High-resolution thermoreflectance microscopy

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ABSTRACT

We present very high-resolution thermal microscopy using the technique of thermoreflectance, a non-contact measurement of the temperature in and around active semiconductor devices. By measuring the local change in reflectivity and comparing to the optical index versus temperature for the interface materials, thermoreflectance can determine the local temperature distribution. Thermoreflectance allows us to work at wavelengths much smaller than those used in typical blackbody imaging, and thus the spatial resolution is significantly improved over that of traditional thermal microscopy. In our experimental setup, we have a confocal scanning optical microscope with a tunable laser, where reflected light is detected by a silicon photodiode in a heterodyne scheme. The sample consists of a 600 nm wide poly-silicon wire embedded in silicon dioxide on top of a silicon substrate. Varying the amount and temporal shape of the current through the poly-silicon wire, we generate a controlled thermal profile to test the imaging capability. Our preliminary results indicate sub-micron thermal resolution.

INTRODUCTION

Thermal microscopy is used widely in the semiconductor industry to determine the temperature in and around active devices. The traditional method used in thermal microscopy is blackbody imaging at infrared wavelengths. However, because wavelengths in the blackbody thermal regime are typically several microns [1], diffraction limited microscopy provides resolution about ten times the size of today's devices (which can be as small as 0.13 μm). The obvious solution to this problem is to decrease the wavelength to the order of magnitude of the structures one wishes to resolve. By heating the sample significantly above the ambient temperature, blackbody imaging can be conducted at reduced wavelengths. However, if one wishes to test the device under normal operating conditions, other methods must be used.

A promising solution is offered by the technique of thermoreflectance. Thermoreflectance is based on the change of refractive index of materials as a function of temperature. Because of this, the intensity of reflected light, R, can be related to temperature, T, in the following manner [2]:

$$\frac{\Delta R(T(t))}{R} = \left[\frac{1}{R}\frac{\partial R}{\partial T}\right]\Delta T(t) = C_{th}\Delta T \qquad (1)$$

Thus, relative temperature can be found by determining the change in reflectance. The advantage is that thermoreflectance allows one to work with light at wavelengths much smaller than that of blackbody imaging, so both spatial and thermal resolution can be significantly improved. Additionally, absolute temperature readings can be determined by finding the initial temperature using a thermocouple [3]. The thermoreflectance constant, C_{th}, is dependent on the material. For silicon, C_{th} is approximately 1.5×10^{-4}, and for most metals it is on the order of 1×10^{-5} [4]. The theoretical limit for thermal resolution using the thermoreflectance technique is 10^{-3} K [1]. In this paper, we examine the conditions which yield the optimal spatial and thermal resolution using thermoreflectance imaging.

EXPERIMENTAL SETUP

The test sample consists of poly-silicon micro-wires of approximately 1 mm lengths and of varying widths on a silicon substrate. The minimum line width is 0.6 μm. Temperature of the lines is controlled by joule heating.

A confocal microscope setup (Fig. 1) capable of operating at wavelengths up to 900 nm is used in conjunction with a tunable cw-Ti:Sapphire laser. Sub-micron scanning is achieved using an x-y-z piezoelectric sample stage. For our purposes, line scans are sufficient, so a silicon p-n photodiode detector is used, opposed to an expensive CCD camera. To obtain the sensitivity needed to detect the small changes in reflectance on the order of the thermoreflectance constant, a lock-in amplification scheme is used [5]. The heating of the metal line is temporally modulated with a square wave pulse.

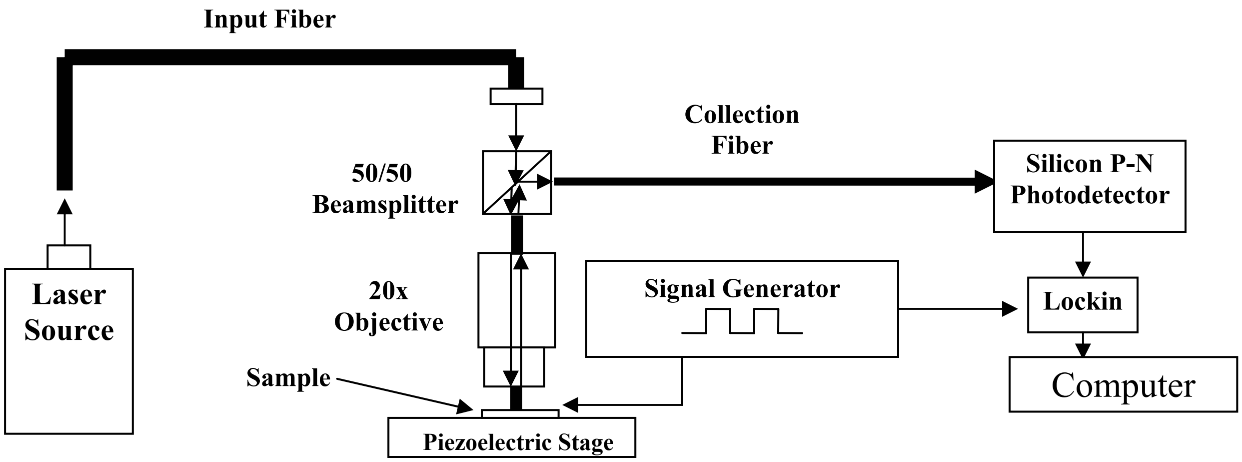


Figure 1. Confocal microscope setup. Both the modulation frequency heating the sample and the wavelength can be varied.

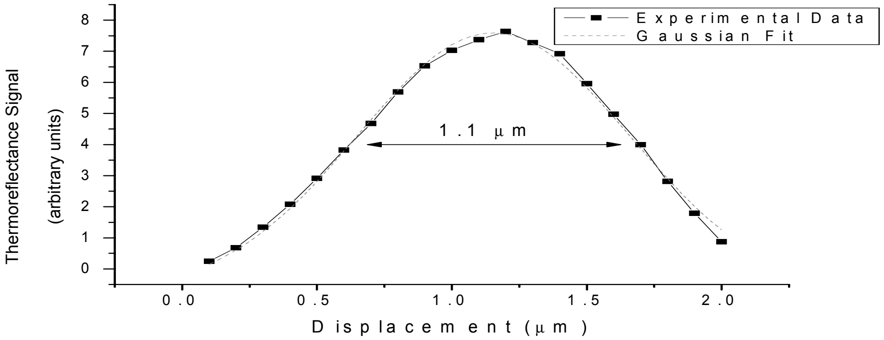


Figure 2. Line scan of 0.6 μm line using 632 nm laser light with electrical modulation of ~500 Hz.

RESULTS

Fig. 2 shows a thermal line scan fitted with a Gaussian. The measured temperature distribution is a result of the convolution of the spot size of the probe beam and the physical shape of the line itself. We assume temperature distribution is Gaussian with a line width equal to the width of the poly-silicon line. Using the smallest line available on the sample (0.6 μm), the resolution was calculated to be about 0.9 μm, which is approximately the diffraction limit.

In order to characterize the performance of our system, we first investigated the effects of changing the modulation frequency. We propose that two phenomena determine the magnitude of the thermoreflectance response with varying modulation frequency. The first is a systematic one: integrating over the same amount of time, a higher modulation frequency yields a more accurate thermoreflectance response because of the larger sampling of data. The second phenomenon is due to the material composition of the sample. There is an intrinsic rate of thermal diffusion associated with every material. If the modulation frequency exceeds the material's ability to channel away the heat, the sample will eventually reach a steady state temperature and there will be no thermoreflectance signal to measure. Shown in Fig. 3 and 4, the limit where this phenomenon starts to take effect is at about 500 Hz for our imaging system and sample.

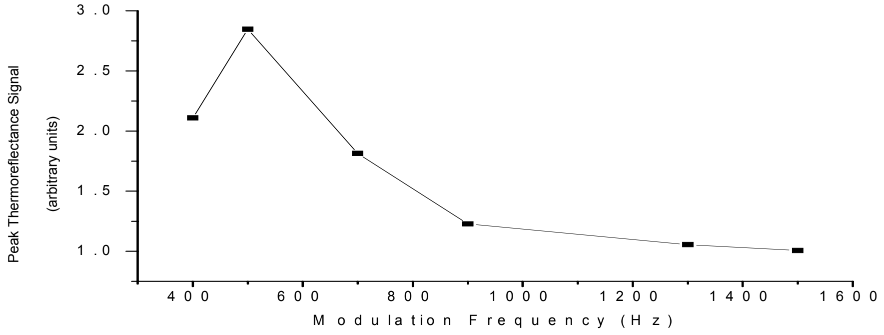
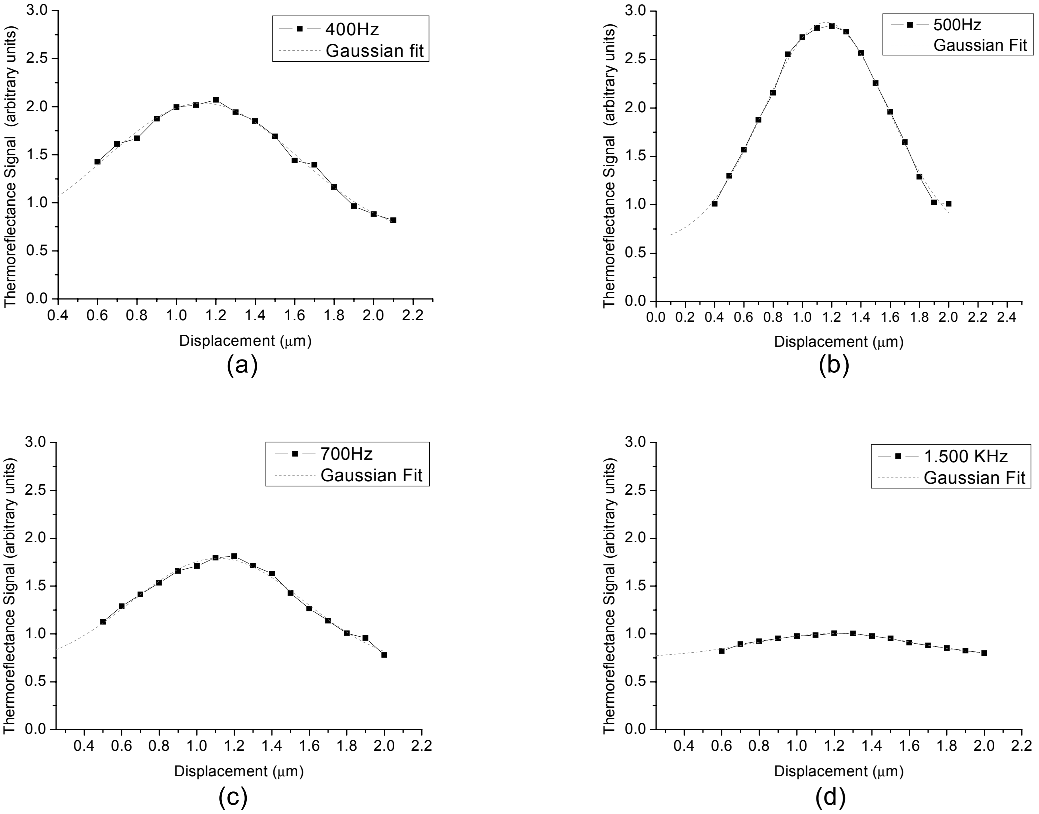


Figure 3. Peak thermoreflectance signal as a function of electrical modulation frequency of the sample. At high frequencies, the signal falls off exponentially as the sample reaches a steady state temperature.



(a) (b) (c) (d)

Figure 4. Line scans of 0.6 μm line at varying electrical modulation: 400 Hz (a), 500 Hz (b), 700 Hz (c), 1.50 KHz (d). At 500 Hz, the thermoreflectance signal is well-defined and exhibits a strong peak. At 1.50 KHz, the signal is barely distinguishable.

We also characterized our system by studying its behavior as a function of wavelength. Shown in Fig. 5, peak thermoreflectance signal is fairly constant at wavelengths below 850 nm (Area 1). In the region between 850 and 930 nm (Area 2), the peak thermoreflectance signal dropped, while above 930 nm (Area 3) the signal began to increase. We assert that the thermoreflectance response as a function of wavelength (Fig. 5) is again a combination of system limitations and physical effects. The system effect in this case is due to the optical components of the microscope. Spherical aberrations in the lenses, as well as attenuation in the optical fibers, degrade the performance of the system above 900 nm, resulting in the sharp dip in Area 2. The other effect is the presence of the band-gap energy of silicon at 1.1 μm. As the probe light approaches this wavelength (Area 3), there is an enhancement in the thermoreflectance due to a greater change in refractive index of the silicon. However, in this area the spherical aberrations in the optics are still present, so although the peak signal is high, spatial resolution continues to degrade. Area 1 depicts the region where the wavelength is too far from the band gap to observe any noticeable enhancement and consequently the optical response of the system is constant.

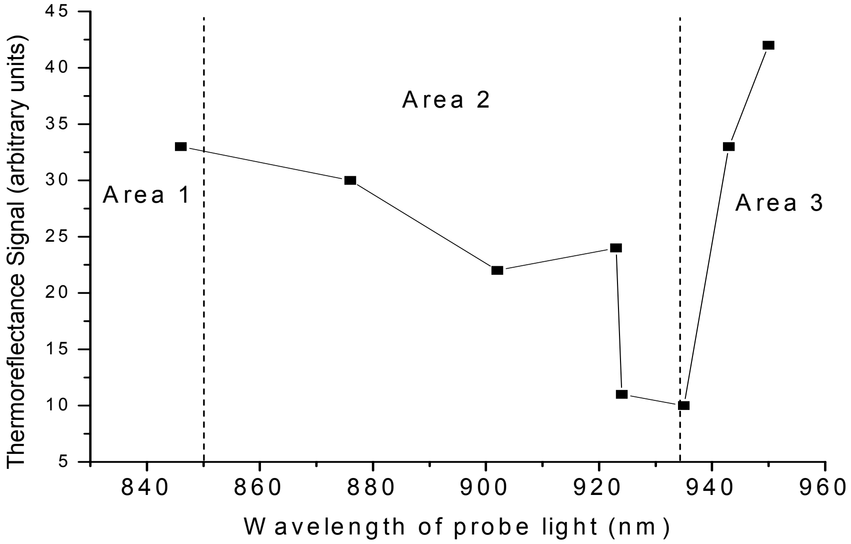


Figure 5. Peak thermoreflectance signal as a function of wavelength of probe light.

CONCLUSION

We have demonstrated the ability of thermoreflectance to resolve sub-micron thermal changes, achieving a spatial resolution of 0.9 µm. First, we found that the thermoreflectance signal is a function of modulation frequency. It is critical to determine the optimal modulation frequency for both the optical system and the sample. We also found that the magnitude of the thermoreflectance signal increases as one approaches the band-gap wavelength of silicon. Although our system did not allow for this, further research is being carried out to investigate probe wavelengths above 1.1 µm. The added benefit of using such wavelengths is that silicon becomes transparent, allowing subsurface features to be thermal imaged. The direct application of this ability is to the microchip industry where previously inaccessible microelectronics can be thermally imaged through the substrate without the interference of topside metallization. Going through the backside of the substrate would also allow for use of a solid-immersion lens to achieve spatial resolutions beyond the diffraction limit of light in air [6, 7].

ACKNOWLEDGEMENTS

The authors would like to thank the DARPA HERETIC as well as the Boston University UROP program for their support.

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