EDFAAO (2019) 1:20-25 1537-0755/$19.00 ©ASM International®

ENSURING ADVANCED SEMICONDUCTOR DEVICE RELIABILITY USING FA AND SUBMICRON DEFECT DETECTION

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INTRODUCTION

Recent industry trends are placing increased requirements on the need to fully understand the thermal behavior of today's advanced semiconductor devices to ensure long-term reliability. Due to the critical nature of applications such as 5G, automotive electronics, artificial intelligence (AI), cloud storage, and military electronic systems, they all demand higher performance while simultaneously placing increased requirements on long-term reliability. Device developments that achieve higher power levels and faster switching speeds with increased functionality are driving device features to submicron levels and increasing complexity. The resulting power densities and potential for higher operating temperatures, localized hot spots, and unanticipated time-dependent thermal anomalies are compounding the challenges of ensuring adequate reliability.

Temperature has a direct impact on device mean-time-to-failure (MTTF). This can be assessed with the Arrhenius equation:

$$\mathrm{MTTF} = Ce^{-E_a/kT} \qquad \text{(Eq 1)}$$

where E_a is the activation energy, k is the Boltzmann constant and T is the absolute temperature.

Figure 1, plotted for an activation energy of 1.84 eV, shows the relationship between temperature and projected MTTF for a typical advanced electronic device. In this case, a 20 degree increase in junction temperature lowers the projected MTTF by an order of magnitude. The higher power densities resulting from shrinking geometries in today's advanced device structures can easily lead to such temperature increases. The key requirement with these devices is the ability to analyze thermal behavior on a scale consistent with their submicron geometries.

While traditional thermal analysis techniques such as IR thermography and µ-Raman spectroscopy have been widely used for years, these techniques fall short due to resolution limitations incompatible with today's advanced devices.[1,2] Relying on traditional thermal analysis techniques risks the possibility of missing important thermal anomalies or small defects that could lead to early device failure.

This article describes a noninvasive thermal imaging approach based on the thermoreflectance principle. This technique can meet the spatial resolution requirements for advanced devices while also providing temporal resolution in the nanosecond range for analyzing time-dependent thermal events.

THERMOREFLECTANCE-BASED THERMAL IMAGING

As the temperature of a material changes, the

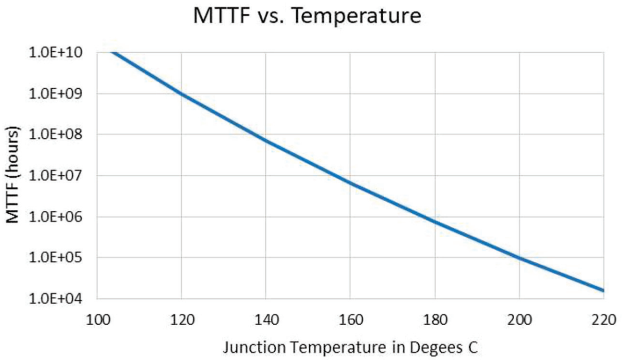


Fig. 1 **MTTF versus device temperature, plotted for an activation energy of 1.84 eV.**

refractive index and therefore the reflectivity of the material also changes. Thermoreflectance thermal imaging (TTI) depends on an accurate measurement of the relative change in surface reflectivity as a function of the material's temperature.[3,4] The change in reflectivity is dependent on the thermoreflectance coefficient, a basic material property that is a function of the illumination wavelength, the material and its surface characteristics, and the ambient temperature. Fortunately, the thermoreflectance coefficient, C_{th}, can be considered constant for the range of pertinent ambient temperatures. The basic concept is shown in Fig. 2. The device under test (DUT) is illuminated with an LED at a wavelength in the visible range and the reflected signal is captured by the CCD camera. Longer wavelengths in the near infrared range are used for through-the-substrate thermal imaging.

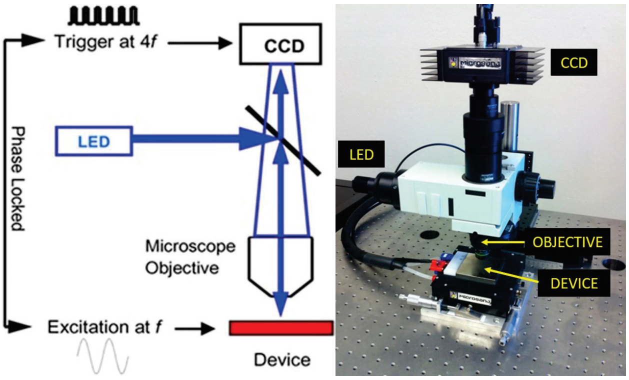


Fig. 2 **Key components comprising the microscopy head with thermoreflectance thermal imaging: An Si CCD camera is used for illumination wavelengths in the visible range and an InGaAs CCD is used for wavelengths in the near-IR range.**

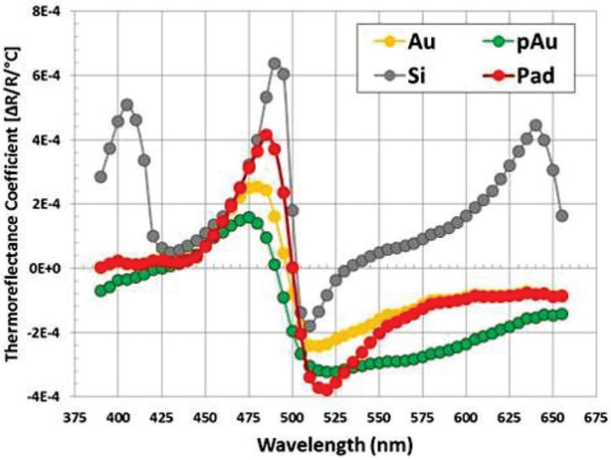


Fig. 3 **Thermoreflectance coefficient vs. wavelength for various materials typically encountered with semiconductor devices.**

A first-order relationship between the normalized change in illumination reflectivity and the change in material temperature can be approximated as:

$$\frac{\Delta R(x,y,\lambda)}{R(x,y,\lambda)} = C_{th}(x,y,\lambda)\Delta T \tag{Eq 2}$$

where C_{th} is the thermoreflectance coefficient and ΔT is the temperature change of the material.

As shown in Fig. 3, C_{th} is quite small—in the order of 10^{-6} to 10^{-3}—for materials typically encountered with semiconductor devices. Therefore, a lock-in technique is employed to enhance the signal-to-noise ratio (SNR). With time averaging and pixel-by-pixel calibration over the region of interest, <0.1°C temperature resolution can be achieved.

With illumination wavelengths in the 400 to 900 nm range, TTI can achieve submicron spatial resolution—as predicted by the Abbe diffraction limit—to meet the imaging requirements of today's advanced devices. In contrast, traditional infrared imaging based on blackbody radiation measures emissions in the infrared range with a resolution of 3 to 5 µm.

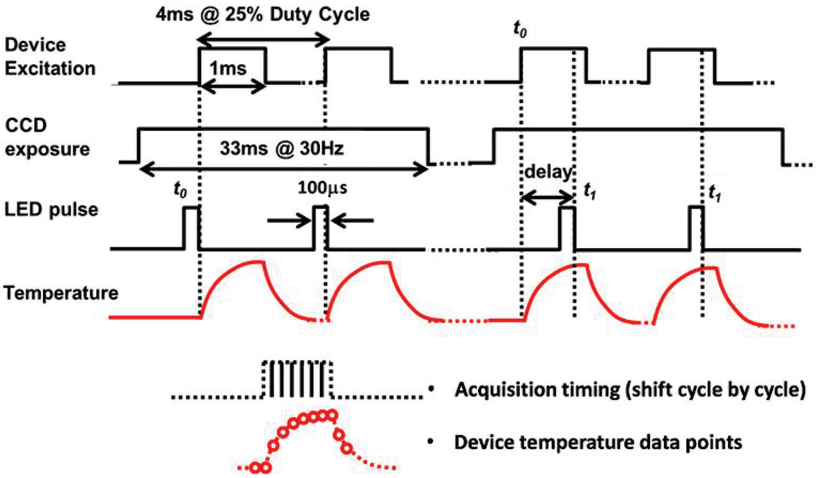


Fig. 4 **Timing diagram shows how time-dependent thermal data is collected. By pulsing the device excitation with a low duty cycle and the LED illumination at a controlled rate and relative time delay, the device temperature is allowed to reach a maximum level and subsequently return to ambient level between device excitation pulses.**

TRANSIENT THERMAL ANALYSIS

In addition to gathering information about time-dependent thermal events, transient thermal analysis can provide the information required to fully evaluate the total heat conduction path in a typical device assembly.[5] The plot in Fig. 5 is derived from the time-dependent thermal analysis after application of a bias to the device. A finite time is required for heat to travel from the device to each of the subsequent layers in the structure and reach steady state approximately 10 seconds after the applied bias. In this example, the chip attach and heat spreader attach are thin, thus enabling rapid heat transfer between layers. However, they each contribute about 1.0° and 0.3°C/W, respectively, to the total thermal impedance of 2.52°C/W. This type of analysis clearly shows the contributions of each element in the heat conduction path.

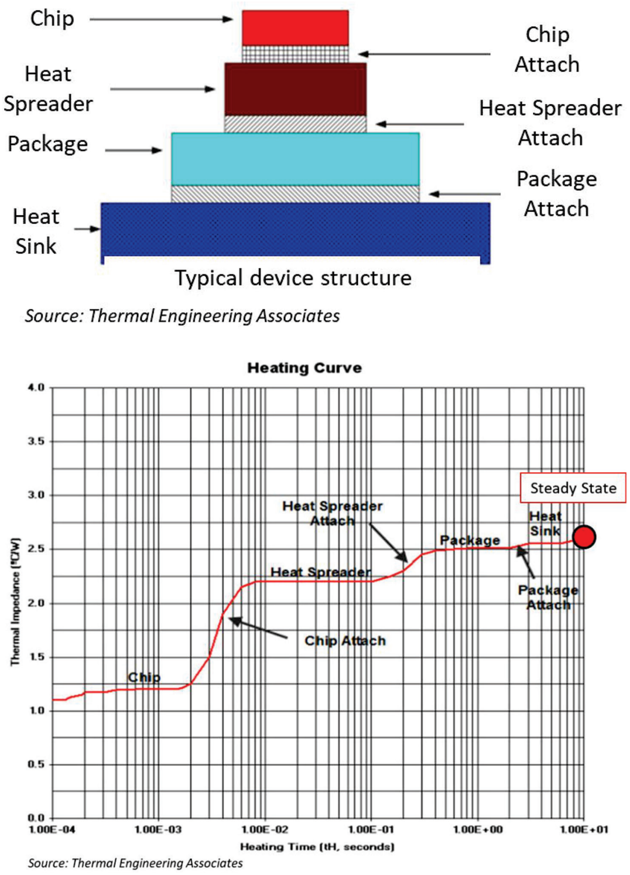
TTI SYSTEM CONFIGURATION

A complete thermoreflectance-based thermal imaging (TTI) system is shown in Fig. 6. Major components include a transient imaging module (TIM), signal generator, and controller. The TIM drives the CCD camera exposure, bias signal for the DUT, and timing signal to the signal generator to sync the LED illumination. These components are interconnected via a GPIB bus to the controller, which coordinates overall system management by means of the embedded SW modules—SanjVIEW for system management and SanjANALYZER for DUT data acquisition and analysis.

The 4-megapixel Si CCD camera used in this system is optimum for illumination wavelengths from 400 to 800 nm and usable from 365 to 1060 nm. Shorter wavelengths in this range support spatial resolution of less than 250 nm.

The configuration shown also includes a temperature controller for a thermal stage, which can be useful for calibration purposes, and an antivibration table.

The key to achieving long-term reliability and maximizing MTTF is the ability to identify defects that may lead to a hot spot and thus to an early device failure. As shown in



Source: Thermal Engineering Associates

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Fig. 5 **The structure being analyzed (a) is shown above the heating curve (b). The x axis in the heating curve shows elapsed time from the beginning of the applied step bias pulse. From this plot, thermal impedance of the various layers in the heat flow path can be quantified.**

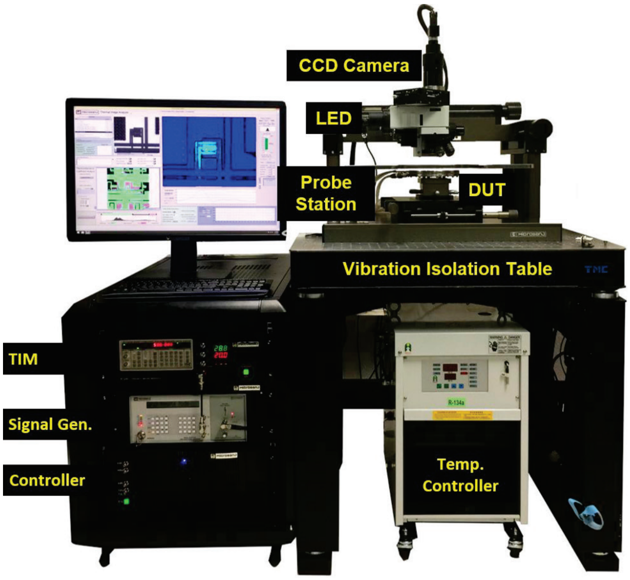


Fig. 6 **Microsanj NT220 imaging system with optional accessories: probe station, thermal stage, and vibration isolation table. Spatial, temporal, and temperature resolution are 245 nm, 20 ns, and 0.1°C, respectively.**

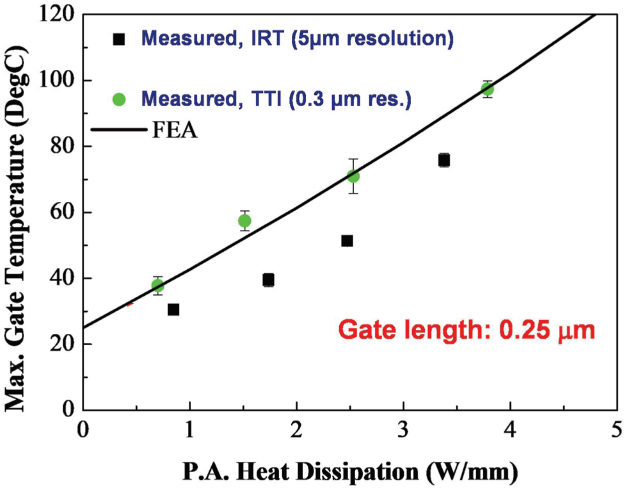


Fig. 7 **Comparison of MMIC gate temperatures measured using IRT and TTI, with gate tempertures calculated using finite element analysis.**

Fig. 1, a 10 to 20 degree hot spot could decrease MTTF by as much as two to 10 times.

EXAMPLES: APPLICATIONS AND BENEFITS

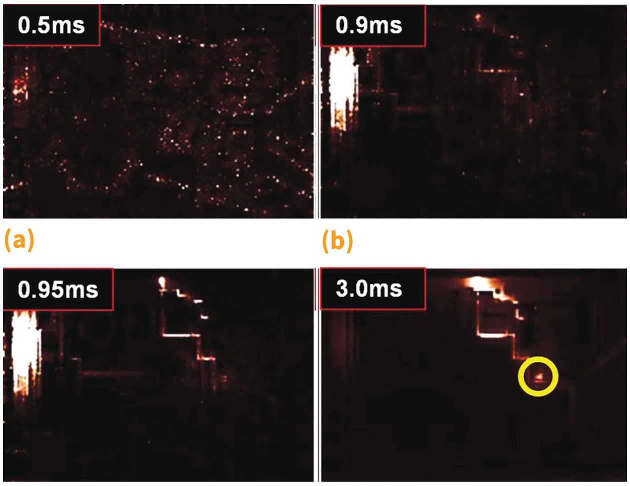
The following examples help illustrate the applications and benefits of TTI for evaluating the thermal behavior of devices.

MMIC POWER AMPLIFIER

The gate temperature of a two-gate MMIC power amplifier was measured using IR thermography (IRT) and TTI.[2] The gate temperature was also calculated using finite element analysis (FEA) and compared with the measured temperatures in Fig. 7. As shown, the agreement between TTI and FEA is much better than between IRT and FEA. The main reason for this discrepancy is the grossly inadequate spatial resolution of IRT (5 µm) for the gate size of the MMIC device of 0.25 µm, whereas the spatial resolution of TTI at 0.3 µm was much better. Another important factor was that the emissivity of the gate surface was very low at about 0.3, which makes IRT less accurate. However, this low emissivity implies high reflectivity, which is ideal for TTI.

LOGIC INTEGRATED CIRCUIT

The following example demonstrates the transient analysis capability with a high speed logic IC.[6] The chip measures 1.6 x 1.1 mm and is 500 mm thick. Figure 8 shows the resulting thermal intensity map at four different time intervals from 0.5 to 3.0 ms after the chip is powered on. The image in Fig. 8a shows the left side of the chip heating almost immediately following the applied bias and reaching a peak at about 0.9 ms, as shown in Fig. 8b. At 0.95 ms, Fig. 8c, another region in the upper central portion of the chip, starts dissipating power. At 3.0 ms, Fig. 8d, the left side of the chip has cooled down and a hot spot is noted in the right central portion of the chip.



(a) (b)

(c) (d)

Fig. 8 **Time sequence of thermal image of logic IC at: (a) 0.5 ms, (b) 0.9 ms, (c) 0.95 ms, and (d) 3.0 ms.**

Based on the device circuit design, the initial heating shown at 0.5 ms on the left side of the device was an anticipated event. The heating at 3.0 ms, however, was not anticipated and is related to a latch-up failure, indicated by the circle on the temperature plot shown in Fig. 8d.

These time-dependent thermal events would not have been detected without transient thermal analysis. Once discovered, it is the circuit designer's role to determine what these events indicate; some may not have an impact on device performance or device reliability, while others may lead to early catastrophic failure.

MULTI-FINGER MOSFET

In this example[7], a small gate defect in a silicon multi-finger MOSFET illustrates the spatial resolution of the thermoreflectance technique in the detection of a hot spot. The LED illumination wavelength for this example is 470 nm. Figure 9a shows the thermal image of the device overlaid on the 50× optical image. Figure 9b provides an enlarged view of the region with the defect. Figure 9c displays the temperature scan along the line-scan shown in Fig. 9b, which passes through the observed hot spot. The full-width-at-half-maximum hot spot size is approximately 1.4 µm.

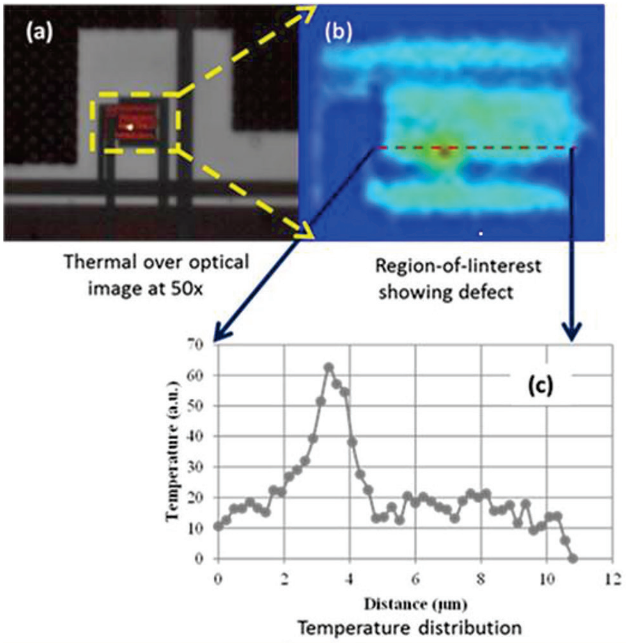


Fig. 9 **Overlay of thermal image on the 50× optical image shows the defect location on the MOSFET. Figure 8(c) shows the temperature plot corresponding to the dashed line in Fig. 9(b).**

An averaging time of 3 minutes for this image enables a temperature resolution of approximately 0.1°C. The temperature rise at the hot spot as shown in Fig. 9c is approximately 50°C.

GaAs AND GaN HEMTS

GaAs and GaN high electron mobility transistors (HEMTs) with submicron features are widely used for a wide variety of high frequency and high power wireless communication applications, including smartphones and military electronics. These applications require high reliability and long operating life. This example illustrates how TTI can be used to analyze and detect a small defect in a GaAs HEMT with submicron features.

A 100× microscope objective and a white light illumination source are used for this example. Figure 10a shows the optical image of a failed die at 100× magnification while Fig. 10b zooms in on the defect location. Figure 10c is the thermal image of the hot spot with an applied bias to the device. The hot spot size is 500 nm.

Figure 11 displays the temperature profile through the hot spot, which indicates a temperature rise of nearly 15°C.

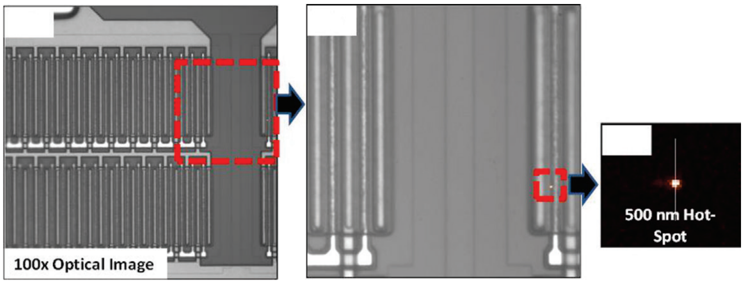


Fig. 10 **Optical image of GaN HEMT with small defect, (a) and (b) and thermal image, (c), of resulting 500 nm hotspot. A 10-minute averaging time enables a 14-microwatt power detection.**

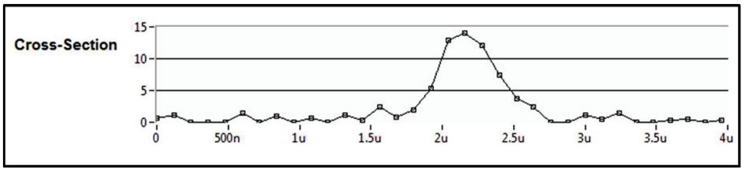


Fig. 11 **Temperature profile passing through the hot spot indicates ~15°C temperature rise.**

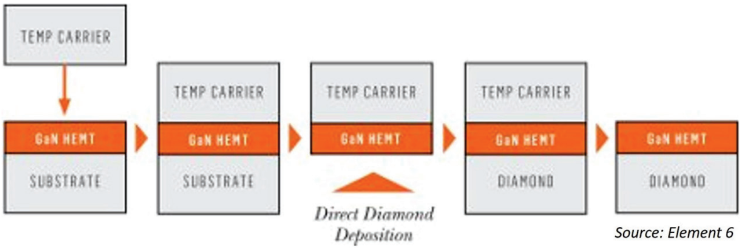


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Fig. 12 **Process steps to implement GaN-on-diamond structure.**

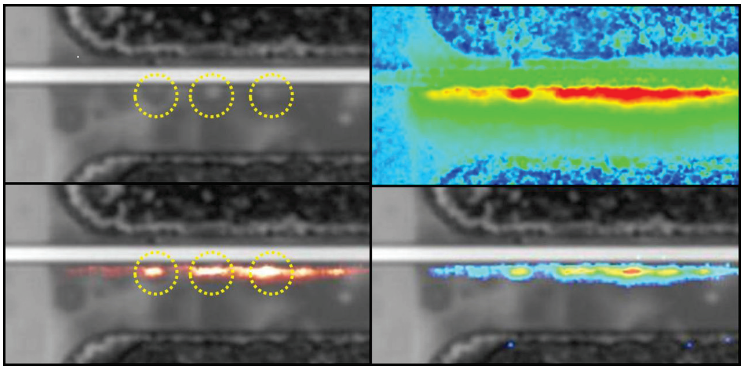

Fig. 13 **Optical and thermal images of HEMT gate region showing hot spots caused by small voids in the HEMT-diamond interface.**

HEMT TO DIAMOND INTERFACE

In this example, thermal imaging is used to investigate the integrity of a device interface, an interface that plays a direct role in determining the device operating temperature.[8]

Diamond, which has a thermal conductivity of 2000 W/mK, is proven to be an effective heat sink material for high power GaN HEMTs. This GaN-on-diamond interface, illustrated in Fig. 12, is formed by: a) bonding the GaN face to a temporary sacrificial carrier; b) etching away the substrate and transition layers; c) depositing a 35-nm-thick dielectric followed by a diamond layer on the backside of the GaN HEMT; and d) removing the sacrificial carrier.

Figure 13 shows the resulting images of the HEMT gate region. A key finding in this analysis is the detection of three hot spots, possibly caused by gaps or imperfections in the GaN-diamond interface.

CONCLUSION

A relatively small temperature increase can have a significant adverse impact on long-term device reliability. Industry trends favor decreased feature sizes and increased device complexity. The resulting power densities are making it more important than ever to possess a full understanding of device thermal behavior under all operating conditions to ensure long-term reliability. While traditional thermal analysis techniques do an adequate job of determining average temperature behavior over a region of interest, they lack the resolution to accurately measure temperature on a submicron scale.

To gain this knowledge, it is necessary to use a thermal analysis technique with a spatial resolution consistent with the device features. Traditional techniques fall short in this regard while thermal imaging systems based on the thermoreflectance principle offer the attributes and performance necessary to meet the thermal challenges presented by today's advanced devices.

The TTI technique depends on observing and measuring reflectivity changes as a function of temperature when the device is illuminated with wavelengths in the visible range. With an illumination wavelength of 365 nm, a spatial resolution of 245 nm with a temporal resolution of 50 ns has been demonstrated. Time averaging enables excellent temperature resolution and power sensitivities less than 50 μW. With these capabilities, TTI can be used to locate minute defects on devices by detecting the location of hot spots due to the presence of defects. It can also be used to characterize device performance by tracing the transient thermal response during operation.

Several examples illustrate the value of this approach in detecting thermal anomalies and defects that likely would be missed using other techniques. Anomalies and defects, no matter how small, can have an adverse impact on device performance and reliability.

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