Microscale Heating and Cooling in Electronic and Optoelectronic Integrated Circuits

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Abstract

Microscale thermal issues are becoming one of the key factors that limit the performance of electronic and optoelectronic integrated circuits. Non-uniform temperature distribution and hot spots in high performance chips increase their failure rate and cause signal propagation delays and faults in digital circuits. Temperature variation is also extremely important in optoelectronic devices used in wavelength division multiplexed fiber optic systems. Some recent results on thermal imaging of optoelectronic devices will be presented with submicron spatial resolution and <0.05C temperature resolution. In addition an overview of thin film heterostructure integrated thermionic coolers based on SiGe and InP-superlattice material will be given. It is shown that localized temperature control on a chip with cooling power density exceeding 500W/cm^2 can be achieved.

Introduction

The on-chip temperature of the packaged very large scale integrated (VLSI) circuits not only can reach as high as 100C on average, but also can vary by as much as a few tens of degrees from one location to another. Because the failure rate of microelectronic devices due to electromigration and oxide breakdown depend strongly on the operating temperature, hot spots due to high local-power dissipation have become a long-term IC reliability concern in diverse applications. In the case of optoelectronic devices temperature stability is very important. Temperature variations are the primary cause of the wavelength drift, and they also affect the threshold current, quantum efficiency and output power in laser sources. Most stable sources such as distributed feedback (DFB) lasers and vertical cavity surface emitting lasers (VCSEL's) can generate large heat power densities on the order of kW/cm^2 over areas as small as 100 μm^2 [1,2]. The output power for a typical DFB laser operating at 1.55μm wavelength changes by approximately 0.4 dB/°C. Typical temperature-dependent wavelength shifts for these laser sources are on the order of 0.1 nm/°C [3]. Therefore a temperature change of only a few degrees in a wavelength division multiplexed (WDM) system with a channel spacing of 0.2-0.4 nm would be enough to switch data from one channel to the adjacent one, and even less of a temperature change could dramatically increase the crosstalk between two channels. Temperature stabilization or refrigeration is commonly performed with conventional thermoelectric (TE) coolers. However since their integration with optoelectronic devices is difficult, component cost is greatly increased because of packaging. The reliability and lifetime of packaged modules is also usually limited by the TE cooler. In addition, when several devices are monolithically integrated on the same chip, non-uniform temperature distribution will be an issue.

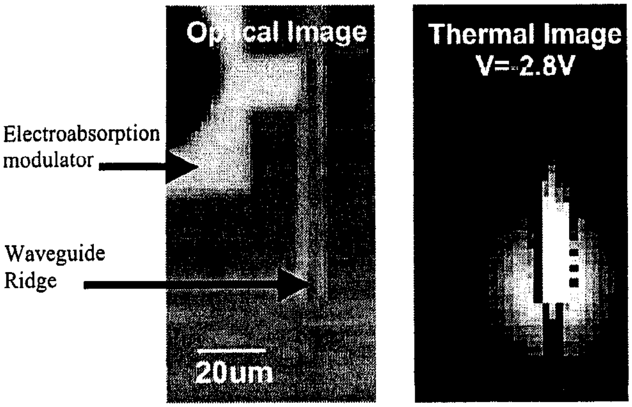

Fig 1. Optical and thermal image of an electroabsorption modulator integrated with a semiconductor laser structure at a bias of -2.8V. Laser wavelength is 1.55μm and power incident to the modulator is ~35mW. ΔT is larger than 110C [4].

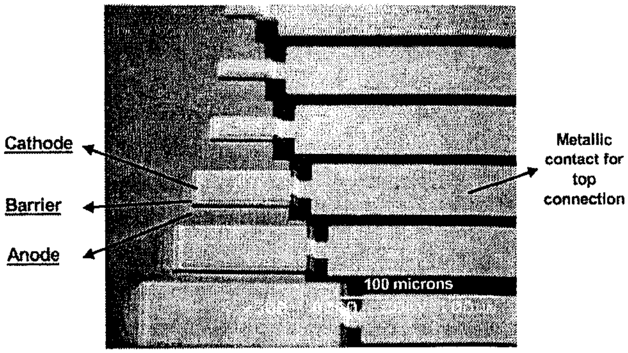

Fig. 2 Scanning electron micrograph of thin-film micro coolers fabricated on silicon substrate.

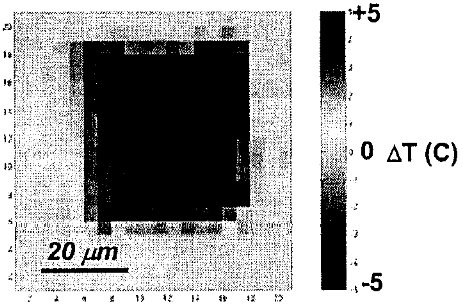

Fig. 3 Thermal image of temperature distribution on top of a 40x40 μm^2 micro refrigerator showing localized cooling.

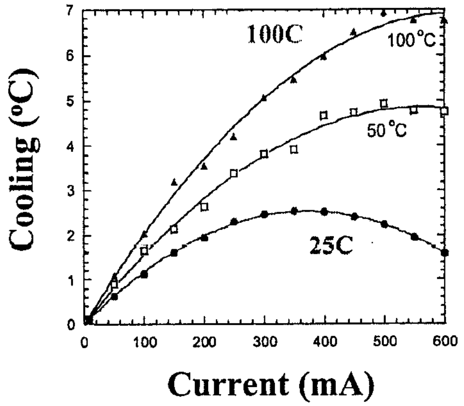

Fig. 4 Cooling below ambient versus current for $40x40\mu m^2$ SiGeC superlattice sample. Different curves correspond to different ambient temperatures.

Experimental results/discussion

Fig. 1 shows the temperature distribution in an electroabsorption modulator integrated with a multi section distributed Bragg reflector semiconductor laser. It can be seen that since most of the incident laser light is absorbed at the input of the modulator, large localized heating exceeding 110C in a region on the order of 20 micron in diameter can be developed [4,5]. Large temperature changes will affect bandgap of the material, absorption edge and electron (hole) population inside the conduction (valance) band. In the case of laser diode arrays and photonic integrated circuits, thermal cross talk is another important issue that needs to be minimized. One attractive solution for microscale temperature control is to integrate thin film thermoelectric coolers with active electronic and optoelectronic devices. Silicon and III-V compound semiconductors have a low thermoelectric figure-of-merit. One can improve the overall cooling performance with the use of thermionic emission in heterostructures and superlattices. Thermionic energy conversion is based on the idea that a high work function cathode in contact with a heat source will emit electrons. Practical vacuum thermionic energy converters are limited by the work function of available metals and by space charge effects. Vacuum thermionic refrigerators were predicted to have efficiencies of over 80% of the Carnot value [6-8], but they could only work at high temperatures (>500K). Using thermionic emission in heterostructures and semiconductor superlattices, one can fabricate room temperature solid state refrigerators. Improvement in thermoelectric figure-of-merit by a factor of 2-3 is predicted [6]. There has been some recent experimental activity in this area in the last couple of years. Thin film coolers based on InP [7] and SiGe [8, Fig. 2] have been demonstrated. Devices fabricated on a conventional silicon substrate and ranging in diameter from 150μm down to 20μm, have achieved 7-8C cooling at 100C ambient temperature [8, Figs.3, 4]. Localized cooling, with power densities exceeding 500W/cm^2 and response time below 30μs have also been demonstrated. Fig. 5 show three heterostructure integrated thermionic (HIT) micro refrigerators/heaters on an InP chip with various shapes. The measured temperature profile is obtained using thermoreflectance imaging. The center device is biased for cooling and outer devices are heating. It can be seen that there is minimum thermal cross-talk when micro coolers/heaters are separated by less than 30 μm. Detailed electro-thermal modeling shows that with material and processing optimizations, the cooling could be improved to reach 20-30C.

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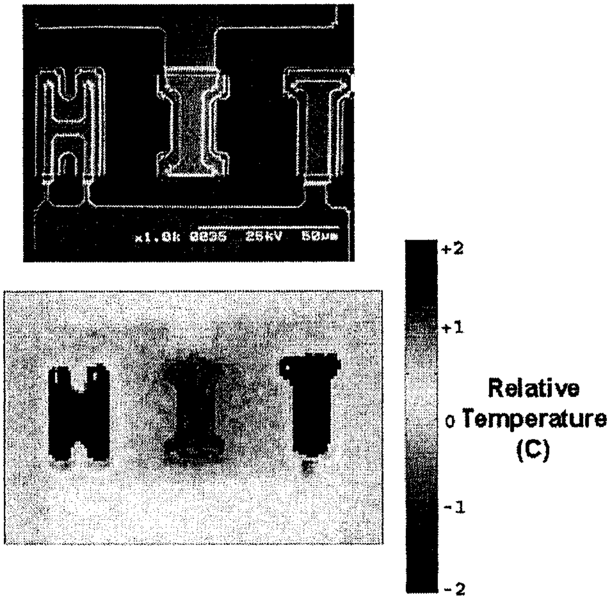

Fig. 5 (a) Scanning electron micrograph of three heterostructure integrated thermionic (HIT) micro refrigerators/heaters on a chip with various shapes. (b) Measured temperature profile using thermoreflectance imaging when the center device is biased for cooling and outer devices are heating. The micro coolers/heaters are separated by less than 30 μm.