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IR sensors based on silicon–germanium–boron alloys deposited by plasma: Fabrication and characterization

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Abstract

We report the study of a fabrication process and characterization of a thermal IR sensor based on silicon–germanium–boron alloys (a-$Si_xGe_yB_z$:H) deposited by plasma at low temperature. The sensor is an un-cooled micro-bolometer fabricated with surface micro-machining techniques and is fully compatible with the CMOS technology. The temperature dependence of conductivity $\sigma(T)$ was measured in the sensor in order to calculate the activation energy, E_a, the temperature coefficient of resistance, TCR and the room temperature conductivity, σ_{RT}. Current–voltage characteristics, $I(U)$, in darkness and under IR radiation were measured in the device in order to calculate its current responsivity, R_I. Spectral noise density was measured and the micro-bolometer detectivity, D^* was calculated. The thermal time constant of the micro-bolometer was also measured.

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Keywords: Amorphous semiconductors; Germanium; Silicon; Sensors

1. Introduction

The incorporation of MEMS structures in the silicon IC technology, through surface micro-machining techniques on thin films, has allowed the development of high performance thermal detectors [1–4]. A bolometer is a thermal sensor, 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 which is measured by an external circuit.

The requirements for high performance micro-bolometers are: a thermo-sensing material with high activation energy, E_a, and consequently a high value of the temperature coefficient of resistance, TCR ($\alpha(T)$), which is related with E_a by $\alpha(T) = E_a/kT^2$, moderated resistivity, low noise, fast thermal response time and compatibility with standard IC fabrication technology.

Hydrogenated intrinsic amorphous silicon (a-Si:H) prepared by PECVD is a material commonly used in micro-bolometers as thermo-sensing film, for room temperature operation [1–4]. It is compatible with the IC technology, presents a high activation energy, $E_a \approx 0.30$ eV and high value of TCR, $\alpha(T) \approx 0.039\ K^{-1}$ [4], however, it also presents a high undesirable resistivity, which often cause a mismatch with the input impedance of 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 presents a significant reduction in its resistivity, with values as low as $\rho \approx 2 \times 10^2\ \Omega\,cm$ at room temperature and cell resistance $R_{cell} \approx 3 \times 10^7\ \Omega$ when is used as thermo-sensing film in micro-bolometers. However, a reduction in E_a and TCR is obtained also, $E_a \approx 0.22$ eV and TCR $\approx 0.028\ K^{-1}$ [4].

In our previous work [5,6] we have employed amorphous silicon–germanium, a-Si_xGe_y:H, deposited by PECVD as thermo-sensing films in un-cooled micro-bolometers. We have obtained high activation energy, $E_a = 0.34$ eV,

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consequently a high value of TCR = 0.043 K^{-1}, improved but still high resistivity $\rho \approx 1.6 \times 10^4\ \Omega$ cm (without doping) and a cell resistance $R_{cell} \approx 5 \times 10^8\ \Omega$.

In order to reduce the resistivity in the a-Si_xGe_y:H films, we have included B during the thermo-sensing film deposition process. In this work we present the fabrication and characterization of a micro-bolometer with a silicon–germanium–boron alloy (a-$Si_xGe_yB_z$:H) as thermo-sensing film and we compare its performance characteristics with those of the micro-bolometer with an a-Si_xGe_y:H intrinsic thermo-sensing film and the B-doped a-Si:H micro-bolometer reported in literature [4].

2. Experimental

The micro-bolometer fabrication process is the following: Initially a c-Si substrate is covered by 0.2 μm-thick SiO_2 film deposited by CVD at temperature $T = 300$ °C and a 2.5 μm-thick aluminum (Al) sacrificial layer is deposited by e-beam evaporation. A lithographic step and wet etching is carried out in order to obtain an Al pattern and over it is deposited a 0.8 μm-thick SiN film by low frequency (LF) PECVD at $T = 350$ °C. The SiN film is patterned by reactive ion etching (RIE) in order to form a SiN bridge over the aluminum sacrificial pattern. A 0.2 μm-thick titanium layer is deposited by e-beam evaporation over the SiN bridge and it is patterned in order to form the contacts. A 0.4 μm-thick a-$Si_xGe_yB_z$:H thermo-sensing film is deposited over the Ti contacts by LF PECVD technique at a RF frequency $f = 110$ kHz, $T = 300$ °C, power $W = 350$ W and pressure $P = 0.6$ Torr. The a-$Si_xGe_yB_z$:H film is deposited from a $SiH_4 + GeH_4 + B_2H_6 + H_2$ mixture with gas flow rates: $Q_{SiH_4} = 50$ sccm, $Q_{GeH_4} = 50$ sccm, $Q_{B_2H_6} = 5$ sccm and $Q_{H_2} = 500$ sccm. This results in a Ge content in solid phase $Y = 0.67$, B solid content $Z = 0.26$ and Si solid content $X = 0.07$. Those results were obtained by SIMS. The thermo-sensing film is covered then with a 0.2 μm-thick SiN absorbing film deposited by LF PECVD. The active area is patterned by RIE and finally the aluminum sacrificial layer is removed with wet etching. The active area of the thermo-sensing film is $A_b = 70 \times 66\ \mu m^2$. Fig. 1 shows the process flow for the micro-bolometer fabrication.

We determined the performance characteristics of the micro-bolometer at room temperature. For the characterization the device was placed in a vacuum thermostat at pressure $P \approx 20$ mTorr, with a zinc selenide window (ZnSe) with transmission of 70% in the range of $\lambda = 0.6$–20 μm. In order to calculate the responsivity we performed current–voltage $I(U)$ measurements in darkness and under IR illumination. We employed an electrometer ('Keithley'-6517-A), which allows us to vary the voltage applied (0–7 V) to the sample and measure current. For the IR illumination we employed a SiC globar source, with an intensity $I_0 = 5.3 \times 10^{-2}$ W/cm^2 and spectrum in the range $\lambda =$ 1–20 μm.

We performed noise measurements in the micro-bolometers employing a lock-in amplifier ('Stanford Research Systems'-SR530). The total noise (system + the micro-bolometer) and the system noise were measured separately, and a subtraction of both was made in order to obtain the micro-bolometer noise. From the $I(U)$ characteristics and noise results we calculated the detectivity D^*. The micro-bolometer thermal time constant was measured also. We applied a voltage pulse to the micro-bolometer and we observed its response current in an oscilloscope.

3. Results

The conductivity $\sigma(T)$, is related to the activation energy E_a, by the equation $\sigma(T) = \sigma_0 \exp(-E_a/kT)$, where σ_0 is the prefactor, k is the Boltzmann constant and T is the temperature. The temperature dependence of $\sigma(T)$ of the a-$Si_xGe_yB_z$:H thermo-sensing film was measured in the range of 300–400 K, we obtained an $E_a = 0.21$ eV, a TCR = 0.027 K^{-1} and a room temperature conductivity $\sigma_{RT}(T) = 1 \times 10^{-2}\ (\Omega\ cm)^{-1}$.

Fig. 2 shows the micro-bolometer $I(U)$ characteristics in darkness and under IR illumination. We observe an increment in current from darkness to IR condition $\Delta I = 65$ nA

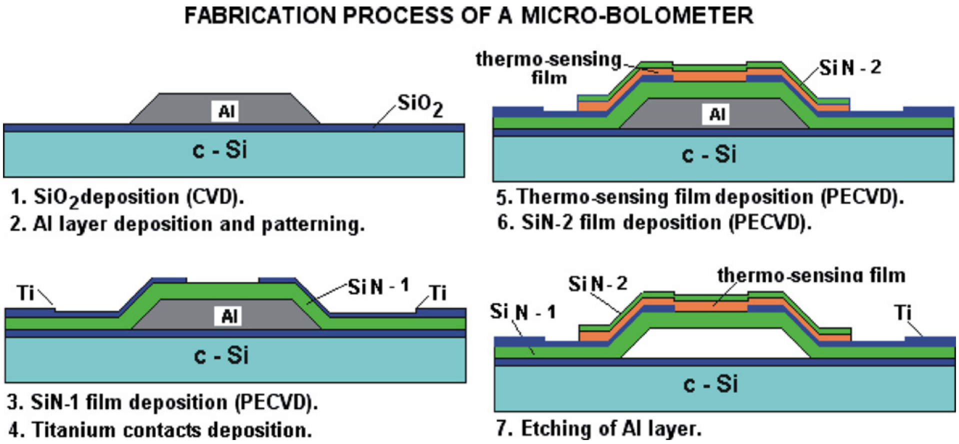

Fig. 1. Fabrication process of a micro-bolometer.

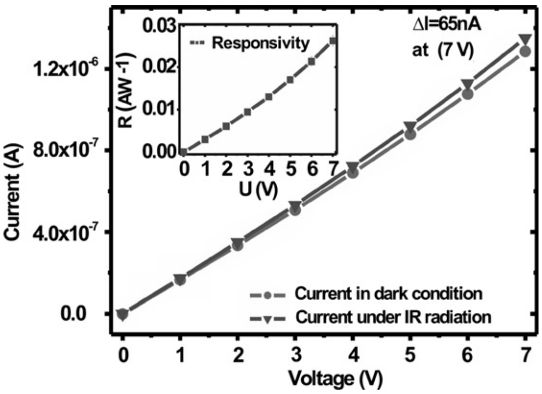

Fig. 2. $I(U)$ characteristics of micro-bolometer with a-$Si_xGe_yB_z$:H film.

(at 7 V), where $\Delta I = I_{IR}–I_{Dark}$, I_{IR} is the current under IR condition and I_{Dark} is the current in darkness. The current responsivity R_I, is defined as $R_I = \Delta I/P_{inc}$, where $P_{inc} = I_0 \times A_b$, I_0 is the IR source incident intensity ($I_0 = 5.3 \times 10^{-2}$ W/cm^2) and A_b is the bolometer area ($A_b = 70 \times 66$ μm^2). The insert in Fig. 2 shows the current responsivity as a function of voltage R_I(V). At 7 V the current responsivity measured is $R_I = 3 \times 10^{-2}$ A/W. From the $I(U)$ characteristics in darkness we obtained the micro-bolometer cell resistance, R_b, obtaining $R_b = 6 \times 10^6$ Ω.

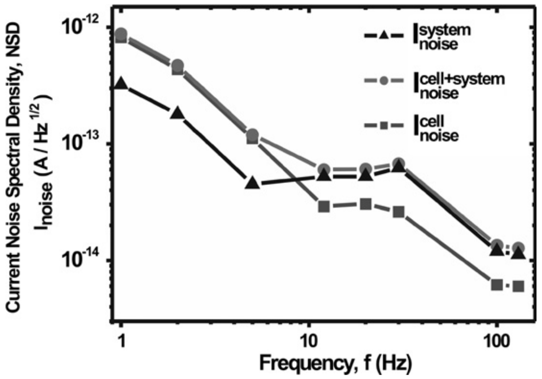

Fig. 3. Spectral density of current noise as a function of frequency of the micro-bolometer with a-$Si_xGe_yB_z$:H film.

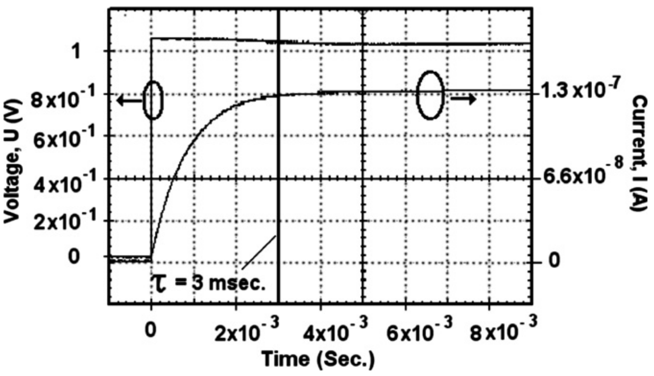

Fig. 4. Response time of the micro-bolometer with a-$Si_xGe_yB_z$:H film.

Table 1
Comparison of the micro-bolometers performance characteristics

Thermo sensing layer	E_a, eV	TCR, αK^{-1}	Pixel area, A_b, μm^2	Pixel resistance, R_b, Ω	Thermal time τ, m s	Voltage responsivity, R_U, VW^{-1}	Current responsivity, R_I, AW^{-1}	Spectral response, μm	Detectivity, D^* cm Hz$^{1/2}$W^{-1}	Ref.
a-Si:H,B	0.22	0.028	48 × 48	3×10^7	11	10^6	–	5–14	–	[4]
a-Si_xGe_y:H (intrinsic)	0.34	0.043	70 × 66	5×10^8	125	7.2×10^{5a}	2×10^{-3}	1–14	7×10^9	[6] Previous work
a-$Si_xGe_yB_z$:H	0.21	0.027	70 × 66	6×10^6	3	2.8×10^{5a}	2.6×10^{-2}	1–14	6×10^9	This work

[a] Voltage responsivity R_U, was calculated from the current responsivity R_I.

Fig. 3 shows the current noise spectral density in the system, $I_{\text{system noise}}$ (f); in the system + the micro-bolometer, $I_{\text{system + bolometer noise}}$ (f) and in the bolometer, $I_{\text{bolometer noise}}$ (f), which is obtained as $(I_{\text{bolometer noise}}(f))^2 = (I_{\text{system + bolometer noise}}(f))^2 - (I_{\text{system noise}}(f))^2$. We observe a current noise spectral density in the micro-bolometer $I_{\text{bolometer noise}}(f) \approx 10^{-14}\ \text{AHz}^{-1/2}$. The detectivity D^*, was calculated as: $D^* = [R_I\ (A_b)^{1/2}]/[I_{\text{bolometer noise}}/(\Delta f)^{1/2}]$ obtaining $D^* \approx 6 \times 10^9\ \text{cm Hz}^{1/2}\ \text{W}^{-1}$.

Fig. 4 shows the micro-bolometer thermal response time, where a voltage step is applied to the micro-bolometer and its current response is recorded. The time necessary to reach the steady state (from 0 to 100% of the final current value) observed is $\tau \approx 3$ m s.

4. Discussion

From the temperature dependence of conductivity measurements we observed that the E_a and σ_{RT} values of the a-$Si_xGe_yB_z$:H thermo-sensing film are similar to those reported for the B doped a-Si:H thermo-sensing film [4]. The σ_{RT} in the a-$Si_xGe_yB_z$:H film is 3 orders of magnitude larger than that of the intrinsic a-Si_xGe_y:H film, however it presents a reduction of 40% in E_a.

From the micro-bolometer $I(U)$ characteristics we calculated a current responsivity $R_I = 3 \times 10^{-2}$ A/W, which is one order of magnitude larger than that of the a-Si_xGe_y:H intrinsic film micro-bolometer. The a-$Si_xGe_yB_z$:H film micro-bolometer cell resistance $R_b = 6 \times 10^6\ \Omega$, is around one order of magnitude smaller than the resistance reported for the B doped a-Si:H micro-bolometer, $R_b = 3 \times 10^7\ \Omega$, and two orders of magnitude smaller than that of the a-Si_xGe_y:H film micro-bolometer, $R_b = 5 \times 10^8\ \Omega$.

From the responsivity and current noise spectral density measured in the micro-bolometer we calculated the detectivity, obtaining $D^* \approx 6 \times 10^9\ \text{cm Hz}^{1/2}\ \text{W}^{-1}$, which is comparable with that of the a-Si_xGe_y:H intrinsic film micro-bolometer ($D^* \approx 7 \times 10^9\ \text{cm Hz}^{1/2}\ \text{W}^{-1}$).

The thermal time constant measured in the device is $\tau \approx 3$ m s, which is faster than the reported for the B doped a-Si:H micro-bolometer ($\tau = 11$ m s) and than that of the a-Si_xGe_y:H intrinsic film micro-bolometer ($\tau \approx 125$ m s). Table 1 presents a comparison in performance characteristics of the a-$Si_xGe_yB_z$:H film micro-bolometer with the a-Si_xGe_y:H intrinsic film micro-bolometer and the a-Si:H micro-bolometer reported in literature.

5. Conclusions

A micro-bolometer with a a-$Si_xGe_yB_z$:H thermo-sensing film has been fabricated using surface micro-machining techniques, at low temperature and compatible with IC Si technology. It presents a low room temperature resistivity $\rho_{RT}(T) = 1 \times 10^2\ \Omega$ cm, which is comparable with that of the B doped a-Si:H film reported in literature [4] and three orders of magnitude less than that of the a-Si_xGe_y:H intrinsic film.

From the characterization results, we can conclude that the micro-bolometer with the a-$Si_xGe_yB_z$:H thermo-sensing film presents advantages, in the performance characteristics in comparison with the B doped a-Si:H micro-bolometer, and the a-Si_xGe_y:H intrinsic film micro-bolometer. These advantages are a significant reduction in the cell resistance and response time, without a decrement in the detectivity, D^*.

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References

[1] J.J. Yon, A. Astier, S. Bisotto, G. Chamingis, A. Durand, J.L. Martin, E. Mottin, J.L. Ouvrier-Buffet, J.L. Tissot, Infrared Tech. Appl. XXXI, SPIE Proc. 5783 (2005) 432.

[2] J.L. Tissot, Opto-Electron. Rev. 12 (1) (2004) 105.

[3] Eric Mottin, Astrid Bain, Jean-Luc Martin, Jean-Louis Ouvrier-Buffet, Sylvette Bisotto, Jean-Jacques Yon, Jean-Luc Tissot, Infrared Tech. Appl. XXVIII, SPIE Proc. 4820 (2003) 200.

[4] A.J. Syllaios, T.R. Schimert, R.W. Gooch, W.L. Mc.Cardel, B.A. Ritchey, J.H. Tregilgas, Mat. Res. Soc. Symp. Proc. 609 A14.4.1 (2000).

[5] R. Ambrosio, A. Torres, A. Kosarev, A. Illinski, C. Zúñiga, A.S. Abramov, J. Non-Cryst. Solids 338–340 (2004) 91.

[6] M. Moreno, A. Kosarev, A. Torres, R. Ambrosio, J. Thin Solid films 515 (19) (2007) 7607.