A digital 25µm pixel-pitch uncooled amorphous silicon TEC-less VGA IRFPA with massive parallel Sigma-Delta-ADC readout

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ABSTRACT

This paper presents an advanced 640 x 480 (VGA) IRFPA based on uncooled microbolometers with a pixel-pitch of 25µm developed by Fraunhofer-IMS. The IRFPA is designed for thermal imaging applications in the LWIR (8 .. 14µm) range with a full-frame frequency of 30 Hz and a high sensitivity with NETD < 100 mK @ f/1. A novel readout architecture which utilizes massively parallel on-chip Sigma-Delta-ADCs located under the microbolometer array results in a high performance digital readout. Sigma-Delta-ADCs are inherently linear. A high resolution of 16 bit for a second-order Sigma-Delta-modulator followed by a third-order digital sinc-filter can be obtained. In addition to several thousand Sigma-Delta-ADCs the readout circuit consists of a configurable sequencer for controlling the readout clocking signals and a temperature sensor for measuring the temperature of the IRFPA. Since packaging is a significant part of IRFPA's price Fraunhofer-IMS uses a chip-scaled package consisting of an IR-transparent window with antireflection coating and a soldering frame for maintaining the vacuum. The IRFPAs are completely fabricated at Fraunhofer-IMS on 8" CMOS wafers with an additional surface micromachining process. In this paper the architecture of the readout electronics, the packaging, and the electro-optical performance characterization are presented.

Keywords: Infrared detector, IRFPA, VGA, uncooled microbolometer, amorphous silicon, Sigma-Delta-ADC on chip

1. INTRODUCTION

Low-cost thermal imaging is dominated by uncooled infrared focal plane arrays (IRFPAs) using microbolometers based on vanadium oxide[1-5] (VO_x) or amorphous silicon[6-8] (a-Si) as the sensing material. Uncooled IRFPAs operate at ambient temperature and benefit from the abdication of a Stirling cooler in terms of low-cost, low power dissipation, low weight, and reduced volume. Typical applications for IRFPAs are thermal imaging, pedestrian detection for automotive driving-assistance systems, fire fighting, biological imagery, or military applications like target recognition.

Fraunhofer IMS is one of over 50 institutes of the Germans "Fraunhofer Gesellschaft". With its competence in the areas of CMOS semiconductor components and technology, sensors and microsystems, circuit design and ASIC production the Fraunhofer IMS covers the complete potential of microelectronics. The Fraunhofer IMS has been certified according to DIN EN ISO 9001:2000 and the IC-Fab according to ISO TS 16949. The presented VGA-IRFPA is completely fabricated at Fraunhofer IMS on 8" CMOS wafers with an additional surface micromachining process for the microbolometers and the vacuum package.

2. IRFPA

The presented IRFPA is based on uncooled microbolometers with a pixel pitch of 25µm and a VGA resolution of 640 x 480 pixel. The IRFPA is designed for a high sensitivity (noise equivalent temperature difference NETD) of NETD < 100 mK at a full frame frequency of 30Hz. Due to the high dynamic range of 16 Bit realized by ΣΔ-ADCs a TEC-less operation in the temperature range between -40 °C and 80 °C is possible.

The technical data of the presented VGA-IRFPA are summarized in table 1.

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Table 1. Parameters of IMS VGA-IRFPA

Parameter	Value
Image format	640 x 480
Frame frequency (progressive)	30 Hz
Output signal	16 bit (digital)
Temperature range	-40 °C ..80 °C
Power supply voltage	3.3 V and 1.8 V (digital) 3.3 V (analog)
NETD	<100 mK (design value)

The block diagram of the presented VGA-IRFPA is shown in figure 1.

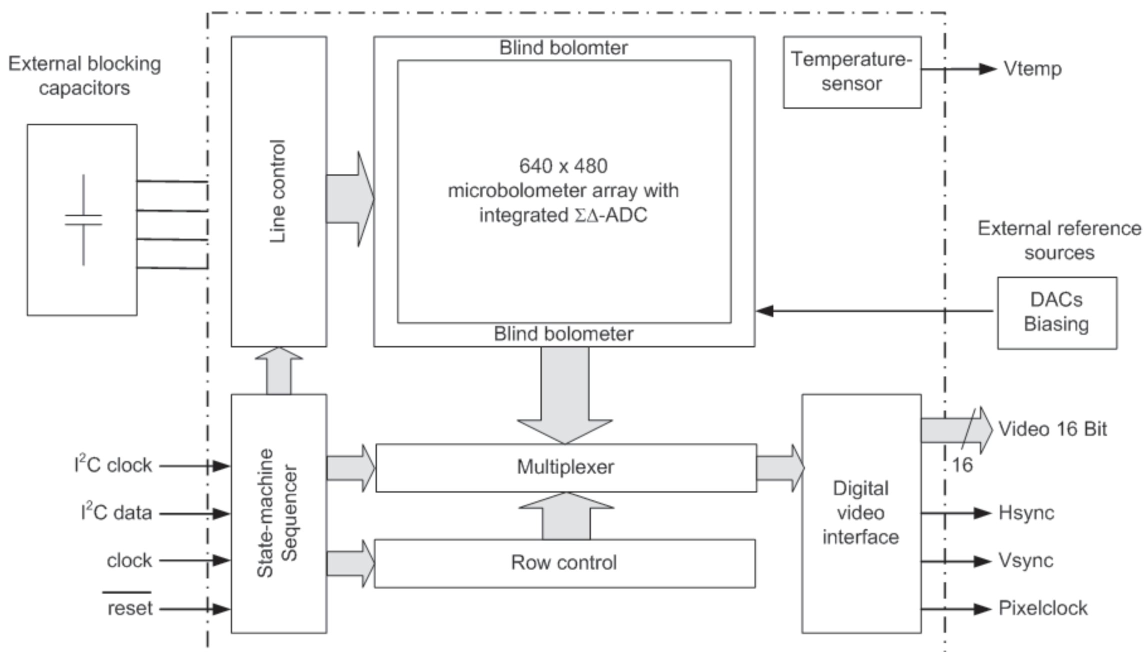


Figure 1. Block diagram of IMS VGA-IRFPA

The 640 x 480 microbolometer array is read out by using massively parallel ΣΔ-ADCs located under the array. A certain amount of microbolometers is multiplexed by one ΣΔ-ADC. Blind microbolometers with a reduced responsivity are located in a ring arround the active microbolometer array. The ΣΔ-ADCs convert the scene dependent resistor change directly into 16 bit digital signals. These 16 bit image signals are fed into the digital video interface by a multiplexer. A sequencer controls the readout pattern by selecting each ΣΔ-ADC using a line and row control block. The configuration of the sequencer can be changed using an I^2C-like interface. A built-in self-test supports the wafer test und reduces test time. The digital video interface provides three synchronization signals (horizontal, vertical and pixelclock) in addition to the image signals. A temperature sensor measures the temperature of the IRFPA. The temperature sensor is realized by three diodes connected in series followed by a buffer as an analog output stage. The temperature signal V_{temp} is an analog voltage proportional to the temperature of the IRFPA and can be used for TEC-less operation. The IRFPA needs one analog supply voltage of $V_{dda} = 3.3$ V and two digital supply voltages of $V_{ddd} = 3.3$ V and $V_{dd2} = 1.8$ V. Five different reference voltages are necessary for biasing the ΣΔ-ADC. Apart from a reset signal and the I^2C configuration signals the IRFPA needs only one digital clock signal.

3. BOLOMETER

An amorphous silicon based microbolometer is employed as the IR sensor. The bolometers are fabricated in a 25µm pixel pitch by post-processing CMOS wafers in the IMS Microsystems lab. The vertical and lateral pixel geometry was kept very simple and straightforward to ensure a solid baseline process with a high pixel operability[8].

A micromachined membrane is suspended approximately 2 µm above a metal reflector on top of the planarized CMOS and absorbs the IR-radiation. The resulting interferometric structure[9] was numerically optimized for maximum absorption in the FIR band. The sensing layer (amorphous silicon) was optimized for low noise and high TCR.

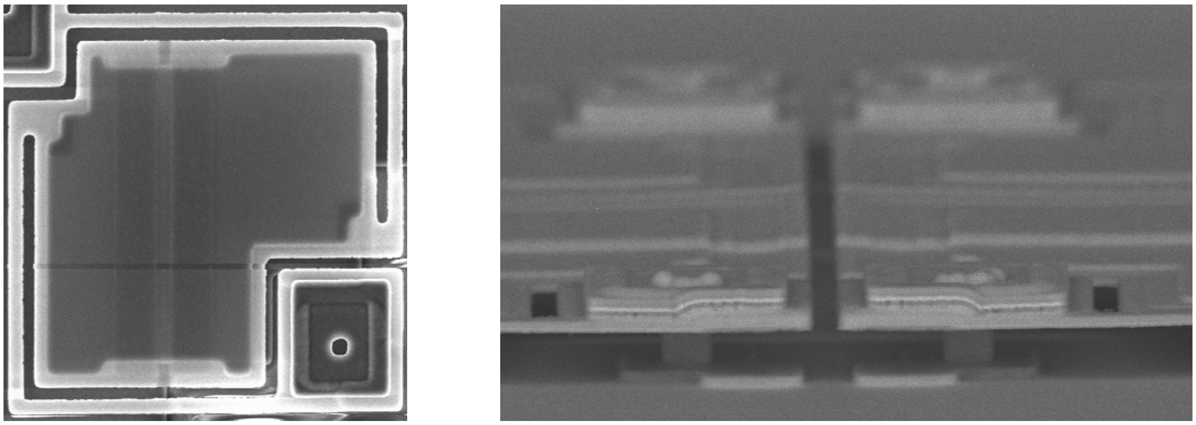


Figure 2. SEM micrograph of a bolometer (top view and cross section)

The left SEM micrograph in figure 2 shows a top view of a typical microbolometer. In the corners, the metal vias connecting the substrate to the membrane can be seen. Two insulating legs are defined along the edges of the central a-Si membrane. The right SEM image shows a sideview of these bolometers and demonstrates that low stress and therefore flat membranes have been achieved.

Some parameters of the IMS bolometer technology are summarized in table 2.

Table 2. Parameters of IMS microbolometers

Parameter	Value
Pixel pitch	25 µm
Spectral response	8 .. 14 µm
Thermal time constant	ca. 15 ms
TCR	> 2.2 % / K
Absorption	ca. 85 %
Fill factor (optical)	> 75 %

4. VACCUM PACKAGE

To reduce thermal losses by gas conduction a vacuum package with an infrared window is required. To reduce packaging costs Fraunhofer-IMS uses a chip-scaled package consisting of an IR-transparent window with an antireflection coating and a soldering frame for maintaining the vacuum. The principle of a chip-scale package is shown in figure 3.

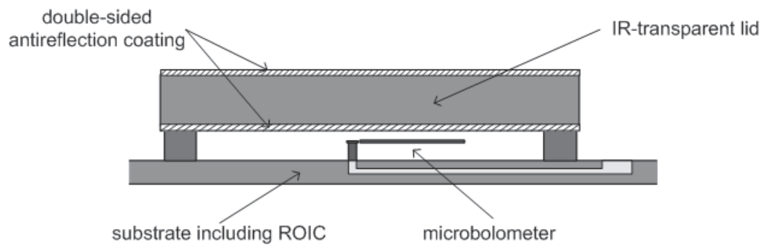


Figure 3. Principle of a chip scale package

The IR-transparent lid consists of silicon with a double-sided antireflection coating and is placed using a solder frame on top of the substrate which includes the readout electronics and the bolometers. The use of silicon as a transparent lid results in lower production costs compared to germanium and causes lower mechanical stress due to equal expansion coefficients between the lid and the substrate. The chip scale package is actually under development in terms of long-time vacuum stability.

Figure 4 illustrates a wafer with partly assembled chip-scale packages.

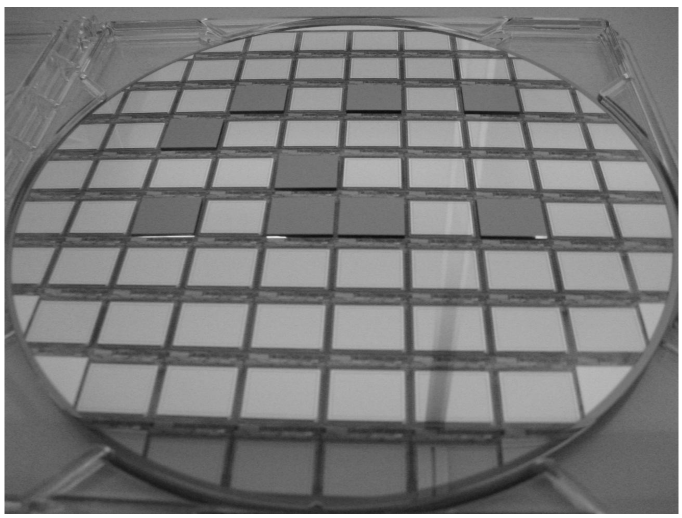


Figure 4. Wafer with chip scale packages

By using a flip-chip technique the lids are placed only on top of "good-tested" chips. This also reduces fabrication costs.

A chip-on-board mounting of this package (figure 5) onto a detector-board is used in the IR-camera system.

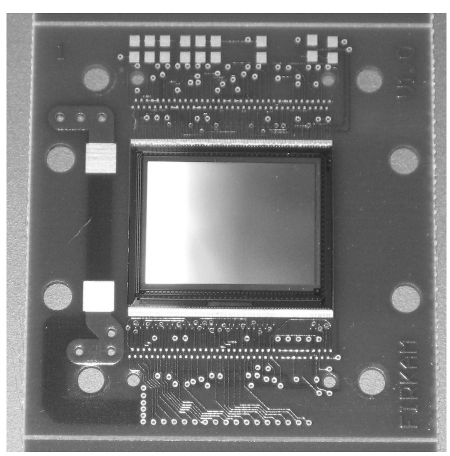


Figure 5. PCB with VGA-IRFPA

The chip-on-board design has a size of 42 mm x 40 mm. The IRFPA can be connected from the back side of the PCB using a board connector.

5. ARCHITECTURE AND DIGITAL READOUT

The electrical signal of a microbolometer is a radiation dependent change of its electrical resistance[10]. A sophisticated readout of a bolometer array integrates the sensor element directly into an ADC. This can be done by using the principle of a sigma-delta ($\Sigma\Delta$) modulator. A $\Sigma\Delta$ modulator achieves a high signal to noise ratio (SNR) by combining oversampling, interpolation, and noise shaping while dispensing with the need of high precision analog components. It relies on the noise spectrum of coarsely quantized input signal being shaped and shifted out of the signal band to higher frequencies to achieve fine quantization.

The readout of the microbolometers based on the use of a 2nd order $\Sigma\Delta$ modulator followed by a 3rd order sinc-filter with a resolution of 16 bit. The 2nd order sigma-delta modulator is realized using single-ended switched capacitor (SC)-technique (figure 6).

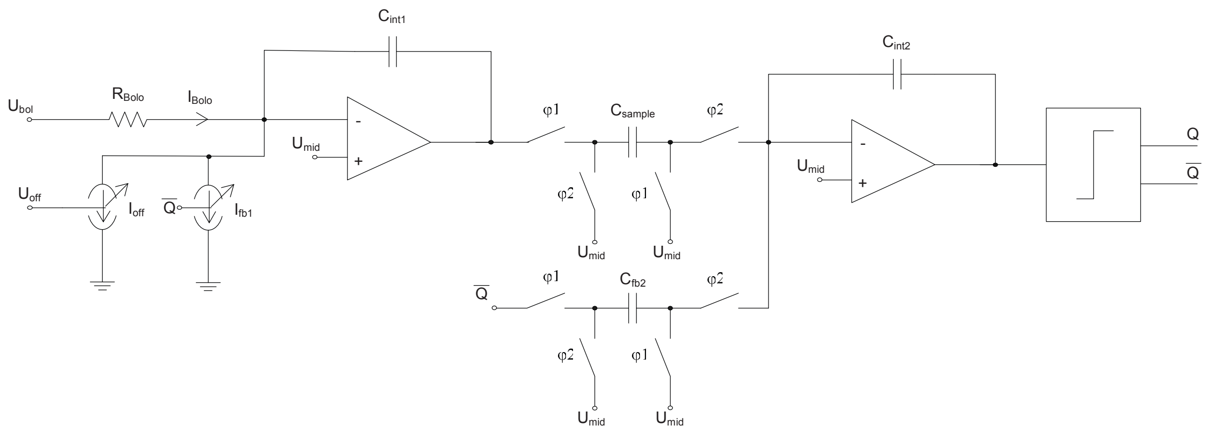


Figure 6. 2nd order $\Sigma\Delta$-modulator

Because of noise requirements the 1st integrator is realized as a continuous-time type with two voltage-controlled current sources, a transconductance amplifier (OTA), and a capacitor C_{int1} in order to realize a current to voltage conversion. A bias voltage U_{bol} is applied to the resistor of the microbolometer R_{Bolo} resulting in a current I_{Bolo}. The signal independent offset part of the current I_{Bolo} will be reduced by a 1st voltage-controlled current source. This current source subtracts the offset current I_{off} from the bolometer current I_{Bolo}. The resulting current difference $I_{Bolo} - I_{off}$ is integrated using the integration capacitor C_{int1} of the left OTA. The $\Sigma\Delta$ principle requires a feedback loop with the output signal which is realized by a further voltage-controlled current source.

The 2nd integrator is realized as a discrete-time type using switched-capacitor technique with a non-overlapping two phase clock. The output voltage of the 1st integrator is sampled at the end of phase Phi1. The resulting charge is shifted into the second integrator capacitor during phase Phi2. The feedback loop of the $\Sigma\Delta$-modulator is carried out by a SC-current source using the capacitor C_{fb2}. The output voltage of the 2nd integrator is valid at the end of phase Phi2 and fed into a comparator. The output of the comparator generates a high frequency bit stream Q. This signal is used as the output signal and for closing the feedback loop of the $\Sigma\Delta$-modulator. The integration coefficients of the 1st and 2nd integrator stage are designed to ensure stable operation of the $\Sigma\Delta$-modulator. The output of the $\Sigma\Delta$ modulator is digitally filtered using a 3rd order sinc-filter. The sinc-filter is used for dezimating and low-pass filtering the bit stream of a $\Sigma\Delta$-modulator .The output of the sinc-filter is a 16 bit digital value. Over 10000 $\Sigma\Delta$ modulators and sinc-filters are integrated for a parallel readout of the microbolometers. Every ADC is multiplexed for read out of a certain amount of microbolometers.

The chip photo of the realized IRFPA is presented in figure 7.

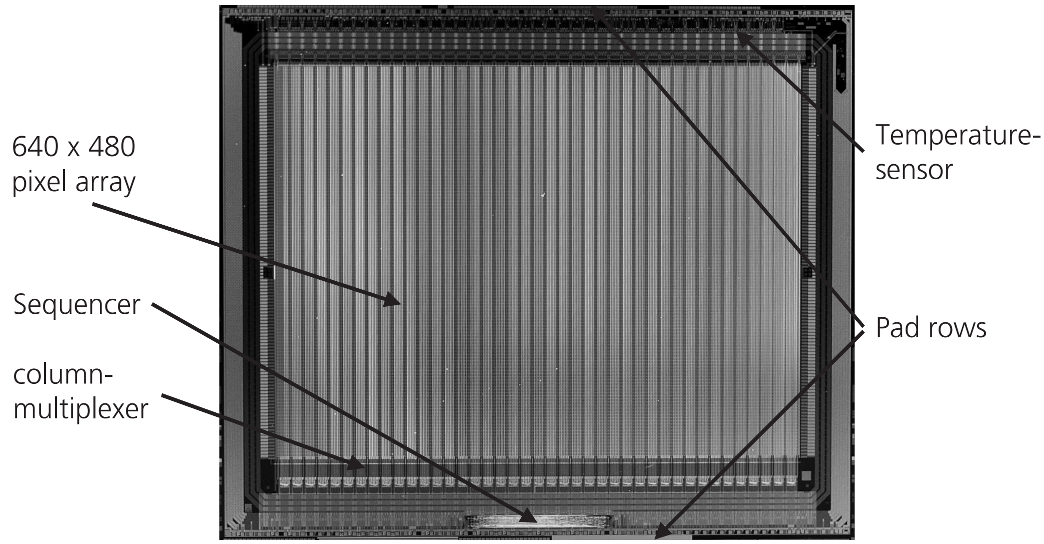


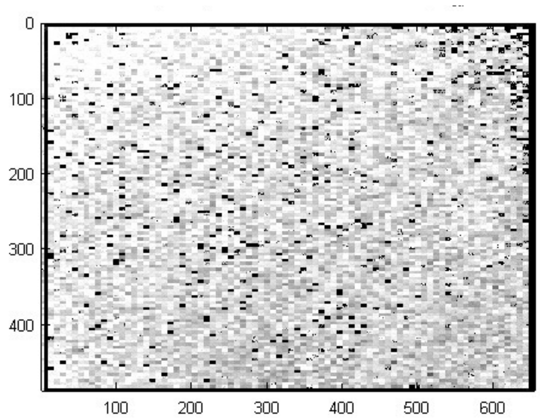
Figure 7. Chip photo VGA-IRFPA

The IRFPA is fabricated in a 0.35 µm CMOS technology with additional micromachining on top of the wafer at Fraunhofer IMS and occupies an area of approx. 326 mm^2 with 13.6 million transistors. The chip-scale package has been removed for this chip photo. Most of the chip area is covered by the microbolometer array at the central part of the IRFPA. Two pad rows at the top and bottom edge of the IRFPA are integrated for the electrical connection of the IRFPA.

6. ELECTRO-OPTICAL CHARACTERIZATION

The IRFPAs are electro-optically characterized using a black body radiation source. The IRFPAs operated at an ambient temperature of 20 °C. The optical conditions correspond to f/1. A dedicated vacuum test package has been used during the characterization.

The local distribution of the responsivity shows figure 8.



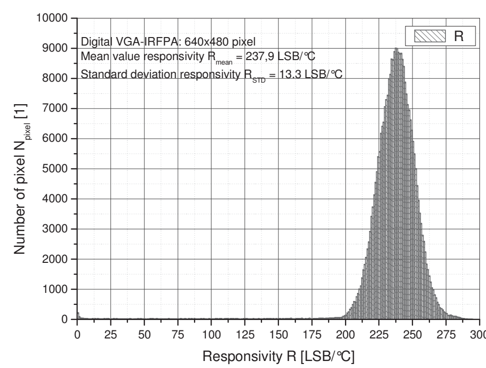


Figure 8. Responsivity (local distribution and histogram)

The responsivity shown in figure 8 is calculated as the change of the digital values as the temperature of the black body is changed from 25 °C to 35 °C dived by 10 °C. The local distribution at the left side of figure 8 shows a homogeneous image. The right side of figure 8 depicts the histogram of the responsivity which shows a Gaussian distribution with a mean value of R_{mean} = 238 LSB/K and a standard deviation of R_{std} = 13 LSB/K.

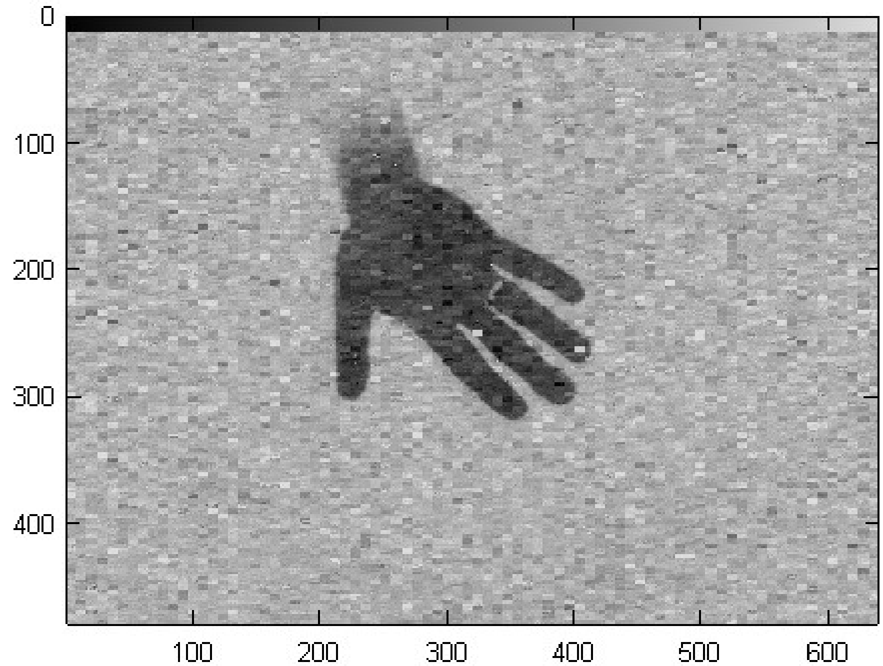


Figure 9. Uncompensated IR image with f/1.2 optics

An IR image of a human hand illustrates figure 9 using a f/1.2 lens. Apart from a simple offset correction the shown image is uncompensated, i.e. no gain, defect pixel, or noise correction has been applied. Further electro-optical characterizations are ongoing.

7. CONCLUSION

A digital IRFPA with 640 x 480 pixel and a 16 bit digital output signal has been designed, fabricated and electro-optically tested. The microbolometers feature a pixel pitch of 25 µm and consist of amorphous silicon as the sensing layer. The digital readout of the microbolometer is based on a massively parallel use of ΣΔ modulators followed by sinc-filters. A chip-scaled package is realized for cost reasons as a vacuum package. For thermal imaging applications a chip-on-board solution is available.

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