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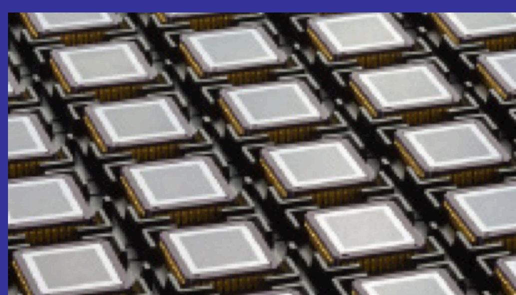
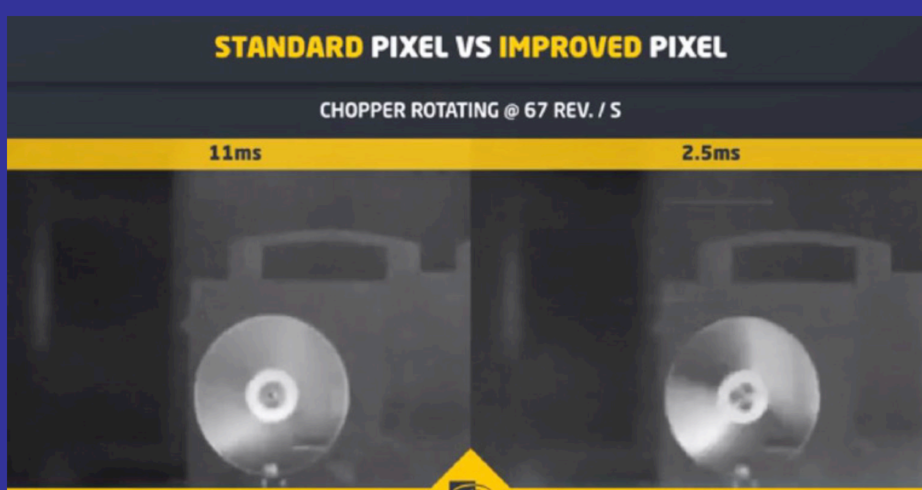
ULIS BOLOMETER IMPROVEMENTS FOR FAST IMAGING APPLICATIONS





ULIS BOLOMETER IMPROVEMENTS FOR FAST IMAGING APPLICATIONS

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Sébastien TINNES, Nicolas BOUDOU, Alain DURAND
ULIS, BP27, 38113 VEUREY VOROIZE, FRANCE, s.tinnes@ulis-ir.com

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ABSTRACT:

Thermal Image Sensor performances for high-end applications can be compared using a factor of Merit (FoM) based on NETD and Thermal Time Constant (τ_{th}). This FoM is defined as FoM = NETDxτ_{th} and is expressed in mK.ms.
Best bolometer FoMs range from 480 to 600mK.ms. When fast response is required from the detector due to short events or fast moving objects in the scene, bolometers can be limited by their τ_{th}, today around 12ms, leading to blurred images. Adjusting the bolometer τ_{th} to reduce smearing can lead to unacceptable NETD performance, keeping FoM globally unchanged.
For these high speed applications requiring good NETD with significantly reduced τ_{th}, ULIS developed an improved 17µm pixel with an exceptional FoM of 120mK.ms, which is 4 times better than the state of the art. The paper will describe the performance obtained in NETD and τ_{th} and describe how they could be combined with existing high frame rate ROIC to address fast imaging applications like machine vision

1. STATE OF THE ART

For the past 15 years, micro bolometer technology has been constantly improving. The race to pixel pitch reduction has been ongoing, from 50µm in the 2000's, to 25µm in 2005, 17µm in 2010 and now 12µm.
On the performance side, the main focus for all Thermal Image Sensor (TIS) manufacturers was to maintain the Noise Equivalent Temperature Difference (NETD), despite pixel pitch reduction.

Depending on markets and applications, NETD around 40 to 50mK are achieved by all main players in the latest full production 17µm pixel pitch technology [1]

Besides NETD, the bolometer Thermal Time Constant (τ_{th}) is also an important parameter for system performances when the application requires fast response time. Typical τ_{th} values ranges from 10 to 16 ms for 17µm pitch bolometers. τ_{th} is an intrinsic characteristic of the bolometer. It is defined by design and cannot be monitored in the product.

A Factor of Merit for the bolometer is defined by

$$\mathrm{FOM} = \mathrm{NETD}.\tau_{\mathrm{th}}$$

This FoM describes the bolometer ability to sense transient events. With this FoM, it is possible to more accurately compare bolometer technologies for high-performance applications which need fast response from the system.
NETD, τ_{th} and resulting FOM for several bolometer manufacturers are described in table 1. Data were collected from websites for VGA/17µm products

Manufacturer	Model	NETD (mk)	τ_{th} (ms)	FOM (mK.ms)
FLIR	Quark2	50	12	600
SCD	Bird640	40	16	640
DRS	U6160	50	14	700
ULIS	PICO640Gen2	40	12	480

Table 1: FOM comparison

Looking at the values above, the best FoMs range from 480mK.ms (40mK, 12ms) to 600mK.ms (50mK, 12ms).

2. BOLOMETER ACQUISITION CHAIN

2.1 Bolometer Thermal Time Constant descriptions

The thermal time constant of a bolometer is a time parameter that expresses how quickly the bolometer reacts to the incoming flux change and reaches its expected level.

The bolometer plate is characterized by its resistor value, which is entirely defined by its temperature. The temperature of the bolometer depends on many parameters, but it follows the simple heat equation law, derived from thermodynamics.

$$\mathrm{C_{th}}.\frac{\partial \mathrm{T}}{\partial \mathrm{t}} = \mathrm{P_{conduction}} + \mathrm{P_{radiation}}$$

$\mathrm{P_{radiation}}$: Total heat power transfer incoming and outgoing by radiation.
$\mathrm{P_{conduction}}$: Total heat power transfer by conduction and convection.
$\mathrm{C_{th}}$: Thermal capacity (J.K-1): capacity to stock heat (depends on material and mass)The power conduction term is easily expressed by:

$$P_{conduction} = -\frac{T_{bol} - T_{out}}{R_{th}}$$

$\mathrm{R_{th}}$: Thermal resistance (of the bolometer/ rest of the world) ($\mathrm{K.W^{-1}}$)

By construction the bolometer is locally linked with only one source: the ROIC at $\mathrm{T_{ROIC}}$ temperature.

$$C_{th}.\frac{\partial T}{\partial t} = -\frac{T_{bol} - T_{ROIC}}{R_{th}} + P_{radiation}(t)$$

As a first order simplification, the radiation power is assumed to be independent from the bolometer temperature. So the solution of this first order differential equation is:

$$T_{bol}(t) = e^{-\frac{t}{\tau_{th}}}.\int_{-\infty}^{t} \frac{P_{radiation}(x)}{C_{th}}.e^{\frac{x}{\tau}}dx + T_{ROIC}$$

$$T_{bol}(t) = \int_{-\infty}^{t} \frac{P_{radiation}(x)}{C_{th}}.e^{\frac{x-t}{\tau_{th}}}dx + T_{ROIC}$$

Where $\mathrm{\tau_{th} = C_{th}.R_{th}}$ (second)

So the temperature is dependent on the incoming flux through a temporal convolution with the exponential function. If we observe a simple step function: (See figure 1)

$$\mathrm{P_{radiation}(x)} = \begin{cases} \mathrm{A\ if\ \ x < t_0} \\ \mathrm{B\ if\ x \geq t_0} \end{cases}$$

$$\mathrm{T_{bol}} = \begin{cases} \mathrm{T_{ROIC} + A.R_{th}\ if\ \ x < t_0} \\ \mathrm{T_{ROIC}} + \left(\mathrm{B + (A - B).e^{\frac{t_0 - t}{\tau_{th}}}}\right).\mathrm{R_{th}} \end{cases}$$

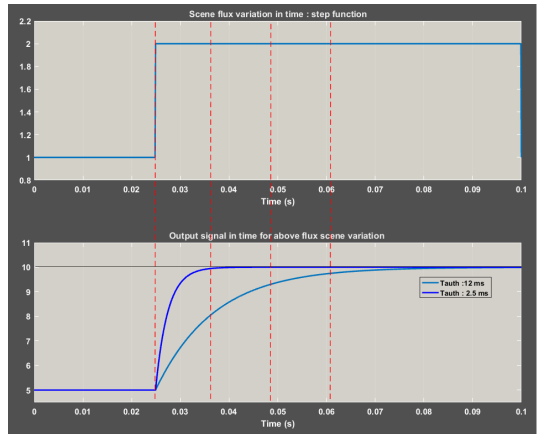

Figure 1: Bolometer response to a step function for two τ_{th} values

The thermal time constant is the parameter of the temporal filter $\mathrm{\tau_{th}}$. It consists in multiplication of the Rth : Thermal Resistor and Cth : Thermal capacity of the bolometer. We can draw a parallel with electronics and namely with temporal filters generated by a capacitance and a resistance. The mathematical function is similar.

As it is shown on fig.1, for a bolometer to react to a step function and reach 95% of the expected output signal, it needs 3*$\mathrm{\tau_{th}}$.

2.2 Bolometer Read Out Integrated Circuit (ROIC)

2.2.1 ROIC global architecture

The bolometer layers are processed directly on top of dedicated imaging CMOS Read Out wafers. This Read Out Integrated Circuit (ROIC) associated to the sensor measures each pixel's thermometer resistance value. It is operated in rolling shutter mode. Each imaging pixel is addressed through a common gate MOS transistor and operates with a skimming blind bolometer, as described in Fig. 2, to remove a large part of the useless offset current going through the bolometer. The pixel signal is provided to the video output through a low noise CTIA

(Capacitive Trans-Impedance Amplifier) used in the input stage of the ROIC. This stage converts the current in the bolometer to a voltage value, and sizes the ROIC gain with the Cint and Tint couple (respectively integration capacitor and integration time).

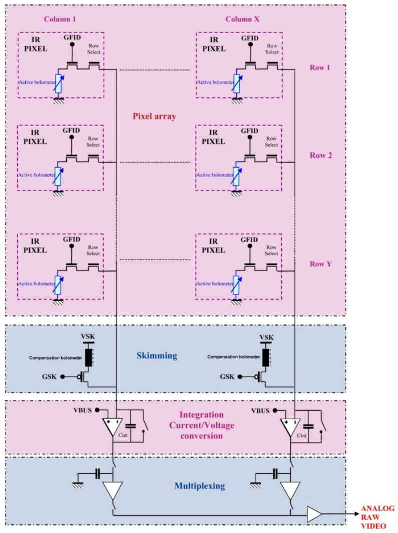

Figure 2: Pixel readout architecture

2.2.2 Integration time versus τ_{th}

Integration time is a ROIC settable parameter. It defines the time bolometers are polarized to measure their resistance. Due to rolling shutter structure, all the bolometers in a row are read simultaneously. The maximum integration time is dependent on frame rate and on the number of rows in the ROIC. For a 320x240 resolution sensor
and a frame rate of 60Hz, the maximum integration time will be approximately 70µs (1/240/60).

As defined in §2.1, Thermal Time Constant is defined by the design of the bolometer. This parameter is not configurable in the product set-up. It is fully independent from the integration time.

2.2.3 High Frame rate ROIC capability

ULIS Pico640Gen2 and Pico1024Gen2 (respectively VGA/17µm and XGA/17µm) products integrate improved ROIC architecture, allowing Focal Plane Array to be read at up to 120 frames per second.

Video outputs and associated video amplifiers were added to the ROICs in order to manage the additional data flow. PICO640gen2 runs at up to 60Hz with one output and has a second output for frame rates above 60Hz and up to 120Hz. Pico1024Gen2 runs with two outputs up to 60Hz and needs four outputs from 60 to 120Hz.

As described §2.2.2, integration time will not be affected by the number of outputs. At 120Hz for a VGA detector, the integration will be around 17µs (1/480/120).

3. Bolometer limitations for fast imaging

3.1 Limitations due to τ_{th}

When it comes to fast-moving scenes, bolometer τ_{th} plays an important role. For an image N to not be affected by the events seen in image N-1, the τ_{th} of the bolometer has to be at least 3 times lower than the event duration in front of a pixel. This means that, with τ_{th} around 10ms, a bolometer can correctly sense a 30ms event and will need around 30ms more to come back to its equilibrium state.

For shorter events (or faster scene movements), it is possible to use the higher frame rate capabilities of ULIS bolometers. This will help in getting more temporal information, but the thermal time constant may limit interest of this information in two ways: S/N ratio and blurring of the image.

3.1.1 Signal to Noise limitation
Due to a higher frame rate, the responsively of the bolometer will be reduced as the integration time is reduced. This drop in signal is independent on the thermal time constant.
The S/N ratio will further drop due to τ_{th}, as τ_{th} defines the time needed by the bolometer to reach its expected level. With short events (shorter than 3*τ_{th}), a bolometer will not heat up to its optimal temperature, leading to signal loss and, as a consequence, signal to noise ratio will be reduced. To get full signal, τ_{th} would have to be reduced.

3.1.2 Image blurring

As the scene flux disappears from a pixel field of view, the bolometer will need 3 τ_{th} to come back to its equilibrium temperature. In the meantime, the pixel will have a residual signal until it reaches a new equilibrium temperature. This leads to blurring in the image, as shown in §5. To reduce this phenomenon, again, shorter τ_{th} is needed.

3.2 Difficulties to reduce τ_{th}

The micro bolometer thermal time constant τ_{th} is usually described as the product of the thermal capacitance Cth and the thermal resistance Rth : τ_{th} = Cth*Rth.
Very often, Cth and Rth are independent quantities, since the Cth is related to the volume of the bolometer membrane and the Rth comes from the bolometer arms geometry.
Obviously, small time constants require a reduction of Cth or/and Rth. This is not a design challenge in itself. Reducing Cth is possible, either by downsizing the membrane surface or by using thinner layers, while small Rth are feasible with larger (and thus easier to fabricate) thermal arms.
Challenges arise when this thermal time constant reduction must not affect others detector figures of merit, in particular thermal sensibility, which is expressed in this paper as NETD (Noise Equivalent Temperature Difference).
The bolometer optical coupling factor is very dependent on the membrane surface which acts as absorber. Downsizing the bolometer membrane will thus degrade this coupling factor and the detector NETD in a direct manner. Moreover, reducing the membrane layers' thickness would cause additional issues, such as higher mechanical instability. Similarly, as the detector response is directly proportional to the thermal resistance, it cannot be reduced without leading to sensitivity degradation.
As a consequence, substantially decreasing the bolometer thermal time constant while maintaining a state of the art sensitivity poses a major technological challenge [2].

4. ULIS FAST BOLOMETER PERFORMANCE

Several low thermal time constant bolometer configurations have been designed, fabricated, and characterized at ULIS facilities.

Fig. 3 is NETD versus thermal time constant plotted for a state of the art 17 µm micro bolometer and for the low τ_{th} ULIS prototypes. It shows a NETD ranging from 43 mK to 51 mK with τ_{th} ranging from 2.5ms to 3.9ms.

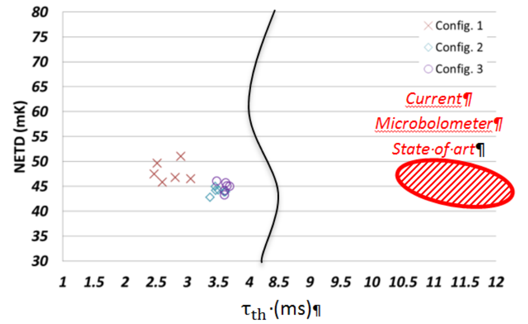

Figure 3: NETD vs τ_{th} for 3 tested configurations (left) and for state of the art micro bolometers (right)

The optimum configuration (n°1) based on τ_{th}, NETD, and mechanical stability presents best performance of 2.5 ms / 48 mK. This performance demonstrates a τ_{th} at least 4 times smaller than the state of the art, with equivalent sensitivity. The corresponding NETD*τ_{th} figure of the merit is, to our knowledge, the best ever reported: 120 mK.ms.

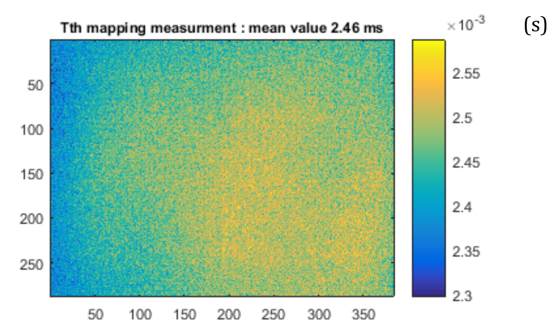

Figure 4: τ_{th} map

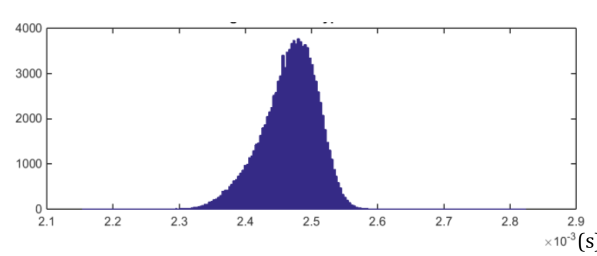

Figure 5: Typical τ_{th} distribution over the array

All these configurations were manufactured in a first batch of feasibility demonstration. The uniformity of the τ_{th} over the Focal Plane Array is represented on figure 4. The distribution in fig 5 shows a mean value of 2.47ms with a standard deviation of 0.04ms. First mechanical qualification under MIL-STD-810 and MIL-STD-883 show no difference with standard bolometers behavior.

5. APPLICATION EXAMPLES

5.1. Simulation of fast moving object detection

In this first example, flying object detection is simulated above buildings in Fig.6. On the left side, the simulation is done with a standard micro bolometer (40mK, 12ms). On the right side, the same object detection is simulated with an improved bolometer (50mK, 2.5ms). The object speed is 850 pixels per second.

Figure 6: Simulation of a fast moving object detection with 12ms bolometer (left) and a 2.5ms bolometer (right)

With the standard bolometer (left), the object is blurred and contrast with the background is reduced compared to the improved bolometer (right). Thanks to the lower τ_{th}, object position is also more accurate with the improved bolometer.

5.2 Chopper image

In this real test, we have two cameras running with a 30Hz frame rate. Figure 7 shows the image of the chopper with a standard Thermal Image Sensor with NETD around 50mk and τ_{th}=10ms. Figure 8 shows the same scene with a τ_{th}=2.5ms bolometer. The chopper rotates at a speed of 100 revolutions per second.

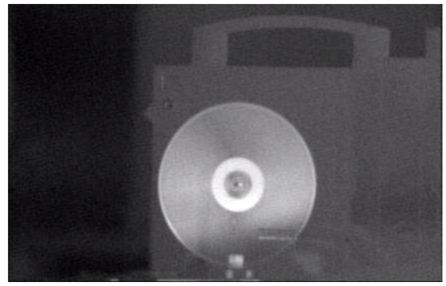

Figure 7: with τ_{th}=10ms

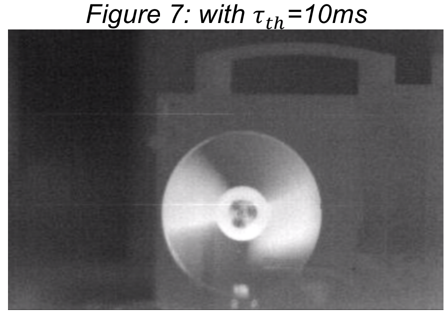

Figure 8: with τ_{th}=2.5ms

It can be seen on Fig. 7 that the chopper blades are not visible due to image blurring, as described in §3.1. We only have a mean signal between the blades and background signal. On Fig. 8, the blades are visible and the contrast between the blades and the background is obvious. The blade shape deformation is due to the rolling shutter architecture.

6. CONCLUSIONS AND PERSPECTIVES

ULIS has established a new record for the FOM of 17µm bolometers. At 120mK.ms, with a τ_{th} of 2.5ms, this bolometer is at least 4 times faster than the state of the art, with comparable level of NETD.

This new pixel is a proof of concept. ULIS's goal is to prove feasibility of such a pixel and collect customer feedback about their interest for this kind of performance. Depending on customer feedback, this pixel could be integrated in a future product with high frame capability.

7. REFERENCES

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373 US Hwy 46W Fairfield, NJ 07004 973-882-0211 Fax: 973-882-0997
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