Thermal Characterization of Thin Film Superlattice Micro Refrigerators

James Christofferson, Daryoosh Vashaee, Ali Shakouri*
Jack Baskin School of Engineering, University of California, Santa Cruz, CA 95064

Xiaofeng Fan, Gehong Zeng, Chris Labounty, and John E. Bowers
Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106

Edward T. Croke III
HRL Laboratories Inc.

* Tel. (831) 459-3821, FAX (831) 459-4829, ali@cse.ucsc.edu

Abstract. Micro refrigerators based on thin film SiGe/Si superlattices are investigated. Cooling performance of 2.7 degrees at room temperature and 10.8 degrees at 200C has been measured. Cooling characterization was done using micro thermocouples, and also with the use of visible wavelength thermoreflectance method. Reflectance images of the temperature distribution are presented with spatial resolution better than traditional infrared cameras.

1.Introduction

For various applications in which optoelectronic or micro electro mechanical devices are used for chemical or biological sensing, it is very useful to control the temperature on a microscopic scale. Semiconductor lasers or other high power devices could also benefit from monolithic components that can provide localized cooling or heating. Traditional thermo electric effect that can provide cooling at the interface between two materials can be enhanced using superlattice barriers (Fig.1) [1]. In this paper fabrication and characterization of SiGe superlattice coolers is described. The p-type device was grown with molecular beam epitaxy (MBE) on a Boron doped Si substrate with resistivity less than 0.006 Ω-cm. The cooler's main part is a 3 μm thick 200 × (5nm $Si_{0.7}Ge_{0.3}$/10nm Si) superlattice grown symmetrically strained on a buffer layer designed so that the in-plane lattice constant was approximately that of relaxed $Si_{0.9}Ge_{0.1}$.

For the relaxed buffer layer, we grew a 10-layer structure, alternating between 150 nm $Si_{0.9}Ge_{0.1}$ and 50 nm $Si_{0.845}Ge_{0.150}C_{0.005}$, roughly following the method suggested by Osten et al. [2]. For the n-type sample, the layers were grown at 390 °C and annealing was performed at 750 °C for 10 minutes after the growth of each $Si_{0.9}Ge_{0.1}$ layer. In the p-type case, the growth temperature was simply alternated between 700 °C for the

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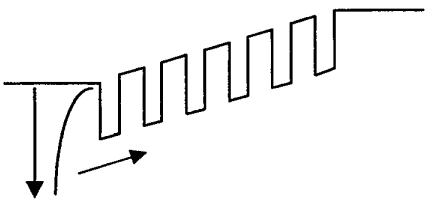

Fig. 1 Current transport from cathode to anode perpendicular to superlattice layers in a unipolar device can create a net cooling at the emitter junction due to evaporative cooling of hole; emitted over the barrier layer.

$Si_{0.9}Ge_{0.1}$ layer and 500 °C for the $Si_{0.845}Ge_{0.150}C_{0.005}$ layer. After the relaxed buffer sequence, another 150 nm thick $Si_{0.9}Ge_{0.1}$ layer was grown at 390 °C for the n-type sample and a 1 μm thick Si0.9Ge0.1 layer was grown at 700 °C for the p-type case. Growth of a 200 period, 5 nm $Si_{0.7}Ge_{0.3}$/ 10 nm Si superlattice then followed at 390 °C (n-type case) and 500 °C (p-type case). Finally, the samples were capped with a heavily doped $Si_{0.9}Ge_{0.1}$ layer sequence to provide for a low-resistance ohmic contact.

Both the superlattice and the buffer layer are doped to 5×10^{19} cm^{-3} with Boron. The $Si_{0.7}Ge_{0.3}$/Si superlattice has a valance band offset of about 0.2 eV, and hot holes going over this barrier produce thermionic cooling. In addition, superlattice structure has many interfaces that increase phonon scattering, and therefore gets lower thermal conductivity. A transmission electron microscopy (TEM) image of the grown p-type SiGe/Si superlattice cooler sample is shown in Fig. 2.

For the cooler device fabrication, mesas with various areas were etched down to the $Si_{0.9}Ge_{0.1}$ buffer layer using reactive ion etching. Metallization was made on the mesa and $Si_{0.9}Ge_{0.1}$ buffer layer for top and bottom contact respectively.

Electrical contact resistance is an important factor that limits the optimum device performance. Low contact resistance is essential for thin film coolers [3]. A 100 nm titanium metal layer was first deposited. This was intended to form a titanium silicide on the silicon surface and to act as a metal barrier to separate Si and Al. Subsequently 1μm thick aluminum layer was deposited. To facilitate wire bonding, an additional metal layer of titanium and gold was used. Annealing was accomplished at temperatures between 400 °C and 600 °C with rapid thermal annealer. TLM (transmission line mode) measurements were carried out to measure the contact resistance. The measured specific contact resistivity is in the mid 10^{-7} Ω-cm^2 range for both n- and p-type devices.

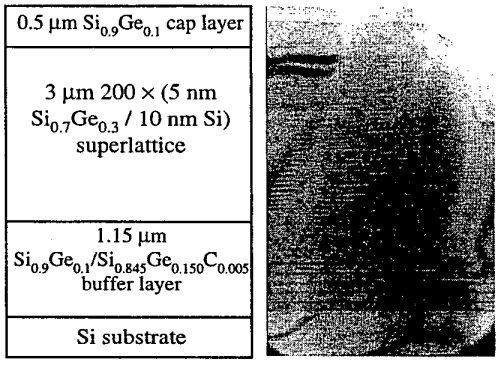

Fig. 2 TEM image of the p-type SiGe/Si superlattice cooler sample.

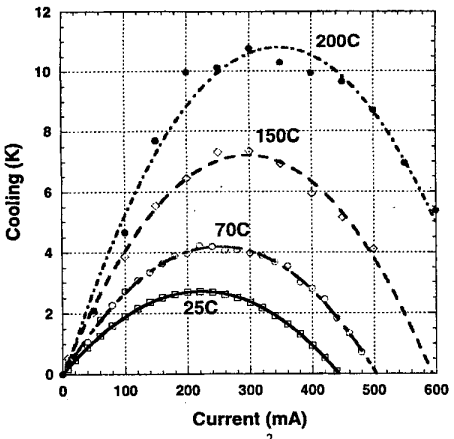

Fig. 3 Cooling on 50x50 μm^2 p SiGe/Si cooler at various substrate (heat sink) temperatures. The measurement was done using 50μm diameter micro thermocouple.

2.Experimental Results

Fig 3 shows experimental cooling results for a 50μm^2 device. A micro thermocouple was used and device cooling is relative to the device temperature at zero current. Cooling by as much as 2.7 K at 25 °C and 10.8 K at 200 °C was obtained. The device cools better at higher temperatures. The reason for the improved performance with the increase in temperature is two fold. First, in the temperature range of our measurements, the thermoelectric figure of merit ZT of SiGe alloy increases with temperature due to smaller thermal conductivity and larger Seebeck coefficient, and second, the thermionic emission cooling power increases due to the larger thermal spread of carriers near the Fermi energy.

Devices of different sizes, from 50 μm^2 to 150 μm^2, were tested. The results on p-type SiGe/Si coolers are shown in Fig 4. 2.7 K cooling is obtained for the 50 μm^2 p-type device. The test results shows the maximum cooling temperature increases as the device size decreases. This cannot be explained with conventional ideal thermoelectric or thermionic cooler models. This is due to the three-dimensional (3D) nature of current spreading in the substrate and the Joule heating from the bonding wires or current probe. For the same wire resistance, smaller devices require a smaller optimum current which is favorable for better cooling performance. 3D simulations that take into account thermoelectric effect at the junction between metal and semiconductor, thermionic emission cooling and heating, as well as Joule heating in various layers, are used to investigate the optimum size of the micro refrigerator. Since majority of the cooling happens over 3μm thick superlattice layer, large cooling power densities on the order of kW/cm^2 can be achieved [1,4].

As the device size gets too small to be characterized by a micro thermocouple (50 microns in diameter),

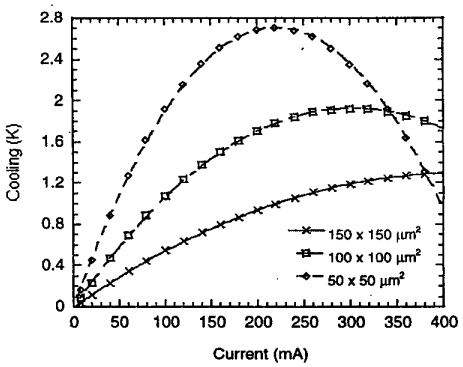

Fig. 4 150μm^2 to 50μm^2 micro thermocouple measurements

other techniques must be used to measure the cooling. The temperature profile on top of the microrefrigerator can be determined by measuring the temperature-induced change in the surface reflectivity[5,6,7]. Lock-in technique is needed to detect the small change in surface reflectivity ($\Delta R/\Delta T \sim 2x10^{-5}$ /°C). One can generate the thermal image of the device by illuminating the whole surface with a white light source and using a photodiode array for lock-in detection of the thermoreflectance signal at different pixels. The main advantage comparing to conventional infrared cameras is the improved spatial resolution. Typical HgCdTe-based cameras have a diffraction limited spatial resolution of 3-5 microns, while visible wavelength thermoreflectance imaging can give submicron resolution. Thus, the cooling or heating over small areas can be measured accurately without the effect of background radiation.

The sample was illuminated with a white light and excited with current pulses at 200Hz, to allow for heterodyne filtering. The detector was the Hammamatsu 16X16 photodiode array, and several National Instruments data acquisition boards were used for parallel processing of the 256 channels. Calibration was done using the thermocouple measurements on larger devices. Absolute calibration is difficult because of the uncertainty in the 'thermoreflectance' constant of the surface metal. Future work will be to calibrate absolutely, so that the error introduced by the thermal mass of the thermocouple can be quantified.

Presented are the images of a 30 micron p-type SiGe/Si superlattice cooler at 25C. Fig 5 shows a CCD image of the cooler. Interpolated thermal reflectance images are shown at different device currents in Figs. 6 and 7. Each data point represents a 1Hz bandwidth FFT at the

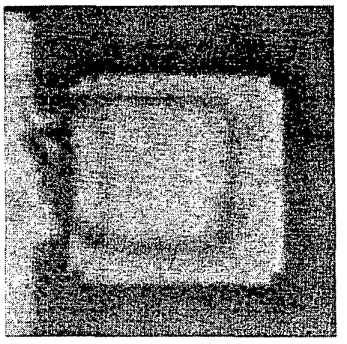

Fig. 5 CCD image of 30μm^2 SiGe/Si p-type superlattice cooler

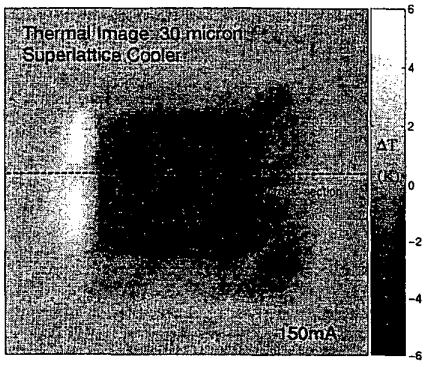

Fig. 6 Thermal image of cooler at 150mA

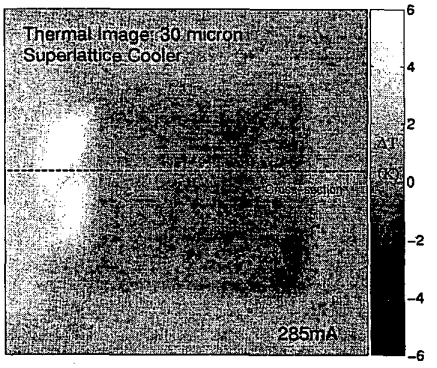

Fig. 7 Thermal image of cooler at 285mA

cycling frequency averaged over 20 seconds. We see that there is cooling, but also heating at the junction between the contact layer and the cooler. A cross-section of the thermal image is shown at different currents in Fig. 8. Approximate regions of the contact layer, cooler and substrate are indicated in the figure. The cooling appears to be limited by a large heat load at the junction from contact layer to cooler. By better understanding the cooling distribution, the devices can be optimized to reduce the heating caused by non-ideal effects.

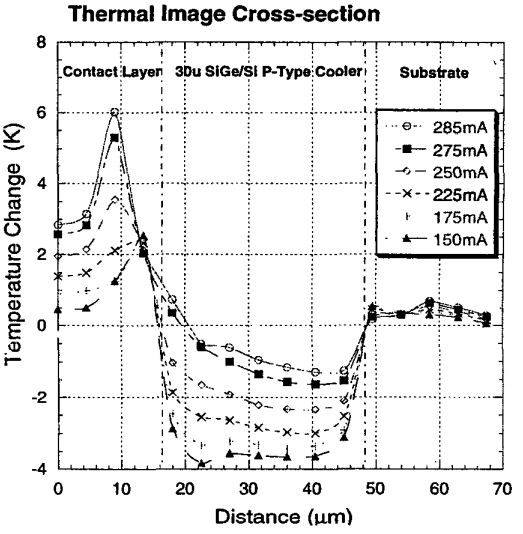

Fig. 8 Cross-section of thermal image

With optimized superlattice material, device design and packaging, cooling up to tens of degrees is possible[8]. More important, the processing of SiGe/Si superlattice coolers is compatible with that of VLSI technology, thus it is possible to integrate these coolers monolithically with Si and SiGe devices to achieve compact and efficient cooling.

3. Conclusion

Cooling up to 10.8 K was measured at 200 °C for a p-type 50 μm^2 Si/Ge superlattice cooler. 3.5 K cooling was measured at room temperature for a 30μm^2 cooler using reflectance imaging, which also showed significant non-ideal heating at the junction from contact layer to cooler.

Presently, non-ideal effects of the heating at the junction with the probe-trace contact layer and the side thermal conduction limit the cooling of the device. Using n and p devices electrically in series and thermally in parallel, superlattice coolers can be optimized to increase the total amount of cooling to tens of degrees at room temperature. We have also shown that thermoreflectance imaging can be used to measure the cooling on devices too small for the thermocouple, and can be a useful tool for identifying the non-ideal effects.

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