High Perfomance Integrated Temperature Sensor based on Amorphous Silicon Diode for Photonics on CMOS

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Abstract: A temperature sensor based on a photonic layer-integrated hydrogenated amorphous silicon p-i-n diode is presented. The linear dependence of the voltage drop across the forward-biased diode on temperature, in a range from 30 °C up to 170 °C, has been used for thermal sensing. A high sensitivity of 11.9 mV/°C in a biasing current range ≈34-40 nA has been measured.

1 INTRODUCTION

Hydrogenated amorphous silicon (a-Si:H) is a promising platform enabling the desired matching between electronics and on-chip photonics (Della Corte, 2013). Thin layers of a-Si:H can be in fact deposited using the CMOS-compatible low-temperature plasma-enhanced chemical vapor deposition technique (LT-PECVD), with no impact at all on the microelectronic layers. Moreover, a-Si:H could be deposited on different substrates where crystalline silicon (c-Si) could not, be it a glass, a metal, an already processed silicon wafer, or even plastic.

Generally, on-chip temperature measurements are explored for thermal variation compensation in many sensing devices such as humidity, pressure, flow, stress and gas concentration sensors (Mansoor, 2015). Moreover, many Si-photonic active devices are temperature-dependent, namely they are sensible to the environment temperature variations due to the large thermo-optic coefficient of Si. The thermal sensitivity of the resonant wavelength for silicon ring resonators is, i.e., of 100 pm/°C about (Yamada, 2011) or, to mention just another example, in a Mach Zehnder (MZ) interferometer the TO effect is responsible of a wavelength shift of 90 pm/°C (Selvaraja, 2010). Consequently, such devices are not practical without thermal compensation. Thermal challenges need to be resolved in order to advance the Silicon Photonics for future network-on-chip interconnection systems.

In this work, a temperature sensor based on a waveguide-integrated a-Si:H p-i-n diode is presented. The linear dependence of the voltage drop across the forward-biased diode on temperature variations from T=30°C up to 170 °C has been accurately measured.

Similar sensors based on a-Si:H diodes were already reported in literature showing however sensitivities lower than 3.3 mV/°C in a temperature range from T=30 up to 80 °C (De Cesare, 2015).

2 AMORPHOUS SILICON P-I-N DIODE TEMPERATURE SENSOR

The diode temperature sensor was integrated in proximity to a Mach Zehnder interferometer (MZI), Figure 1(a), and in particular close to the MZI arm where the propagating optical signal phase shift is achieved by electric-field induced p-i-n diode carrier depletion. The schematic layout of the realized device is shown in Figure 1(d) together with its geometrical dimensions. More details about the MZI fabrication are provided in (Rao, 2012).

The schematic cross section of the fabricated a-Si:H waveguide vertical-integrated p-i-n diode is shown Figure 1 (c). It consists of an intrinsic a-Si:H layer, 2-µm-thick, between a p-doped a-SiC:H, 2-µm-thick, and an n-doped a-SiC:H, 300-nm-thick. The p-i-n cathode top contact is a 200-nm-thick Al layer. The active area of device is $2.25 \cdot 10^{-4}$ cm^2.

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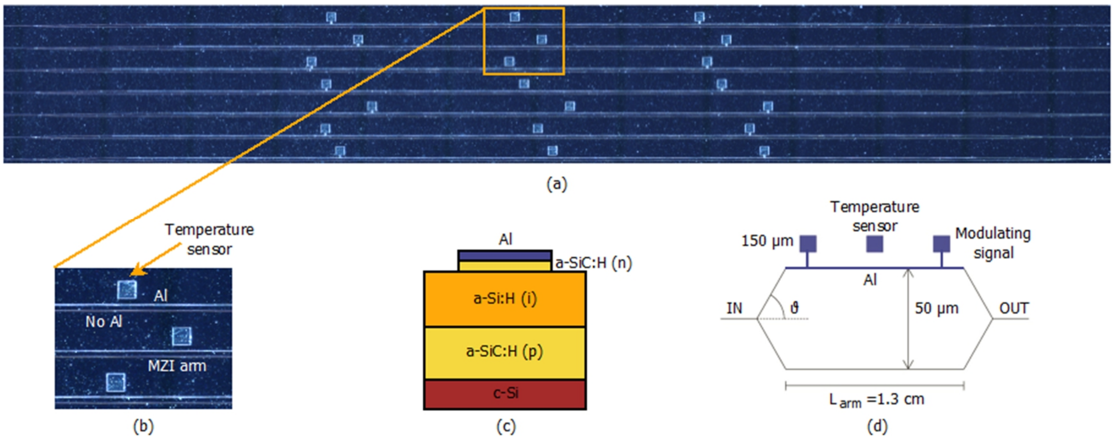

Figure 1: (a) A Optical microscope (top view) of the MZI a-Si:H based modulators and temperature sensors. (b) Top view and schematic cross section (c) of integrated a-Si:H p-i-n diode temperature sensor. (d) Schematic MZI, plot not in scale.

As well-known, the I_D current flowing in a p-i-n diode at a given applied voltage V_D can be analytically described using the following formula:

$$I_D = I_S\left(e^{\frac{qV_D}{\eta kT}} - 1\right) \qquad (1)$$

where η is the ideality factor, I_s is the saturation current, q is the electric charge and k is the Boltzmann constant.

The characterization of the sensor output has been performed under forward bias condition where, at constant DC current, the voltage across the diode is linearly dependent on the temperature.

In fact, for $qV_D >> \eta kT$ the voltage dependence on temperature can be obtained from (1), yielding:

$$V_D = \frac{kT}{q}\eta \ln\left(\frac{I_D}{I_S}\right) \qquad (2)$$

Equation (2) makes explicit the linear dependence V_D-T as long as the non-linear contribution of Is can be considered negligible with respect to I_D.

3 EXPERIMENTAL RESULTS

In our setup, the p-i-n diodes have been biased with a current I_D kept constant in the whole temperature range. The devices were tested in a climatic chamber (Galli Genviro-030-C) setting the reference temperature through its internal PID digital microcontroller. A calibrated PT100 sensor, with an accuracy of ±0.3 °C, was placed in contact with the device under test in order to monitor, during the measurements, the exact temperature set points gradually varied from (to) 30 to (from) 170 °C.

The bias current I_D was varied in a range from 1 nA to 100 nA and the corresponding voltage drop V_D across the a-Si:H p-i-n diode was measured by using the Agilent 4155C Semiconductor Parameter Analyser. In Figure 2 we report the I_D-V_D characteristics, for different temperatures in a range from 30 up to 170°C.

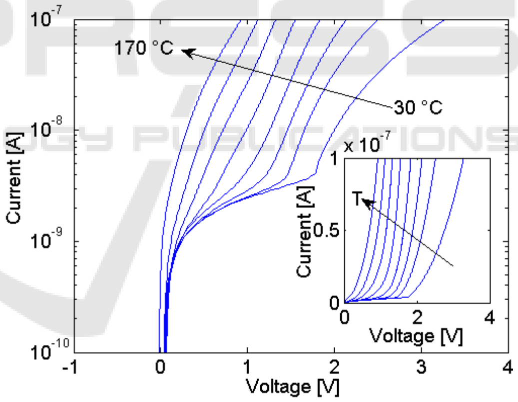

Figure 2: Forward Current-Voltage Characteristics for Temperatures Ranging from 30 up to 170°C. the Inset Shows a Detail of the I_D-V_D-T Characteristics in Linear Scale.

From I_D-V_D-T measurements, the highly linear dependence of the drop voltage across the p-i-n diode on different temperatures have been extracted as shown in Figure 3.

In our analysis, the coefficient of determination (R^2) has been calculated to evaluate the agreement between the experimental measurements and their linear best-fit, $f_L(T)$. In particular, R^2 allowed us to quantify the sensor linearity goodness by fitting the experimental data with a linear model.

In the same figure, the measured data are fitted with the best-calculated linear model showing a good degree of linearity (R^2>0.99) for the whole considered range of I_D, 3.7 nA to 100 nA.

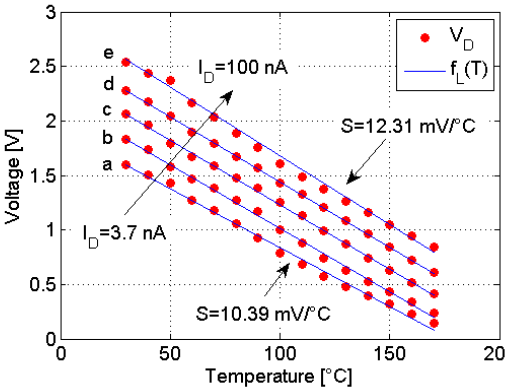

Figure 3: Measured (points) forward voltages versus temperature at different polarization currents. Experimental data are fitted with the best-calculated linear model $f_L(T)$.

The sensor sensitivity, S, is defined as the temperature derivative of equation (2) and, therefore, it can be calculated from the slope of the V_D-T characteristics. The calculated values of S for the five cases shown in the figure are reported in Table I.

For I_D=3.7 nA the sensitivity is 10.39 mV/°C and increases up to 12.31 mV/°C for I_D=100 nA.

Table 1: Sensor sensitivity, S, calculated from V_D-T characteristics.

lines of Fig. 5	I_D [nA]	S [mV/°C]
a	3.7	10.39
b	38	11.9
c	52	11.99
d	76	12.12
e	100	12.31

A more detailed analysis of R^2 and S is shown in Figure 4 for all values of I_D in steps of 100 pA.

It is worth noting that the coefficient of determination varies by only 0.25% from an average of R_a^2=0.9972 over the considered temperature range leading to a temperature sensor with a highly linear behavior in a wide range of biasing currents. The maximum of R^2~0.9996 has been calculated in the current range ≈34-40 nA corresponding to a sensitivity S=11.9 mV/°C.

To evaluate the mismatch between the calculated linear best-fit, $f_L(T)$, and the experimental measurements, the corresponding root mean square error (rmse) was first calculated and subsequently converted into a temperature error value using the following formula:

$$e_T = \frac{\sqrt{\frac{\sum_{i=1}^{n}(V_D(T_i) - f_L(T_i))^2}{n}}}{S} \tag{3}$$

where n is the number of the temperature set points.

The calculated plot, e_T versus I_D, for the considered temperature range is reported in Figure 5. e_T is always lower than 5 °C while the minimum e_T=0.87 °C is obtained for I_D=37.3±3.3 nA.

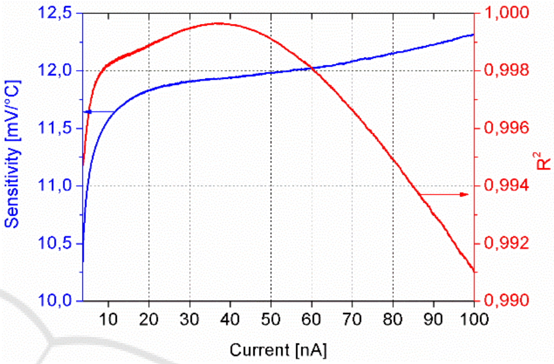

Figure 4: Coefficient of determination and sensitivity calculated for bias currents between I_D=3.7 nA-100 nA.

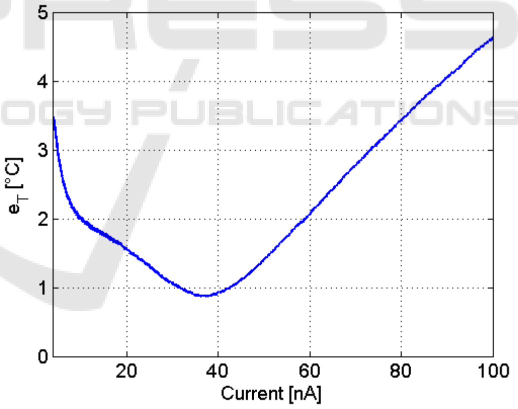

Figure 5: r.m.s. error versus bias current.

4 CONCLUSIONS

A temperature sensor based on a waveguide integrated a-Si:H p-i-n diode has been designed and characterized. The linear dependence of the voltage drop across the forward-biased diode on temperature, in a range from 30° up to 170°C was demonstrated.

Measurements showed both a high degree of linearity (R^2=0.9996) and a high sensitivity (S=11.9 mV/°C) in the biasing current range ≈34-40 nA.

Such devices can be integrated into photonic integrated circuits (PICs) for sensing applications and in CMOS compatible photonic active devices for which the temperature variation is an issue.

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