On-chip Diode Temperature Sensors on InP-based Generic Foundry Platform

1st Wenjing Tian
Eindhoven Hendrik Casimir Institute
Eindhoven University of Technology
Eindhoven, Netherlands
w.tian1@tue.nl

2nd Dylan Harmsen
Department of Electrical Engineering
Eindhoven University of Technology
Eindhoven, Netherlands
d.a.harmsen@student.tue.nl

3rd Ozan Çirkinoglu
Eindhoven Hendrik Casimir Institute
Eindhoven University of Technology
Eindhoven, Netherlands
h.o.cirkinoglu@tue.nl

4th Bart Bas
Department of Electrical Engineering
Eindhoven University of Technology
Eindhoven, Netherlands
b.j.a.bas@student.tue.nl

5th Pascal van den Berg
Department of Electrical Engineering
Eindhoven University of Technology
Eindhoven, Netherlands
p.v.d.berg@student.tue.nl

6th Roel de Meulder
Department of Electrical Engineering
Eindhoven University of Technology
Eindhoven, Netherlands
r.d.meulder@student.tue.nl

7th Dzmitry Pustakhod
Photonic Integration Technology Center (PITC)
Eindhoven, Netherlands
dima.pustakhod@pitc.nl

8th Kevin Williams
Eindhoven Hendrik Casimir Institute
Eindhoven University of Technology
Eindhoven, Netherlands
K.A.Williams@tue.nl

9th Xaveer Leijtens
Eindhoven Hendrik Casimir Institute
Eindhoven University of Technology
Eindhoven, Netherlands
X.J.M.Leijtens@tue.nl

***Abstract*—We developed two types of diode temperature sensors on the InP-based generic foundry platform, with no process adaptations required. These sensors showed sensitivity from - 1.1 to - 2.1 mV/K and were not affected by on-chip light.**

***Index Terms*—Temperature Sensors, Thermal Management, Photonic Integration.**

I. Introduction

The performance of photonic components and devices can depend critically on temperature [1], [2]. For example, temperature changes can significantly affect the properties of semiconductor lasers, such as output power, wavelength, and spectral width [3]. To ensure the predictable stable performance of photonic integrated circuits, monolithically integrated temperature sensors are proposed for accurate and fast temperature measurement in close proximity to the heat source, avoiding the use of bulk, off-chip temperature sensors such as negative temperature coefficient (NTC) thermistors.

Several types of integrated temperature sensors have been explored in the photonic field, including ring resonators [4], waveguide Bragg gratings [5], and photonic crystals [6]. However, their reliance on external tunable lasers limits their potential for higher integration density, and the laser also provides unwanted excess heat. Diode temperature sensors offer a promising alternative to address this issue because they eliminate the need for external optical sources. In addition, the diode temperature sensors offer several advantages such as a simple structure, high linearity, and compatibility with the CMOS technology [7]–[9]. However, CMOS diode temperature sensors are not used in InP-based photonic integrated circuits because of differences in materials and fabrication processes.

In this paper, we present two types of monolithic diode temperature sensors based on two standard building blocks, one with a multi-quantum well (MQW) layer stack and the other with a bulk InGaAsP quaternary layer stack (Q1.25), both available in the InP-based generic photonic integration technology [10], [11]. The temperature was measured directly by detecting the change in the forward bias voltage of the diode temperature sensor, which is dependent on temperature. The presented sensors were based on InP MQW and Q1.25 layer stacks that can be sensitive to on-chip (stray) light, such as that emitted by lasers on the same chip, which may cause a deviation in the diode forward voltage and extracted temperature. A semiconductor laser was adopted as an on-chip light source or a combined heat and light source in a pulsed mode to evaluate the influence of on-chip light on the sensors. The paper includes a detailed description of the device design, operational principle, and measurement results.

II. Device Design, Fabrication, and Operation

In this section, the design and operation principle of the diode temperature sensors will be described, followed by a brief overview of the semiconductor laser.

This work was supported by Microsoft Research through its Ph.D. Scholarship Programme.

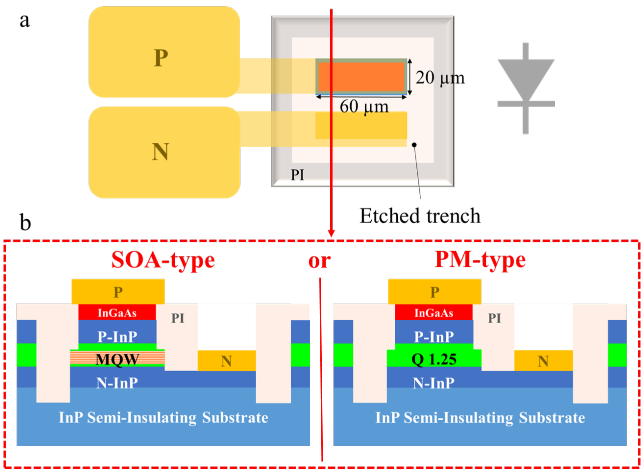

Fig. 1. Diode temperature sensor: a. Schematic of the diode temperature sensor (60 x 20 µm) with two access pads for electrical probing; b. schematic of a cross-section view of the diode temperature sensor, left: SOA-type with an MQW layer stack, right: PM-type with a bulk Q1.25 layer stack. (PI: Polyimide, InP S-I substrate: InP Semi-Insulating substrate.)

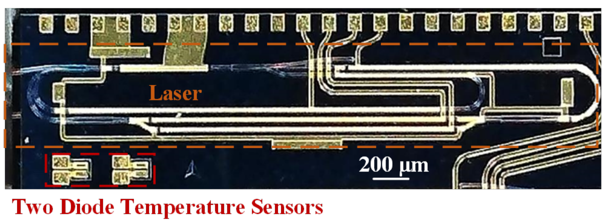

Fig. 2. Microscope image of the fabricated devices: two diode temperature sensors and a semiconductor laser on the same chip; the left sensor: SOA-type with an active MQW layer stack, the right sensor: PM-type with a passive bulk Q1.25 layer stack.

A. Diode Temperature Sensor

As illustrated in Fig. 1, the diode temperature sensor consists of a p-i-n junction in an etched trench with two access pads for electrical probing. The diode junction measures 60 x 20 µm. The sensors were developed based on either a semiconductor optical amplifier (SOA) building block with an MQW layer stack or an electro-refraction phase modulator (PM) building block with a bulk Q1.25 layer stack. Because the SOA and the PM building blocks are diodes, the sensors based on them required no changes in the fabrication process except at the mask design level. The sensors were fabricated in a multi-project wafer run offered by Smart Photonics, an open-access generic integration foundry, via the JePPIX platform [12]. Fig. 2 shows the microscope image of two fabricated diode temperature sensors with the same junction dimensions (60 x 20 µm), the left one is based on the SOA building block, and the right one is based on the PM building block.

The operation of the diode temperature sensor is based on the principle that the current-voltage (I-V) relationship of a diode varies with temperature [7], [8]. At a fixed small forward current through the diode, the voltage over the diode and the temperature have an approximately linear relation [8]. The I-V characteristics of the sensors were simulated and measured at various temperatures, as reported in [13]. The results indeed showed a linear relationship between the forward voltage and temperature. The sensitivity was measured to be between -1.1 and -2.2 mV/K, which is comparable to that of CMOS temperature sensors [8].

B. Semiconductor Laser

The high compatibility in the InP-based generic integration process made the monolithic diode temperature sensors suitable for on-chip temperature measurement of photonic integrated circuits, for example, semiconductor lasers. However, the layer stacks of the sensors can be sensitive to on-chip light. To check the influence of on-chip (stray) light on the operations of the sensors, a semiconductor laser was adopted as an on-chip light source as well as a heat source. Fig. 2 depicts the microscope image of a semiconductor laser, consisting of a 500-µm-long SOA and three phase shifters integrated into a race-track ring resonator.

III. Measurement Results

In this section, we will first describe the results of the I-V characteristics of a diode temperature sensor and how they vary with temperature, namely, the voltage-temperature relation. Next, we will present the light-current-voltage (L-I-V) characterization of a semiconductor laser. Subsequently, we explored the impact of on-chip light on the sensors using the laser as a light source, or a combined light and heat source, in pulse measurements.

A. Sensor: Voltage-Temperature Relation

Two diode temperature sensors, the SOA-type and PM-type sensors, were characterized at a constant current of 12 µA (i.e., 1 A/cm^2) over a temperature range of 16 to 60 °C. The 12 µA was chosen for the highest sensitivity based on the measurement results reported in [13]. The forward-bias currents and voltages were sent and measured by a source meter (Keithley 2602B). The temperature was controlled by

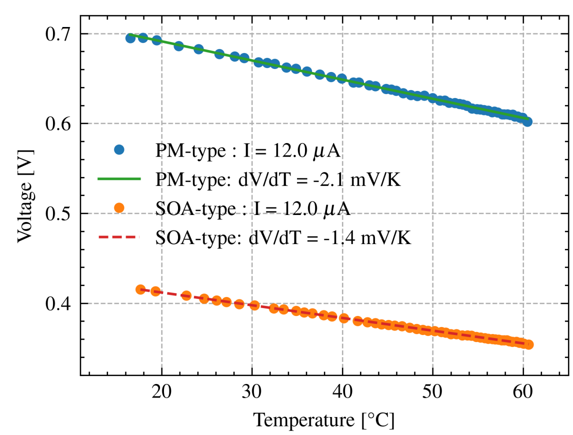

Fig. 3. I-V characteristics of the SOA-type and PM-type diode temperature sensors (60 x 20 µm) at a constant current of 12 µA (i.e., 1 A/cm^2) over a temperature range of 18 to 60 °C.

a thermoelectric cooler (TEC) and monitored by an off-chip NTC thermistor as a reference temperature sensor. Fig. 3 shows the characterization results of the voltage-temperature relation: the sensitivity of the temperature sensors, given from the slope, was calculated to be - 1.4 mV/K (SOA-type) and - 2.1 mV/K (PM-type).

B. Laser Characteristics

Fig. 4 shows the L-I-V characteristics of the semiconductor laser measured at a stabilized temperature of 18 °C using a TEC. The 18 °C was measured by an NTC thermistor and stabilized by a feedback control loop. The turn-on voltage of the laser was found to be around 0.7 V. The threshold current was found to be 37 mA, which corresponds to a current density of 3700 A/cm^2 in the SOA. The series resistance was calculated to be 16 Ω, based on the slope of the I-V curve at 18 °C. The output optical power was measured to be approximately 0.3 mW in an optical fiber at an injected current of around 75 mA (i.e., 7500 A/cm^2), which was recorded by a power meter (Agilent 81636B). After subtracting a typical insertion loss of 5 dB, the optical power in the waveguides was estimated to be 1 mW.

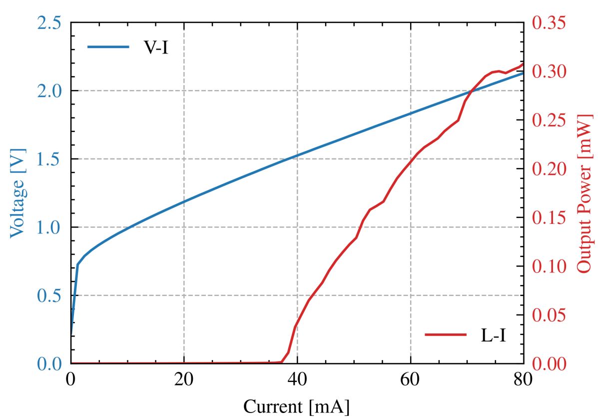

Fig. 4. L-I-V curve of the semiconductor laser with a 500-µm-long SOA, measured at stabilized temperature of 18 °C.

C. Impact of On-chip Light

The impact of on-chip light on the sensors was evaluated in pulse measurements which were performed at room temperature (22 °C) without TEC cooling. A reference temperature sensor, the NTC thermistor inserted in the chip holder (copper chuck), was used to measure the temperature of the chip holder. The NTC thermistor indicated the overall temperature of the device under test. The laser was turned on and off frequently by injecting pulsed currents with varying frequency, duration, and duty cycle under two different conditions: fast (10 kHz with a 1 % duty cycle) or slow (1 Hz with a 50 % duty cycle) current pulses. The current pulses were converted from voltage pulses generated by a pulse generator (Agilent 8114A), which were measured by an oscilloscope (LeCroy LT584L). At the same time, a diode temperature sensor, either the SOA-type or the PM-type, was continuously operated by

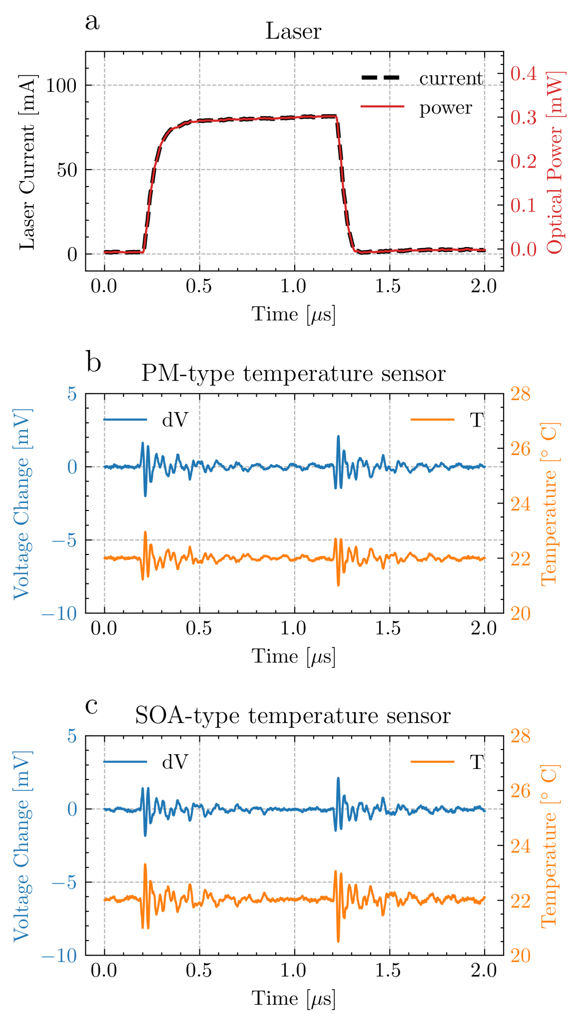

Fig. 5. Fast pulse measurement results: a. Laser: the measured current pulse to the laser (left axis), with converted output power from the laser in an optical fiber (right axis), over a time duration of 2 µs. using an integration time of 10 ns. The current pulse was set to be 10 kHz with a 1 % duty cycle, corresponding to a pulse duration of 1 µs; b. The PM-type temperature sensor, or c. the SOA-type temperature sensor: the measured forward-bias voltage (left axis) of the sensor at 12 µA, with converted temperature (right axis), over the same time duration of 2 µs. Note that the voltage and temperature fluctuations observed were due to inductance coupling. This issue can be resolved by properly shielding the electrical wiring during measurement.

injecting a constant current of 12 µA using a source meter (Keithley 2602B). The forward-bias voltages of the sensor were monitored, by the oscilloscope (LeCroy LT584L), as an indication of temperature changes.

Fig. 5 shows the results of the fast current pulse measurement. The laser was turned on for 1 µs and off for 99 µs in a pulse period of 100 µs. The measured current pulse to the laser has a peak value of about 75 mA as shown in Fig. 5a, which corresponds to about 0.3 mW output optical power in the optical fiber, and about 1 mW in the waveguide, as shown in Fig 4. In the 1-µs pulse duration, the laser light was emitted, however, the heat had no time to dissipate from the waveguide core of the laser to the location of the sensors (500-µm away).

This allowed the laser to be used as a fast light source. As a result, no thermally induced changes in the forward voltage occurred in either type of temperature sensor, as shown in Fig. 5b and 5c. Although there were some inductance-induced fluctuations, these can be eliminated by properly shielding the electrical wiring during measurement.

In contrast, noticeable changes in the forward voltage of the sensor were observed in the longer pulse measurement, as shown in Fig. 6. In this case, the laser was injected with longer current pulses of about 75 mA in a 0.5s turn-on time duration. The time duration was long enough for the heat to dissipate from the laser to the temperature sensor (500-µm away from the laser). This allowed the laser to be used as a combined light and heat source. Due to the high series resistance of the semiconductor laser (also with a typical external quantum efficiency of 6-30 % [14]), a significant portion of the injected power is converted to heat. As shown in Fig. 6b, the voltage of the PM-type temperature sensor, for instance, was decreased by about 6 mV relative to the voltage measured when the laser was off. This decrease was due to the resulting increase in temperature when the laser was turned on. This represents a temperature change of around 3 °C, as calculated using the sensitivity of - 2.1 mV/K. Simultaneously, we monitored the temperature measured by the NTC thermistor in the chip holder. Such a fast temperature change cannot be measured by the off-chip NTC thermistor.

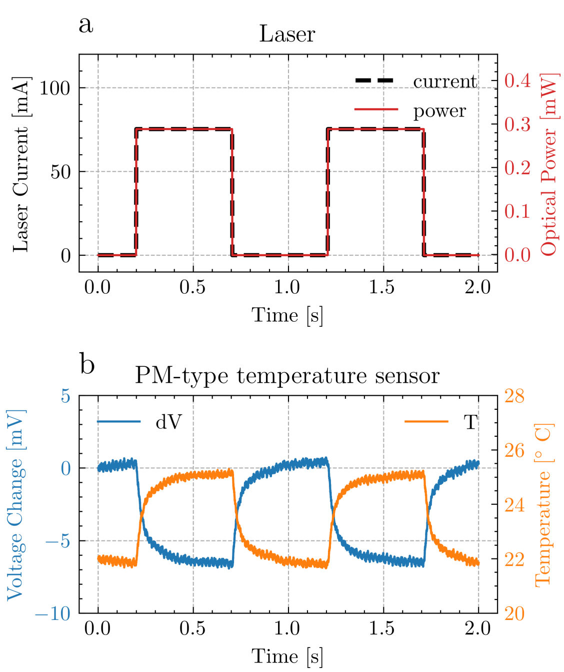

Fig. 6. Slow pulse measurement results: a. Laser: the measured current pulse to the laser (left axis), with converted output power from the laser in an optical fiber (right axis), over a time duration of 2s. using an integration time of 1 ms. The current pulse was set to be 1 Hz with a 50 % duty cycle, corresponding to a pulse duration of 0.5s; b. The PM-type temperature sensor: the measured forward-bias voltage (left axis) of the sensor at 12 µA, with converted temperature (right axis), over the same time duration of 2s.

IV. Conclusion

In conclusion, we developed diode temperature sensors with two different layer stacks (MQW or Q1.25), stemming from the standard building blocks in the InP-based generic photonic integration technology, without any modifications to the fabrication process. The measurement results showed that the sensors had a linear voltage-temperature relation with sensitivity from - 1.1 to - 2.1 mV/K, which is comparable to that of CMOS temperature sensors [8]. Notably, the temperature measurements using these sensors were not affected by on-chip light. Our findings demonstrate the feasibility of on-chip temperature measurements and thermal management for high-performance photonic devices.

Acknowledgment

The authors thank Yi Wang for fruitful discussions on the thermal management of photonic integrated devices. The authors appreciate Sander Reniers's input on pulsed measurements.

References

[1] M. Smit, K. Williams, and J. van der Tol, "Past, present, and future of InP-based photonic integration," *Apl Photonics*, vol. 4, no. 5, 2019.

[2] K. Williams and Y. Jiao, "Large-scale photonic integration with indium phosphide monolithic circuits," in *2022 27th OptoElectronics and Communications Conference (OECC) and 2022 International Conference on Photonics in Switching and Computing (PSC)*. IEEE, 2022.

[3] L. A. Coldren, S. W. Corzine, and M. L. Mašanović, *Diode Lasers and Photonic Integrated Circuits*. John Wiley & Sons, Inc., 2012.

[4] H. T. Kim and M. Yu, "Cascaded ring resonator-based temperature sensor with simultaneously enhanced sensitivity and range," *Opt Express*, vol. 24, no. 9, pp. 9501–10, 2016, kim, Hyun-Tae Yu, Miao eng 2016/05/04 Opt Express. 2016 May 2;24(9):9501-10. doi: 10.1364/OE.24.009501.

[5] N. N. Klimov, S. Mittal, M. Berger, and Z. Ahmed, "On-chip silicon waveguide bragg grating photonic temperature sensor," *Optics Letters*, vol. 40, no. 17, p. 3934, 2015.

[6] H. Lu, B. Sadani, G. Ulliac, C. Guyot, N. Courjal, M. Collet, F. I. Baida, and M. P. Bernal, "Integrated temperature sensor based on an enhanced pyroelectric photonic crystal," *Opt Express*, vol. 21, no. 14, pp. 16 311–8, 2013.

[7] S. M. Sze, Y. Li, and K. K. Ng, *Physics of semiconductor devices*. John Wiley & Sons, Inc., 2007.

[8] F. Udrea, S. Santra, and J. W. Gardner, "CMOS temperature sensors - concepts, state-of-the-art and prospects," in *2008 International Semiconductor Conference*, vol. 1, 2013, Conference Proceedings, pp. 31–40.

[9] K. A. A. Makinwa, "Smart temperature sensors in standard CMOS," *Procedia Engineering*, vol. 5, pp. 930–939, 2010.

[10] M. Smit, X. Leijtens, H. Ambrosius, E. Bente, J. van der Tol, B. Smalbrugge, T. de Vries, E.-J. Geluk, et., al., and D. Robbins, "An introduction to InP-based generic integration technology," *Semiconductor Science and Technology*, vol. 29, no. 8, 2014.

[11] L. M. Augustin, R. Santos, E. den Haan, S. Kleijn, P. J. A. Thijs, S. Latkowski, D. Zhao, W. Yao, J. Bolk, H. Ambrosius, S. Mingaleev, A. Richter, A. Bakker, and T. Korthorst, "InP-based generic foundry platform for photonic integrated circuits," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 24, no. 1, pp. 1–10, 2018.

[12] X. Leijtens, "JePPIX: the platform for Indium Phosphide-based photonics," *IET optoelectronics*, vol. 5, no. 5, p. 202, 2011.

[13] W. Tian, B. Bas, D. Harmsen, P. Berg, R. Meulder, D. Pustakhod, K. Williams, and X. Leijtens, "Monolithically integrated temperature sensor in an InP-based generic integration technology," in *the 26th Annual Symposium of the IEEE Photonics Society Benelux Chapter*. IEEE, 2022.

[14] S. O. Kasap, "Optoelectronics and photonics: Principles and practices," 2013.