Superlattices and Microstructures 38 (2005) 69–75

Superlattices and Microstructures

www.elsevier.com/locate/superlattices

Dynamical behavior of the scanning thermal microscope (SThM) thermal resistive probe studied using Si/SiGe microcoolers

Y. Ezzahri[a,*], L.D. Patiño Lopez[a], O. Chapuis[b], S. Dilhaire[a], S. Grauby[a], W. Claeys[a], S. Volz[b]

[a] *Centre de Physique Moléculaire, Optique et Hertzienne, Université Bordeaux 1, 351, cours de la Libération, 33405 Talence cedex, France*

[b] *Ecole Centrale Paris, Grande Voie des Vignes (F), 92295 Châtenay-Malabry cedex, France*

Received 31 January 2005; received in revised form 14 April 2005; accepted 18 April 2005
Available online 15 June 2005

Abstract

We present a simple method for the characterization of the dynamical behavior of the SThM Wollaston wire thermal resistive probe using Si/SiGe microcoolers. Measurements show a time response of about 186 μs. This value confirms the value found in the literature. Measurements also allow us to determine the total thermal tip–sample contact resistance Z_{Th}^{C}.

Keywords: SThM technique; Microcooler; Wollaston wire; SThM thermal probe time response; Tip–sample contact resistance

1. Introduction

Since its invention in 1994 [1], the Scanning Thermal Microscope (SThM) based on a resistive wire probe has been applied in the determination of local thermophysical properties. This determination provides improvements in the modeling of microsystems, for

* Corresponding author. Tel.: +33 5 40 00 27 93; fax: +33 5 40 00 69 70.
E-mail address: y.ezzahri@cpmoh.u-bordeaux1.fr (Y. Ezzahri).

0749-6036/$ - see front matter
doi:10.1016/j.spmi.2005.04.005

the detection of local heating such as hot spots inside microelectronic and optoelectronic components. In addition, this technique has had until now the best spatial resolution of about 50 nm, which represents the diameter of the tip–sample thermal contact [2,3]. This technique is therefore a powerful tool in microthermal and nanothermal characterization.

In a previous work, Buzin et al. [4] have found the time response of the SThM Wollaston wire thermal resistive probe in air to be $\tau_1 = 200$ μs for heating, and $\tau_2 = 270$ μs for cooling. In this paper we present results of an experiment where Si/SiGe microcoolers were used to characterize the time response of this SThM probe. Results also allow the determination of the total thermal tip–sample contact resistance Z^C_{Th}, which is a key datum in the SThM calibration [5].

A Si/SiGe microcooler is a thermoelectric device, in which the main element is a Si/SiGe superlattice [6]. For an optimized geometry device size 60×60 μm^2, this microcooler has demonstrated a maximum cooling of about 4.5 °C at 600 mA, with a cooling power density of about 600 W/cm^2 [7]. In addition, it presents the advantage that it can be monolithically integrated with microelectronic and optoelectronic components [8]. Fig. 1(a) shows a Scanning Electron Microscopy (SEM) picture of different microcoolers with different sizes. Fig. 1(b) shows a schematic diagram of this device.

2. Experiment and discussion

Fig. 2(a) shows a SEM picture of the SThM thermal resistive probe. It is made up of a Wollaston wire shaped as a tip. The uncovered platinum core is heating when a current passes through it. The measurement of the tip resistance leads to either the tip temperature or the heat flux dissipated by the probe.

Previous experimental study of Si/SiGe microcoolers has shown a time response smaller than 30 μs [9]. We checked this value by exciting the coolers with an AC current at several frequencies. A laser light is reflected [10] by the microdevice surface. Its normalized amplitude is reported in Fig. 3 as a function of the excitation frequency and for different microcooler sizes [11]. This result obtained by reflectometry confirms that the cut-off frequency depends slightly on the device size and is about 24 kHz, which corresponds to a time response of about 7 μs.

Now, we use an analogy with a technique for characterization of the cut-off frequency of electronic devices. As a matter of fact, sine-wave generators are used in order to characterize the frequency response of systems. They provide signals with constant amplitude, and variable frequency. The device transfer function is then directly extracted from the response to the well-known excitation signal coming from the generator. In our case, the microcooler can be considered as a temperature sine-wave generator. It provides a constant temperature variation in a high frequency range for characterizing the transfer function of the SThM thermal resistive probe. The SThM is used in the temperature mode. Its response to the microcooler excitation will only be the image of the SThM probe transfer function for frequencies below 24 kHz. For more details on the operation of the SThM technique, readers are invited to see Refs. [2,12].

The Si/SiGe microcooler is supplied by a sinusoidal current of the form $I = I_0 \cos(2\pi f t)$; the thermal resistive probe is put on the top surface of the microcooler as

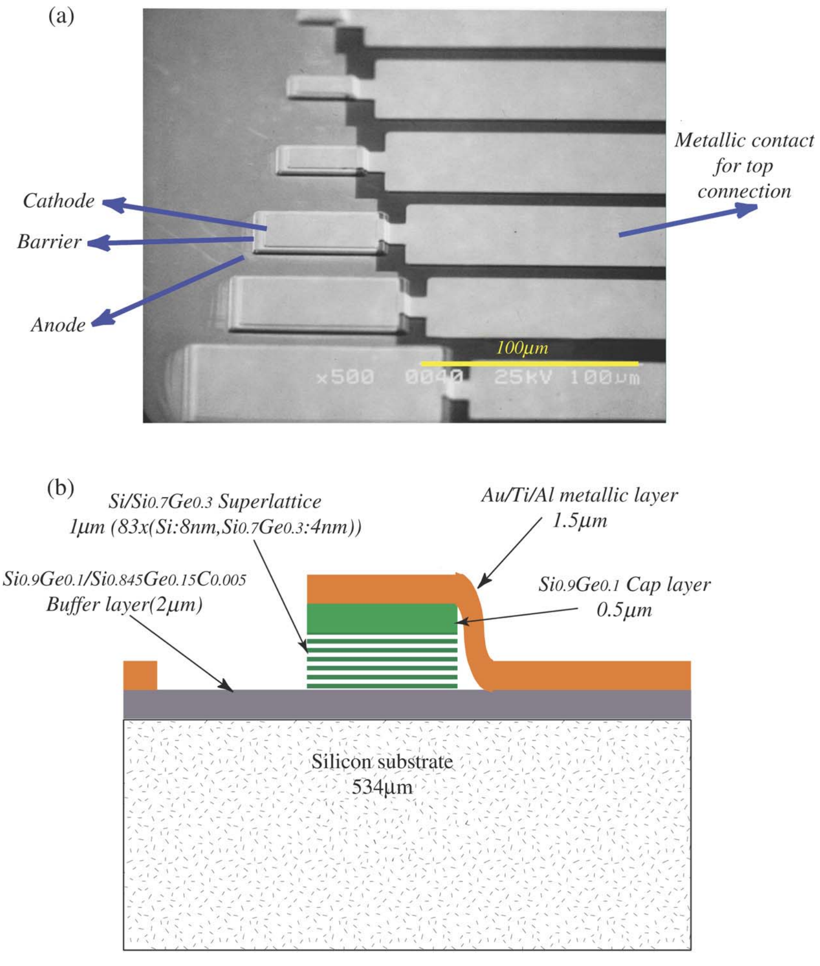

Fig. 1. (a) Scanning Electron Microscopy (SEM) picture of the Si/SiGe microcooler, (b) Schematic diagram of the Si/SiGe microcooler.

shown in Fig. 2(b). The thermal response is analyzed with respect to the frequency. Fig. 4 shows the variation of the normalized modulus of the probe voltage, for two microcooler sizes (circles and stars). The dashed line is a theoretical fit with a first order transfer function:

$$H(f) = \frac{H_0}{1 + j\frac{f}{f^{\mathrm{SThM}}_{\mathrm{Cut-off}}}} \tag{1}$$

where H_0, f, and $f^{\mathrm{SThM}}_{\mathrm{Cut-off}}$ are respectively the maximum gain, frequency of excitation, and cut-off frequency of the SThM thermal probe. The best fit is found when the cut-off

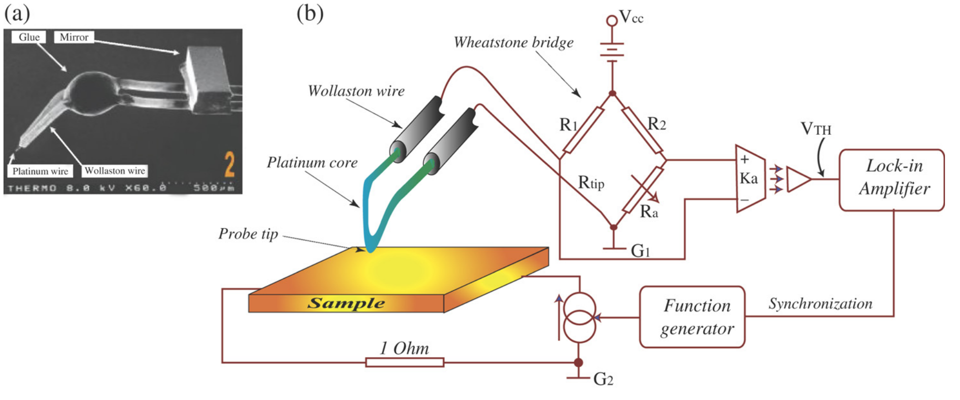

Fig. 2. (a) Scanning Electron Microscopy (SEM) picture of the Scanning Thermal Microscope (SThM) thermal probe, (b) experimental set-up for the SThM technique.

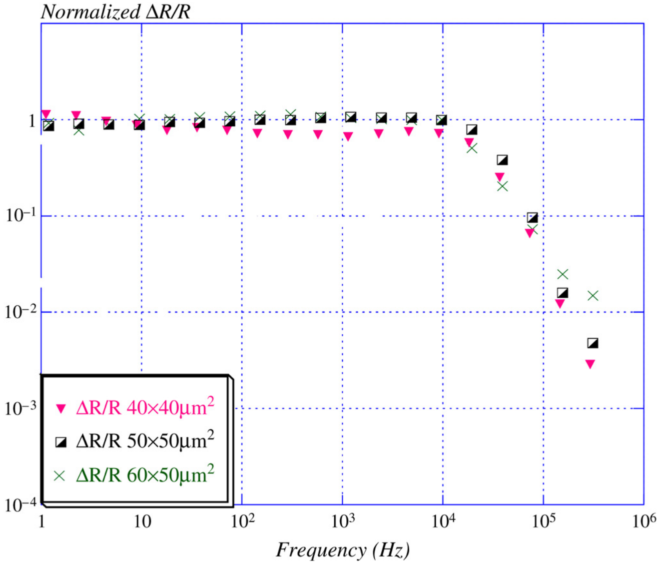

Fig. 3. Normalized reflectivity change on the top surface of Si/SiGe microcoolers, for different sizes as a function of the excitation frequency.

frequency is $f_{\text{Cut-off}}^{\text{SThM}} \simeq (857 \pm 20)$ Hz. If we change from the frequency to the time domain:

$$\tau = \frac{1}{2\pi f_{\text{Cut-off}}^{\text{SThM}}} \tag{2}$$

we obtain the corresponding time constant $\tau \simeq (186 \pm 4)$ µs, which confirms the value found by Buzin et al. [4]. We should note here that this value depends on the nature of the probe and its geometry, since each one is made by hand.

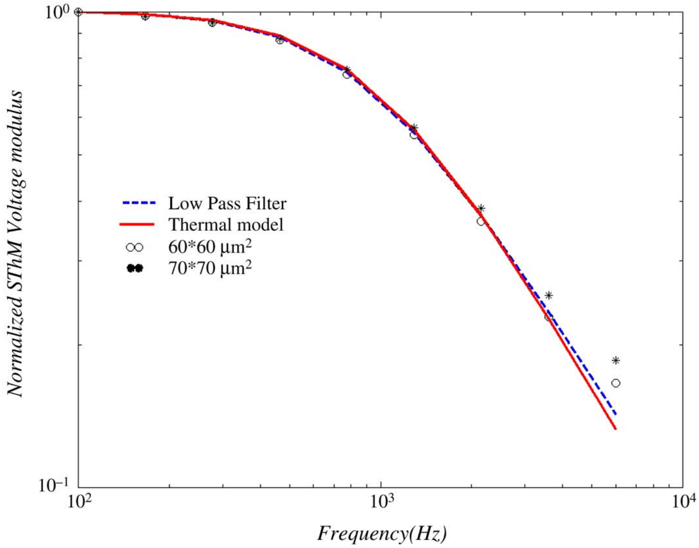

Fig. 4. Normalized variation of the modulus of the SThM voltage on the top surface of the Si/SiGe microcooler as a function of the excitation frequency for two different sizes 60 × 60 μm^2 (circles), and 70 × 70 μm^2 (stars).

The experimental results also allow us to identify the total thermal tip–sample contact resistance Z_{Th}^{C}. This parameter includes all modes of heat transfer occurring between the tip and the sample surface when they are in contact: (i) solid–solid conduction, which is intrinsic each time two solids are in contact; (ii) solid–solid thermal constriction which only occurs when both sides of the solids in contact have different geometries; (iii) near-field radiation; (iv) gas conduction (in our case the gas is air); and (v) the conduction via the meniscus of the liquid which is formed between the tip and the sample surface [2]. To get Z_{Th}^{C}, we have developed a theoretical model for heat transfer inside the SThM thermal probe. This model is based on the Thermal Quadrupoles Method [13]. Here we only present the main formula of this model, which we have used to fit experimental results. More details of the model can be found in the Ref. [14]. This formula is given as follows:

$$V_{\mathrm{Th}} = E\gamma \frac{ch(qL) - 1}{qL[sh(qL) + 2\pi r^2 \beta_{\mathrm{p}} q Z_{\mathrm{Th}}^{C} ch(qL)]}\theta_{\mathrm{s}} = F(q)\theta_{\mathrm{s}} \tag{3}$$

where $q = \sqrt{\frac{2\pi j\omega}{\alpha_{\mathrm{p}}} + \frac{2h}{\beta_{\mathrm{p}} r}}$, and $E = \frac{V_{cc} K_a R_1 R_0}{(R_1 + R_0)^2}$ is a function which depends on the electronic components used in the amplification chain stage. V_{Th} and θ_{s} are, respectively, the measurement system output voltage and the top sample surface temperature. γ, α_{p}, β_{p}, Z_{Th}^{C}, r, L, h, and $j\omega$ are respectively the temperature coefficient of the electrical SThM probe resistance, the thermal diffusivity and the thermal conductivity of the platinum probe tip, the total thermal tip–sample contact resistance, the radius of the probe section, the half-length of the platinum wire, the platinum wire convection–radiation coefficient, and the Fourier variable. In Table 1 are listed all SThM thermal resistive probe properties [15] and acquisition circuit characteristics.

Table 1
SThM thermal resistive probe properties [15] and acquisition circuit characteristics

Property	Value
Platinum thermal conductivity β_p (W/m K)	38
Platinum thermal diffusivity α_p (m^2/s)	1.27×10^{-5}
Wire convection–radiation coefficient h (W/m^2 K)	1000
Non-cladded wire half-length L (m)	100×10^{-6}
Platinum wire radius r (m)	2.5×10^{-6}
Wire cross-section $S_p(m^2) = \pi r^2$	1.96×10^{-11}
Wire still resistance R_0 (Ω)	2.1
Wire temperature coefficient γ (K^{-1})	1.66×10^{-3}
Total thermal tip–sample contact resistance Z_{Th}^{C} (K/W)[a]	6.3×10^4
Isolating amplifier gain K_a	2500
Bridge resistance R_1 (Ω)	250
Bridge feeding voltage V_{cc} (V)	2.5

[a] Adjustable parameter.

Fitting V_{Th} with this formula makes it possible to extract the value of Z_{Th}^{C} for the two Si/SiGe microcooler device sizes. We found for both sizes $Z_{Th}^{C} = (6.3 \pm 0.8) \times 10^4$ K/W. This value is in a good agreement with those found in the literature [2]. Fig. 4 also includes the best theoretical fit (solid line) corresponding to our quadrupoles model.

3. Conclusion

We have used the frequency behavior of thin film Si/SiGe microcoolers to estimate the SThM thermal resistive probe transfer function. The values found for both the cut-off frequency and the total thermal tip–sample contact resistance, Z_{Th}^{C}, are in very good agreement with the values in the literature. Consequently, microcoolers appear to be useful and simple tools for use in the full characterization of the SThM thermal resistive probe.

Acknowledgments

The authors would like to thank Pr Ali Shakouri and his group for manufacturing and providing the samples. This work is supported by “la région Aquitaine”, and the FEDER fellowship.

References

[1] R.B. Dinwiddie, R.J. Pylkki, P.E. West, Thermal conductivity contrast imaging with a scanning thermal microscope, in: T.W. Tong (Ed.), Thermal Conductivity, vol. 22, Technomic Publishing Co., Lancaster, 1994, pp. 668–677.
[2] A. Majumdar, Annu. Rev. Mater. Sci. 29 (1999) 505–585.
[3] E. Gmelin, R. Fischer, R. Stitzinger, Thermochim. Acta 310 (1998) 1–17.
[4] A.I. Buzin, P. Kamasa, M. Pyda, B. Wunderlich, Thermochim. Acta 381 (2002) 9–18.
[5] S. Lefévre, S. Volz, J.B. Saulnier, C. Fuentes, N. Trannoy, Rev. Sci. Instrum. 74 (2003) 2418–2423.

[6] Y. Zhang, G. Zeng, R. Singh, J. Christofferson, E. Croke, J.E. Bowers, A. Shakouri, 21st International Conference on Thermoelectrics, 25–29 August 2002, Long Beach USA, 2002, pp. 329–332.
[7] Y. Zhang, D. Vashaee, J. Christofferson, A. Shakouri, G. Zeng, C. Labounty, J. Piprek, E. Croke, International Mechanical Engineering Congress and Exposition, 16–21 November 2003, Washington, DC, 2003.
[8] X. Fan, G. Zeng, C. Labounty, J.E. Bowers, E. Croke, C.C. Ahn, S. Huxtable, A. Majumdar, A. Shakouri, Appl. Phys. Lett. 78 (2001) 1580–1582.
[9] A. Fitting, J. Christofferson, A. Shakouri, X. Fan, G. Zeng, C. Labounty, J.E. Bowers, E.T. Croke, ASME Heat Transfer Division Conference: 2001 IMECE.
[10] V. Quintard, G. Deboy, S. Dilhaire, D. Lewis, T. Phan, W. Claeys, Microelectron. Eng. 31 (1996) 291–298.
[11] S. Dilhaire, Y. Ezzahri, S. Grauby, W. Claeys, J. Christofferson, Y. Zhang, A. Shakouri, 23rd International Conference on Thermoelectrics, 17–21 August 2003, La Grande Motte, France, 2003, pp. 519–523.
[12] S. Gomès, N. Trannoy, P. Grossel, Meas. Sci. Technol. 10 (1999) 805–811.
[13] D. Maillet, S. André, J.C. Batsale, A. Degiovanni, C. Moyne, Thermal Quadrupoles: Solving the Heat Equation through Integral Transforms, John Wiley & Sons, 2000.
[14] L.d. Patiño-Lopez, Ph.D. Thesis, Université Bordeaux 1, 2004.
[15] Explorer Topometrix®.