http://dx.doi.org/10.21611/qirt.1998.040

Uncooled IRFPA developments review

by J.L. Tissot, F. Rothan, C. Vedel, M. Vilain and J.J. Yon

LETI / CEA.G – DOPT – 38054 GRENOBLE Cedex 9 – FRANCE

Abstract

Today, large number of uncooled infrared detector developments are under progress due to the availability of silicon technology that enables realization of low cost 2D IR arrays. Development of such a structure involves a lot of trade-offs between the different parameters which characterize these detectors:

- infrared flux absorption,
- measurement of the temperature increase due to the incoming infrared flux absorption,
- thermal insulation between detector and readout circuit,
- readout of thermometer temperature variation.

These trade-offs explain the number of different approaches that are under worldwide development. We present a rapid survey of the state of the art through these developments. LETI/LIR has chosen resistive amorphous silicon as thermometer for his uncooled microbolometer development. After a first phase dedicated to the acquisition of the most important detector parameters in order to help the modeling and the technological development, an IRCMOS laboratory model (256 x 64 with a pitch of 50 µm) was realized and characterized. It was shown that NETD of 80 mK at f/1.25 Hz and 300 K background can be obtained with high thermal insulation (1.2 10^7 K/W).

1. Uncooled infrared detectors structure

Today, large number of uncooled infrared detector developments are under progress due to the availability of silicon technology that enables realization of low cost 2D IR arrays. These low-cost infrared imagers can enter new civilian and military markets, which are incompatible with cooled detector costs. Thermal detectors are based on the measurement of a temperature change due to absorbed IR photons by a sensitive element. Temperature change is measured by a resistance change (bolometer), a pyroelectric effect or a thermoelectric junction. The structure of an uncooled infrared detector is shown in figure 1.

1.1. Resistive bolometers

The most common detection mechanism is the resistive bolometer. Absorption of infrared radiation causes a change in thermometer resistance which is sensed by the readout circuit. Then the figure of merit of this thermometer is the temperature coefficient of resistance (α) which could be positive or negative depending on the conduction mechanism in the material used for the thermometer. The temperature coefficient α is defined by the following expression:

$$\alpha = \frac{1}{R_e}\frac{dR_e}{dT} \tag{1}$$

where R_e is the bolometer resistance and T the operating temperature. Usual values for α are from a few 0,1 %/K for metal to 1 to 10 %/K for semiconductor or more for superconductor.

http://dx.doi.org/10.21611/qirt.1998.046

1.2 Pyroelectric and ferroelectric detector

Pyroelectric effect enables the realization of very sensitive thermometer. Below the Curie temperature T_c, a change of thermometer temperature induces a transient change in the surface charge thereby causing a transient current which could be measured by an external readout circuit. The figure of merit of these detectors is the pyroelectric coefficient p which is the slope of the material polarization P versus temperature at the operating temperature (figure 2):

$$p = \frac{dP}{dT} \tag{2}$$

By applying an electric field, pyroelectric effect could be increase by the temperature dependence of the dielectric permittivity effect. This is called field-enhanced pyroelectric effect or ferroelectric bolometer effect. The pyroelectric coefficient is then:

$$p = p_0 + \int_0^E \frac{\partial \varepsilon}{\partial T} dE \tag{3}$$

where p_0 is the pyroelectric coefficient without bias, ε is the dielectric permittivity and E is the applied electric field.

It is important to keep in mind that pyroelectric detector and ferroelectric detector are only sensitive to temperature change and they need a chopper in order to modulate incoming infrared radiations. In consequences, they suffer disadvantages on the available amount of IR radiation, and hence IR power for absorber heating. Moreover the chopper increases the system complexity and the power consumption.

1.3 Absorber

In most of the structures which are under development, the absorption of the incoming infrared radiation is realized in a quarter wave optical cavity peaked at 10 µm realized in the thermometer material itself. With current optical diffraction indexes, a thickness of one micrometer or more of active material is involved to absorb thermal radiation from 8 to 14 µm of wavelength.

1.4 Thermal insulation

The thermal insulation function is generally realized in two different manners. In hybrid structure, the detector and readout silicon are separately fabricated and then assembled together in a final process step. In monolithic approach, the detector is realized above readout circuit and a sacrificial layer is etched away to release microbridge structure. This second approach leads to higher thermal insulation values which is a key parameter to obtain high electro-optical performances.

2. State of the art of developments in uncooled infrared detector

2.1. Introduction

Work on uncooled infrared detectors is currently showing rapid growth as a result of developments in silicon technology which pave the way for production of low-cost, high-performance detection arrays. Development of this type of detector involves a lot of trade-offs between the different parameters which characterize each function. These trade-offs explain the number of different approaches which are under worldwide development.

http://dx.doi.org/10.21611/qirt.1998.046

The earliest reported activity in the development of ambient temperature IR arrays can be credited to the United States and Great Britain with work published since 1991 by Honeywell, Texas Instruments and GEC. Since that time, several new actors have appeared and we will look particularly at the work directed in Japan by several large industrial companies.

2.2. United States of America

Very advanced work has been carried out in the U.S.A. at Texas Instruments and Honeywell. Texas Instruments has developed technologies based on the use of amorphous silicon [1] and on $Ba_{1-x}Sr_xTiO_3$ (BST) ferroelectric ceramic hybridized by indium bumps [2] and is continuing with studies on Lead Zirconium Titanate with or without lanthanum doping (PZT and PLZT) with microbridge structures. Indium bump hybridization used in the BST technology enables to optimize detector technology independently of the readout circuits. In contrast, thermal insulation is more difficult to achieve and consequently Texas Instruments has developed a technique of insulating polymer pads which take on the interconnection bumps between the detector and the readout circuit.

Honeywell has developed a high performance monolithic technology based on resistive vanadium oxide on microbridges [3] and has transferred this to Raytheon Amber, Alliant Techsystems, Hughes SBRC, Lockheed Martin and Boeing North American (previously Rockwell). The difficulties of these licence holders in reproducing the Honeywell stacking technology has long been recognized by all. Different government programs have been initiated to improve the productivity and reduce the manufacturing costs (Flexible manufacturing, TRP: Technical Reinvestment Program, ULTRA: Uncooled Low-cost Technology Reinvestment Alliance).

From these American developments we can appreciate the know-how represented by 320 x 240 arrays with a pitch of 46 to 50 µm and very high performance of 90 to 110 mK for f/1 and 30 Hz at the camera level and 40 to 60 mK at the detector level, but at a cost of technologies very difficult to master which are not directly based on silicon technology. In addition, the thermal resistance of the American microbridges, typically $5 \cdot 10^6$ K/W, is currently cited as the main limitation of the performance. Recent result published by HUGHES SBRC shows the high performance potentiality of a well mastered technology [4] (NETD < 20 mK, f/1, 30 Hz, 300 K).

2.3. Japan

Considerable effort is currently being made in Japan to develop uncooled IR detection technology. The most advanced companies working in this field are NEC and Mitsubishi. Mitsubishi has started a program taking the option of using a resistive thermometer in polycrystalline silicon on microbridges [5]. The component developed is a 160 x 120 array with a pitch of 80 µm and a fill factor of 41%. A great deal of technological effort has been spent to improve the thermal resistance of the microbridges which went from $2.2 \cdot 10^6$ K/W in 1995 to 10^7 K/W in 1996. We can consider that the NETD at f/1 of 0.5 K, published at Orlando in April 1996 has been improved since then.

NEC, after having worked on thermopile detection [6], is now developing a resistive titanium film technology. A camera using this latest thermometer is already marketed with an NETD performance of 0.5 K. At a laboratory level, NETD of 70 mK at f/1 has been published in April 1997 [7]. Recently NEC published work on vanadium oxide detector of 256 x 256 at a pitch of 50 µm [8] with NETD of 150 mK.

We can appreciate that the development of uncooled IR technology in Japan is being achieved with concern for compatibility with silicon microelectronics technology and that in consequence progress is very rapid. Besides, in addition to NEC and Mitsubishi who have published some results of their activities, other companies, like Toyota [9], are also working in this field.

http://dx.doi.org/10.21611/qirt.1998.046

2.4. Europe

The most advanced industrial work is lead by the GEC group [10] with the support of DERA in Great Britain [11]. These developments cover technologies with an architecture similar to that of Texas Instruments but using a thinned pyroelectric Lead Zirconium Titanate (PZT) thermometer bumped onto the readout circuit. This industrialized technology is complex due to the series of operations: thinning and processing of ceramic followed by hybridization to the readout circuit. The performance reaches 100 mK under standard conditions (f/1, 30 Hz). Developments are continuing to produce a monolithic technology using thermally insulated thin film thermometers interconnected by a microbridge structure [12].

2.5. Other Important Studies

In Canada, a program for the development of a technology based on vanadium oxide at the National Optical Institute (INO/ONI) [13] has lead to the commercialization of high performance linear and 2 dimensional arrays by Infravision. Besides, cooperation between the Australian Defense Research Establishment (DSTO) and the Swedish National Defense research Establishment (FOA) [14] has been established. This operation is aimed at developing and evaluating uncooled DSTO detectors hybridized on readout circuits designed by FOA. The detector part is based on the use of amorphous silicon and germanium. The microbridge structure offers a thermal resistance of $2.5\cdot10^6$ K/W and a calculated NETD of 150 mK for an αSi:N material deposited by sputtering. 16 x 16 pixel demonstrators with a pitch of 40 µm used for testing are currently being assembled.

2.6. Conclusion

This rapid review shows that several materials are potentially usable for uncooled infrared detection. The choice should be rigorously made in the knowledge that experience acquired for a specific material, except in rare cases, cannot be reused for another material or another structure. Besides, even if the low cost of the components is related to the absence of cryogenics, it is just as important to be able to use collective microelectronics techniques and therefore to select detection materials compatible with these techniques in order to be able to lower the production costs and enter new markets for infrared night vision.

To complete this review and to demonstrate, through the use of concrete examples, the difficulties related to the development of production technologies for uncooled infrared detectors; we present below the ongoing developments at LETI/LIR in this field.

3. Uncooled IRFPA development at LETI/LIR

We planned to develop at LETI/LIR a device with a monolithically integrated structure, over a fully completed readout integrated circuit (ROIC) specially designed for this application, from a commercially available 0.8 µm design rules CMOS line. This strategy avoids long and costly specific IC developments for bolometer integration within CMOS flow, and lends itself to high fill factors, because the entire pixel area is available for detector implementation. On the other hand, the whole bolometer process must comply with back-end thermal limitations, with no degradation of functional integrity of CMOS parameters (typically less than 400°C). The demonstrator developed today is a 256 x 64 array with a pitch of 50 µm.

http://dx.doi.org/10.21611/qirt.1998.046

3.1. Pixel design and fabrication

The bolometer comprises a microbridge thermometer provided with an IR partially absorbing arrangement, supported by two legs anchored over the silicon substrate by metal studs (figure 3). The microbridge is built on a sacrificial polyimide layer, and is freed in a final step when the polyimide is ashed away.

The microbridge comprises a thin layer (0.1 µm) of doped amorphous silicon. This layer acts as the thermometer with a temperature coefficient of 2,5 %/K and does not contribute significantly to direct IR absorption. This function is performed by very thin reactively sputtered titanium nitride. The electrode thickness is adjusted according to the TiN resistivity to obtain a mean value of square resistance comparable to that of vacuum (377 Ω/sq). This square resistance was defined by numerical 2D simulation and microbridge reflection measurements to optimize coupling of IR waves in the 8 to 14 µm range, owing to the electrode design and the presence of quarter wavelength cavity underneath. Amorphous silicon is obtained from house-modified standard deposition equipment. The doping level is obtained by proper source gas mixing, and controls both the resistivity and temperature coefficient of resistivity (TCR) as usual in semiconductors. Microbridge I(V) characteristics are perfectly linear, at least in the –5V, +5V range.

A thin aluminum layer on top of the ROIC reflects the IR energy transmitted by the microbridge back to the bolometer. Due to the stud height of 2.5µm, there results quarter wavelength cavity effect which peaks the spectral response at 10 µm. The geometric fill factor is close to 80 %. Standard microbolometers are designed with two 3 µm wide, 10 µm long legs, leading to ~ 1.2×10^7 K/W thermal resistance. The thermal capacity (C_{th}) of the suspended parts amounts to 0.35 nJ/K, the thermal time constant $T_{th} = R_{th} \cdot C_{th}$ is then ~ 4.2 ms, largely compatible with 25 Hz frame rates.

3.2. Readout circuit design

The configuration of our demonstrator is a 256 x 64 array with a pitch of 50 µm. Each pixel has a bolometer coupled by direct injection. The current from the bolometer is integrated in a capacitive transimpedance amplifier (CTIA) at the end of the row. Before integration, most of the background current is suppressed by using one blind bolometer for each row. The 2D arrangement of the detector needs a multiplexer circuit to select individual pixels. The FPA is read out on a column by column basis with random access possibilities. Each of the row outputs is addressed via multiplexing circuitry located at the end of row alongside the sensitive area. At the end of a column read, the amplifiers are reset before the next row reading. The frame time is 40 ms.

4. Results

Several 256 x 64 microbolometer FPAs were assembled for performance testing and imaging demonstration. Electro-optical tests were performed under standard conditions including operating temperature of 295K and flood illumination from a blackbody through a f/1 limiting aperture. The blackbody temperature is typically modulated between 293K and 303K to produce a signal flux. The LIR 256 x 64 microbolometer FPAs demonstrate a responsivity of about 12 mV/K with a non-uniformity (std/mean) of 8 %. The resulting NETD is about 76 mK as shown in figure 4. It is noteworthy that the operability of our FPAs is over 99 %. This technology provides us with a very responsive bolometer. The potentiality is not yet fully demonstrated: the 1/f noise still limits the performance of the detector. However technological studies are currently being carried out to reduce this phenomenon. The FPAs have also been used for infrared imaging. Single frame examples obtained at a 25 Hz frame rate is shown in figure 5.

http://dx.doi.org/10.21611/qirt.1998.046

5. Conclusions

Important technological developments are being made worldwide in uncooled infrared imaging technology. These developments are likely to have a major impact in the use of thermal imaging systems both for military and civil applications providing they really result in the expected low cost of manufacture. Consequently, from the set of parameters which have guided the choices made at LETI/LIR, our priorities lie in simplification of construction of the microbolometer and its thermal insulation to ensure quick development of the basic technology and easy transfer to industry in the near future.

The first results demonstrate the potential of the technology and support the choices made. Analysis of the results shows that thermometer 1/f noise is a performance-limiting factor and work is still under progress to improve this parameter.

Acknowledgments

The authors would like to thank the DGA/DTCO and the CEA for supporting these studies and all the staff of the LETI/LIR who took part in them.

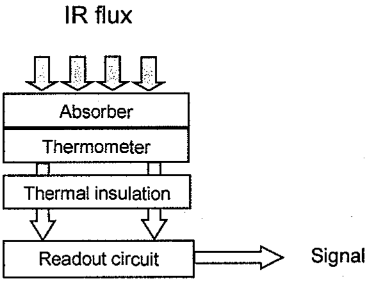

Fig. 1. Schematic representation of an uncooled IR microbolometer

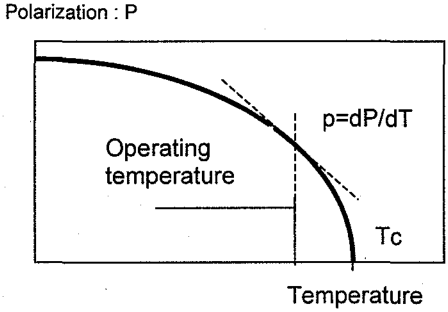

Fig. 2. Pyrolelectric effect

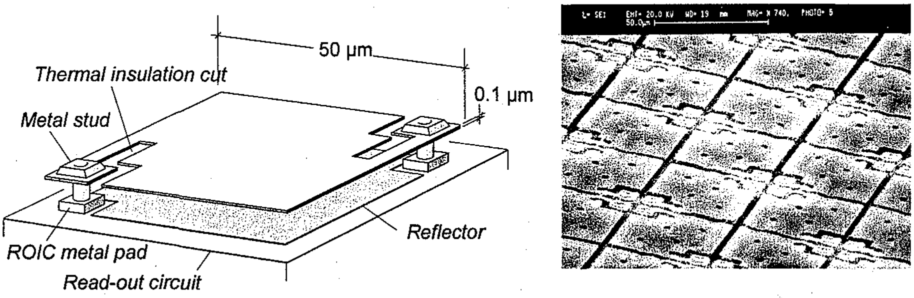

Fig. 3. Schematic structure and SEM view of pixel

http://dx.doi.org/10.21611/qirt.1998.046

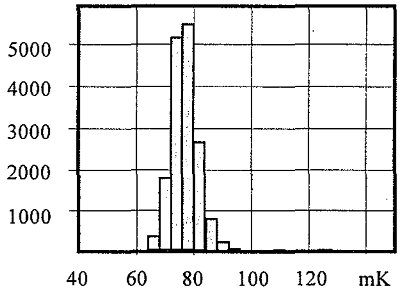

Fig. 4. NETD characteristic of IRFPA

Fig. 5. 256 x 64 IR images

REFERENCES

[1] *United State Patent N°5,367,167*, Nov. 22, 1994.

[2] C. Hanson (C.), Beratan (H.), Owen (R.), Mac Corbin, Mc Kenney (S.), - *Uncooled Thermal Imaging at Texas Instruments*, SPIE Vol. 1735, Infrared Detectors: State of the Art, pp. 17-26, 1992.

[3] Wood (R.A.) - *Uncooled Thermal Imaging With Monolithic Silicon Focal Planes*, SPIE Vol. 2020, Infrared Technology XIX, pp. 322-329, 1993.

[4] Published in Optical Science, Engineering and Instrumentation, SPIE Conference, Infrared Technology and Application XXIV, San Diego, 19-24 July, 1998.

[5] Sone (T.) et al - *Performance of new handheld IR Camera using Uncooled Bolometer FPA*, SPIE Vol. 2744, pp. 52-60, 1994.

[6] Kanno (K.) et al - *Uncooled Infrared Focal Plane Array having 128 x 128 Thermopile Detector Elements*, SPIE Vol. 2269, pp. 450-459, 1994.

[7] Tanaka (A.) et al - *Influence of Bias Heating on Titanium Bolometer Infrared Sensor*, SPIE Vol. 3061, Infrared Technology and applications XXIII, 1997.

[8] Wada (H.) et al, - *Design and Performance of 256 x 256 Bolometer-type Uncooled Infrared Detector*, SPIE Vol. 3379, Infrared Detectors and Focal Plane Arrays V, pp. 90-100, 1998.

[9] Fujitsuka (N.) et al - *Monolithic pyroelectric infrared image sensor using PVDF thin film*, Sens. Actuators A, Phys. (Switzerland), vol. A66, n° 1-3, pp. 237-243, 1 April 1998.

[10] Whatmore (R.W.), Stringfellows (S.B.), Shorrocks (N.M.) - *Ferroelectric Materials for Uncooled Thermal Imaging*, SPIE Vol. 2020, Infrared technology XIX, pp. 391-402, 1993.

[11] Watton (R.), Dennis (P.N.J.), Gilham (J.P.), Manning (P.A), Perkins (M.C.S.), Todd (M.A.) - *Infrared Bolometer Arrays: The Route to Uncooled, Affordable Thermal Imaging*, SPIE 2020, Infrared Technology XIX, pp. 379-390, 1993.

[12] Conference CMD17 – JMC 6, Grenoble, 25-29 August 1998, Vol. 22E, G. Thomas (Mulhouse) Editor.

[13] Jerominek (H.) et al, - *64 x 64, 128 x 128 and 320 x 340 pixel uncooled IR bolometric detector arrays*, SPIE Vol. 3061, Infrared Technology and Applications XXIII, 1997.

[14] Liddiard (K.C.), Ringh (U.), Janson (C.) - *Status of Uncooled Focal Plane Detector Arrays for Smart IR Sensors*, SPIE Vol. 2746, Infrared Detectors andFocal Plane Arrays IV, pp. 72-79, 1996.