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Application of lock-in thermography for failure analysis in integrated circuits using quantitative phase shift analysis

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ABSTRACT

Lock-in thermography (LIT), which is a well established technique for non-destructive evaluation, can also be used to identify and locate thermal active electrically defects like shorts and resistive opens in microelectronic devices. Defect localization on the level of the integrated circuits (IC) requires a μm resolution. But LIT can also be applied to locate buried thermal active defects within fully packaged microelectronic devices by analysing the thermal signal detected at the surface of the device. In addition to the lateral localization of the hot spot, its depth can also be determined by analysing the phase shift of the thermal signal. This is especially valued for non destructive defect localization in complex 3D integrated system in package devices (3D SiP). In comparison to competitive thermal imaging techniques, like liquid crystal imaging or fluorescent micro thermal imaging, LIT is easier to apply since it does not need any foreign thermal sensitive layer at the surface of the device. Also, the sensitivity limit of this technique within μK range is significantly better. In addition the dynamic character of LIT reduces thermal blurring, and the problem of inhomogeneous IR emissivity can be overcome by using the phase image or the $0^\circ/-90^\circ$ image. The spatial resolution limit of the used microscopic thermal imaging setup performed in the mid-wavelength range is about 5 μm, but can be improved to 1.5 μm by applying solid immersion lenses. Within the paper, the principle theory of LIT and the practical use for both, single and multiple IC devices is presented.

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1. Introduction

Since many years the complexity of microelectronic devices steadily increases and the dimension and power consumption of their basic elements (transistors etc.) steadily reduces. According to this trend failure analysis (FA) is an increasingly demanding challenge. Defects could be built in as structural weaknesses during device fabrication or could be caused by electrical overstress during operation. The task of FA is to look for root causes of such failures in order to improve fabrication processes and to increase reliability and robustness of the devices. Many of the possible faults in microelectronic devices are connected with local heat dissipation, such as electrical shorts, oxide or junction breakdowns, high resistive opens, latch-ups, and many more. Therefore, besides microscopic techniques light microscopic thermography methods are widely used for localizing such defects within the complex wiring of the device. In the last decades, the most popular micro-thermography methods were liquid crystal (LC) microscopy [1], fluorescent micro thermal imaging (FMI) [2], and steady-state thermal infrared microscopy [3]. The latter method seems to be the most elegant one, since, in contrast to the other methods; it does not need to apply any foreign layer at the surface. However, here the microscopic image is given by the product of IR irradiation (associated to the temperature increase) and emissivity ε, which may be between 0.01 and 1. On reflecting surfaces like metallization ε is below 0.1, but on black surfaces it approaches 1. Correcting this so-called emissivity contrast is possible, but experimentally demanding and time-consuming [3]. The temperature resolution of all these previous thermography techniques is in the order of 0.1 K. However, many faults are leading to very small temperature signals in the order of 1 mK or less. Therefore, steady-state thermography techniques were only able to detect relatively strong heat sources above the threshold of 100 mK. Moreover, in the investigated device the heat naturally tends to spread away laterally. This leads to a very blurred appearance of thermal images, even if the heat sources are very local. Especially for the application of defect localization at microelectronic devices, the resulting spatial resolution of micro-thermography is often not sufficient. There are

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a number of laser-based thermographic techniques like internal infrared laser deflection or transmission Fabry–Perot interference thermometry [4,5]. Since these techniques are sequentially scanning and require a quite complex setup, they have not become popular in thermal failure analysis yet.

Lock-in thermography (LIT) works on the principle that heat sources are periodically intensity-modulated at a certain lock-in frequency and that only the local temperature modulation is evaluated according to the lock-in principle and averaged over many lock-in periods [6]. Since the last decade, LIT is used systematically for FA on ICs [7]. Due to the dynamic nature of LIT, the lateral heat diffusion is widely suppressed, hence the effective spatial resolution is improved. Due to the averaging nature of LIT, after a certain acquisition time (typically some minutes), tiny temperature modulations in the order of 0.1 mK can be detected. This has lead to a strong expansion of the application field of thermal analysis in microelectronic FA. Since LIT two-channel lock-in correlation is used, the phase image can be displayed where the emissivity contrast is inherently compensated. This phase information can be further used for investigating the device internal heat propagation. Although the direct optical access to the defective area is blocked by opaque material layers, heat can propagate through these layers resulting in a local temperature variation at the device surface. This propagation process is time-depending and in consequence creates a phase shift between excitation signal and detected thermal response. Knowing the internal structure and the thermal properties of the device under test, the quantitative phase shift determination can be used for defect depth allocations. This information in combination with lateral defect localization enables non destructive defect localization within all three dimensions. This approach was successfully demonstrated on test samples in [8] and real devices [9]. Furthermore, previous works have treated theoretically such kind of measurements in ICs [10].

More recently, CCD-based thermoreflectance microscopy has appeared as another useful microthermal inspection method [11]. Here the property of any reflection coefficient to depend on temperature is used. Like LIT, this method is working in lock-in mode, leading to an improved sensitivity and spatial resolution. Due to the lower wavelength used for imaging, its spatial resolution is superior to LIT. However, due to the low temperature coefficients of the reflection (in the order of 10^{-4}/K) the detection limit of thermoreflectance microscopy is well below that of LIT.

2. Theory of heat propagation

LIT bases on the principle theory of thermal wave propagation which are generated as a cause of a harmonic temperature excitation [12]. Therefore, heat propagation through an opaque layer is depending on the angular stimulation frequency, distance of the buried defect to the surface and the thermal parameters of the propagated material layers. Considering a semi-infinite body of the thickness z which surface temperature is a harmonic signal function with the angular frequency ω, the resulting temperature signal can be regarded and calculated as a “thermal wave” by the expression:

$$T(z) = A \cdot \sin(\omega t - \varphi) \tag{1}$$

with A as the amplitude:

$$T_{z=0} \cdot e^{-z/\mu} \tag{2}$$

and φ representing the phase of the wave:

$$\varphi = \frac{z}{\mu} = \frac{z}{\sqrt{2a/\omega}} \tag{3}$$

The parameter which describes the influence of the thermal properties of a material layer is named as thermal diffusion length (μ) and

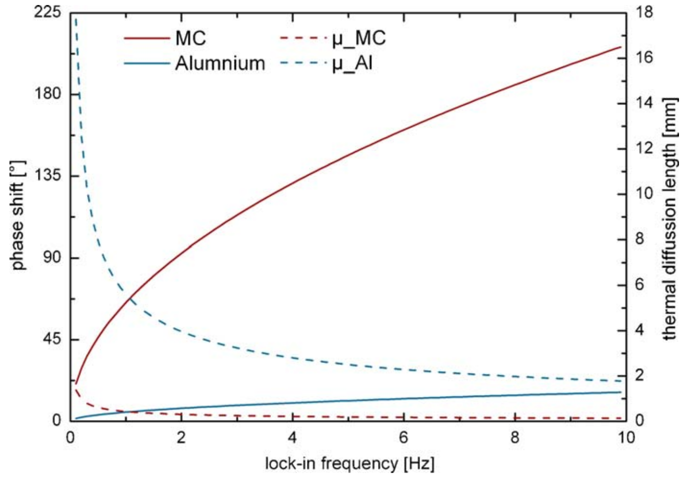

Fig. 1. Phase shift vs. frequency relationship for buried defects under an opaque layer of aluminium (blue) and MC (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

defines the damping of the thermal wave inside of a bulk material. It can be calculated by knowing heat conductivity (λ in W/m K), specific heat capacity (c_p in J/g K), density (ρ in g/cm^3) and the applied lock-in frequency ($f_{\text{lock-in}}$ in Hz). The thermal parameters of the material can be summarized as the thermal diffusivity (a in mm^2/s):

$$a = \frac{\lambda}{c_p \cdot \rho} \tag{4}$$

Investigating buried heat sources in opaque materials, the thermal diffusion length can be seen as the damping factor to the thermal wave which affects both amplitude and phase signal. Higher lock-in frequencies results in a stronger delay between excitation signal at the defect position and the thermal response at the device surface. Therefore, an increase of the phase shift as a function of the increased lock-in frequency can be regarded. Fig. 1 shows the resulting phase shift vs. frequency relationship for assumed buried defects under 500 μm mould compound and aluminium layer. Both materials are considered as opaque.

The fact that the resulting phase shift depends on both thermal diffusion length and geometrical thickness can be used for a “fingerprint” determination of hot spots depths within multi-layer devices, Fig. 2.

Depending on the defect depth, heat has to propagate through different numbers of material layers before reaching the device surface. Each opaque layer contributes a discrete value to the overall phase shift. Hence, knowing these values buried defects can be located within the layer stack by measuring the overall phase shift. Knowing the thermal behaviour of each layer the phase shifts contributions can be calculated. Alternatively the phase shift values can be experimentally determined at reference devices by removing each layer step by step and measuring the corresponding phase shift for the residual layer stack. As an example, stacked die devices

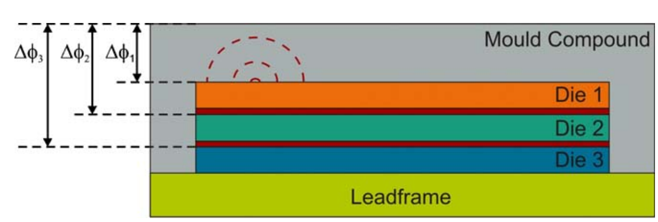

Fig. 2. Simplified sketch of a stacked die device and illustration of the resulting phase shift values per defect depths.

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