Monolithically Integrated Temperature Sensor in an InP-based Generic Integration Technology

Monolithically Integrated Temperature Sensor in an InP-based Generic Integration Technology

W. Tian,[1]* B. J. A. Bas,[1] D. A. Harmsen,[1] P. van den Berg,[1] R. de Meulder,[1]

D. Pustakhod,[2] K. A. Williams,[1] and X. J. M. Leijtens[1]

[1] Eindhoven Hendrik Casimir Institute, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands

[2] Photonic Integration Technology Center (PITC), 5600 MB Eindhoven, The Netherlands

We have developed various monolithically integrated temperature sensors to locally measure the temperature of InP-based photonic integrated circuits. These sensors are based on InP diodes with either an active multi-quantum well structure or a passive bulk quaternary structure. They have been fabricated in the generic integration process of SMART Photonics. We theoretically and experimentally explored the temperature dependence in the diode characteristics. Our results show that the devices are suitable for on-chip monitoring of the operating temperature of photonic integrated circuits. Integrating a temperature sensor on-chip enables a more local temperature measurement compared to using an external temperature sensor. This should be advantageous for temperature control of photonic integrated circuits.

Introduction

Photonic integrated circuits (PICs) have received considerable interest and are finding their way into many applications, such as optical communications, LIDAR, and quantum information processing [1-3]. PICs, with a broad range of functionalities, can be created using generic integration technology. Based on indium phosphide (InP), this technology is an integration process with basic building blocks, such as semiconductor optical amplifiers (SOAs), phase modulators (PMs), and photodetectors. The generic integration technology helps reduce the prototyping costs and throughput time of PICs by using highly standardized processes [1].

High-performance and multi-functional PICs are sensitive to temperature changes, such as SOAs, micro-ring resonators, and lasers [4]. Accurate thermal measurement and temperature control of PICs are important for many applications. Conventionally, discrete temperature sensors, such as thermistors, thermocouples, and resistive temperature detectors, have been used [5, 6]. However, they are bulky and add to the complexity of a system. In addition, these bulk sensors are placed separately in photonic modules and are at some distance from the PICs, which increases the overall module size and measures the temperature at a different location.

Integrated temperature sensors are favorable because of their compact size and local thermal measurement, which therefore provides more precise temperature control of the PICs. A diode temperature sensor is a basic and accurate integrated temperature sensor. The diode sensor is a commonly used integrated temperature sensor in CMOS technology [6]. However, such a diode structure is not being used for temperature sensing and monitoring purposes for InP-based PICs.

In this work, we designed various monolithically integrated temperature sensors based on InP pin diodes. We exploited the temperature dependence of the diode current-voltage (I-V) characteristics. Experimental results confirm that this can be used for local thermal measurement and temperature control of InP-based PICs.

Concept

The forward voltage of a diode has a linear dependency on temperature when the diode is driven by a constant current [5, 6]. Two types of integrated temperature sensors are proposed which stem from two diode basic building blocks in the InP-based generic integration technology: an SOA with an active multi-quantum well (MQW) structure, and a PM with a passive bulk quaternary structure (Q1.25). Figure 1 shows a simplified schematic of the two different layer structures. Both building blocks are pin diodes and can be used for temperature sensing.

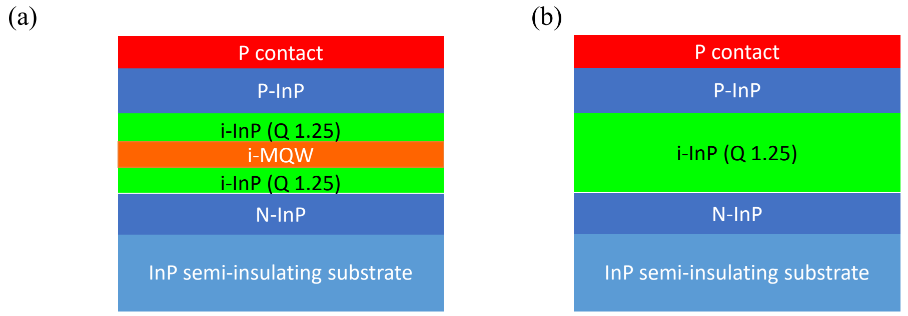

Figure 1. Simplified schematic of the layer stacks of the integrated temperature sensors stemming from two basic building blocks in the InP-based generic integration technology: (a) The SOA-type: layer stack of the active multi-quantum well structure; (b) The PM-type: layer stack of the passive bulk quaternary structure.

The integrated temperature sensor is schematically depicted in Figure 2. It is composed of either an SOA or PM building block and an etched trench around it. The trench is designed to prevent leaking currents and scattering light from surrounding devices. Note that the PM-type sensor is less affected by light on the chip. The sensors were fabricated by SMART Photonics which offers InP-based generic integration technology.

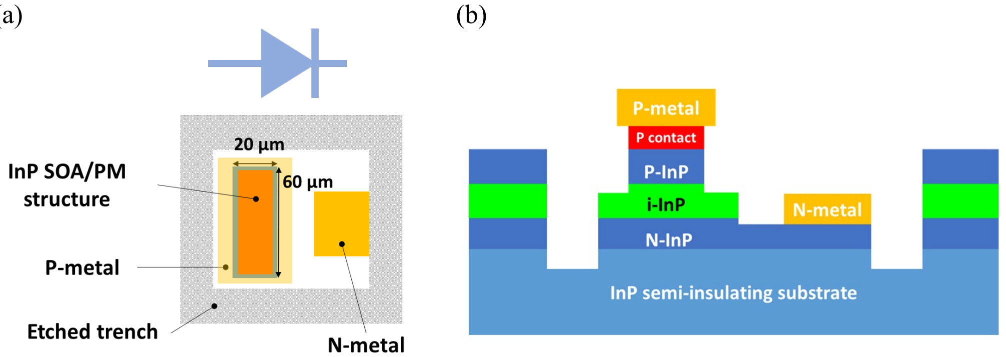

Figure 2. Schematic of an integrated temperature sensor: (a) Simplified top-view layout of an integrated temperature sensor of width = 20 µm and length = 60 µm.; (b) Simplified cross-section view of an integrated temperature sensor with the PM-type passive layer stack.

Simulation

We simulated both types of diodes in Harold software from Photon Design which is an advanced hetero-structure simulator. In the simulation, we constructed the layer stacks of both diodes shown in Figure 1. Low current densities were used ranging from 1×10^{-4} A/cm^2 to 50 A/cm^2, which corresponds to currents of 1×10^{-9} A to 5×10^{-4} A in a diode that measures 10 µm x 100 µm. Using low currents can minimise self-heating in the diodes. Then, the forward voltages of the diodes were simulated at temperatures ranging from 0 - 300 °C. The simulation results are shown in Figure 3.

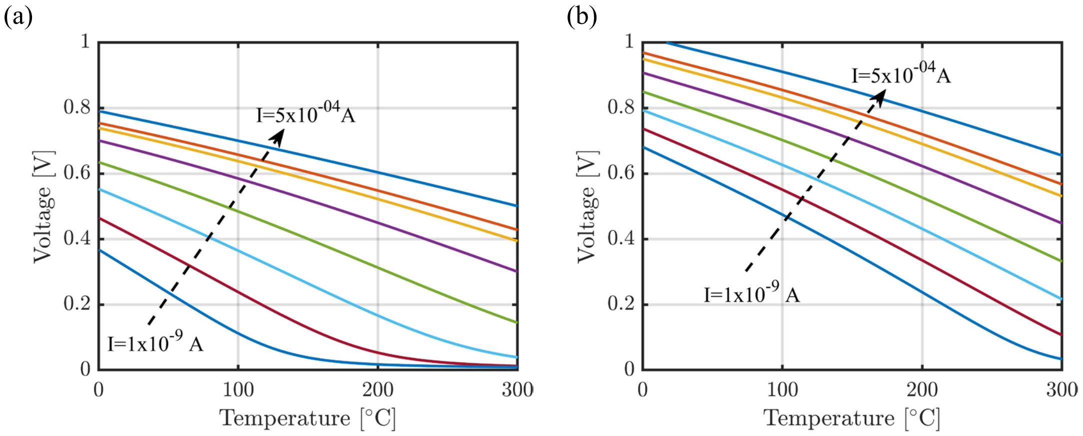

Figure 3. Simulated forward voltage-temperature (V-T) relation of two types of integrated temperature sensors (10 µm x 100 µm) operated in forward current mode over temperature range of 0 - 300 °C: (a) The SOA-type sensor with an active multi-quantum well structure; (b) The PM-type sensor with a passive bulk quaternary structure. In both plots: 8 curves, from bottom left to top right, represent currents of 1×10^{-9}, 1×10^{-8}, 1×10^{-7}, 1×10^{-6}, 1×10^{-5}, 5×10^{-5}, 1×10^{-4}, 5×10^{-4} A.

For both types of integrated temperature sensors, a linear dependency between forward voltage and temperature was observed. Besides that, using a higher forward-bias current leads to a wider linear range. However, there is a trade-off between the linear range and the sensitivity depending on the forward-bias currents. The sensitivity of a diode temperature sensor is given by the slope of the voltage-temperature (V-T) curve in the linear dependency range. For both types of sensors, using a lower forward-bias current leads to a steeper slope, which represents a higher sensitivity. In detail, the sensitivity of the SOA-type sensor varies from -0.9 to -2.6 mV/°C in correlation with the variation in current from 5×10^{-4} to 1×10^{-9} A. For the PM-type sensor driven by the same current range, its sensitivity varies from -1.1 to -2.1 mV/°C. Overall, the sensitivity of both types of InP-based integrated temperature sensors is in the same range as CMOS sensors, which is -1.2 to -2.2 mV/°C [6].

Experimental Results

A chip with several integrated temperature sensors was mounted on a copper block, of which the temperature is controlled by a thermoelectric cooler (TEC) and monitored by a reference thermistor. The electrical signals to the diode were set and measured by Keithley 2402B source meter. At first, we measured the I-V characteristics of both types of sensors with the same dimension at temperatures of 20, 40, and 60 °C. Results are shown in Figure 4(a) and (b): in both types of sensors, the forward voltage decreases with increasing temperature at the same current levels, for example, at 100 µA.

Then, we measured the V-T relation of both types of integrated temperature sensors in a wider temperature range of 18 to 60 °C, using four constant driving currents of 10, 50, 100, and 500 µA, as shown in Figure 4(c) and (d). The voltage was measured during temperature rising (18 to 60 °C) and temperature falling (60 to 18 °C), which is a typical operating temperature range of PICs. Both types of sensors show linear dependency between forward voltage and temperature. Besides, the slopes of V-T curves in Figure 4(d) are steeper than the slopes in Figure 4(c). It means that the sensitivity of the PM-type sensor, -1.7 to -2.2 mV/°C, is higher than the sensitivity of SOA-type, -1.0 to -1.4 mV/°C, at currents of 10, 50, 100, and 500 µA.

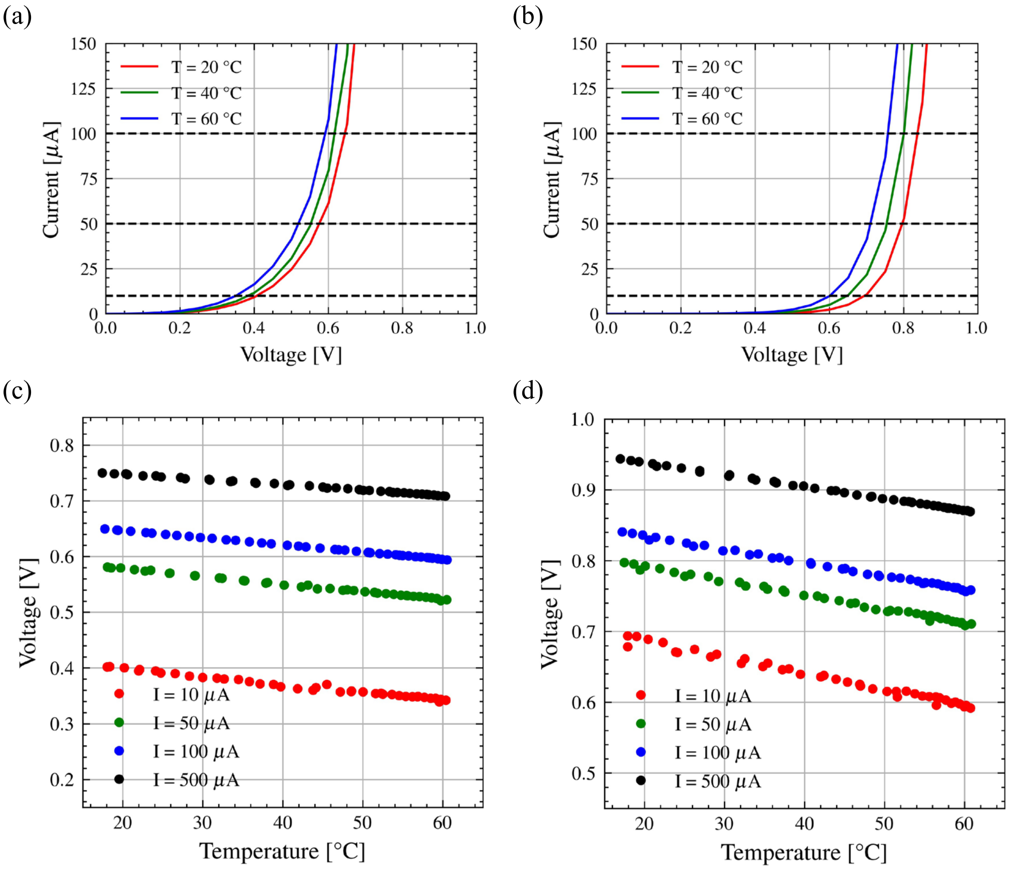

Figure 4. Experimental results. (a) and (b): Comparison of I-V characteristics of (a) the SOA-type and (b) the PM-type of integrated temperature sensors at temperatures of 20, 40, and 60 °C. (c) and (d): Comparison of V-T relation of (c) the SOA-type and (d) the PM-type of integrated temperature sensors at temperature ranging from 18 to 60 °C. Both diodes have the same dimension of 20 x 60 μm.

Conclusion

In this paper, we proposed integrated temperature sensors based on pin diodes stemming from two basic building blocks, SOA and PM, in the InP-based generic integration technology. Both types of sensors show linear dependency between forward voltage and temperature at the current injection mode. Their sensitivity is comparable to CMOS sensors [6]. Especially, the PM-type sensor shows higher sensitivity and is less affected by light on the chip which is more favorable than the SOA-type sensor. The results are promising for on-chip thermal management and temperature control of PICs.

References

[1] M. Smit, X. Leijtens, et. al., “An introduction to InP-based generic integration technology,” *Semiconductor Science and Technology,* vol. 29, no. 8, 2014.

[2] T. Baba, et. al, “Silicon Photonics FMCW LiDAR Chip with a Slow-Light Grating Beam Scanner,” *IEEE Journal of Selected Topics in Quantum Electronics,* vol. 28, no. 5, pp. 1-8, 2022.

[3] A. Elshaari, et. al., “Hybrid integrated quantum photonic circuits,” *Nat Photonics,* vol. 14, no. 5, 2020.

[4] L. Carroll, J.-S. Lee, et. al., “Photonic Packaging: Transforming Silicon Photonic Integrated Circuits into Photonic Devices,” Applied Sciences, vol. 6, no. 12, 2016.

[5] G. C. M. Meijer, “Thermal sensors based on transistors,” *Sensors and Actuators,* vol. 10, no. 1, pp. 103-125, 1986/09/10/, 1986.

[6] 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, 2008, pp. 31-40.