CMOS IMAGE SENSOR PACKAGING TECHNOLOGY FOR AUTOMOTIVE APPLICATIONS

Teoh Eng Kang[1], Alastair Attard[2], Jonathan Abela[2]

[1]*UTAC Group, Corporate Advanced Packaging R&D*
22 Ang Mo Kio Industrial Park 2, Singapore 569506
engkang_teoh@utacgroup.com

[2]*UTAC Group, Global Sales Europe*
Chemin du Bre 15, 1023 Crissier, Switzerland
alastair_attard@utacgroup.com / jon_abela@utacgroup.com

Abstract

As the automotive industry makes further progress in the areas of advanced driver assistance systems (ADAS) and autonomous driving (AD) technologies, the demand for imaging cameras is steadily increasing to support applications such as lane detection, traffic sign detection, pedestrian/vehicle recognition and driver monitoring, to name a few. This is, in turn, driving higher demand for image sensor packages that can meet stringent automotive reliability requirements. Whereas high reliability image sensor packages are typically based on ceramic packages, these tend to have considerably higher costs and longer development cycles than laminate-based packages which are normally used in other market segments. In this paper, we present novel methods for packaging image sensors on laminate substrates, enabling a reduction in cost, form factor and time-to-market whilst simultaneously meeting automotive reliability grades typically required for such devices. Examples of package constructions and fundamental assembly requirements to achieve high assembly yield and increased package reliability will be presented. The key challenges to qualify automotive image sensor packages and methods to mitigate risk will also be discussed.

Keywords: Imaging, Image Sensor, Packaging, BGA, Automotive, ADAS

Introduction

CMOS Image Sensors (CIS) have been constantly evolving from having increased miniaturization and higher pixel counts towards technologies that enable better image quality and functionality. As with smartphones, manufacturers no longer use pixel count as a key differentiator for the imaging cameras of their end products. Instead, the market trend has moved towards having cameras with more innovative features, such as 3D sensing, LED flicker mitigation, larger viewing angles, high dynamic range (HDR), and faster frame rates, whilst at the same time having better reliability and a longer product lifetime, especially in harsh working conditions. Two key markets developing similar requirements are the automotive camera market, to address the evolving advanced driver assistance systems (ADAS) and autonomous driving (AD) technologies, along with the industrial camera market, targeting advanced machine vision, factory automation, and surveillance cameras.

In the automotive market, digital cameras with image sensors were first adopted to cover blind spots at the front and rear of the vehicle as parking aids. Recently, the focus of automotive imaging has shifted, and auto makers are now equipping their vehicles with several imaging cameras per vehicle, with the key targets in this case being to increase vehicle safety and enhance driving comfort. Several advanced safety features, typically grouped under the term ADAS, rely on imaging cameras for their operation, normally in conjunction with other sensor types using sensor fusion solutions [1]. Examples of ADAS using image sensors include: lane detection for active lane keeping; traffic sign detection to inform the driver of speed limits and road situations; pedestrian & vehicle detection to automatically stop the car to avoid an accident; driver monitoring which can detect drowsiness/health status and automatically bring the car to a stop in an emergency situation; and enhanced visibility at night time or in bad weather conditions using IR imaging cameras [2] [3] [4]. For increased driving comfort, cameras allow for easier parking by providing up to a full 360° view around the car, to assist the driver in observing the vehicle surroundings. On some car models, the input from the cameras, as well as other sensors such as radars, allow the car to park automatically in a space sufficiently big for the car to fit in. Furthermore, other novel applications such as e-mirrors are also gaining traction, with the aim to replace physical side mirrors with cameras whose images are then displayed on a monitor inside the vehicle cabin, to improve car design and aerodynamics.

This increase in automotive safety and comfort features will require even more image sensors to be integrated in the future car as the level of automation increases [5] [6]. Studies made by IHS Markit [7] predict around 6 cameras per vehicle for Level 3 AD ("Hands-off") and 9 cameras per vehicle for Level 5 ("Full Automation"), as outlined in Table 1. In total, the automotive camera market size is expected to grow at a CAGR of around 19% for the period 2017-2023, reaching an estimated total value of USD 19 billion in 2023 [8].

	L3	L4	L5
Exterior Camera	5	8	8
Interior Camera	1	1	1
Total Camera Content	**6**	**9**	**9**

Table 1 – Typical camera module content by autonomous driving level

The desired levels of reliability of automotive imaging cameras are considerably higher than what is demanded for consumer applications, since the lifetime of a car is expected to be more than ten years, and the cost of recalls or repairs due to component failures can grow exponentially having significant negative effects on an automaker's bottom line (as well as impacts to the Tier 1 and Tier 2 suppliers). Typically, the AEC-Q100 specification [9] is referred to when qualifying new automotive CIS packages, with this document defining the stress conditions the package must endure to be qualified for automotive use. The reliability requirements of such automotive camera packages are very much dictated by their positioning within the car, the type of environmental conditions they are exposed to, as well as the criticality of their function, and this will greatly influence the package structure, material selection, and assembly process of such image sensor packages. These considerations will be discussed in the next section, explaining how the right selections are made to achieve an automotive grade reliable package.

CIS Package Assembly Requirements

The assembly of CIS packages is a demanding task since this needs to fulfil various design- and application-related expectations linked to optical, electrical, thermal and package reliability considerations. Listed below are some of the key challenges that need to be addressed to have an adequate CIS package assembly process.

Cleanliness

An ultraclean manufacturing environment is compulsory for image sensor package assembly, especially for assembly processes where the CIS die is still exposed to the external environment. A cleanroom class of 100 or below (according to FED STD 209E standards) will be required at these processes to ensure that defects attributable to removable or non-removable dust particles are minimized, thereby achieving a good device yield at functional test after assembly. Figure 1 shows a typical Class 10 cleanroom booth used to house image sensor package assembly equipment at UTAC Singapore to guarantee a clean and high-yielding assembly environment. Unique cleanroom setup and maintenance procedures, dedicated machines designed specifically for image sensor assembly, coupled with good practices by the operation personnel within the assembly line, are additional factors needed to achieve good assembly yield. UTAC Singapore has over 16 years of image sensor assembly experience and this has become one of the core competencies of this assembly site, with very low yield defects related to dust particles.

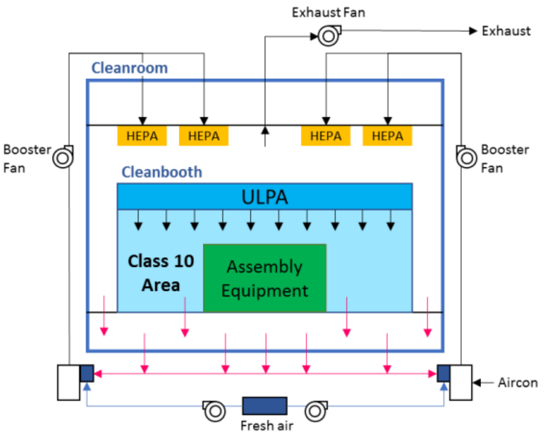

Figure 1 – Schematic of Class 10 cleanroom booth setup used for CIS package assembly

Assembly Accuracy & Process Capability

Most image sensor packages require very precise assembly processes, mainly to achieve the desired optical and dimensional characteristics of the package. This is particularly true during die attach (bond line thickness, XY placement, rotational orientation, die tilt, and epoxy bleeding clearance), wire bonding (ball and stitch bond location, and loop profile consistency), and glass attach (bond line thickness, XY placement, rotational orientation, and glass tilt). State of the art equipment, together with design and process development considerations, enable UTAC to develop and assemble CIS packages to the required specifications.

Apart from requiring highly accurate processes, good process capability is also mandatory to maintain stable processes which can deal with the expected variations of high-volume production. Based on the AEC-Q100 standard, process capabilities of at least 5 sigma (Cpk $\geq$ 1.67) are required to have sufficiently robust processes. To reach this level of consistency, careful and thorough process characterization and a deep understanding of machine consistency with good pro-active and preventive maintenance procedures are required.

Device Traceability

CIS packages are complex assemblies consisting of the image sensor die itself as well as the materials used to package the die. As with any manufacturing process, it is challenging to maintain uniformity, especially during the development stage of a product. The CIS assembly process at UTAC makes use of device traceability to be able to uniquely identify packages: from the identification code and supporting logging database, it is possible to determine the assembly lot number, image sensor wafer lot ID and die location on the wafer, substrate ID and module location on the strip, materials, and equipment used to assemble the package. This assembly data is particularly useful when correlated to the package optical test data, to be able to identify possible improvements in the assembly process and implement them through further engineering activities.

Quality & Reliability

All automotive grade image sensor packages are subjected to package level qualification based on AEC-Q100 standard. However, apart from the package level qualification standards that need to be met, the assembly site also needs to have been certified for the production of automotive parts, to ensure that the appropriate automotive quality is maintained during manufacturing. The main certifications which are typically required are the ISO/TS 16949 (Quality Management System for Automotive-related Products), and more recently the IATF 16949 (Quality Management System for Automotive Industry), which has now superseded the ISO/TS 16949. All UTAC sites are IATF 16949 certified, thus allowing them to manufacture packages for the automotive industry. Moreover, UTAC is also certifying its key automotive sites to ISO 26262 standard, which is aimed at ensuring the functional safety of electronic systems in vehicles and is particularly relevant for electronics used for ADAS and AD.

Comparison of Different CIS Packaging Solutions

Image sensor packages are typically comprised of a substrate (ceramic, lead frame or laminate), sensor die, wire bonds to electrically connect the die to the package, and a cover glass to provide optical access to the environment. Adhesives are used to bond the various components together, and some form of encapsulant is used to protect the device from the external environment. Different termination types (lands, bumps, balls or pins) provide the package with interconnects used to connect it to the final product printed circuit board. The choice of substrate used for the sensor package has a significant influence on the package form factor, performance, reliability, and cost, as is explained in the following sections and outlined in Table 2.

	Ceramic	Lead frame	Laminate
Moisture resistance	High	High / Moderate	Moderate
Unit cost	High	Low	Low
NRE cost	High	Low	Low
Substrate lead time	Long (12-24wks)	Short (8-12wks)	Short (8-12wks)
Design flexibility	Moderate	Low	High
Reliability	High	Moderate	Moderate
Performance	High	Moderate	Moderate

Table 2 – Comparison of key CIS package attributes by substrate type

Ceramic-based CIS Packages

Earlier generations of CIS packages mostly used ceramic substrates due to the advantageous ceramic material properties. Figure 2 shows the structure of a commonly used Ceramic Leadless Chip Carrier (CLCC) package for image sensors, which is using a ceramic substrate.

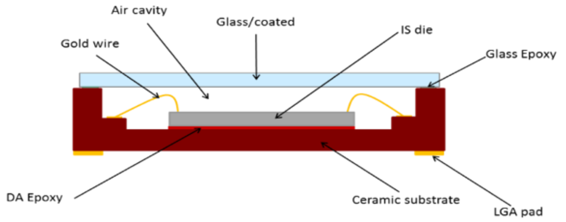

Figure 2 – Schematic of a CLCC ceramic image sensor package structure

Ceramic substrates allow the CTE (coefficient of thermal expansion) mismatch to be minimized, thus reducing package warpage during thermal excursions. This reduced warpage helps improve both the reliability of the package as well as the optical performance. The good coplanarity to the CIS die offered by the ceramic substrate is another factor which helps to provide better optical performance. Ceramic packages also exhibit better moisture protection and thermal performance due to low moisture absorption and higher thermal conductivities, which are also desired features for a CIS device. The multiple metal layer construction possible with ceramic substrates allows for rather complex and numerous interconnects to be handled whilst remaining within a small package footprint, albeit this is typically sacrificed for a large package height. Nevertheless, the enhanced performance of a ceramic package does come at a price: ceramic substrate suppliers are rather limited, ceramic substrates tend to be quite expensive, and incur long lead times and high NRE costs due to their complex manufacturing process, thereby impacting development cycles and time-to-market of new CIS devices. Notwithstanding these limitations, ceramic CIS packages are still a key package solution today, especially where very high performance and harsh environmental resistance are required.

Lead frame-based CIS Packages

In some cases, metal lead frames are selected due to their lower cost and good moisture protection (capable of achieving MSL1). However, lead frames offer limited capability in terms of design flexibility and interconnect density, especially when complex interconnects or high pin counts are required. This stems mainly from the fact that lead frames offer only single layer routing which is also limited in terms of trace width and spacing due to the stamping or etching processes used to manufacture the lead frames. Furthermore, since lead frames are normally made of copper, there is a very large CTE mismatch which can result in high package warpage, especially on larger devices, which can detrimentally affect package reliability and optical performance. Molded interconnect substrates (MIS) represent the next evolution of lead frames by being able to offer multi-layer and denser routing capabilities, thus overcoming some limitations of traditional lead frames, although there are still some restrictions in terms of cost, yield, reliability and moisture sensitivity which need to be considered when selecting such a substrate for a CIS package.

Laminate-based CIS Packages

Compared to ceramic substrates, laminate substrates have undergone significant technology advancements, mainly driven by the aggressive miniaturization and high cost sensitivity arising from the consumer device market, namely the smartphone industry. Laminate substrates can now be sourced at a low unit price, with short lead times, and entail lower development costs. They can also offer very dense routing, allowing high pin count and optimal form factors. Nevertheless, due to their constituent material properties, laminate substrate warpage and moisture sensitivity are not as good as their ceramic substrate counterparts. Package warpage can, however, be mitigated through careful package design and with the help of thermo-mechanical software simulations. Factors such as substrate design (symmetrical construction, copper balancing, and copper structuring for large copper areas), package structure (die thickness, glass size, glass thickness) and material property choice (low CTE and high T_g materials) can be taken into consideration at design stage to create an optimal laminate-based CIS package with minimal warpage, thus meeting stringent reliability requirements. Over the last few years, UTAC has worked intensively to successfully develop a robust and high-performing laminate-based image sensor package, termed iBGA (imaging Ball Grid Array). The structure of an iBGA package is shown in Figure 3.

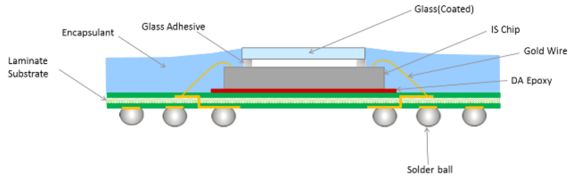

Figure 3 – Schematic of the iBGA package structure, with cover glass inboard of the wire bonds

Several assembly steps, each having finely tuned processes, together with meticulous inspection and quality control procedures, are required to manufacture an iBGA package to the required optical and electrical performance, yield, cost target, and reliability level. The high-level assembly process flow used to manufacture an iBGA package is shown in **Error! Reference source not found.**, highlighting the key process steps. For the latest generation of image sensors utilising advanced CMOS nodes and low-k dielectrics, a laser grooving process is performed to prevent passivation layer delamination and mitigate edge chipping during the wafer sawing process. The IS wafer sawing process is performed with the wafer fully submerged in water, to prevent deposition of non-removeable silicon debris onto the pixel area, and to help wash away removeable sawing debris, guaranteeing wafer cleanliness after sawing. The die attach, wire bonding and glass attach processes, where the image sensor die is still exposed to the atmosphere, are all performed in a Class 10 environment with intermediate ultrasonic dry cleaning steps, again to ensure that no particles are present on the image sensor surface prior to glass attach process. One can also observe that for this package structure a dam and fill liquid encapsulation method is chosen over more traditional molding solutions. This not only helps to reduce the number of assembly process steps, package cost and NREs (no need for a dedicated mold chase), but software simulations and reliability results have also shown that a dam and fill encapsulation subjects the package to lower overall stress, resulting in better reliability performance.

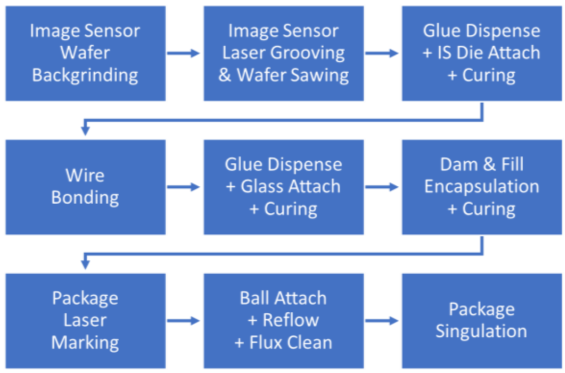

Figure 4 – iBGA package assembly process flow

The cover glass used in an automotive CIS package is normally coated (with anti-reflective, IR and/or frequency sensitive filter coatings) and is a key contributor to the bill of material cost of a CIS package. Conventional CIS packages based on ceramic cavity substrates need a large cover glass extending to the package edge, which increases the overall package cost. Utilising a laminate-based CIS package such as iBGA, whereby the glass is stacked on top of the CIS die using adhesive (as can be seen in Figure 3), the glass size is kept to a minimum, covering only the active pixel area and hence helping to reduce the overall package cost. This package structure also helps to reduce the total package height. One disadvantage of this approach, however, is that a dedicated space is required on the image sensor die surface to allow for glass adhesive dispensing, without bleeding onto the wire bonding or active pixel areas. While some die designs can allow this, other denser sensor designs have active pixel areas which are very close to the wire bonding pads and no area is available for glass glue dispensing. To overcome this limitation, UTAC has developed a 2nd generation of iBGA packages, named iBGA2, which can support these denser designs (Figure 5).

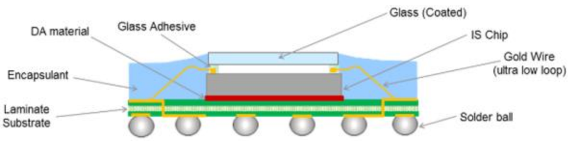

Figure 5 – Schematic of the iBGA2 package structure, with cover glass extending over the wire bonds

With an iBGA2 structure, an ultra-low loop wire bond profile is used (with an average height of 55µm), and the glass adhesive is dispensed over the wire bond pads. The cover glass, which can be as large as the sensor die, is attached very precisely in height, such that the wire bonds are embedded in the glass adhesive bond line (having minimum thickness of 80µm) without touching the glass (Figure 6).

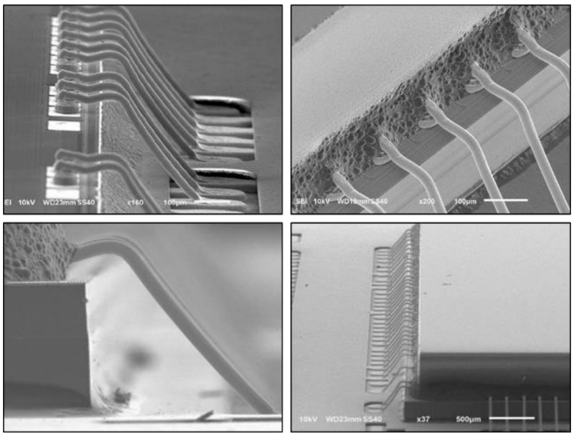

Figure 6 – SEM images showing ultra-low wire loops (top left), wires embedded in glass attach adhesive (top right & bottom left), and cover glass attached over wire bonds (bottom right), in an iBGA 2 package

This structure eliminates the need of dedicated die area for glass adhesive dispense, allows denser die designs to be used (for example to migrate from expensive ceramic packages to iBGA2 laminate package without new wafer tape-out), and also brings more freedom to glass size and package design choice.

iBGA Package Qualification for Automotive AEC-Q100 Grade 2 Reliability

As discussed in the introduction, there is currently a significant growth in demand for image sensor packages for automotive camera applications. Since most automotive cameras are located within the cabin or on the vehicle bodywork rather than near the engine or drivetrain, the environmental conditions are not so harsh and thus an AEC-Q100 Grade 2 reliability specification, representing an ambient operating temperature range from -40°C to +105°C, is adequate for these devices. The automotive grade also defines the stress tests which need to be applied in order qualify the package, as shown in Table 3.

Stress	Standard JEDEC Conditions	AEC-Q100 Grade 0	AEC-Q100 Grade 1	AEC-Q100 Grade 2&3
Preconditioning	**MSL 1:** 85°C/85% RH for 168 hours, unlimited floor life **MSL 2:** 85°C/60% RH for 168 hours, one year floor life **MSL 2a:** 30°C/60% RH for 696 hours, four weeks floor life **MSL 3:** 30°C/60% RH for 192 hours, one week floor life	Min Level 3, per J-Std-020	Min Level 3, per J-Std-020	Min Level 3, per J-Std-020
Temperature Cycling	Condition A: -55°C – 85°C Condition B: -55°C – 125°C Condition C: -65°C – 150°C	Precondition before -55°C – 150°C for 2000 cycles	Precondition before -55°C – 150°C for 1000 cycles -65°C – 150°C for 500 cycles	Precondition before **Grade 2:** -55°C – 125°C for 1000 cycles **Grade 3:** -55°C – 125°C for 500 cycles
Temperature Humidity Bias	THB: 85°C/85% RH for 1000 hours	Precondition before THB: 85°C/85% RH for 1000 hours		
Unbiased HAST	Unbiased HAST: 130°C/85% RH for 96 hours or 110°C/85% RH for 264 hours	Precondition before Unbiased HAST: 130°C/85% RH for 96 hours or 110°C/85% RH for 264 hours		
High Temp Storage Life	Condition A: +125°C Condition B: +150°C Condition C: +175°C	175°C for 1000 hours or 150°C for 2000 hours	150°C for 1000 hours or 175°C for 500 hours	125°C for 1000 hours or 150°C for 500 hours

Table 3 – AEC-Q100 qualification stress tests

As the number of cameras per vehicle increases, cost reduction of the CIS package becomes more appealing, yet the package must still be able to meet these demanding automotive quality standards. UTAC has developed this laminate-based iBGA package solution targeting a lower cost yet reliable alternative to ceramic packages for automotive camera applications. A package cross-section of an assembled iBGA device can be seen in Figure 7, whilst the package top view at various phases of the assembly flow are shown in Figure 8 **Error! Reference source not found.**.

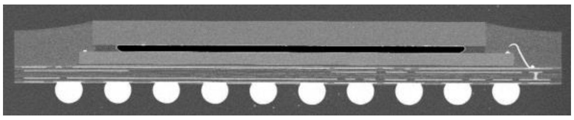

Figure 7 – iBGA package cross-section

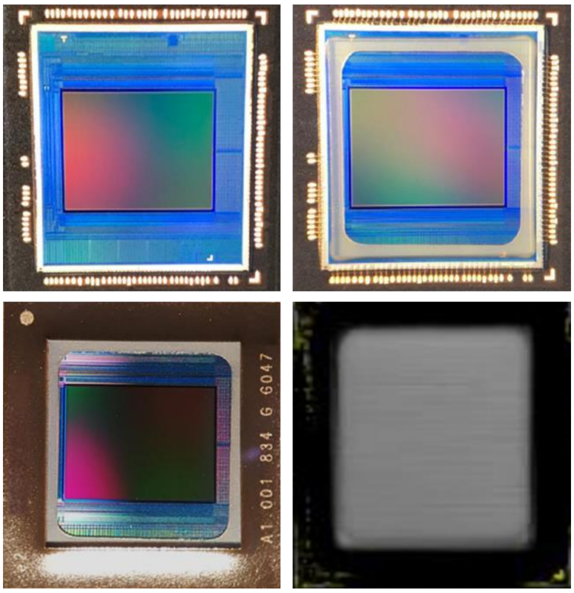

Figure 8 – iBGA package top view after: IS die attach (top left); wire bonding & glass attach (top right); encapsulation, laser marking, ball attach & singulation (bottom left); and after SAM delamination check post reliability stress testing (1000TC / 1000hr THB / 1000hr HTSL), with no delamination observed (bottom right).

Using a robust bill of materials and thorough process characterisation, the iBGA/iBGA2 packages can meet 5 sigma processes (Cpk ≥ 1.67) and pass AEC-Q100-G2 qualification (see Table 4). To enable this, several key challenges had to be addressed. The correct substrate design and materials have been chosen to attain the desired moisture resistance level and minimize package warpage. The materials were selected with a focus on adequate adhesive strength to prevent any package delamination, and appropriate properties such as modulus, CTE and T_g to mitigate package stress. The overall package structure and stack-up was optimized to minimize the package warpage and prevent package delamination and glass cracks from occurring, especially during temperature cycling. All these factors were investigated at design stage with the help of software simulations, and hence the correct package design considerations could be narrowed down prior to substrate tape-out and actual sample assembly builds for process and reliability validation, thus mitigating risk and reducing overall development time.

	Time Zero	Post Precon	1000cyc / 1000hrs
Preconditioning MSL3 + Reflow	PASS	PASS	PASS
TC (-55°C/+125°C)	PASS	N/A	PASS
THB (85°C/85% RH)	PASS	N/A	PASS
HTSL (125°C)	PASS	N/A	PASS

Table 4 – Summary of reliability results on iBGA/iBGA2 packages as per AEC-Q100-G2 standard

Conclusion

The increase in demand of automotive cameras for ADAS and autonomous driving applications has created the need for novel packaging concepts for image sensors, which have a lower cost and can still guarantee excellent optical and electrical performance, as well as high levels of reliability. UTAC has developed its iBGA packages to address this need and demonstrated that the iBGA packages are capable of meeting AEC-Q100-G2 requirements. With its cost competitive positioning and very good performance characteristics, the iBGA package is therefore being adopted in the automotive segment and is also expected to become an interesting packaging solution for other emerging application areas, such as machine vision and advanced imaging for smart factory applications.

References

[1] "Sensor fusion for autonomous driving," Infineon Technologies AG, [Online]. Available: https://www.infineon.com/cms/en/applications/automotive/chassis-safety-and-adas/advanced-driver-assistant-systems-adas/sensor-fusion/. [Accessed 2019].

[2] Nicolas Roux, "Automotive In-cabin Sensing Solutions," STMicroelectronics, 2018.

[3] "Audi Driver Assistance Systems," AUDI AG, 2017. [Online]. Available: https://www.audi-mediacenter.com/en/technology-lexicon-7180/driver-assistance-systems-7184.

[4] "From assisted to automated driving," Infineon Technologies AG, [Online]. Available: https://www.infineon.com/cms/en/discoveries/adas-to-ad/. [Accessed 2019].

[5] "SAE J3016 Levels of Driving Automation," 2018. [Online]. Available: https://www.sae.org/news/press-room/2018/12/sae-international-releases-updated-visual-chart-for-its-%E2%80%9Clevels-of-driving-automation%E2%80%9D-standard-for-self-driving-vehicles.

[6] "Automation: From Driver Assistance Systems to Automated Driving," VDA Verband der Automobilindustrie e.V, Berlin, 2015.

[7] Akhilesh Kona, "(R)Evolution of Automotive Electronics," Semicon Europa, Munich, 2017.

[8] "Global Automotive Camera Market Research Report - Forecast 2023," Market Research Future, 2017.

[9] Automotive Electronics Council, "AEC-Q100 Rev H: Failure Mechanism Based Stress Test Qualification for Integrated Circuits," Automotive Electronics Council, 2014.