High Speed Localized Cooling using SiGe Superlattice Microrefrigerators

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Abstract

In this paper, thin film based SiGe superlattice microrefrigerators are fabricated and characterized in terms of maximum cooling, power density and transient response. The localized cooling and fast transient response less than 40μs, demonstrate the potential for hot spot cooling of optoelectronics, microprocessor and IC chips.

Keywords

superlattice, microrefrigerators, hot spots, optoelectronics, thin-film cooler, thermoelectric, thermionic

Introduction

The current trend in optoelectronic and microelectric devices is to increase the level of integration with minimizing the die size, and at the same time increase clock speed (higher frequency). This results in higher power dissipation and an increase in the die temperature. According to the chip manufacture predictions, within the next five to ten years, the power requirements of the IC chip is going to exceed current cooling techniques [1], the case temperature need to be 20-300C lower than its current values. Increasing device temperature causes problems for optoelectronics and IC chips. Typically temperature-dependent wavelength shifts for conventional laser sources are on the order of 0.1nm/°C. Furthermore, according to electromigration model, the lifetime of IC chip is exponentially depend on its temperature, which could be represented by Black's equation [2]:

$\tau = A/J^2 * \exp(Ea/kT)$ (eqn. 1)

(τ, mean time to failure, A, proportional constant, J, current density, Ea is the activation energy, typical value for silicon is about 0.68eV, k, Boltzmann's constant, T, absolute temperature)

One distinguished characteristic of IC chips is uneven temperature distribution, leading to "hot spots". The temperature inside the chip could vary 5°C~30°C from one location to another in microprocessor. For the case of optoelectronic devices, temperature difference between the active region and the heat sink area can be 100's of degrees. In terms of heat flux, current microprocessors have an average heat flux of 10-50 W/cm^2, however, peak flux reaches as high as six times of its average value. [1] Thermal designs are driven by these hot spots instead of the whole chip temperature.

Generally there are three alternative cooling technologies [1] with their own advantages and disadvantages:

First, circulated liquid cooling, which could move heat sink away from processors therefore increase the surface area. However, it could not get effective heat sink resistance less than 0.0 C/W; and reliability is also a concern if the liquid hose is leaking.

Second method is refrigeration. The active cooling can provide an effective heat sink resistance less than 0.0 C/W. However, as the same problem as the first method, the limited space and reliability are the main concerns.

The third methods are Thermoelectronic (TE) devices. Active cooling with no moving parts could provide an effective heat sink resistance less than 0.0 C/W. However, the low figure of merit, ZT, of current material impedes its industrial applications because of low efficiency. $ZT=S^2\sigma T/\beta$, where S is the seebeck coefficient, σ, electrical conductivity, β, thermal conductivity and T, absolute temperature. Coefficient of performance (COP) of thermoelectric modules is directly related to ZT value. Typical commercial modules have a ZT~1, which corresponds to COP~0.6 for 30°C temperature difference. In addition, BiTe/SbTe and PbTe, the common TE materials are both bulk technology, which is not compatible with standard microprocessor chips. The current smallest thermoelectric micro-modules have a short leg length on the order of 0.2-0.3mm, but with ceramic cap and thermal paste etc, the whole module is still near to 1mm thick and 3-4mm in diameter [3]. This is still too large for spot cooling.

Another approach to eliminate hot spots is by theoretical simulation through optimized cell placement [4]. The temperature gradient inside the chip could be improved by a factor of two though at the cost of increasing wire length and cell area, which limits minimization and may bring more joule heating inside the chip. Through statistical methods of power and timing analysis, like McPower[5] and Mean Estimator of Density (MED)[6] etc., it is possible to find the nominal on-chip temperature profile. However these methods could not fundamentally remove the hot spots and reduce the IC temperature. Thus developing high cooling power density thin film refrigerators compatible with micro-fabrication process could have a strong impact in IC optimization. [7]

Some recent exciting developments of thin film coolers and quantum dots devices have shown promising ZTs. For example, Rama Venkatasubramanian[8] demonstrated that the BiTe/SbTe superlattice could reach a ZT of 2.4 at 300K. Harman et. al.[9] at MIT Lincoln lab demonstrated PbTe quantum dots with ZT of 1.6 -2.0 at 300K. All these could be developed for hot spot coolings. In our studies, we mainly focused on SiGe and InP materials, which are the substrate materials for microprocessor and optoelectronics. In previous studies, thin film coolers based on InP[10] and SiGe [11] have been demonstrated. Devices fabricated on a conventional silicon substrate and diameter ranging from 150μm down to 20μm, have achieved 7-8°C cooling at 100°C ambient

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temperature [12]. Localized cooling, with power densities exceeding $500W/cm^2$ has also been achieved [13]. In this paper, integrated thin film heaters on top of micro refrigerators are used to characterize high speed cooling performance of these devices. The high cooling power and fast transient response shows promising application in microelectronic and optoelectronic spot cooling.

Experiments

The superlattice samples were grown with a molecular beam epitaxy (MBE) machine on five inch diameter (001)-oriented Si substrates, doped to 0.001 ~ 0.006 Ω-cm with Boron. The structure of the microrefrigerator consisted of a 3 μm thick 200 × (3nm Si/12nm $Si_{0.75}Ge_{0.25}$) superlattice grown symmetrically strained on a $Si_{0.8}Ge_{0.2}$ buffer layer on top of Si substrate. The doping level is 5×10^{19} cm^{-3} for the superlattice.

Figure 1 shows a Scanning Electron Micrograph (SEM) picture of the SiGe/Si superlattice microrefrigerators.

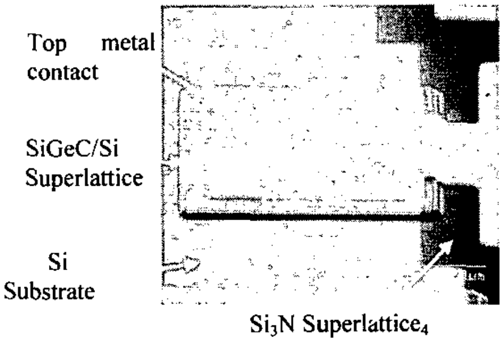

Figure 1 Scanning Electron Micrograph (SEM) pictures of SiGe superlattice microrefrigerator

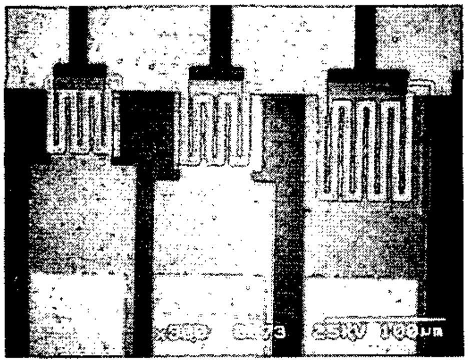

Figure 2 SEM picture of SiGe/Si microrefrigerators integrated with thin film heaters/sensors

For convenient measurements of cooling, power density and transient response, we integrated a thin layer of metal heater/sensor on top of micro-coolers.

Figure 2 shows a SEM picture of the mirorefrigerators integrated with a layer of thin film metallic wires. The integrated wires could work both as a sensor for temperature measurements thermistor and supply heat on top of the device.

The sample was assembled into a package using silver paste for good thermal conductivity and bonded with gold wire for biasing connected. The whole package was placed on a temperature control stage to keep the substrate temperature constant. First heater resistance was calibrated with stage temperature change from 15°C to 45°C. The coefficient of its resistance changing with temperature is obtained. An automatic Labview program was used to measure the cooling of the microrefrigerators. A constant current supplied to the refrigerator was changing from 0mA to 500mA in a step of 25mA; the resistance of the heater was recorded at every step, which could be converted to the temperature. Thus the microrefrigerator cooling with the current could be obtained.

When measuring the cooling power of the refrigerator, metal wire was used as a heat load source. A constant current was supplied to the heater, and the cooling of microrefrigerators was measured by thermocouple. By increasing the constant current to the heaters, more heat load was added on top of the refrigerators. The maximum cooling power is defined as the heat load power density that makes the device's maximum cooling temperature equal to zero.

To measure the thermal transient response, a pulsed current with 1KHZ frequency was applied to the heater. The resulting temperature difference across the superlattice creates a thermoelectric voltage. Textronic oscilloscope TDS 3054 was used to monitor the thermoelectric voltage time response shown in Figure 3. The collected data was an average of 512 measurements, and could fit well with an exponential curve. The decay time constant of the exponential function was defined as the transient response time of the microrefrigerators.

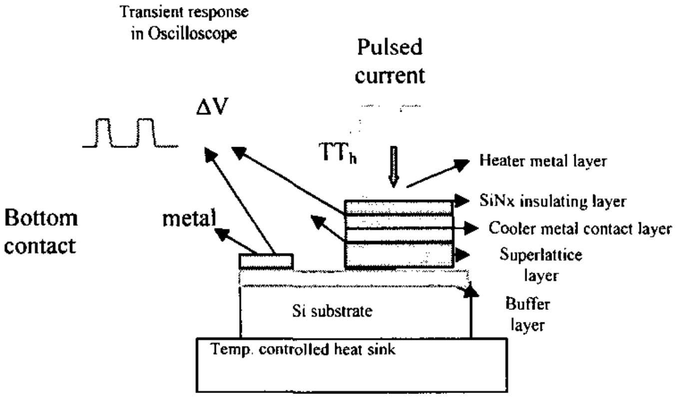

Figure 3 schematic of Transient response measurements

Results and Discussions

Conventional thermoelectric refrigerators are based on Peltier effect at the junction between two dissimilar materials, e.g. a metal and a semiconductor. Upon current flow, electrons absorb thermal energy from lattice at one junction and transport it to another junction further away. Using SiGe/Si superlattice material and thermionic emission of electrons over heterostructure barriers, one can improve the cooling performance by evaporative cooling of electron gas and by reducing the lattice thermal conductivity between hot and cold junctions. Experimental results showed the cooling efficiency could improve four times with the superlattice-designed structure as compared with bulk materials [13].

A useful TE cooler must have a good temperature difference across the device. There are three ways to characterize cooling of our devices. First, the most traditional and reliable method, thermocouple measurements; second, non-contact thermo-reflectance measurements [14], [15]; Figure 4 shows the temperature distribution on top of three devices fabricated with the shape of "HIT" (Heterostructure Integrated Thermionic coolers). One can see localized heating and cooling for devices separated less than 30µm. Through thermoreflectance image, the temperature distribution on top of the surface could be clearly observed. The shown heating and cooling are very well locally controlled. This will be suitable for hot spot cooling in optoelectronics. Third method is integrating a heater sensor on top of the refrigerator, as shown in SEM picture of Figure 4.

Figure 5 is a thermoreflectance image of an operating heater. From the picture, heating of the thin film wire is localized on top of refrigerator device. This ensures the accuracy of measurement for cooling power density. The change in resistance of the heater wire with temperature is a linear function. Since the heater/sensor has a very small thermal mass, it could be used to measure high speed cooling performance of micro refrigerators. The localized heating will be a good source for cooling power measurements.

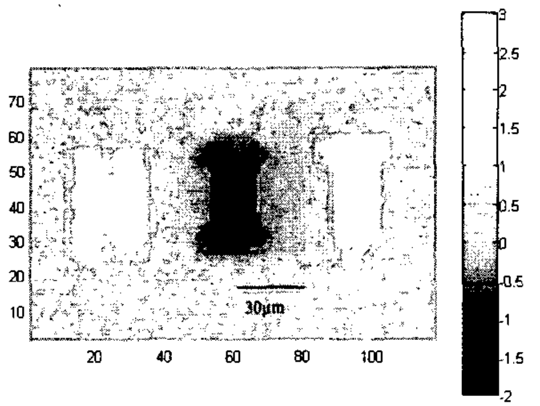

Figure 4 HIT refrigerator picture shows the localized cooling and heating of the device

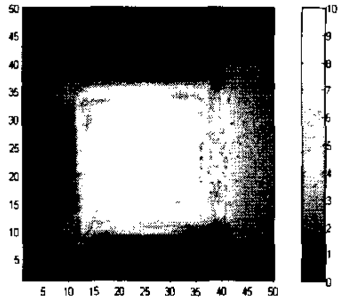

Figure 5 Thermoreflectance imaging of the localized heating of the device integrated with heater sensor on top

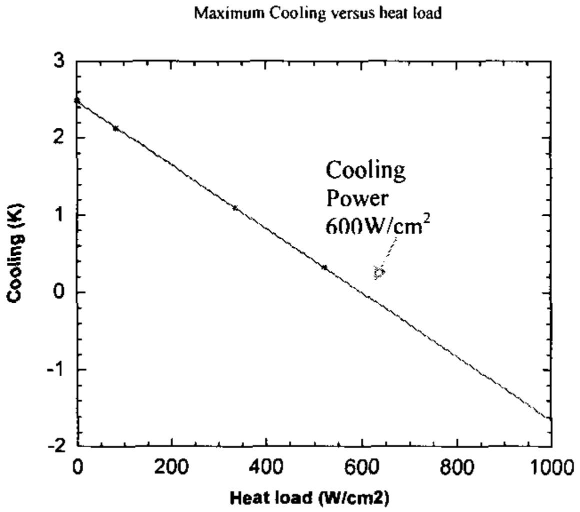

Figure 6 Maximum cooling versus heat load for a typical SiGe microrefrigerator (size: 40x40µm)

When comparing with bulk thermoelectronic modules, there are mainly three advantages for thin film integrated SiGe/Si superlattice microrefrigerators:

First of all, its micro-size and standard microprocessor fabrication method makes it suitable for monolithic integration inside IC chips. It is possible to put the refrigerator near the device and cool the hot spot directly.

Second, as the high cooling power density is one of the main advantages as compared with commercial bulk TE refrigerators. A conventional bulk TE refrigerator only has cooling power density around 1 w/cm^2. Figure 6 shows the maximum cooling versus heat load generated by increasing the heat power to the integrated heater on top of the device. The maximum cooling power was defined as heat load per unit area when maximum cooling temperature equals to zero. The heat load of the heater could be calculated by $Q=I^2*R$ (Q, heat load; I, current supplied to the thin film wire, R, its resistance). Maximum cooling power density of the device is, $P = Q/S$, (Q heat load, S refrigerator area). A maximum cooling power of 600 W/cm^2 was measured in Figure 6 for this sample. This is over hundred times higher as compared with bulk thermoelectric devices. Even with the best module, the cooling power only could reach a few 10's W/cm^2. [3,16] Figure 7 shows cooling versus current at different ambient temperatures. It can be seen that maximum cooling increases substantially at higher temperatures.

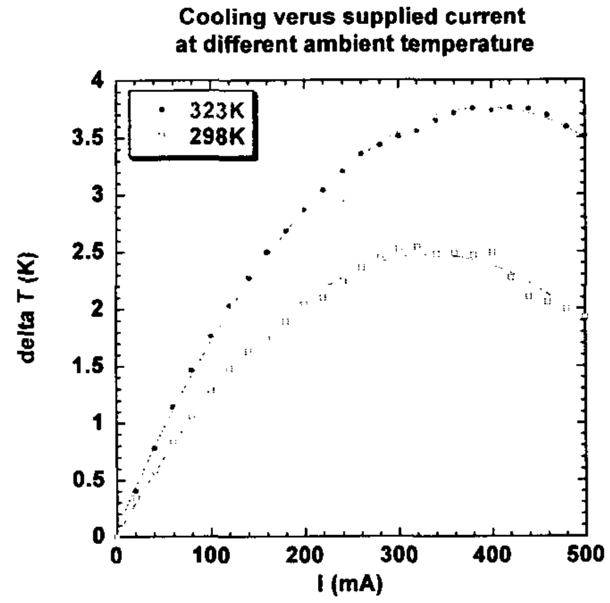

Figure 7 Cooling versus current at different ambient temperature, sample size: (60μmx60μm)

Third, the transient response of the current SiGe/Si superlattice refrigerator is several orders of magnitude better than the bulk TE refrigerators. The standard commercial TE refrigerator has a response on the order of 10's seconds. Figure 8 shows the fitted transient response of a typical SiGe/Si superlattice sample, the decay time constant is ~34μs, which is in an order of 10^5 faster than the bulk TE refrigerators.

In fact, the actual transient response of the device is faster than the measured value. The thermoreflectance method shows a transient response of ~20μs [17]. The transient response measured by heater sensor method is limited by thermal mass of metal lines.

According to the theoretical simulation, the current limitation of the superlattice coolers still lies in the contact resistance between the metal and cap/buffer layer, which is on the order of 10-6 Ωcm^2. It predicts a 20-30°C of cooling with a cooling power density exceeding several 1000's W/cm^2 is possible with the optimized SiGe superlattice structure. [18,19]

Future research interests will also focus on integrating microrefrigerators with electronic and optoelectronic devices.

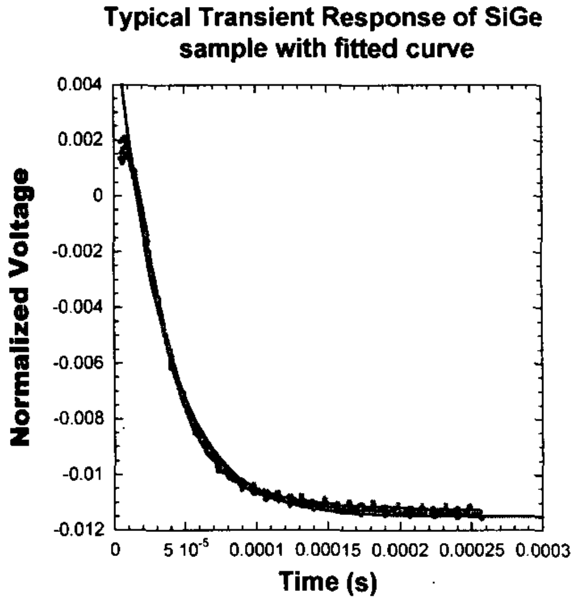

Figure 8 Fitted transient response of SiGe/Si superlattice microrefrigerator

Conclusion

In this paper, we presented localized cooling power density exceeding 500 W/cm^2 and fast transient response of the SiGe/Si superlattice micro-refrigerators less than 40μs. As compared with conventional bulk TE modules, thin film integrated SiGe/Si superlattice microrefrigerators have potential application in high power, high-speed optoelectronics devices and microprocessors for on chip cooling.

Acknowledgement

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