High-sensitivity Uncooled IRFPAs for Driver Vision Enhancement

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Abstract

Recently the emergence of a new generation of infrared sensors particularly suited to operate at ambient temperature – the microbolometer technology – has opened the opportunity for achieving low cost infrared imaging systems for both military and commercial applications. In a first part, this paper gives an overview of this challenging technology developed at LETI. A special highlight is given on recent results obtained from a 160x120 focal plane array, 35µm pixel pitch, developed for Driver Vision Enhancement. In a second part, the use of this technology in automotive safety field is illustrated through an application of detection of moving objects in front of a vehicle. The results shows that infrared sensors based on well-designed microbolometers represent a real middle-term alternative to usual video sensors.

1 Background

The automotive industry increasingly looks to Microsystems to put intelligence into cars. Safety improvement is particularly concerned with this trend: acceleration sensors for airbags, tire pressure monitoring and collision avoidance radar system. However, despite all of the automotive safety breakthroughs of this last decade, drivers still face potential hazards during conditions of darkness or obscured visibility such as is present with fog, heavy rain or snow. A challenging concern for the next few years is to improve vehicle safety in such adverse conditions with the operation of front-hazard warning devices and reliable collision avoidance systems.

One of the major issues of such safety systems largely deals with the availability of adequate sensors that allow an early and reliable detection of road obstacles in front of the car. Infrared thermal imaging is particularly suited for this purpose as it provides an effective nighttime viewing system that could tackle the inefficiency of the usual sensors and fulfils the night driving safety requirements.

For various technological and financial reasons, infrared imaging has been primarily developed for military applications. Such systems were originally based on quantum devices that typically operate at liquid nitrogen temperature [1]. This low temperature requirement leads to high cost systems and has dramatically restricted the use of thermal imaging. But recently the emergence of a new generation of sensors – the microbolometer technology – based on an infrared thermal detection mechanism which is particularly suited to operate at ambient temperature has opened the opportunity for achieving low cost infrared imaging systems for both military and commercial applications [2].

In this context, CEA/LETI has been involved in amorphous silicon uncooled microbolometer development since 1992 [3]. The French company ULIS now commercialises this high performance infrared technology in mass production and will rapidly meet the market ramping up demands like car safety applications. In order to prepare the next infrared launch into automotive industry, CEA/LETI is involved in two European projects that aim at improving automotive safety. In EURIMUS framework, a project named ICAR is under progress to develop a specific camera for affordable Driver Vision Enhancement (DVE) systems [4]. Besides, the SAVE-U project, partially funded by the European Commission INFSO DG under IST program aims to develop an enhanced vulnerable road users (VRU) detection system based on several detectors: a 24 GHz radar network coupled with a vision part composed of both visible and infrared imaging sensors (http://www.save-u.org [13]).

In a first part, this paper gives an overview of microbolometer technology highlighting the main characteristics of these sensors that are particularly relevant to automotive applications. Then the paper will focus on recent results obtained from a 160x120 microbolometer infrared focal plane array (IRFPA) with a pixel pitch of 35µm that has been specifically designed for automotive Driver Vision Enhancement in the scope of ICAR project. In a second part, the use of this technology in automotive safety field is illustrated through an application of detection of moving objects in front of a vehicle highlighting the potential of this technology for pedestrian detection in the context of the SAVE-U project.

2 Microbolometer development at CEA/LETI

2.1 Thermal detector structure

As a general rule, an uncooled thermal detector measure the temperature rise due to IR radiation absorption by a thermally insulated element. For this purpose, thermal detectors are mainly composed of an infrared absorber embedded in closed contact with a thermometer element. The thermometer element senses incoming IR induced temperature rise and converts it into an electric signal. The most common detection mechanism is the resistive bolometer whose resistance changes with temperature, but various other mechanisms can be used, such as pyroelectrics effect [5], thermoelectric junction [6], P-N junction conductivity [7] or thermal stress induced mechanical deflection [8]. Considering a two dimensional array of detectors, a readout integrated circuit (ROIC) is generally designed to measure the resistance of each bolometer and to format the results into a single data stream for video imaging purpose. Finally, due to the strong correlation between thermal insulation and sensitivity, the high performance uncooled IR detector must be operated under vacuum – typically 10^{-2} Torr – in a specific package supplied with an infrared window.

2.2 CEA/LETI technology

In the footsteps of MEMS devices, microbolometer sensors have taken benefits from the latest silicon technology advances. Unique surface micro machining techniques have been developed at CEA/LETI in order to produce above the full custom CMOS readout circuit, very thin membranes made from amorphous silicon that are very sensitive to infrared incoming radiations heating. Figure 1 shows schematically the structure of such a pixel, figure 2 describes its manufacturing process flow, whereas figure 3 shows scanning electron microscopy pictures of a pixel and the detail of the metallic stud that interconnect the microbolometer detector to the ROIC through the thermal insulation leg.

On this technological baseline, a first generation of bolometer technology focused on 45µm pitch was developed and transferred to ULIS in early 2000. ULIS is currently manufacturing and commercialising two different products (figure 4) based on a 320x240 focal plane array. These are both packaged under vacuum in a metallic package. The UL01 01 1 device is a general purpose imaging uncooled infrared array whereas UL01 02 1 E device, as it is supplied with an internal thermal shield, is more suited for radiometric applications.

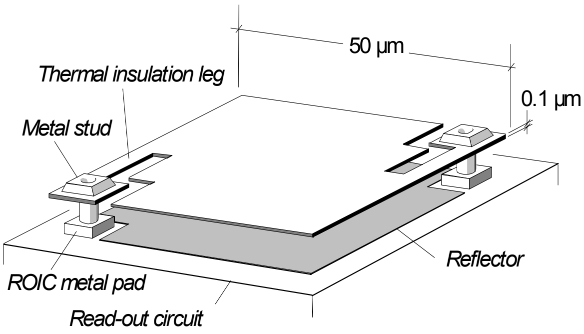

Fig. 1 Schematic of microbolometer pixel

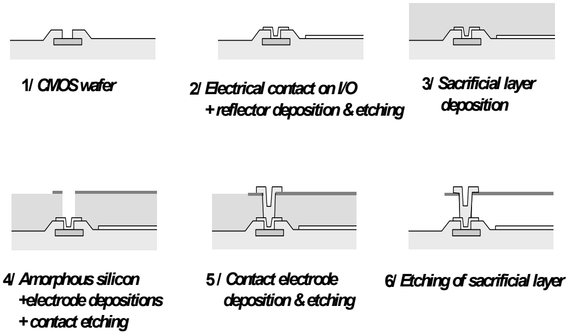

Fig. 2 Process flow of microbolometer technology

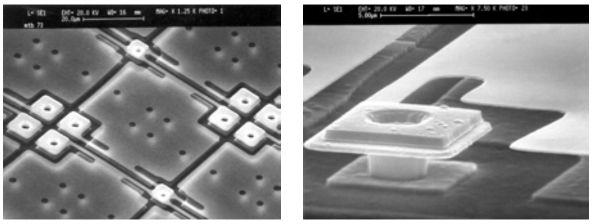

Fig. 3 SEM views of pixels and their electrical interconnection

Fig. 4 ULIS uncooled staring arrays UL 01 01 1 (left), UL 01 02 1E (right)

2.3 Cost reduction studies

The requirements of automotive application like the Driver Vision Enhancement system is mainly constrained by objective cost of the overall system. CEA/LETI and ULIS technology is particularly designed to meet these requirements. In fact, one of the key point of CEA/LETI and ULIS microbolometer technology has been to elect a thermometer material made from amorphous silicon that features absolute compatibility with standard silicon processing. This basic option leads to a high yield monolithic arrangement fully compatible with commercially available CMOS silicon wafers. This feature intrinsically guaranties low cost attainment ideally suited for large market distribution. Nevertheless, to extend this low cost high volume approach even more some further developments are under progress at CEA/LETI in partnership with ULIS. The main point consists in reducing the pixel size. Another key point is to develop advanced packaging techniques as it is well stated that vacuum packaging is a cost driver in MEMS devices and particularly in uncooled IRFPA. A third point is to increase the integration of advanced functions on the focal plane in order to facilitate its integration into system equipments.

2.4 Pitch reduction studies

Cost reduction has multifold benefits from this pitch reduction approach. Obviously, owing to the increase of the number of dies per wafer, this will reduce the cost of the bolometer array itself. Besides, given a processing defects density, the manufacturing yield is directly linked with the focal plane array size. Furthermore, this size reduction will impact on both the dimension of the bolometer packaging and the form factor of the camera and consequently their cost. Finally, we can expect a dramatic drop of volume, weight and cost of the infrared optics as the diameters of the lens are directly linked with the size of the pixel for a given field of view and optical aperture.

To maintain a high level of performance despite the decrease of the pixel size, CEA/LETI in partnership with ULIS have engaged in deep technological developments for the last couple of years. These developments aim at increasing the thermal insulation of the pixel and at reducing the 1/f noise. In order to address this issue, an innovative second-generation technological embodiment, totally compatible with the ULIS industrial process, has been developed. This so called second generation amorphous silicon microbolometer technology exhibits dramatically enhanced sensitivity and enables the decrease of pixel pitch to 35µm, keeping a level of performance entirely compatible with automotive night vision requirements. Typical characteristics of this second generation technology for a 35µm pixel pitch are summarized in table 1. This second generation technology is now completely matured and has been transferred from CEA/LETI research line to ULIS production line in 2003.

320x240 IRFPA 35 µm pitch	Pitch µm	Rth 10^6K/W	Tth ms	NETD mK
1st generation a-Si	45	12	4	80
2nd generation a-Si	35	42	12	36

Table 1 : Comparison of first and second generation (a-Si) technology

2.5 Advanced readout development

Taking profit from the achievement and maturing of the second generation microbolometer technology ULIS and CEA/LETI have designed a 160 x 120 2D arrays in the scope of ICAR project with particular attention to the low cost automotive market. This new IRFPA is fed with a number of innovative on-chip features to simplify the use of this focal plane keeping a very small silicon ROIC area down to 0.7 cm² for the 160 x 120 array, in order to reduce wafer-level processing costs per die. This new 160 x 120 is designed to fulfil low resolution, low cost applications. One of the most promising functions is the possibility to adjust the skimming of the common mode current for each pixel by an automatic acquisition and storage of non-uniformity coefficients in a first step and readout pixel signal in a second step. At power on, the detector acquires its pixel compensation coefficients and stores them in on-chip memory for performing the current compensation during the following images acquisition and readout sequences. This automatic mode of operation could be changed to an external driving mode with non-uniformity coefficients stored in an external memory (see figure 5). The video output is available in analog or digital format with an on-chip 12 bits (2 x 6) ADC. Most of the biases are generated inside of the ROIC for friendly user operation.

Several 160 x 120 microbolometer IRFPAs has been integrated under vacuum package and the usual electro-optical tests were performed under standard conditions including an operating temperature of 295K, a 100Hz frame rate and a flood illumination from a 300K blackbody through an f/1 limiting aperture. The resulting characteristics are summarized in table 2, whereas figure 6 shows a typical NETD histogram highlighting the weak dispersion of the IRFPA characteristics.

	Mean	Std deviation (%)
Responsivity	16 mV/K	1.4%
Total output noise	880µV	10.4%
NETD	56mK	10.5%
Operability	>98%	

Table 2 : Typical electro-optical characteristics of a 35µm pitch, 160x120 a-Si IRFPA

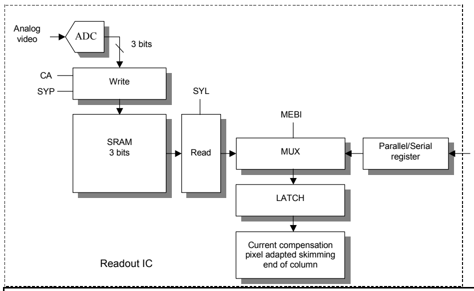

Fig. 5 Synoptic of 160x120 array on chip non-uniformity compensating operation

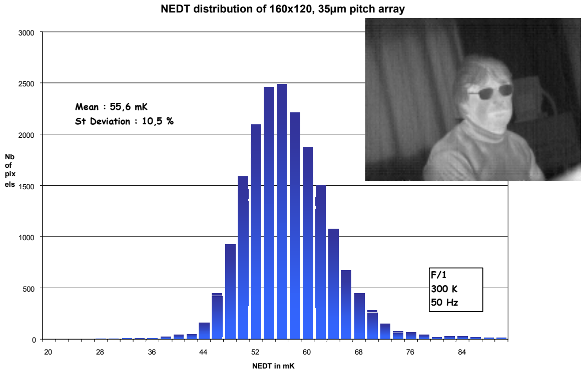

Fig. 6 NETD distribution and single frame obtained from a 35µm pitch, 160x120 IRFPA

2.6 Packaging development

2.6.1 Metallic package

Metallic packages belong to the first generation of package used to integrate the microbolometer chip (figure 5), but their cost remains a large part of the total detector cost and this trend will be amplified in the near future as the pixel pitch will be reduced. As a consequence a less expensive package technology is used and various developments are under progress in this field. Figure 7 (left) shows a "telecom" package used for 160 x 120 / 35 µm device integration.

2.6.2 Ceramic package

Ceramic packages (figure 7 right) are currently developed at ULIS. This technology is using available technologies developed for chips made in high volume production. Only the process used to assemble chip carrier and window carrier is adapted to take into account the required greater than 10 year lifetime under vacuum. These package constructions are compatible with automatic assembling machines that will contribute to decrease manufacturing cost.

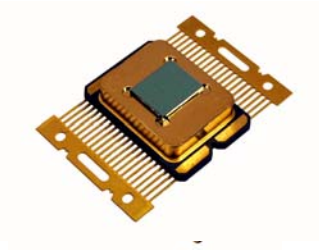

Fig. 7 ULIS metallic package (left) and ceramic package (right) developed for 160x120 IRFPA

2.6.3 Wafer level packaging

Beside these rather standard packaging techniques, CEA / LETI is working on the development of a wafer level packaging system (fig 8) in order to achieve the ultimate reduced manufacturing cost. This goal is completed in a 4 steps process. First, thanks to bulk micro machining techniques, a silicon microchip carrier is prepared on a silicon wafer. In a similar way, a second silicon wafer is processed in order to achieve an infrared window. These two substrates mainly consist of cavities and metallic thin film rings used for interconnecting and welding purpose. Then, individual microbolometer IRFPAs are positioned and wire bonded into each chip carrier cavity. Finally, the collective assembly (welding process) of the two wafers is carried out under vacuum leading to microbolometer IRFPAs shut under vacuum into silicon cavities. The major advantage of this technique in comparison to competitive option studied elsewhere [9], is that it does not require any extra soldering area on microbolometer die and consequently it contributes to IRFPAs cost reduction.

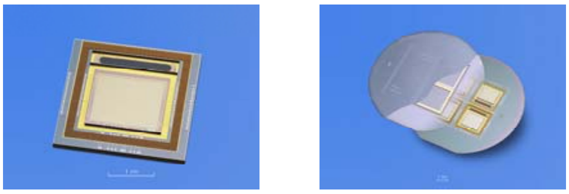

Fig. 8 Silicon chip carrier for microbolometer IRFPA (left) calls for a collective 4 microbolometer IRFPAs sealing (right) completely performed at the wafer level

3 Application in automotive driver assistance

Vision based systems represent one of the promising research areas for driver assistance. But as it is true for drivers, it is also true for video cameras, in bad weather conditions, at night, their visibility is reduced. Unfortunately, in such conditions, the number of accident is increasing. Therefore, infrared video sensors, because they are not too much affected by poor conditions of light, are well adapted to automotive applications. In the SAVE-U project, it has been chosen to use an infrared video sensor (based on microbolometer technology) in addition to a visible wavelength video sensor and a radar to cope with most of the possible situations. The application described in this paper was developed within the SAVE-U project. The objective was to detect obstacles coming in front of the vehicle in order to perform, in a later stage, their classification (not presented here). For a recent survey on pre-impact sensing for pedestrian detection, using various sensors (video, radar, laser scanner), see [10]. The final objective of SAVE-U is to improve pedestrians and cyclists protection through the development of a reliable vulnerable road users detection system. The main purpose is to anticipate a predictable accident in order to warn the driver and/or modify vehicle behaviour (activating the brakes, for instance) well before impact occurs.

Traffic accidents happen when unexpected changes occur in the vehicle vicinity, therefore one of the main important task is to detect those changes. With a static camera, changes are mainly due to the motion of objects in the field of view and simple algorithms like background subtraction enable to find what is moving. Looking at a scene taken by a camera mounted on a vehicle, it appears that main changes are due to vehicle motion while minor changes are rather related to other moving objects such as cars, bicycles or pedestrians. Then, if we estimate the global camera induced 2D motion field and use it to align two successive images, regions with secondary motions will be badly corrected in this case and can be retrieved. This approach is based on image compensation techniques.

3.2 Camera motion model

In the 3D world, the camera motion is described by a translation T and a rotation Ω . Due to camera motion, a scene point P appears to be moving with rotation $-\Omega$ and translation $-T$. After the modelling of the camera orientation and location, the projection of the real scene on the 2D sensor plane can be modelled using a perspective projection where the expression is not free from the depth parameter. To get rid of the depth parameter, the scene is approximated by a plane. Then it is possible to find an affine 2D motion model, which is free from the depth parameter and which is able to handle translation, rotation and scaling [11] [12]:

$$\begin{bmatrix}\dot{x}\\ \dot{y}\end{bmatrix} = \begin{bmatrix} a_1\mathrm{x} + a_2y + a_0 \\ a_4\mathrm{x} + a_5\mathrm{by} + a_3\end{bmatrix} = \mathrm{m}(\,(\mathrm{x},\,\mathrm{y})\,,(\mathrm{a}_i)_i\,)$$

3.3 Estimation scheme

Camera motion estimation can be performed by a robust least square formulation. But the criterion to minimise is non linear. To handle this problem, a common solution is to follow an incremental minimisation scheme. In that case, the criterion can be linearized.

In addition, to cope with large motions, a coarse to fine strategy is used: a pyramid of low-pass filtered and sub-sampled images is constructed. At each level the image resolution is cut by half and low motion is first estimated at coarse level using the iterative scheme. The computed flow field is then projected to the next level of the pyramid.

3.4 Results

Several experiments in various situations are presented. As said previously, the dominant motion between two successive frames is estimated, the first image is then warped and subtracted to the second (left images in figures) to obtain the image of residuals. This one is then binarised to build the detection map representing areas where non conform motions are detected (right images).

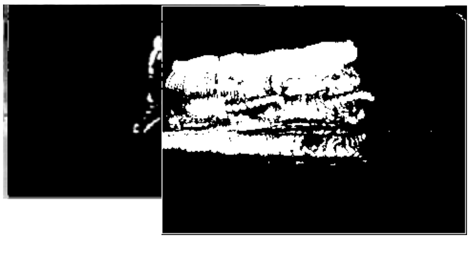

Fig. 9 Detection with a pedestrian crossing the road and below, his trajectory over several images.

Fig. 10 Detection of a pedestrian coming in front of the vehicle.

Fig. 11 Detection in a complex sequence.

4 Conclusion

This paper has put emphasis on the main features of CEA/LETI infrared microbolometer technology. One of the key points has been to elect a sensitive material made from amorphous silicon that features absolute compatibility with standard silicon processing. This basic option leads to high performance and low cost infrared imaging systems particularly suited for large market distribution such as automotive applications. This technology is now commercialised in mass production by the French company ULIS, while a brand new advanced technological arrangement has been demonstrated at CEA/LETI. The advent of this second generation of the technology results in a fivefold performance improvement compared to the current industrial process and NETD of 56 mK obtained from 35µm pitch, 160x120 IRFPA has been demonstrated.

The results of detection by image processing techniques on infrared video sequences indicate that the approach gives better results compared to those obtained with images coming from video cameras working at visible wavelength. One reason seems to be that IR images present less detail but they are nevertheless textured enough for motion estimation. From that point they represent a very good alternative to visible wavelength sensors.

5 Literature

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