by the need for size and cost reduction, the use of QFNs in cars has significantly increased. The automotive industry, however, requires a special version of the QFN, which has side-solderable flanks. Automotive component manufacturers require inspectable solder joints that can't be done with standard QFNs. **Figure 5** shows details of side-solderable QFNs. Both UTAC and Amkor Technology have patents for side-solderable QFN solutions.

Traditionally, automotive players used to stick to standard lead frame packages with proven reliability. Due to the proliferation of semiconductor applications in vehicles, there has been an increase in the use of advanced packaging solutions. **Figure 6** shows a general automotive package roadmap. While standard packages will continue to be used for years to come, advanced packages are now being used and are increasingly showing up in the automotive package roadmap. The advanced packaging solutions are being used in products such as radars (wafer-level chip-scale packages [WLCSPs] and system-in-package [SiP]), high-performance CPUs (high-pin count FCBGA and SiP), and multi-function modules (SIP and embedded solutions).

The use of sensors in cars has proliferated significantly—it is estimated that there are more than fifty sensors in a standard automobile today. Whereas microelectromechanical systems (MEMS) sensors, such as accelerometers and gyros, are using more standard laminate- or ceramic-based packages, many of the other sensors, such as oil pressure or oil level sensors, require unique packaging solutions. The increased use of cameras in automotive applications is driving ceramic or unique laminate-based CIS solutions, as well as wafer-level packaging (for infotainment). LIDARs are deemed essential for full autonomous vehicles. Many IDMs, as well as design houses, are working on solid-

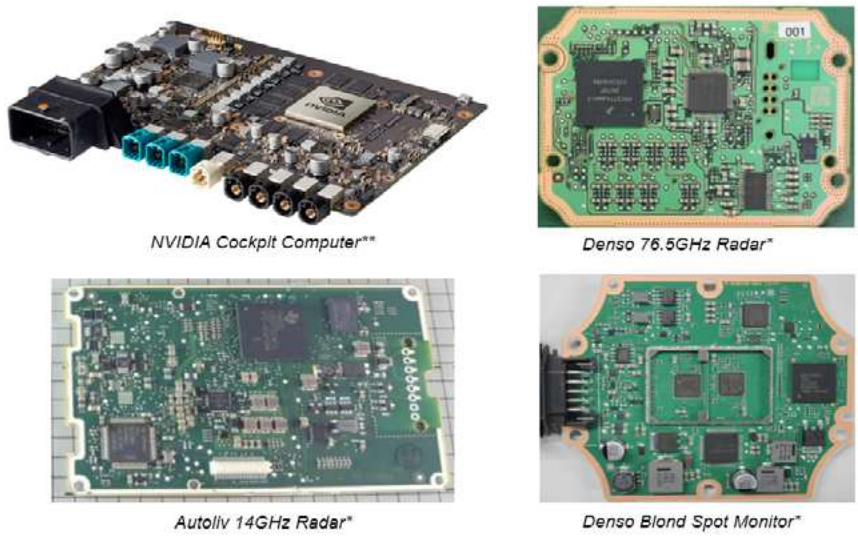


Figure 4: Examples of various automotive application modules showing high usage of lead frame packages. SOURCE: *TechSearch International; **NVIDIA

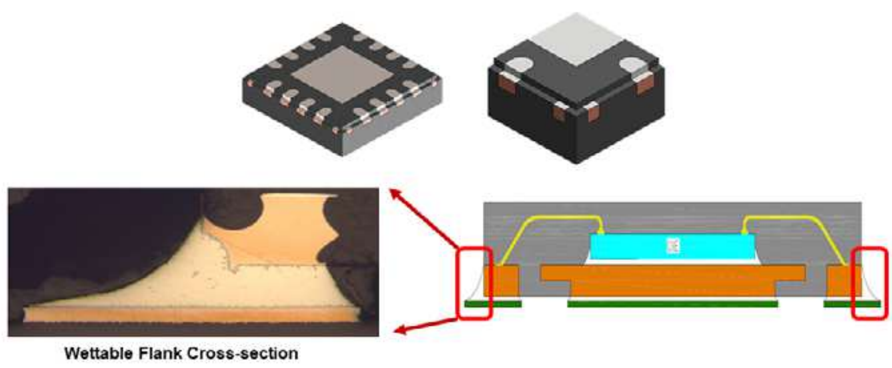


Figure 5: The automotive industry requires side-solderable QFNs allowing inspection of the board-level solder joint.

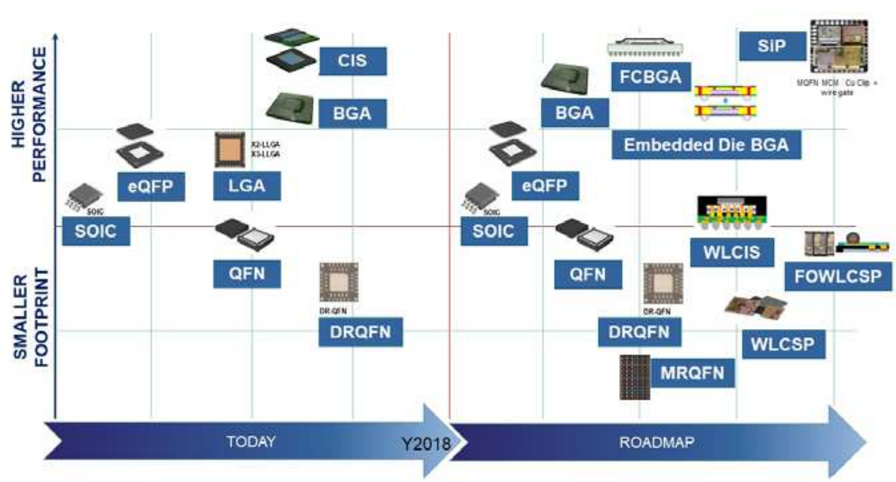


Figure 6: High-level automotive packaging roadmap showing increasing usage of advanced packaging technology.

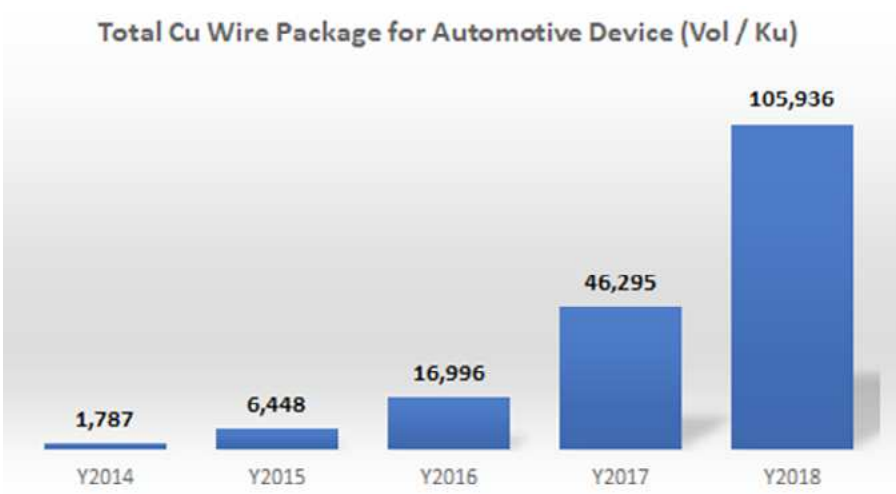


Figure 7: UTAC's historical shipment of package types with Cu wire interconnect technology for automotive application.

state LIDAR technology that requires a full-custom packaging solution utilizing advanced technology and materials.

Automotive packaging requirements also drive the development of higher performance materials, such as mold compound and die attach material for higher operating temperature under-the-hood and high-power applications. Cu-Clip is increasingly used as an interconnect technology for high-power and high-current applications as shown in **Figure 3** for power products. Cu wires have been widely adopted in standard automotive packages to reduce cost. **Figure 7** shows the growth of Cu wire in automotive applications for UTAC. The Cu wire shipment started in 2015 and since then, we have shipped over 163 billion units of QFN with Cu wire with no quality issues.

Semiconductors in automotive warranty claims

According to a TechSearch International report on automotive semiconductor packaging, about 4% of annual warranty cost for a car today is related to semiconductor products [3]. This is not surprising with the proliferation of semiconductor products in today's automobiles. Of that 4% of semiconductor-related failures, over 50% of the failures are related to assembly and final test. **Figure 8** shows the breakdown of the semiconductor failures. So, the pressure to continuously improve quality towards "zero defects" is acute everywhere in the automotive supply chain including OSATS.

OSAT assembly and test challenges

Table 3 compares the differences between some of the key high-level requirements between automotive and consumer products. Some of the key differences that can have significant impact on business are long qualification times resulting in ~24-48 months to start production. Automotive companies may require 15~20 years of supply guarantee with a similar time frame for all production-related data retention. Changes are typically not allowed with a long drawn out product change notification (PCN) approval process that can take up to 30 months. Then there is the drive towards "zero defects," which requires a certain higher quality standard and continuous improvement mindset by all levels within the OSAT organization.

The OSAT challenges for automotive assembly and test can perhaps be bucketed in five separate areas: a) Qualification and reliability, b) Release to manufacturing, c) High-volume manufacturing/operations, d) Logistics & resources, and e) Cost management.

Qualification and reliability. Packaging is an integral part of the quality of automotive semiconductor products. The best product development process requires IDMs to engage with OSATS early in the development phase to ensure the correct device-package interaction. This will require OSATS to run several sets of reliability tests as the IDMs tweak their device design or fab process. Additionally, and especially for sensor devices, OSATS may have to run several sets of package design and material design of experiments (DOE) trials to fine-tune package-device interactions. This is especially true for MEMS sensors, for example. For new package and process development, advanced product quality planning (APQP) will need to be followed, which is essentially a phase-gate development methodology designed to adequately catch and address any issues as (or if)

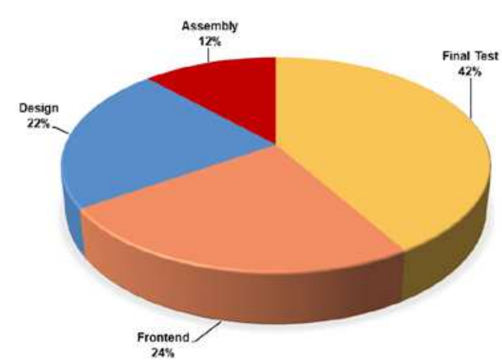


Figure 8: Breakdown of warranty defects for semiconductor devices by manufacturing process [3].

Topic	Automotive	Consumer
Qualification Cycle	18 to 24 months	3 to 6 months
Time to HVM / Revenue	24 to 48 months	6 months
Supply Lifetime	15 to 20 years	2-5 years
Acceptable Failure Rates	Target Zero Defect	~300 parts per million
Production Data Retention	15 to 20 years	2 to 3 years
PCN Cycle Time	18 to 30 months	6 to 12 months

Table 3: Key high-level differences between automotive and consumer semiconductor assembly and test businesses.

they develop during the development cycle. Additionally, design and process failure modes and effects analyses (FMEAs) are required to be established, addressed and updated throughout the development process.

AEC-Q100 specifications are used for automotive package qualification, which are more stringent than the standard qualification process for consumer products. **Table 4** summarizes some of the fundamental differences between typical consumer and automotive product qualification requirements. AEC-Q100 classifies automotive grade classification from zero to four in line with exposure to the operating temperature range. Grade Zero is considered the highest grade and requires the most stringent reliability testing. Every reliability test, as well as sample size and CpK for automotive products, requires higher standards. Two key reliability tests, temperature cycling (TC) and high-temperature storage (HTS) conditions for various automotive grade reliability testing are summarized in **Table 5**. Again, note that these tests show stringent automotive requirements. **Figure 9** shows examples of automotive grade product requirements depending on application and usage of the product. For example, powertrain modules operating under harsher conditions require either Grade 1 or 0, whereas components going into the dashboard inside the car require Grade 3.

Topic	Automotive	Consumer
Stress Condition / Operating Temperature Range	Grade 0: -40°C to 150°C Grade 1: -40°C to 125°C Grade 2: -40°C to 105°C Grade 3: -40°C to 845°C Grade 4: 0°C to 70°C	-40°C to 85°C
Test Hours / Cycle Time	>1000 hours/cycle → Test to failure	500 ~ 1000 hours/cycle
Electrical Test	Room, hot and cold temperature	Room temperature
CPK	≥1.67	Meet datasheet spec
Unique Stress Tests to Automotive Qualification	1. Power Temperature Cycle 2. Bond Pull after Temperature Cycle 3. Early Life Failure Rate	None
Composition of Qualification Lots	3 non-consecutive wafer lots and 3 non-consecutive assembly lots for all qualification lots; 77 units / lot	Wafer fab technology qualification = 3 wafer lots and package qualification = 3 assembly lots; 30 units / lot

Table 4: Difference between automotive and consumer product qualification methods. SOURCE: TechSearch International

Figure 9: Examples of different grades of automotive semiconductor products based on application. SOURCE: TechSearch International

Package STRESS	ABV	TEST METHOD			Duration			
		Standard	Condition	Unit	Grade 3	Grade 2	Grade 1	Grade 0
Temperature Cycling	TC	AEC-Q100, JESD22-A104	-50 ~ +175C	cycles				1000
			-50 ~ +150C		500	500	1000	2000
High Temperature Storage Life	HTSL	AEC-Q100, JESD22-A103	+175C	hours			500	1000
			+150C		500	500	1000	2000

Table 5: Temperature cycle and high-temperature storage life reliability test conditions for automotive qualification. SOURCE: TechSearch International

Release to production. Once the automotive product is fully qualified, extensive documentation related to all aspects of the design and qualification of the product is required before starting mass production. The Automotive Industry Action Group (AIAG) has created this documentation process called production part approval process, or PPAP. PPAP is used to ensure that manufacturers and suppliers communicate and approve production designs and processes before and during volume manufacturing. The PPAP documentation is typically not required to be submitted by the OSATS, but is required by the IDMs to provide to the Tier 1 suppliers. Increasingly, however, the automotive players are requiring assembly and test data from OSATS. The data set can be extensive, so it is good to have a brief fundamental understanding of the PPAP process. The documentation requires the following and recording of certain data throughout the package development and qualification process.

- Design records
- Engineering change document
- Design FMEA
- Process flow diagrams
- Process FMEA
- Control plan
- MSA
- Dimensional analysis
- Material performance reviews
- Initial process studies
- Qualified laboratory documentation
- ARR Master sample
- Checking aids
- Records of compliance
- PSW
- Sample product

Table 6: AIAG check-list for automotive PPAP process [4].

The complete automotive PPAP checklist is summarized in **Table 6** [4]. There are five different levels of PPAP documentation and data that need to be submitted during the various stages of the qualification and release processes. The key is to ensure that all items are documented, especially any changes in design or process. As mentioned in an earlier section, design and process FMEAs are required, which is not necessarily standard practice for OSATS

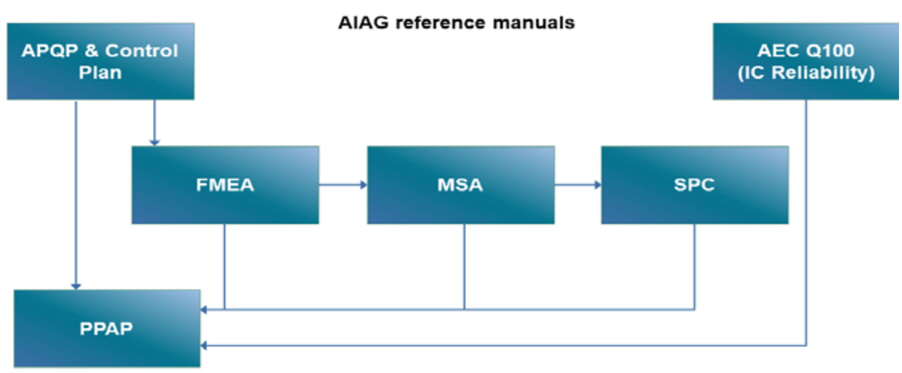


Figure 10: The link of all key aspects of automotive product development required by the PPAP process [4].

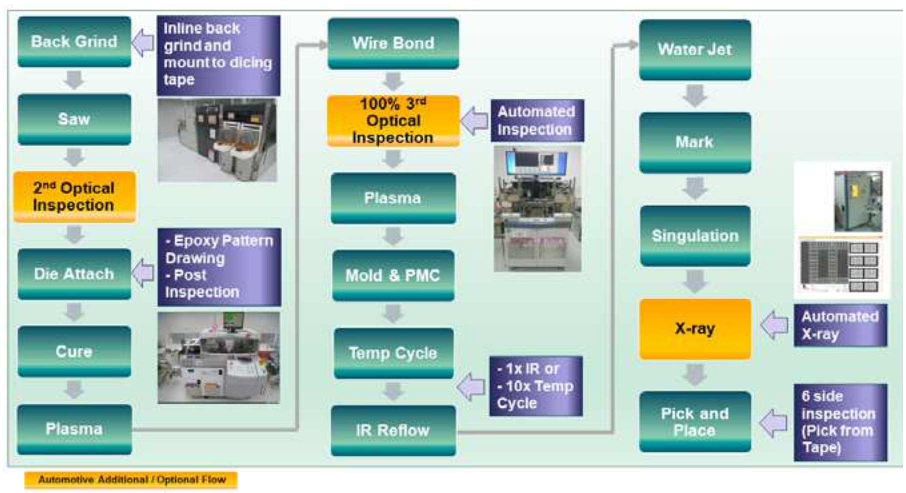


Figure 11: Comparison of automotive and standard (non-automotive) assembly process flows.

running non-automotive products. All these practices are geared towards developing a six-sigma process that targets higher quality products. The relevant documentation from these development processes becomes part of the PPAP documentation. **Figure 10** demonstrates the link among all the key aspects of automotive product development that is required for PPAP. Most OSATS today are not very familiar with the PPAP process as it relates to automotive assembly and test development. The key for OSATS is to work closely with the IDM to ensure a clear understanding of what is required from them for PPAP from the project get-go. Otherwise, OSATS can find themselves in a PPAP "nightmare" if the required documentation has not been prepared before going into mass production.

High-volume manufacturing. The assembly and test manufacturing flow is quite different between automotive and standard products as shown in **Figure 11**. Automotive flow requires additional process steps such as plasma cleaning, additional inspection steps, as well as tri-temperature testing. Once in production, the operations team needs to stay vigilant to ensure quality throughout the lifetime of the assembly process. Operations will need to ensure that ALL process parameters finalized during the assembly and test qualification are locked and cannot be changed without permission. This will mean digitally locking out the possibility of accidentally changing any process parameters in each piece of manufacturing equipment. Beyond that, automotive customers ask for continuous improvement to drive the defect level down to zero. This typically requires a higher level of skill sets by the operators who run the automotive products. For example, we use specially certified operators to handle the automotive assembly and test process. Many automotive products also require going through a reliability monitoring program (RMP) to ensure that quality targets are met on a continuing basis. **Figure 12** shows a typical RMP flow. The RMP allows monitoring of the reliability of key wafer fab and assembly processes under accelerated conditions. Any failures are verified and analyzed, and failure analysis results are used to establish corrective actions to eliminate the failure mechanism of future production lots.

Wafer sort and final test for most automotive products require testing in three temperature conditions, room, cold (typically -40ºC) and hot (typically 150ºC). This requires special handlers that can drive capital expenditure. Additionally, many IDMs require part average testing (PAT) for wafer sort test to drive towards zero defects. The objective of PAT is to detect outliers within a wafer. PAT can capture every die in the wafer that falls outside the tighter sigma limit. **Figure 13** shows an example of the statistical bin limits of PAT testing for a wafer. Additionally, some automotive customers require burn-in testing (to eliminate early failures) service as well. The challenge here is incurring capital expenditures for burn-in infrastructure (ovens and boards). However, with the typical long-life span of automotive products, return on investment is typically a non-issue.

Logistics and resources. As already discussed and outlined in **Table 4**, automotive customers' requirements are very different from traditional applications with which most OSATS are familiar. Because automotive lines require each equipment set to be qualified, it makes the planning process less flexible. OSATS are increasingly using a "designated" line approach as opposed to "dedicated" lines for running automotive products. The "designated" line approach qualifies multiple equipment sets for each process step to ensure loading flexibility for automotive products. OSATS need to ensure continuous quality vigilance through the "sort, set, shine, standardize, sustain (5S)" approach, agree to a long PCN approval

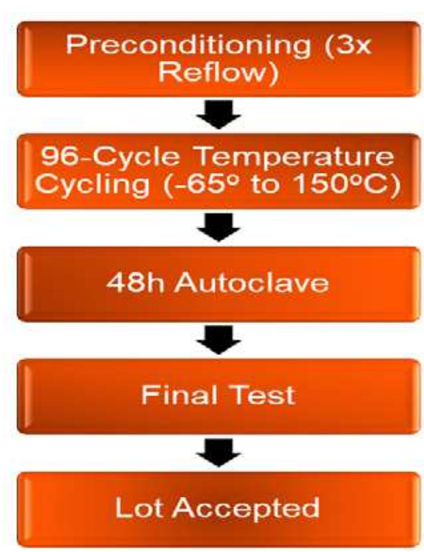


Figure 12: Lot acceptance reliability test for automotive products during high-volume manufacturing.

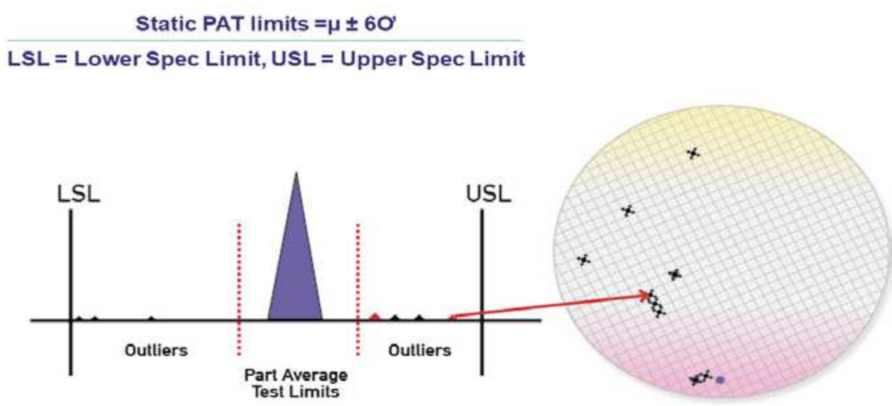


Figure 13: The diagram shows how part average testing (PAT) detects outliers within a wafer.

process, and guarantee over ten years of continuous service and data retention. Additionally, any quality excursions require a diligent problem-solving approach such as the "8 disciplines" (8D), as well as disciplined failure-analysis methods such as fault tree analysis (FTA). Automotive customers require fast response times to any quality excursions. To ensure the level of support required for automotive product development and manufacturing, OSATS will need automotive trained resources in all key functions such as R&D, operations, supply chain, and of course, the quality group.

Finally, top automotive customers frequently demand more stringent warranty clauses in their service agreements. OSATS will need to carefully weigh the potential impact of such warranty claims if such situations arise.

Cost management. Finally, managing cost reduction in line with IDM and Tier 1 expectations poses a serious challenge. Some Tier 1s are expecting a 5% price reduction quarter-over-quarter, while a 5% year-over-year reduction is becoming quite common. The biggest challenge in cost reducing automotive products is that the customer does not allow any changes without a PCN, which can take anywhere between 18 to 30 months after qualifying the change (process or bill of materials [BOM]). For consumer and even industrial assembly and test applications, major cost reduction is achieved through process simplification or consolidation, and/or using lower cost BOM while keeping the same quality. However, this is not possible for automotive products without the long qualification and PCN cycle. On the flip side, there are many instances where automotive customers want OSATS to introduce new process control steps (other than those originally agreed upon), which introduces additional costs. Yet, most of the IDMs and Tier 1s are unwilling to adjust the pricing accordingly. This makes the annual cost reduction even more difficult. Automation of some of the key process steps, such as visual inspections and x-ray, not only reduces cost, but also improves quality through the reduction of manual handling.

While it may sound like a cliché, the successful OSAT will need to ensure upfront due diligence on selection of the final process flow, BOM and detailed analysis of the financial models of each individual automotive request for quotations (RFQs). It can work to both parties' advantage to agree on price reduction roadmaps and paths to achieve such cost reductions from the beginning of the RFQ process. Reviewing various "what if" scenarios for potential process flow and BOM changes during the qualification process, while understanding the price reduction roadmap and running the cost models accordingly, will provide insight and intelligence into the possible business outcome.

Summary

Getting a slice of the automotive assembly and test business is not easy and comes with its share of challenges. It's certainly challenging for OSATS with a different set of stringent requirements than standard assembly and test services they typically provide, which generates most of their revenue. The long qualification cycle and significantly longer time-to-revenue of automotive semiconductor products sometimes works as a deterrent for many OSATS to get into this market. The ones that are trying to penetrate today may find themselves years behind the competitors who have established themselves as an automotive grade supplier over many years. A lot of valuable engineering time and resources go into designing, qualifying and launching an automotive package. It may take up to four years to realize any material revenue from years of such hard work and effort. However, once qualified and designed into an automotive socket, the reward is a continuous steady stream of revenue that can last well over ten years. It certainly provides a nice cushion in an otherwise volatile industry.

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Biography

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