Microscopic lock-in thermography investigation of leakage sites in integrated circuits

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(Received 28 March 2000; accepted for publication 19 June 2000)

The detection limit of infrared thermographic investigations can be improved down to 10 µK by using a highly sensitive high-speed infrared camera in an on-line averaging lock-in thermography system. Together with a microscope objective, this allows lock-in thermography to be used as a simple and sensitive technique to localize the sites of leakage currents and other heat sources in electronic components. The practical realization of a novel lock-in thermography system is described and both test measurements and practical applications are introduced. The detection limit for surface-near local heat sources in silicon is a few microwatts with a spatial resolution down to 5 µm. Leakage sites in several microelectronic structures are imaged and assigned to the layout of the integrated circuit by comparing direct images with lock-in ones. The direct comparison of an averaged and background-subtracted stationary thermogram with a lock-in one, both measured under similar conditions at the same sample, clearly demonstrates the gain in information obtained by using lock-in thermography. © 2000 American Institute of Physics.

I. INTRODUCTION

The localization of defects in integrated circuits is a requirement for an effective and fast failure analysis. Defects caused by some current leakage as, e.g., a gate oxide breakdown and conducting particles in the conducting network, cannot be detected solely by conventional electrical testing. To find leakage sites by electrical testing, focused-ion-beam device modification can be used to separate the complex integrated circuit (IC) structures by cutting them step by step into partial segments. This method, however, is expensive and very time consuming. Light emission microscopy can localize quiescent power-supply currents in complementary metal–oxide–semiconductor (CMOS) circuits, but it does not detect all types of leakage defects. If the leakage current is strong enough to generate a sufficient amount of heat, microscopic thermographic techniques can be used to detect leakage sites. For this purpose liquid crystal techniques and fluorescent microthermal imaging (FMI) have been established. The sensitivity limit of the commercial thermochrome liquid crystal method is, at best, on the order of 0.05 K. The sensitivity of the FMI technique was reported to be 0.01 K, which corresponds to local power sources of about 0.1 mW. Although the theoretical spatial resolution of both techniques is below 1 µm, their practical resolution can be considerably worse, if they are working stationary. As it will be shown below, the lateral heat conductivity of silicon devices leads to a dramatic degradation of the spatial resolution of stationary thermal methods. On the other hand, thermal scanning probe techniques may be more sensitive down to a few mK and may have a submicron spatial resolution. However, their application is usually limited to small areas of only some 10 or 100 µm in size, which often does not allow a heat source to be localized anywhere within a whole IC. Moreover, sensitive thermal scanning probe techniques are time consuming and contacting, which may impede the investigation of ICs. In summary, thermal methods are already established for investigating the reliability of integrated circuits, but their sensitivity, their measurement expense, and their practically available spatial resolution still have to be improved.

In this article, the highly sensitive infrared lock-in thermography is presented as an easy-to-use, reliable, and sensitive noncontacting technique of localizing even weak leakage sites and other local heat sources in ICs and other electronic components. This technique allows leakage currents of about 1 mA to be localized in a testing time of seconds and currents of some µA to be detected after less than 1 h averaging. The following section outlines the basic principles of the lock-in thermography. Besides, our measurement system is described and test measurements demonstrating the detection limit of the system are introduced. The practical potential of this technique is demonstrated by investigating different leakage phenomena in CMOS integrated circuits, followed by some outlook for a wider application of this technique to semiconductor device testing.
II. FUNDAMENTALS OF THE LOCK-IN THERMOGRAPHY

The lock-in thermography has become an established technique of the nondestructive testing of materials and devices. For example, Kuo et al. have used lock-in thermography to detect microcracks in Cu foils deposited on polyimide substrates. Balageas et al. have characterized the spatial distribution of electromagnetic fields by using thin resistive photothermal films and lock-in thermography. Local inhomogeneities of the thermal diffusion properties of construction components due to local delaminations or voids in various depths below the surface can be localized by imaging local differences in the surface temperature modulation caused by the periodic irradiation with light. Lock-in thermography has also been widely used for the investigation of local strains in construction devices by utilizing the thermoelastic effect. The principle of the lock-in thermography consists of introducing periodically modulated heat into an object and monitoring only the periodic surface temperature modulation phase referred to the modulated heat supply. Hence, if the surface temperature is measured via an infrared (IR) thermocamera, lock-in thermography means that the information of each pixel of the image is processed as if it were fed into a lock-in amplifier. Alternatively, lock-in thermography can also be applied as a sequentially measuring scanning probe technique as in the case of dynamic precision contact thermography, which is cheaper but far more time consuming than if a thermocamera is used. Since both the amplitude and the phase of the measured surface temperature modulation can change with the position, a two-phase lock-in detection has to be used. Thus, a lock-in thermography measurement can yield either an amplitude and a phase image, or an in-phase and a quadrature image, referring to the phase of the periodic heat supply. While the amplitude signal is always positive by definition, the in-phase and the quadrature signals can be both positive and negative, depending on the signal phase. For nondestructive testing purposes the phase image is often more informative than that of the amplitude since the latter is more influenced by the local IR emissivity. For detecting local heat sources in electronic devices, however, the amplitude signal is the more informative one, since it is directly related to the locally dissipated power.

The advantage of the lock-in thermography over the stationary thermography is not only of significantly improved sensitivity owing to the ac averaging technique, but also an improved spatial resolution of the images. This spatial resolution is strongly related to the thermal diffusion length, which for silicon is about 1 mm at $f_{\text{lock-in}} = 30$ Hz and reduces with $1/\sqrt{f_{\text{lock-in}}}$. Hence, a good spatial resolution requires $f_{\text{lock-in}}$ to be as high as possible. On the other hand, a high frequency leads to a reduced T-modulation signal owing to the heat capacity of the sample. Hence, microscopic lock-in thermography should be based on a highly sensitive detection system allowing lock-in frequencies as high as possible.

If a thermocamera is used for the lock-in thermography, there are several possibilities of the lock-in correlation. In general, a digital output thermocamera has to be used, and the lock-in correlation proceeds via an attached computer system. At least three different principles have been published for the lock-in correlation of thermograms: the four-point correlation used, e.g., by Busse et al., the digital sine/cos correlation used by Potet, and the fast Fourier transform (FFT) correlation used by Kaminski et al. The FFT correlation is only possible off-line after the measurement, because all images have to be stored to be available at the same time. This limits the possible number of frames involved, and it considerably delays the whole procedure. Hence, from a practical point of view, FFT correlation is not optimum for detecting weak signals. The four-point correlation requires the lowest processing power and can be performed on-line during the measurement. However, it is based on the presence of a harmonic temperature signal. Hence, the power supply should also be harmonic. This is hard to manage, if the heat introduction is performed by applying a bias to an electronic component. Note that the current–voltage ($I$–$V$) characteristic of a leakage current is often highly nonlinear.

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**FIG. 1.** Principle of the sin/cos lock-in correlation procedure. The incoming frames are successively multiplied by two sets of weighting factors and summed up in two frame storages.
Moreover, leakage sites usually have to be tested at a well-defined point of their $I-V$ characteristic. Hence, a constant current has to be switched on and off, yielding a square wave shape of the heat supply. Therefore, the sin/cos correlation, which is sensitive only to the basic harmonic of the signal, seems to be optimum for the lock-in thermography. For a sufficiently high processing power, this correlation can also be performed on-line (during the measurement), not requiring a harmonic heat supply. Figure 1 shows the principle of the sin/cos correlation procedure for the case of 16 frames per lock-in period. The correlation implies two channels. In each channel each pixel value of each incoming frame is multiplied by a weighting factor and added into a frame storage, set to zero before the measurement. During the measurement, the process sketched in Fig. 1 for one period, is repeated over many periods, and respective results are summarized for a certain measure time, as usually done for lock-in measurements. This principle can be used down to four frames per period, where this process becomes equivalent to the four-point correlation procedure.\(^7\) Hence, using the procedure of Fig. 1, the maximum possible lock-in frequency is $1/4$ of the frame rate of the camera. Let the number of frames per lock-in period be $n$, the number of averaged lock-in periods during one measurement $N$, the pixel values of the incoming frames $F_{i,j}(x,y)$, and the weighting factors $K_j$. Then, the correlated signal value $S(x,y)$ (which may be either the in-phase or the quadrature component, depending on the set of weighting factors chosen) is given by the following relation:

$$S(x,y) = \frac{\sqrt{2}}{nN} \sum_{i=1}^{N} \sum_{j=1}^{n} K_j F_{i,j}(x,y).$$  \hspace{1cm} (1)

The weighting factors $K_j$ of one channel (in-phase signal) are the values of the sin function and that of the other channel (quadrature signal) the $-\cos$ function within one period. The $-\cos$ function should be selected instead of the $+\cos$ one in order to have an essentially positive result in this channel, since the temperature modulation is always more or less delayed with respect to the phase of the heat supply. As a result, the first frame storage contains the in-phase ($0^\circ$) image. According to Eq. (1) the result is the effective value of the corresponding phase component. Since there is a perfect balance between positive and negative weighting factors, the static image (topography), which is not affected by the heat supply, is totally canceled out by the correlation procedure. Moreover, the measurement is not affected by temperature drifts of the object or the detection system. This simplifies the procedure essentially with respect to conventional thermography since, as a rule, the sample need not be thermostated. Only if large amounts of heat are supplied, so that the sample temperature may exceed the linearity range of the camera, is thermostating necessary.

III. THE MEASUREMENT SYSTEM

Regarding the requirements mentioned in Sec. II, the aim of this development was to construct a system as sensitive as possible, which allows one to use lock-in frequencies as high as possible. Decisive for using the IR camera is not only its sensitivity, usually given by the noise-equivalent temperature difference (NETD), but also the exposure or integration time $\tau_i$ necessary to reach this NETD, because $\tau_i$ may limit the frame rate $f_r$. Note that for a given NETD, the signal-to-noise ratio for a given measure time is proportional to $\sqrt{\tau}$, since at higher frame rates a larger number of frames is involved in the averaging process. Today’s most sensitive IR cameras are focal-plane array (FPA) cameras based on mercury–cadmium–telluride (MCT) or indium antimonide (InSb) FPAs. The NETD is influenced not only by the FPA material but also by the pitch size (hence the active detecting area). According to Eq. (1) the result is the effective value of the corresponding phase component. Since there is a perfect balance between positive and negative weighting factors, the static image (topography), which is not affected by the heat supply, is totally canceled out by the correlation procedure. Moreover, the measurement is not affected by temperature drifts of the object or the detection system. This simplifies the procedure essentially with respect to conventional thermography since, as a rule, the sample need not be thermostated. Only if large amounts of heat are supplied, so that the sample temperature may exceed the linearity range of the camera, is thermostating necessary.

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range cameras, in general, allow higher frame rates to be applied owing to their lower $\tau_i$. In practice, however, the maximum frame rate of a camera, limited by the read-out circuit of the FPA, can also be used at optimum $\tau_i$ for most mid-range FPAs. Most recent cameras based on quantum well infrared detector FPAs show an even lower NETD than MCT- and InSb-based cameras, but they still need a longer $\tau_i$ on the order of 20 ms, which would limit the frame rate to $<50$ Hz.

Our measurement system is based on the Amber 4128 camera, comprising a LN$_2$-cooled 128×128 pixel InSb FPA running at a frame rate of 217 Hz. Via a digital interface, with an accuracy of 12 bit, the camera controller feeds the data to a frame grabber board. The pixel readout rate is 3.5 million pixels/s. Note that it is necessary to ensure that, during the measurement, each of the frames is implemented in the correlation procedure. Otherwise the symmetry between added and subtracted images would be disturbed and the result would contain residuals of the topography. Moreover, artifacts can be caused by any movement or vibration of the object during a measurement. There are two different possibilities of performing the correlation. Either the processor of the PC performs the correlation, or an “intelligent” frame grabber board with a separate digital signal processor (DSP) is used for the correlation. Then, only the final result is transferred to the PC, and during the measurement the PC is free for other duties. In principle, modern microprocessors allow one to handle even much higher data rates on-line. However, the Windows NT operating system, which is used for this application, is not specialized for time-critical applications so that it is difficult to ensure that not a single frame gets lost during the whole measurement process. In order to simplify the programming of our Windows application, we have decided to perform the correlation on a separate DSP on the frame grabber board. We use the FPG-44 Power Grabber from Dipix Technologies Inc., which contains a 60 MHz floating point processor TMS320C44 and 2 MBit of static random access memory on board. Nevertheless, the processing power of one board was just sufficient to process one of the two correlation channels on-line. Therefore, two of these boards are running in parallel with the same DSP program, but using different sets of weighting factors. Figure 2 shows the schematic of the whole lock-in thermography system. A hard-wired synchronization line between the digital ports of the two frame grabbers ensures that both correlations start with exactly the same incoming frame. Another output port of one of the grabbers is used to release the lock-in reference trigger signal to control the adjustable power supply. The latter is used to modulate the leakage current of the device under investigation. The camera may be equipped with either a normal 25 mm objective or a special two-stage microscope objective, allowing pixel resolutions of $\approx ... 0.23$ mm, depending on the object distance, and 13 $\mu$m, respectively. Via different lens extenders any pixel resolution above 5 $\mu$m can be chosen. These lens extenders, of course, degrade the sensitivity as the acceptance angle of the camera decreases. However, they do not impair a visible degradation of the imaging quality. Using lock-in frequencies above 10 Hz enables the measurement under normal laboratory conditions, with no darkening or shading of the setup. Though some spurious signals caused by some action in the lab might be introduced via the reflectivity of the sample, their frequency spectrum is low enough to be filtered out by the lock-in correlation procedure for $f_{\text{lock-in}} > 10$ Hz.

### IV. TEST RESULTS

The test was performed on a uniformly electrically heated, 5 mm wide and 230 $\mu$m thick Ni stripe. On its back, this stripe was electrically insulated, and its front was covered with a blackened plastic film of 20 $\mu$m thickness. This film provided an IR emissivity of about one and was used to suck the test object on a thermostated vacuum chuck. Prior to the test measurement, the conversion factor of the camera of 3.0 digits/mK was measured. Due to the thermal insulation through the electrically insulated back of the stripe, the measured thermal relaxation time of the mounted test object was of on the order of 1 s. Hence, above a modulation frequency of 1 Hz, the mounting of the test object can be regarded as adiabatic, and the whole volume of the test object is heated homogeneously. For a pulsed heating at a constant power, the expected T-modulation amplitude should be proportional to $1/f_{\text{lock-in}}$, because each heating cycle takes half the lock-in period. Figure 3 shows the measured dependence of the T-modulation amplitude of this test object and of the noise level on the lock-in frequency for the fixed measure time of 16 s. Note that, as expected, from 1 to 20 Hz the signal decreases with $1/f_{\text{lock-in}}$, whereas the noise level is nearly

![Image](image_url)
independent of $f_{\text{lock-in}}$. The slight increase of the noise level at lower frequencies may be due to some $1/f$ contribution to the noise spectrum. The additional drop of the signal amplitude for $f_{\text{lock-in}} > 20$ Hz is due to the thermal insulation and heat capacity of the blackened plastic film. Indeed, using a thicker film has shifted the beginning of the stronger signal drop to lower frequencies. This behavior proves that up to $f_{\text{lock-in}} = 20$ Hz, the vacuum-attached 20 $\mu$m thick blackened plastic film follows the temperature modulation of the surface immediately.

The noise level measured at a frequency of 13.5 Hz as a function of the measure time $t_{\text{meas}}$ is shown in Fig. 4. As had also been recently demonstrated by Potzick,\textsuperscript{14} the noise level of an averaged digital signal decreases with $1/\sqrt{t_{\text{meas}}}$ well below the digitizing resolution, if the noise level before digitizing exceeds 1 least significant bit. After a measure time of 1/2 h (1800 s) the noise level is below 10 $\mu$K (eff). As far as we know this sensitivity is the best of all lock-in thermography systems published hitherto.

V. INVESTIGATION OF LEAKAGE SITES IN ICS

In our first example, we analyze the current through one pad of an integrated circuit, which ought to have a diodelike input characteristic. It should have a negligible current for a bias up to 600 mV, and an exponentially increasing one for higher biases. In the defective sample, however, a parallel resistance of about 10 k$\Omega$ was present, leading to a leakage current of 60 $\mu$A at a bias of 600 mV. At this bias, the power generated by the leakage current should occur solely at the leakage site so that its position should be revealed via the lock-in thermography. Since this conducting network was largely spread in the chip layout, the leakage site could be anywhere in the circuit. Figure 5(a) shows the direct IR image (topogram) of one corner of the bare IC using the microscope objective with a lateral resolution of 13 $\mu$m. This topogram can be easily correlated with the optical microscope image of the IC layout. The infrared contrast is given by the difference of the dark-appearing metallized areas, caused by their high reflectivity corresponding to a low IR emissivity, and the isolating materials with a higher IR emissivity. A lock-in thermogram (amplitude image) of this area, obtained via the same setup, is given in Fig. 5(b), whereas in Fig. 5(c) both images are superimposed. For the lock-in measurement, a lock-in frequency of 13.5 Hz (16 frames per period) and averaging over 30 000 periods was used, making a measure time of 36 min. The lock-in thermogram shows the leakage site as a bright spot within the pixel resolution of 13 $\mu$m.

As a second example, Fig. 6 shows corresponding results of the investigation of a special CMOS test structure. Here, the gates of several CMOS test transistors were connected with one pad. An unusually large gate leakage current was measured. Since all sources of the transistors were switched together and the output characteristics of all transistors were as expected, the electrical investigations could not reveal the leakage site. Again, Figs. 6(a), 6(b), and 6(c) show the topogram, the lock-in amplitude image, and the superposition of both images of the same region with a spatial resolution of 5 $\mu$m achieved by using a 35 mm long lens extender for the microscope objective. Here the leakage current was 1 mA for a bias of 0.6 V. For a lock-in frequency of 54 Hz (four frames per period) the measure time was 10 min. It is obvious that the heating power is generated in the extension of a metallization line within a vertically elongated region.

Finally, two CMOS ICs have been investigated, one of them having an unexpectedly high supply current. These circuits have their own clock generator and show certain CMOS activities. Figure 7 presents the lock-in thermograms (amplitude signal) of an intact IC (a) and of the defective one (b), both measured at 54 Hz for 2 min with the pixel resolution of 50 $\mu$m. It is quite obvious that the defective circuit...
dissipates heat in more additional positions than the intact one does. The strong local additional heat source at the bottom is due to an additional dc power source in the defective CMOS IC. The other extended weak heat sources are caused by some unexpected CMOS activities in these regions. Thus, the lock-in thermography does not only allow one to image leakage sites but also local regions of some CMOS activity, if the clock frequency is high enough. In this respect, IR lock-in thermography may yield information similar to that of light emission microscopy. For comparison, a stationary thermogram of the defective circuit has been taken. In order to improve the signal-to-noise ratio and to compensate the topographic contrast, 4000 frames have been averaged both with and without supply voltage applied to the circuit, which took about 18 s each. The difference between these two averaged images is shown in Fig. 7(c). Here the chip is heated up almost homogeneously, mainly revealing the local differences in the IR emissivity given by the metallization lines of the IC. Comparing Figs. 7(b) and 7(c) proves the enormous gain in information for the investigation of local heat sources in integrated circuits when switching from any kind of stationary thermography to lock-in thermography.

VI. DISCUSSION AND OUTLOOK

The lock-in thermography using a fast FPA thermocamera and the on-line sin/cos lock-in correlation is an easy-to-use, reliable, and sensitive technique of imaging even weak local heat sources in ICs and other electronic devices. For qualitative investigations (local detection of heat sources, as demonstrated in this contribution) this technique needs no special sample preparation. However, covering the sample with an IR-emitting layer may improve the sensitivity and reduce inhomogeneities caused by a nonuniform IR emissivity. The noise level of the detected signal decreases with increasing measure time as $1/\sqrt{t_{\text{meas}}}$. Let us assume a minimum signal-to-noise ratio of 3 for the successful localization of a leakage site. Then, according to the signal-to-noise ratios we measured, the detection limit for an unambiguous localization of a point-like heat source in a silicon IC is given for our setup by the following estimate:

$$P_{\text{min}} = \frac{100 \ \mu W}{\sqrt{t_{\text{meas}}[s]}}.$$  \hspace{1cm} (2)

Hence, after a measure time of 1/2 h (1800 s) a local heat source of $<3 \ \mu W$ is still detectable, and for longer measure times this limit even decreases. Compared to FMI,\(^2\) here the sensitivity improves by a factor of at least 30. Together with the significantly enhanced spatial resolution given by the ac principle, this technique opens a broad field of new applications of thermography, which had not been possible with the earlier thermal methods due to poor sensitivity and resolution.

Of course, owing to the wavelength range of the camera (3–5 μm) the spatial resolution of the lock-in thermography is limited to this range, which prevents leakage sites from being detected in the submicron range. However, the use of the lock-in-thermography for localizing defects in a range smaller than 10 μm has been proven as a helpful tool for failure analysis. The final localization may follow via plausibility considerations, some additional focused-ion-beam device modification,\(^1\) or by applying atomic force microscope-based microthermography.\(^4\)

Meanwhile, the processing power of PCs has been further enhanced. In addition, new thermocameras are commercially available with FPA sizes of 256×256 and above. The knowledge based on the system described has encouraged the development of an advanced commercial system TDL 384 “lock in,” which comprises a linear Stirling-cooled mid-range 384×288 pixel MCT FPA camera with a pixel rate up to 18 MHz and 14 bit resolution.\(^{15}\)

ACKNOWLEDGMENTS

The authors are indebted to K. Iwig (MSC-Technik, Halle) and C. Downing (Dipix Inc., Ottawa) for their active help in programming the DSP code of the frame grabbers. This work has been supported by the German BMBF under Contract No. 0329743B.

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