Uncooled IRFPAs based on scalable nanotube microbolometers with 6 µm pixel pitch for thermal imaging

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Abstract

Fraunhofer IMS developed a manufacturing process for uncooled IRFPAs based on scalable nanotube microbolometers for thermal imaging. This manufacturing process allows for a variable scaling of the pixel pitch with a lower limit at a pixel pitch of only 6 µm. However, this lower limit of the pixel pitch is not owed to restrictions in the manufacturing process itself but to the fundamental optical limit in the LWIR, occurring at a wavelength of approximately 5 µm. In this regard, the variable scalability of Fraunhofer IMS's nanotube microbolometer technology is enabled by means of vertically oriented nanotubes arranged underneath the actual sensor membrane, resulting in a decoupling of the thermal insulation from the latter. In this publication, the electro-optical performance of a fully integrated IRFPA realized by a nanotube microbolometer array with a pixel pitch of 6 µm at QVGA resolution is evaluated. Key parameters as electro-optical responsivity, noise, NETD and thermal time constant are extracted by means of a digital ROIC. Despite the downscaling of the pixel pitch close to the fundamental optical limit in the LWIR, full electro-optical functionality of the IRFPA is maintained.

1 Introduction

Over the last few years, the interest for uncooled IRFPAs (IRFPA: "infrared focal plane array") for thermal imaging has continuously grown, reaching its climax in the current COVID-19 pandemic with a drastically increased need for contactless measurement of body temperature. However, besides the thermal resolution (NETD: "noise equivalent temperature difference") or the frame rate of the IRFPA, its actual size in terms of the camera body may be a limiting factor for a constant use in mass market applications. In this regard, not only the lens optics itself but above all the actual pixel size of each sensor element determines the resulting size of the IRFPA. State of the art values for microbolometers are sensor elements with a pixel pitch of 10 µm, providing an optical resolution from QVGA (320 x 240) up to Full HD (1920 x 1080) [1,2]. To achieve even higher optical resolutions at a constant size of the actual IRFPA, a further downscaling of the pixel pitch is indispensably required.

Fraunhofer IMS's nanotube microbolometers are based on an amorphous silicon technology to realize uncooled thermal imagers being designed for the LWIR ("long wave infrared") regime. The sensor membrane itself is attached to two vertically oriented nanotubes being connected to the digital ROIC ("readout integrated circuit"). Thus, these nanotubes not only serve as electrical contacts but also realize the actual thermal insulation of the microbolometers. The common design and concept ideas are identical to Fraunhofer IMS's previous works on nanotube microbolometers [3,4].

The electro-optical performance is evaluated by implementing the nanotube microbolometers with a pixel size of 6 µm on Fraunhofer IMS's 17 µm digital ROIC providing QVGA resolution [5]. A homogeneous absorption over the whole array is ensured by placing non-active microbolometers with a pixel size of 6 µm periodically between the active microbolometers of the same pixel size with the latter being electrical connected to the ROIC. Thus, a homogeneous distribution of pixels as well as a constant distance between each pixel is ensured over the whole die. In addition, this incorporation of non-active pixels, which are constructed equally to the active ones, ensures the infrared absorption being comparable between each pixel.

2 Electro-optical parameters

2.1 Responsivity and noise

Responsivity $\mathfrak{R}$ is determined by means of an electro-optical characterization based on a test setup with two black body radiators at different temperatures. Black body temperatures are set to 20 °C and 50 °C, respectively. The responsivity can be calculated by measuring the difference of the digital output values ΔD_{out} stemming from the ROIC providing a 16-bit resolution in relation to the difference of the two black body temperatures ΔT_{BB}:

$$\mathfrak{R} = \frac{\Delta D_{out}}{\Delta T_{BB}}. \tag{1}$$

The electrical noise of the digital output values $\langle D_{out} \rangle$ is estimated by considering 50 frames per pixel.

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ISBN 978-3-8007-5835-7

The distribution of the responsivity for a device with 6 µm pixel size on top of a 17 µm digital ROIC in QVGA resolution is shown in **Figure 1** with a median responsivity of 6.7 LSB/K (LSB: "least significant bit") as visible from the histogram.

The median noise was calculated to $\langle D_{out} \rangle = 4.1$ LSB at 20 °C test temperature.

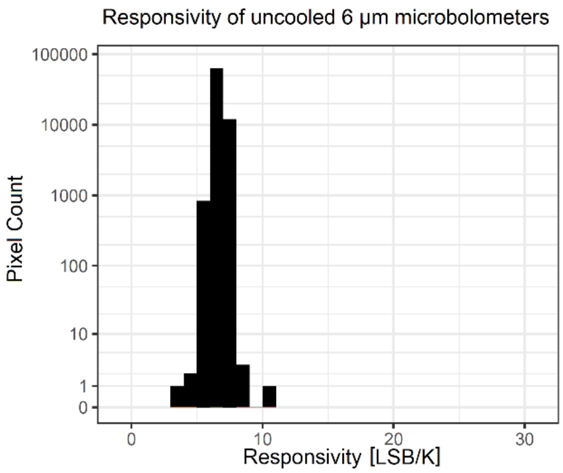

Figure 1 Responsivity of an uncooled thermal imager with 6 µm pixel size on top of a 17 µm QVGA-ROIC.

2.2 NETD

Key parameter for the sensitivity of a thermal imager is given by the noise equivalent temperature difference:

$$\mathrm{NETD} = \frac{\sqrt{\langle D_{out} \rangle^2}}{\Re}. \tag{2}$$

As shown in **Figure 2**, the NETD of our 6 µm nanotube microbolometers is about 611 mK. Although the actual value is still above the NETD level of commercially available uncooled thermal imagers, our 6 µm nanotube microbolometers only require one third of the active sensing area as compared to the standard imagers providing a pixel pitch of 10 µm. [2]

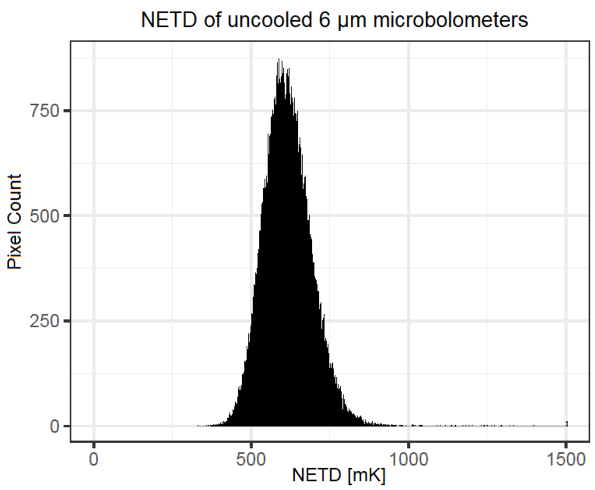

Figure 2 NETD of an uncooled thermal imager with 6 µm pixel size on top of a 17 µm QVGA-ROIC [4].

3 Thermal time constant

The thermal time constant τ is an additional parameter evaluating the performance of an uncooled thermal imager. Typical imagers' frame rates in the range of ~ 30 Hz require thermal time constants < 10 ms to be capable to compensate self-heating effects of the microbolometers due to the readout current.

Definition of the thermal time constant is given as the ratio of the thermal capacitance c and the thermal conductance g:

$$\tau = \frac{c}{g}. \tag{3}$$

3.1 Test setup and measurement

The thermal time constant is determined by measuring the required time for a signal rise and signal drop, respectively, of the digital output values D_{out} towards a stable plateau in a dynamic scene with two defined temperature levels. For that purpose, a chopper wheel is used to periodically interrupt the optical path between the IRFPA and a black body radiator (see **Figure 3**). Surface temperature of the black body radiator is set to 95 °C to achieve a sufficient temperature difference between the surface of the black body radiator and the blades of the chopper wheel with the latter remaining at ambient temperature.

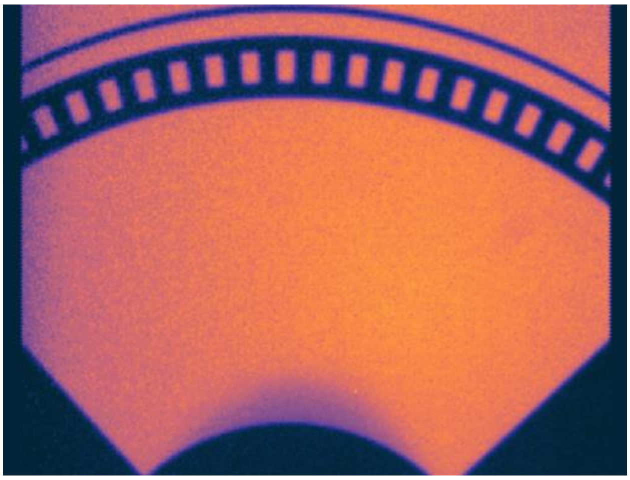

Figure 3 Image of chopper wheel and black body radiator, taken by a 6 µm thermal imager in QVGA resolution.

Frequency of the chopper wheel is set to 4 Hz to ensure a saturation of the digital output values D_{out} at both the lower and the upper temperature, corresponding to the blades of the chopper wheel and the surface of the black body radiator, respectively. In turn, the thermal time constant τ is estimated by an exponential fit following $\propto e^{-t/\tau}$ at the rising or falling edge of the time-resolved signal of the digital output values D_{out} for the selected part of the 6 µm pixels in the middle of the QVGA array that is given by the opening of the chopper wheel itself (see **Figure 4**). The time-resolved signal results from averaging over 72 periods with a period length of 250 ms.

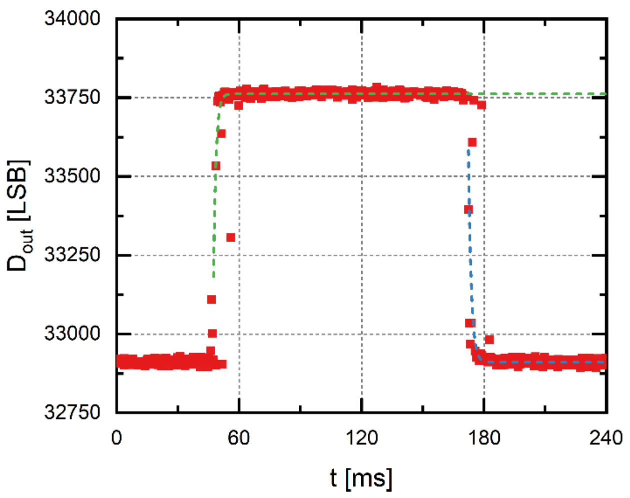

Figure 4 Time-resolved signal of the digital output values D_{out} for the selected part of the 6 µm pixels in the middle of the QVGA array. The exponential fit following $\propto e^{-t/\tau}$ at the rising or falling edge is indicated in a dashed green and blue line, respectively.

3.2 Results and discussion

The exponential fit following $\propto e^{-t/\tau}$ at the rising or falling edge of the time-resolved signal of the digital output values D_{out} for the selected part of the 6 µm pixels in the middle of the QVGA array indicates a value of the thermal time constant in the range of $\tau = (1.2 \pm 0.1)$ ms. This value is nearly one order of magnitude lower than the required value of $\tau < 10$ ms. In consequence, our nanotube microbolometers with pixel size of 6 µm are capable of compensating self-heating effects of the microbolometers due to the readout current and thus, of resolving typical imagers' frame rates in the range of at least ~ 30 Hz.

4 Imager performance

An overview about the key parameters of our uncooled thermal imager based on nanotube microbolometers with 6 µm pixel size is given in **Table 1**.

Parameter	Value
Pixel size	6 µm
NETD	611 mK
Thermal time constant τ	(1.2 ± 0.1) ms
NETD · τ	730 mK · ms

Table 1 6 µm thermal imager's key parameters.

In this regard, the product of NETD and thermal time constant serves as a figure of merit to evaluate both the thermal and the time-resolved resolution of a microbolometer at the same time. The achieved value of 730 mK · ms is roughly a factor of 2 higher than state of the art microbolometers aiming for high performance in terms of thermal resolution, but at a larger pixel size > 6 µm.

5 Summary and discussion

The current limited performance of our nanotube microbolometers with 6 µm pixel size in terms of the figure of merit mostly stems from a too high thermal conductance due to a non-optimized fabrication method of the nanotube contact itself. Future improvements may be achieved by an integration of new material compositions which are suitable for an implementation in our fabrication process on the one hand and provide a lower thermal conductivity on the other hand. In addition, the electrical resistance of the 6 µm nanotube microbolometers was not yet accordingly matched to the operating point of the ROIC, thus resulting in a non-balanced signal-to-noise ratio.

Taking these future improvements into account, a further reduction of the figure of merit may be enabled.

6 Literature

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