REAL TIME SUB-MICRON THERMAL IMAGING USING THERMOREFLECTANCE

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ABSTRACT

Thermal measurements on a sub-micron scale are non-trivial, but are important for the characterization of modern semiconductor and opto-electronic devices. In this paper we will discuss the application of the thermoreflectance method for real time sub-micron thermal imaging. By using light in the visible spectrum, the diffraction limit, and thus spatial resolution is improved over a traditional infrared camera based on blackbody emission. With active excitation of the sample and frequency domain filtering, thermal images with 100mK temperature resolution are obtained. Experiments performed on semiconductor micro-coolers and micro-heaters are presented.

1. INTRODUCTION

Modern semiconductor devices are routinely fabricated with sub-micron features, which are smaller than the wavelength of infrared thermal radiation at room temperature. Therefore, in order to obtain high-resolution thermal images of such devices, it is necessary to improve upon the traditional method of infrared imaging based on blackbody emission. Typical HgCdTe infrared imagers are limited to ~5 micron spatial resolution, and tens of degrees temperature resolution. Even though commercial cryogenically cooled imagers specify a temperature resolution of 25mK, the actual resolution over small areas in integrated circuits is tens of degrees. This is partly due to the fact that metals have a low emissivity and semiconductor materials such as silicon are transparent to infrared radiation. In addition, radiation from large areas in the scene buries the signal from small regions on the order of a micron

Many measurement techniques have been proposed [1] for high-resolution thermal imaging applications that exploit different temperature dependent properties of materials. By using the thermoreflectance [2-6] method, we show that real time, thermal images with sub-micron spatial resolution, and 100mK thermal resolution can be generated on active semiconductor devices. We will see how experimental results on micro-coolers, and micro-heaters provide design engineers with important information to optimize the device geometry.

2. THERMOREFLECTANCE TECHNIQUE

The thermoreflectance technique exploits the temperature dependent reflection coefficient for generating surface thermal measurements. Previous experiments have used this technique for point measurements[2,3] and thermal mapping has been achieved by scanning a laser[4,5].

It is useful to define the change of the reflection coefficient for each degree of surface temperature change. This is called the thermoreflectance coefficient and is denoted C_{th}. In general this value is material and wavelength[7] dependent, so to obtain accurate thermal measurements, it is necessary to calibrate the thermoreflectance coefficient with an absolute temperature measurement (eg. with a micro-thermocouple). For metals and using light in the visible spectrum Garfinkel[7] suggests that C_{th} is on the order of 10^{-5}, and the calibration for our experimental setup yields a value of 7.6×10^{-5} per degree for the gold surface of our devices. Resolving the reflection to this accuracy is the main challenge of this measurement technique. In order to obtain measurements with good signal to noise, a lock in amplifier, or filtering with a fast Fourier transform (FFT) is required.

By active thermal modulation of the device under test at a known frequency a by narrow bandwidth filtering of the reflected light, one can reduce the white shot, thermal noises, and also the 1/f noise. During the measurements, the device substrate is sitting on a temperature-controlled stage to avoid the long term drifting of the base temperature. Since IC devices are typically thin films and

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have a small thermal mass, their temperature can be modulated with frequencies as high as several KHz. Typically a 1 Hz bandwidth filter is used which provides adequate signal to noise, depending on the intensity of the reflected light and size of the area being measured. With a spot of 3 micron diameter from a 655 nm 5mW semiconductor laser, and a 1Hz bandwidth window, 10mK temperature resolution on a gold surface is possible. However, in our imaging experiments the thermal resolution was less, due to the fact that a less focused white light is used, and the area of integration was smaller. With our 150W quartz tungsten halogen (QTH) illuminator concentrated over an area of several millimeters, we achieved a temperature resolution of 100mK, for an area of integration on the device of less than 3 square microns. Significant loss of illumination on the surface of the device under test was from the coupling loss into the microscope objective. By using a more intense small arc illuminator, one order of magnitude improvement in signal to noise should be possible, and thus one could approach spatial resolution down to the diffraction limit of the visible optics (~400nm).

3. EXPERIMENT SETUP

Thermal images were obtained for several devices, micro-coolers[8], and also, micro-heaters[9] High-resolution thermal imaging can provide useful feedback to the design engineers for the device diagnostic and optimization. The experimental setup is shown in Fig. 1. The device under test is placed on a thermoelectric (TE) temperature-controlled stage, and is excited with current pulses less then 1KHz. White light from a 150W Quartz Tungsten Halogen (QTH) Illuminator is focused through an 80X objective and is reflected back through a beam splitter so that the enlarged image is incident on the imager. Two different image acquisition methods were used, scanning, and real-time imaging. In the scanning method, a single photodiode was scanned across the reflected image using a precision translation stage. For real-time imaging a PIN photo diode array sensor was used with parallel processing of each pixel.

4. PROCESSING THE DATA

Because each surface in the thermal image has a different thermoreflectance coefficient, for accurate thermal measurements, it must be calibrated separately with the use of e.g. a micro-thermocouple. For the following images, there are only two reflection surfaces, the gold layer on top of the device and also the silicon substrate, surrounding the device. Since the reflection coefficient of gold and silicon are very different, the image intensity histogram is bi-modal. This can be exploited for automatic image processing to take into account different surfaces. Calibration complicates this technique, but is similar to the calibration procedure for the emissivity of different surfaces for an infrared imager.

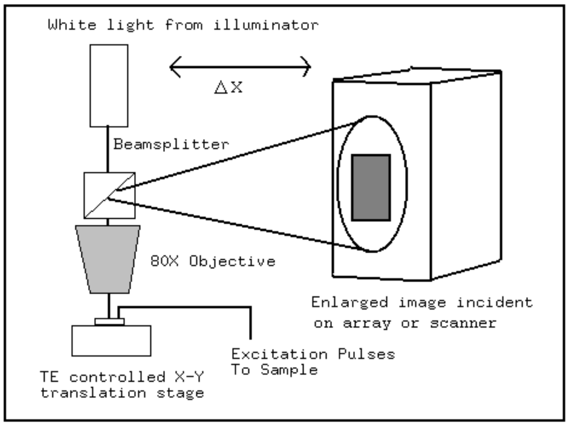

Figure 1. Experimental Setup

5. SCANNED THERMOREFLECTANCE IMAGES

High resolution thermal images can be achieved with the use of a single photodetector and a scanning translation stage. The image acquisition time can be very long but such a system can easily be made from off the shelf components. For the scanning experiments, a pinhole and a photodiode are used. The pinhole is 100 microns in diameter. When used with a 16X microscope objective and a distance ΔX=45cm (see Fig. 1), this corresponds to about 2.5 square microns of for each data point in the thermal image. The distance ΔX can be adjusted for a different zoom of the device under test. There is a trade off between the thermal resolution, and also the image acquisition time, and the size of the integration area. The thermal or spatial resolution can be improved by integrating longer at each pixel and thus reducing the bandwidth and white noise further, however, the image acquisition time is increased. All thermal images presented show the surface temperature change from the average stage temperature in degrees C. Figure 2 shows the geometry of the micro-cooler samples used in the experiment, depicting the cooler at one end, and a long side contact layer. Figure 3 shows the reflected image and thermal image of a 40x40 micron square micro cooler operating at 200mA current. Stage temperature was 25C and excitation frequency 1Khz. For the 50 by 120 pixel image presented in Fig. 3, a 1 Hz bandwidth filter was used, and 3-second stabilization time was used after each move of the computer controlled translation stage. Thus, image acquisition took over 6 hours. In Fig. 3 we see the contact layer and heating caused by the current probe, while the surface of the micro-cooler is about 3.5 degrees C cooler then the ambient temperature. Another scanned image showing the temperature distribution on top of a micro heater is shown in Figure 4. The 50x50 micron micro-heater fabricated was fabricated on silicon substrate and it showed heating of 5 degrees for a current of 100mA. A thin silicon nitride insulation layer covers some of the metallic areas on top of the device. Thus the actual temperature values could be a little of and further calibration is needed.

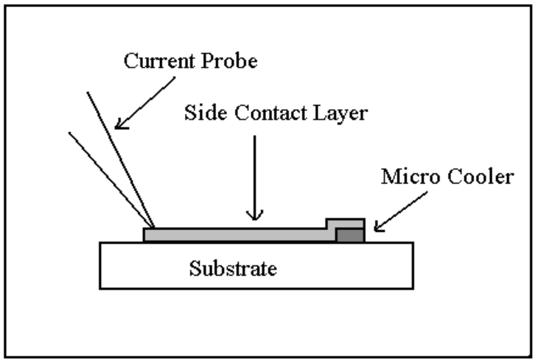

Figure 2. Geometry of Micro-Cooler Samples

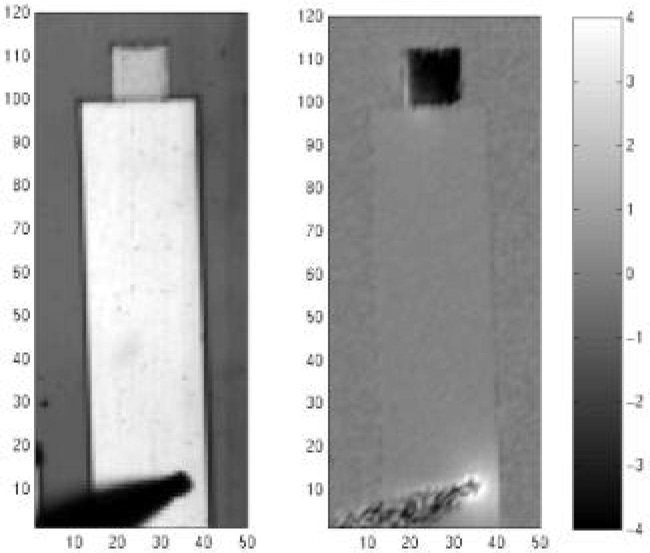

Figure 3. Top view Reflection Image, and Thermal Image of 40x40 micron Micro-cooler

6. REAL TIME THERMOREFLECTANCE IMAGING

In order to avoid the long image acquisition of the scanning method, one can produce the entire image in parallel with an array of detectors and with parallel processing at each pixel. Previous experiments have attempted to obtain thermoreflectance images by using a traditional charge coupled device (CCD) camera, then filtering the noise by processing a series of frames [6]. Unfortunately, such experiments were limited by the quantization and noise of the CCD, and only achieved tens of degrees temperature resolution. Quite simply, for one degree of temperature resolution it is necessary to have an image acquisition system with a dynamic range on the order of the thermoreflectance coefficient. This exceeds the 16-bits available on high performance CCD's. In order to increase the temperature resolution and achieve real

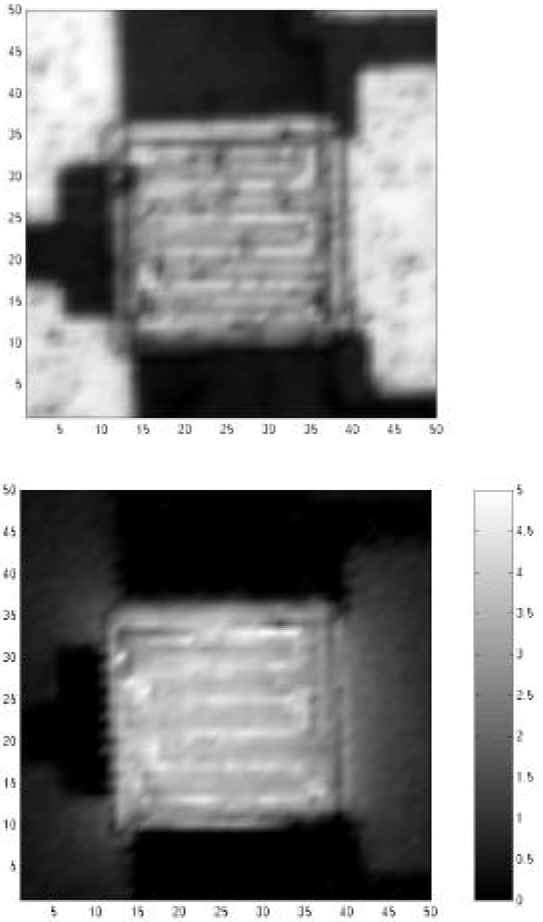

Figure 4. Reflection Image and Thermal Image of an Active 50x50 micron Square Heater Fabricated on Silicon Substrate

time imaging, special signal processing hardware must be used.

For real time thermoreflectance imaging a 16x16 element camera designed at SRI International was used. This camera has AC coupled sensing elements, meaning that the large DC reflection component is filtered prior to the analog to digital conversion (ADC), thus more gain can be used without saturating and all 16-bits of the ADC are used to convert only the change in the reflection coefficient. A fast Fourier transform (FFT) is performed at each pixel, and with a one second integration time, the system can display images and keep up with the image acquisition. Figure 5 shows the FFT of the signal from one pixel in a noisy lab, along with the raw, real-time thermal image of a 20x20 micron micro-cooler surface using 1Hz bandwidth filtering. The FFT spectrum in Fig. 5, shows a lot of flicker noise from our illuminator, in particular a large 120Hz ripple. The device under test was thermally modulated at 200Hz so the thermal signal is the small peak at that frequency. Figure 6 shows a CCD image of the micro-cooler surface, and the interpolated thermal image acquired by the camera. Finally in Fig. 7, we see a cross section of the 30x30 micron cooler for different device currents. It can be seen that there is a parasitic source of heating at the junction between the side contact and the layer and the top of the device, and good cooling on the surface of the cooler. The spatial resolution of the real-time system is limited by the intensity of the illumination source and various noise sources in from different components. From the interpolated cross-section, the spatial resolution of this thermal image is about a micron, and the temperature resolution about 100mK.

7. CONCLUSION

Real time thermal imaging of microelectronic devices with 100mK temperature resolution and micron spatial resolution has been described. PIN array experiments on micro devices showed good results, with spatial resolution slightly greater than one micron. With the use of a higher intensity and more stable illuminator, spatial resolution down to the diffraction limit of the optics (~400nm) should easily be achieved. Thermoreflectance imaging improves both spatial and thermal resolution of traditional infrared cameras with the use of visible light.

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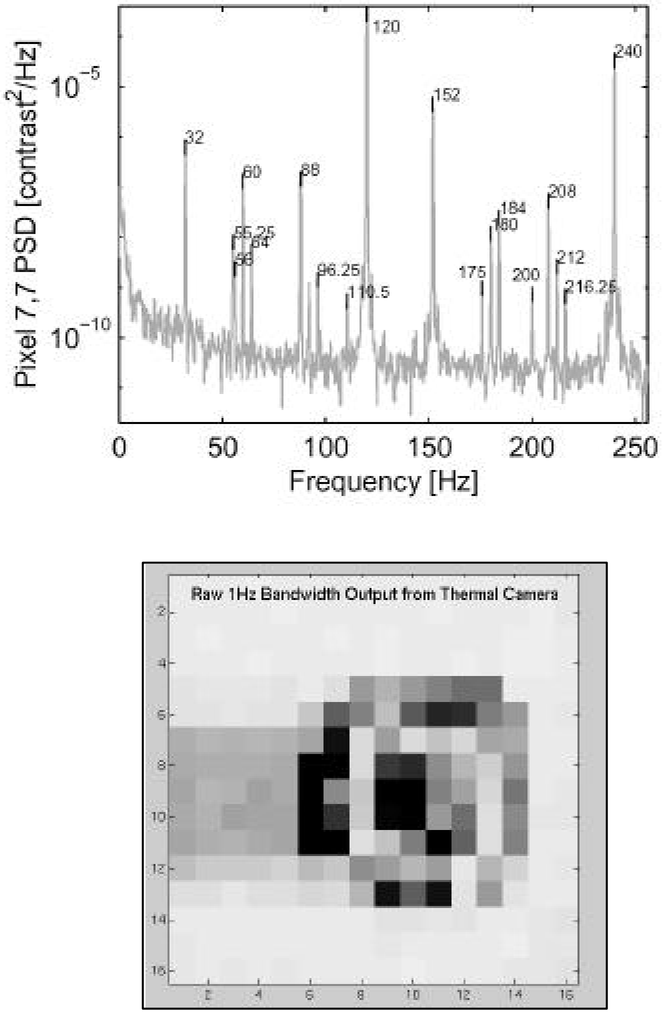

Figure 5. FFT of One Pixel, and Unprocessed Real Time Thermal Image

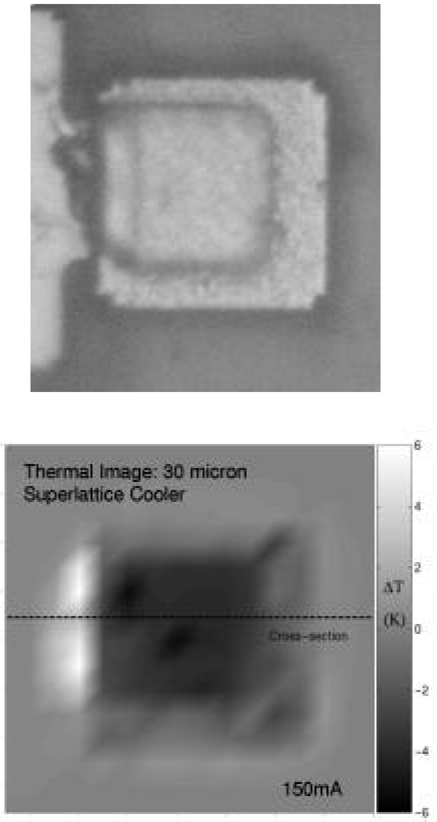

Figure 6. CCD Image of Micro Cooler Surface and Processed Real Time Thermal Image

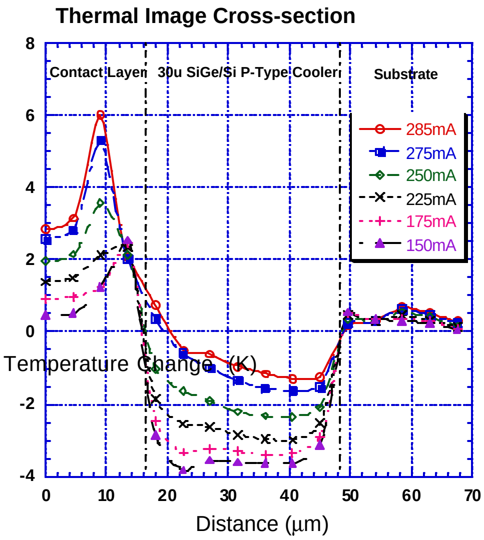

Figure 7. Thermal Image Cross-section for Increasing Device Current Showing Heating on the Contact Layer and Cooling on the Surface

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