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Low-Cost Far-Infrared FPA based on High-Volume Pressure Sensor Process

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Abstract

In order to achieve substantial cost reduction for far-infrared focal plane arrays (FPA), consequent adoption of existing high-volume MEMS processes is required. For that reason we used a high-volume pressure sensor process for fabrication of thermodiode FPA. While 1st Gen FPA successfully proved the suitability of the fabrication process, performance was strongly improved for the 2nd Gen FPA to meet customer demands for low-cost thermal imaging and thermal sensitivity of 270 mK @ f/1.0 and 9 Hz frame rate was achieved. In addition development of the 3rd Gen FPA with QVGA format, 28 µm pixel pitch and 100 mK thermal sensitivity is ongoing.

Key words: Focal plane array, low-cost far-infrared imaging, thermodiode, APSM process

Introduction

Far-infrared imaging with uncooled focal plane arrays enables a widespread field of applications in different market segments like automotive, industry and security. Nevertheless the production volumes of FPAs are still very limited due to a high price level very unusual for MEMS markets. Key point for establishing a real high-volume market is the availability of FPA and infrared optics for a strongly reduced price level. For many applications even a performance reduction compared to well-established high-end FPA is acceptable.

Typically resistive FPA made from VOx, a-Si or SiGe, but also thermodiode FPA use dedicated processes for this kind of device [1,2]. However dedicated processes in conjunction with low production volumes are a fundamental barrier for significant cost reduction as known from high-volume MEMS products like pressure sensors, accelerometers or gyroscopes.

The approach shown in this paper is the other way round: in order to produce low-cost FPA we use a high-volume MEMS process for pressure sensors. This process is in production since 2007 and more than 100 million sensors were fabricated since then. By this means substantial economies-of-scale become possible for low-cost FPA production.

Low-cost thermodiode FPA concept

The high-volume fabrication process of the thermodiode FPA is based upon the unique Advanced Porous Silicon Membrane (APSM) process [3] which enables the fabrication of free-standing membranes made of monocrystalline silicon. This material allows the formation of pn junctions with a very low 1/f noise. The combination of low-cost micromechanics with excellent electrical performance offers the opportunity for fabrication of thermally isolated pn junctions, also called thermodiodes [2]. Compared to resistive bolometers the thermodiodes also offer the advantage that the sensitivity of the sensing element does not depend on process variations of the resistive layer or the MEMS process, but only on the very well defined semiconductor processes for fabrication of pn junctions. Moreover the sensitivity is less sensitive on device temperature compared to resistive bolometers. Last but not least the self-decoupling capability of diode arrays enables addressing from the array sides without the need of switching elements underneath the pixels.

Generations of thermodiode FPA

Work on thermodiode FPA at Bosch started in 2007 with the public funded project ADOSE (Tab. 1). The 1st Gen of FPA successfully demonstrated the suitability of the APSM process for thermodiode fabrication. The device consisted of a 42*28 pixel array with a relatively large pixel pitch of 230 µm and four thermodiodes per pixel. The Read-out IC (ROIC) part was monolithically integrated side-by-side to the pixel array (Fig. 1).

Tab. 1: Generations of thermodiodes FPA

	1st Gen	2nd Gen	3rd Gen
Status	Study finished (ADOSE)	Series development ongoing	Study ongoing (RTFIR)
Pixel Count	42*28	100*50 80*60	320*240
Pixel Pitch	230 µm	100 µm	28 µm
NETD @ f/1.0	400 mK @ 3 Hz	270 mK @ 9Hz	100 mK (Specification)

Based on these successful results the 2nd Gen FPA was designed to meet more demanding targets for pixel count, pixel pitch, frame rate and thermal sensitivity. The concept of the device remained identical to the 1st Gen except for poly silicon replacing AlSiCu as electric lead material for the suspensions in order to enhance thermal isolation. Based on positive customer feedback series development has been started for the commercialization of the 2nd Gen FPA.

The sensor concept shown in Fig. 1 allows the use of well-established design and fabrication processes at Bosch. However, pixel pitch and by this means the number of pixels are limited due to common layout rules for both ROIC and thermodiode pixels. In order to broaden the portfolio, development of the 3rd Gen FPA was started with the support of the public funded project RTFIR.

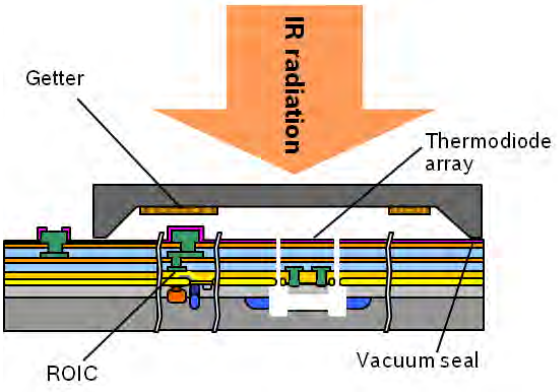

Fig. 1. Schematic of 1st and 2nd Gen FPA with ROIC side-by-side to the pixel array. Glasfrit waferbonding and getter provide vacuum inside the cavity.

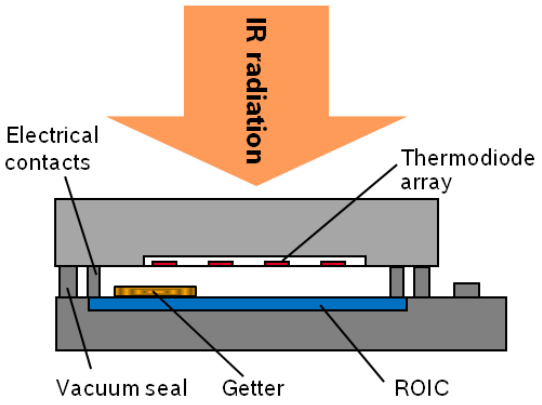

Fig.2: Schematic of 3rd Gen FPA.

The 3rd Gen will continue to use thermodiodes using the APSM process. The ROIC will make use of an advanced CMOS process and will be attached to the sensor by a waferbonding process (Fig. 2). By this means thermodiodes and ROIC can be optimized separately. The waferbonding process will provide both vacuum encapsulation and electrical contacts from sensor chip to ROIC. This unique concept is enabled by the self-decoupling property of a diode array. While resistive bolometer pixels require some type of switching element per pixel, a diode array can be accessed using just row and column lines, reducing the number of required contacts to the ASIC by more than 2 orders of magnitude.

Sensor process flow and sensor design

The fabrication of the thermodiode FPA starts with the so called Advanced Porous Silicon Membrane (APSM) process. The main steps of this surface micromachining process are local anodic etching of porous silicon, followed by thermal rearrangement of the porous silicon and finally epitaxial growth of a silicon layer. More details on the process can be found in [3]. By this means a monocrystalline membrane layer on top of vacuum cavities can be formed in the region of the pixel array.

Following the APSM process, pn junctions are implanted in the monocrystalline silicon membrane. As a next step, dielectric and metallization layers are deposited (Fig. 3), using the standard high-volume process for pressure sensor fabrication. For 1st Gen and 2nd Gen FPA these process steps are also used for ROIC fabrication side-by-side to the pixel array. Then the pixels are released by etching the dielectric layers and the monocrystalline silicon membrane. Afterwards isotropic undercutting is applied to remove the monocrystalline silicon underneath the suspensions in order to reduce their thermal conductivity.

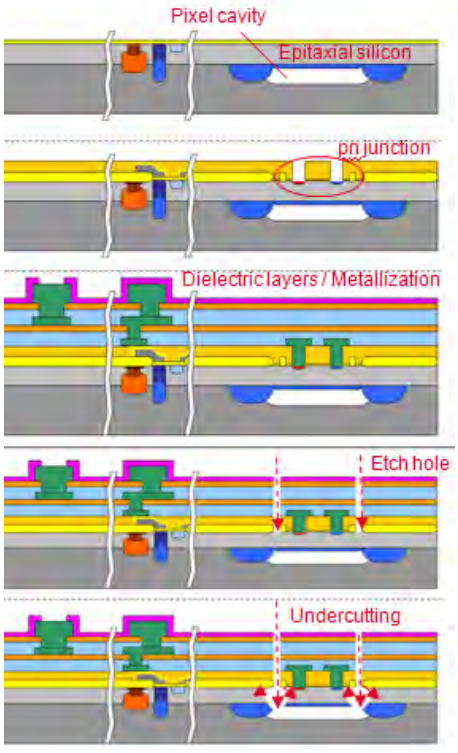

Fig. 3. Process flow for fabrication of the pn junctions and the ROIC and for release of the pixels.

Fig. 4 and 5 show the chip layout for 1st and 2nd Gen FPA. Additionally a single pixel with four pn junctions in series and the suspensions for thermal isolation and electrical interconnects is shown in Fig. 4. Pixel pitch and fill factor are 230µm and 56% for 1st Gen FPA and 100µm and 52% for 2nd Gen FPA respectively.

For 1st and 2nd Gen FPA wafer processing is completed by standard glasfrit waferbonding to provide vacuum encapsulation. The getter is located on the inner surface of the silicon cap wafer.

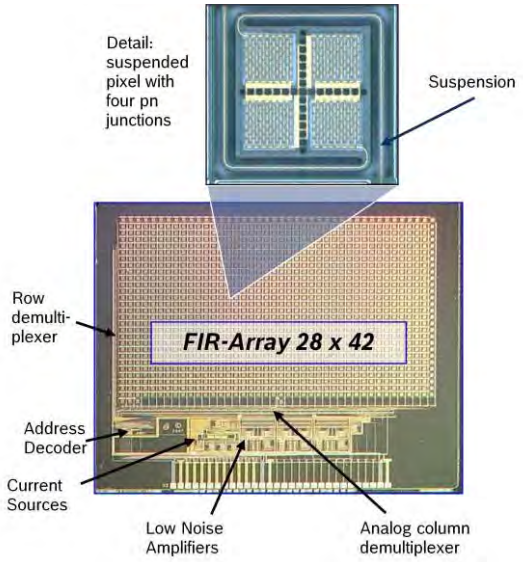

Fig. 4. Picture of 1st Gen FPA and single pixel with 4 thermodiodes (without cap wafer).

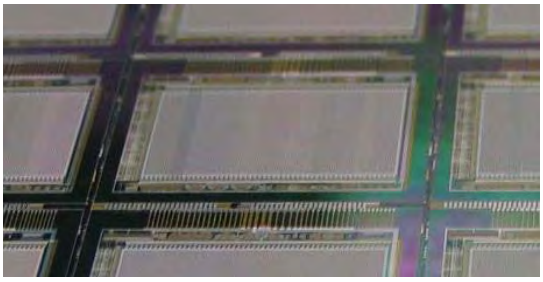

*Fig. 5. Picture of 2nd Gen FPA with 100*50 pixel on wafer (without cap wafer).*

For 3rd Gen FPA the sensor chip will no longer contain the ROIC. As a result, the process flow and layout rules can be adapted to decrease the pixel pitch, thermal mass and sensitivity.

Results

1st Gen FPA was designed as proof-of-concept for thermodiodes using the APSM process. With relatively large pixels (230µm pitch), a low pixel count of 42*28 pixels and a 3-channel differential amplifier a thermal sensitivity (Noise equivalent temperature difference - NETD) of 400 mK was achieved at a frame rate of 3Hz and with f/1.0 optics. Detailed noise analysis revealed that the ROIC was the dominating noise source. Using an improved low noise amplifier, NETD of <50mK seems feasible as a result of the advantageous large absorption area of the pixels.

For 2nd Gen FPA the requirements were adapted to achieve a competitive specification regarding pixel count and pixel pitch, thermal sensitivity (NETD) and frame rate. In addition a low power consumption of only 25mW was achieved.

With 100*50 pixels and 100 µm pixel pitch a thermal sensitivity of 180 mK @ f/0.8 and 9 Hz frame rate was achieved, corresponding to 270mK @ f/1.0 . The NETD measurement was performed at room temperature after calibration at 25°C and 35°C blackbody temperature.

Frame rate for 2nd Gen FPA is limited by the thermal time constant of heat flow from pixel to substrate. Measurements of the thermal time constant were performed by exploiting the self-heating effect of the pixels: the electrical current through the pixel was changed and the time dependency of the applied voltage was analyzed. This resulted in a thermal time constant $t_{63\%} \approx 120$ ms which is sufficient for 9 Hz frame rate, well-suited for many applications and fitting to export control regulations.

In order to quantify the heat dissipation through the suspensions and the residual gas, the thermal time constant was also measured at different pressure values inside a vacuum chamber using a sensor chip without cap. The measurements confirmed that for time constants $t_{63\%} \approx 120$ ms the heat dissipation through the suspensions exceeds the one through the residual gas.

This demonstrates how effective the getter reduces the residual gas pressure taking into account outgasing during standard glasfrit bonding.

In addition, the quality of the thermodiodes was characterized using their thermal coefficient. Typical values of -2,1..-2,2 mV/K were measured per pn junction showing good agreement with theoretical calculations [4].

A typical image taken with these 2nd Gen FPA is shown in Fig.6.

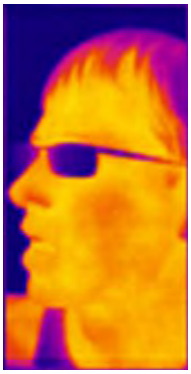

*Fig. 6. Example of image taken with 2nd Gen FPA (100*50 pixel sensor chip). The image was upscaled to 300*150 pixel by pixel interpolation*

Summary

Low-cost far-infrared sensor arrays were successfully fabricated using a high volume MEMS manufacturing process for pressure sensors. Advanced porous silicon membrane process (APSM) was used for fabrication of thermally isolated Si membranes. Thermodiodes were integrated in the membranes for temperature to voltage conversion. APSM provides monocrystalline membranes which is beneficial for reducing 1/f noise of the thermodiodes.
Specification of the FPA was adapted to low-cost applications. For the 2nd Gen FPA using 100*50 pixels and 100µm pitch a thermal sensitivity (NETD) of 270mK @ f/1.0 at 9 Hz frame rate was achieved. Future developments focus on further performance improvements for both 2nd and 3rd Gen FPA.

Acknowledgements

Part of the research leading to the results of 1st and 2nd Gen FPA 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)". Work on the 3rd Gen FPA currently receives funding from the German ministry for education and research (BMBF) within the excellence cluster MicroTEC Südwest as project number 16SV5128 (RTFIR).

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