Thin Film Coolers for Localized Temperature Control in Optoelectronic Integrated Circuits

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Abstract

The overheating and temperature-sensitive properties of optoelectronic are constraints for high frequency high power operation, and for high level of integration. We propose a possible solution integrating an InGaAs/InP superlattice cooler based on InP substrate. We describe the basic cooling theory of the heterostructure-based microcooler, device structure, and preliminary experimental cooling versus supplied current. In addition, we developed a new technique to measure the transient response of the device. The experimental data demonstrates the maximum cooling of device could reach as high as 2.5 ^{0}C at room temperature in vacuum with a minimum supplied current of 300mA, corresponding to a cooling power density over 100W/cm^2. The transient response of the devices is less than 40μs, which is 1e5 times faster than conventional thermoelectronic coolers.

Keywords

InGaAs/InP Superlattice, microcooler, thermoelectronic, thermionic, optoelectronic, transient, integration

Introduction

I. Thermal Issue in Optoelectronic Devices

The on-chip temperature of the packaged VLSI circuits can reach as high as 100^{0}C with temperature varying by as much as 40^{0}C degrees from one location to another. Lasers and optoelectronic devices are very sensitive to temperature. The accumulative heating in laser active region has the following detrimental effects on the device performance:

1) Changing the emitted wavelength. Typical temperature dependent wavelength shift for an InP-based distributed Bragg reflector laser (DBR) is approximately 0.28nm/^{0}C and for a distributed-feedback laser (DFB) is about 0.07 nm/^{0}C. [1] However, for a typical wavelength multiplexed optical communication system, the channel spacing is only about 0.2 to 0.4 nm. One- or two-degree temperature change could dramatically increase the crosstalk between two channels.

2) Increasing threshold current density. The consequent high power thermal runaway results in failure of the device.

3) Decreasing output power of the laser. For a typical long wavelength (1.55μm) vertical-cavity surface-emitting laser (VCSEL), the output power could drop from 0.45mW at 20^{0}C to less than 0.02mW at 85^{0}C[2].

4) Broadening the spectral linewidth. Though it is not a significant consequence of temperature, linewidth broadening does affect its speed.

The present techniques used to overcome these problems include: 1) Using sophisticated heterostructures to lower threshold current resulting in a lower junction temperature, e.g. including quantum barriers into a double heaterostructure laser [3]. This technique could alleviate the heating but not fundamentally solve the problem, especially for high power lasers. 2) Flipping the laser over and mounting the junction closer to heat sink. However, this technique does not apply to top emitting surface emitting lasers, like VCELs. 3) Using external cooling such as liquid N_2 or a thermoelectric cooler. These strategies work well on individual devices, but are unsuitable for optical integrated circuits (OIC) devices because its high integration density and limited space. Thus an alternative novel cooling solution is in highly desirable.

II. Superlattice thermonic cooling

Conventional thermoelectric (TE) coolers are based on Peltier effect at metal/semiconductor junctions. When electrons flow from a material in which they have average transport energy smaller than the Fermi energy to another material in which their average transport energy is higher, they absorb thermal energy from the lattice and this will cool the junction between two materials. In our thin film device, we add in a superlattice layer between the metal and substrate. In the thermionic emission process, hot electrons from a cathode layer are selectively emitted over a barrier to the anode junction. Since the energy distribution of emitted electrons is almost exclusively on one side of Fermi energy, when current flows, strong carrier-carrier and carrier-lattice scatterings tend to restore the quasi-equilibrium Fermi distribution in the cathode by absorbing energy form the lattice, and thus cooling the emitter junction. The phonon blocking superlattice strategy strives to reduce the material thermal conductivity by modifying the number of phonon modes and phonon transport, while leaving the electrical conductivity unaltered. Quoted improvements [4,5,6] estimate and experimentally proved a ZT_{ave} of around 2.5 at room temperature, which would translate to a more respectable maximum Coefficient of Performance (COP) of between 2 and 3. In addition, the experimental results showed the superlattice structure could cool four times better than the bulk material device [7].

The performance of the device could be varied with doping concentration, superlattice barrier thickness and device size. Thus to achieve the best cooling various parameters need to be carefully designed. In this paper, we fabricated and measured several InGaAs/InP superlattice microcoolers. Different barrier thickness (1 μm and 2 μm) samples and different sample size (ranging from 3200μm^2 to 7200μm^2) were characterized in terms of their cooling versus current. In addition, with an optical thermoreflectance technique, the transient response of InGaAs/InP superlattice cooler was measured.

Device Structure

The heterostructure-integrated thermonic (HIT) cooler structure generally consists of a superlattice barrier layer of InGaAs/InP, the superlattice composition and doping concentration as well as the device size are the variables to be adjusted to find the optimal combination values. A layer of InGaAs with higher doping concentration was grown on top and underneath of the barrier by metal organic chemical vapor deposition (MOCVD). These high doping InGaAs layers acted as cathode and anode, with a layer thickness of 0.3 μm and 0.5 μm respectively. Ni/AuGe/Ni/Au was used to make ohmic contacts to both the electrodes.

Experiments

The cooling of the devices versus supplied current was measured by standard E-type micro-thermocouple with the tip size of 50μm. The ILX Lightwave LDX3220 current source was used to supply the stable current to the cooler through probes. The thermocouple tips were placed on top of the sample and the substrate. HP 34420A Nanovoltage/microohm meter was used to measure the voltage difference between the two-thermocouple tips. A LabView™ program was developed to automatically control measurements and convert the voltage difference to temperature by using temperature calibration table offered by the manufacture. A schematic drawing of experimental step-up was illustrated in Figure 1.

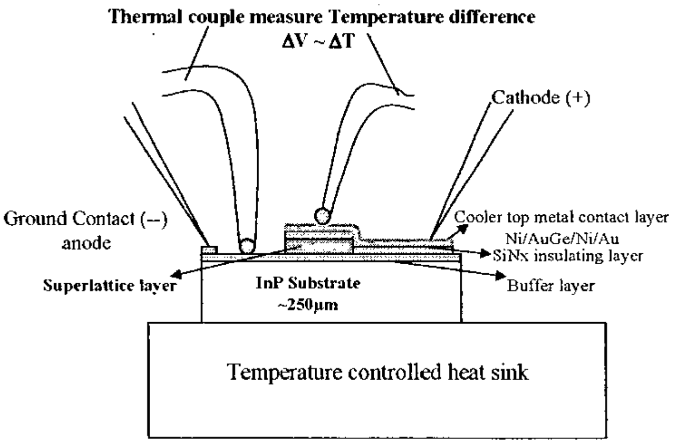

Figure 1 Thermocouple measurement schematic (drawing not to scale)

To measure the thermal transient response, we evaporated a metallic thin film heater on top of the cooler device. A pulsed current with 1KHZ frequency was applied to the heater. The resulting temperature difference across the superlattice creates a thermoelectric voltage according to the seebeck effect. With the heater turning on and off, the resulting thermoelectric voltage across the superlattice will response to the changes. Textronic oscilloscope TDS 3054 with 500MHZ bandwidth was used to monitor the thermoelectric voltage response. The obvious rising and falling edge could be observed. We choose the falling edge to study the time constant. Though this measurement is not a direct measurement of cooling transient, but the cooling and heating transport are through the same superlattice layers. In this case, the heating transient is equivalent to the cooling transient. A schematic set-up of the measurements is shown in Figure 2. 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 of the thin film superlattice cooler.

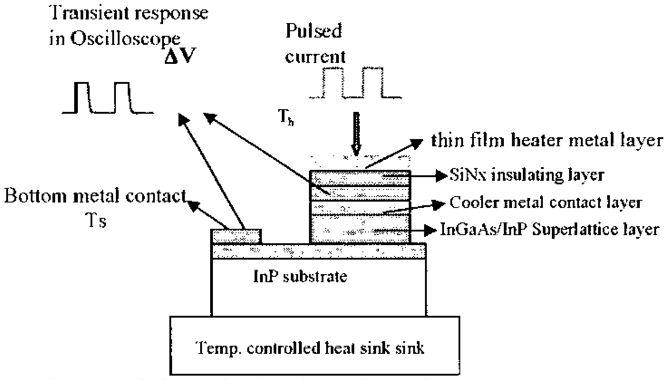

Figure 2 Schematic drawing of transient response set-up (drawing not to scale)

Results

Figure 3 shows a thermal image of an operating InGaAs/InP superlattice cooler with a thermoreflectnace technique the cooling distribution of device and substrate can be seen [8,9]. This is for a 1600μm^2 size device cooling by 1-1.5 ^{0}C. The signal cross-section down microcoolers shows the localized cooling of the device.

Figure 4 shows the cooling versus current for three different structure superlattice devices with the same size 4900μm^2. The first sample has 2μm thick superlattice with doping concentration of 1e17 cm^{-3}. It showed a maximum cooling of 1.15^{0}C at 120mA. The second sample only has 1μm barrier height with doping concentration of 1e19cm^{-3}, which shows a cooling of 0.65^{0}C at 80mA, almost only half of the first sample. The third sample has the same superlattice structure as the second sample but with different doping concentration of 8e18cm^{-3}. The cooling of the third sample has only slight difference, 0.1^{0}C, from the second sample. It shows a 0.55^{0}C cooling at 60mA.

Figure 5 shows the cooling versus current for 2μm barrier device but with different sample sizes. The arc of quadratic curve shape is much wider than the cooling curve shown in Figure 4 because it is a N-type device thus more current is required to reach maximum cooling. However we could adjust the P-type device to have the same current for maximum cooling by changing the geometry. The figure shows very clear the significant influence of the device size on the effect of cooling. The 3200μm2 microcooler could reach the maximum cooling of 2.5^{0}C at 300mA, however for the 7200μm^2, 16200μm^2, and 20000μm^2 device, they only cool 0.3^{0}C at 150mA. The size 5000μm^2 sample's performance is also not desirable, with a maximum cooling of 0.9^{0}C at 175mA.

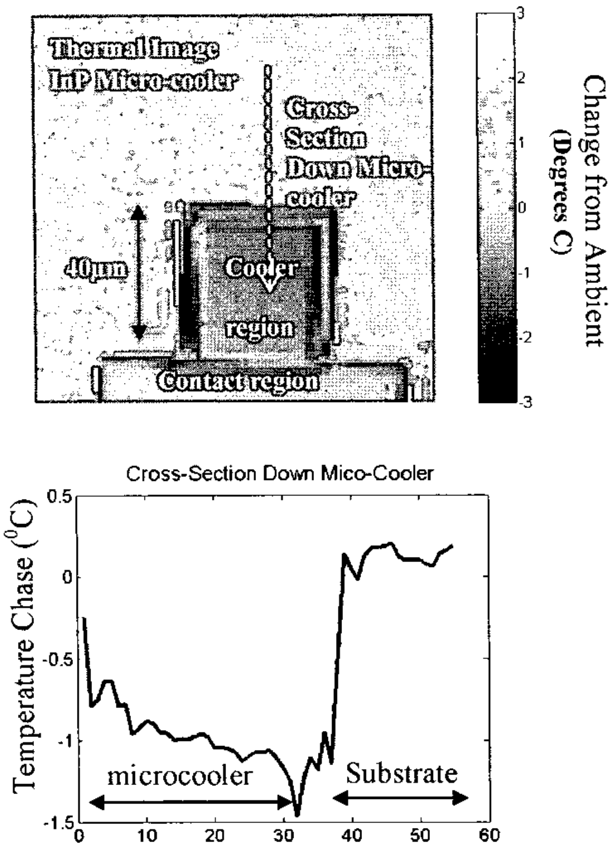

Figure 3 Thermoreflectance image of a $1600\mu m^2$ microcooler

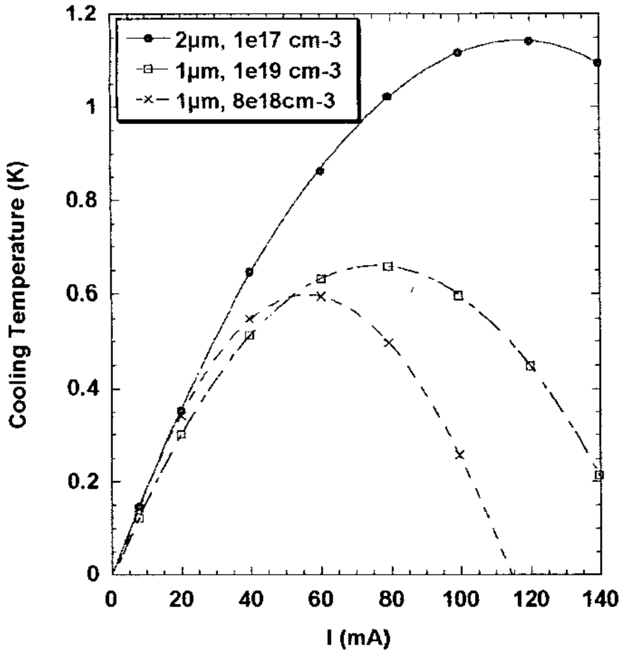

Figure 4 P-type InP superlattice micro-refrigerator cooling versus current (same sample size $4900um^2$; superlattice structure: for 1µm barrier, 1.3Q superlattice; for 2µm barrier, 80x(20InGaAs/5InP))

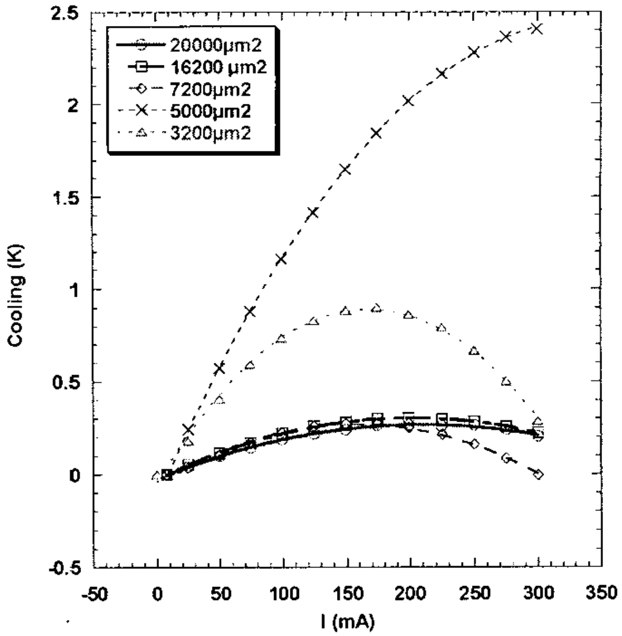

Figure 5 N-type InP substrate InGaAs/InP superlattice microcooler cooling versus current for different size devices (superlattice structure: 80x(20InGaAs/5InP), 2µm thickness with doping concentration 5.0e18 cm^{-3}

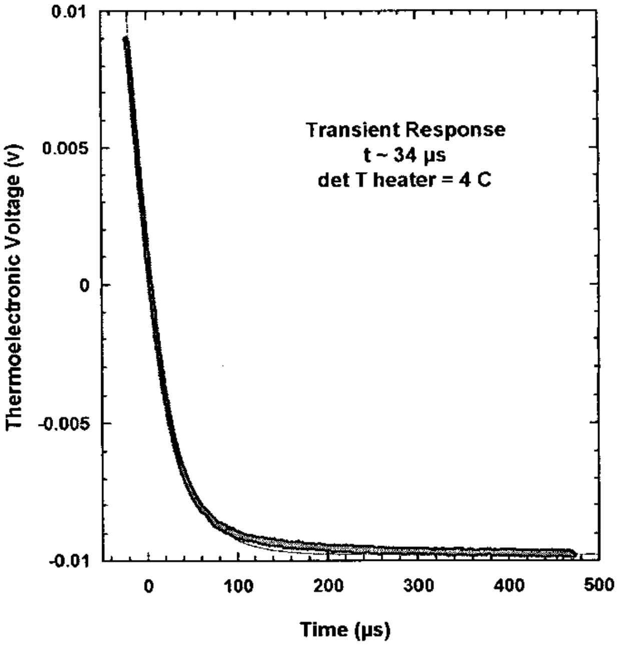

Figure 6 A typical transient response fitted curve for InGaAs/InP superlattice samples (superlattice structure: 2µm thick with doping concentration of $2e18cm^{-3}$, 250x(5nm InGaAs n-doped/3nm InAlAs undoped)

In general, the doping concentration, superlattice composition and thickness, and device size are the basic parameters to be optimized for maximum cooling.

In Figure 6, the transient response of the micro-cooler shows a value of 34μs, which is much faster than the conventional Theremoelectric (TE) coolers in the order of few seconds. Thus, this microcooler is in the order of 1e5 faster than the conventional TE coolers.

Discussion

The hoping for monolithically integrated thermoelectric coolers could be traced back to the early 1970's. In 1984, Hava et al. [10] demonstrated a 2^0C decrease in junction temperature using 6A of a cooler current in a monolithically integrated thermoelectric cooler. However, the huge amount of current injection cause more joule heating and reduce the thermoelectric cooling. One year later, Dutta et al.[11] in a monolithically integrated cooled InGaAsP/InP laser diode, observed a $\pm$ 2.5^0C change in active region temperature using 50mA of thermoelectric cooler current. In 1991 Berger et al.[12] achieved a $\pm$ 7.5^0C temperature change in active region by using 100mA of thermoelectric cooler current for GaAs/AlGaAs vertical-cavity surface-emitting laser (VCSEL). All devices are basically metal-substrate coolers based on Peltier effect, which is bulk thermoelectronic cooling. Our devices are based on heterostructure, and its cooling power density has been improved. The superlattice layer could reduce the thermal conductivity to prevent the heat flow back from the substrate to the top-cooling surface. The temperature difference created by the previous TE coolers seems promising, however they were over several hundred micrometers substrates. If we calculate the corresponding cooling power density, the value is only about a few W/cm^2. The cooling power density is a key parameter for removing hot spots in optoelectronics devices. For our device, a cooling power density of 200-300 W/cm^2 has been predicted for a cooling of 2.5^0C [13], which is about hundred times larger than the bulk TE devices.

With the current device capability: localized cooling over 200W/cm^2, with transient response less than 40μs. The device will be good enough to integrate with some optoelectronic devices mainly for temperature tuning applications. Meanwhile, at higher temperature, the device will cool better. At 80^0C the superlattice device could cool twice as much as room temperature value [13,14]. Labounty et al. demonstrated the preliminary results of integrating a thin-film cooler with a pin diode [13]. Though the cooling efficiency is not as high as desired, several non-ideal effects could be improved.

3D Electrothermal simulations have shown that the current InGaAs/InP superlattice should be able to cool 15 – 20^0C by removing non-ideal effects [15,16]. The current device is mainly limited by the parasitic effects: like metal-semiconductor contact resistance, thermal resistance of the substrate, side contact Joule heating and heat conduction. The possible solutions to reduce these non-ideal effects will be further investigated.

The same limitation also affects the transient response. In fact, the inherent transient response of the device should be faster than the measured value. Thermoreflectance transmit measurement shows a response of ~20μs [17]. The current transient response is mainly dominated by the thermal mass of heater sensor metal lines.

Besides phonon blocking superlattices [18,19], there are some other recent advanced strategies to improve the COP of thermoelectric coolers. The other two approache are receiving most of the attention –thin film/quantum confinement [20,21] and skutterudites[22]. These also could be developed into the alternative cooling solutions for optoelectronic devices.

Conclusions/Future work

InP-based superlattice samples could reach a maximum cooling of 2.5^0C at room temperature. The localized cooling power density could reaches as high as 200-300w/cm^2 with a transient response less than 40μs. These devices have potential application for removing hot spots in fast Optical Integrated Circuits (OICs). By resolving the non-ideal effects, we expect a net cooling of 15-20^0C at room temperature.

Acknowledgments

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