

Automotive CMOS Image Sensors

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Abstract

After penetrating over a decade the consumer and industrial world, digital imaging is slowly but inevitably gaining marketshare in the automotive world. Cameras will become a key sensor in increasing car safety, driving assistance and driving comfort. The image sensors for automotive will be dominated by CMOS sensors as the requirements are different from the consumer market or the industrial or medical markets. Dynamic range, temperature range, cost, speed and many others are key parameters that need to be optimized. For this reason, automotive sensors differ from the other market's sensors and need to use different design and processing techniques in order to achieve the automotive specifications. This paper will show how Melexis has developed two CMOS imagers to target the automotive safety market and automotive CMOS imagers in general.

1 Introduction

For the past decade, CMOS and CCD image sensors have driven the creation of many new consumer applications like mobile camera phones. The introduction of imaging sensors in cars has suffered from a serious lag, because high-speed buses, high quality displays and compact low-cost signal processing units and memories were not yet available. Also, previous generation camera sensors were not yet performing sufficiently well and did not match sufficiently the stringent automotive needs. Today, with the availability of the newly developed Automotive Camera sensors, the Tier 1's can create revolutionary safety and comfort features for the car of tomorrow. Current camera IC's having high dynamic range, high sensitivity over a broad spectrum (both Visible and Near Infra Red), fast frame rate, non-blooming, low cost and in-field testable capabilities are giving the automotive designers the ability to offer drivers options previously not possible.

Two different kinds of applications exist, both with clearly distinct requirements and needs: Human Vision Applications, typically for comfort systems and Machine Vision Applications, typically safety critical and to be used in driver assistance systems

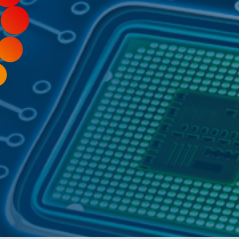
In the first application group, the task of the imager is to show one or several camera pictures to the driver. These applications usually need a small and autonomous colour sensor, most of the time generating an NTSC or equivalent signal for plug-and-play operation. In this set we find for example park assist, assisted overtaking (see the other-side road from another point of view like the left mirror), some sort of blind-spot detection systems. A sub-set of the display set is night vision where a black and white sensor of a higher cost and a higher resolution might be preferred.

The second set of applications is the one dealing with image processing and usually safety related applications like lane tracking, seat occupancy for smart airbags, automatic blind-spot detection, automatic cruise control,... In these applications it is crucial that the sensor is a snapshot, black and white + NIR, fully testable, highly reliable CMOS imager. As the connection is to be made to a computation unit and not a display, parallel digital output is preferred to the common video standards. Although the Melexis sensors were designed to meet the demanding criteria of the safety critical applications, and perfectly match the machine vision applications' needs, they can also be easily used to build prototypes of the first category (Human Vision).

Good examples to explain the need for an 'intelligent camera' in the "image processing" category are unintended lane departures. Such events were cited in 43% of all fatal accidents occurring in 2001. Rumble strips on the outside of the road have been proven to reduce lane departure accidents by 30-55%. Intelligent cameras could be applied to provide lane departure warning on nearly all roads. Once consumers realize the significance of an intelligent camera it will become a 'must have' feature. Existing systems just give a warning, but take no real action. (e.g. Sound alarm, vibrations in the seat, flashing light, ...) A final goal is a car that can control the steering and braking based on intelligent camera and other sensor inputs, but this is very far away. The intermediate situation is smooth guidance through a combination of multiple sensor inputs.



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In this paper we will mostly discuss the sensors for machine vision (image processing) and safety related applications in particular.

A CMOS Imager in automotive applications must meet several goals: low price, good performance at high and low temperature, little or no ageing under the influence of the severe environmental factors found in motor vehicles and rigorous testability in production and in the field.

As a reply to these demanding automotive requirements, Melexis has developed two CMOS snapshot camera chips for both inside and outside vision requirements. This paper will show how these two parts MLX75006 (CIF, 352x288 = 0.1Mpixels) and MLX75007 (Panoramic VGA, 750x400 = 0.3Mpixels) have met these challenges. The chip design ensures a wide spectrum high sensitivity, an excellent dynamic range, all at a high frame rate, and without CCD imager issues like blooming and difficult control. For surviving the harsh automotive conditions, an over moulded plastic package with integrated focus free glass lens stack has been developed. This compact chip-package-lens combination can meet the price expectations of the market, while allowing the necessary flexibility in Field of View and NIR optimization. These devices are fully verified in production and can be tested for integrity in real time in the field.

2 Automotive Imager Requirements and Melexis Solutions

2.1. Technical and Commercial Requirements

As discussed in the Introduction, an Automotive Image Sensor should comply with the several different requirements in order to meet the automotive market demands

- 1) Good Image Quality: High Sensitivity over a wide Spectrum and Wide Dynamical Range, all this over a broad temperature range: -40degC ... +105degC and vibration modes (Snapshot). Some applications also require Color
- 2) Reliability: camera designed for good testcoverage, well tested in production, and allowing the user to do in-field self testing and real time integrity checks
- 3) Compact System, with optimum cost: highly integrated camera with lots of internal features (ADC, ...), easy programmable and preferable with a matched glass lens system, again at minimum size and cost but without compromising the automotive qualification requirements.

2.2. Solutions for Good Image Quality

Although not necessarily meaning the same thing, “Good Image Quality” is required for both Machine and Human Vision Applications. Although Vision Applications will have more emphasis on the aesthetic aspects of the image, and Machine Vision Applications will focus more on sharpness, allowing edge and pattern detection, “seeing” is key for both. The sensor needs to be sensitive enough to give a “good” image under all circumstances.

As “seeing” is key, Melexis uses an optimized process for NIR sensitivity, yielding to the response curve shown below with the peak of sensitivity at a wavelength of 700nm and a high sensitivity up to 900nm. A high absolute value in sensitivity is met by using the relatively large 10um x 10um pixel size.

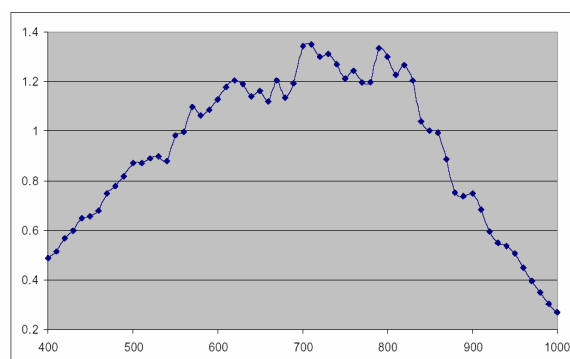


Fig. 1. Spectral response relative to 555nm

As light conditions can change drastically (full sunlight, shadowing, tunnels, snow and rain, night, ...) and a good picture is required under all those circumstances, an automotive image sensor needs to have an extremely high dynamical range.

Dynamic range is one of the most limiting factors of common consumer image sensors. These sensors never have to deal with dark objects in the shadows surrounded by reflecting light on a wet road with the sun low on at the horizon. Consumer sensors are usually able to make pictures of very bright and very dark scenes but not both at the same time. This is a must-have-feature for automotive image sensors.

CMOS image sensors offer the possibility to have non-linear pixel responses. This non-linearity can be a piecewise linear response (also called multiple slopes), a logarithmic response or a mix of different responses. Melexis' solution is the piecewise linear response where the total integration time is distributed over all the pixels so that the brightest ones see a lower integration time than the darkest ones and thus do not saturate. Non-saturating allows detection of objects in very bright areas and thus extends the dynamic range to higher limits. As the darkest pixels see a normal linear response, their noise level remains low and the dynamic range close to the lowest limit is unchanged. Together, this results in a significantly extended dynamical range, exceeding 100dB. Exact dynamical range calculations can differ strongly, dependent on the calculation methods and assumptions used. Optimistic calculations can reach up to 120, 130dB, but one could wonder if all noise sources, and temperature effects are taken into account



Fig. 2. Examples of high dynamic range pictures

As the automotive world requires temperature ranges from -40degC up to +85degC at least, the image sensor must be designed and tuned to fit this broad range. By optimizing both design and technology, the Melexis sensors offer a guaranteed operational optical quality level from -40degC up to +105degC.

The physical limitation of good high temperature behavior is leakage. This effect is an exponential function of temperature and will degrade the image sensor's response in a non-uniform and non-predictable way, limiting the dynamical range and creating white spots randomly over the image map. The Melexis sensors include an internal "hot spot" rejection and general black level compensation to counteract some of the high temperature leakage effects and exceeding the +85degC limit with good image quality.

The next figure compares two identical scenes at different temperatures. The first picture is taken at room temperature and must be compared to the second picture taken at 105°C, with "hot spot" cancellation and offset compensation, but with identical integration time and speed settings.

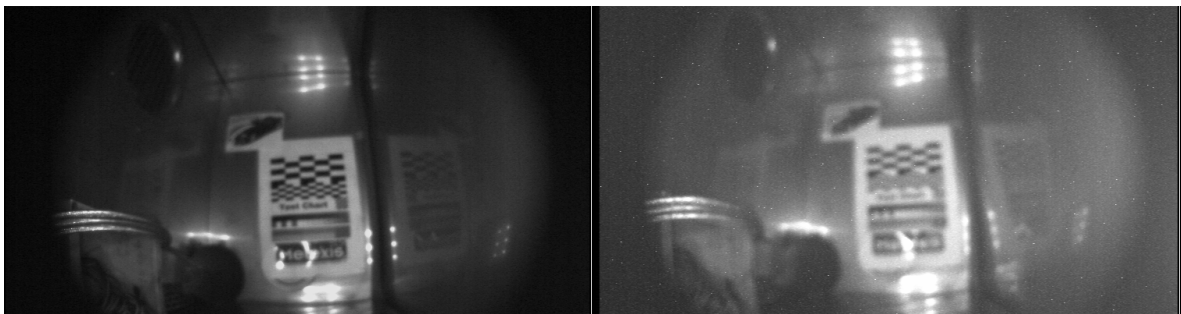


Fig. 3. The same scene at 25°C and at 105°C.

In order to sustain the high quality level and avoid skewing of the images under all (automotive driving & vibration) conditions, a global shutter where all pixels integrate and “freeze the image” at the same moment in time is a key feature. Whereas for Human Vision Applications, a Global Shutter requirement is probably overkill, and not worth the disadvantages (more complex pixel), for Safety Critical Machine Vision Applications, a Global Shutter is a must.

Whereas in a “Rolling Shutter” camera, every pixel or line samples the image at a different moment in time, in a “Global shutter”, every pixel in the whole array, integrates and samples (locks) the image at the same identical moment. Together with the possibility of having very high frame rates, the Melexis cameras have the capability of monitoring very fast moving objects, like a rotating fan, without any blurry effects. In order to design a good Global Shutter camera, one needs to have an efficient “memory” cell in every individual pixel, and sufficiently advanced technology in order to keep the image info stored in this cell during a complete read out cycle. Under extreme sunlight conditions, this is not evident for all global shutter sensors in the market. The parameter with which this limitation is measured is called “shutter efficiency” and its behaviour is strongly dependent on the pixel design itself.

In Machine Vision Applications, complex algorithms are constantly searching to identify edge transitions, correlations or other abrupt intensity changes. No human brain can help to interpret some strange artefacts and any extra software overhead to compensate the potential misalignments due to a rolling shutter are preferably to be avoided, therefore for this group of applications, a Global Shutter is an absolute requirement

The colour option, is at the other hand a must for Human Vision Applications (due to market requirements of exigent high end users) but not always necessary for Machine Vision (only required if the colour offers a significant difference in machine interpretation)

Melexis and its partners have developed colour filters that can be added on top of a black & white camera in order to make a true colour camera. We have chosen for a repetitive colour pattern of RGB filter, known as the Bayer pattern. Each block of 2x2 pixels equals then a 3 colour pixel and can be used to reconstruct a colour picture. As shown in the pictures below, a high fidelity can be reached.



Fig. 4. Some colour pictures

2.3. Solutions for Automotive Reliability & Testability for Image Sensors

As for any other component that plays a key role in automotive safety applications, reliability is an important topic that has to be addressed during the design and production phase of an automotive image sensor.

The Melexis strategy of automotive image sensors follows the same line as used for all other automotive components:

- 1) Design for Testability on sensorlevel (target is to reach efficiently high testcoverages on chip) and on application level by using DFMEAs
- 2) Automotive AEC-Q100 set of Qualification Tests,
- 3) 100% optical and electrical tests during production at different temperatures,
- 4) several built-in testmodes and real-time integrity checks to allow the user to monitor its application in the field.

Getting high testcoverage in a complex sensorchip like an imager is not straightforward. Therefore, special attention has been put into this, during the design cycles. The high testcoverage is reached by using full electrical separation of some blocks, using advanced software tools to write optimized test patterns and last but not least, using the continuous data stream flow of the sensor to incorporate info of internal nodes during operation. Together with a lead Tier1 supplier, several DFMEA discussion were held on application level, in order to make sure Melexis can offer an image sensor meeting the automotive standards.

Before releasing the imager to automotive production, the standard Automotive Qualification Tests are performed on the parts, all with appropriate temperature levels. As only standard processes are used, no major problems are to be expected. However, also the less standard color filter technology and the integrated lens stack (see further) will be qualified following the same guidelines.

In order to reach the automotive target of a few ppm's EOL fail levels, one needs to test 100% the outgoing production parts. With a sensor designed for test and high coverage, an efficient and optimized test procedure can be installed. Here, Melexis uses the experience and know-how build up during several years on testing another optical safety critical part, the MLX90255 linear optical array. Melexis is capable of doing a full optical & electrical test both at wafer level and final test, at any temperature between -40degC and +125degC with automated, high volume test equipment.



Fig. 5. Mass Volume Automated Test Equipment

Building a robust safety critical application requires advanced integrity checks on all critical building blocks. As most machine vision applications require a powerful processing unit, and the built-in space is very limited, some systems are made by means of a so called “two-box-solution”: one part consists of the imager, lens and some discrete electronics put at the critical sensing area, whereas the processing unit and voltage references are placed in a other part inside the car. Such a system build requires not only good validation of the building blocks themselves, but also a good monitoring of the communication lines.

The Melexis imagers offer several features to allow the user to indeed build a robust application, even using the two box concept. After completion of every image, several known testpatterns are sent by the camera to the processor, allowing the user to validate both uplink and downlink communication lines (also the used command word is sent back) As modern image sensors integrated in standard CMOS technology compose of several other features like an

internal ADC, white spot correction, advanced programming features etc... , it is also important to have integrity verifications of this system on a chip itself available.. Mixed after every line, and at the end of a full picture, known testpatterns are sent by the camera, allowing the user to verify the integrity of several internal nodes both in the analog and digital domain of the imagers itself. All these integrity modes are real time and can be interleaved with normal operation with very high efficiency. However, if something would go wrong, extra more advanced test modes, are also available to the user to identify where exactly a problem might occur. To access these advanced test modes, the sensor has to be put out of normal operation, but fast single frame switching between testmode and normal mode is possible at all times.

Although the expected failure rate of electronic sensors qualified for automotive usage (including image sensors!) is in the ppm range, full visibility of all key components, including the wiring is crucial in order to build a robust final system. By means of the variety of testmodes implemented and made available with the Melexis imagers, one can guarantee this. However, first generation, safety critical driver assistance systems, will certainly not overtake the drivers' decisions, but mainly provide assistance and help in potentially dangerous situations.

2.4. Solutions for Optimum Size & Cost

In the automotive world, besides performance and reliability, size and cost are also criteria of extreme importance.

Using the experience and know how of the optical linear array, Melexis has further developed with its partners the plastic overmoulded cavity package concept. This solution offers several advantages:

- 1) a well known, standard packaging technology, relatively lowly priced and offering similar quality performances as several other plastic package used in the automotive world.
- 2) although the cavity offers an easy path to the light to enter the sensors sensitive optical area, all other parts are overmoulded, including some sensitive electronics, and of course, the bondwires and bondpads
- 3) because the optical sensing area can be accessed freely, there is also the opportunity of focus free lens mounting, giving several extra advantages to the end user in terms of size, ease of handling and in the end total cost.

Several years of experience with the plastic cavity concept used for the optical linear array, have allowed us to elaborate the plastic cavity package concept into a general image sensor package technology. Using standard processes and compound, standard automotive quality levels can be reached. MSL level 3 is standard, but with the choice of adequate compound, MSL level 1 can be the target. Currently, leadframe based solutions like MQFP type packages are widely accepted in the automotive world, but if QFN technology would receive the same acceptance level as MQFP, the same cavity technology can be applied to leadless QFN types.

One of the most critical points in reliability of a package are the bondwires and the bondpads. As those are overmoulded in exactly the same way as with any other standard automotive plastic package, no difference in quality is to be expected. As long as a sufficient guard band is kept between the cavity and the bondpad positions, the plastic cavity packaging concept gives equal reliability performances as the standard plastic packages. As the sensitive non-optical electronics is covered with plastic, no extra metal layers are required for coverage. This can allow for a cheaper sensor technology and can also improve some electrical behavior like speed or matching. Also, a thick layer of plastic is a much higher efficient optical sealant than thin metal layers.

All optical systems require one or multiple lenses. This open package technology allows to directly mount a lens on the sensor.. An integrated lens stack, consisting of multiple lens interfaces optimized to the so called Panoramic VGA resolution of the MLX75007 image sensor, has been developed for this purpose.. The lens offers a 60 degree Field Of View and a $F\# = 2.5$. The optical design is matched our sensors performances, and optimized for a broad wavelength range up to the Near Infra Red. Edge distortion is limited to a minimum and an MTF of 40% at 50lp/mm can typically be achieved over a broad wavelength range and Field Of View.

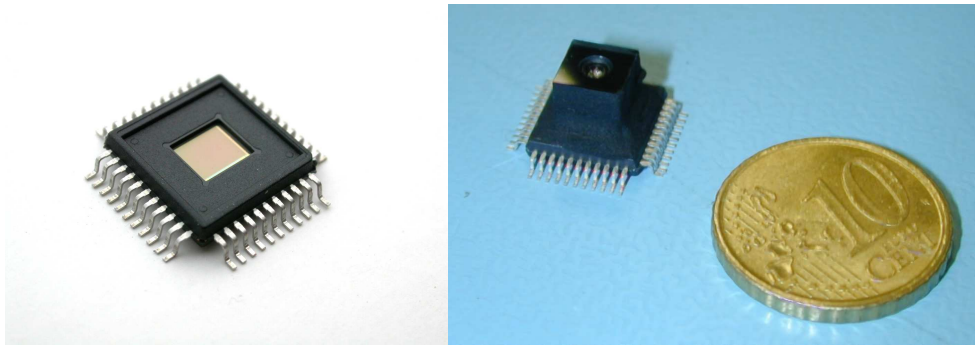


Fig. 6. MLX75006 (CIF sensor) in MQFP44 package, with and without Integrated Lens Stack

When mounting a lens, using the plastic package or PCB board as a reference, extra means of adjusting are required due to the high build up of tolerances. By placing the Integrated Lens Stack (ILS) directly inside the package, with the sensor area as reference plane, and by well controlling the tolerances, we can offer a fully focus free, Integrated lens solution. Besides optimum size, the ease of processing also gives several advantages to the user:

- 1) no focusing required by the end user, nor the possibility to get out of focus (by design)
- 2) the module: sensor + lens interface can be completely tested by Melexis before shipping
- 3) the target is to offer a complete hermetically and optically sealed solution, capable of withstanding the standard soldering techniques, and as such to be a plug & play component, similar to a lot of other currently used sensors.

2.5 How to design an automotive vision application: “in search for the best compromise”.

Crucial to the end success of any (vision) application will be the good judgement of all application needs and the correct choice of both hardware and software needs. Every building block has its specific advantages, but also its price, therefore - as always –designing well means making optimized and well balanced compromises.

As described in this paper, concerning the image sensor, several specification requirements can and should be weighed against each other: global shutter vs. rolling shutter, color vs. black & white, pixel size and resolution.

As described before in the paper, a global shutter is a very interesting feature for a camera, but it requires a complex pixel design. Therefore, if not required, a rolling shutter might be an interesting alternative, with probably a higher light sensitivity for a lower price. The same is valid for color. Nice to have, but its need should be carefully balanced and questioned in the total system, as it will have a significant lower light sensitivity and dynamical range for an increased cost.

Pixel size and resolution will determine largely the end cost of the imager, but can also impact on the lens cost and software needs. Too large lenses will be prohibitively expensive for the mass volume automotive market. Extremely high bandwidths and processing power due to megapixels image streams at very high frames/sec are probably also prohibitive for both processor requirements and EMC qualifications. For some specific applications, the “old-fashioned” CCD solution might even still be the best choice nowadays. For other applications however, a CMOS global shutter image sensor will be required.

A final automotive vision application will be the end result of a series of these balanced judgments: the right parts with the optimized software to get a correct performance at an acceptable marketprice.

3 Conclusions

This paper has presented the main criteria to which an image sensor should comply if it is to be used in the highly demanding automotive world. Next to obvious parameters like image quality, size and cost, also reliability and integrity verification means will determine the possibility of integration of an automotive image sensor in a safety critical automotive application. Furthermore, the unique combination of the overmoulded open package with a focus free integrated lens stack, can address successfully the dimensional and cost requirements.

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