Modulated thermoreflectance imaging of hidden electric current distributions in thin-film layered structures

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Thermal imaging of hidden electric current distributions with a resolution of several ten micrometers is demonstrated. It is shown that the thermoreflectance technique is capable of monitoring current-induced temperature variations on as well as beneath the surface of thin layered structures. A temperature pattern was generated by Joule heating using an ac current in a 2.5 μm thick structured gold film that was evaporated on a glass substrate and covered by a TiO_x layer. The current density distribution in the gold film is revealed by the measured photothermal pattern, provided that both laser beam diameter and thermal diffusion length are smaller than the desired lateral resolution.

In recent years photothermal imaging techniques with high spatial resolution[1,2] have been developed for the nondestructive evaluation of a great variety of defects and inhomogeneities in various kinds of materials. In most of these experiments modulated laser light was used to create thermal diffusion waves for imaging the surface as well as buried structures.[3–5] However, in some cases, strong nonthermal components also arise.[6,7] Recently, several techniques have been applied to measure temperature variations induced by Joule heating by ac currents in metals and semiconductors.[8–12] Also, optical refractive index changes arising from electron-hole plasma effects have been used to investigate fast electronic processes in semiconductor devices.[13]

In future, an important application of thermal imaging will be the investigation of current distributions in conducting stripes and hot spots in semiconductor structures or high T_c superconducting films. In addition, the ac current heating technique might be used for the same purpose as conventional techniques, i.e., inspection of material properties such as composition, quality of thermal bonding, change in film thickness, and subsurface defects. Finally, high resolution measurements of current distributions in layered structures versus thin-film thickness could be used to study structure-related and thickness-dependent material properties such as thermal and electric conductivities of thin films.

The sample configuration and the experimental setup used in the experiments reported here are shown in Figs. 1 and 2, respectively. This particular sample configuration was chosen to create a simple current density pattern. The gold film (2.5 μm) on the quartz glass substrate was connected to the ac current source by two small feeding stripes. A current density of about $j = 10^5$ A cm^{-2} in the stripes caused a dc temperature rise of about 80 °C and, due to modulation, a periodic surface temperature variation of about 0.2 °C. The latter acted as the source for the surface change in reflectivity and was detected by a HeNe probe laser beam focused onto the sample and monitored in reflection by a silicon photodetector (see Fig. 2). The

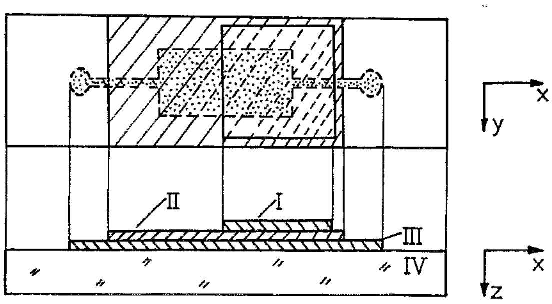

FIG. 1. Sample configuration: 2.5 μm Au film (10×30 mm) with feeding stripes (width 2 mm) [III] on a quartz substrate [IV], covered by a 100 nm TiO_x film [II], in region I half coated with a 10 nm thick Au overlayer enhancing the thermoreflectance signal.

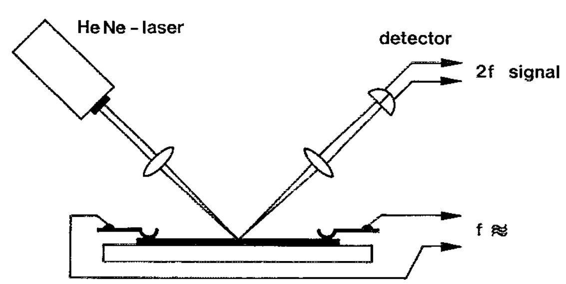

FIG. 2. Experimental setup for thermoreflectance measurements on ac current heated samples.

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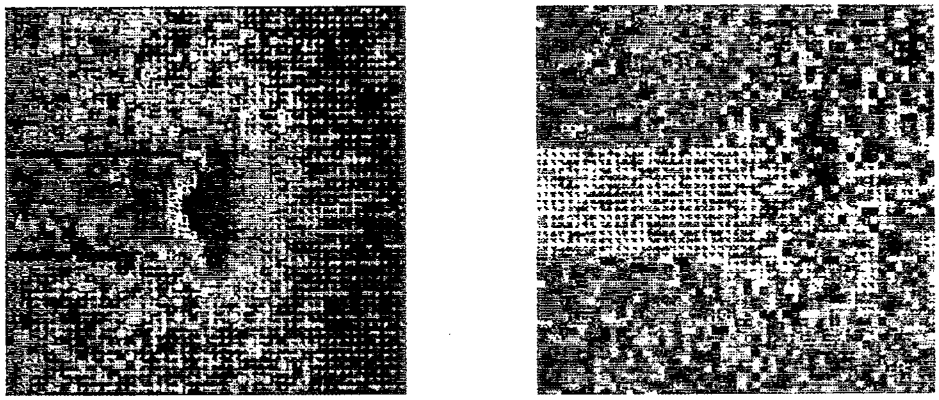

(a) (b)

FIG. 3. Amplitude (a) and phase (b) of the TR image at 17 kHz modulation frequency in the contact region of the hidden Au film on quartz. Color scale: black, blue, red, yellow, green, cyan, white representing range from zero signal to maximum signal in amplitude and $-180°$ to $+180°$ in phase.

thermoreflectance technique (TR) is a well established method in photothermal science; its basic principles are described elsewhere.[14,15] A TiO_x overlayer (100 nm) on top of the conducting metal film guaranteed good electric isolation as well as opaqueness for the hidden thermal structure. In order to improve the sensitivity for TR operation, half of the TiO_x cover film was coated with an additional gold overlayer (10 nm). This thermally thin overlayer had no influence on the thermal image, however, it facilitated a conveniently measurable reflectivity change of $\Delta R/R \approx 10^{-3}$ for 1 K temperature rise at the probe laser wavelength of 632 nm.[15] The photodiode signal was processed by a lock-in amplifier, which operated at twice the current modulation frequency f ranging from 1 to 20 kHz. The sample motion was controlled by an x-y positioning table which allowed 2D scanning of the sample surface with a reproducibility of $\pm 0.1\ \mu$m.

Figure 3 shows false color images of amplitude (a) and phase (b) of the thermoreflectance signal for a 2D scan over 16 mm^2 in the contact region of the sample with the TiO_x-covered conducting gold film as sketched in Fig. 1.

Results for the hidden gold film and for a similar uncovered one, not displayed here, are identical. A constant signal in the narrow feeding stripe is followed by a sharp decrease in amplitude in the transition region to the main rectangular sheet, while the phase is almost constant over the whole measurable area. A constant phase would be expected if the measured photothermal signal would reflect the dissipated power density distribution $p(x,y) = (1/\sigma)\, j(x,y)^2$, unaffected by lateral heat diffusion,[16,17] where σ is the electrical conductivity of the gold film. The observed slight systematic change of phase beyond the feeding stripe [see Fig. 3(b)] is an indication that under the chosen experimental conditions the lateral heat diffusion is not completely negligible. To explain this we recall that the influence of the heat diffusion is governed by the ratio of the thermal diffusion length, $L_{\text{th}} \sim f^{-1/2}$, to the lateral extension of the temperature gradient. Hence, the obtainable lateral resolution in a measurement of the current density with this method depends on the modulation frequency f. In our images a pixel size of about 80 μm $> L_{\text{th}} \simeq 50\ \mu$m was chosen. In principle, the ultimate lateral resolution is not only determined by the thermal broadening, but also by the focal diameter of the probe beam. By using a probe beam waist of 10 μm that is small compared to both the pixel size and the thermal diffusion length no additional blurring is introduced and the image reproduces the predicted current distribution with an accuracy only limited by the 80 μm translation step width. A more quantitative discussion of these findings will be presented in a forthcoming paper[18] where the measured photothermal image will be compared to the calculated current density distribution in the sample. Since it is possible to use the thermoreflectance technique at much higher frequencies[19] the overall resolution of such imaging experiments could be enhanced by improvements of the experimental setup to an ultimate limit of about 1 μm determined by the probe laser beam waist only.

We expect that thermal wave inspection of integrated circuits with the proposed method will be a powerful tool for detecting thermal and electric inhomogeneities. The possibility of using such type of experiments for the absolute calibration of photothermal measurements and in connection with other detection techniques will be discussed in a forthcoming paper.[18]

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