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MICROBOLOMETERS FABRICATED WITH SURFACE MICROMACHINING WITH a-Si-Ge:H THERMO-SENSING FILMS

MARIO MORENO

Electronics Department, Institute National of Astrophysics, Optics and Electronics, L. Erro No. 1 Tonanzintla, Puebla, 72840, Mexico
mmoreno@inaoep.mx

ANDREY KOSAREV

Electronics Department, Institute National of Astrophysics, Optics and Electronics, L. Erro No. 1 Tonanzintla, Puebla, 72840, Mexico
akosarev@inaoep.mx

ALFONSO TORRES

Electronics Department, Institute National of Astrophysics, Optics and Electronics, L. Erro No. 1 Tonanzintla, Puebla, 72840, Mexico
atorres@inaoep.mx

ROBERTO AMBROSIO

Universidad Autónoma de Ciudad Juárez, Av. Del Charro No. 610 Norte
Ciudad Juárez, 72840, Chihuahua
rambrosi@uacj.mx

In this work we present the process flow for the fabrication of un-cooled IR detectors employing surface micro-machining techniques over silicon substrates. These detectors are based on thin films deposited by plasma at low temperatures. The thermo sensing film used is an intrinsic a-Si_xGe_{1-x}:H film, which has demonstrated a very high temperature coefficient of resistance (TCR), and a moderated resistivity, these properties are better than those of the a-Si:H intrinsic film, which is commonly used in commercial IR devices. Two device configurations have been designed and fabricated, labeled planar and sandwich. The former is the configuration commonly used in commercial micro-bolometers, while the latter is proposed in order to reduce the high cell resistance observed in this kind of devices, without the necessity of doping the intrinsic film, which results in a decrement of the TCR and therefore in responsivity. Finally some performance characteristics of the devices studied are discussed in comparison with data reported in literature.

Keywords: Germanium; IR detectors; plasma enhanced chemical vapor deposition.

1. Introduction

Differing from photo-detectors bolometer senses radiation by rising the temperature of the thermo-sensing layer due to radiation absorption, as a result there are changes of the electronic properties i.e. conductivity. Photo-detectors have spectral limitations because the structure of the electron energy levels, while bolometers do not have this kind of

limitation. Recent interest in bolometers is related to both, new materials (non-crystalline semiconductors with high temperature coefficient of resistance (TCR)), and micromachining technology that provides efficient thermo-isolation. The conjunction of these factors and their compatibility with the silicon CMOS technology for integral circuit (IC), have made possible the fabrication of the bolometer and the read-out circuitry on the same chip.

A micro-bolometer is formed by three components: a supporting structure or micro-bridge (deposited over a sacrificial layer), which provides thermo isolation to the thermo-sensing film, the thermo-sensing film itself, and an IR absorbing film. Among the materials that have been used as thermo-sensing layer in micro-bolometers it can be mentioned vanadium oxide, amorphous and poly-crystalline semiconductors and some metals[1-6]. Vanadium oxide has a high value of TCR, but it is not a standard material in the IC technology. Metals are compatible with the IC technology but have low TCR values. Non-crystalline semiconductors deposited by plasma e.g. amorphous silicon (a-Si:H) has shown a high TCR value. It is deposited at low temperature and is fully compatible with the silicon technology[1-2]. Intrinsic amorphous semiconductors have a very high resistance and Boron doping has been reported to reduce its high resistance[3]. But doping reduces the TCR and consequently the responsivity, therefore there is a trade off between responsivity and the resistance of the cell. Polycrystalline Si-Ge films reported as thermo-sensing films[6] require higher deposition temperature ($T_{dep} \approx 600$ ˚C) and demonstrate lower TCR values (TCR ≈ 2%/K) resulting in lower voltage responsivity ($R_U \approx 10^4$ V/W) and detectivity ($D^* \approx 3x10^8$ cmHz$^{1/2}$/W) in comparison with plasma deposited films: T_{dep} = 300 ˚C, TCR = 4%/K, $R_U = 10^5$ V/W and $D^* = (4\text{-}7)x10^9$ cmHz$^{1/2}$/W presented in this work.

In our previous works we have reported a-Si_xGe_{1-x}:H films deposited by low frequency plasma enhanced chemical vapor deposition (LF PECVD), these films have been employed as thermo-sensing layers in un-cooled microbolometers[7]. High activation energy (E_a) and consequently high TCR have been observed in these films, at the same time they showed a low for PE CVD films room temperature conductivity (σ_{RT}), which provides a sufficiently low device cell resistance. The majority of micro-bolometers reported in the literature have a "planar" configuration, that is, the current flows parallel to the surface of the film and the resistance of the device is set by the inter-electrode distance (which is in the range of 25 – 60 μm). An alternative micro-bolometer configuration is labeled "sandwich", in which the current flows perpendicular to the surface of the film, in this case the contact electrodes are separated by the thickness of the thermo-sensing film (which is in the range of 0.5 – 1 μm), resulting in a considerable reduction of the resistance of the device. Liddiard[8] reported the design of a sandwich configuration on a dielectric membrane, but only were fabricated and characterized the gap geometry planar structures with Si or Ge films deposited by r.f. sputtering, which resulted in the following performance characteristics: TCR = 2%/K, $R_U = 2x10^4$ V/W and $D^* = 4.5x10^8$ cmHz$^{1/2}$/W.

In this work we present a study of planar and sandwich bridge configurations of uncooled micro-bolometers. The structures were fabricated by surface micro-machining techniques based on thin films deposited by LF PECVD, emphasis is made on the fabrication process, and the key issues in order to have a large yield at the end of the fabrication of the devices are discussed.

2. Experimental

The device structures were fabricated on a (001) silicon wafer with resistivity ≈ 2000 Ohm-cm, as it is depicted in Fig.1, the fabrication process starts with the deposition of a 0.3 μm thick oxide layer by CVD at a substrate temperature T_{dep}= 350 ^{o}C, followed by the deposition of an Al film (thickness of 2.5 μm), by e-beam evaporation. Wet etching patterns the Al film in order to form a sacrificial structure. In this step, a solution based on H_3PO_4 - CH_3COOH – HNO_3 is used for obtaining a well-controlled sidewall angle on the Al sacrificial structure. A supporting SiN_x -1 film 0.8 μm thick is deposited over the Al structure by LF PECVD at a discharge frequency f=110 kHz and T_{dep} = 350 ^{o}C. The depositing conditions for this film have been optimized for achieving high resistance to the subsequent chemical etchings and good mechanical and thermal properties. Reactive Ion Etching - RIE, patterns the SiNx -1 film in order to form the SiN_x micro-bridge on which the micro-bolometer will be built. Up to this point, the fabrication process steps for both planar and sandwich structures are the same.

For the planar configuration the fabrication process continues as follows: a 0.2 μm thick Ti layer is deposited by e-beam evaporation over the SiN_x-1 film and patterned in order to form the electrodes (stripes), contact lines and bonding pads. Then above the patterned metal the thermo-sensing a-Si_xGe_{1-x}:H film (thickness of 0.5 μm) and an IR absorber SiN_x-2 (thickness of 0.2 μm) are deposited consequently by LF PECVD at T_{dep}= 300 and 350 ˚C, respectively. The active area is patterned by RIE and finally the Al – sacrificial film is etched with Al-etch solution, in order to form the micro-bridge.

For the sandwich configuration the fabrication process is as follows: a Ti layer (0.2 μm thick), is deposited by e-beam evaporation and patterned forming the bottom electrode. Then the thermo-sensing a-Si_xGe_{1-x}:H film (thickness of 0.5 μm) and a IR absorber SiN_x-2 film (thickness of 0.2 μm), are consequently deposited by LF PECVD, at T_s = 300 ^{o}C and 350 ^{o}C, respectively. A window is opened in the top SiN_x-2 film by RIE and a 10 nm thick Ti layer is deposited, in order to form the top electrode. A second thicker Ti layer (thickness of 0.2 μm) is deposited in order to contact the thin top electrode with the contact pad. The active area is patterned by RIE and finally the Al sacrificial layer is removed by wet Al-etch solution. Fig. 2 depicts both structures illustrating their difference. In Table 1 are shown the main films employed in the fabrication of the microbolometers and their key features on the device. The performance characteristics of the micro-bolometers were measured in vacuum chamber at a pressure P= 20 mTorr. The chamber is equipped with micro-probes and has a ZnSe window, providing a transmission T=70% in the vicinity of the wavelength λ=10 μm.

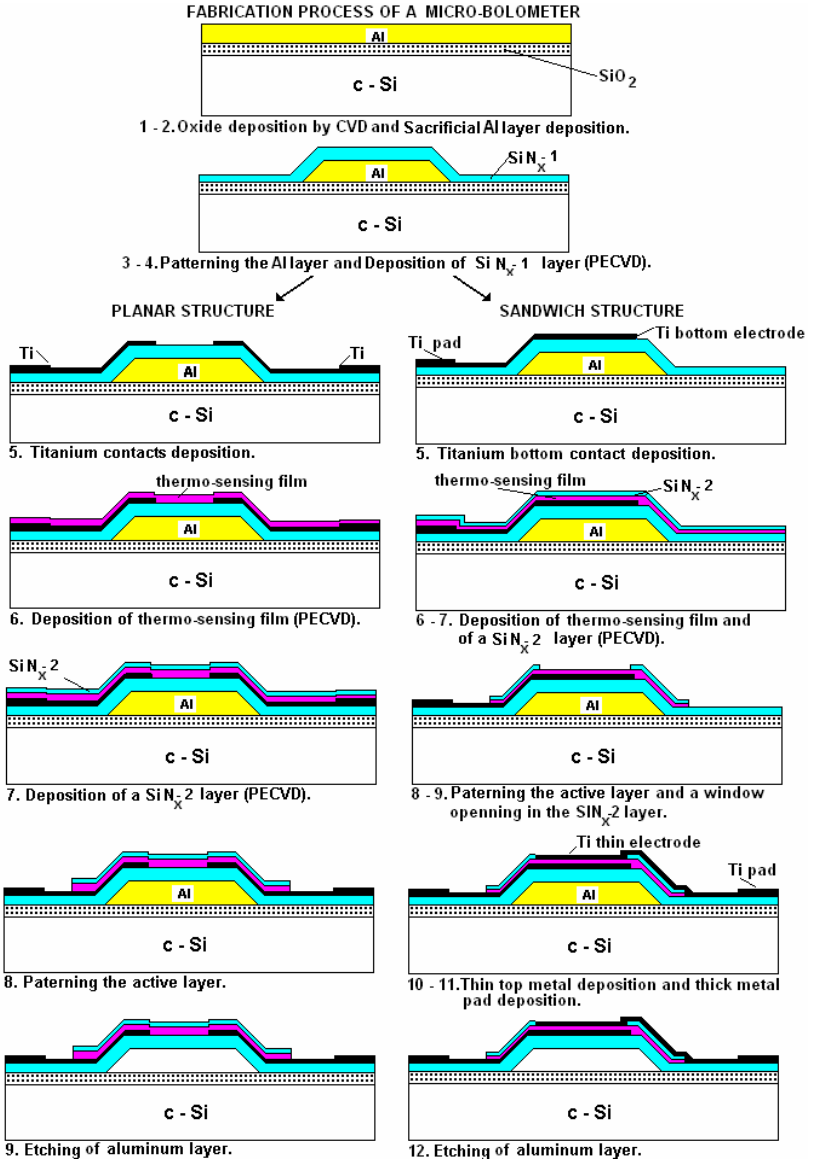


Fig. 1. Fabrication process flow of the two micro-bolometers structures.

An electrometer ("Keythley"-6517A) was used for the current-voltage measurement on the fabricated devices. The IR illumination was obtained from a globar source ("Jobin Yvon" model LSH-GB) providing a light intensity $I_0 = 5.3\text{x}10^{-2}$ W/cm^2 on the surface of the device. Noise measurements were performed in the micro-bolometers by using a lock-in amplifier ("Stanford Research Systems Inc." – SR-530), and the detectivity was calculated from the measured I(U) characteristics and the noise measurements.

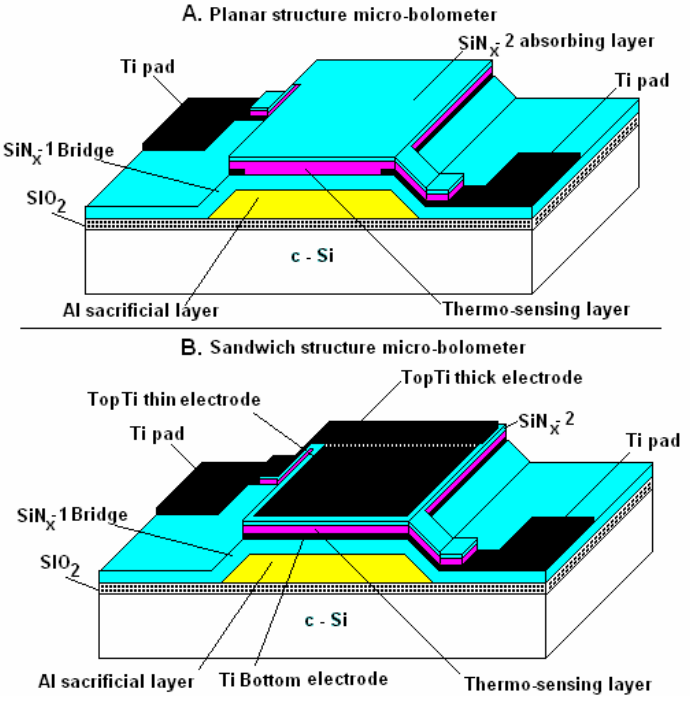


Fig. 2. Micro-bolometer configurations. A. Planar structure, B. Sandwich structure.

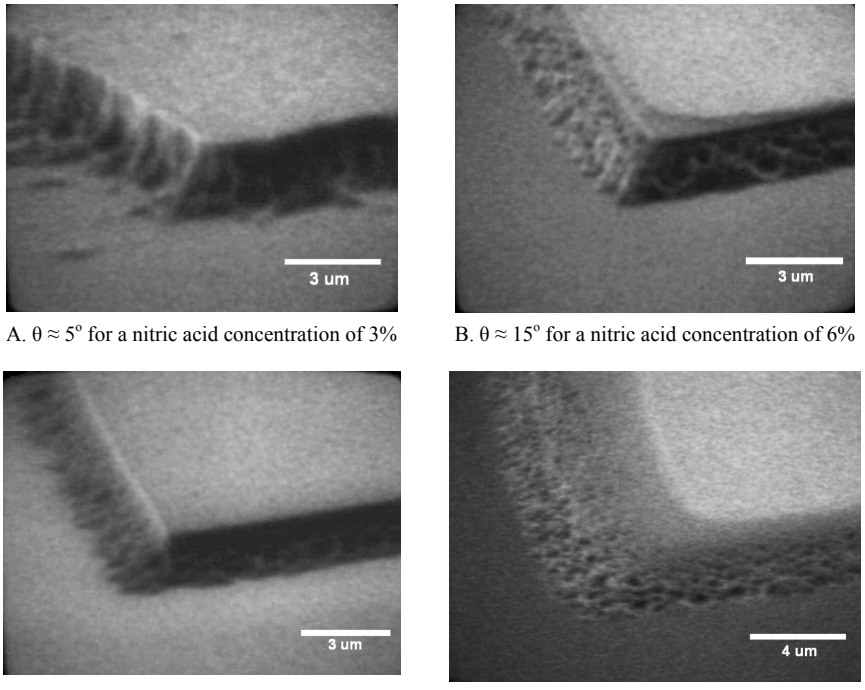
3. Results and discussion

In our firsts attempts of device fabrication, the Al patterns of the sacrificial film were obtained with the standard Al etch solution. The etching solution consisted of the following: H_3PO_4 - 75%, CH_3COOH – 22%, HNO_3 – 3%, and resulted in a small sidewall angle $\theta \approx 5^{\circ}$ as is shown in Fig. 3A. It was observed that such abrupt step could not be well covered by the supporting and electrode layers, resulting in mechanical destruction of the bridge after removing the sacrificial layer and/or destruction of electrical contacts to the electrodes.

In order to solve the aforementioned problems, the Al-etch solution was modified for controlling the sidewall angle of the Al sacrificial structures. We have found that varying the nitric acid (HNO_3) ratio in Al etch, cause a variation in the sidewall angle of the Al patterns as it is depicted in Figs.3 A –D.

Table 1. Films used in the fabrication of the micro-bolometers and their features.

Film Function	Film material	Features
Sacrificial film	Al	e-beam evaporation
		Etched patterns with side wall angle ~ 30 ^{o}
Supporting film	SiN_x-1	Temperature of deposition ~ T = 350 ^oC
		Resistant to solutions for Al etching
		High mechanical stability for micro-machining
Thermo-sensing film	a-Si_xGe_y:H	Temperature of deposition ~ T = 300 ^oC
		High E_a = 0.34 eV and TCR = 0.043 K^{-1}
		Room temperature conductivity, σ_{RT} = 6 x10^{-5} Ω^{-1} cm^{-1}
IR absorbing film	SiN_x-2	Temperature of deposition ~ T = 350 ^oC
		More than 50 % of IR absorption in 7 – 14 μm,



A. θ ≈ 5° for a nitric acid concentration of 3%

B. θ ≈ 15° for a nitric acid concentration of 6%

C. θ ≈ 30° for a nitric acid concentration of 9%

D. θ ≈ 35° for a nitric acid concentration of 12%

Fig. 3. Side wall angle, θ, of Al patterns etched with Al wet etching at different nitric acid concentration.

In Fig. 4 is plotted the dependence of the sidewall angle of the Al patterns with the nitric acid (HNO_3) concentration in the Al-etch solution at room temperature. For the fabrication of the micro-bolometers, the HNO_3 concentration used for the Al patterning was 9%, which provides a slope of θ = 30 ^{o} in the legs of the SiN_x micro-bridges. The optimization of sidewall angle θ, resulted in reducing the number of destroyed bridges

and consequently in an improvement of the yield of the micro-bolometers having a response under IR illumination. The observed enhancement in the yield was from Y < 30 % to Y > 60 %. In Fig. 5 it is shown a fabricated micro-bolometer. The active area of the micro-bolometer is $A_B = 70 \times 66\ \mu m^2$.

Fig. 6 shows the current – voltage I(U), characteristics in dark and under IR radiation of the devices fabricated (planar and sandwich). m. It is clear that a change in the electrodes configuration of the micro-bolometers, have a strong effect in the cell resistance.

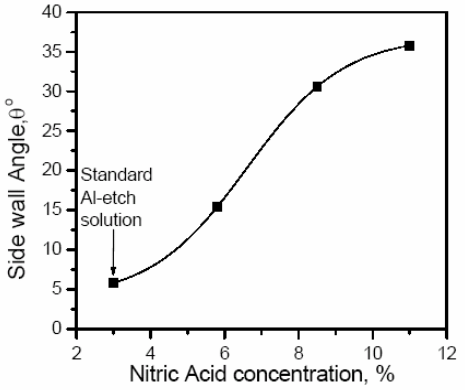
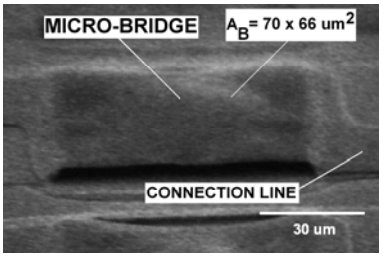
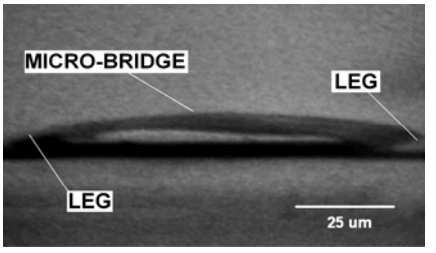


Fig. 4. Side wall angle of Al patterns etched with Al-etch at different nitric acid concentration.

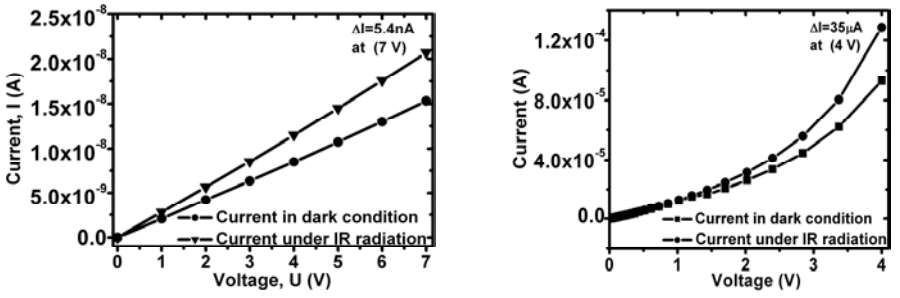


A. SEM top view of a planar structure micro-bolometer.



B. SEM cross section view of a planar structure micro-bolometer.

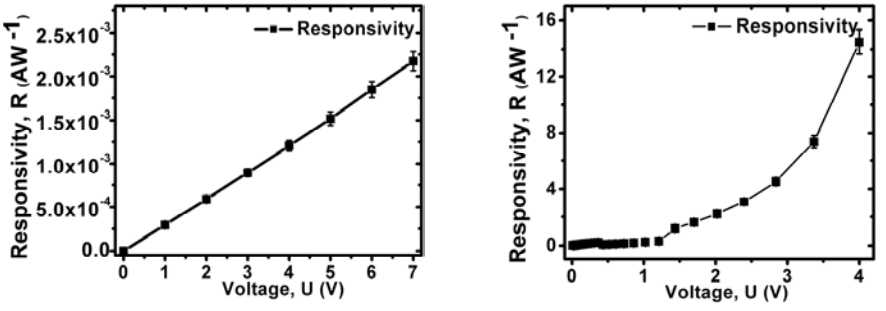
Fig. 5. SEM images of one cell of a planar structure micro-bolometer with a-Si_xGe_y:H thermo-sensing film.



A. Planar configuration with a a-Si_xGe_{1-x}:H film. B. Sandwich configuration with a a-Si_xGe_{1-x}:H film.

Fig. 6. Current – Voltage characteristics of two micro-bolometer configurations.

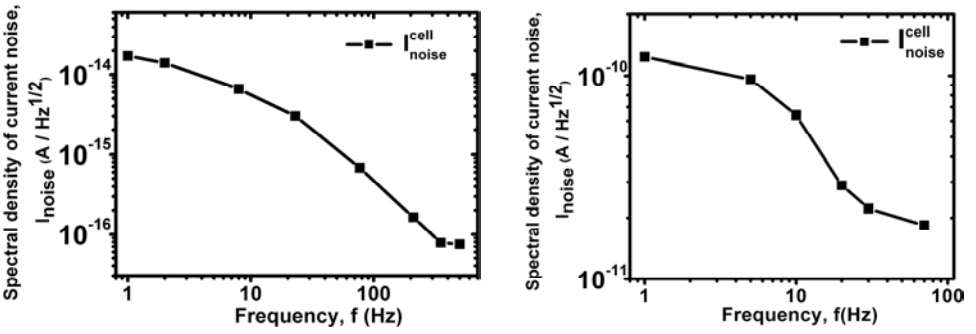
The increment of current from dark to IR illumination (ΔI) in the planar configuration is ΔI = 5.4 nA (at U=7 V), while for the sandwich configuration is ΔI=35 μA (at U=4 V). By changing the configuration of the electrodes in the micro-bolometer, a significantly change in ΔI is obtained. The difference in ΔI is mainly related to the distance between electrodes; in the planar structure the electrodes are separated by 40 μm, while in the sandwich structure are separated by 0.5 μm. The current responsivity (R_I) is defined as $R_I = \Delta I / P_{inc}$ (where P_{inc} is the incident IR power in the sample surface), and $\Delta I \sim 1/(R_{cell} x TCR)$. Fig. 7 shows the current responsivity (R_I) of both configurations: planar and sandwich. The R_I in the sandwich structure is more than 3 orders of magnitude larger than that of the planar structures.



A. Planar configuration with a-Si_xGe_{1-x}:H film. B. Sandwich configuration with a-Si_xGe_{1-x}:H film.

Fig. 7. Responsivity of two micro-bolometer configurations.

Fig. 8 shows the spectral density of current noise in both configurations (I_{noise}), the noise of the system ($I_{system\ noise}$) was measured separately and was subtracted from the system + cell noise ($I_{system+cell\ noise}$) in order to obtain the cell noise ($I_{cell\ noise}$). The $I_{cell\ noise}$ in the sandwich structure is significantly larger than that in the planar structure.



A. Planar configuration with a a-Si_xGe_{1-x}:H film. B. Sandwich configuration with a a-Si_xGe_{1-x}:H film.

Fig. 8. Spectral density of current noise of two micro-bolometer configurations.

Detectivity (D^*) in both structures was calculated from R_I and "white" noise level from $I_{cell\ noise}$ measurements. In Table 2 it is shown the main performance characteristics of the fabricated micro-bolometers, and these are compared with data reported in literature.

Table 2. Performance characteristics of the fabricated micro-bolometers and compared with data from literature.

Thermo sensing Layer	E_a, eV	TCR, K^{-1}	Cell resistance, R_{cell}, Ohm	Voltage responsivity, R_U, VW^{-1}	Current responsivity, R_I, AW^{-1}	Detecti vity, D^* $cmHz^{1/2}W^{-1}$	References
VO_X	0.16	0.021	-	2.5 x 10^7	-	-	Planar [5]
a-Si:H,B	0.22	0.028	3 x10^7	10^6	-	-	Planar [1-2]
a-Si:H	0.30	0.039	-	-	-	-	Planar [3]
a-Si_xGe_y:H	0.34	0.043	5x10^8	7.2x10^5	2x10^{-3}	7.9x10^9	Planar [This work]
a-Si_xGe_y:H	0.34	0.043	1x10^5	2.2x10^5	0.3 - 14	4x10^9	Sandwich [This work]

Because of the data published do no cover all the figures of merit considered in this work; our discussion is limited by the comparison of the available data and our two structures: planar and sandwich. The micro-bolometers here studied demonstrated the highest activation energy E_a and, consequently a higher TCR value however; their resistances were about one order of magnitude higher than those in a-SiH,B [1-2]. The sandwich structure showed the lowest cell resistance, which implies that will be well matched to input of a standard IC. The voltage responsivity in the fabricated samples resulted to be about one order of magnitude less than those reported. We have not found any published data about current responsivity, which is a more practical figure of merit for high resistive samples. Our study showed very a high current responsivity and also a higher noise in the sandwich configuration. (Table 2), when compared with those devices found

in literature. However, the detectivity of both planar and sandwich configurations were similar and close to the theoretical limit determined by the background photon noise[7].

4. Conclusions

We have fabricated and studied planar and sandwich configurations of micro-bolometers by using surface micro-machining techniques on the surface of silicon wafer. The fabrication process here presented, would allow the integration of the micro-bolometer structure and the read-out circuitry on the same chip. To achieve an effective thermo-isolation both configurations used a simple two-leg bridge construction providing mechanical support for the thermo-sensing, electrode and IR absorber layers. It has been shown that the optimization of side wall angle improved the yield from 30 % to a yield higher than 60 % with the modified Al-etch solution. The performance characteristics of the micro-bolometers have been analyzed and compared with those reported in the available literature. The use of plasma deposited silicon-germanium films as thermo-sensing layer on both device structures, have provided a high TCR and, as a consequence a higher responsivity. In spite of the high cell resistance measured in our planar structure, they have demonstrated higher responsivity, low noise level and high detectivity. The sandwich structure demonstrated a very high current responsivity and a low cell resistance, which make this devices very promising for its integration with the circuitry in the same chip, avoiding the problems of matching with the standard input of the most common amplifier circuits. The measured detectivity on both kinds of fabricated devices, despite of the high noise level measured in the sandwich structure, resulted in the values close to the theoretical limit determined by the photon statistics.

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