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PICOSECOND TRANSIENT THERMAL IMAGING USING A CCD BASED THERMOREFLECTANCE SYSTEM

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ABSTRACT

A new Charge Coupled Device (CCD) based, full-field thermoreflectance thermal imaging technique is demonstrated with 800 picoseconds temporal resolution. Transient thermal images of pulsed heating in single interconnect vias of 350nm and 550nm in diameter are shown. The use of pulsed laser diodes and dedicated synchronization circuits can significantly lower the cost and the image acquisition time compared to the scanning pump-probe laser systems. Also the same set up can be used to study transient thermal phenomena in a wide dynamic range from sub nanoseconds to seconds.

INTRODUCTION

Thermal imaging is an important tool for the electronics and optoelectronic industry. In product design, manufacturing, and reliability, thermal imaging can help verify optimum thermal management and identify process failures or defects. Such measurements can be carried out at the system, package, or device level. In addition, transient thermal techniques are used to characterize the package thermal resistance, the thermal conductivity of thin film materials and the interface thermal boundary resistances. We have developed a thermoreflectance imaging technique for active devices with high spatial and temporal resolution. Thermoreflectance is based on measuring the temperature dependence of material's reflection coefficient. Laser based pump-probe technique as well as CCD based transient thermal imaging systems have been successfully used for such characterizations[1-5] Previously we have shown that a CCD based thermoreflectance system can acquire thermal images with 100ns temporal, 200nm spatial and about 0.05K temperature resolution, given an averaging time of about 2 minutes per image. The transient thermal image series was obtained by flashing an LED at a precise delay relative to the heating cycle, thus enabling a thermal 'snapshot' of the device at a given time.

The initial idea for the current system is adapted from a pump-probe characterization technique commonly used for measuring the transient reflectivity. A typical Ti-Sapphire pump-probe laser setup has a very high temporal resolution of 100 femtoseconds but it is inherently a single point measurement. Full field imaging requires time consuming scans, not to mention the cost and complexity of the ultrafast lasers and optical delay set ups. Here, we propose a simple new technique for transient thermal imaging using a picosecond pulsed laser diode for illumination and CCD image acquisition, which provides very high temporal and spatial resolutions. The limitation of the previous CCD based imaging system is mitigated by a custom designed timing circuit, as well as using a diode laser for illumination.

With the use of a commercially available picosecond delay generator along with low jitter pulse generators, it is possible to ensure a time resolution at the flash duration of the diode laser, which can be adjusted from 300-900ps. This technique could be adapted to use with a femtosecond laser heating source as well. The measurement is performed by monitoring the change in the reflection coefficient between two different phases as the device (or material) heats. Phase 1 is acquired just prior to the start of the heating cycle, and phase 2 is pre-programmed to trigger the 'snapshot' at arbitrary delay. Typical values are; 800ps laser pulse width with a 500 KHz repetition rate, 50ns device excitation period, transient image series of 200 frames acquired every 1ns. Contrary to the mode-locked Ti-Sapphire or fiber lasers, it is easy to adjust the repetition rate of the laser diode from Hz to MHz and thus obtain transient thermal data in a wide dynamic range.

EXPERIMENTAL SETUP

The experimental setup is shown in figure 1. A 440nm wavelength picosecond pulsed laser is reflected off a translating mirror and enters a fiber bundle where it is coupled through a diffuser to a brightfield microscope. Full-field thermal images of micrometer sized devices are acquired by a 128x128 pixel scientific grade electron multiplying charge coupled device (EMCCD). One challenge of high-resolution microscopy with coherent laser illumination is that with the typical use of a diffuser to spread the beam, static diffuser grains, and mode speckle patterns emerge degrading the image quality. To improve the image, one can induce a very slight laser translation into the fiber bundle which allows the light to strike the diffuser from slightly different angles and the static grain pattern is averaged, as well as any interference fringes.

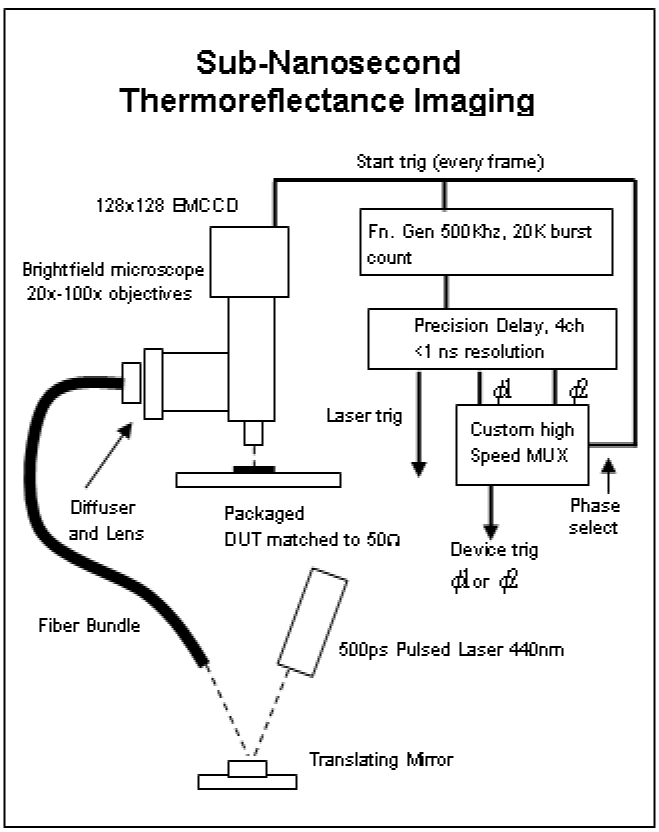

Figure 1: Experimental setup for picosecond thermal imaging.

Figure 2 shows the comparison of a full-field laser image when the mirror is static and when the mirror is actively translating by 1 millimeter at 150Hz. Additionally, the translation frequency is controllable, such that aliasing into the EMCCD can be avoided.

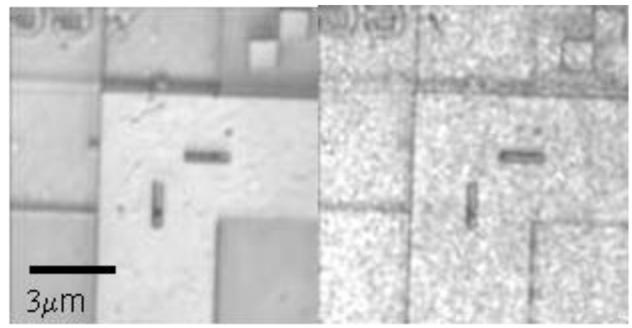

Figure 2: Comparison of images with 100x objective with (left) and without (right) mirror movement. When the mirror is stationary, diffuser grains and speckle pattern degrade the image.

Previous work[2] has shown that it is possible to obtain transient thermal images with 100ns time resolution, where the limitation was the turn-on time of typical high-speed light emitting diodes (LED), and the 12ns quantization of the timing circuit creating the delay signals. With the goal of thermal images at less then one nanosecond, in addition to the use of a picosecond pulsed laser diode, the electronics generating the timing signals need to be replaced with low-jitter delay generators. To this end, precision delay generators were used, and a custom low delay multiplexer was built with typical TTL logic to enable tri-state buffers for each timing path. It is very important to have exactly the same circuit path for both the normalization and measurement timing signals, as even one extra gate delay in one path, can lead to a few nanoseconds skew between the two signals.

The entire system is controlled by custom LabVIEW application programming, and the generated thermal images can be processed using standard image processing subroutines.

METHODOLOGY

The method to obtain sub-nanosecond thermal images is borrowed from the single point, laser pump-probe optical sampling technique. In the latter case, one often uses a free-space translation between the pump and probe beams to achieve 100 femtosecond time resolution. Since our setup is in the picosecond time scale, it becomes relatively straightforward to use an electronic delay to obtain the time series.

The picosecond full-field thermal imaging scheme works as follows: The user, through software, requests a new thermal image at a specific time delay, at a set averaging time.

In the following example the EMCCD is running at 20 frames/sec, corresponding to > 20,000 laser, and electronic heating pulses, every 2µs, in each EMCCD frame. Typical averaging times can be 10sec-1min or more depending on desired signal to noise (SNR). Between each EMCCD frame, the multiplexer is switched, and either the reference frame or the measurement frame is acquired. One advantage to this approach is that the differential thermoreflectance signal is acquired at one half the frame rate used, which contributes to noise reduction.

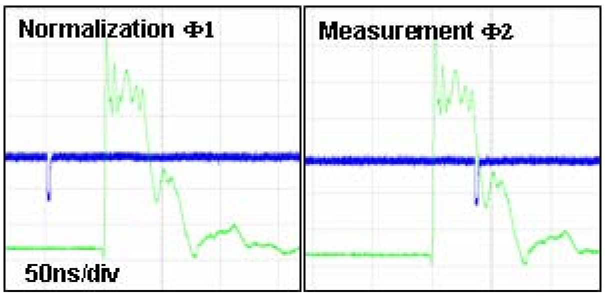

Figure 3: Oscilloscope traces showing electrical pulse across device (green) and sync from laser (blue). Reference phase is on the left, and the measurement phase on the right.

Figure 3 shows an oscilloscope trace from the experiment. The rise time across the device was measured to be 2ns, and there is a small ringing from imperfect high speed packaging. The pulse width of the laser is shorter then the electronic signal displayed for timing. The figure shows the voltage pulse across the device in green, and the timing signal from the laser in blue. The left figure indicates the reference phase because the laser pulse occurs before the device is excited. The next EMCCD frame is the measurement phase, and we see that the laser is flashed during the heating cycle of the device. In this experiment the laser duration is estimated to be 800ps. It is important to use a low duty cycle for the device excitation, as it is desirable for the device to cool to ambient prior to the next heating cycle. The data presented uses 50ns device heating pulse at 500KHz repetition corresponding to 2.5% duty cycle.

Once the data is acquired, the time dependent reflectivity change data can be converted to temperature profile using the calibrated thermoreflectance coefficient for the surface under study [9]. Figure 4 shows the thermal image of a single submicron via in an interconnect layer, that is merged with the optical image, for visualization.

THERMAL IMAGING OF INTERCONNECT VIA TEST STRUCTURES

In order to test picosecond thermal imaging, a sample of interconnect test vias was used. This proved to be very useful because the submicron via can heat up rapidly in nanoseconds time scale so that we can study heat diffusion in the metal layer. Figure 5 shows a thermal image of a chain of 10 vias 55ns after the start of the heating current just as the excitation pulse is decaying. The buried vias are not visible in the optical image, but they are clearly seen in the thermal image.

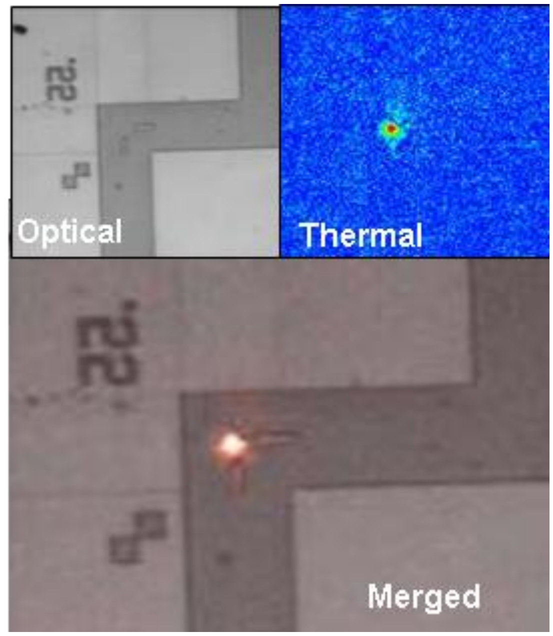

Figure 4: Thermal image of a single interconnect via demonstrating image merging for visualization.

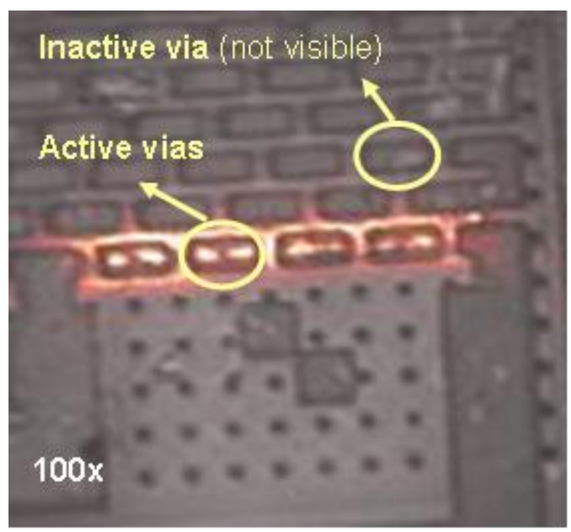

Figure 5: Thermal image of chain of 10 sub-micron vias under 50ns long pulsed current excitation. The temperature profile at 55ns delay is shown. Heating from individual buried vias are visible.

Thermal imaging was done for two different single vias which are 350 and 550nm in diameter. The 550nm via is heated by pulsing currents up to 600mA at 50ns. While this is quite high current density, the low duty cycle reduces the total power dissipation. Figure 6 shows the thermal images of the 550nm single via at 23 and 83ns delay. During turn-on the temperature field is very localized to the via, however after turn-off the heat begins to diffuse into the metal. By using a small region of 25 pixels in the center of the thermal image one can step through the image series and determine the average temperature on top of the metal where the via is buried.

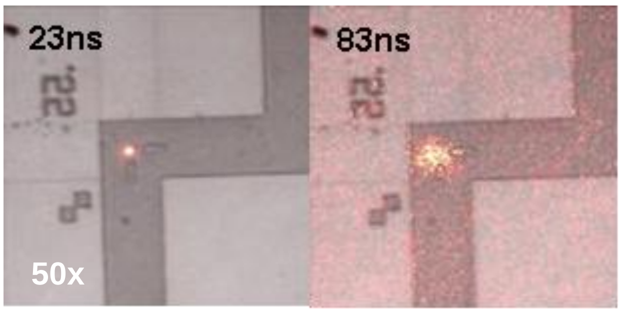

Figure 6: Merged thermal images of heating in 550nm diameter interconnect via test structure. Image on left is at 23ns delay, and the one on the right is at 83ns delay. The excitation pulse is 50ns

Figure 7 shows the transient temperature increase for two via sizes in the first 200ns. 50ns long electrical excitation pulse was used. The peak temperature is actually higher than the average presented here. The red curve (open circle dot) for the 550nm via was acquired with an averaging of only 10sec per frame. The entire thermal movie was acquired in less than an hour. The blue curve (open rectangular dot) for the 350nm via was acquired with 30sec averaging per frame, about 3 hours total. The advantage of the extra averaging can be seen best in the tail of the data series, where the 350nm via data shows less noise. The temperature sensitivity is about 1 degree C for a ~30 second average per frame. This is worse than the previous thermal imaging results with 100ns resolution. This is mainly from the increased image noise in the laser illumination. Figure 8 shows a normalized cross-section of the two thermal images, after 19ns delay. The data was fit with a Gaussian distribution and yields a full width half max (FWHM) of 300nm for the 350nm via and 430nm for the 550nm via. As expected, the data suggests that the 350nm via creates a more concentrated temperature field than the 550nm via at early turn-on times and demonstrates the high spatial resolution capability of the technique.

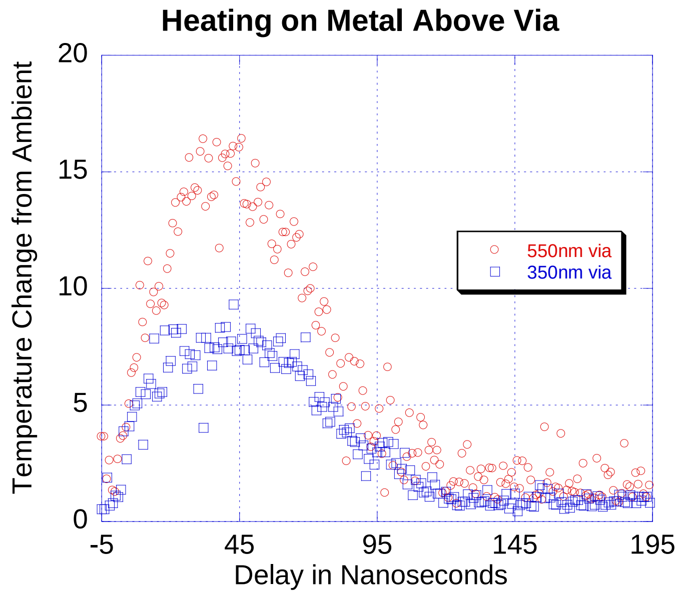

Figure 7: By processing the 200 frame thermal image movie one can look at a small region (25 pixels) around the hot spot to determine the transient turn-on time of the via. The data suggests that both vias achieve turn-on on the nano-second scale. To actually compare rise times, the system should go into thermal equilibrium, which is not achieved in the first 50ns

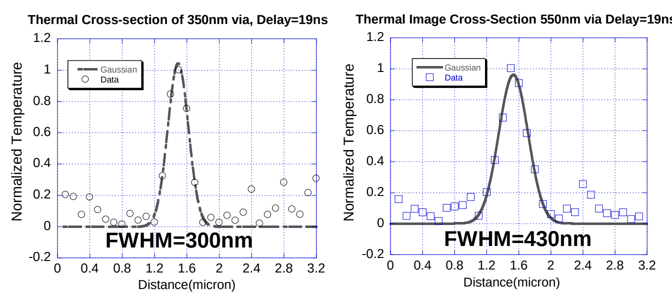

Figure 8: In the first 19ns, as the via heats up, it becomes possible to resolve the size difference between the 350nm (left) and 550nm (right) diameter vias. The Gaussian fit yields FWHM of 300, and 430nm for the different sized vias. This shows the excellent spatial resolution of the visible wavelength thermoreflectance method

CONCLUSION

A new full-field thermoreflectance thermal imaging technique is presented showing 800 picoseconds temporal resolution and sub-micron spatial resolution. The technique enables quick imaging of active electronic and optoelectronic devices. The set up using picosecond laser diode and electronic delay is simpler than the typical single point pump-probe laser set ups with optical delay line. In addition, a wide transient dynamic range from 800ps up to seconds could be studied. Transient thermal transient images of single interconnect vias of 350nm and 550nm in diameter were presented revealing the high spatial and temporal resolution of the experimental setup.

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