Low-cost Approach for Far-Infrared Sensor Arrays for Hot-spot Detection in Automotive Night Vision Systems.

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Abstract

Sensor data fusion of active near infrared (NIR) and passive far infrared (FIR) for reliable detection of vulnerable road users in future warning automotive night vision systems requires for low-cost, mid-resolution FIR sensor arrays for hot spot detection. We present a new cost efficient technology for FIR arrays adopting a volume proven integrated MEMS process for the production of a suspended thermo-diode array. In contrast to established bolometer production all steps of the process developed are fully semiconductor compatible as the sensor element formation is an integral part of the read out IC processing and does not require ASIC backend processing with dedicated equipment. Vacuum wafer-level packaging compatibility further reduces cost. In a first step the proposed process has been verified with small integrated FIR arrays consisting of 42x28 pixels. The FIR array development reported is part of the EU FP7 project 'ADOSE'.

1 Introduction

Next generation automotive night vision systems for driver assistance will improve the safety of vulnerable road users with active warning signals and in future systems also automatic system action. Reliable detection with low false alarm rates is essential for such systems.

In contrast to stand alone FIR night vision with expensive high resolution bolometers, a fused NIR/FIR system combining high resolution NIR and lower resolution FIR, allows excellent image display quality using the active NIR image from affordable good resolution CMOS image sensors. In addition, this combined system facilitates reliable identification of vulnerable road users, supported by hot spot detection from an FIR-array sensitive in the 7-14 µm wavelength range.

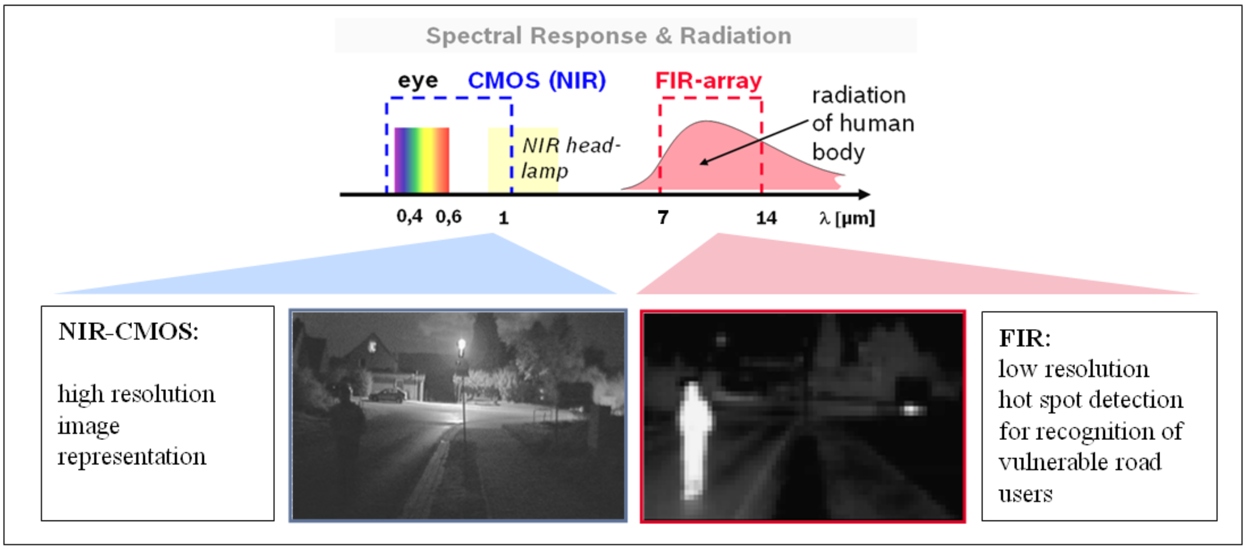

Fig. 1. Multi-spectral approach for warning night vision with NIR / FIR data fusion (top). Identical night vision scene with different sensors (bottom); CMOS-NIR imager without active light (left) and low resolution FIR-array (right).

Various different un-cooled sensors are in the market or under development [1]. Despite somewhat reduced resolution requirements for hot spot detection compared to FIR-imaging, automotive sensor cost-demands remain a challenge for the sensor technology. Present established un-cooled bolometer technologies e.g. based on vanadium oxide VOx [2] or amorphous silicon [3] do not allow meeting the stringent cost targets for FIR add-on sensors – mainly because of the expensive manufacturing process requiring back-end processing of completely finished read-out ASIC wafers within a dedicated production environment due to incompatibility of sensor material or process-flow with standard semiconductor manufacturing. Additionally batch vacuum wafer-level packaging is not applied for these bolometer technologies. Other alternative FIR concepts proposed, like [4], apply silicon-germanium multilayer films for the sensor requiring temperature budgets above the limits to which a substrate carrying a fully processed ROIC can withstand. This means to employ sophisticated and expensive transfer processes for the sensor film onto the ASIC wafer.

In this paper we propose a fully CMOS production compatible process adopting a volume proven integrated MEMS process and vacuum wafer-level packaging. This process - described in more details in section 3 - together with the reduced resolution requirements of a non-imaging FIR add-on sensor for hot spot detection allows us to meet the aggressive automotive cost targets.

2 Requirements

Several relevant use-cases for an automotive night vision system comprising active CMOS-NIR imaging and additional FIR hot spot detection have been analyzed within the European project ADOSE. The requirements for the FIR–add-on sensors for hot-spot detection haven been derived there and are listed in figure 2. It was derived that an array resolution of 100 horizontal and 50 vertical pixels should already be sufficient for detecting a person as a hot spot at a specified minimum viewing distance of 120m.

FIR camera requirements		**Remark**
Horizontal Field of View (FOV):	**± 12°**	For data fusion with NIR
Angular Resolution:	4,18 pixel / °	Defined by smallest object to be resolved @ 120m
Object Temperature resolution:	< 500 mK	for hot-spot detection; no greyscale image display NETD < 300mK for chip @ F#1 optics
Frame Response:	> 12,5 Hz	for 3 verifications of object in the NIR image
Array Size:	100 x 50 pixels	Defined by FOV and angular resolution
Wavelength Range:	7-14 µm	Spectral emission maximum of vulnerable road users

Fig. 2. Typical requirements for a FIR sensor in warning night vision based on FIR/NIR data fusion.

Concerning the sensor cost, only few 10€ cost are acceptable for the whole add-on sensor comprising the FIR-array chip, optics, electronics and packaging, as the sensor is an additional part of the warning night vision system. FIR array and optics are the dominating cost drivers. Although in the ADOSE project low cost FIR optics is addressed as well, in this paper we will focus on the technical results from a new process set up for considerably reducing the array costs for small to medium resolution FIR arrays.

3 Sensor Technology

3.1 Sensor Concept

In order to allow integration of the sensor element processing into a semiconductor process flow we use mono-crystalline silicon for the sensor material together with a suspended thermo-diode detector similar to [5, 6, 7]. Additional advantage from using diodes instead of a resistor array is the inherent decoupling of the matrix without need for a pixel transistor and for stacking the sensor above the electronics. This allows us simultaneous production of the sensor element within the readout-ASIC manufacturing process.

The basic concept for generating a suspended semiconductor device is illustrated in figure 3. Latest generations of surface micro-machined pressure sensor process modules support integrated circuits in an epitaxial mono-crystalline silicon layer above a pre-structured vacuum cavity [8, 9]. This process was only slightly adapted and the FIR pixel designs have been made to cope with the layers available from the ASIC process. We also found the absorption of pixel's layer stack to be sufficient for about 50% absorption which allowed us to avoid further absorption structures like the expensive thermal radiation collectors described in [6]. This design allows fully exploiting the cost savings from synergy with high volume semiconductor manufacturing.

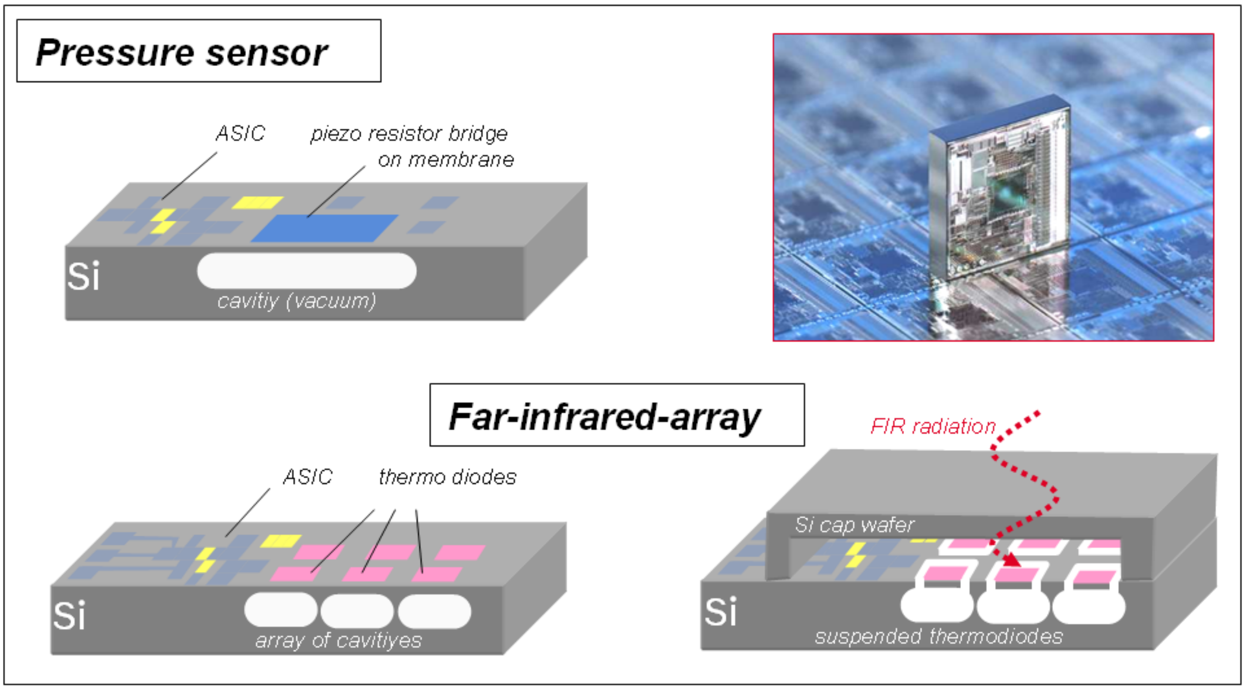

Fig. 3. A production proven integrated MEMS process for surface micro-machined pressure sensors (top) is adapted for manufacturing suspended thermo-diodes for FIR sensor arrays with a single additional mask step and wafer-level vacuum packaging (bottom).

3.2 Process flow

First a cavity below an epitaxial layer of mono-crystalline-quality silicon is formed by means of local porosification of silicon, followed by deposition of an epitaxial silicon layer. Cavity formation occurs due to thermal rearrangement of the porous region due to the high temperature process [8]. With the substrate prepared in this way a standard ASIC process can be run in the epi-silicon layer generating the read-out ASIC and the p+/n-epi sensing thermo-diode array simultaneously during a single process sequence. Finally openings of the cavity are produced by reactive etching the epitaxial layer and simultaneously removing the silicon under the suspension arms in order to generate suspended thermo-diode islands only connected to the substrate by two bridges of dielectric material and contact metal. This is required for thermally and electrically decoupling the diodes from the substrate. The general processing sequence is shown in figure 4.

A final vacuum encapsulation on wafer level finishes the process and provides easily testable and dice-able chips suited for direct application in a chip-on-board assembly. The cap wafer is micromechanically pre-structured with a cavity in the active array area and with openings to keep the bond-pad region free. As bonding material we use standard screen printed seal glass. This established MEMS process is production proven in high volumes e.g. for accelerometers or gyros and can be used for mono-crystalline FIR-arrays without problems in contrary to other bolometer materials like VOx, which do not withstand the temperature budgets involved.

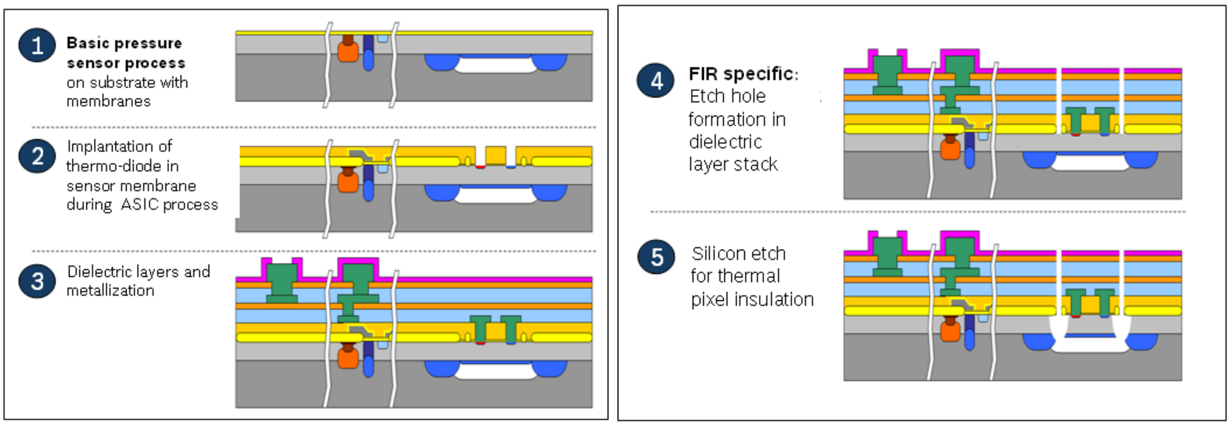

Fig. 4. Basic process flow for the FIR sensor: Steps 1, 2 and 3 schematically represent the steps adapted from the integrated pressure sensor; 4 and 5 show the cavity opening as FIR-array specific process step.

3.3 Sensor Test Design

Thermal insulation of the detector structure is the key parameter in any thermal FIR-detector design in order to achieve a high temperature increase from the small amounts of thermal irradiation on the pixel. The heat conduction through the suspension arms dominates the quality of thermal insulation besides radiation losses and heat conduction through the residual gas. We use L-type suspension arms (figure 5, left) giving the best compromise of thermal insulation and pixel area reduction due to the in-plane construction. The suspension and pixel surface material consists of the dielectric layer stack out of the semiconductor process and incorporates also the connection lines to the diodes suspended below the pixel surface. The contact-lines are made in the ASIC's metal 1 layer material and add the largest contribution to the thermal leakage. In order to achieve the same electrical characteristics for the pixel and the substrate temperature reference diodes, we use the same suspended diode design for both, but have the suspension arms thermally short-circuited in the case of the reference diode. Figure 5 shows the simulated temperature increase due to the same incident radiant power of 50nW for both structures. The small thermal response of the reference diode is acceptable and is further improved if the diode is additionally shielded with a metal layer against thermal irradiation.

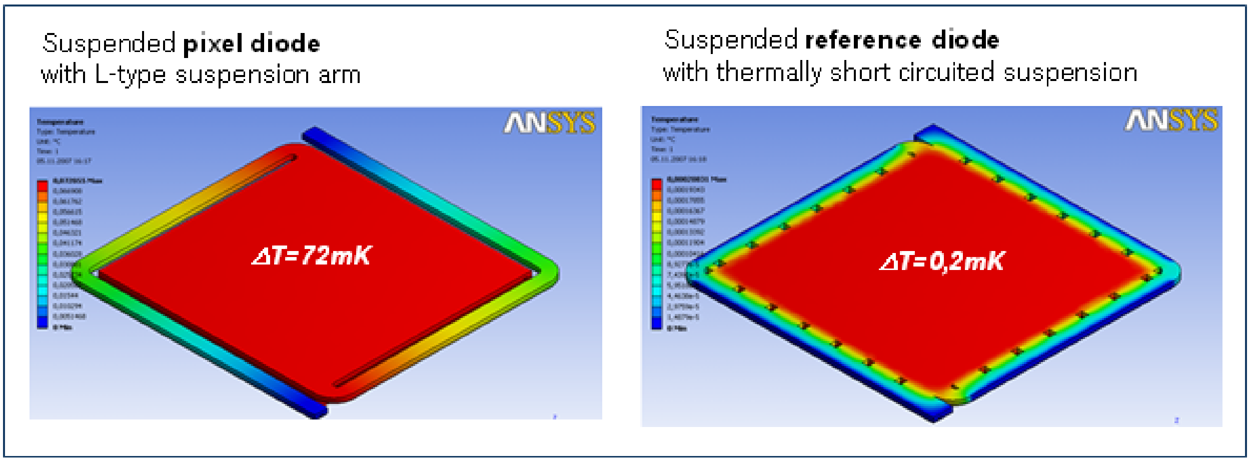

Fig. 5. Pixel diode and reference diode with simulation of the temperature increase from an incident radiant power of 50nW.

As test device for verification of the process and concept we designed and realized small integrated arrays with 42 x 28 pixels at a pixel pitch of 225 µm with a supporting monolithic addressing and readout circuit for the diode array.

4 Results

4.1 Technology run

Suspended diodes (see figure 6) produced in the test run have been characterized on wafer-level also with regard to temperature behaviour. Figure 7 shows the characteristics of a typical diode for three temperatures measured on wafer level. The thermal sensitivity of the diodes with constant current operation at 1µA was extracted to be -2.3 mV/K at 25°C.

Responsivity was measured after wafer-level vacuum packaging with 7-14µm thermal radiation and was found to be in the range of 150 V/W for simple single diode pixel designs without any further means like absorption adaptation, gettering or anti-reflection coatings on the silicon window.

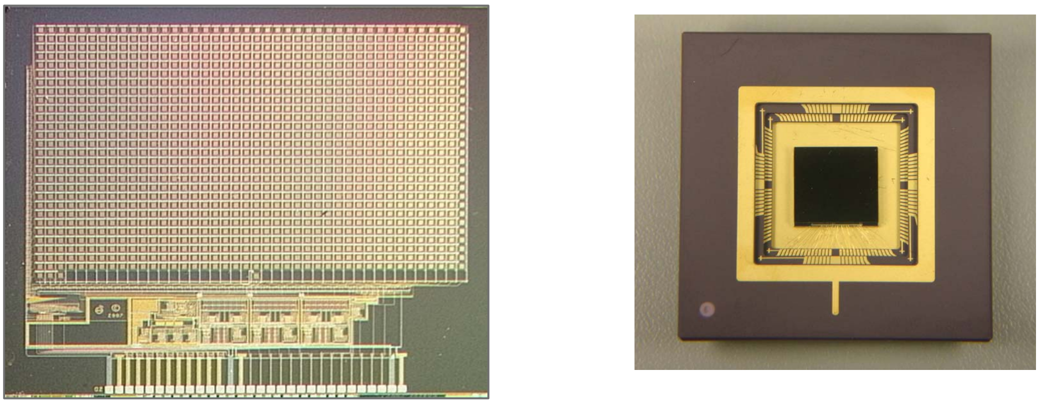

Fig. 6. Photo of the 42 x28 FIR diode test array made with the new process and final vacuum wafer-level packaged chip bonded into a test package.

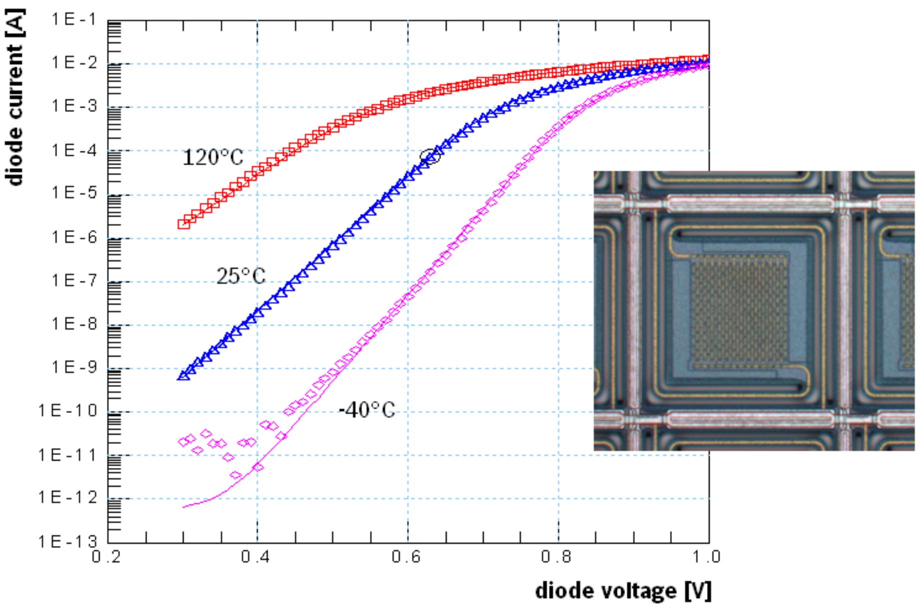

Fig. 7. Current/voltage diagram of a FIR-Diode at different temperatures (left; points: measurement; lines: diode model); photo of a pixel with a suspended thermo-diode (right)

4.2 Results from integrated test arrays

The processing and integration compatible technology has been verified with first small arrays consisting of 42 x 28 pixels and an integrated electronics enabling simple sequential readout of the individual pixels of the array. The electronics provide a column addressing de-multiplexer and multiplexed constant current sources driving the pixels from the row side. Figure 8 shows the basic readout implemented. A low noise differential amplifier provides +40dB pre-amplification of the signal difference between the selected pixel diode and the reference diode. All other signal processing was made in a flexible external electronics with an FPGA providing timing, addressing, first level offset correction algorithms as well as data transfer to a PC.

Figure 8 shows a picture taken with the 42x28 array after 4 times pixel interpolation and a cosine shaped contrast increase. In the optical setup we used an Umicore GasIR® doublet lens with a focal length of 9mm and f/1. The frame rate was restricted to 5 Hz due to the pixel sequential read-out principle. This test device with relatively poor thermal insulation due to the full dielectric stack and the metal tracks present on the suspension arms, together with the single diode pixels allowed us resolving object-temperature differences of about 1K.

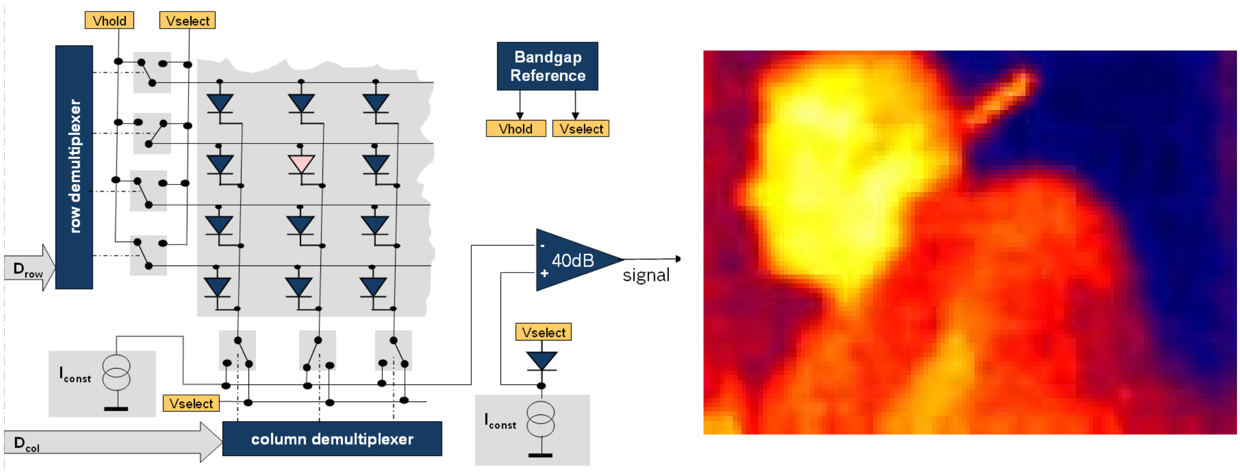

Fig. 8. Basic integrated readout circuit with diode serial addressing for testing (left) and picture taken from a person with the chip (right).

5 Discussion and outlook

In order to reach the automotive requirements discussed in chapter 2, further improvements together with a pixel shrink are currently under development in the EU FP7 project 'ADOSE'. The automotive design will also implement faster column-parallel array read-out. Several options for overall sensitivity improvement exist to compensate the unwelcome effects resulting from shrinking the pixels. As the noise of the mono-crystalline thermo-diodes is less than the amplifier input noise, multiple diodes per pixel in series can be applied to boost responsivity. The residual gas pressure originating from seal glass out-gassing during the encapsulation process presently is another limitation if no getter material is used. We expect from future seal-glass free wafer-level encapsulation processes to gain at least a factor of 2 in sensitivity even without getter material deposition. Additional improvements of the pixel's thermal insulation are possible by reducing suspension thickness or by using poly silicon with reduced thermal conductance as contact material instead of the metal.

6 Summary

A new cost effective and fully semiconductor compatible process has been described which is suitable to manufacture far-infrared sensor arrays for hot spot detection in automotive night vision. A first integration run with the new process was successful and yielded functional integrated 42x28 FIR-arrays. Development of a 100x50 FIR array according to automotive specification is ongoing in the ADOSE Project.

The research leading to these results has received funding from the European Community's Seventh Framework Programme under grant agreement n° 216049, relating to the project 'Reliable Application Specific Detection of Road Users with On-Board sensors (ADOSE)'.

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Keywords: far-infrared, sensor array, automotive night vision, infrared sensor technology, mems