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# Measurements of thermal characteristics in silicon germanium un-cooled micro-bolometers

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We present a study of the thermal characteristics of an infrared detector (un-cooled micro-bolometer), based on an amorphous silicon germanium film (a-$Si_xGe_y$:H), deposited by plasma at low temperature (~ 300 °C) and compatible with the standard CMOS technology. These films have been studied due to their high performance characteristics as high activation energy ($E_a \approx$ 0.37 eV), high temperature coefficient of resistance (TCR≈ -0.047 $K^{-1}$) and moderate room temperature conductivity ($\sigma_{RT} \approx 2x10^{-5}$ Ω cm), which provides a moderate pixel resistance ($R_{cell} \approx 3.5x10^8 \Omega$). We have used two simple methods to calculate the thermal characteristics of the micro-bolometer. The thermal conductance ($G_{th}$) has been obtained from the electrical I(U) characteristics in the range where self heating due to bias is not presented. The temperature dependence of the electrical resistance and as well the temperature dependence of the thermal resistance have been obtained by measuring the I(U) characteristics in the device at different temperature values. Finally the results of both methods have been compared.



**1 Introduction** Hydrogenated amorphous silicon (a-Si:H) deposited by plasma is a mature material used as thermo-sensing film in commercial infrared detectors as micro-bolometer arrays [1, 2], since it is fully compatible wit the CMOS technology, has a very high activation energy ($E_a \approx$ 1 eV) and as consequence a very high thermal coefficient of resistance, TCR ($\alpha \approx$ -0.13 $K^{-1}$), which results in pixel devices with very high responsivity values.

However a-Si:H has a very low room temperature conductivity ($\sigma_{RT} \leq 1x10^{-9}$ $(\Omega cm)^{-1}$) , providing a very high pixel resistance ($R_{pixel} \geq 10^9$ Ω), which cause a mismatch with the input impedance of the CMOS read-out circuits. Usually born doping is used in order to reduce the a-Si:H high resistance (to arround $R_{pixel} \approx 3x10^7$ Ω), however it also results in a reduction on the $E_a$ (0.22 eV) and TCR (-0.028 $K^{-1}$) [3], and therefore in a decrement of the pixel performance.

A variety of materials have been studied as alternative choice for micro-bolometers, such as Poly-SiGe [4], YBaCuO [5], and $Ge_xSi_{1-x}O_y$ [6] among others. Poly-SiGe have a moderate TCR value ($\alpha \approx$-0.024 $K^{-1}$), however the deposition temperature is high ($T_{sub} \geq$ 600 °C), which make it non compatible for a post process of fabrication in the wafer surface where is already presented the CMOS read-out circuit. YBaCuO has relatively high TCR value ($\alpha \approx$ -0.033 $K^{-1}$), however the contamination of the wafer surface due to Cu is an issue. $Ge_xSi_{1-x}O_y$ deposited by sputtering has a very high TCR value ($\alpha \approx$ -0.048 $K^{-1}$) and moderated room temperature conductivity ($\sigma_{RT} \approx 2.6x10^{-5}$ $(\Omega cm)^{-1}$), however a very well control on the oxygen content in the film is needed. Intrinsic amorphous silicon germanium (a-$Si_xGe_y$:H) deposited by plasma at low temperature ($T_{sub} \leq$ 300 °C), appears as a serious candidate as thermo sensing element for high performance un-cooled micro-bolometers. Since it is compatible with the CMOS technology, has a high activation energy ($E_a$ = 0.37 eV), high TCR value ($\alpha$ = -0.047 $K^{-1}$), a moderated room temperature conductivity ($\sigma_{RT} \approx 6x10^{-5}$ $(\Omega cm)^{-1}$) [7], and a moderated pixel resistance ($R_{cell} \approx 3.7x10^8$ Ω).

One of the key parameters that characterize the performance of thermal detectors are the thermal characteristics such as: the thermal conductance, the temperature dependence of the electrical resistance and as well the temperature dependence of thermal resistance. Several methods have been used to obtain the thermal characteristics of IR detectors [8-11], however most of them are based on complex experimental setups, which usually are no easy to implement. In this work are presented two simple methods based on electrical measurements to obtain the thermal characteristics of a un-cooled micro-bolometer with a-$Si_xGe_y$:H thermo sensing film. The thermal conductance ($G_{th}$) of the micro-bolometer has been extracted from the I(U) characteristics, before to produce a self heating due to the applied bias. The temperature dependence of the electrical resistance (calibration curve) and the temperature dependence of the thermal resistance were also obtained by measuring the I(U) characteristics at different temperature values.

## 2 Experimental

**2.1 Device fabrication** The micro-bolometer was fabricated using surface micromachining techniques. First a 2.5 μm-thick sacrificial aluminum layer was deposited by e-beam evaporation over a c-Si wafer in which previously was deposited a thin $SiO_2$ film. The Al layer was patterned in a square structure with a side wall angle of 30º and a 0.8 μm-thick $SiN_x$ film was deposited over it by plasma in a PECVD reactor at substrate temperature of 350 °C. The $SiN_x$ film was patterned by reactive ion etching (RIE) in order to form a micro-bridge, and a 0.2 μm-thick titanium contacts were deposited by e-beam evaporation over it. The thermo-sensing a-$Ge_xSi_y$:H film of thickness of 0.5 μm was deposited by plasma at 300 °C, and pressure of 0.6 Torr, from a $SiH_4$ - $GeH_4$ - $H_2$ gas mixture. A 0.2 μm-thick absorbing $SiN_x$ film was deposited over the thermo–sensing film and finally the aluminum sacrificial layer was removed using wet etching. The active area of the micro-bolometer is $A_b$=70x66 μm$^2$. Figure 1 A) shows the scheme of one micro-bolometer, while Figure 1 B) shows a SEM image of the detector.

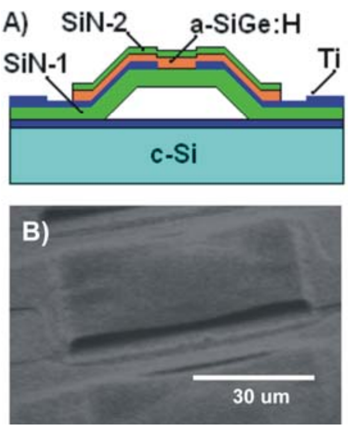


**Figure 1** Micro-bolometer: A) scheme, B) SEM image.

**2.2 Thermal characterization** The micro-bolometer was placed in a vacuum thermostat at pressure of 20 mTorr. The measurement of I(U) characteristics were performed using an electrometer ("Keithley"- 6517-A), which also works as a bias source. In order to obtain the thermal conductance ($G_{th}$) of the micro-bolometer, I(U) measurements were performed in a wide range. We take the I(U) experimental points before self-heating and re-ploted the data as I/U vs. $I^2$. By fitting this curve as a line, is possible to obtain a curve in the form showed by Eq. (1) [12] where $a = 1/R_B$, b = $E_a/G_{th}$, $R_B$ is the micro-bolometer resistance, $G_{th}$ is its thermal conductance and $E_a$ is the activation energy.

$$\frac{I}{U} = \frac{1}{R_B} + \frac{E_a}{G_{th}} \cdot I^2 \qquad (1)$$

In order to estimate the temperature dependence of the thermal resistance of the micro-bolometer, I(U) measurements were performed at different temperatures. The linear part of the I(U) curves is used to obtain the electrical resistance of the micro-bolometer. In this way is possible to graph the micro-bolometer electrical resistance as a function of the temperature, commonly called the calibration curve of the device. By combining the data of the I(U) characteristics and the calibration curve is possible to extract the increment in temperature (ΔT) as function of the power applied to the micro-bolometer. Finally the thermal resistance, $R_{th}$, is obtained as the slope of the curves of ΔT as a function of the power, for the different temperature values.

## 3 Results and discussion

**3.1 Thermal conductance** For the extraction of the thermal conductance ($G_{th}$) of the micro-bolometer we measured the I(U) characteristics from 0 to 50 V as is shown in Fig. 2. The wide range of the applied voltage causes a self heating in the device.

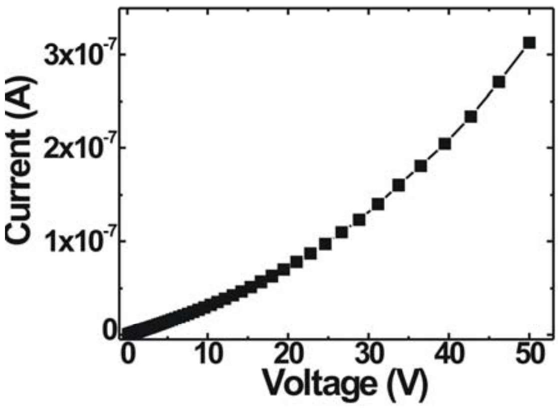


**Figure 2** I(U) characteristic of a micro-bolometer with an a-$Si_xGe_y$:H film.

If the data from the I(U) characteristics (Fig. 2) is re-plotted as the electrical resistance (R = U/I) in function of the power (P = U*I), then the curve shown in Fig. 3 is obtained. This plot is more suitable in order to determine at which bias value self heating appears on the device.

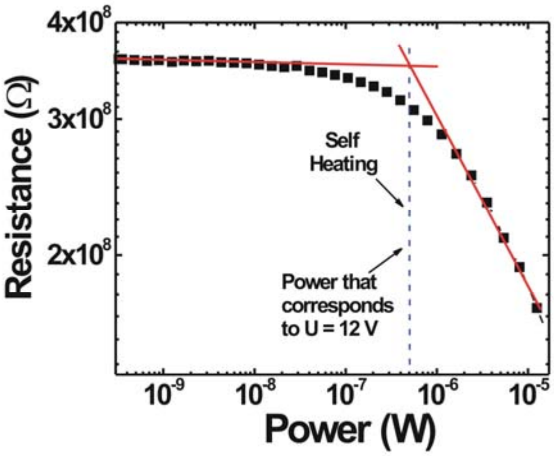


**Figure 3** Micro-bolometer resistance with an a-$Si_xGe_y$:H film as a function of power.

The cone of the curve of Fig. 3 corresponds to the power at which self heating appears in the micro-bolometer due to the bias. The value of power of $5x10^{-7}$ W corresponds to a bias of 12 V, thus larger bias will produce self-heating on the device. If we take the I(U) experimental points before self-heating (i.e. points from 0 to 12 V) and re-plot the data as I/U vs. $I^2$ , then we will get the curve shown in Fig. 4.

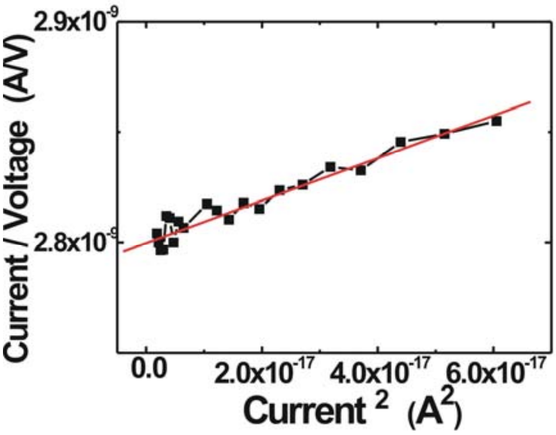


**Figure 4** I(U) characteristics re-plotted as (I/U) as a function of $I^2$ of a micro-bolometer with an a-$Si_xGe_y$:H film.

The linear fit of the curve I/U vs. $I^2$ (Fig. 4) using the equations 1 and 2 discussed in section 2.2, will give as a result: $a = 2.7x10^{-9}$ and $b = 961265$. If the activation energy is $E_a$= 0.37 eV, then is possible to obtain the value of $G_{th}$ and the electrical resistance: $G_{th} = E_a/b = 3.8 \times 10^{-7}$ $WK^{-1}$ and $R_B = 1/a = 3.7 \times 10^8$ Ω.

**3.2 Temperature dependence of thermal resistance** In order to estimate the temperature dependence of the thermal resistance of the micro-bolometer, I(U) measurements were performed , in the range from 260 K to 360 K, as is shown in Fig. 5, where the bias is plotted as a function of current.

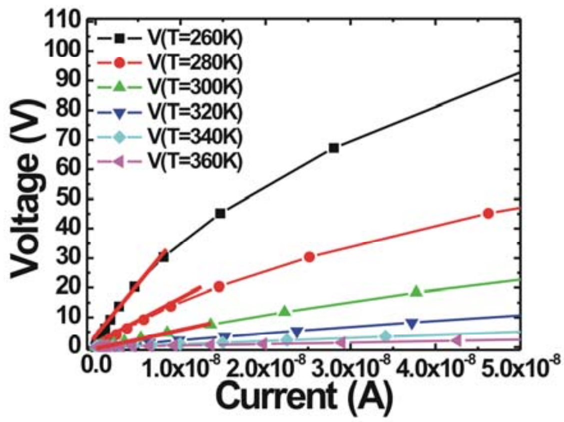


**Figure 5** I(U) characteristics of a micro-bolometer with an a-$Si_xGe_y$:H film, at different temperature, from 260 K to 360 K.

The slope of the linear part of each curve shown in Fig. 5 corresponds to the electrical resistance of the micro-bolometer for various temperature values. Thus is possible to graph the temperature dependence of the electrical resistance of the micro-bolometer, or also called the calibration curve, as is shown in Fig. 6.

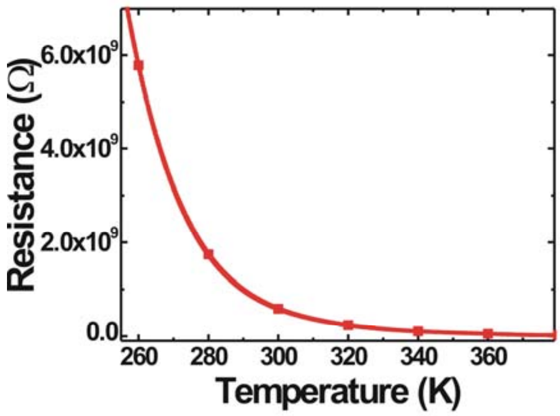


**Figure 6** The temperature dependence of the electrical resistance of a micro-bolometer with an a-$Si_xGe_y$:H film or calibration curve.

By combining the data of the I(U) characteristics (Fig. 5) and the calibration curve (Fig. 6), it is possible to extract the increment of temperature (ΔT) as a function of the power (P=U*I) applied to the micro-bolometer, for each temperature , as is shown in Fig. 7.

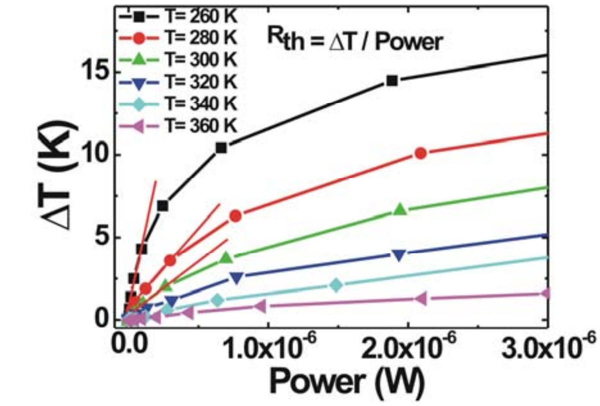


**Figure 7** Increment of temperature on the micro-bolometer with an a-$Si_xGe_y$:H film as a function of the power applied to it.

The thermal resistance of the micro-bolometer, $R_{th}$, is then obtained as the slope of the increment of temperature in the micro-bolometer ($\Delta T$) as a function of the power applied to it, for each temperature value. Figure 8 shows the temperature dependence of the thermal resistance ($R_{th}$).

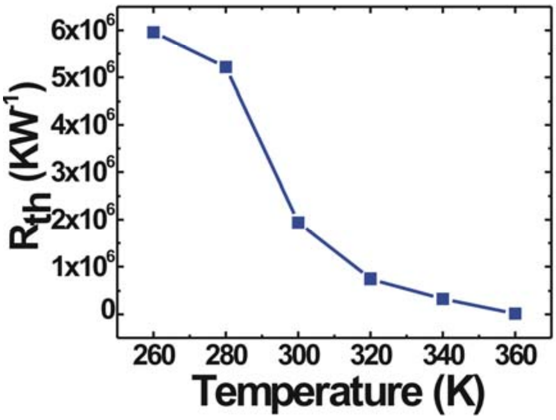


**Figure 8** Temperature dependence of the thermal resistance ($R_{th}$) of a un-cooled micro-bolometer with a-$Si_xGe_y$:H film.

From the results of section 3.1, where the micro-bolometer thermal conductance was obtained at room temperature ($G_{th}$ = 3.8 x $10^{-7}$ $WK^{-1}$), the inverse of $G_{th}$, was evaluated to obtain the thermal resistance ($R_{th} = 1/G_{th}$ = 2.6 x $10^6$ $KW^{-1}$). Comparing this result with the value of the thermal resistance at room temperature extracted from the graph of Fig. 8 ($R_{th} \approx$ 2 x $10^6$ $KW^{-1}$), we found that both values are very similar, suggesting that both methods are precise in order to calculate the thermal characteristics of the IR detectors. Finally Table 1 shows the performance characteristics of micro-bolometers with different thermo sensing films, where the device presented in this work has the larger detectivty, resulted from its larger responsivity; low noise [7] and its very low thermal conductivity.

| Thermo sensing Layer | TCR, $K^{-1}$ | Cell resistance, $R_{cell}$, Ohm | Voltage responsivity, $R_U$, $VW^{-1}$ | Detecti vity, $D^*$ $cmHz^{1/2}W^{-1}$ | Thermal conductivity (W/K) |
|---|---|---|---|---|---|
| a-Si:H,B [3] | -0.028 | 3 x$10^7$ | $10^6$ | - | 2.5x$10^{-8}$ |
| Poly-SiGe [4] | -0.24 | 1x$10^5$ | 1.3x$10^5$ | 2.3x$10^9$ | 1.5x$10^{-7}$ |
| YBaCuO [5] | -0.03 | 1x$10^7$ | 0.8x$10^4$ | 2x$10^7$ | $10^{-5}$ |
| $Ge_xSi_{1-x}O_y$ [6] | -0.048 | 7x$10^5$ | 1x$10^5$ | 7x$10^8$ | 1.3x$10^{-7}$ |
| a-$Si_xGe_y$:H [7] | -0.043 | 5x$10^8$ | 7.2x$10^5$ | 7x$10^9$ | 3.8 x $10^{-7}$ |

**Table 1** Performance characteristics of different bolometers.

**4 Conclusions** We have studied two methods for extract the thermal characteristics of un-cooled micro-bolometers, based on measurements of the I(U) characteristics. Three important parameters have been extracted from this characterization, which are the room temperature thermal conductance ($G_{th}$), the calibration curve of the device, which is the electrical resistance as a function of temperature, and the temperature dependence of the thermal resistance of the micro-bolometer. Finally we compared the results obtained from both methods and observed that both are in agreement.

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