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Fluorescent Microthermal Imaging - Theory and Methodology for Achieving High Thermal Resolution Images

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The fluorescent microthermal imaging technique (FMI) involves coating a sample surface with an inorganic-based thin film that, upon exposure to UV light, emits temperature-dependent fluorescence [1-8]. FMI offers the ability to create thermal maps of integrated circuits with a thermal resolution theoretically limited to 1 m°C and a spatial resolution which is diffraction-limited to 0.3 μm . Even though the fluorescent microthermal imaging (FMI) technique has been around for more than a decade, many factors that can significantly affect the thermal image quality have not been systematically studied and characterized. After a brief review of FMI theory, we will present our recent results demonstrating for the first time three important factors that have a dramatic impact on the thermal quality and sensitivity of FMI. First, the limitations imparted by photon shot noise and improvement in the signal-to-noise ratio realized through signal averaging will be discussed. Second, ultraviolet bleaching, an unavoidable problem with FMI as it currently is performed, will be characterized to identify ways to minimize its effect. Finally, the impact of film dilution on thermal sensitivity will be discussed.

1. FLUORESCENT MICROTHERMAL IMAGING THEORY

To better understand the theory behind FMI, we need to discuss the process which gives the fluorescing film a temperature dependent fluorescent quantum yield. Figure 1 shows the molar excitation coefficient (or loosely, the absorption spectra) versus wavelength for europium thenoyltrifluoroacetate (EuTTA) in an ethanol solution. There are several characteristics associated with absorption spectrum of EuTTA. First, there is a broad absorption peak centered around 335 nm where the TTA ligand absorbs energy. Second, the amount of incident radiation that is absorbed falls off strongly after about 360 nm. The two peaks at 460 nm and 525 nm are consistent with Eu^{3+} absorption levels. Third, there is a lack of absorption for wavelengths much above 500 nm.

The UV radiation used to excite the EuTTA fluorescence does so through an intermolecular energy transfer. The TTA ligand absorbs the UV light then transfers the energy to the europium ion. While several fluorescent lines are excited, the transition from the Eu^{3+} $^5\text{D}_0$ energy level to the $^7\text{F}_2$ level is the most efficient. This transition generates a

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bright fluorescent line at 612 nm which is used for FMI. Figure 2 shows the emission spectrum for crystalline EuTTA at 25 °C.

For thermal imaging applications, we need to know how the emission spectra changes with temperature. Figure 3 shows the measured absolute quantum yield versus temperature and figure 4 shows the decay time of the fluorescent yield versus temperature. Both of these plots were generated for EuTTA in an ether:iso- pentane:ethanol (5:5:2) solution. For the FMI application, a curve will need to be generated for each compound mixture that is used. These data have been included to illustrate the temperature dependence of EuTTA.

The temperature-dependent quantum efficiency ($Q(T)$) of the EuTTA compound in figure 3 can be fit to an equation of the form,

$$Q(T) = A + B e^{-\alpha T}. \quad (1)$$

Monitoring changes in the quantum yield provides a simple way of imaging the temperature of an object.

The standard FMI technique for EuTTA is to incorporate the chelate into a PMMA (polymethyl- methacrylate) matrix. A typical base-mixture solution consists of 1.2 wt% EuTTA, 1.8 wt% PMMA, and 97 wt% MEK (methylethylketone). The MEK is a very high vapor pressure solvent that evaporates rapidly leaving the EuTTA/PMMA mixture on the sample [1]. Typically this mixture is spun on the sample and allowed to cure in an oven at 125 °C for about 30 minutes. Ideally, the film should be only several optical absorption lengths thick. At an excitation wavelength of 365 nm, a 300 nm film is approximately 3.5 optical absorption lengths thick. The concept is to have the film thick enough that most of the UV light is absorbed, but thin enough that the thermal profile of the sample surface is not distorted. The film should be as uniform as possible, but great pains to achieve perfect uniformity of film composition and thickness are not necessary. The advantage of using EuTTA/PMMA-based mixture is that it can easily removed once the thermal analysis is completed. Rinsing the sample in acetone will dissolve the film in several minutes.

Now that we have an understanding of the fluorescent film properties which allow us to use this technique to generate thermal images, we need to cover how that information is converted to temperature data. The light intensity at a given point, (x,y) , on the image can be represented by

$$S(x,y) = I(x,y) \cdot \eta(x,y) \cdot r(x,y) \cdot Q(T(x,y)) \quad (2)$$

where $I(x,y)$ is the illumination intensity, $\eta(x,y)$ is the optical collection efficiency, $r(x,y)$ is the sample reflectivity, and $Q(T(x,y))$ is the quantum efficiency. Assuming that there are no variations in $I(x,y)$, $\eta(x,y)$ and $r(x,y)$ during the measurements, dividing an image taken with the sample without bias, i.e. a cold image, by one under bias, i.e. a hot image gives the ratio of quantum efficiencies between the cold and hot images

$$S_R(x,y) = \frac{S_C(x,y)}{S_H(x,y)} = \frac{I(x,y) \cdot \eta(x,y) \cdot r(x,y) \cdot Q(T_C(x,y))}{I(x,y) \cdot \eta(x,y) \cdot r(x,y) \cdot Q(T_H(x,y))} = \frac{Q(T_C(x,y))}{Q(T_H(x,y))}. \quad (3)$$

The expression of the quantum efficiency ratio can be greatly simplified at the expense of a slight loss in accuracy for temperature determination if we ignore the leading constant in the expression of $Q(T)$ which makes the natural logarithm of the quantum efficiency ratio proportional to the change in temperature. The proportionality constant, α , is determined experimentally for a given film composition and can be used to calculate a relative temperature change at a given pixel location.

$$\delta T \approx \alpha^{-1} \cdot \ln \left[\frac{Q(T_C)}{Q(T_H)} \right] = \alpha^{-1} \cdot \ln \left[\frac{S_C(x,y)}{S_H(x,y)} \right]. \quad (4)$$

Figure 1 - Absorption spectrum for EuTTA (in solution) [3]

Figure 2 - Emission spectrum of EuTTA (Crystalline) at 25 °C [3]

Figure 3 - Absolute quantum yield for EuTTA as a function of temperature [4].

Figure 4 - Fluorescence decay time for EuTTA as a function of temperature [4].

In FMI, a thermal image is generated either by dividing a cold image by a hot image (*cold/hot* configuration) or vice versa (*hot/cold* configuration). Using the *cold/hot* configuration, hot areas in the resulting thermal image appear bright whereas they appear dark in the *hot/cold* configuration. In this paper, all the thermal images were generated by the *cold/hot* configuration.

Implementation of the FMI technique is very straightforward. The main system requirements are a UV light source, a camera system, and an optical platform. The most common light sources used in FMI are Hg or Hg(Xe) arc lamps that have strong output in the 365-400 nm range. Lasers can also be used as excitation sources. Most FMI systems use slow-scan CCD cameras that are designed for quantitative imaging applications. A standard

metallographic microscope generally can be used as an optical platform with a few modifications to house the UV source and the camera. The diagram in figure 5 shows an example of an FMI system that uses a Hg arc lamp with oblique illumination where the UV source does not go through the internal optics of the optical microscope.

Figure 5 - Implementation of FMI Using a Hg Arc Lamp and Oblique Illumination

2. PHOTON SHOT NOISE AND SIGNAL AVERAGING

In absence of all other noise sources, the signal-to-noise ratio in high photon flux imaging applications is limited by photon shot noise. The statistics describing photon shot noise follows a Poisson distribution. From elementary probability and statistics, a random variable, x , is said to have a Poisson distribution if the probability mass function is

$$p(x; \lambda) = \frac{e^{-\lambda} \lambda^x}{x!} \quad (5)$$

for some $\lambda > 0$. The variable, λ , is frequently a rate per unit time per unit area. In order to obtain any meaningful thermal information, it is crucial that we can separate the thermal signals from the photon shot noise. Figures 6 and 7 are shown to illustrate this point. Figure 6 shows a histogram of pixel intensity for a FMI thermal image of an unbiased, metal test structure coated with a base-mixture film. The image was taken at a magnification where the test structure did not fill the field of view, thus including a background area as well as a hot region as would be found in most applications. Since no current runs through the metal test structure, the histogram in figure 6 contains no thermal information which means that the peak observed is mostly due to photon shot noise. As expected, the histogram shows a relatively good fit to the Poisson distribution, except on the right-hand side of the curve. The slight deviation is the result of ultraviolet bleaching that will be subject of discussion in the next section. Figure 7 shows a series of histograms of FMI thermal images for the same test structure biased at currents of 0 mA, 35 mA and 50 mA, respectively. In both the 35 mA and 50 mA histograms, an extra peak on the right hand side of the Poisson peak was observed. This peak contains thermal information associated with the heating of the metal test structure. As expected, this peak becomes more pronounced as the current in the test structure increases.

Another interesting feature in figure 7 is the shift in the Poisson-peak position as the current increases. We attribute this shift to the increase in the background temperature

surrounding the test structure. We can easily convert the position shift to the relative increase in temperature using equation (4), with the slope (α) for the base-mixture film being obtained experimentally (see the section on the film dilution). For the histograms in figure 7, a background temperature increases of 0.6 °C and 0.9 °C are calculated from the 35 mA and 50 mA histograms, respectively. As expected, the relative increase in background temperature varies linearly with respect to the input power of the test structure (figure 8).

Since photon shot noise is due to the quantum nature of light, there is no way to eliminate it totally; however, it is possible to reduce its effects through signal averaging. Figure 9 shows histograms of a single cold/hot image pair and of an average of ten pairs. The Poisson peak from the averaged image shows a narrower width than the single image one, while there is virtually no change between the two thermal peaks. Figure 10 shows a comparison of the two corresponding FMI images. Both of the images were made with a current of 50 mA flowing through the metal test structure during the hot image exposure and a five second per frame exposure time on a UV-stabilized film. The image made from a single cold/hot image pair shows a grainy texture away from the test structure while the averaged image has a very smooth appearance. Clearly, signal averaging has improved the signal to noise of the FMI image by reducing the photon shot noise.

Figure 6 - Histogram of an FMI image of an unbiased test structure and its Poisson fit.

Figure 7 -Histograms of FMI images for a test structure biased at various currents.

Figure 8 - Change in background temperature calculated from the Poisson peak shift in and an Figure 7.

Figure 9 - A comparison of FMI image histograms of a single image pair average of ten pairs.

Figure 10 - A comparison of thermal images made with single cold/hot image pair (left) and an average of ten pairs (right).

3. EFFECTS OF ULTRAVIOLET BLEACHING ON THE QUALITY OF FMI IMAGES

Inorganic-based films such as EuTTA are known to gradually lose their ability to fluoresce under UV illumination leading to decreasing fluorescent intensity with increasing UV exposure time. This gradual loss in fluorescent intensity is known as bleaching. Since bleaching is unavoidable in EuTTA films, we must characterize its behavior to identify methods to minimize its effect. Figure 11 shows the bleaching behavior of three EuTTA/PMMA films of various dilutions to continuous exposure to UV light. In all three films, fluorescent intensity decays rapidly initially and stabilizes after approximately 20 minutes of UV exposure. The diluted films, however, show a larger decrease in intensity before stabilization than the base mixture film.

In FMI, a thermal image is generated either by dividing a cold image by a hot image or vice versa. Ideally, the fluorescence intensity in the hot and cold images should be identical in areas where no temperature changes occur. With bleaching, this ideal condition is not possible, resulting in the generation of unwanted non-thermal signals, the so-called spatial artifacts. To this process, a series of FMI images were taken after 20 seconds, 10 minutes and 20 minutes of UV exposure of an unbiased test structure coated with a base mixture film. The histograms of these images are shown in figure 12. It is clear from figure 12 that bleaching causes a shift in the position of the Poisson peak which has the apparent effect of changing the background temperature as was previously described. The maximum shift in this example occurs between the 20 second exposure and 10 minute exposure histograms, giving an apparent change in temperature of 0.60 °C. The *apparent* thermal signals caused by bleaching manifest themselves as spatial artifacts the thermal images..

To demonstrate this effect when thermal information is also present, the same structure was biased with a current of 50 mA and the experiment was repeated. Figure 13 shows a series of FMI thermal images taken after the same UV exposure times used in figure 12. The images show that the spatial features are very pronounced in the left image (taken after 20

seconds of UV exposure) due to the rapid initial decrease in fluorescent intensity and less noticeable in the right image (after 20 minutes of exposure) after the fluorescent intensity had stabilized.

Figure 11 - Changes in fluorescent yield versus UV exposure for three different mixture dilutions.

Figure 12 - Histograms of FMI images of an unbiased test structure after various bleaching times.

Figure 13 - Fluorescent microthermal images illustrating the reduction in spatial features after UV film stabilization (left to right: $t = 20$ sec, $t = 600$ sec, $t = 1200$ sec).

4. EFFECTS OF FILM DILUTION ON THERMAL SENSITIVITY

In many situations it is impractical to spin the EuTTA/PMMA mixture onto packaged integrated circuits. For these applications, a thinned mixture is typically applied without spinning. Until now, it has always been assumed that the dilution of the mixture has no effect on the logarithmic slope and hence the sensitivity of the film. In order to examine this effect, three film dilutions were characterized. The base mixture, a 20:1 dilution with MEK, and a 50:1 dilution with MEK were applied to several slices of scrap silicon. The change in fluorescent yield above room temperature was measured by heating the coated wafers with a hot stage. Figure 14 shows the results of this experiment. Based on equation (4), the slopes (α) extracted from the curves in figure 14 were calculated to be 0.0245, 0.015 and 0.008 for base-mixture, 20:1 mixture and 50:1 mixture films, respectively. This data shows that α is not independent of film dilution as has usually been assumed.

Figure 15 illustrates the effect of a change in logarithmic slope on thermal image quality. The image on the left was made with a current of 50 mA using a base mixture film after twenty minutes of UV exposure while the image on the right was made with a 20-minute bleached 20:1 film at the same 50 mA current. To ensure all images have the same signal-to-noise ratio (i.e., the same amount of photons are collected), the exposure time for the right image is increased by a factor of 10 over the left image. It is clear from figure 15 that the FMI image of the base-mixture film is far superior to that of the 20: 1 film with stronger thermal signals due to larger value of slope (α). In addition, the spatial artifacts are much less pronounced in the image made from the base-mixture film.

Figure 14- Temperature dependence of the natural log of the quantum efficiency ratio for several film dilutions.

Figure 15- FMI Images of a test structure (biased at a current of 50 mA) using a base-mixture film (left) and 20:1 film (right).

5. CONCLUSIONS

In this paper we have systematically studied three key factors that have a significant impact on the FMI thermal image quality and sensitivity. These factors include photon shot noise, ultra-violet bleaching, and film dilution. We have demonstrated for the first time how each factor affects the FMI thermal image quality. We have also shown how proper film

preparation and data collection method can dramatically improve the quality of FMI thermal images.

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