Low threshold PbEuSeTe/PbTe separate confinement buried heterostructure diode lasers

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Continuous wave (cw) operating temperature of 223 K was achieved with molecular beam epitaxy grown separate confinement buried heterostructure (SCBH) PbTe diode lasers with PbEuSeTe electrical and optical confinement layers. This is the highest cw operating temperature reported for midinfrared diode lasers. The active region of the SCBH diode lasers varies laterally to form a crescent-shaped waveguide with a maximum thickness of 0.15 μm and a lateral width of 2 μm. Exceptionally low threshold currents of 102 mA at 200 K, 166 mA at 210 K, and 249 mA at 215 K were measured. © *1996 American Institute of Physics.* [S0003-6951(96)01906-2]

Laser sources for the mid- to long-infrared spectral region (3–30 μm) offer rich possibilities for areas such as atmospheric pollution measurement, noninvasive medical diagnostics, automotive engine exhaust diagnostics, and industrial process monitoring and control. The advantages of diode laser sources for such applications lie in their superb sensitivity, high resolution, and system size. These lasers were mostly used in spectroscopy-related applications, where they provide measurement capabilities far beyond that of conventional instruments.[1,2] Despite modest investments in the study and fabrication of lead-salt diode lasers, substantial progress has been reported by Partin[3] with the introduction of molecular beam epitaxy (MBE) technology and rare-earth elements, i.e., Eu. The impact of the improved devices was significant since they eliminated the need for a large and heavy closed-cycle He refrigeration system, replacing it with a compact liquid nitrogen dewar assembly which operates in the 80–120 K temperature range. However, theoretical considerations by Rosman *et al.*[4] indicated that Pb salts are fully capable of higher power and higher operating temperatures. Experimental results reported for MBE grown single quantum well PbTe/PbEuSeTe diode lasers (175 K in cw at 4.4 μm and 270 K in pulsed operation),[5] MBE grown PbSe/PbSrSe double heterostructure (DH) diode lasers (169 K in cw and 290 K in pulsed mode),[6] hot wall epitaxy (HWE) grown PbS/PbSrS quantum well diode lasers (225 K in pulsed mode),[7] and buried heterostructure (BH) PbTe/PbEuSeTe diode lasers (203 K in cw mode)[8] support the conclusions of Rosman *et al.*[4] These recent advances and the theoretical predictions for even higher cw operating temperature present the potential of the replacement of liquid nitrogen cooling with a smaller thermoelectrically cooled assembly and are therefore the motivation for the present effort.

In a continuous effort to further increase the cw operating temperature of Pb-salt midinfrared diode lasers, we concentrated on the development of PbEuSeTe/PbTe separate confinement buried heterostructure (SCBH) diode laser structures.[9]

The separate confinement (SC) design replaces the DH design which consists of a three-region slab waveguide in which one layer (active) with larger index of refraction is sandwiched between two regions of smaller index of refraction (cladding layers). The active layer functions both as the optical guiding layer and as the carrier confinement region. The SC heterostructure is a five-region slab waveguide design in which the injected carriers are confined in a region within the optical waveguide. The two outer layers (with smaller index of refraction) serve as cladding layers. The carriers are confined to the active (middle) layer by two inner electrical confinement layers. This way the thickness of the active layer can be minimized to achieve lower threshold currents without compromising the power filling factor (the radiation confinement factor) since the modal power propagates through the inner three-layer slab that consists of the active layer sandwiched between the two electrical confinement layers. This approach was tested recently with a preliminary SCBH design that produced cw operation up to 215 K.[9] Further improvements in performance resulted as a consequence of a design with considerably thinner active layer and electrical confinement layers.

Growth of lattice-matched PbEuSeTe and PbTe epilayers was carried out in a standard Varian Gen II MBE system by combining molecular beam fluxes from PbTe, Eu, PbSe, and Te effusion sources. $T1_2Te$ and Bi_2Te_2 effusion sources were used for *p* and *n* doping, respectively. For substrates we used vapor grown (100)PbTe wafers, grown, sliced, and polished in our laboratory. Buried heterostructure technology requires MBE growth in a two-stage growth process. The first-stage growth consists of a 1 μm thick PbTe buffer layer followed by the first PbEuSeTe optical confinement, electrical confinement, and PbTe active layers. Using standard photolithographic techniques the active stripes are etched to their final crescent shape. The second MBE growth stage is therefore performed on a nonplanar surface that includes the etched PbTe active stripes. In this stage, the second electrical and optical confinement layers and the contacting layer are grown. The growth temperature is between 300 and 350 K. A SEM micrograph of a cleaved facet with the individual layers exposed by preferential etching is presented in Fig. 1. Table I contains information about device dimensions and layer composition for SCBH devices in this publication and in Ref. 9.

As shown in Table I, the main difference between the two SCBH structures is in the thickness of the active stripe and both confinement layers. The last two rows of the table compare operating temperature and threshold currents.

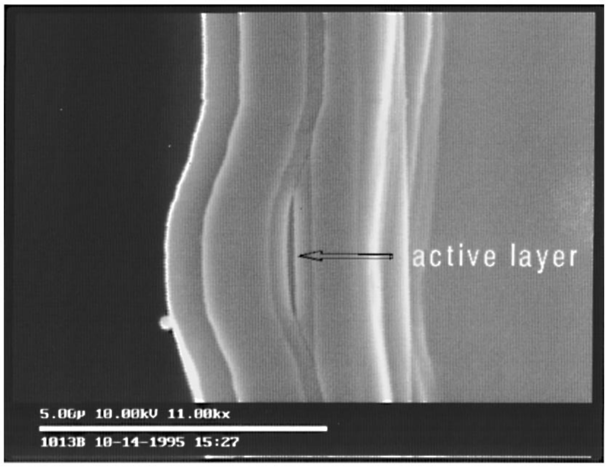

FIG. 1. A SEM micrograph of a chemically revealed active layer stripe of a PbEuSeTe/PbTe SCBH diode laser.

Electrical and optical measurements as a function of temperatures were performed with the devices mounted in a closed-cycle He refrigerator capable of providing stable temperatures within the range of 10–300 K. The dependence of the cw threshold current on heat sink temperature for diode lasers 5285.83 (the present study) and 2052.82 (Ref. 9), is presented in Fig. 2. Based on approximated threshold calculations we expected lower threshold currents for thinner active layers. This indeed is the case for $T > 150$ K where we found significant reduction in threshold currents for devices with 0.15 μm thick active layers over devices with 0.3 μm thick active layers which otherwise have the same active stripe area. In fact, the majority of diode lasers with 0.15 μm thick active layers that were tested operated in cw mode at temperatures greater than 215 K with some operating at 218, 220, and 225 K. The power of diode laser 5254.84 at 225 K was hardly detectable due to absorption by CO_2 molecules in the air residing along the laser beam path between the cold head and the infrared detector. For this device we could not measure emission wavelength at operating temperatures above 218 K.

In principle, these SCBH PbEuSeTe/PbTe diode lasers can be operated in cw mode when mounted on a multistage thermoelectric cooler; however, the performance of these devices can be further enhanced with the proper investment in substrate quality, wafer handling, contacting, and packaging technology. The initial dislocation density of bulk PbTe crystals grown in our laboratory averages 10^4 cm^{-2}. Following

TABLE I. SCBH dimensions and layer compositions.

	Device 5285.83	Device 2052.82 (Ref. 9)
Active layer composition	PbTe	PbTe
Active layer width	2 μm	2 μm
Active layer thickness	0.15 μm	0.3 μm
Laser length	250 μm	250 μm
Electr. confinement compos.	$Pb_{0.976}Eu_{0.024}SeTe$	$Pb_{0.976}Eu_{0.024}SeTe$
Electr. confinement thick.	0.3 μm	0.35 μm
Optic. confinement compos.	$Pb_{0.952}Eu_{0.048}SeTe$	$Pb_{0.949}Eu_{0.051}SeTe$
Optic. confinement thick.	1.2 μm	1.3 μm
Max. cw operating temp.	223 K	215 K
Threshold current at 200 K	102 mA	253 mA

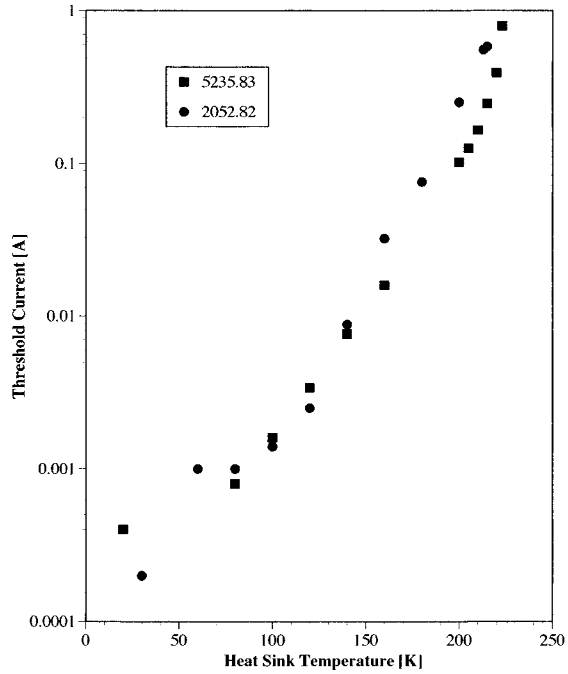

FIG. 2. cw threshold currents vs heat sink temperature for diode lasers 5235.83 and 2052.82 (Ref. 9) both with equal current injection area.

extensive wafer handling during wafer preparation, growth and diode production, the average dislocation density increases to 10^6-10^8 cm^{-2} due to the inherent crystal softness. Pb-salt diode laser packaging technology, which is based on cold pressing using thickly electroplated indium, as shown in Fig. 3, does not provide good thermal dissipation. With thermal conductivity considerably lower than found in III–V compounds, heat dissipation becomes critical for high-temperature operation. We also believe that it is necessary to replace the present Au contacting technology in order to reduce contact resistance.

In summary, we have developed modified SCBH PbEuSeTe/PbTe lasers with PbTe active layers that are capable of cw operation at temperatures greater than 220 K. Analysis of the state-of-the-art bulk crystal growth and pro-

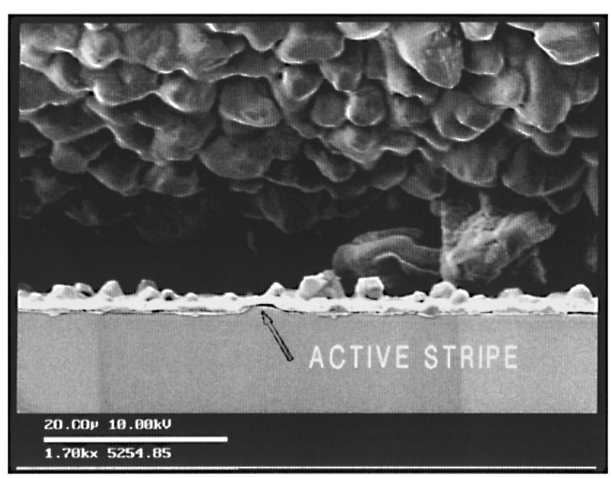

FIG. 3. A SEM micrograph of diode laser 5254.85 packaged for commercial applications. The upper part of the figure shows the large grain of the electroplated indium on the package. The lighter layer adjacent to the device is an evaporated indium layer with small grain.

duction technology for the Pb-salt diode laser suggests that implementation of production technologies developed in the last two decades for cadmium mercury telluride (CMT) infrared detectors and some of the ''softer'' III–V compounds will most probably enable room temperature or near-room-temperature cw operation for Pb-salt diode lasers.

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