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Fabrication and characterization of un-cooled micro-bolometers based on silicon germanium thin films obtained by low frequency plasma deposition

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We report the study of a fabrication process and characterization of un-cooled micro-bolometers based on silicon germanium thin films deposited by low frequency PE CVD technique at low temperature and fully compatible with the IC fabrication technology. Surface micro-machining techniques were used for the micro-bolometer fabrication onto a silicon wafer. The a-Si_xGe_{1-x}:H thermo-sensing film used in those devices have shown high activation energy providing high thermal coefficient of resistance and improved but still high resistance. We studied the effect on the electrical properties of the device when boron is incorporated in the a-Si_xGe_{1-x}:H film. The temperature dependence of conductivity σ(T), current-voltage characteristics I(U) and noise spectral density have been measured in order to characterize and compare the performance of micro-bolometers with both types of films: a-Si_xGe_{1-x}:H and a-$Ge_xB_ySi_z$:H.

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

En este trabajo se reporta el estudio del proceso de fabricación y caracterización de micro-bolómetros no enfriados basados en películas delgadas de silicio germanio depositadas por medio de la técnica PE CVD a baja frecuencia, baja temperatura y completamente compatibles con la fabricación de CI's. Se usaron técnicas de micro-maquinado superficial para la fabricación de los micro-bolómetros sobre obleas de silicio. La película termo-sensora de a-Si_xGe_{1-x}:H usada en estos dispositivos ha mostrado alta energía de activación, dando un alto coeficiente térmico de resistencia y una mejorada pero alta resistencia. Se estudió el efecto en las propiedades del dispositivo cuando boro es incrporado en la película a-Si_xGe_{1-x}:H. Se midió la dependencia de la conductividad con la temperatura, las características corriente-voltaje I(U) y la densidad espectral de ruido, con el objetivo de caracterizar y comparar el rendimiento de los micro-bolómetros con los dos tipos de películas: a-Si_xGe_{1-x}:H y a-$Ge_xB_ySi_z$:H.

Descriptores: Germanio; depósito químico en fase vapor asistido por plasma; detectores infrarojos.

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1. Introduction

The incorporation of surface micro-machining techniques for thin films in the Silicon IC fabrication technology have resulted in the development of low cost and reliable night vision systems based on un-cooled thermal detectors. Among the thermal detectors used in these systems, the bolometer is one of them. A bolometer is an IR sensor and its operation is based on the temperature increase of its thermo-sensing film by the absorption of incident IR radiation. The change in temperature causes a change in its electrical resistance. The main requirements for the thermo-sensing materials used in micro-bolometers are: a high value of the temperature coefficient of resistance, TCR (α(T)), defined as α(T) = (1/R)(dR/dT), moderate resistivity, low noise and compatibility with standard IC fabrication processes. Several materials have been used as thermo-sensing elements in micro-bolometers; the most employed are vanadium oxide, amorphous and polycrystalline semiconductors, and some metals [1–5]. Those materials have shown good characteristics, but also some disadvantages. Vanadium oxide presents a high value of TCR, but it is not a standard material in IC technology. Metals that are compatible with the standard IC fabrication technology present a low resistance, but have low values of TCR. Amorphous semiconductors (a-Si:H) have shown a high value of TCR and are fully compatible with the silicon technology. However, intrinsic amorphous semiconductors have a very high resistance. In order to reduce the high resistance of amorphous materials, boron doping has been employed [1]. In our previous work [6–8] a-Si_xGe_{1-x}:H films obtained by PE CVD were used as thermo-sensing layers in the fabrication of micro-bolometers, providing high activation energy and improved but still high resistance. In this work we study the effect in the micro-bolometer performance characteristics when a-$Ge_xB_ySi_z$:H (with boron) is used as thermo-sensing film and we made a comparison with the characteristics of the micro-bolometer with an intrinsic germanium thermo-sensing film (a-Si_xGe_{1-x}:H).

2. Experimental details

The micro-bolometer fabrication process is as follows. A 200 nm-thick SiO_2 layer was deposited by CVD on a c-Si wafer and a 2.5 μm-thick aluminum sacrificial layer was deposited by e-beam evaporation and patterned with wet etching. A 0.8 μm-thick SiN film was deposited at 350°C by low frequency (LF)PECVD. The SiN film is patterned by reactive ion etching (RIE) in order to form a SiN bridge over the aluminum pattern. Titanium (Ti) pads that were 0.2 μm-thick were de-

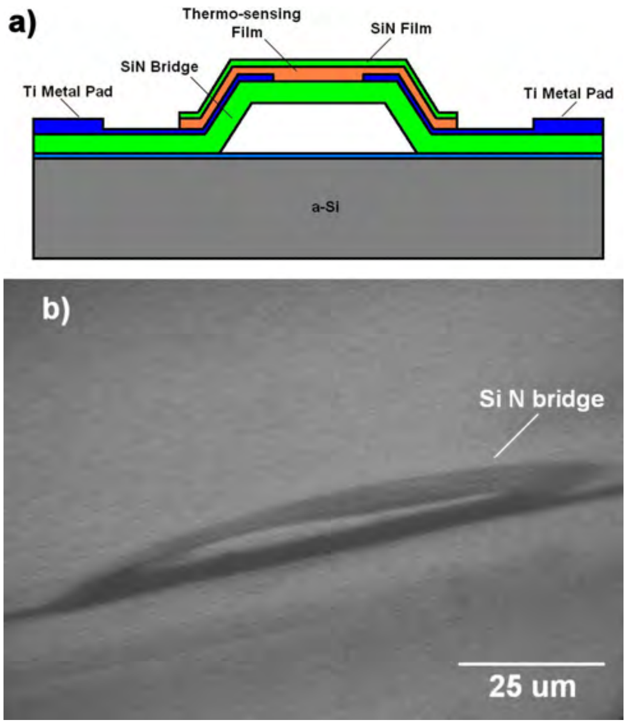

FIGURE 1. a) Micro-bolometer structure. b) SEM photograph of one micro-bolometer.

posited by e-beam evaporation over the SiN bridge. A 0.5 μm-thick thermo-sensing film a-Si_xGe_{1-x}:H was deposited over the Ti pads by LF PECVD technique at a frequency f=110 kHz, temperature T=300°C, power W=350 W and pressure P=0.6 Torr. The a-Si_xGe_{1-x}:H film was deposited from a SiH_4 (100%)+GeH_4 (100 %)+H_2 (100%) mixture with gas flows: Q_{SiH4}=25sccm, Q_{GeH4} =25 sccm, Q_{H2}=1000 sccm. This results in a Ge content of 88%, Si content of 11.7% and H content of 0.3% in the film, those values were obtained by SIMS. The thermo-sensing film was covered with a 0.2 μm-thick SiN film deposited by LF PECVD. The active area was patterned by RIE, and finally, the aluminum sacrificial layer was removed with wet etching.

The boron alloy thermo-sensing film (a-$Ge_xB_ySi_z$:H), was deposited with the conditions used for the previous film, with different gas mixture. The a-$Ge_xB_ySi_z$:H film was deposited from a SiH_4 (100%)+GeH_4 (100%)+B_2H_6 (1% in Hydrogen) mixture with gas flows: Q_{SiH4}=50sccm, Q_{GeH4} =50 sccm, Q_{B2H6}=5 sccm. This results in a Ge content of 67%, Si content of 6%, B content of 26% and H content of 1% in the film, those values were obtained by SIMS. The active area of the thermo-sensing layer is A_b=70×66 μm^2. A sketch of the micro-bolometer is shown in Fig. 1a and a SEM photograph of the device is shown in Fig. 1b.

The performance of the devices was determined through the measurement of I(U) characteristics in dark and under IR illumination from a "Globar" source which provides an intensity I=5.3×10^{-2} W/cm^2 on the sample surface. The sample was placed in a vacuum thermostat ("MMR Inc.") with a Zinc Selenide window (ZnSe) which has a transmission percentage of 70 % in the range of λ=0.6-20 μm. I(U) measurements were performed at a pressure P ≈10mTorr at room temperature with an electrometer ("Keithley"- 6517-A) and the applied voltage was varied from 0 to 7 V. The responsivity was calculated from I(U) results. Noise measurements in the micro-bolometers were made using a lock-in amplifier ("Stanford Research Systems" - SR530). The noise of the system and the total noise (system + cell noise) were measured separately, and a subtraction of both was made in order to obtain the noise of the device. The detectivity was calculated from I(U) characteristics and noise results.

3. Results and discussion

Figure 2 shows the conductivity dependence with temperature when temperature increases and decreases from 300 to 400 K of the a-Si_xGe_{1-x}:H and the a-$Ge_xB_ySi_z$:H thermo-sensing films, respectively. The slope of those curves is the activation energy (E_a). The E_a of the a-Si_xGe_{1-x}:H thermo-sensing film measured in a test structure is E_a=0.34 eV providing a TCR =0.043 K^{-1} and the

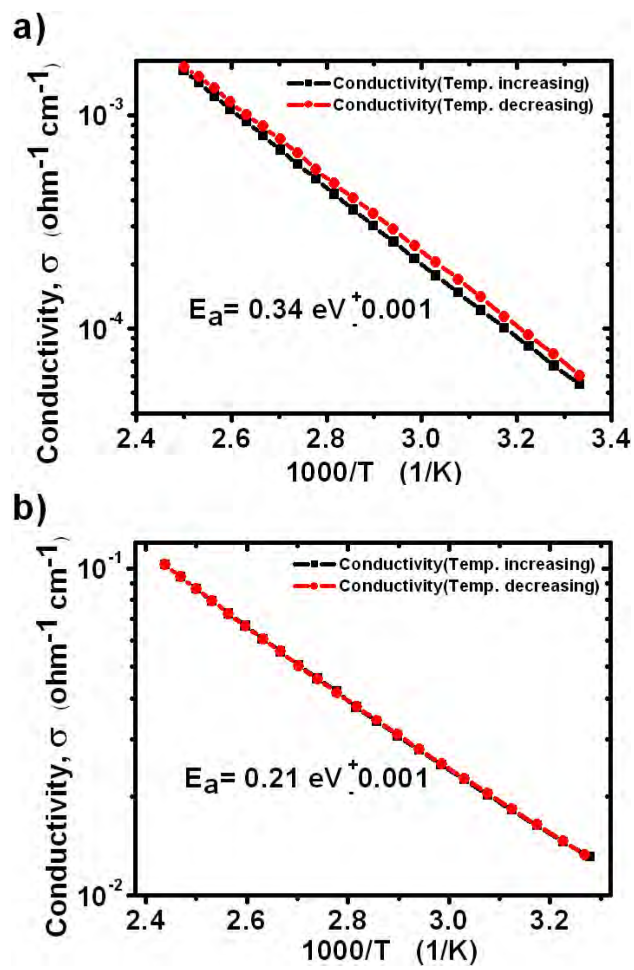

FIGURE 2. Temperature dependence of conductivity of thermo-sensing layer a) a-Si_xGe_{1-x}:H film b) a-$Ge_xB_ySi_z$:H film.

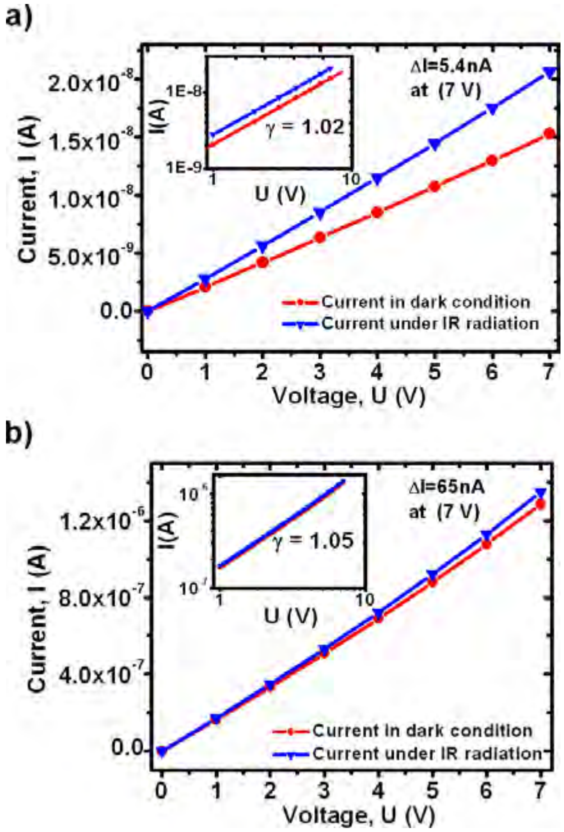

FIGURE 3. I(U) characteristics of the micro-bolometer with a) a-Si_xGe_{1-x}:H film and b) a-$Ge_xB_ySi_z$:H film.

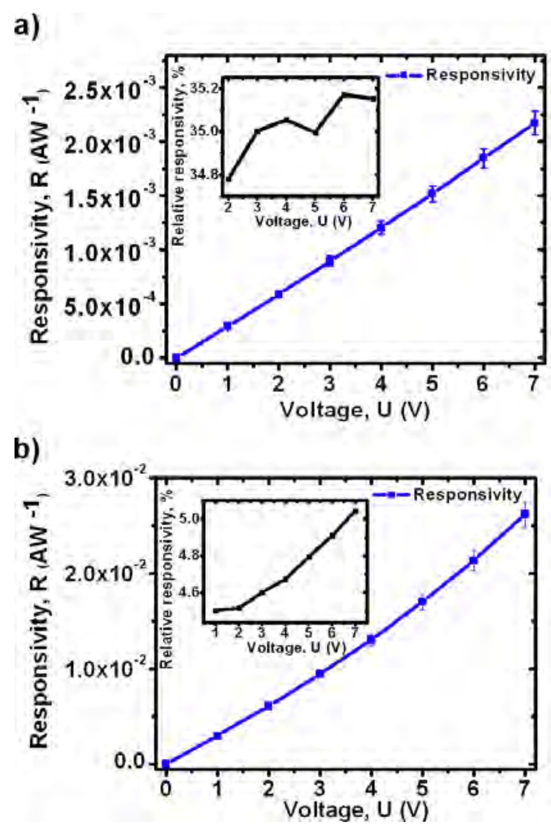

FIGURE 4. Responsivity of the micro-bolometer with a) a-Si_xGe_{1-x}:H film and b) a-$Ge_xB_ySi_z$:H film.

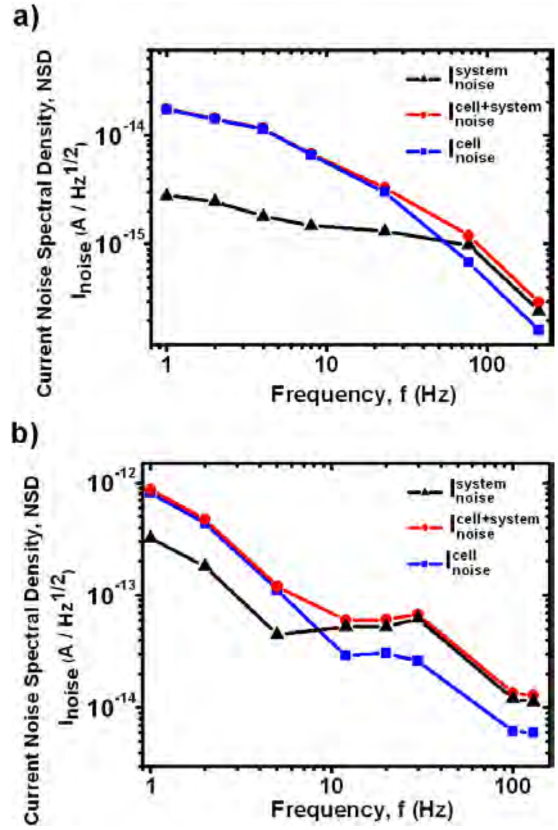

FIGURE 5. Current noise spectral density (NSD), I_{noise} as a function of frequency, of the system + the micro-bolometer cell, the system and the micro-bolometer cell with a) a-Si_xGe_{1-x}:H film and b) a-$Ge_xB_ySi_z$:H film.

conductivity at room temperature (σ_{RT}) is σ_{RT}=6×10^{-5} ohm^{-1}cm^{-1}, while the E_a of the a-$Ge_xB_ySi_z$:H thermo-sensing film is E_a=0.21 eV, providing a TCR = 0.027 K^{-1} and σ_{RT}=1.3×10^{-2} ohm^{-1}cm^{-1}. Current-voltage, I(U) characteristics in dark and under IR illumination are shown in Fig. 3 for both micro-bolometers with the a-Si_xGe_{1-x}:H and the a-$Ge_xB_ySi_z$:H thermo-sensing films, respectively. Linear I(U)characteristics are observed for both devices as it is demonstrated in the insert in Figs. 3a and 3b. Figure 4 shows the current responsivity of the micro-bolometers with the a-Si_xGe_{1-x}:H and a-$Ge_xB_ySi_z$:H thermo-sensing films, respectively. Current responsivity R_I is defined as $R_I = (I_{IR} - I_D)/I_0$, where, I_{IR} is the current under IR illumination, I_D is the dark current, and I_0 is the incident IR intensity. R_I is one order of magnitude less in the a-Si_xGe_{1-x}:H film micro-bolometer than in the a-$Ge_xB_ySi_z$:H film micro-bolometer.

The current noise spectral density (NSD) is shown in Fig. 5 as a function of frequency for both micro-bolometers, where $I_{noise}^{cell+system}(f)$ is the NSD measured in the micro-bolometer cell together with the measuring system, $I_{noise}^{system}(f)$ is the NSD measured in the system without the micro-bolometer cell and a substraction of both is made in order to obtain the NSD of the micro-bolometer cell, $I_{noise}^{cell}(f) = I_{noise}^{cell+system}(f) - I_{noise}^{system}(f)$. The $I_{noise}^{cell}(f)$

TABLE I. Comparison of the characteristics of the micro-bolometers with literature.

Thermo-sensing layer	E_a	TCR	Pixel area	Pixel Resistance	Voltage Responsivity	Current Responsivity	Spectral Response	Detectivity	Ref.
	eV	K^{-1}	μm^2	Ohm	VW^{-1}	AW^{-1}	μm	$cmHz^{1/2}W^{-1}$	
$Ge_xSi_{1-x}O_y$	-	0.048	50×50	-	1×10^5	-	10	6.7×10^8	[1]
a-Si:H,B	-	0.028-0.039	48×48	3×10^7	10^6	-	5 - 14	-	[2]
a-Si_xGe_{1-x}:H	0.34	0.048	70×66	5×10^8	7.2×10^5	2×10^{-3}	0.6 - 20	7×10^9	This Work
a-$Ge_xB_ySi_z$:H	0.21	0.027	70×66	6×10^6	2.8×10^5	2.6×10^{-2}	0.6 - 20	5.9×10^9	This Work

values observed for the a-Si_xGe_{1-x}:H film micro-bolometer are around one order of magnitude less than those observed for the a-$Ge_xB_ySi_z$:H film micro-bolometer. From the measured responsivity and noise, we calculated detectivity D^* in both devices. For the a-Si_xGe_{1-x}:H thermo-sensing film micro-bolometer, we obtained $D^*=7\times10^9$ $cmHz^{1/2}W^{-1}$, while for the a-$Ge_xB_ySi_z$:H thermo-sensing film micro-bolometer, we obtained $D^*=5.9\times10^9$ $cmHz^{1/2}W^{-1}$, both values of detectivity are similar, the reason for this is that the a-$Ge_xB_ySi_z$:H film micro-bolometer has one order of magnitude larger responsivity but also one order of magnitude larger noise than the a-Si_xGe_{1-x}:H film device. The obtained values of both micro-bolometers studied are listed in Table I and are compared with data reported in literature.

4. Conclusions

We have compared the performance characteristics of two uncooled micro-bolometers fabricated with the same fabrication process with different thermo-sensing films: a-Si_xGe_{1-x}:H and a-$Ge_xB_ySi_z$:H. From the characterization we can stress the following: the a-Si_xGe_{1-x}:H thermo-sensing film has a larger activation energy (E_a = 0.34 eV) and consequently higher TCR than the a-$Ge_xB_ySi_z$:H thermo-sensing film (E_a = 0.21 eV); however, the a-Si_xGe_{1-x}:H film resistivity is 3 orders of magnitude larger than the a-$Ge_xB_ySi_z$:H film resistivity. The current responsivity of the a-$Ge_xB_ySi_z$:H film micro-bolometer is one order of magnitude larger than that of the a-Si_xGe_{1-x}:H film micro-bolometer; however, the current noise density of the a-Si_xGe_{1-x}:H film micro-bolometer is one order of magnitude less than that of the a-$Ge_xB_ySi_z$:H film micro-bolometer. Therefore, the detectivity of both devices is similar, D^*=7x10^9 $cmHz^{1/2}W^{-1}$ for the a-Si_xGe_{1-x}:H film micro-bolometer and D^*=5.9x10^9 $cmHz^{1/2}W^{-1}$ for the a-$Ge_xB_ySi_z$:H film micro-bolometer. Even when both devices have similar detectivity, the a-$Ge_xB_ySi_z$:H film micro-bolometer has 2 orders less resistance.

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