Transient response of thin film SiGe micro coolers

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ABSTRACT
The transient response of thin film SiGe micro coolers is measured using a thremoreflectance technique. Response time on the order of 20-40 μs is obtained. The effect of device size and substrate thickness was investigated.

1 Introduction

There are many applications where micro coolers are needed. Telecommunications lasers require a high degree of temperature control because their wavelength and power output are very temperature sensitive. Infrared detectors also need cooling because they have a much greater sensitivity at lower temperatures. One of the main factors that limits speed and miniaturization of very large scale integration (VLSI) circuits is their heat dissipation. Currently, conventional thermoelectric (TE) devices are used in many of these applications.

Several features of thin film SiGe micro coolers give them an advantage over conventional bismuth telluride-based TE coolers in optoelectronic and electronic applications. They are better suited for applications where the needed cooling area is small and cost and reliability are important factors. Thin film SiGe micro coolers have the advantage of being fabricated from conventional semiconductor materials with processes that have been refined by the semiconductor manufacturing industry. This gives the possibility of monolithic integration with the devices to be cooled (Shakouri, et. al. 1997). The small size of thin film coolers will also permit much faster temperature control.

The characterization of the transient response of thin film SiGe micro coolers is needed to evaluate their applicability to cool modern electronic and optoelectronic devices

2 Background

The transient measurement was made using the thermoreflectance technique. All materials have the property that the amount of light they reflect is dependent on their temperature. The thermoreflectance coefficient is the amount of change in reflected light from a material due to a change in temperature. A light source is reflected from the surface to be measured, and the reflected signal gives the relative temperature change. This method has been used to measure the steady-state temperature distributions in metal interconnects

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(Quintard, et. al., 1999). This method has also been used to obtain high-spatial resolution thermal images of SiGe micro coolers (J. Christofferson, et. al. 2001). The thermoreflectance method is not limited by the thermal mass of the sensing element in contact with the device to be measured and it has been demonstrated as a valid and effective method for short time-scale thermometry by the creation of thermal maps of transistors and metal interconnects on a 10 ns time scale (Ju and Goodson, 1998).

Figure 1 shows a cross-section of the devices. They were fabricated on Si substrate. The main part of the cooler is a 3 μm $Si_{0.8}Ge_{0.2}$ layer doped with boron to about 5×10^{19} cm^{-3}. This layer was grown using molecular beam epitaxy (MBE). Since the lattice constant of SiGe is different from Si, in order to grow couple of microns thick layers, a buffer layer is required. Following the barrier growth, a 0.3 μm $Si_{0.8}Ge_{0.2}$ cap layer was grown with a boron doping of 2×10^{20} cm^{-3} to get a good ohmic contact to the device. The SiGe micro coolers are fabricated with standard silicon integrated circuit technology. The cooler device areas were defined by etching mesas down to the SiGe buffer layer. Ti/Al metallization was made on top of the mesa and on the SiGe buffer layer next to the mesa for top and bottom contacts respectively. SiGe micro coolers with mesa sizes ranging from 30×30 μm^2 to 150×150 μm^2 were fabricated on the same wafer (Fan, et. al. 2001).

Theoretical predictions of the response time of the SiGe micro coolers must take into account several factors. The heating and the cooling due to the thermionic and thermoelectric effects are expected to happen almost instantaneously at different interfaces of the device with a response on the order of electron-phonon energy relaxation time. The Joule heating is happening in the bulk resistive regions. Because thermoelectric/thermionic cooling and Joule heating have different bias dependencies, the former is proportional to current and the latter is proportional to square of current, there is an optimum current for which maximum steady state cooling happens. (Shakouri et. al. 1998) The relative temperature change is measured on the top metal surface of the device when a current pulse is applied. The response time is determined by the transient heat conduction through the device as well as the transient response due to the different thermal masses connected to the device (metal contact layer, substrate, etc.).

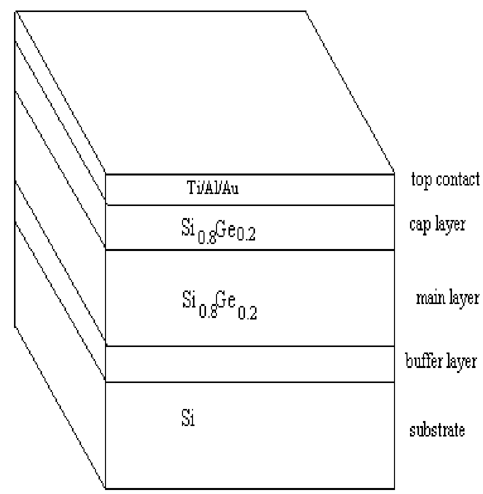

Figure 1 - cross section of SiGe micro cooler.

3 Experimental Set-up

In order to measure the transient response, SiGe micro coolers were excited with current pulses and the cooling was measured on a microsecond time scale. A laser was reflected from the top, cooling surface of the device and the reflected signal was measured. The transient response was characterized from the measurements. A schematic experimental setup is shown in Figure 2.

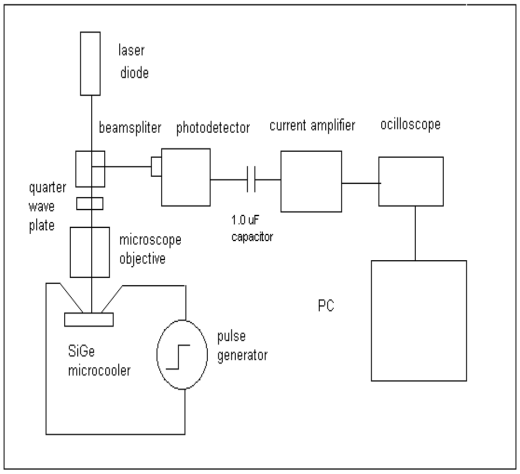

Figure 2 - Schematic of experimental Setup for measuring the transient response SiGe micro coolers

A pulse generator provides the excitation signal to the device. A 10-mW laser diode is focused on the device using a microscope objective. A were used to route the reflected laser signal. The signal was measured by a photo-detector with a built-in amplifier stage. A 1.0 µF capacitor was used to AC-couple the signal to a current amplifier. The signal was then sent to digital oscilloscope. A PC was connected to the oscilloscope through a GPIB port to provide the necessary data analysis. Averaging was used on the data to reduce the noise.

4 Results

A measurement of the response time of the optical system was first made to determine the limits of the experimental set-up. Figure 3 shows the response of the system, which was generated by modulating the laser diode driver with a square wave. The response is on the order of 13 µs, with an additional 2 µs delay.

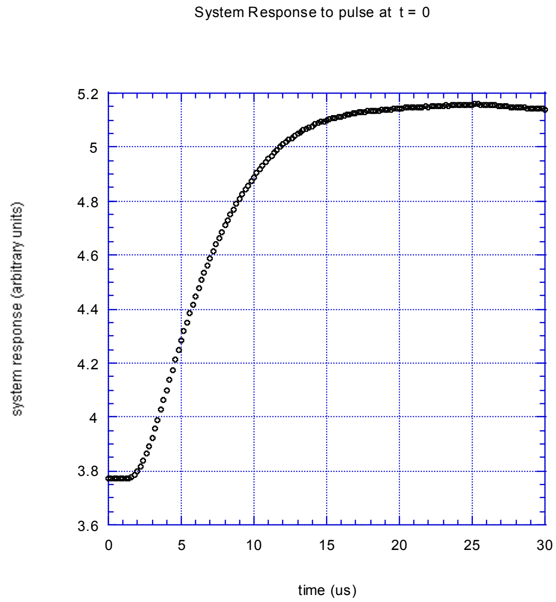

Figure 3- System response to an applied pulse.

Various measurements of cooling signals were then taken on different size devices. Figure 4 shows the response of two coolers of different sizes. The measured response time is on the order of 20 to 30 µs.

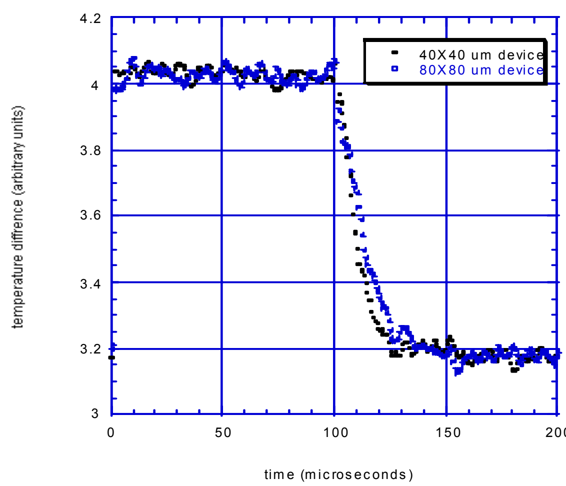

Figure 4- Temperature change of two coolers of different dimensions as a function of time. The response time is on the order of 20 to 30 microseconds.

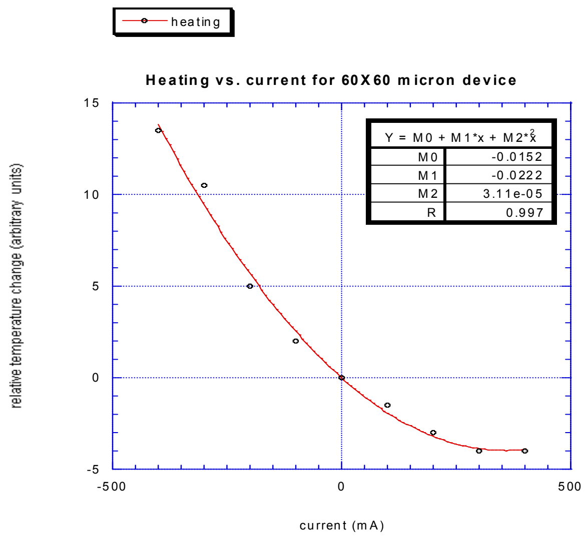

Figure 5 – Magnitude of cooling signal as a function of current. The curve is quadratic because of Joule heating.

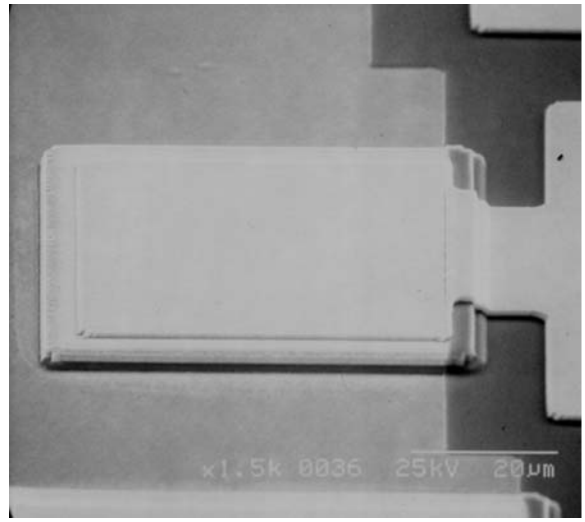

Figure 6 – Image of 60x60 micron cooler taken using a SEM at UCSB.

Figure 5 shows the amplitude of the cooling signal measured as a function of current. It is a quadratic because the Joule heating is dependent on the square of the current while the thermoelectric and thermionic cooling varies linearly with current. This measurement verified that the measured signals were in fact the real cooling and heating signals. The absolute amount of cooling was characterized using a micro thermocouple probe with DC current. At 300mA, 3-4C cooling was obtained.

Measurements were taken to determine the heat conduction through the metal side contact. Figure 6 shows a scanning electron microscope (SEM) image of the cooler to illustrate the relative dimensions. The side contact extends to the right and it provides a contact to the top surface of the device and some thermal isolation from the Joule heating generated by the probes used to apply the current. Figure 7 shows the cooling signal obtained from different regions on a 60x60 µm cooler. Measurements were taken on the cooling surface of the device and on the side contact trace 20 and 50 µm away. The response time measured

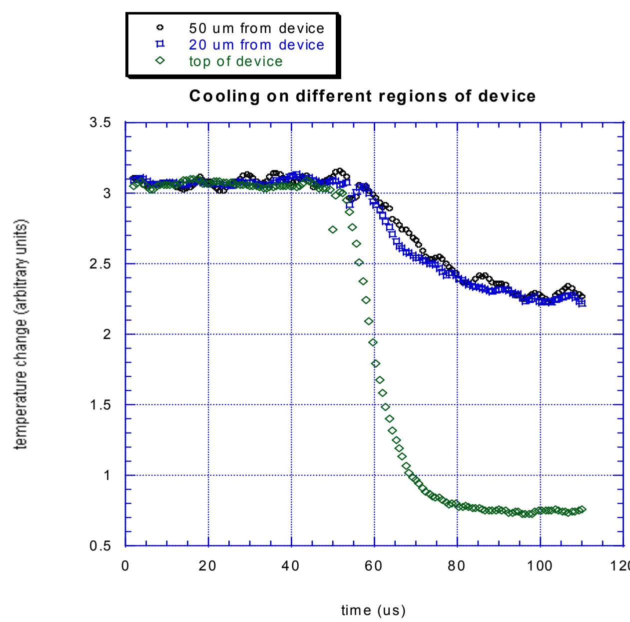

Figure 7 – Cooling of different regions of a 20x20 micron cooler. There is a slower response on the side contact due to the additional thermal mass. The excitation pulse was applied at t = 50µs.

on the surface of the device is on the order of 25 µs, in agreement with other measurements. A slower and smaller cooling signal is observed on the side contact trace due to the additional thermal mass involved.

Measurements were also taken to determine the effect that the substrate thickness had on the response time of the device. Two devices were characterized which had the same dimensions except for the thickness of the substrate they were fabricated on, which were 150 and 500 µm respectively. Figure 8 shows the cooling signal obtained from the two 40X40µm devices.

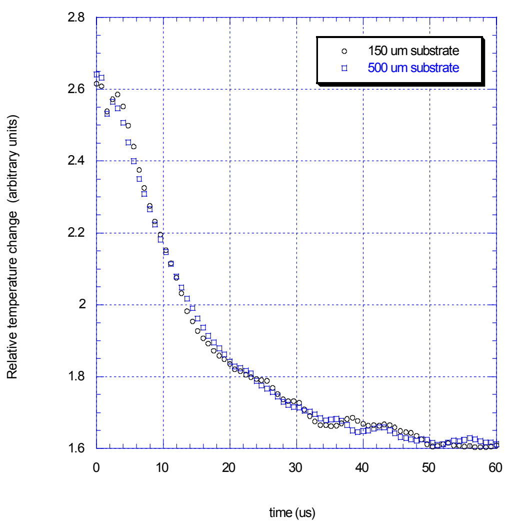

Figure 8 – Cooling signals on two 70x70 micron devices on two different substrate thick nesses.

There is very little difference in the response time. This shows that response time is limited by the top layer structure and not the thermal mass of the substrate.

4 Conclusions and Future Work

SiGe micro coolers have the potential to improve thermal management of high-speed electronic and optoelectronic circuits by providing localized and high density cooling. Measurements of the transient response were made using a thermoreflectance technique. Response times on the order of 20 to 30 µs were measured. This response time is much faster than that of conventional BiTe TE coolers and demonstrates that SiGe micro coolers are better-suited for certain high-speed applications. The response time is approximately independent of device size and substrate thickness. In order to verify these results an electrical measurement based of the time response of the Seebeck effect will be performed.

This measurement would be a good way to verify the results as it is based on completely different phenomena.

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