# Short Time Transient Behavior of SiGe-based Microrefrigerators.

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# Short Time Transient Behavior of SiGe-based Microrefrigerators

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## ABSTRACT

We use a Thermoreflectance Thermal Imaging technique to study the transient cooling of SiGe-based microrefrigerators. Thermal imaging with submicron spatial resolution, 0.1C temperature resolution and 100 nanosecond temporal resolution is achieved. Transient temperature profiles of SiGe-based superlattice microrefrigerator devices of different sizes are obtained. The dynamic behavior of these microrefrigerators, show an interplay between Peltier and Joule effects. On the top surface of the device, Peltier cooling appears first with a time constant of about 10-30 microseconds, then Joule heating in the device starts taking over with a time constant of about 100-150 microseconds. The experimental results agree very well with the theoretical predictions based on Thermal Quadrupoles Method. The difference in the two time constants can be explained considering the thermal resistance and capacitance of the thin film. In addition this shows that the Joule heating at the top metal/semiconductor interface does not dominate the microrefrigerator performance or else we would have obtained the same time constants for the Peltier and Joule effects. Experimental results show that under high current values, pulse-operation the microrefrigerator device can provide cooling for about 30 microseconds, even though steady state measurements show heating. Temperature distribution on the metal leads connected to the microrefrigerator's cold junction show the interplay between Joule heating in the metal as well as heat conduction to the substrate. Modeling is used to study the effect of different physical and geometrical parameters of the device on its transient cooling. 3D geometry of heat and current flow in the device plays an important role. One of the goals is to maximize cooling over the shortest time scales.

## INTRODUCTION

Much work has been conducted in the past to study the cooling performance of SiGe-based microrefrigerators both theoretically and experimentally in steady state or direct current (DC) and alternative current (AC) regimes [1-4]. Both superlattice based on Si/SiGe and also bulk SiGe thin film devices have been fabricated and characterized. Direct measurement of the cooling and cooling power density; along with material characterization have allowed extracting the key factors limiting the performance of these microrefrigerators [5]. SiGe-based microrefrigerators's cooling performance is based on the thermoelectric effect with thermionic enhancement. These devices can be monolithically integrated with Si microelectronics and optoelectronics in the IC industry. They can provide active cooling and offer an attractive, green and silent way to eliminate hot spots [5], thus the transient thermal behavior is important not only for improving device performance but to verify thermal models. It is well known that bulk material BiTe thermoelectric devices can have better cooling performance under pulsed mode operation [6], meaning that they can momentarily reach a colder temperature than when measured in the steady state. A similar behavior was predicted for the 3D SiGe-based thin films microrefrigerators devices. However limited metrology methods have prevented measurements.

## EXPERIMENT

To investigate the transient thermal behavior of thin film superlattice microrefrigerators, we have used Thermoreflectance Thermal Imaging technique (TRI) [7]. TRI is one of the most sensitive thermal measurement techniques and offers much higher spatial, thermal and temporal resolution than infrared (IR) imaging. It is an optical non contact and non destructive tool for device thermal characterization that is based on the very small (0.01% per degree C) temperature dependence of the material reflection coefficient [7-9]. It is an active technique that uses light of the visible spectrum, usually a blue (~450nm) or green (~530nm) light emitting diode (LED), but in general can be optimized to the surface material of the device under test [7-9]. For thermal transient measurements, TRI is advantageous because it is an active technique. During the device's heating cycle, very bright, short light pulses are reflected off the device, and the duration of the LED light pulse is what determines the temporal image resolution.

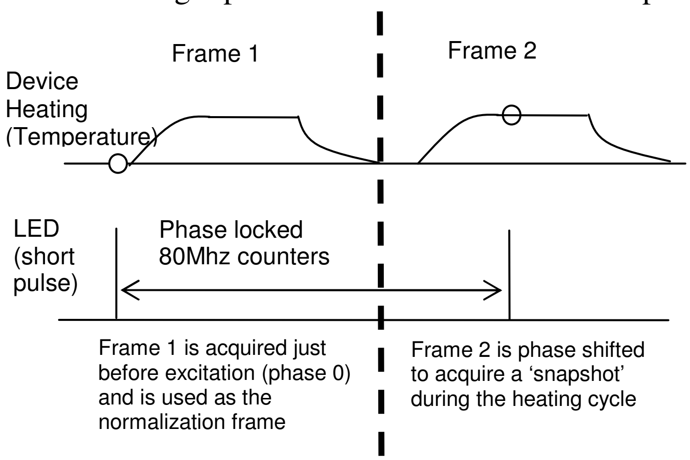


**Figure 1:** Transient thermal imaging scheme, illustrating timing of a short pulse LED for acquisition of a thermal *"snapshot"* of the device during the temperature cycle. By utilizing separate phase locked, programmable counters, different phases of the temperature cycle are obtained.

Using TRI, thermal transient information can be obtained using time domain or frequency domain techniques [8, 9]. The main challenge of such measurements is to resolve the small thermoreflectance signal among the various noise sources in the lab, and so extensive image averaging, and filtering is used. In this experiment, we have pursued a time domain, pulsed illumination technique, for several reasons, one primary reason being the simplicity in set-up, and lack of complex computer computation on the high-resolution CCD data, allowing for more averaging per unit time. Additionally, visualization of the time domain transient response is sometimes more intuitive, and results can be analyzed using Network Identification by Deconvolution (NID) method [10]. The latter is a powerful method to extract information about the various thermal resistances and capacitances of the device under study along the heat flux propagation path. Finally, by utilizing a high speed imaging laser diode that can be pulsed on the picosecond scale, the time domain transient TRI technique has the potential to provide ultra-short time scale (~ps) thermal images for characterization of material properties under excitation from a heating laser. The transient TRI experiment presented here utilizes a similar principle to the Pump-Probe Transient Thermoreflectance experiment performed with a femtosecond laser [11]. The primary difference being that in the case of transient TRI, the heating is created electrically rather than optically. In this experiment, the present limit for short time scale thermal imaging is 100ns, limited by the short pulse turn-on time of the LED used. At higher speeds, care must be taken to provide high-speed packaging for the LED, and additionally coaxial biasing probes must be used for device biasing.

Previous work on CCD based thermoreflectance transient measurements [12] used a very simple single pulse "*boxcar averaging technique*", which is sufficient to find transient information to the microsecond scale, however, as the time resolution increases (shorter light pulses) there is less light available on the CCD and the temperature sensitivity is decreased. The solution allowing for 100ns images, depicted in figure 1, is to provide many short light pulses for each CCD frame, and as long as we maintain precise timing (phase lock) between the device excitation pulse, and the LED illumination pulse, it becomes possible to obtain a single thermal *"snapshot"* of the device heating at a precise time in the heating cycle. The system was implemented using a combination of National Instruments programmable counter/time boards and TTL logic, necessary for the precise timing of signals. Because of the small thermoreflectance coefficient $\kappa$ it becomes necessary to compare the value of the reflection coefficient at any time in the heating cycle to the value when the device is 'off' $R_0$, which removes the large DC term. At any time of the heating cycle, the CCD frames are averaged and differenced to obtain the change in the reflection coefficient ($\Delta R/R_0$) which is proportional to the change in the device surface temperature ($\Delta T$) as function of time $\Delta R/R_0(t)=\kappa\times\Delta T(t)$. More technical details on the experiment can be found in the recent work of Christofferson et al [13].

## THEORY

Modeling of the transient cooling performance of the 3D SiGe microrefrigerator is based on Thermal Quadrupoles Method (TQM) [14]. The TQM is a general analytical model that can be used to calculate electrical and thermal responses in a 3D geometry and in the AC regime, thus making it possible to distinguish, in some cases, the Peltier effect from the Joule effect. In the case of a pure sine wave electrical excitation, the Peltier effect appears at the same frequency as the operating current, whereas the Joule effect appears at the double frequency. The TQM is based on the solution of the one-dimensional Fourier's Heat Diffusion Equation in Laplace domain with a zero initial temperature. The TQM was used successfully to model the steady state and dynamic cooling performance of 3D SiGe based microrefrigerators [3, 4] and the results agree very well with thermocouple, and TRI measurements.

In the modeling of the transient cooling behavior, the microrefrigerator is assumed to be excited by a step electrical current and the top surface temperature variation as a function of time is calculated by taking into account all possible mechanisms of heat generation and conduction within the entire device. 3D heat and current spreading in the substrate is taken into account using analytic formulas. Besides, heat generation and conduction in the top metal lead of the device is also calculated using TQM. Because of the small temperature variations, all material properties are considered to be temperature independent [4]. In this paper, one will limit oneself to only discuss the theoretical predictions in comparison with some experimental TRI results. The full detail of the application of TQM method to model the short time or transient cooling behavior of the 3D microrefrigerator will be presented in a future work.

## DISCUSSION

Various samples ranging in size from 10x10µm² to 80x80 µm² were thermally imaged and compared to theoretical models. Figures 2(a-c) show the TRI results in comparison with the TQM simulation for two sizes 50x50µm² and 80x80µm².

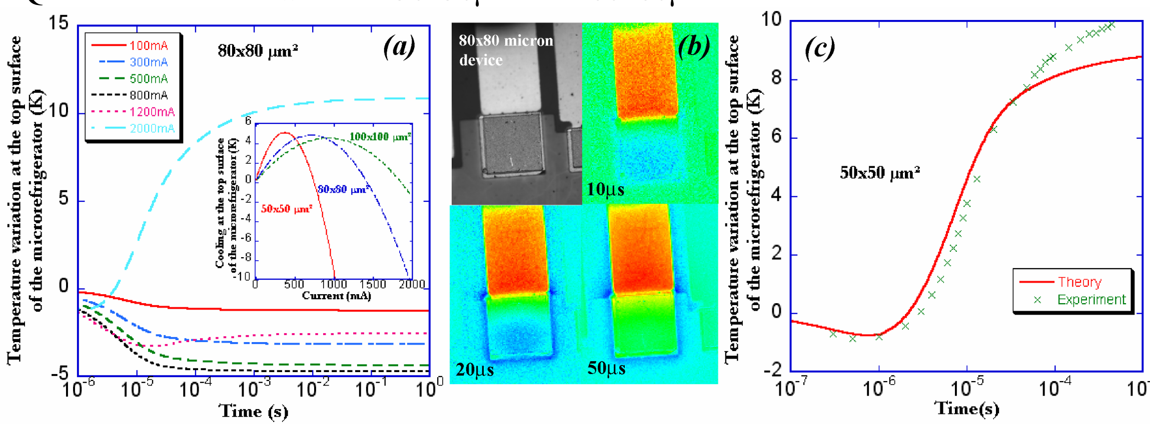


**Figure 2:** (a) Simulation of the transient temperature variation at the top surface of an 80x80µm² device for different electrical current amplitudes. The inset shows the steady state behavior for three different microrefrigerator sizes. (b) Image of the same device and transient thermal images as a response to a 1.7A, 166µs pulse. (c) Comparison between transient TRI result and TQM simulation for a 50x50µm² microrefrigerator obtained from 500ns to 500µs.

Figure 2(a) shows the simulation results using TQM, of the temperature variation at the top surface of an 80x80µm² device as a function of time, as a response to a step electrical current pulse of different amplitudes. The ohmic contact resistance at the top metal/semiconductor surface was taken to be $r_{oc}=10^{-6}\Omega.cm^2$ which is a realistic value for these devices [5]. For current amplitudes below the optimum value where the linear behavior of Peltier cooling dominates [inset of figure 2(a)], the temperature decreases as a function of time to stabilize in the cooling regime. On the other hand, when the current amplitude is higher than the optimum value, the temperature first decreases to reach a minimum and then it starts increasing. More interestingly is that the thin-film device can momentary cool below the ambient, even though the steady state shows heating [inset of figure 2(a)]. In figure 2(b), we can see that transient TRI results demonstrate clearly that we can capture the transient evolution of the microrefrigerator top surface performance as it goes from cooling to heating. The thermal images are taken on the top surface of an 80x80µm² SiGe based superlattice device and are acquired at 10µs, 20µs and 50µs. The frames are acquired every 10µs and the images are the response to a 1.7A, 166µs electrical excitation pulse [13]. These results confirm the simulation predictions in figure 2(a).

Figure 2(c) shows the results of transient TRI acquired from 500ns to 500µs on the top surface of a 50x50µm² SiGe based superlattice microrefrigerator and plotted in a logarithmic scale in comparison with TQM simulation. We have a satisfactory agreement between theory and experiment especially at short time scale. The dynamic behavior shows an interplay between Peltier and Joule effects. Peltier cooling is an interface effect located closer to the top surface of the device. It appears first with a time constant of about 10-30µs. On the other hand Joule heating is a volume or bulk effect that takes certain time to reach the surface. Joule heating in the device starts taking over with a time constant of about 100-150µs. The difference in the two time constants can be explained considering the thermal resistance and capacitance of the thin film. In addition this shows that the Joule heating at the top metal/semiconductor interface does not dominate the microrefrigerator performance. If this was the case, we would have obtained the same time constants for Peltier and Joule effects.

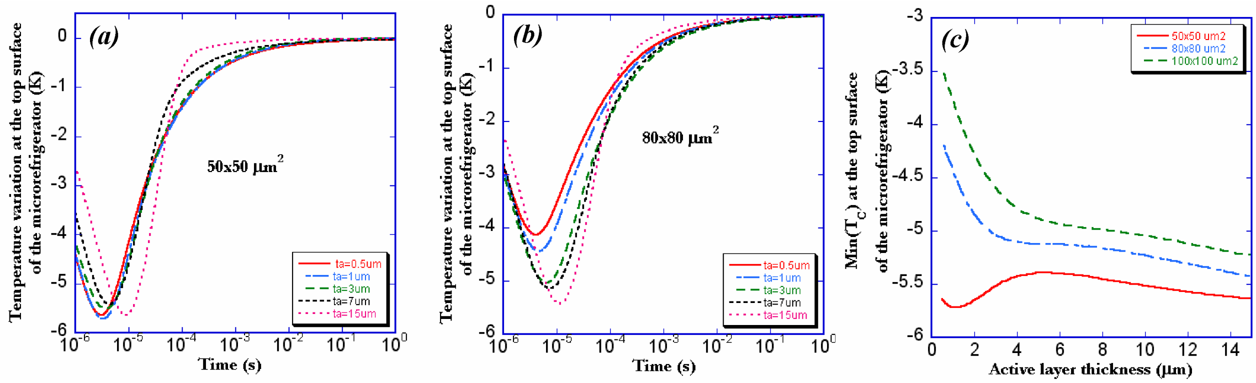


**Figure 3:** Variation of the transient temperature as a function of time at the top surface of a 50x50µm² (a) and an 80x80µm² (b) for different active layer thicknesses. (c) shows the variation of Min($T_C$) as a function of the active layer thickness.

There are many material parameters that can be adjusted in the TQM simulations. Modeling is used to study the effect of different physical and geometrical parameters of the device on its transient cooling. Figures 3(a) and 3(b) show the transient cooling of a 50x50µm² and 80x80µm², respectively, from 1µs to 1s as a response to a step electrical current, calculated for different values of the thickness of the active SiGe layer $t_{AL}$. For this simulations, $r_{oc}$ is taken to be $r_{oc}$=0. The amplitude of the electrical current is chosen to be the one for which the temperature at the top surface of the device vanishes at the steady state. We can see how changing $t_{AL}$ affects the maximum cooling and the shape of the transient temperature over the time interval. This behavior is well captured in figure 3(c) that shows the variation of the minimum transient temperature or maximum transient cooling at the top surface of different device sizes over the same time interval, as a function of $t_{AL}$. Different behaviors occur depending on the microrefrigerator size. This effect is due to the 3D geometry of heat and current flow in the device that plays a very important role. The maximum cooling seems to manifest a slight minimum that is more pronounced for small sizes and disappears as the microrefrigerator size increases. Generally the maximum cooling increases by increasing $t_{AL}$. This behavior can be explained by considering the thermal capacitance of the active layer. The thermal capacitance increases by increasing $t_{AL}$ and then it takes more time for Joule effect, which is a volume effect, to reach the top surface of the device where the temperature variation is considered. Since Peltier effect location does not change, this effect becomes more and more dominant as we increase $t_{AL}$.

For an 80x80µm²microrefrigerator size and fixed $t_{AL}$, we change respectively, the electrical conductivity $\sigma_{AL}$, the thermal conductivity $\beta_{AL}$ and Seebeck coefficient $S_{AL}$ of the active layer and we plot the maximum cooling and cooling power density over a time interval from 1µs to 1s. The curves are produced using the same conditions as in figure 3 above. As we can see in figures 4, both the maximum cooling and maximum cooling power density increase by increasing $\sigma_{AL}$ and $S_{AL}$. On the other hand, the two of them decrease by increasing $\beta_{AL}$. As a mater of fact, increasing $\sigma_{AL}$ and $S_{AL}$ decreases Joule heating and increases Peltier cooling, respectively. On the other hand, increasing $\beta_{AL}$ increases thermal conduction between the bottom and the top surface of the device where temperature variation and cooling power density are considered.

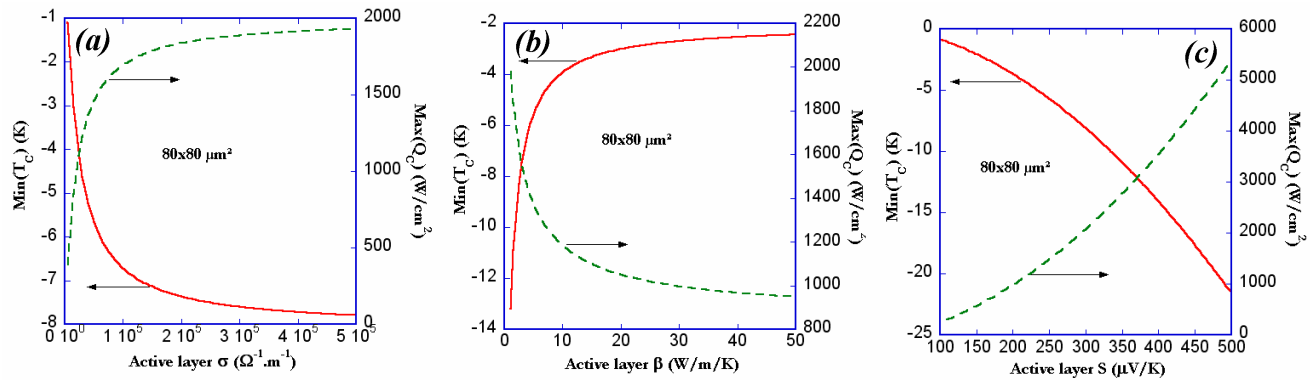


**Figure 4:** Variation of the transient maximum cooling and maximum cooling power density at the top surface of an 80x80µm² microrefrigerator over a time interval from 1µs to 1s as a function of the electrical conductivity $\sigma_{AL}$ (a), thermal conductivity $\beta_{AL}$ (b) and Seebeck coefficient $S_{AL}$ (c) of the active SiGe layer.

Finally in figure 5, we show the behavior of the maximum cooling and maximum cooling power density at the top surface of the same 80x80µm² microrefrigerator device as a function of $r_{oc}$. By increasing $r_{oc}$, the Joule heating at the interface top metal/semiconductor, which is located on the same location as the Peltier cooling, increases. This effect decreases the cooling performance of the microrefrigerator and it appears to be one of the most key parameters. We have reached the same conclusion when dealing with the steady state behavior of microrefrigerators [4].

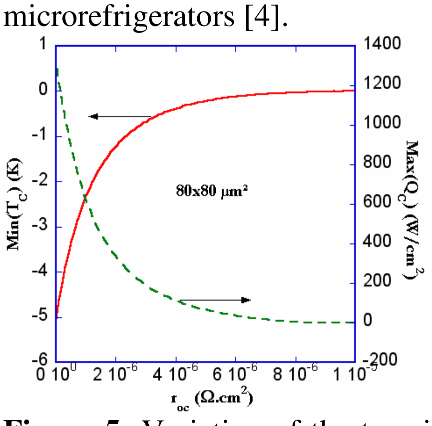


**Figure 5:** Variation of the transient maximum cooling and maximum cooling power density at the top surface of an 80x80µm² microrefrigerator over a time interval from 1µs to 1s as a function of the ohmic contact resistance at the top metal/semiconductor interface $r_{oc}$.

## CONCLUSIONS

A CCD based transient Thermoreflectance Thermal Imaging system with 100ns temporal, 200nm spatial, 0.1C thermal resolution has been demonstrated. The thermal images can be acquired over 4 orders of magnitude, from 100 nanoseconds to 1 millisecond. The measured results on a SiGe based microrefrigerator device are in a satisfactory agreement with the TQM simulation based on a step function excitation type. Simulation and experiment show that the device can achieve a cooling below ambient temperatures under moderate currents for the first few tens of microseconds, even though steady state shows a net heating. This dynamic behavior shows an interplay between Peltier and Joule effects. Peltier cooling is an interface effect located closer to the top surface of the device. It appears first with a time constant of about 10-30µs. On the other hand Joule heating is a volume or bulk effect that takes certain time to reach the surface. Joule heating in the device starts taking over with a time constant of about 100-150µs. The difference in the two time constants can be explained considering the thermal resistance and capacitance of the thin film. We have considered only the variation of the active layer properties and the preliminary simulations results have shed some light on some of the key parameters. The top metal/semiconductor interface ohmic resistance seems to be one of the most dominant parameters. Further work planed is to consider the variation of the properties of the substrate and the top metal contact layer to investigate their effects on the total transient cooling performance of the microrefrigerator.

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