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Refereed paper

Study of thermal effects in GaAs micromachined power sensor microsystems by an optical interferometer technique

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A contactless and non-invasive optical interferometric method is used to study the temperature distribution and thermal time response in a GaAs micromachined power sensor. Temperature variations in the sensor active area—a cantilever beam—are sensed by an infrared laser beam. The temperature increase due to pulsed power dissipation in the cantilever induces an increase both in the GaAs refractive index and in the cantilever thickness. This results in a change in the phase and intensity of the reflected laser beam which is interferometrically detected. The spatial temperature distribution along the cantilever beam is studied using measurements of the optical phase and intensity as a function of the dissipated power. The optical signal is analysed taking into account Fabry–Perot interference. The thermal time constant of the sensor of about 5 msec is obtained from transient optical signal measurements. Results of the optical analysis are consistent with those of electrical characterization of the sensor and with the simulation of the temperature distribution. © 1998 Published by Elsevier Science Ltd. All rights reserved.

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1. Introduction

Extended exploitation of high-speed switching components like power converters and inverter power sources in industrial electronics has evoked an increasing demand for a broad frequency range of power measurements. Power sensors based on the power–temperature conversion fulfil these requirements and are also of interest for metrology applications. Recently, a novel concept of a GaAs micromachined sensor based on the principle of a dual three-terminal thermoconverter has been reported [1, 2]. A good calibration and circuit connection of the sensor necessitates a knowledge of the temperature distribution and the time response of the sensor. Experimental investigation of these sensor parameters together with the thermal simulation are required for optimization of the structure design and circuitry of the thermal bridge.

In this paper we present a study of thermal characteristics in such a micromachined power sensor using a contactless optical interferometric method described in Ref. [3]. In comparison with pyrometric techniques [4] and liquid crystal temperature mapping [5], this method allows highly sensitive and non-invasive measurements of the temperature under dynamic conditions in a broad range of device operation frequencies and with a high spatial resolution. After a description of the experimental set-up in Section 2, measurements of the spatial temperature distribution and the thermal time constant are presented and discussed in Section 3 together with a methodology of thermo-optical measurements.

2. Experiments

2.1. Sensor description

A simplified schematic of the sensor is shown in Fig. 1. The sensor microsystem was prepared on an MBE-grown GaAs/GaAlAs/GaAs heterostructure with a GaAlAs etch stop layer [2]. The

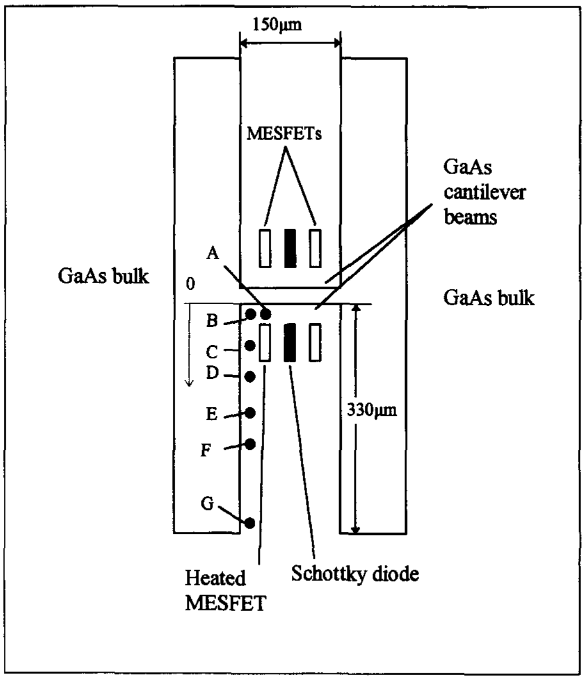

Fig. 1. Schematic picture of the GaAs sensor system consisting of two cantilever beams. Measurement positions of the probe optical beam are indicated by circles. Zero position is also marked.

sensor consists of two symmetrically placed power-controlled GaAs MESFETs as heaters and a central Schottky diode as temperature detector. The sensor is fabricated on a GaAs cantilever beam with $330\times150\,\mu m$ dimensions prepared by a selective reactive ion beam etching. The cantilever beam thickness is small (about $9\,\mu m$) in order to increase the power–temperature efficiency (thermal resistance) of the microsystem. Two cantilever beams are used for the whole microsystem in order to suppress the influence of environmental temperature fluctuations. The principle of the sensor is to balance the unknown power dissipated by one heater by a known power on the second one while maintaining a constant sensor temperature (of about 100°C) sensed by the Schottky diode [1]. Controlling the power on the second heater by the current at constant voltage or by the voltage at constant current, a power/current or power/voltage converter, respectively, is obtained.

2.2. Optical method

The principle of the interferometric method is to detect the temperature-induced optical phase and intensity changes of an infrared laser beam (wavelength λ=1.3 μm, spot diameter $\approx$6–8 μm) reflected from the GaAs cantilever. The temperature increase ΔT in the cantilever beam causes the increase in the optical thickness L_{OPT} of the cantilever due to: (i) the increase in the GaAs refractive index caused by the thermo-optical effect [6]; and (ii) the increase in the cantilever thickness due to the thermal expansion. Assuming a homogeneous temperature distribution in the cantilever along the optical beam path and neglecting second order terms in ΔT, L_{OPT} can be expressed as:

$$L_{OPT} = \left[n_{GaAs} + \frac{dn}{dT}\Delta T + n_{GaAs}\frac{1}{L}\frac{dL}{dT}\Delta T \right] \cdot L \tag{1}$$

where n_{GaAs} is the GaAs refractive index at room temperature, L is the cantilever beam thickness at room temperature, dn/dT is the temperature coefficient of the GaAs refractive index ($\approx$1.5–4$\times 10^{-4}$ K^{-1} [6, 7]), and $1/L \bullet dL/dT$ is the linear thermal expansion coefficient ($\approx 7\times 10^{-6}$ K^{-1} [8]). The second and third term in eq. (1) correspond to the optical thickness change due to the thermo-optical and thermal expansion effects, respectively. Since the effect of the thermal expansion is only 6–15% from the thermo-optical effect, the latter is thus the dominant one. The phase and intensity are measured by a two-beam heterodyne technique described in Ref. [3]. In this study a probe beam is placed on the cantilever beam where the temperature is changed due to pulsed heating. The beam undergoes multiple reflections from the back and the top side of the GaAs cantilever, which acts as a Fabry–Perot resonator. A second beam, the reference beam, is positioned on a place with a negligible temperature change (e.g. on the second non-heated cantilever beam). In our configuration, both optical beams are directed from the back side of the cantilevers. The temperature induced changes in the optical thickness cause variations in the measured phase ϕ and reflectivity R of the probe beam and can be expressed as [9]:

$$\phi = \arctan\left[\frac{r_2(1-r_1^2)\sin(2L_{NORM})}{r_1(1+r_2^2)+r_2(1+r_1^2)\cos(2L_{NORM})}\right] \tag{2}$$

$$R = \frac{r_1^2 + r_2^2 + 2r_1r_2\cos(2L_{NORM})}{1 + r_1^2r_2^2 + 2r_1r_2\cos(2L_{NORM})} \tag{3}$$

with

$$L_{NORM} = \frac{2\pi L_{OPT}}{\lambda} \tag{4}$$

where r_1 and r_2 are the reflection coefficients on the back and top side of the cantilever, respectively (for the air/GaAs/air system r_2=$-r_1$=0.54), L_{NORM} is the normalized optical thickness and λ is the free space laser wavelength. The reflected beams interfere in a photodetector and provide an electrical signal which is averaged and displayed in a digital oscilloscope. The phase change is obtained as a difference between the measured phases ϕ_0 and ϕ_H related to the oscilloscope signals S_0 and S_H (referred to here as the optical signals) for zero and a non-zero device heating, respectively:

$$S_{0,H} = A_{0,H}\sin(\phi_{0,H}) \tag{5}$$

where A_0 and A_H are the corresponding oscilloscope signal amplitudes which can be measured under dc operation of the MESFET. The quantity A_H/A_0, referred to here as the normalized optical intensity, is proportional to the square root of the reflectivity R. Theoretical dependencies of the phase and square root of the reflectivity on the normalized optical thickness for one period are shown in Fig. 2.

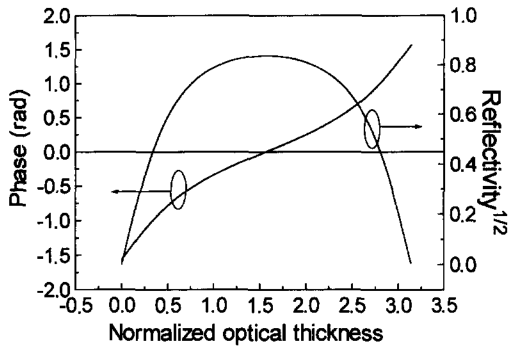

Fig. 2. Calculated phase of the reflected probe beam and square root of the reflectivity as a function of the normalized optical layer thickness of the cantilever beam.

It should be noted that the complex refractive index in GaAs also varies with changes in free carrier concentration [10] and electric field [11]. We have investigated the influence of these electro-optical effects under the electrical bias conditions where no heat dissipation occurs (pulsed gate-source voltage V_{GS} =−4/0 V, drain-source voltage V_{DS} =0 V). The changes in the optical signal from these effects were found to be negligible in comparison with the thermo-optical effect. In addition, the phase and intensity of the optical beam can also be influenced by temperature changes in the optical absorption coefficient. However, as the absorption in this spectral region is very small, this effect can be neglected.

All the measurements were performed at room temperature with a pulsed heat dissipation in one of the two MESFETs. The gate-source bias V_{GS} was pulsed between −4 V (zero heating) and a value in the −3 to 0 V range (heating). The pulse repetition rate was chosen in such a way that cooling down to room temperature was assured between heating pulses. The drain-source voltage V_{DS} was varied in the 0–3 V range. The amount of dissipated power was calculated from the dc I–V characteristics of MESFET. The time resolution of the optical measurements was about 1 μsec. Transient thermal effects were additionally evaluated by two kinds of electrical transient measurements: (i) the voltage variation on the Schottky diode was detected under a forward dc current biasing of 10 μA; and (ii) the evolution of the drain current I_D of the MESFET was measured as a voltage drop on a small resistor connected in series with the source. Both time dependencies were monitored on a digital oscilloscope.

3. Results

3.1. Spatial measurements

Figure 3 shows a typical dependence of the phase and intensity of the laser beam as a function of the power for a beam positioned at the GaAs surface close to the power source (position A in Fig. 1). The decrease in the optical intensity and the increase in phase change with increasing power (temperature) are consistent with the theoretical curves shown in Fig. 2. It can be seen from Fig. 2 that the slope of the phase and intensity curve varies with the normalized optical thickness, so the value of the measured phase change and intensity change will depend on the position of the 'optical working point' (i.e. on the value of L_{NORM}). This means that for a constant temperature change, different phase and intensity change values will be measured for different L values. For a study of

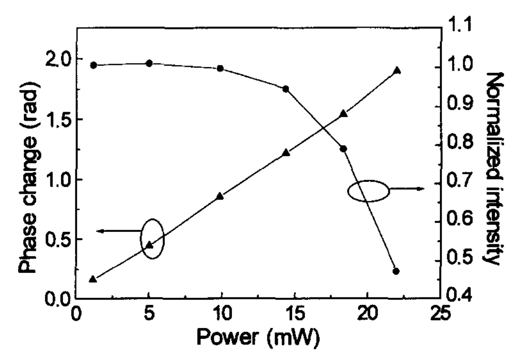

Fig. 3. Measured phase change and normalized intensity of the reflected probe beam on position A as a function of the power dissipated in the MESFET.

the temperature spatial dependence it is therefore necessary to measure on places with the same thickness L, i.e. at the same optical working point. Note that the cantilever thickness is different at different positions. In addition, the reflection from the metallized surface also change the intensity and phase curves, and therefore also the optical working point, owing to the change in the reflection coefficient at the top cantilever side. As a consequence, the optical measurements should be performed on places with identical reflection properties. Figure 4 shows the phase change and the normalized intensity power dependencies obtained at five positions B–F (see Fig. 1) of the probe laser beam along the cantilever beam. The same optical working point at these positions has been verified by measuring the optical signal amplitudes A_0 (zero power dissipation, laser diode intensity was held constant), which have been found to be equal at all positions. The decrease in the normalized intensity with increasing power (i.e. temperature) in Fig. 4(a) confirms that the optical working point is the same at these places. The normalized optical thickness for this working point is near $\pi/2$, corresponding to the maximum of the intensity curve in Fig. 2. In order to obtain the absolute values of temperature changes from the measured curves in Fig. 4, it would be necessary to analyse these data using the expressions for the Fabry–Perot interference, which will be described in the next section. In the following, we will estimate the ratio of the temperature change at the measurement points from the measured phase change [Fig. 4(b)]. Figure 5 shows a spatial distribution of the phase change along the cantilever beam for three power values. It can be seen from Fig. 2 that the phase curve near the optical working point ($\approx\pi/2$) can be approximated by a linear function. Since the phase change here is proportional to the temperature change, the temperature change ratio at these locations is the same as the ratio of the respective measured phase changes. This ratio is near three for point C in the vicinity of the heated MESFET and point E in the middle of the cantilever beam (Fig. 5). From other optical measurements we found that the temperature change ratio at the position in the middle (E) and at the beginning of the cantilever beam (G) is between three and four, which is

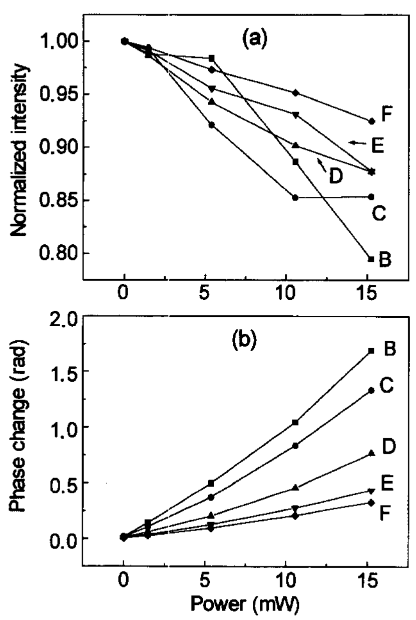

Fig. 4. Power dependencies of the (a) normalized intensity and (b) phase change of the reflected laser beam measured at positions B–F along the cantilever beam (see Fig. 1).

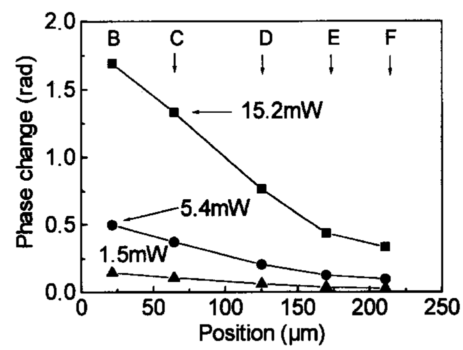

Fig. 5. Optical phase change as a function of the position along the cantilever beam (see Fig. 1) for three different power levels.

consistent with the results of the numerical thermal simulation of the temperature distribution [12].

3.2. Measurement methodology improvement

To obtain absolute values of the temperature at various positions, two different approaches are discussed. One possible way is to compare the measured data with the theoretical Fabry–Perot expressions for phase and intensity. In this case, the optical measurements should be performed in a large temperature (power) range to assure a sufficient fitting precision. This is not always possible owing to a power limitation of the MESFET. Moreover, in such an analysis, the value of dn/dT must be known exactly. The literature values of dn/dT vary, however, within a factor of two [6, 7], making the temperature evaluation difficult.

In the following we describe a different approach for obtaining the absolute temperature values at any measurement position. Here, it is not necessary to know the dn/dT value, nor does fitting have to be carried out. The measurement method is based on comparing two sets of experimental curves. At first, the intensity and phase of the reflected probe beam at each measurement position have to be measured as a function of a known cantilever temperature by using an external sample heating (steady-state thermal conditions). In such a calibration measurement, reference normalized intensity and phase temperature dependencies will be obtained. If the temperature range of the measurement is sufficiently high, intensity maxima and minima due to Fabry–Perot interference will appear in the intensity curve. Note that in such measurements the whole sample is heated, so the reference beam should be properly placed. When measuring only the intensity variations, both beams can be placed on positions with the same cantilever thickness (same optical working point). Since the signals from both beams are equivalent in this case, the optical signal will be proportional to the reflectivity R instead of $\sqrt{R}$ (see eq. (3)). On the other hand, in order to obtain a good interferometric reference in the case of phase measurements, the reference beam can be placed outside the sample. Alternatively, the measurements can be performed from the top side, placing the reference beam on a reflecting metallization pad whose reflectivity does not change significantly with temperature. As a further step, measurements similar to those presented in this contribution have to be performed to obtain the dependencies of the normalized optical intensity and phase change as a function of the dissipated power. Finally, comparing the intensity and phase power curves with the reference intensity and phase temperature dependencies, the temperature change for a particular power value can be obtained. We emphasize that if the temperature mapping is to be performed at places with the same optical properties (same optical working point), the calibration measurement procedure has to be carried out only at one position.

3.3. Time domain measurements

Figure 6 shows the time dependencies of the optical signal, the Schottky diode voltage and the drain current for two different drain voltages under pulsed gate bias conditions. The optical working point for these measurements is close to the flat maximum of the intensity signal ($L_{NORM} \approx \pi/2$). Therefore, for small power changes the amplitude A in eq. (5) is nearly independent of power ($A_0 \approx A_H$), and the optical signal is proportional to the phase change. It can be seen from Fig. 6(a) (V_{DS}=1 V, dissipated power ≈5 mW) that the optical time constant, defined as a reciprocal initial slope of the optical signal, is of the order of 5 msec. As the optical signal under this low power condition is directly proportional to the temperature variation, this time constant is the thermal time constant of the sensor. In Fig. 6(a) the time response of the optical signal is seen to be in agreement with the time variation of the Schottky diode voltage, the latter also being

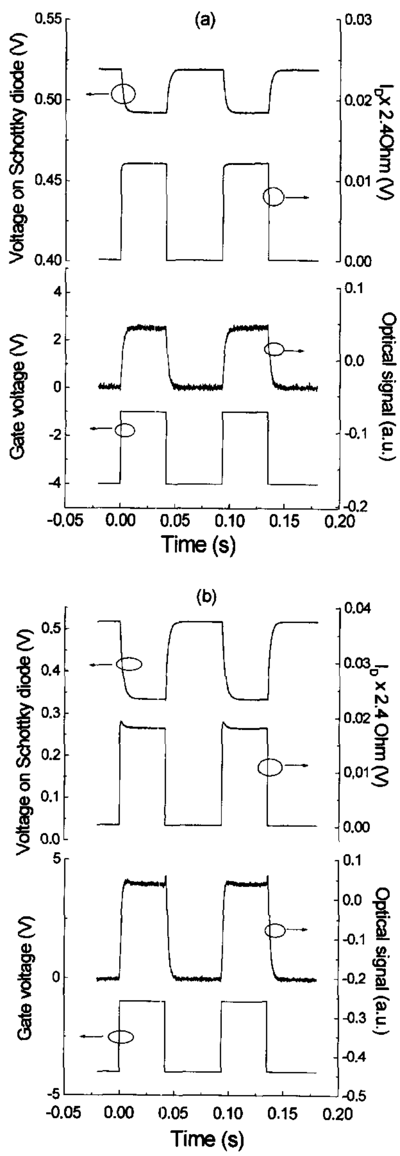

Fig. 6. Time response of the optical signal, the Schottky diode voltage and the drain current I_D for a pulsed gate bias V_{GS} and two drain voltages V_{DS}: (a) 1 V; (b) 3 V. The drain current is monitored as a voltage drop across a 2.4Ω resistor connected in series with the source. The heat is dissipated at the high gate-pulse level.

directly related to the temperature. On the other hand, the small drain current increase observed under this low power condition is caused by the carrier trapping on slow surface states [13]. Figure 6(b) shows an apparent deformation of the optical signal on the 'on' side (a rapid increase and a small decrease) and on the 'off' side (signal peaking) of a high power pulse (V_{DS}=3 V, dissipated power ≈22 mW). The signal distortion is caused by a combined effect of the time variation of the intensity and phase change, and will be discussed elsewhere. In this case the time dependence of the optical signal is not directly related to the thermal dynamics. However, the heating effect is visible on the drain current time dependence [Fig. 6(b)], where the current during the heating pulse initially decreases with the same time constant as the optical signal in Fig. 6(a). The current decrease has a thermal origin and is the reason for a negative differential resistance observed in the dc *I–V* characteristics of the MESFET [2].

Our contactless laser measurements confirm that the measured optical time constant has a pure thermal origin, and that it has no electrical origin (like an RC parasitic component of the input pads of the MESFET or trap charging effects). Such a large thermal time constant is due to a high thermal resistance of the cantilever beam, which is of the order of 6000 K/W [2].

4. Conclusions

We have shown that the laser interferometric technique can successfully be applied to studying the temperature dynamics in a GaAs micromachined power sensor. A thermal time constant of the system is obtained from the transient optical measurements under low power dissipation conditions. A value of 5 msec for the time constant is consistent with the electrical measurements. The measurements of the spatial temperature distribution provide the ratio of the temperature change values at different places on the cantilever beam. A qualitative agreement with the temperature distribution obtained from thermal modelling is found. In addition, we have proposed a methodology for the thermo-optical measurements. This can be applied to studying local temperature effects in any micromachined or microelectronic system where the temperature in the device active area is homogeneously distributed along the optical beam path.

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