Optical temperature sensor and thermal expansion measurement using a femtosecond micromachined grating in 6H-SiC

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Received 4 February 2008; revised 7 May 2008; accepted 18 June 2008; posted 20 June 2008 (Doc. ID 92132); published 11 July 2008

An optical temperature sensor was created using a femtosecond micromachined diffraction grating inside transparent bulk 6H-SiC, and to the best of our knowledge, this is a novel technique of measuring temperature. Other methods of measuring temperature using fiber Bragg gratings have been devised by other groups such as Zhang and Kahrizi [in *MEMS, NANO, and Smart Systems* (IEEE, 2005)]. This temperature sensor was, to the best of our knowledge, also used for a novel method of measuring the linear and nonlinear coefficients of the thermal expansion of transparent and nontransparent materials by means of the grating first-order diffracted beam. Furthermore the coefficient of thermal expansion of 6H-SiC was measured using this new technique. A He–Ne laser beam was used with the SiC grating to produce a first-order diffracted beam where the change in deflection height was measured as a function of temperature. The grating was micromachined with a $20\,\mu$m spacing and has dimensions of approximately $500\,\mu\text{m} \times 500\,\mu\text{m}$ ($l \times w$) and is roughly $0.5\,\mu$m deep into the 6H-SiC bulk. A minimum temperature of 26.7 °C and a maximum temperature of 399 °C were measured, which gives a ΔT of 372.3 °C. The sensitivity of the technique is $\Delta T = 5\,°\text{C}$. A maximum deflection angle of 1.81° was measured in the first-order diffracted beam. The trend of the deflection with increasing temperature is a nonlinear polynomial of the second-order. This optical SiC thermal sensor has many high-temperature electronic applications such as aircraft turbine and gas tank monitoring for commercial and military applications. © 2008 Optical Society of America

OCIS codes: 280.6780, 050.7330.

1. Introduction

Diffraction gratings have a variety of applications and are constructed by a number of techniques. The grating here was fabricated using a femtosecond laser and an anamorphic lens [1]. We chose transparent 6H-SiC with a $500\,\mu\text{m} \times 500\,\mu\text{m} \times 0.5\,\mu\text{m}$ ($l \times w \times d$) grating with $20\,\mu$m spacing micromachined using the anamorphic lens technique [1]. This study represents, to the best of our knowledge, the first time such a grating has been employed in this novel method of measuring temperature and the linear and nonlinear coefficients of thermal expansion.

SiC is an attractive alternative material for a variety of semiconductor devices where silicon lacks the environmental resistance that carbon furnishes in SiC [2]. SiC devices can be used in high-power, high-voltage switching applications, high-temperature electronics, and avionics where it is desired to keep

0003-6935/08/213773-05$15.00/0
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sensitive silicon-based electronics and temperature sensors away from extreme environments onboard an aircraft (such as turbines and fuel compartments) [2]. Furthermore SiC is now becoming practical for small traditional and large space-based telescope optical applications for its unique physical and thermal properties [3]. For these reasons it is of interest to study the use of SiC as a noncontact high-temperature sensor. The SiC used for this study has the characteristics shown in Table 1.

Different types of temperature sensors were investigated and compared with the noncontact optical SiC sensor. Compared with other types of noncontact temperature sensors, the method described here has a few advantages: the measurement of the temperature of transparent and nontransparent materials, the remote measurement of extremely high temperatures, and the ability to measure the linear and nonlinear coefficients of the thermal expansion of transparent and nontransparent materials.

2. Experimental Setup

Figure 1 shows the experimental setup for the SiC temperature sensor. It consists of an 800 μm diameter collimated 632.8 nm He–Ne laser, the SiC grating seated in a copper mount, and a CCD camera to record the change in the first-order height (Δx). The camera is a Cohu 4812 model, and it utilizes Spiricon laser beam analysis software to measure the vertical centroid direction in micrometers. Each of the first-order beams in the figure represents different heights due to increasing temperature (not to scale). The camera is calibrated against neutral density filters, and the background lighting is measured by a Fieldmax power meter. The total power measured from the zero order to the first order yields a measurement of the grating efficiency, and η of the diffracted beam is the ratio of the first and zero orders ($\eta = 2P_1/P_0$, where 2 represents the ± 1 orders) that, for completeness, resulted as 0.6%. The change in Δx was measured and plotted as a function of temperature.

The 6H-SiC grating was mounted in a 2.25 in. × 2.25 in. (5.72 cm × 5.72 cm) copper mount with a 0.5 in. (1.27 cm) square hole where the sample was placed so the He–Ne beam could propagate through the grating. The copper mount had two 0.125 in. (3.175 mm) diameters by 2 in. (5.08 cm) deep holes for the J-type thermal couple and the cartridge heater. The copper mount and SiC sample together were insulated with ceramic shielding, and the SiC temperature was monitored with a K-type thermal couple to ensure the grating was the same temperature as the copper. The cartridge heater started at 26.7 °C (about 10 °C above the laboratory temperature) and in 50° increments reached 399 °C.

The temperature was measured and controlled with an Omega temperature controller CN7800 that has ± 1 °C resolution, and with the ceramic insulation, the measurements were consistently within ± 3 °C due to the temperature of the laboratory convection. Most of the error in measurement came from the Spiricon resolution, which has a spatial accuracy of $\pm 0.5\%$ and a beam width accuracy of $\pm 2\%$. A typical He–Ne laser system has an inherent pointing stability associated with it, however, due to convection caused from the laboratory cooling system, the first-order deflected He–Ne beam had a combined (laser plus convection) pointing stability of $\sim 35\%$. This was observed at higher temperatures and was due to the air convection from the cooler lab temperatures and the heated sample. To help reduce the variation from thermal convection, the beam centroid was averaged over 88,000 images (45 min time average for each data point). This dropped the error in Δx measurement down to a maximum of $\pm 1.2\%$. This measurement can be further improved by imaging both the zero- and first-order spots so the relative displacement can be measured. This helps to normalize the effects of thermal convection. In addition, the second or higher orders can be used to increase sensitivity.

3. Theoretical Results

The SiC temperature sensor is considered a volume transmission grating. Therefore standard diffraction grating theory was applied to predict grating performance. The mechanism to explain the change in the spacing of the grating is thermal expansion, which causes the first-order deflected beam to drop back to the zero order. It was initially assumed that the thermal coefficient of 6H-SiC would be linear, but it becomes nonlinear when ΔT becomes too large for the linear approximation. Starting from the thermal coefficient and grating equations, the change in grating spacing as a function of temperature, Δd, can be derived.

The 6H-SiC grating spacing, d, is initially 20 μm and changes by [4]

$$\Delta d = \alpha d \Delta T, \tag{1}$$

where α is the coefficient of thermal expansion solved after Δd was found experimentally as shown in Fig. 2. Equation (1) was applied to the grating equation as stated in [5]

$$m\lambda = d(\sin(\theta) + \sin(\beta)). \tag{2}$$

Here, in Eq. (2), m is the order ($m = 1$), β is the input angle into the grating, and θ is the reflection

Table 1. Characteristics of a Semi-Insulating-Type SiC Sample[a]

Sample	Grating and Beam Orientation	Dopant	Resistivity (Ω cm)	Thickness (μm)	Crystal Growth Orientation
SiC semi-insulating	c-plane, 6H 0° on axis	Undoped	3×10^7	340	Silicon-face (0001)

[a] The semi-insulating SiC sample used was supplied by Intrinsic Corporation, and the gratings were micromachined by G. L. DesAutels.

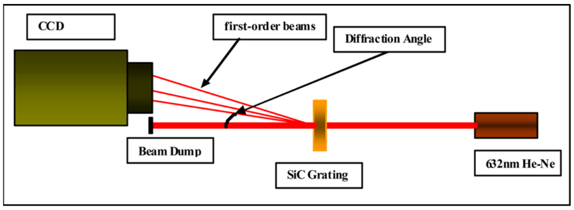

Fig. 1. (Color online) SiC temperature sensor experimental setup. The incident angle to the grating is zero, and the diffraction angle is clockwise from the zero order.

or transmit angle. The deflection (Δx) is derived by solving for θ, the grating spacing and the change in the grating spacing, as a function of temperature:

$$\Delta x = [\tan(\theta)L] - [\tan(\Delta\theta)L], \tag{3}$$

where L is the distance from the grating to the CCD camera, and $\Delta\theta$ is given by

$$\Delta\theta = \sin^{-1}\left(\frac{\lambda}{(d + (\alpha d \Delta T))} - \sin(\beta)\right). \tag{4}$$

Equation (4) suggests that when $\Delta T = 0$, $\Delta\theta = \theta$, or that when ΔT is zero, there is no change in Δd due to temperature. From these equations the Δx can be predicted for each given temperature. Given the experimental Δx, the thermal coefficient, α, can be calculated from backing out Δd and using Eq. (1). The change in Δd is derived from

$$\tan\left(\frac{\lambda}{d + \Delta d}\right) = \frac{x - \Delta x}{L}, \tag{5}$$

$$\Delta d = \frac{\lambda - \tan^{-1}\left(\frac{x - \Delta x}{L}\right)}{\tan^{-1}\left(\frac{x - \Delta x}{L}\right)} d, \tag{6}$$

where x is the original deflection of the first-order beam before the temperature is increased, and Δx is the change in the first-order deflection due to increasing temperature and increasing grating spacing. The experimental second-order polynomial thermal coefficient equation (α) can now be solved by relating the measured Δx values to derive Δd from Eq. (6) and be substituted back into Eq. (1) and solved for α, which is plotted as a function of temperature in Fig. 3. A polynomial fit to the trend is applied, as shown in Fig. 3, that yields

$$\alpha = -1.38 \times 10^{-11} \Delta T^2 + 1.23 \times 10^{-8} \Delta T + 3.84 \times 10^{-6}. \tag{7}$$

4. Experimental Results

The experimental results conclude that a maximum deflection for 399 °C (starting from 26.7 °C) was 140 μm as shown in Fig. 2.

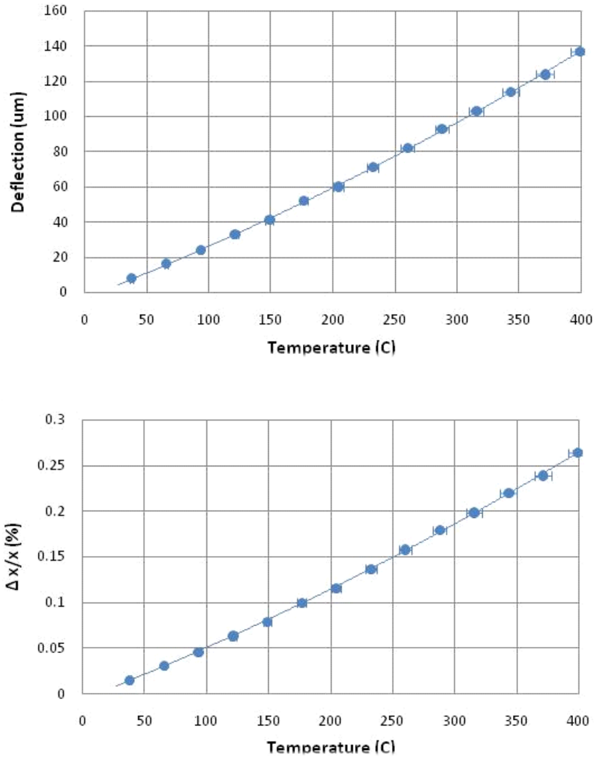

Fig. 2. (Color online) (top) Deflection (Δx) as a function of temperature. (bottom) The $\Delta x/x$ ratio as a function of temperature, which is a common way of displaying the material expansion. The charts show a maximum of ~5% error bars.

The line fitting the points is a polynomial fit of the second order. A second-order polynomial fit is common for this type of measurement. The error bars for each data point is $\pm 1.2\%$ maximum, as mentioned previously. The 1.2% error bars relate to a 5 °C absolute temperature variation. The maximum Δx for 1640 mm from the grating is 140 μm, which corresponds to 6.5×10^{-6} 1/°C from Eqs. (1), (2), and (6) and is shown in Fig. 3. The percentage of the $\Delta x/x$ for 400 °C is 0.26%, which corresponds to the findings of Bhatt and Palczer [6].

Figure 3 shows the nonlinear coefficient of thermal expansion as well as the coefficient of linear

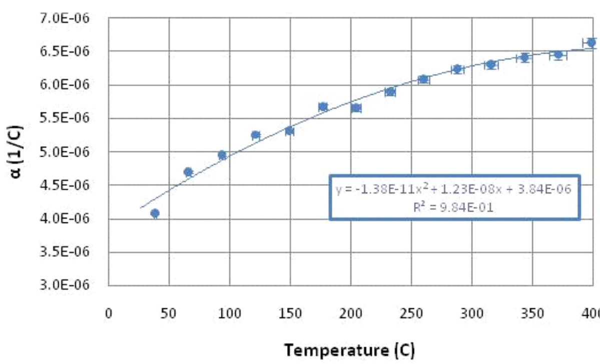

Fig. 3. (Color online) 6H-SiC thermal coefficient as a function of temperature with a maximum of 5% error bars. The second-order polynomial is given in Eq. (1).

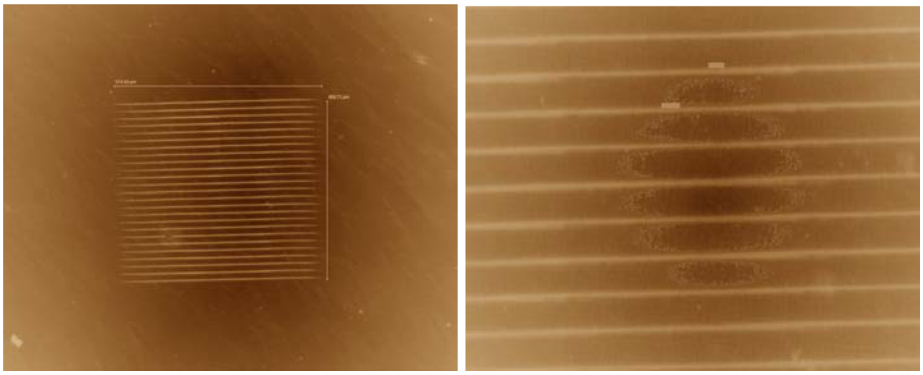

Fig. 4. (Color online) (left) SiC grating at 10× magnification. (right) The SiC grating after 50× magnification. The images were processed for easier viewing and obtained using Nomarski DIC on an optical microscope [2].

expansion ($4.25 \times 10^{-6}\,°\mathrm{C}^{-1}$) of 6H-SiC, which is in good agreement with Li and Bradt [7], who also found the coefficient of thermal expansion to be a second-order polynomial trend for 4H-SiC as well as a coefficient of the linear expansion of $4.47 \times 10^{-6}\,1/°\mathrm{C}$. In addition to Li and Bradt, Talwar and Sherbondy [8] found a similar trend in the coefficient of thermal expansion plus the coefficient of the linear expansion of $3.5 \times 10^{-6}\,1/\mathrm{K}$.

5. SiC Volume Phase Grating

Here the 6H-SiC volume phase grating used is shown, and no change occurred after being annealed up to 399 °C. Shown in Fig. 4 are the optical microscope images of the SiC grating at 10× and 50×.

The 6H-SiC grating was micromachined using three anamorphic femtosecond laser lines in series with $\sim 10\,\mu$m of overlap between each anamorphic processed line. Each processed line has $3\,\mu\mathrm{m} \times 190\,\mu\mathrm{m}$ dimensions and a $20\,\mu$m grating spacing. The overlap of the three lines causes a complex diffraction pattern described by using the Fourier analysis [9] of this grating convoluted with a Gaussian He–Ne beam. The mathematical transmittance function of this grating convoluted with the He–Ne beam is as follows:

$$t_a(x,y) = \left[\left\{ e^{-\pi\left(\frac{x^2}{A^2}+\frac{y^2}{B^2}\right)} + e^{-\pi\left(\frac{(x\pm x_0)^2}{A^2}+\frac{y^2}{B^2}\right)} \right\} \otimes \left\{ \left[\frac{1}{L}\mathrm{comb}\left(\frac{y}{L}\right)\delta(x)\right]\mathrm{rect}\left(\frac{y}{NL}\right)\right\}\right] \times e^{-\pi\cdot\frac{r^2}{\omega_o^2}}. \tag{8}$$

The first two terms in Eq. (8) represent the femtosecond micromachined processed anamorphic lines (3 lines), which are convoluted with the grating comb function and multiplied by the He–Ne Gaussian function for spot size, ω_o. The variables A and B represent the width and length of the processed grating lines, and L is the grating spacing. The femtosecond beam is also represented using a Gaussian function for simplicity but is actually a secant-squared function. The theoretical and experimental results of the diffraction pattern as stated above are given below.

Figure 5 above shows very good agreement with the theory and the experimental results. Order spacing and the number of minor orders agree, however, the first- and second-order peaks saturate the CCD camera, so it is uncertain if their amplitudes agree, but considering they both saturate and the minor orders agree, it can be assumed that they are in close agreement considering the method by which the data was acquired. The experimental results were collected using a common digital camera. The line-out

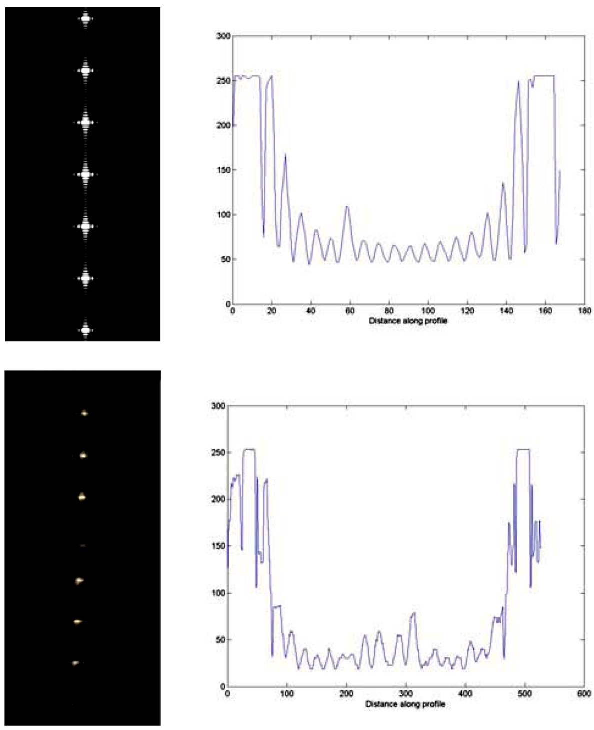

Fig. 5. (Color online) (top) Theoretical Fraunhofer diffraction pattern with a line-out of two of the orders. (bottom) The experimental Fraunhofer diffraction pattern with a line-out of two of the orders. The horizontal axes only represent the number of points in the matrix calculation for the theoretical plot, and for the experimental plot it represents the number of points taken from a line-out (both performed in MATLAB).

results were produced using MATLAB code. From the model the grating structure can be designed to provide the desired diffraction pattern. These results show primarily that the SiC grating structure morphology is understood since the Fourier model results agree with experimental results.

6. Conclusion

We report a new noncontact method of measuring the thermal coefficient of transparent and nontransparent materials using diffraction gratings. We also report the measurement of the 6H-SiC coefficient of the nonlinear thermal expansion and the coefficient of linear expansion. Finally a new high-temperature sensor using gratings micromachined in 6H-SiC was developed that can be used for high temperatures.

Special thanks are given to the Air Force Research Laboratory personal at the Wright-Patterson Air Force Base, the University of Dayton, and F. Baxely for assisting in discussions regarding these measurements.

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