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Quantitative thermal imaging of current densities and heat flow in electronic microstructures

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Abstract. The thermoreflectance technique is applied for imaging electric current distributions and thermal transfer in a temperature reference resistor heated by an alternating current and a high power transistor tested for its internal thermal management. High frequency scans allow imaging of the current density distribution in conducting strips of the resistor while scans of amplitude and phase of the surface temperature variation at lower frequencies reveal plane, cylindrical and spherical thermal waves. We investigate wave dimensionality as a function of heating geometry and thermal length, and present a method allowing a quantitative thermal analysis by exploiting the phase profile of cylindrical thermal waves.

1. INTRODUCTION

Due to their increasing compactness, electronic microdevices suffer from intensive heating limiting their lifetime. Therefore, thermal management, i.e. localizing and avoiding strong heat sources, plays an important role in the design of integrated circuits. Photothermal imaging techniques are well suited to monitor heat sources, diffusion and to localize hot spots with micron-resolution[1,2,3] in semiconducting materials and devices.[4,5,6,7,8,9].

The technique applied here is based on periodic Joule heating of an electrically conducting sample and a visualization of temperature oscillations at the surface. By a variation of the alternating current (ac) frequency we aim to separate the contributions of local Joule heating and thermal waves and we study the role of thermal wave dimensionality. Cylindrical waves are utilized to measure heat transfer to the substrate by analyzing phase profiles. Furthermore we elucidate thermal transfer in a high power transistor used for automotive applications.

2. EXPERIMENTAL

The experimental setup is outlined in Fig. 1 and operates similar to other photothermal microscopes using thermoreflectance technique reported in literature.[10] The output signal of a function generator is amplified by a commercial audio amplifier to obtain an average heating power of about 2W. Using a commercial microscope we obtain a spot size of a few microns for the HeNe probe laser beam on the sample. A structure of platinum conduction strips on an Al_2O_3-substrate was chosen as the sample. This device is commercially used as a resistive thermometer. Conducting strips of 2 μm thickness form a maze in which the electric current passes through loops, serpentines and bottlenecks resulting in an inhomogeneous current density distribution and a thermal pattern of hot spots and cold regions. Measurements were performed at frequencies ranging from 0.03kHz to 30kHz.

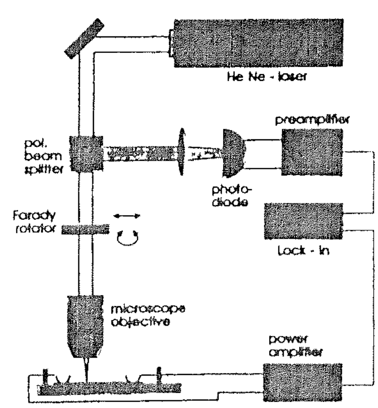

Figure 1

3. BASIC PRINCIPLES OF CURRENT DENSITY IMAGING

Neglecting capacitance and induction effects, we assume that the current density $j(\mathbf{r},t)$ oscillates at any location $\mathbf{r}$ with frequency ω and the same phase. The Joule heating power per unit volume resulting from the electric current density $j(\mathbf{r},t) = j_0(\mathbf{r},t)\sin(\omega t)$ can be splitted into a constant and an oscillating part:

$$\frac{dP(\mathbf{r},t)_{Joule}}{dV} = \frac{j^2(\mathbf{r},t)}{2\sigma} = \frac{j_0^{\,2}(\mathbf{r})}{2\sigma} + \frac{j_0^{\,2}(\mathbf{r})}{2\sigma}\exp(i2\omega t), \qquad (1)$$

where σ is the specific resistivity of the sample.

The oscillating term $(j_o^2(r)/2\sigma)\exp(i2\omega t)$ causes a pattern of thermal waves oscillating at twice the ac frequency. The decay of the heavily damped waves can roughly be described by the thermal diffusion length $L_{th}=\sqrt{2D/2\omega}$, where $D=\sqrt{\kappa/\rho c_p}$ is the thermal diffusivity combining the thermal conductivity κ with the specific heat c_p and the density ρ. L_{th} is the decay length of plane thermal waves, while attenuation is stronger for cylindrical and spherical wave geometries.

Our test sample allows the study of thermal waves of different dimensionality that are depicted schematically in Fig. 2.

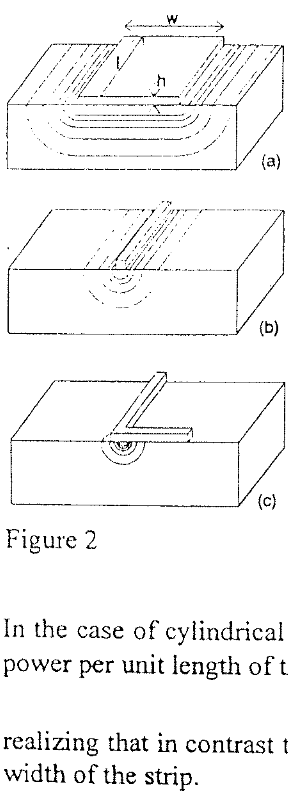

Figure 2

A conducting strip of length l, thickness h and lateral size w larger than the thermal diffusion length causes a plane wave in vertical direction (Fig. 2(a)). The wave originating from a conducting strip being narrower than the thermal length ($w<L_{th}$) can approximately be described by a cylindrical wave (Fig. 2(b)). Sharp bends in a conducting strip give rise to highly localized current densities and result in point-like heat sources (hot spots) forming spherical waves (Fig. 2(c)).

Consider a rectangular conducting strip carrying an ac electric current of amplitude I_0, which gives rise to an ac current density $j_0 = I_0/hw$. The resulting modulated heating power deposited in the entire strip is

$$P = (dP/dV)wlh = I_0^2 l/(2\sigma wh). \qquad (2)$$

For one-dimensional heat flow the photothermal amplitude a is proportional to the heating power per unit area, i.e. $a \sim P/lw$. Using Eq. (2) we obtain:

$$a \sim I_0^2/(2\sigma hw^2) \qquad (3)$$

In the case of cylindrical heat flow the photothermal amplitude is proportional to the heating power per unit length of the strip: $a \sim P/l$. We obtain:

$$a \sim I_0^2/(2\sigma hw\ ) \qquad (4)$$

realizing that in contrast to one-dimensional heat flow the signal is proportional to the inverse width of the strip.

Heat transfer through the Al_2O_3-substrat was analyzed by measuring the phase profile of a cylindrical thermal wave that can approximately being described by

$$T(r) = T_o(r)\exp\left(i\left(2\omega t - r/L_{th}\right)\right), \qquad (5)$$

with r being the radial distance from the source and $T_0(r)$ the wave amplitude that is difficult to express analytically.[11] The phase slope of the photothermal signal is

$$\chi := d\varphi/dr = 1/L_{th} = \sqrt{2\omega/2D} \qquad (6)$$

allowing for a determination of the thermal diffusivity.

4. EXPERIMENTAL RESULTS AND DISCUSSION

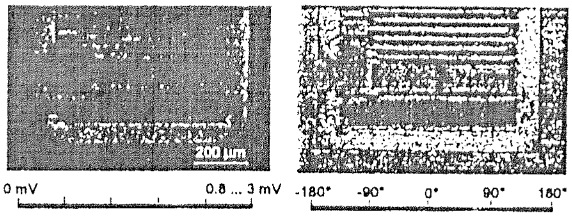

Figure 3(a) (b)

Figure 3 (a) and (b) present photothermal scans on the lower half of the resistor recorded at a modulation frequency of 1kHz. Different values of current densities are distinguished by an elevated amplitude represented by different grey shadings in Fig. 3(a). From the amplitude image (Fig. 3(a)) the influence of the conducting cross section on the current density affecting the photothermal amplitude can clearly be seen. In the three narrow conducting strips an amplitude much higher than in the broad ones was measured. As the width of these strips (20 µm) is smaller than the thermal length at 1kHz of 39µm heat flow is best described by cylindrical waves. The electric current concentrates at the inner edges of right angles yielding elevated local temperature oscillations in the corners.

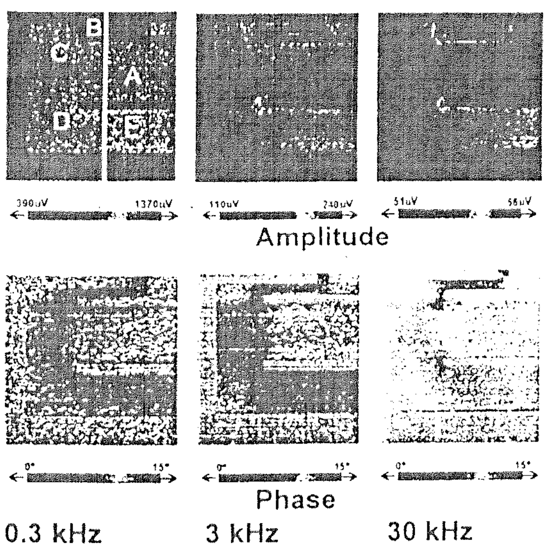

Figure 4

To investigate thermal diffusion in the lower left region of Fig. 3 we recorded amplitude and phase images at various frequencies ranging from 0.3kHz to 30kHz (Fig. 4). Figure 5 visualizes thermal wave propagation by drawing lines of equal phase for the various frequencies. The capital letters in this figure denote various areas of interest that will be discussed in the following. As no electric current passes through the broad horizontal conducting strip **A** forming a dead end, the temperature oscillations measured there can only be caused by thermal waves from the adjacent heated strips. These are cylindrical waves originating from the strongly heated horizontal conducting strip **B** and the spherical waves starting at the edges of the current path **C** and **D**. As expected, with increasing frequency these thermal waves have a shorter range in region **A**. Phase images in Fig. 4 show that the phase gradient of the cylindrical wave increases with increasing frequency. The isophaselines in Fig. 5 clearly demonstrate this behaviour. Similarly, the hot spot at the right angle **D** is best resolved at high frequencies.

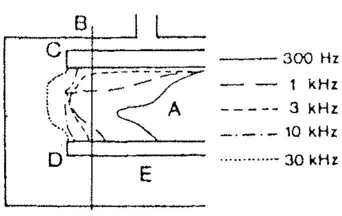

Figure 5

For a more detailed analysis we investigated amplitude and phase profiles at 1kHz measured along the straight line indicated in Figs. 4 and 5. On the conducting strips **B** and **E** approximately constant amplitudes were measured according to the homogeneous direct heating. The amplitude decreases towards the edges of the strips where there is both vertical and lateral heat flow. The phase plot Fig. 6(c) shows a decrease on the left and on the right half of the conducting strip **A**, due to thermal waves propagating from **B** and **D**, respectively. On the conducting strips **B** and **E** a constant phase was measured since these parts of the platinum layer were heated directly.

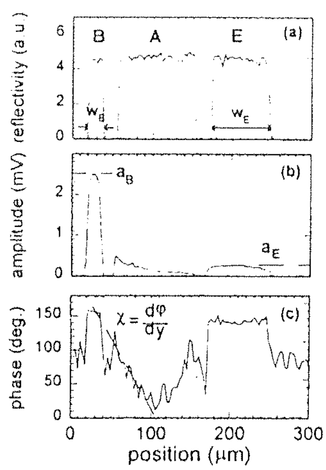

Figure 6

For comparing the amplitudes a_B and a_E in the centre of the conducting strips B and E (Fig. 6(b)) at frequencies in the range 0.03kHz to 30kHz we plotted a_E/a_B as a function of frequency in Fig. 7. For a thermal length smaller than the width of the conducting strips (w_B=20μm, w_E=80μm, Fig. 6(a)) heat flow from both strips can be assumed to be fairly one-dimensional. As a consequence the ratio a_E/a_B according to Eq. 3 is expected to be equal to the inverse ratio squared of the strip width $(w_B/w_E)^2$=1/16 and can be clearly seen in Fig. 7. With decreasing frequency the thermal length becomes larger than the width of the conducting strip B. This causes the thermal wave starting at B to develop a cylindrical shape, while heat flow from E is still one-dimensional resulting in an increase of the ratio a_E/a_B towards low frequencies. Further decrease of frequency leads to cylindrical thermal waves originating from B and E yielding an amplitude ratio a_E/a_B equal to w_B/w_E which is experimentally confirmed in Fig. 7. At the smallest frequency measured the thermal length is large compared to the length of the conducting strip B acting as a thermal point source. The resulting spherical wave cools B more efficiently, which explains the further rise of a_E/a_B towards lower frequencies.

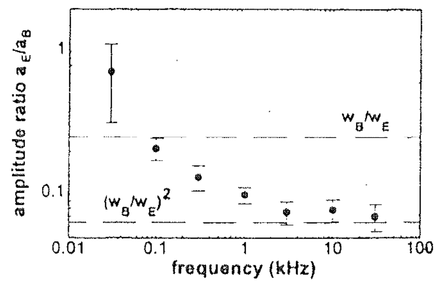

Figure 7

We analyzed heat transfer into the Al_2O_3 substrate by obtaining the slope χ of the phase of the cylindrical thermal wave starting at B from the dashed line drawn in Fig. 6(c) for frequencies of 0.2kHz, 0.5kHz, 2kHz, 3kHz and 10kHz. We assume heat flow to takes place entirely in the substrate, neglecting heat diffusion in the platinum coating and a possible thermal resistance between coating and substrate. Figure 8 is the plot of χ^2 as a function of frequency. From the slope of the fit line we obtain a diffusivity of (0.10±0.03) cm^2/s. This value is in good agreement with the values published by the manufacturer (D=0.074 ... 0.098 cm^2/s) for the temperature range 25°C to 500°C and confirms our hypothesis that the decrease in phase is accurately described by Eq. 6.

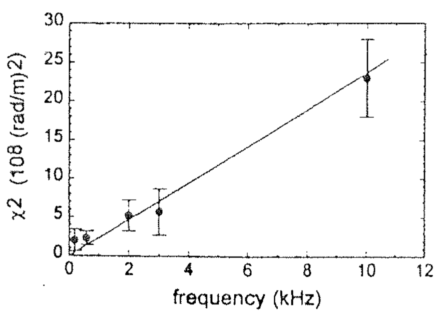

Figure 8

Figure 9 shows a practical example of the photothermal imaging technique to test thermal management in a high-power-transistor used for automotive applications. The left image is a photography of the device, while on the right amplitude and phase of a photothermal scan at 1kHz are shown. As expected the amplitude is highest in the centre of the structure where most of the heat is produced. Interestingly, regions inside the rectangular loops are much less heated than regions between the loops. The amplitude slowly decays towards the outer regions. The gradient present in the phase image reveals that this is not only due to diminished heating but also a result of diffusive heat transfer in vertical direction. The smooth temperature pattern indicates a very good overall thermal management of the structure. High amplitudes are only found at some edges of electrodes.

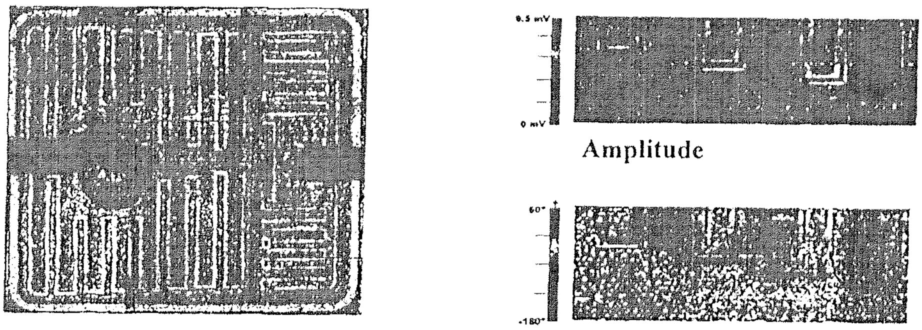

Figure 9

5. CONCLUSIONS

In this work we demonstrated a technique to image electric current densities in conducting microstructures. We visualized the path of the electric current clearly displaying hot spots that produced a signal contrast in both amplitude and phase images. It was shown, that resolution of hot spots is best at frequencies above 10kHz, while diffusion and thermal waves can best be studied at lower frequencies. We imaged thermal waves of plane, cylindrical and spherical shape and correlated the dimensionality of the waves to conducting strip geometry and thermal length. A comparision of amplitudes on conducting strips confirmed that the ratio of thermal length to the extent of the heating surface area is crucial to the dimensionality of heat diffusion. We measured the substrate diffusivity by a simple analysis of the phase profile on a micrometer scale and thereby confirmed the validity of the simple equation describing cylindrical wave propagation. Monitoring the temperature distribution of a high-power-transistor shows the applicability of our setup for the thermal management control of electronic devices.

6. ACKNOWLEDGMENTS

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