Monolithically Peltier-cooled vertical-cavity surface-emitting lasers

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We report the first tunable monolithically integrated thermoelectric controlled GaAs/AlGaAs vertical-cavity surface-emitting laser diode. The thermoelectric element is the n^+-GaAs substrate based on the Peltier effect. A variation of active region temperature of ±7.5 °C has been achieved using ±100 mA of thermoelectric cooler current. The observed wavelength tuning associated with this temperature shift is ±6 Å. The device is useful for applications that require a high degree of frequency stability or small frequency tuning. Some examples of potential applications are in high data rate lightwave transmission, self-electro-optic device switches, and spectroscopy.

Single-frequency injection laser diodes have many applications. Among the applications where single-frequency sources are needed are high data rate lightwave transmission systems,[1] self-electro-optic device (SEED) switches,[2] and spectroscopy. All of these applications benefit from frequency tunability and stability. The emission frequency of an injection laser varies with the temperature of the active region.[3] The temperature stability of the injection laser used in many of these applications can be achieved either by an "external" thermoelectric cooler, or a monolithically integrated thermoelectric cooler. Hava *et al.*[4] observed a 2 °C decrease in junction temperature using 6 A of cooler current in a monolithically integrated cooled AlGaAs laser. Also, in a monolithically integrated thermoelectric cooled InGaAsP/InP laser diode, Dutta *et al.*[5] demonstrated a ±2.5 °C change in active region temperature using 50 mA of thermoelectric cooler current. Here we report the first monolithic integration of a thermoelectric cooler with a GaAs/AlGaAs vertical-cavity surface-emitting laser (VCSEL).

Our device structure uses the n^+-GaAs substrate as the thermoelectric cooler element as detailed below. The principle of operation of the device is as follows. The laser diode is thermally isolated by etching a mesa structure encircling the laser down to below the active region. Placing n contacts at the base of the mesa and on the substrate backside completes the thermoelectric cooler, as shown in Fig. 1. When the laser diode is under forward bias, near and above lasing threshold, most of the heat (from nonradiative recombination and absorbed radiative recombination) is generated near the active region. Thus we expect a thermal gradient from the active region to the upper n contact.[6] This thermal gradient also appears between the top n contact beside the mesa and the lower n contact on the n^+-GaAs substrate. The thermoelectric (Peltier) effect of the n^+-GaAs substrate can be used to vary the temperature difference between the two junctions (top and bottom n contact) by passing a cooler current. The Peltier effect is the process by which heat is pumped away from an electrode by the electrons which are removed from it. Since the top contact is close to the active region of the laser, the active region temperature and hence emission frequency can be easily controlled (or tuned) by varying the cooler current.

The device fabrication involved the following processing steps. First, the device structure, shown in Fig. 1, is grown by molecular beam epitaxy (MBE). A similar design was reported by Deppe *et al.*[7] who demonstrated 3×3 arrays of VCSELs. It employs a bottom mirror consisting of 23.5 pairs of a quarter-wave n-AlAs/n-GaAs (576 Å/723 Å) multilayer distributed Bragg reflector (DBR). The active region consists of a 1.0-μm-thick p-GaAs layer. The lower and upper $Al_{0.3}Ga_{0.7}As$ cladding regions are 0.9 and 0.4 μm thick, respectively. The upper contact layer is p^+-GaAs. The entire structure is grown on an n^+-GaAs substrate with a p-up configuration. After MBE growth, 60-μm-diam mesas (4.3 μm deep) were etched on the wafer. The bottom of the mesa is about 1.25 μm from the bottom of the lower DBR mirror. The upper n contact for the cooler of AuGe/Ni/Ti/Au is defined and annealed at 350 °C for 30 s. The lower n contact is In, which is pressed on the backside and annealed on a heater. The upper mirror is deposited by lifting off 20-μm-diam Ag/Au dots. The Ag acts as both a p contact and a mirror for the surface-emitting laser[8] with reflectivity ~95%. The evanescent tail of the field into the Ag is extinguished before reaching the Au layer which acts to prevent oxidation and scratching of the Ag during probing.

The light characteristics were measured from gain-guided structures. The threshold current for pulsed operation was 40 mA at 20 °C for 20-μm-diam lasers. The emission wavelength is ~8700 Å. The wavelength shift in the

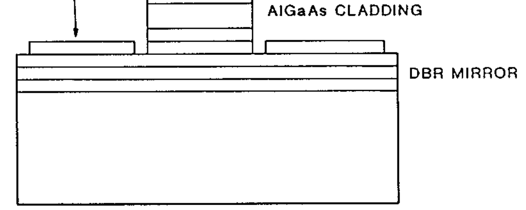

FIG. 1. Schematic of the monolithically integrated thermoelectric controlled surface-emitting laser structure.

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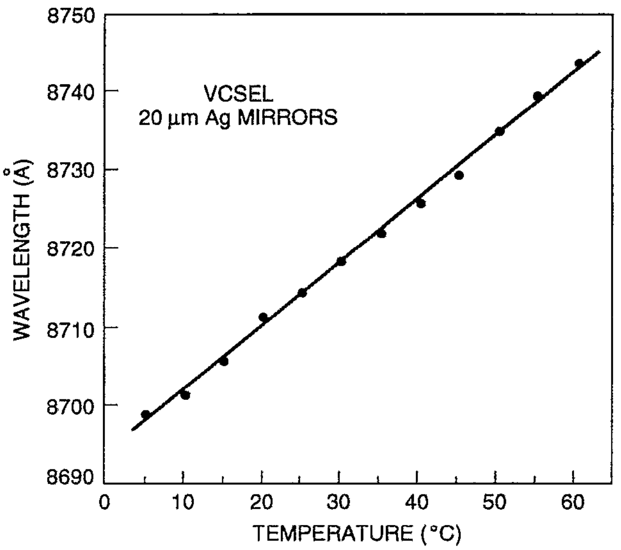

FIG. 2. Variation of the emission wavelength from the active region as a function of temperature using an external thermoelectric cooler.

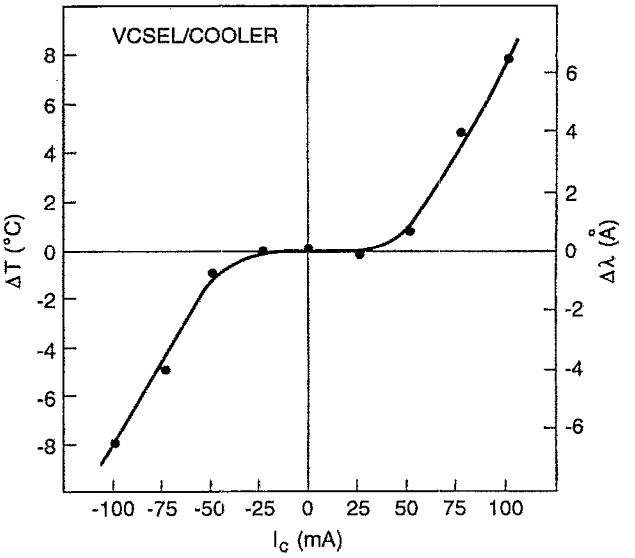

FIG. 3. Variation of the wavelength as a function of thermoelectric cooler current.

emitted spectrum was measured with changing temperature by use of a commercially available external thermoelectric controller. The wavelength dependence is shown in Fig. 2, and shows a shift in wavelength of 0.8 Å/°C.

The spectrum of the device was measured as a function of integrated thermoelectric controller current (I_c). For a 100 mA positive cooler current, the spectrum shifts about 15 Å to a higher wavelength, and for a 100 mA cooler current in the opposite direction, it shifts also in the positive direction about 3.5 Å. Two competing factors are responsible for the spectrum shift. These are cooling and resistance heating. The net heat removed, W, is given by

$$W = \Pi\, I_c - \tfrac{1}{2} I_c^2 R_b - I_c^2 r_c, \qquad (1)$$

where R_b is the bulk series resistance, r_c is the contact resistance, Π is the Peltier coefficient, and I_c is the shift in wavelength with cooler current. Thus an asymmetry of the shift in wavelength with positive and negative cooler current will be present if significant Peltier cooling is taking place. The Peltier effect induced wavelength shift versus cooler current is plotted in Fig. 3, and shows tuning of ±6 Å. From the data in Fig. 2, this corresponds to a temperature change of ±7.5 °C.

We have also fabricated devices where the mesas are etched past the DBR mirror stack to the n^+-GaAs substrate. This reduces r_c significantly due to the higher doping and lower band gap. However, the Peltier coefficient Π is also significantly reduced due to high doping. Cortes *et al.*[9] calculated the doping level dependence of Peltier coefficient (Π) for n-GaAs. It is given by

$$\Pi = kT/q[\ln(N_c/N_d) + 2], \qquad (2)$$

with

$$N_c = 2(2\pi m_c kT/h^2)^{3/2}, \qquad (3)$$

where k is the Boltzmann constant, T is the absolute temperature, m_c is the conduction-band effective mass, h is the Planck's constant, e is the electron charge, and N_d is the carrier concentration. Figure 4 shows the calculated Π for n-GaAs using $m_c = 0.07 m_0$ where m_0 is the free-electron mass. Figure 4 also shows the variation of the bulk resistivity of n-GaAs as a function of doping. The dashed line (in Fig. 4) is calculated assuming a mobility of 2000 cm^2 V^{-1} s^{-1} for n-GaAs with a carrier concentration of 10^{18} cm^{-3}. Figure 4 shows the trade off between Π and R for optimization of the thermoelectric controller.

In summary, we have fabricated a monolithically integrated thermoelectrically controlled vertical-cavity surface-emitting laser. A variation of active region temperature of ±7.5 °C has been achieved with ~100 mA of thermoelectric cooler current. The device is useful for applications which require a high degree of frequency stability or small frequency tuning. The frequency stability can be achieved using a feedback loop on the thermoelectric

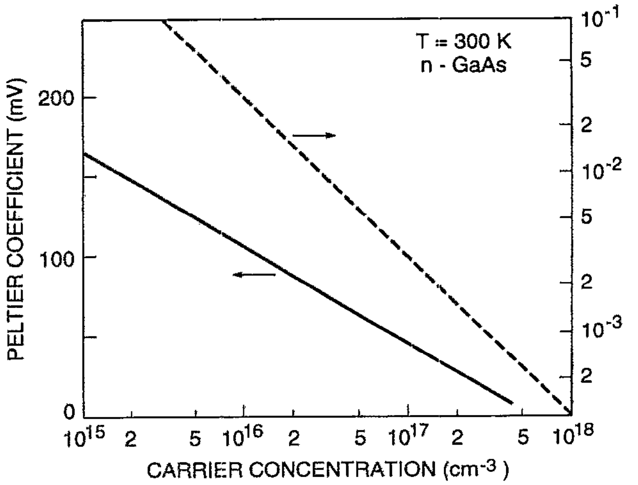

FIG. 4. Calculated Peltier coefficient and resistivity of n-GaAs at 300 K.

controller circuit. Such a monolithic scheme is expected to have a significantly higher performance (e.g., faster response) than conventional "external" thermoelectric coolers because of the small thermal mass ($\sim$mass of laser chip).

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