Camera For Thermal Imaging of Semiconductor Devices Based on Thermoreflectance

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Abstract

A thermal imaging camera suitable for use on micron-sized active semiconductor devices has been developed. Based on a visible light thermoreflectance technique, this camera achieves 50mK temperature sensitivity and sub-micron spatial resolution when imaging the top metal contact layer. By using a photodiode array, sensitivity is improved over what is possible with a CCD (Charge Coupled Device) based system. Thermal imaging results of an ultra small 10 micron diameter SiGe micro-cooler is also presented.

Keywords

Thermal Imaging, Thermoreflectance, Photothermal Imaging

1. Introduction

Thermal imaging is a valuable tool in the design and analysis of reliable semiconductor devices. Many techniques can be employed[1], but there is some advantage in simplicity and performance in using a thermoreflectance technique. Thermoreflectance is a non-contact, optical characterization of surface temperature by exploiting the temperature dependence of a material's reflection coefficient. With the use of visible light, the diffraction limited spatial resolution is improved over the 3-5 micron sensitivity of infrared 'blackbody' cameras. However, the challenge of the thermoreflectance method is to resolve the small change in the reflection coefficient. Typically for metals, the reflection coefficient only changes by about 1 part per 10^5 for each degree Celsius change in surface temperature. For high resolution thermal measurements it is necessary to use a high gain photodiode and lock-in amplifier, while thermally cycling the active device at a known frequency.

Figure 1 shows a typical thermal image acquired with a scanning thermoreflectance technique of two 10x20 micron platinum heaters. Two suspended heaters are thermally imaged while one is biased to heat at about 4 degrees C above the ambient. This image is generated by scanning a single photodiode across the reflection image. Because of the minute thermoreflectance signal, each data point is filtered using a lock-in amplifier with a one second time constant. Since one has to wait a few seconds at each pixel, an 80x80 point scan has a total image acquisition time of over seven hours. This can be especially problematic for samples that need to be cooled, and held under vacuum.

2. Thermoreflectance Array Imaging

To decrease the thermal image acquisition time, it is desirable to acquire many data points simultaneously using a CCD sensor or a photodiode array. However, the signal to noise requirement needed to capture a thermoreflectance image is very stringent.

Surface temperature measurement based on thermoreflectance uses the change of the reflectance coefficient[2]. It is useful to define the material and wavelength dependent thermoreflectance coefficient Cth. Assume that R0 is the reflection coefficient at the ambient temperature while R1 is the coefficient under thermal excitation ΔT. The difference R1-R0 is what is measured by the lock-in amplifier.

$$C_{th} = \frac{1}{R_0}\frac{dR}{dT} \quad (1.0)$$

$$R(T) = R_0 + \frac{dR}{dT} * \Delta T \quad (1.1)$$

$$\Delta T = \frac{(R_1 - R_0)}{C_{th} * R_0} \quad (1.2)$$

Thermocouple calibration yields a value of the thermoreflectance coefficient, Cth of gold to be 8.1e-5 using a 150W Hg arc lamp. For 100mK resolution, each pixel must have a minimum 120dB dynamic range to resolve the small AC signal in the large DC background. In the single element scanning setup the photodiode signal is AC coupled and boosted with the lock-in amplifier. Typically, a one-degree thermoreflectance signal will be much smaller than the white thermal and shot noises of the photodiode and electronics. In order to obtain sub-degree resolution it is necessary to use a bandwidth limiting technique on the photodiode signal such as a lock-in amplifier or a fast Fourier transform (FFT) with high frequency resolution. In practice, considering gold or aluminum, a 1Hz bandwidth window will reduce the noise to around 100mK temperature resolution.

High performance CCD's are very sensitive to low light levels, accomplished with high gains at each pixel. However, very high DC coupled gain cannot be used because the DC reflection will saturate the pixel. In addition, high performance CCD's are binned to 14 bits of amplitude quantization, which will only allow for 16K bins of dynamic range, and thus one bit corresponds to several degrees of a thermoreflectance signal. Finally, a 1 Hz bandwidth filter is necessary per pixel, accomplished with a lock-in amplifier or FFT filtering, it is thus practical to have a frame rate on the order of kHz while most CCD's sample less then 100Hz. While it is not impossible to have a CCD based thermoreflectance system, there a many advantages to taking an alternative approach.

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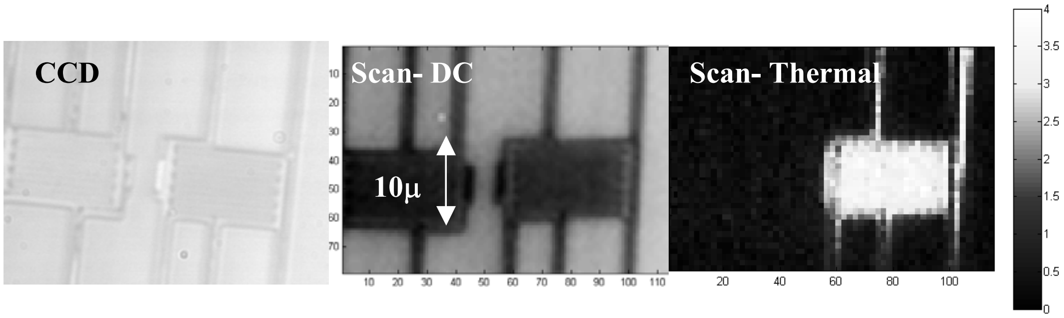

Fig 1:CCD image, reflection image, and thermal image of a 10x20 micron platinum micro-heater with one heater active. This structure is used to characterize heat transfer across a nano-wire suspended between the heaters. The images were acquired with a scanning thermoreflectance technique through a quartz cryostat window while the sample was under vacuum. Acquisition time was about 6 hours.

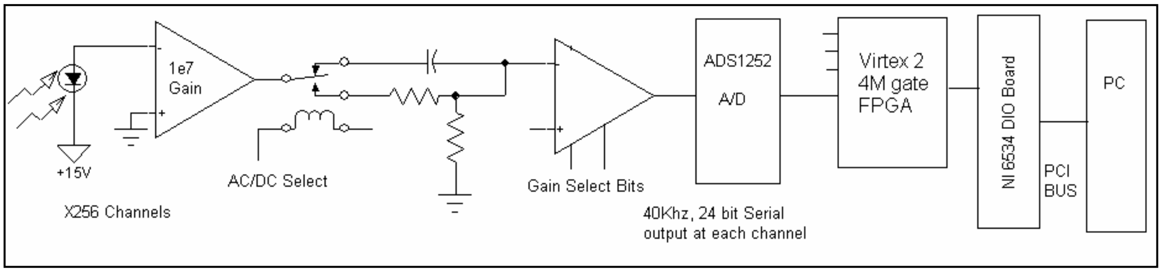

Figure 2: Single pixel block diagram of the thermal imaging camera. Each pixel is AC or DC coupled and selectable extra gain is provided. The ADC used is a delta sigma 24-bit converter from analog devices. By providing each pixel with its own ADC, rather then multiplexing, noise is reduced, and the pixels are sampled simultaneously.

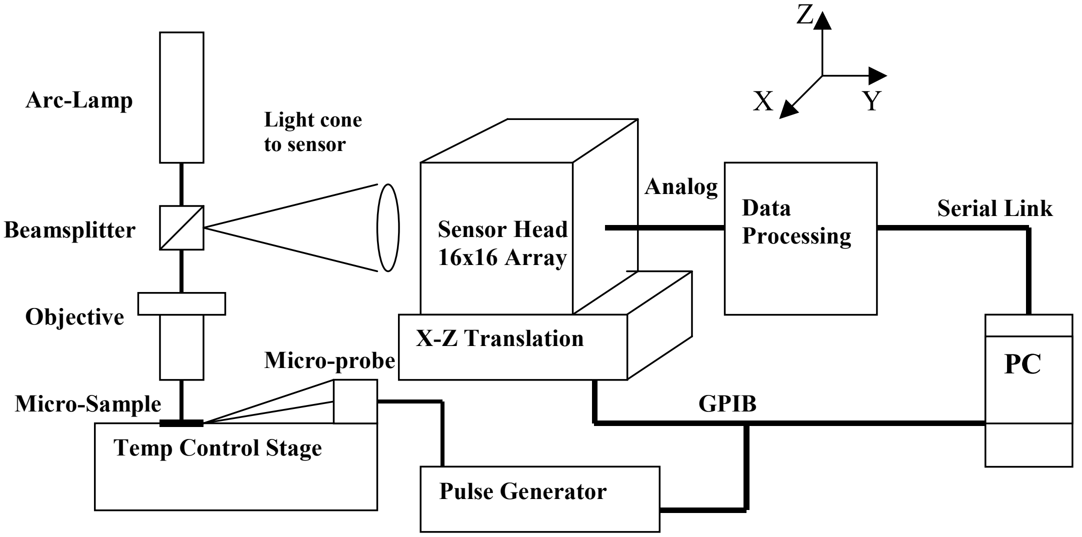

Figure 3: Experimental Setup; An image of the micro-sample is incident on the sensor head. The data is processed by the ADC's and a PC while a second PC is used to monitor other variables and control the X-Z translation of the sensor head.

Grauby et al[3] utilize a CCD sensor, frequency down conversion, and substantial signal processing to thermally image the heating in a resistor. Such experiments show that 10's of degrees C temperature resolution is possible, but in many thermal imaging applications the highest possible resolution is required. In general, a CCD sensor's sensitivity is limited by the dynamic range of the full well electron capacity of the sensing pixel, the read noise of the electronics, and low 1/f noise immunity from a slow frame rate. All these factors set a limit on the temperature resolution that can be achieved in CCD based thermoreflectance systems, to several degrees C of temperature change.

3. Thermoreflectance Camera Design

In contrast to a CCD based thermal imaging system, using a photodiode array sensor can give overall a higher sensitivity. A photodiode array sensor does not 'integrate and shift out' like a CCD sensor, but instead, the continuous photocurrent of each pixel is monitored. In this way, each pixel can be AC coupled and the gain of the small thermoreflectance signal can be boosted prior to the analog to digital conversion. The disadvantage of a photodiode array is that the high sensitivity comes at the price of a low pixel count.

A block diagram of a single pixel of the thermal imaging camera is shown in figure 2, while the overall experimental setup is shown in figure 3. Our goal was to provide both DC and AC coupled images which is necessary to normalize the thermoreflectance response of different surfaces and account for surface texture. In addition, higher speed modulations are possible in order to investigate transient phenomena in devices. The thermoreflectance camera uses the Hamamatsu C4675 amplified photodiode array head, which has a precision 10^7 transimpedance gain amplifier at each pixel. Each pixel is then multiplexed to be AC or DC coupled while the AC path has additionally selectable 1-100 gain. The conditioned analog signal is digitized by the Analog Devices ADS1252, a 40KHz, 24-bit delta sigma analog to digital converter. Finally, the 256 digitized channels are sent serially to a Xilinx FPGA where they are buffered, and sent to the host PC. A National Instruments digital interface board is used with LabView to display the images. A one or two second FFT is performed by the LabView software which provides the necessary bandwidth filtering. The data processing system connected to the sensor consists of 4 PCB's (Printed Circuit Board) designed in-house each containing 64 channels. The PCB's are mated directly to a FPGA development kit designed by Avnet Design Services.

The camera is designed to capture thermal images up to the 16KHz analog bandwidth of the sensor head, with a 40KHz maximum frame rate, however this means processing up to 15Mb per second. By using a 64Mb buffer directly after the analog to digital conversion, several seconds of continuous 24-bit data from each pixel, is stored. This is necessary to allow for the computer to perform a FFT algorithm over the 256 channels, because the computer cannot process enough data before the next set of data arrives. In practice, the frame rate is controlled through the software and a 5KHz frame rate is usually sufficient for thermal imaging. A DC coupled FFT of one pixel is presented figure 4 and the thermal signal is the peak at 580Hz. In addition the same signal is shown AC coupled at the maximum 10^9 overall gain and can be used to estimate the signal to noise ratio. Based on thermocouple calibration the thermal signal presented corresponds to about 30 degrees change from the ambient at 100μV, while the noise floor is at least three orders below, 0.1μV. This would suggest a 30mK temperature sensitivity, however many factors should be considered, including

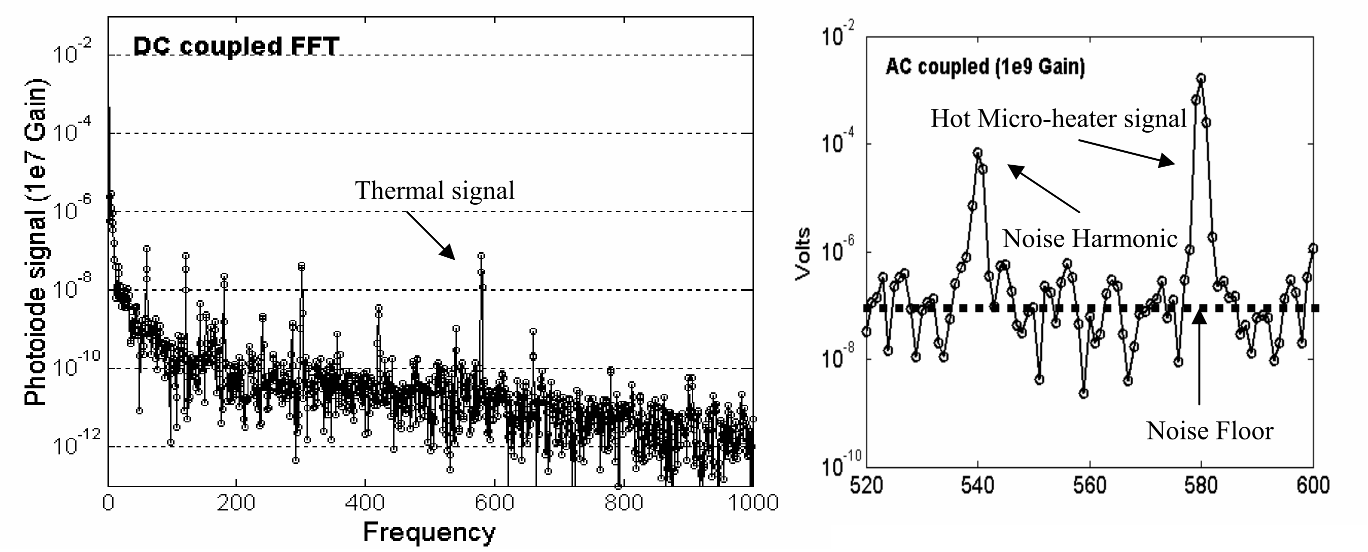

Figure 4: DC coupled FFT spectrum and AC coupled FFT at maximum gain, showing noise harmonics and thermal signal at 580Hz. This was the signal from a micro-heater at 30 degrees C, while the noise floor is greater then three orders below.

surface reflectivity, area of light integration, and light power incident on the sample. In practice, approximately 50mK sensitivity is achieved for micron-sized data points using our 150W arc lamp when reflecting off the metal contact layer.

The camera system is designed to be fully reprogrammable and the next step will be to program a full lock-in algorithm in the hardware, which will allow for fully synchronous frames to be acquired relative to the reference signal. Currently, all channels sample at the same time, thus the phase is preserved within a frame but not between frames taken at different times

4. Experimental Results

As previously noted, the high sensitivity of the camera comes at the price of low pixel count. To increase the spatial resolution of the thermal image, the photodiode array is mounted onto a computer controlled translation stage and multiple frames are stitched together. To avoid a long scan range, or image deconvolution, a pinhole array was used for increasing the spatial resolution of the thermal image.

By using a 220micron diameter pinhole to cover the 1.2mm^2 pixels of the Photodiode array, a 16x16 single frame can be enhanced to 80x80 samples. Figure 5 illustrates the enhancement achieved when acquiring images of a 75x75 micron heater structure. Figure 5 shows that the camera exhibits some fixed pattern noise. This is from the variance in responsivity at each pixel, and the variation in the pinhole size. The fixed pattern noise should be eliminated in the thermal image, because the thermal image is normalized by the overall amount of DC light reflection.

In addition to a micro-heater, thermal images were acquired of SiGe based micro-coolers. Figure 6 shows a 40x40 micron micro-cooler at two different biasing conditions. At 300mA the cooler cools by more then 2C below the room temperature and the temperature is very localized to the cooling surface. For comparison the thermal images at 300mA and 400mA are presented on the temperature same scale of 1 degree C maximum. Under the higher biasing condition, the heating from the current probe and contact layer, as well as the parasitic heating from the substrate can clearly be seen, which limits the device performance.

Images were acquired of an ultra-small 10x10 micron micro-cooler at different biasing conditions, shown in figure 7. Previous measurements yield that this device should cool below the ambient a maximum of about 1C. Figure 7 shows the acquired images. We see that with 45mA bias current the device cools about 0.5 C below the ambient and the signal is localized on the device itself. However, under a higher bias of 75mA, there is significant heating occurring in the substrate around the device. These images show the amplitude of the thermoreflectance signal. With additional signal processing, it is possible to distinguish between heating and cooling surfaces in the images.

5. Conclusions

A thermal imaging camera suitable for semiconductor device inspection has been built and characterized. The system can acquire several seconds of data at 40K frames/sec, which is sufficient for bandwidth filtering over the 16KHz analog bandwidth of the sensor head. Better than 50mK temperature resolution over fundamental electronic noise has been achieved when reflecting of the gold contact layer. To increase the low pixel count the sensor was mounted on a translation stage for image enhancement.

Acknowledgments

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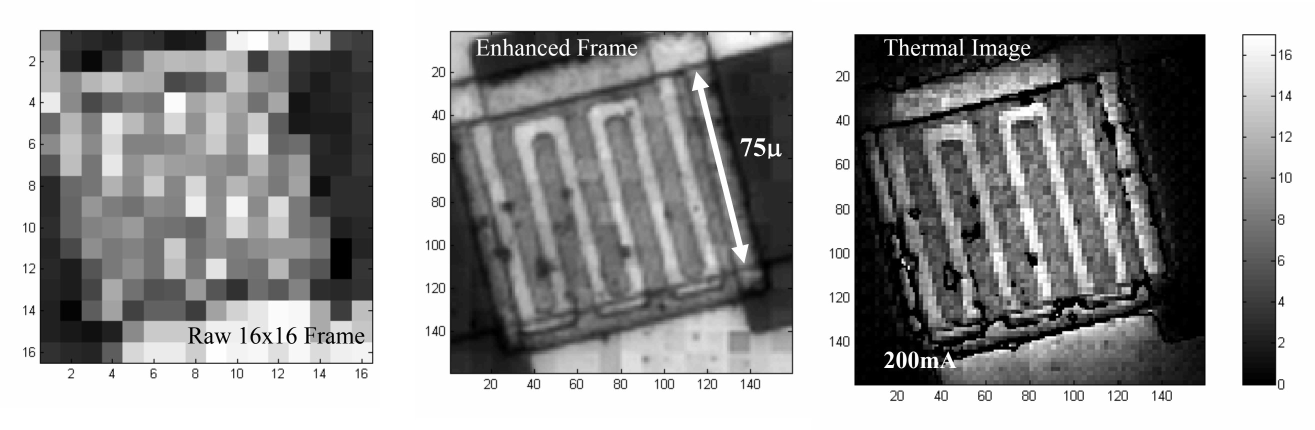

Figure 5: Single 16x16 frame, Enhanced frame combined from 25 sub-frames, Thermal image of micro-heater functioning at 200mA. Some fixed pattern noise is present in the enhanced frame but is normalized in the thermal image

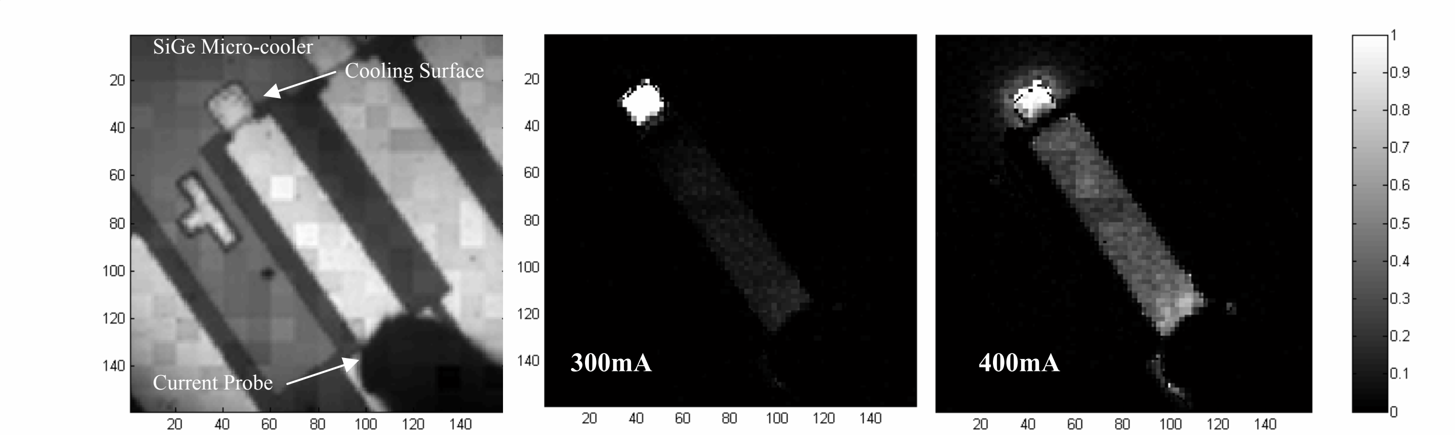

Figure 6: Thermal images of a 40x40 micron SiGe based micro-cooler. At 300mA the cooling is localized on the device surface while at higher current the heating on the contact layer and substrate limit the maximum cooling of the device. These images took approximately 3 minutes each for acquisition and processing.

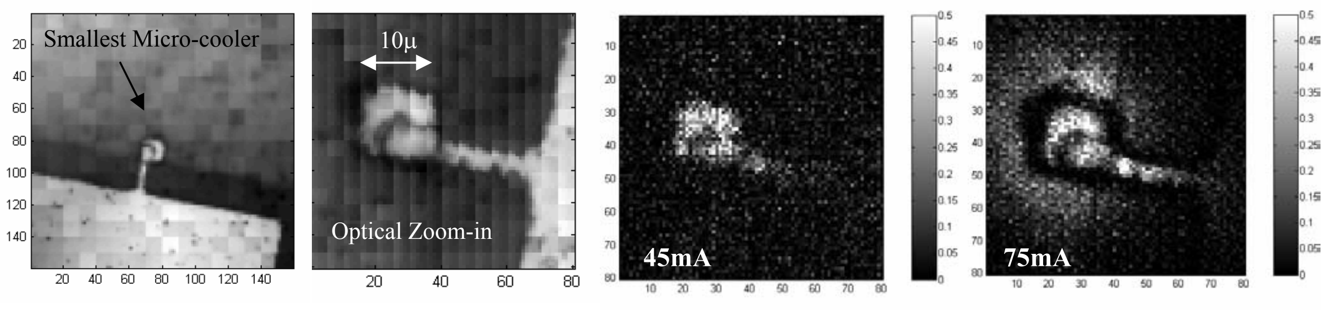

Figure 7: Images, and Thermal images of the smallest micro-cooler. This is approaching the resolution limit of the imaging system. At low currents the device cools by about 0.5C below the ambient, while at higher current the heat conduction from the substrate limits the device performance.