Through the Substrate, Backside Thermal Measurements on Active Semiconductor Devices Using Near IR Thermoreflectance

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Abstract

Topside, thermal imaging on micro-devices using visible wavelength thermoreflectance has previously been demonstrated with sub-micron spatial and 100mK temperature resolution. Now, by using a laser with a wavelength that is transparent to the substrate, the temperature of active semiconductor devices can be measured from the backside, through the substrate using the same thermoreflectance technique. Point measurements on Si/SiGe based thin film micro-coolers grown on Silicon substrates are performed using a 1310nm laser. Temperature resolution better than 100mK has been achieved through a 200micron substrate. Preliminary thermal images are also presented.

Keywords

Thermal Imaging, Thermoreflectance, Backside Imaging, Through the substrate imaging.

Introduction

Thermal characterization of active semiconductor devices is important for the design of reliable semiconductor components, and can also be used for failure inspection. We have previously demonstrated a thermal microscope with 100mK temperature resolution and sub-micron spatial resolution when visible light is reflecting off the topside IC chip [1,2]. The microscope is based on thermoreflectance, a well-known method that exploits the temperature dependence of the reflection coefficient [3,4]. Figure 1 shows an active micro-heater structure fabricated on top of a 50x50 micron thin film micro-refrigerator [5]. The image indicates that although the heater heats 8 degrees from the ambient temperature the structure has a short in the last rung due to a fabrication error. Such failures are easily identified with thermal imaging.

By using laser light that is transparent to the substrate, the thermoreflectance microscope can also be used to obtain thermal measurements through the substrate by reflecting off the backside of the metal. In developing this methodology we hope to be able to easily measure failures in bonded 'Flip Chip' IC's.

Thermoreflectance Temperature Measurements

Thermoreflectance temperature measurements exploit the change in the reflection coefficient with temperature. Typically, for metals, the reflection coefficient only changes by one part in 10^4 -10^5 per degree, and thus a differential measurement on active devices is necessary to obtain high signal to noise. The reflection coefficient of the sample is the initial reflection coefficient at ambient, R_0, plus the change in the reflection coefficient due to device excitation:

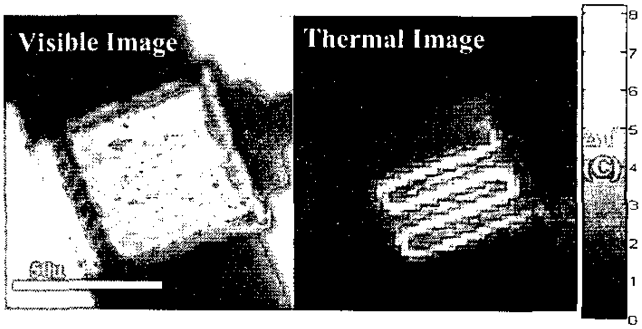

Fig 1: Topside visible image, left and thermoreflectance thermal image, right of active micro-heater structure. The therma image indicates that there is a short in the last rung of the heater due to a fabrication error.

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

Let I_{ref} be the thermoreflectance probe intensity reflected from the sample, and acquired by a photo detector, and I_{in} be the incident intensity on the sample. In the simple topside case where there is only one reflection surface, one can write:

$$I_{ref} = I_{in} R_0 + I_{in} \frac{dR}{dT} * \Delta T$$

In order to measure the small changes in reflectivity, the device is modulated at a frequency ω and a lock-in amplifier is used to measure I_{ω}, the reflected intensity at ω. The DC terms can be ignored;

$$I_{\omega} = I_{in} \frac{dR}{dT} * \Delta T \qquad C_{th} = \frac{1}{R_0} \frac{dR}{dT}$$

It is convenient to introduce C_{th}, the wavelength and material dependent thermoreflectance coefficient which can be obtained with an external calibration[6], and I_{in}*R_0 is simply the unmodulated, DC reflectivity of the sample. Now we have a simple expression relating the device excitation temperature to experimentally obtained intensity values;

$$\Delta T = \frac{I_\omega}{(I_{in} * R_0 * C_{th})}$$

Therefore, the experimentally obtained change in device temperature is the modulated signal intensity divided by the normalization, which is the unmodulated DC reflection magnitude, times the thermoreflectance coefficient.

Backside Thermoreflectance

When attempting thermoreflectance through the substrate, multiple reflection paths between top and bottom surfaces, and absorption in the substrate should be considered. A schematic of the backside thermoreflectance is shown in figure 2. The figure shows the main thermal sources under a device excitation, the induced temperature change from the device itself, as well as the bulk Joule heating from the current flow through the substrate. From the backside of the device, two different measurements can be performed. By using visible light, the probe will not penetrate into the substrate and the heating at the bottom surface of the substrate will be measured. However, with a laser that has low absorption in the substrate, the resulting light will be a combination of the thermoreflectance signal off the bottom of the substrate, as well off the underside metal of the device. Figure 2 illustrates the contributions for through the substrate thermoreflectance. R_1, and R_2 represent the reflection coefficients off the bottom surface, and the underside metal, C_{th1} and C_{th2} represent the the thermoreflectance coefficients off these two interfaces, and ΔT_B and ΔT_D represent the temperature change at the bottom substrate and the device-metal interface. Because the micro-cooling layer of the device has nearly the same index as the substrate, the reflection contribution from this layer is neglected. First consider the contribution from the bottom substrate thermoreflectance. For a first order model one can start with the reflected intensity that we see at the detector:

$$I_{ref} = I_{in} R_1 + I_{in}(1 - R_1)^2 R_2 e^{-2\alpha x}$$

Where the first term in the sum is the light that is initially reflected off the bottom surface, and the second term is the contribution that is transmitted, absorbed, and reflected off the metal. The higher order reflections are neglected in this simple analysis. Now we are interested in the change at the bottom surface under device excitation;

$$I_{ref} = I_{in}\left(R_1 + \frac{dR_1}{dT} * \Delta T_B\right) + I_{in} R_2 e^{-2\alpha x}\left(1 - R_1 - \frac{dR_1}{dT} * \Delta T_B\right)^2$$

The expression can be simplified by neglecting DC terms and second order effects to yield an expression proportional to the temperature change on the bottom surface;

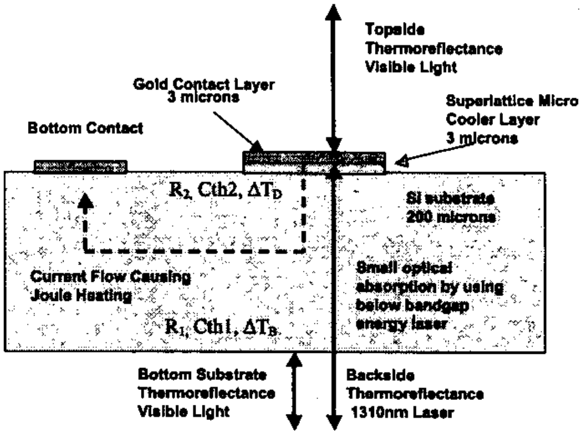

Fig 2: Cross Section of Structure. When Biased, a Temperature Gradient Occurs Across the Cooling Layer, the Sign of Which Depends on the Current Polarity

$$I_\omega = I_{in}\left(1 + 2R_2 e^{-2\alpha x}(R_1 - 1)\right)\frac{dR_1}{dT} * \Delta T_B$$

Next we consider the thermoreflectance contribution from the underside of the device metal, and use the definition of the thermoreflectance coefficient:

$$R(T) = R_2 + \frac{dR_2}{dT} * \Delta T_D \qquad C_{th} = \frac{1}{R}\frac{dR}{dT}$$

The final expression indicates the measured signal from the lock in is a contribution of the temperature change at the bottom of the substrate and the underside of the device.

$$I_\omega = \left[I_{in}\left(1 + R_2 e^{-2\alpha x}(R_1 - 1)\right)R_1 C_{th1}\right] * \Delta T_B + \left[I_{in} R_2 (1 - R_1)^2 e^{-2\alpha x} R_2 C_{th2}\right] * \Delta T_D$$

Unfortunately The thermoreflectance coefficients of the 1310 laser incident on the air-substrate interface, C_{th1}, and the substrate-metal interface C_{th2}, are not known. However, by using calibrated topside visible light measurements, the temperature as measured through the substrate can be compared to topside results, as the thin metal should be the same temperature on the top and bottom. For the thermal measurements of the micro-coolers it is expected that there is not much temperature change on the bottom of the substrate, and the main contribution should be from the temperature of the device.

Experimental Setup

The experimental setup is shown in Figure 3. Topside light from a quartz tungsten halogen (QTH) illuminator is reflected from the sample and the image is captured by an infrared sensitive camera, while simultaneously, a 1310 nm, 5mW laser diode is focused on the underside of the active device under test. With this configuration, the location and

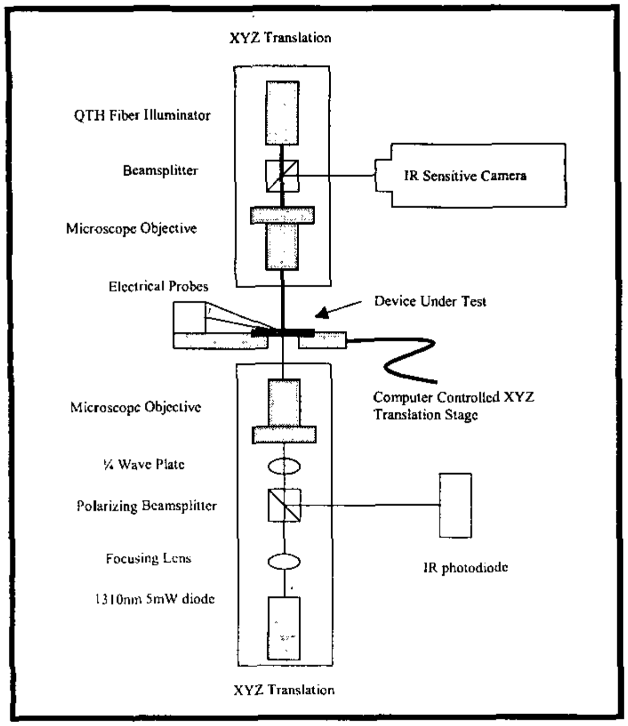

Fig 3: Experimental setup for through the substrate thermoreflectance measurements

size of the laser spot can easily be seen as in figure 4. Figure 4 shows the device under test and the laser spot that is used for the backside thermoreflectance temperature point measurement. In order to obtain high signal to noise the device must be thermally cycled, and the resulting reflected light is amplified and filtered with a lock-in amplifier. Figure 4 shows that there is some distortion in the laser spot due to the fact that the bottom surface is not polished to be optically flat and there is some scattering in the substrate, which may limit the spatial resolution of this technique especially in imaging experiments. Others [7] have suggested the necessity of surface preparation, including the use of an anti reflection coating, to ensure high signal to noise measurements. For point measurements we have a laser spot that appears on the order of 20 square microns.

Point Measurement Results

Figure 2 is a schematic of the measurement. We are mainly interested in the temperature of the gold contact layer on top of the micro-cooler as measured from the backside and reflecting off the underside of the metal.

The temperature of the micro-cooler device as a function of the bias current can be represented by the following equation.

$$\Delta T_D \propto \alpha I + \beta I^2$$

Where α is a constant describing the Peltier cooling, while β is the heating constant from the non-zero device resistance, and I is the applied current. When the sign of the current is negative, the device can cool, until the quadratic heating from the device resistance becomes greater. This equation leads to the typical quadratic cooling curve as measured by the topside temperature shown in figure 5.

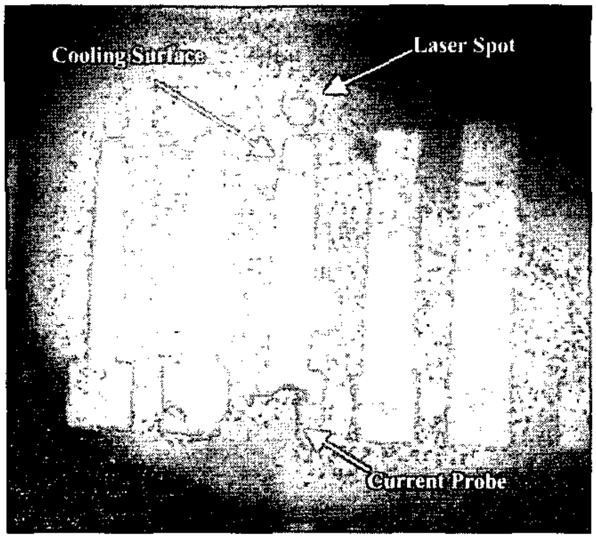

Fig 4: Scheme for laser alignment, topside light illuminates the device while the 1310nm laser penetrates from the bottom.

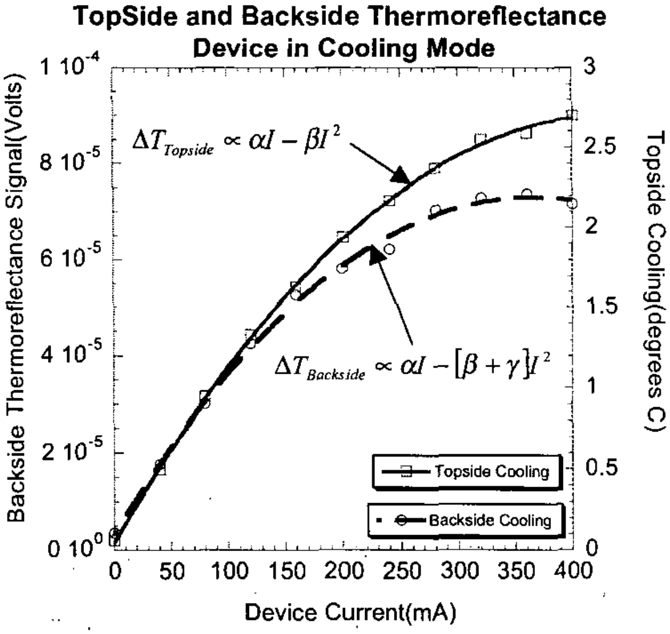

Fig 5: Device cooling performance as measured from the topside, and through the substrate. The curves do not overlap because the backside measurement is a combination of the device temperature and the heating at the bottom of the substrate.

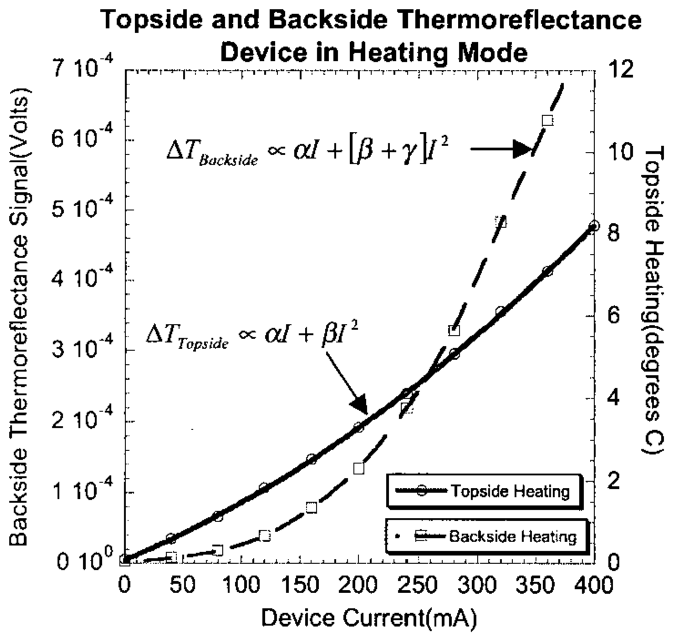

Fig 6: Micro-cooler operating as a heater as measured from the topside and through the substrate. The backside measurement has a higher quadratic term because of the added Joule heating in the substrate

From the backside however the temperature measured as a function of device current can be written;

$$\Delta T \propto \alpha I + [\beta + \gamma] I^2$$

The introduced term γ represents some contribution from the heating in the substrate that is measured by the thermoreflectance probe. Since this source of heating is far from the device, it is not measured from the topside. As expected, shown in figure 5, the temperature change as a function of bias current measured from the backside exhibits a higher quadratic coefficient.

Because the topside light has previously been calibrated, figure 5 indicates that the maximum measured cooling change from the ambient stage temperature of 25C is about 2.7 degrees C. From the curves we can estimate that that the temperature resolution of the backside measurement is better than 100mK, when using a 1 second integration time.

In figure 6 the temperature of the device was measured from the topside and backside, with the opposite current flow. In this case, the α and β terms add together, and the mico-refrigerator becomes a heater. The results are as expected, that the topside and backside measurement show device heating, but the backside shows a higher quadratic dependence on bias current from the additional heating term from the substrate resistance.

Figures 5 and 6 demonstrate that through the substrate point measurements are possible with good signal to noise.

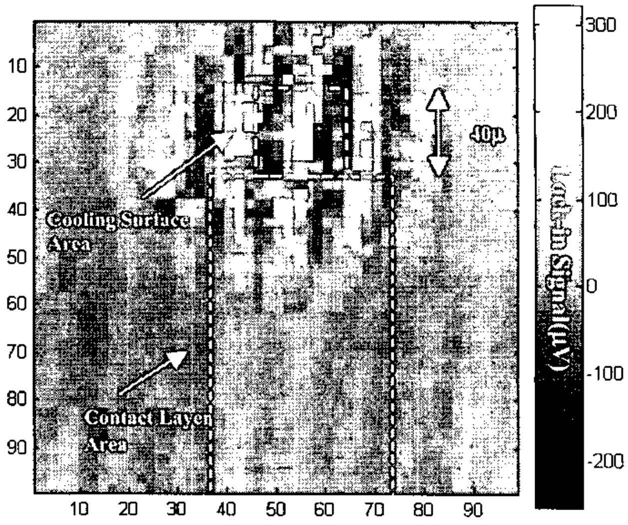

Fig7: Scanned Thermal image acquired through the substrate of the active micro-cooler. The data indicates that the substrate makes a Fabry-Perot etalon, which distorts the image as the laser scans because the sample is not lapped exactly flat. By using an anti-reflection coating this distortion should be reduced.

However, more work needs to be done to determine the thermoreflectance coefficients of the air-substrate interface, and the substrate-metal interface so that the Joule heating in the substrate can be subtracted in order to obtain accurate backside device measurements.

Thermal Imaging Results

Once the point measurements were acquired, the next step was to attempt laser scanning for thermal imaging of the device under test. Figure 7 shows the magnitude of the lock-in signal scanned over a 200x200 micron region around the active device. The dotted lines indicated the approximate position of the device under test. There is a periodic variation in the thermal image due to the Fabry-Perot etalon created by the substrate, and the fact that the substrate of the sample has not been lapped perfectly flat. This shows up in the image as bands across the image. However, one can see the temperature change due to the device. In addition to the reflection off the metal, the image indicates that there is also some contribution around the device. This is because the substrate-air interface reflects the laser, and thus the points that are off the metal are the measured thermal signal of the top substrate-air interface around the device. The next step for thermal imaging will be to use an anti-reflection coating which would reduce the contribution from the Joule heating in the substrate and the Fabry-Perot effect.

Conclusions

Single point thermoreflectance measurements were acquired through the substrate from the underside of an active device by using a 1310nm laser that is transparent to the substrate. The results indicate that the thermal signal is a contribution from the device and also the heating in the substrate. Such measurements are possible and better than 100mK temperature resolution has been demonstrated through a 200micron substrate. However, backside measurements are more complex than the simple topside thermoreflectance, because of the different, multiple reflection surfaces. In addition scanned thermal imaging was performed through the substrate, but the results indicate the necessity of using an anti-reflection coating to reduce the Fabry-Perot effect inside the substrate. One potential application for developing this technology is for failure inspection of 'Flip Chip' bonded IC's, where hot spots indicating failures of active devices could easily be located.

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