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An overview of uncooled infrared sensors technology based on amorphous silicon and silicon germanium alloys

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At the present time there are commercially available large un-cooled micro-bolometer arrays (as large as 1024×768 pixels) for a variety of thermal imaging applications. Different thermo-sensing materials have been employed as thermo sensing elements as Vanadium Oxide (VO_x), metals, and amorphous and polycrystalline semiconductors. Those materials present good characteristics but also have some disadvantages. As a consequence none of the commercially available arrays contain optimum pixels with an optimum thermo-sensing material. This paper reviews the development of the un-cooled bolometer technology and the research achievements on this area, with special attention on the key factors that would lead to improve the pixels performance characteristics. The work considers the R&D of microbolometer arrays and the integration with MEMS and IC technologies. A comparative study with the state of the art and data reported in literature is presented. Finally, further directions of uncooled bolometer based in thin films materials are also discussed in this paper.

1 Introduction The thermal imaging applications of IR systems are in continuous growth, such as security, surveillance, fire fighting, biomedical and preventive maintenance. IR technology has been widely investigated but still it is an important field of study, while trying to satisfy the need of low cost and high performance IR imaging systems. There are two fundamental methods for detecting IR radiation, photon detectors and thermal detectors [1]. In comparison with photon detectors, thermal detectors operate at room temperature, reducing significantly the cost of operation and have not limitation on the wavelength at which they will respond; however its response time is in the range of milliseconds, which is larger than that of photon detectors. A bolometer is one of many different types of thermal detectors. The absorption of incident IR radiation in a bolometer increases the temperature of its thermo-sensing material, so that a change in temperature causes a change in its electrical resistance. The main requirements for the thermo-sensing materials used in microbolometers are the following: high value of the temperature coefficient of resistance, TCR (α), moderate resistivity, low noise and compatibility with silicon (Si) IC fabrication processes. Several materials have been used as thermo-sensing elements in microbolometers; the most employed are VO_x, amorphous, polycrystalline semiconductors and some metals [2-6]. However, these thermo-sensing materials have not been optimized to obtain the best performance characteristics; such as: fast thermal response time, high responsivity, high detectivity and low noise. Since IR sensors respond on a change of temperature induced by radiation, it is important that the sensing element of the sensor to be thermally insulated. Therefore the thermal isolation is a key issue to obtain high performance in the IR sensors. To reduce heat losses, different fabrication process have been proposed, these include the use of materials with low thermal conductivity like porous silicon [7]. The best thermal insulation and the lowest thermal capacitance have been obtained in micromachined structures. As the MEMS

(Micro-Electro-Mechanical Systems) technology has matured, combined bulk and surface micromachining techniques are currently used in IRFPA (Infrared Focal Plane Arrays) systems. The micromachining techniques are used to suspend the thermo-sensing element above the substrate in a bridge structure to minimize the heat lost by thermal conduction through the substrate; Fig. 1(a) shows a scheme of one microbolometer structure [8]. A number of books and reviewed articles on IR technology have been published in recent years [1,8,9]. However any specialized of IR sensor based on amorphous materials. This work presents a perspective of the developments in uncooled IR sensor technology; using a-Si:H and a-SiGe:H films focused to improve the performance characteristics of IR sensors. The work considers the R&D of microbolometer using thin film materials and its fabrication process, and also a comparative study with the state of the art and data reported in literature.

2 Uncooled bolometer manufacturing

2.1 Thermal isolation For achieving thermal insulation of the detector, micromachining of the active element in the form of a self sustained, suspended membrane, or by depositing the active element on top of a thermally insulated membrane are some of the commonly used approaches.

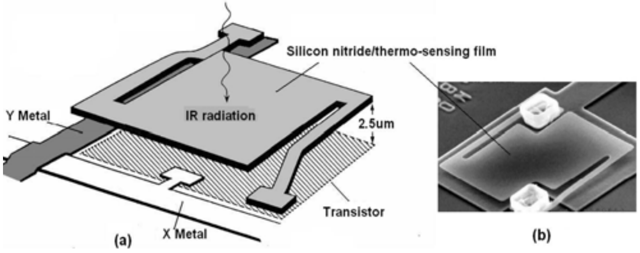

Figure 1 (a) Microbolometer scheme [8], (b) Two- level microbolometer SEM image [3].

There are three mechanisms of heat transfer that occur in a thermal detector; which are: 1) Conduction mechanisms, which occur when the heat flows from the thermo-sensing area along the supporting legs to the substrate. 2) Convection which occurs when the heat flows in the presence of a surrounding atmosphere; this mechanism is not very important if the detector is encapsulated in a vacuum package. 3) Radiation mechanism is presented by the fact that the detector radiates energy back to its surroundings and the surroundings radiate to it. When the microbolometers are encapsulated in an evacuated package, with an IR transmitting window, convection and radiation mechanism are minimized. Thus the main loss of heat mechanism is conduction from the thermo-sensing material to the substrate through the supporting structure. The supporting structure is a very important part of thermal detectors, it provides three functions: mechanical support, electrical conducting path and thermal conducting path. The development of arrays of uncooled IR sensors depends on the ability to form thermal isolation structures which should be compact, robust and easy to fabricate. MEMS technology greatly contributed to the reduction of thermal conductance and sensitivity improvement. The micromachined microbolometers reported to date are classified in two design categories: one level and two level configurations, as shown in Fig. 2.

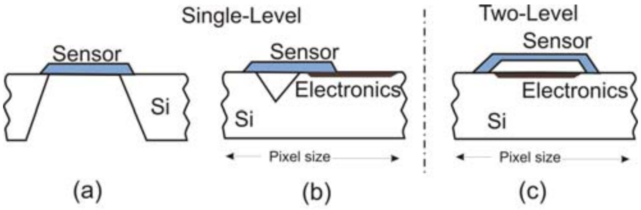

Figure 2 Two categories of the microbolometer designs: a) One-level, complete etch under the area of sensor, b) type-V structure, and c) two level configuration by surface micromachining [9].

Single level configuration consist in deposit a membrane over the Si substrate and after that, open a hole in the Si substrate, employing bulk micromachining techniques. Bulk micromachining consumes area, since the Si substrate is etched with a side wall angle of 54.9 degrees. The electronic circuit (which forms part of the read out) is fabricated next to the pixel, consuming area also. That result in a 20% fill factor. Another type of one level configuration is provided by a micromachining partially the bulk, which results in “V-type” structures (see Fig. 2b), obtaining a poor fill factor. The two-level configuration allows the fabrication of the electronics circuit in the substrate and after that, the fabrication of the microbolometer in a low temperature post-processing over the electronics, by using the surface micromachining techniques. With this configuration is saved substrate area, achieving a fill factor of 70%, Fig. 1b shows a picture of a two-level micro-bolometer [3]. Two-level microbolometers configuration is the most used for commercial IRFPA. In order to fabricate thermal sensors in a post process, it is necessary to use low temperatures during the fabrication process. By employing Plasma Enhanced Chemical Vapor deposition (PECVD), it is possible to deposit thin films at relatively low temperatures (~350-400 ºC). In our work [10-12], we developed a complete process for IR sensor at 350 ºC.

2.2 Thermo-sensing films The thermo-sensing material is perhaps the most important element in a microbolometer, since it determines the electrical signal caused by a temperature change. Low electrical resistivity is required in order to obtain minimized Johnson noise and good compatibility of the detector with the read-out circuitry. The thermo-sensing material should have a large temperature coefficient of resistance, TCR (α(T)), which is defined by Eq. (1), where E_a is the activation energy, k is the Boltzman constant and T is temperature.

$$\alpha(T) = \left(\frac{1}{R}\right)\left[\frac{dR}{dT}\right] \approx \frac{E_a}{kT^2} \tag{1}$$

A large TCR means that a small change in temperature in the sensing material will result in a large change in resistance *R*. Equation (1) shows that the TCR and E_a are directly related, thus a high E_a in the material is desired. VO_x, is one of the most commercial thermo-sensing material used in uncooled microbolometers [2, 13], since it has a relatively high TCR, $\alpha(T) \approx 0.021$ K^{-1}; However it is not a standard material in silicon technology and requires post deposition annealing at 500 ºC to obtain high values of TCR, losing the advantage of post-CMOS compatibility. Intrinsic hydrogenated amorphous silicon (a-Si:H) prepared by PECVD is another commercial material [3,4,16]. It is compatible with the Si technology, has a high activation energy, $E_a \approx 1$ eV and high value of TCR, $\alpha(T) \approx -0.13$ K^{-1}; However it also has a high undesirable resistivity, which causes a mismatch of input impedance with the read-out circuits. In order to reduce the a-Si:H high resistance, boron doping has been employed. The B doped a-Si:H films present a significant reduction in its resistivity, however a reduction in E_a and TCR is obtained also, $E_a \approx$ 0.22eV and TCR$\approx$0.028K^{-1} [3]. Amorphous $Ge_xSi_{1-x}O_y$ films have been employed in sandwich structure microbolometers [5], these films are compatible with the CMOS technology and present a high TCR, around 0.042 K^{-1}; however it has a high resistance and is deposited by sputtering where doping is not possible to perform. In our R&D work [10], amorphous silicon-germanium, a-Si_xGe_y:H, deposited by PECVD has been employed as thermo-sensing films, obtaining high activation energy, E_a= 0.34 eV, consequently a high value of TCR=0.043 K^{-1} was improved with a moderate high resistivity. Table 1 shows the most common materials employed as thermo-sensing films in microbolometers.

Table 1 Materials employed as thermo-sensing films in microbolometers.

Material	TCR(K^{-1})	E_a (eV)	σ_{RT} (Ω cm^{-1})	Ref
VOx	0.021	0.16	$2x10^{-1}$	[2, 13]
Poly-SiGe	0.024	0.18	$9x10^{-2}$	[6]
a-Si:H	0.013	0.1	$\sim 1x10^{-9}$	[4]
a-Si:H,B	0.028	0.22	$5x10^{-3}$	[3]
a-SiGe:H	0.043	0.34	$1.6x10^{-6}$	[10,12]
$Ge_xSi_{1-x}O_y$	0.042	0.32	$2.6x10^{-2}$	[5]
a-$Si_xGe_yB_z$:H	0.027	0.21	$1.3\ x10^{-2}$	[11]

As can be seen in Table 1, a-Si:H and a-SiGe:H, show the largest TCR values, however they have also the smallest values of room temperature conductivity, σ_{RT}. As an alternative to reduce the high resistivity presented in a-SiGe films, we propose amorphous silicon-germanium-boron alloys a-$Si_xGe_yB_z$:H. These films have demonstrated an increment in their conductivity (σ) (between 2 and 3 orders of magnitude) in comparison of that of the intrinsic a-Si_xGe_y:H film [10]. However the increment in σ was accompanied by a reduction in TCR, around 0.028 K^{-1}. The a-$Si_xGe_yB_z$:H films compared with the another thermo-sensing materials, have better performance characteristics, which are: fully compatible with the Si technology, moderated values of TCR, comparables with those of the VO_x and a-Si:H films, and reduced resistivity. In general the a-$Si_xGe_yB_z$:H alloys have similar characteristics than those of the a-Si:H,B thermo-sensing film [11], but present one order of magnitude shorter values of resistivity.

2.3 Infrared absorber films An absorber element is part of uncooled IR microbolometers; its role is based in the absorption of IR radiation and the transfer of heat to the thermo-sensing material. The main requirements of absorbing materials are: A high absorbance coefficient in the range λ = 8-12 µm, simple fabrication and compatibility with the Si technology. The IR absorption can be improved employing a resonant micro-cavity (Fabry-Perot), as is shown in Fig. 3a, where the thermo-sensing film is separated from the substrate by a gap equivalent to one quarter of the wavelength at which it will be operating. A mirror (Al or Ti) is deposited over the substrate surface, under the thermo-sensing material. In this configuration the radiation that was not absorbed by the thermo-sensing film will bounce inside the cavity and will be re-absorbed by the thermo-sensing element.

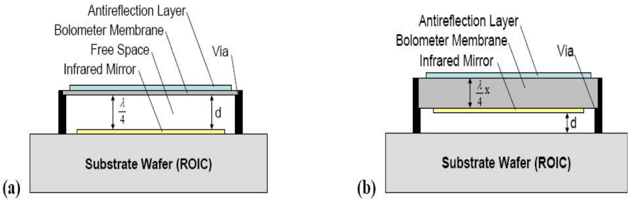

Figure 3 Two bolometer designs with resonant optical cavities for high absorption of the incident radiation [14].

A second type of resonant optical cavity design is shown in Fig. 3b in which the resonant optical cavity is part of the bolometer membrane. The mirror of this type of bouncing optical cavity is placed at the lower surface of the bolometer membrane and the thickness of the bolometer membrane defines the resonant optical cavity [14]. Terrestrial objects have temperatures around of 300 K, with IR emission around 10µm. Thus uncooled microbolometers employed for detection of objects at room temperature, should have a gap from the substrate of ~2.5 µm, for the fabrication of the resonant micro-cavity. Material such as gold black film has been employed as absorbing film in microbolometers, which was deposited over the thermo-sensing film [15], due to high absorption coefficient of IR radiation (more than 90 %). However it is not a standard material in Si technology. SiN_x films are employed commonly as absorber films in microbolometers [6, 10], since its absorption coefficient can be tuned by the deposition parameters and is a standard material in IC technology. In our work [10-12] we do not use mirrors which results in a reduction of the number of steps during process fabrication. We used as absorber material SiN_x which is deposited by PECVD, reducing the cost and time for mass production.

3 Sate of the art in IR focal plane arrays Nowadays two technologies of uncooled microbolometer IR-FPAs are used in the USA, these are based in the development carried out in the decade of 1980 by two main companies: TI and Honeywell. VO_x technology, previously developed by Honeywell, is now continued under development by three main companies: Raytheon Infrared Operation, BAe systems and DRS technologies. Meanwhile a-Si:H technology previously developed by TI and later by Raytheon Commercial Infrared, is now in development by L-3 communications/infrared products. In Europe, specifically in France, at ULIS (CEA/LETI), there is an important development in microbolometers arrays based on a-Si:H technology. The information related to uncooled microbolometer IR-FPAs is not completely open and some performance characteristics of sensor are not available. Table 2 summarizes the advances in the development of uncooled IR-FPAs and the performance characteristics for the three main IR-FPAs which are available commercially based on a-Si:H and compared with VO_x technology. Information about D* is not showed by these companies. The tendency is clear, an increment in the number of pixels, a reduction in the pixel pitch and an improvement in the pixel performance characteristics, such as the reduction in the thermal time constant, a reduction in the NETD and an increment in detectivity, D*. Development of microbolometer technology based on a-Si:H has continued to improve performance and resolution. The demonstrated performance is closer to the photonic detectors with the advantages of integration, power consumption and cost.

Table 2 Performance characteristics in the main microbolometer IRFPAs commercially available [3,4,16].

Performance Parameter	Company Raytheon	 L-3 Communications	 ULIS
Thermo-sensing material	VO_x	a-Si:H,B	a-Si:H
Array Dimensions	640x480	1024x768	1024x768
Pixel pitch (μm)^2	25x25	17x17	17x17
Pixel Resistance (MΩ)	-	30	-
Spectral response (μm)	8-14	5-14	8-14
Responsivity (V/W)	$>2.5x10^7$	$1x10^6$	-
NETD at f/1 (mK)	50	50	85
Frame Rate (Hz)	-	-	60
Thermal time const (ms)	-	11	7

The future requirements will depend on the application market, for example in surveillance and military a high resolution must be accomplished with megapixels arrays with lowest NETD [14]. The R&D will be conducted to reduce the 1/f noise in the amorphous materials. One of the challenges is the incorporation of the a-SiGe:H alloys into commercial arrays due to the fact that these materials have demonstrated to improve the performance of the sensors and can be obtained at low cost production.

4 Conclusions

Uncooled bolometers are reaching performance levels which previously only were possible with cooled infrared photon detectors. For uncooled IR bolometer arrays based on amorphous silicon films the efforts have been conducted to increase the number of pixels included in the arrays, rather than improve performance characteristics of the micro-bolometers. Plasma deposited Si-Ge Boron (Si-Ge-B) alloys used as thermo-sensing layer have provided a high TCR and as a consequence, a higher responsivity and high detectivity. Si-Ge-B is a very promising alloy material for its integration in IR sensor development, and its circuitry in the same chip, avoiding the problems of matching with the standard input of the electronic circuits. The manufacturing of those devices are aligned with standard CMOS and MEMS foundry processes. Si-Ge-B alloys met the requirements for large volume fabrication and the technology development progress in order to improve the performance of IR FPAs.

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