International Symposium on Compound Semiconductors, Monterey CA, 2000

Thermoreflectance Imaging of Superlattice Micro Refrigerators

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Extended Abstract:
For various applications in optoelectronic or high power electronic devices, it is useful to control the temperature on a microscopic scale. For example, semiconductor lasers used in wavelength division multiplexed fiber optics communication systems require less than a degree centigrade variation in their operating temperature in order to have stable wavelength and output power. Traditional thermo electric effect that can provide cooling at the interface between two materials can be enhanced using thermionic emission in superlattice barriers [1]. By integrating thin film thermionic coolers with various devices, one can improve the packaging and the overall performance.

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 $Si_{0.9}Ge_{0.1}$. The buffer layer consisted of 1 μm 5× (150 nm $Si_{0.9}Ge_{0.1}$/50 nm $Si_{0.845}Ge_{0.150}C_{0.005}$) and 1 μm $Si_{0.9}Ge_{0.1}$. 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,

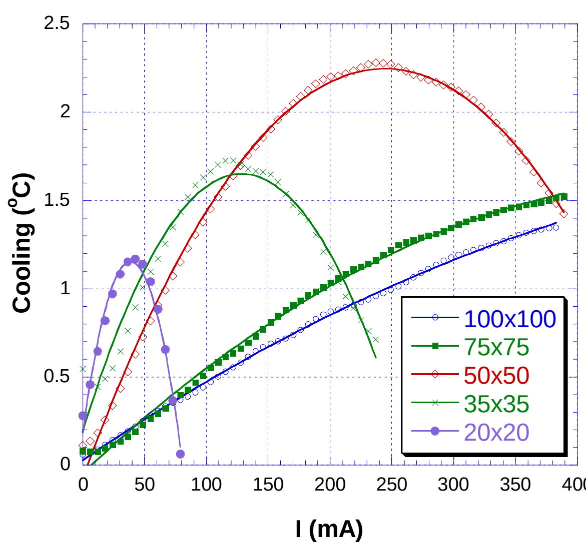

Fig. 1 100μm^2 to 20μm^2 micro cooler laser thermoreflectance measurements

superlattice structure has many interfaces that increase phonon scattering, and therefore gets lower thermal conductivity. 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. In order to measure the temperature with a micrometer spatial resolution, we use the change in the reflection coefficient of material with temperature [2,3,4,5]. Using visible wavelength one can achieve submicron spatial resolution. Figure 1 shows the temperature on top of a micro refrigerators made of thin film SiGe/Si superlattice. The device size is ranging from 100x100μm^2 down to 20x20μm^2. The measurement was done using 690nm semiconductor laser with 5mW power. Lock-in technique is used to detect the small change in surface reflectivity due to temperature change ($\Delta R/\Delta T$~6×10^{-5} /^{o}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. On the other hand, the cooling or heating over small areas can be measured accurately without the effect of background radiation.

Fig. 2 displays the image of a 30x30μm^2 SiGe/Si p-type superlattice cooler. The device was excited with current pulses at 200Hz to allow for heterodyne filtering. The detector was a Hamamatsu 16X16 photodiode array, and several National Instruments data acquisition boards were used for parallel processing and Fast Fourier Transform (FFT) of 256 channels.

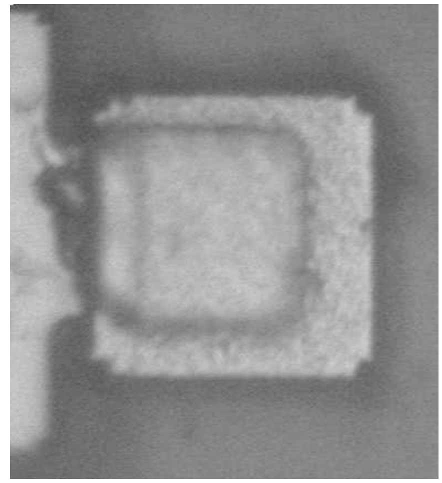

Fig. 2 CCD image of 30x30μm^2 SiGe/Si p-type superlattice cooler

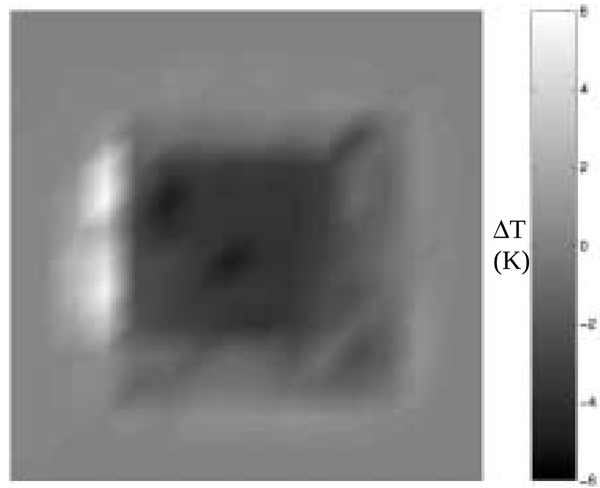

Fig.3 Thermal image of cooler at 150mA current

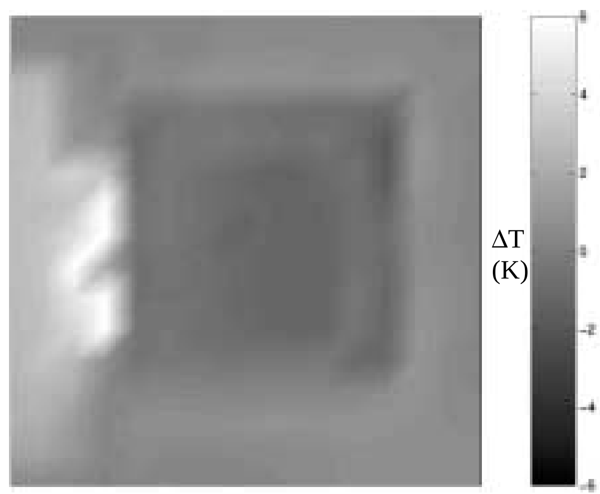

Fig. 4 Thermal image of cooler at 285mA current

Figs. 3 and 4 display the thermal image of the micro refrigerator at a current of 150mA and 285mA, respectively. Each data point represents a 1Hz bandwidth FFT at the cycling frequency averaged over 10 seconds. Calibration was done using micro thermocouple measurements on larger devices (>50x50μm^2). Absolute calibration is difficult because of the uncertainty in the 'thermoreflectance' constant of the metal surface. Future work will be to improve the calibration and to quantify the error introduced by the thermal mass of the thermocouple.

One can see that there is net cooling on top of the device, but also heating at the junction between the contact layer and the cooler. Fig. 5 shows the cooling of the device averaged over the data points on the top surface. At high currents the Joule heating in the device starts to dominate and the cooling performance deteriorates. A cross-section of the thermal image is shown at different currents in Fig. 6. Approximate regions of the contact layer, cooler and substrate are indicated in the figure. The cooling appears to be limited by large heat generation at the junction between contact layer and the device. This is due to imperfect metallization at the edge of the mesa. By better understanding the cooling distribution, the devices can be optimized to reduce the heating caused by non-ideal effects. With optimized superlattice material, device design and packaging, cooling up to 20-30 of degrees is possible [6,7].

In summary thermoreflectance imaging is used to determine the performance of superlattice coolers. This method can be applied to other active devices and integrated circuits,

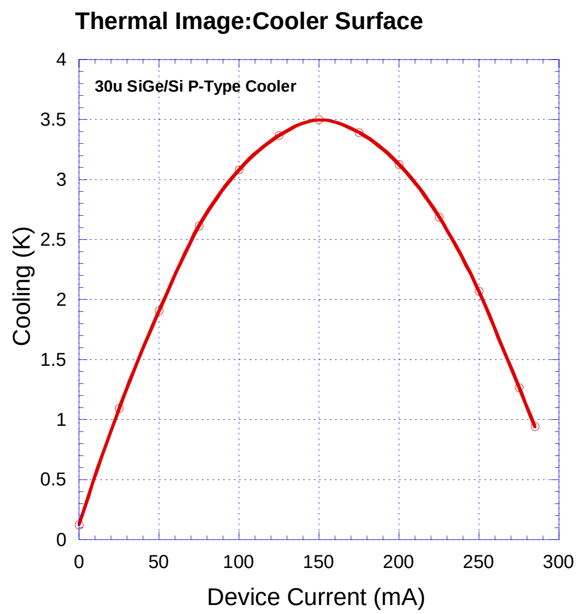

Fig. 5 Device cooling, average over cooling surface

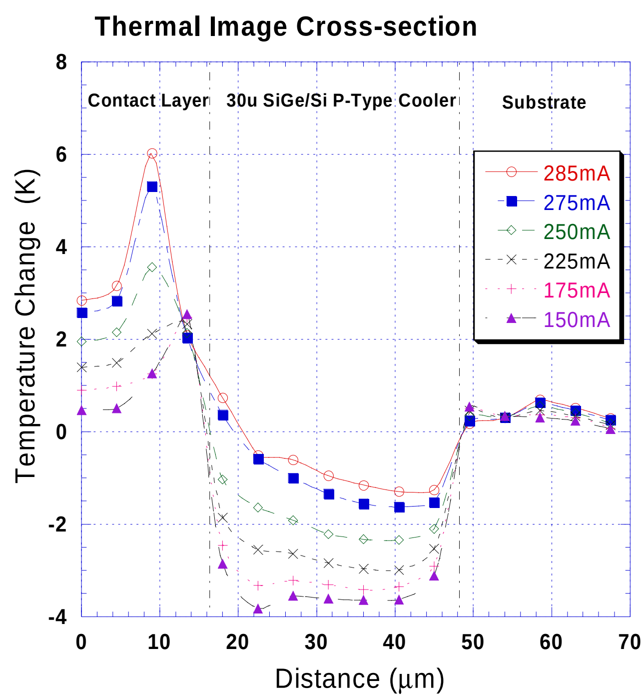

Fig. 6 Cross-section of the thermal reflectance image, showing cooling on the surface and heating at the junction with the contacting layer.

and can have better spatial resolution then traditional IR cameras.

References

[1] A. Shakouri, J.E. Bowers 1997 *Appl. Phys. Lett*. **71**, p1234

[2] Y.S. Ju, K.E. Goodson 1998 *Journal of Heat Transfer* **120** p306

[3] V.Quintard, S. Dilhaire, T. Phan, W. Claeys 1999 *IEEE Transactions on Instrumentation and Measurement* **48** 1 p69

[4] J.A. Batista, A.M Mansanares, E.C. da Silva, M.B.C. Pimentel, N. Jannuzzi, D. Fournier 1998 *Sensors and Actuators* A **71** p40

[5] S. Grauby, B.C Forget, S. Hole, D.Fournier 1999 Review of Scientific Instruments **70** 9

[6] G. Zeng, A. Shakouri, C. LaBounty, G. Robinson, E. Croke, P. Abraham, X. Fan, H. Reese and J. E. Bowers 1999 *Electronics Letters*, **35**, p2146

[7] A. Shakouri, C. Labounty, P. Abraham, J. Piprek, and J. E. Bowers, *Material Research Society Symposium Proceedings*, Vol. 545, December 1998, p449