Materials Science Forum
ISSN: 1662-9752, Vol. 1089, pp 81-85
doi:10.4028/p-9j6d42

Submitted: 2022-09-10
Revised: 2022-10-14
Accepted: 2022-11-25
Online: 2023-05-26

Accurate Determination of the Temperature Dependence of the Refractive Index of 4H-SiC at the Wavelength of 632 nm

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Keywords: thermo-optic coefficient, refractive index, temperature dependence.

Abstract. The growing interest for the use of 4H-SiC in photonics is triggering the interest for more accurate characterizations of this semiconductor from the optical and opto-electronic point of view. In this work we report about new measurements run on an undoped 4H-SiC substrate, finalized at determining the precise dependence of its refractive index on temperature in the visible spectrum, and precisely at the wavelength of λ=632.8 nm, in a temperature range from room temperature (RT) to 400K. Measurements are performed by exploiting the properties of a Fabry-Perot cavity interrogated with a laser beam. It is known that the transmitted radiation intensity shows fringes that shift with temperature and the refractive index. By precisely monitoring the transmitted signal, the thermo-optic coefficient dn/dT can be determined with a resolution that approaches 10^{-6} K^{-1}.

Introduction

In recent years, the successful exploitation of Silicon Carbide (SiC) for the fabrication of high power electronic devices, presently unrivaled in many industrial context, has unavoidably triggered a parallel interest for its optoelectronic properties in view of the possible use of this semiconductor for the design and fabrication of active and passive photonic devices which, for example, could be potentially matched, under a technological point of view, with existing power devices. The target could be, in essence, a smart power element which monolithically integrates efficient power handling capabilities and optical communication features. As a matter of fact, it must be recognized that SiC already has a relevant role in optoelectronics, at least as far as ultra-violet (UV) LEDs and photodetectors are concerned. To date, for example, some practical applications have been successfully demonstrated, such as ultraviolet (UV) photodetectors [1,2], optical sensors, or for integrated quantum and nonlinear photonics [3]. However, the optical communication arena still remains a rather unexplored field, although some notable results have been reported [4,5]. Similarly to what happened with Silicon (Si) and its related Silicon Photonics outstanding successes, it is expected that SiC Photonics will also catch more and more the interest of research centres and industry. In connection, it should be comparatively highlighted that SiC shows high transparency in the visible range of wavelengths, which is not the case for Si. This might constitute a notable advantage in terms of design, because the device sizes obviously scale with the wavelength.

The careful design of any photonic device necessitates, however, the knowledge of many properties of all involved materials, including e.g. the real and imaginary refractive indexes and their dependences on technological processes made on them (for example chemical composition, doping, association with different materials) and on external solicitations (for example electric or magnetic fields, light intensity, temperature).

The intent of this work was to enrich the dataset available in literature about the temperature dependence of the real part of refractive index in 4H-SiC. As experimental data are to date mainly limited to the UV spectrum, we explored the visible range, in particular at the wavelength λ=632.8 nm. We characterized the refractive index variation with temperature (*T*), by precisely measuring the thermo-optic coefficient (TOC), dn/dT. These data complement those provided in a previous work [6], where we reported results about the TOC dependence on *T* for a semi-insulating <0001> 4H-SiC substrate [7] at the fiber-optic communication wavelength of λ=1550 nm, in a temperature range from room-temperature (RT) to 480 K.

Experimental Setup

The evaluation of the thermo-optic coefficient was performed by the experimental setup shown in Fig 1.

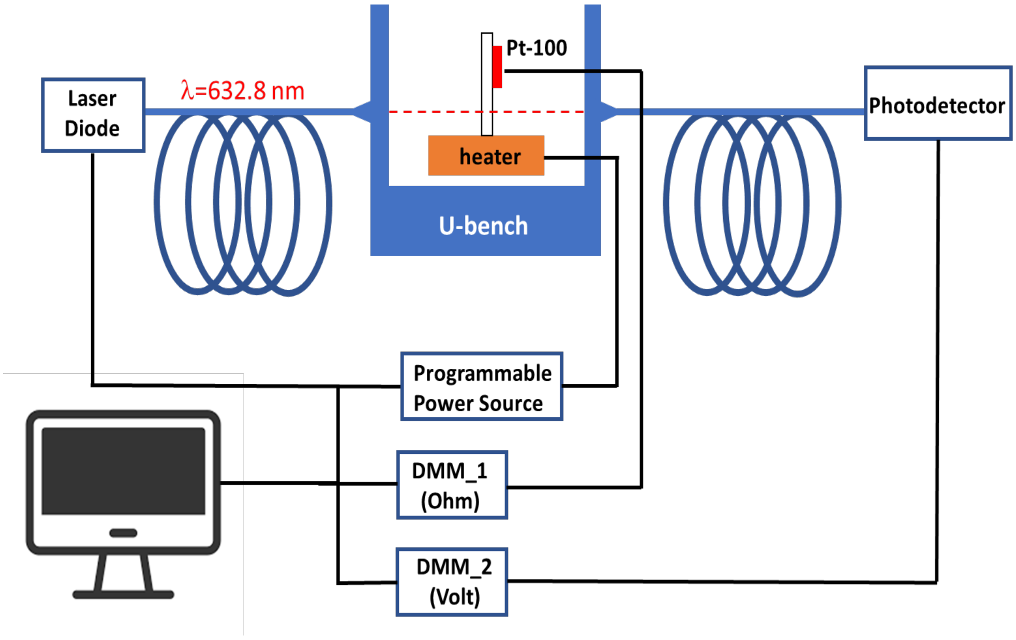

Fig. 1. Experimental setup exploited for TOC characterization vs. temperature.

The basic idea is to use the semi-insulating <0001> 4H-SiC substrate, double-side polished at an optical grade, as a Fabry-Perot (FP) cavity. The TOC evaluation is based on the measurements of the temperature variation that causes a complete detuning of the FP cavity, which is L=2 mm-long. Therefore, the sample is placed on a resistive heater and its temperature is periodically monitored by a high-sensitivity resistance temperature sensor (PT-100). A laser optical beam at a fixed wavelength is launched orthogonally to the sample and the transmitted optical signal is collected by a photodetector. In order to extract the TOC and its dependence on *T*, the optical tuning and detuning are monitored while the temperature is slowly changing.

The FP cavity transmitted light signal I_t depends, in fact, on the interference taking place into the cavity and it is expressed by:

$$I_t = \frac{I_o}{1 + \frac{4F^2}{\pi^2} sin^2 \emptyset} \tag{1}$$

where I_o is the incident optical intensity, F is the reflecting finesse, and Ø is the signal phase.

The temperature variation of the phase term is regulated by the following equation:

$$\frac{\partial \phi}{\partial T} = \frac{2\pi L}{\lambda}\left(\frac{\partial n}{\partial T} + \alpha(T)n(T)\right) \quad (2)$$

where L is the cavity length and the term α=∂L⁄L∂T is the thermal expansion coefficient.

All of the known physical and geometric parameters of the sample under investigation are listed in Table 1. The refractive indices at λ=632.8 nm and 1550 nm, measured using ellipsometric techniques, are reported in the same table.

Table 1. Main physical and geometrical parameters of the 4H-SiC sample.

Resistivity	Roughness	Thickness *L*	Thermal expansion coefficient α (10^{-6} [K^{-1}]) [8]	*n* (*T*=300K)
>10^5 [Ω×cm]	<0.5 [nm]	2 [mm]	$-1.0971\times10^{-5}T^2+1.8967\times10^{-2}T-1.9755$	2.65 (λ=632.8 nm) 2.59 (λ=1550 nm)

Experimental Results

A temperature variation from RT to 400 K, with a step in *T* of the order of a few mK, is induced. The transmitted FP pattern, as a function of *T*, is reported in Fig. 2. By measuring the temperature shifts between two consecutive maximum peaks (or minimum valleys), ΔT_π, corresponding to a phase shift of Φ= π, the TOC is extracted from Eq. (2).

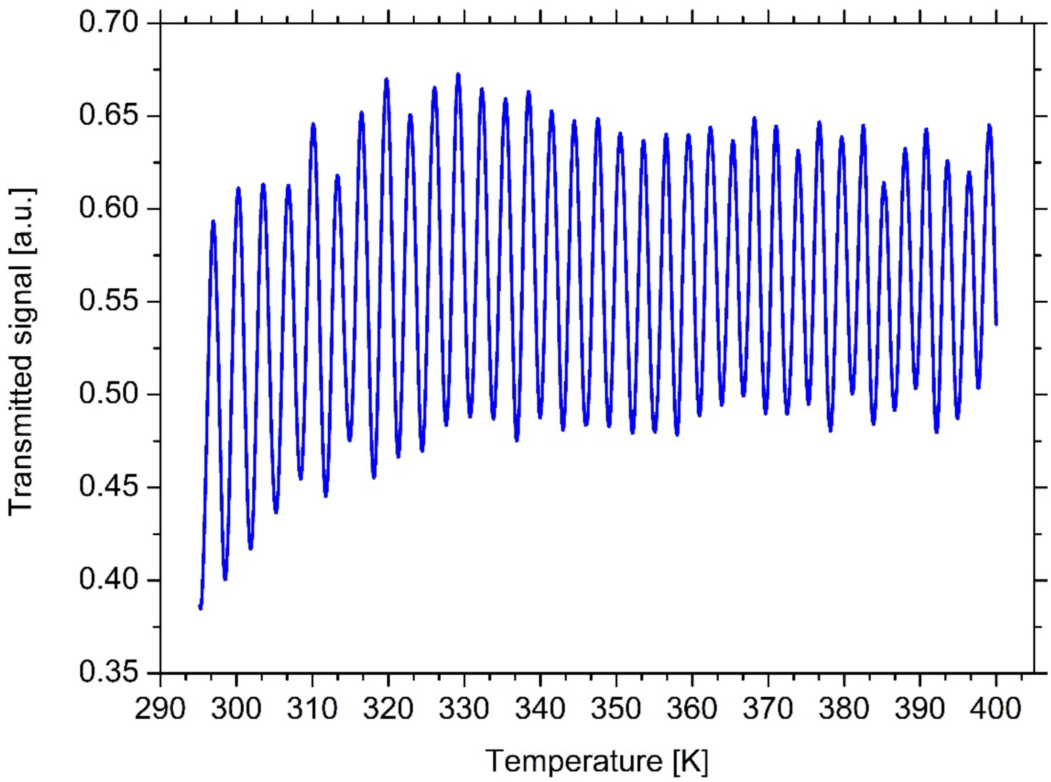

Fig. 2. FP transmission pattern as a function of temperature at λ=632.8 nm.

It's worth noting that the values of α(*T*) and n(*T*) are updated at each temperature step. α(*T*) is calculated by means of the equation shown in Table 1, while the evaluation of n(*T*) is defined with a recursive method considering the TOC value extracted at the previous temperature step.

To avoid measurement errors, the transmitted optical signal and the corresponding temperature provided by the PT-100 sensor, at each temperature, were averaged over five successive acquisitions. The final result, the TOC versus *T*, is reported in Fig. 3 where the experimental data at λ=632.8 nm are compared to the previous measurements performed at λ=1550 nm.

The achieved temperature dependence of the TOC, at wavelength λ=632.8 nm, can be well approximated by a linear expression, described by the following formula:

$$\frac{dn}{dT} = 7.36 \cdot 10^{-8} T + 1.83 \cdot 10^{-5} \quad (3)$$

The experimental data and the corresponding linear fitting curve are in good agreement with a high coefficient of determination of R^2=0.98.

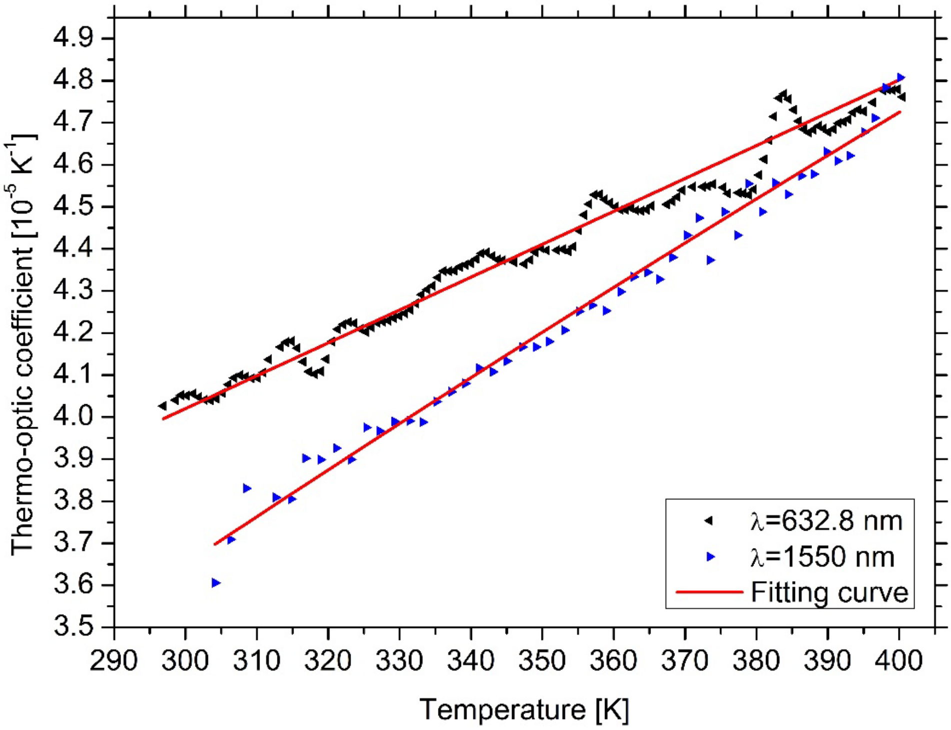

Fig. 3. Thermo-optic coefficients vs. T at λ=1550 nm and λ=632.8 nm.

Summary

In this work, the evaluation of the thermo-optic coefficient of a semi-insulating 4H-SiC substrate is reported. For this purpose, an experimental method based on the periodicity of the transmitted signal of a Fabry-Perot cavity was applied. The thermo-optic coefficient was evaluated in a temperature range from RT to 400K in the visible spectrum, at the wavelength of λ=632.8 nm. The experimental data have been fitted using a linear approximation. The obtained fitting curve matches very well the experimental data with a coefficient of determination (R^2) of 0.98.

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