WIDELY TUNABLE (PbSn)Te LASERS USING ETCHED CAVITIES FOR MASS PRODUCTION†

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SUMMARY

Lead salt diode lasers are being used increasingly as tunable sources of monochromatic infrared radiation in a variety of spectroscopic systems. These devices are particularly useful, both in the laboratory and in the field, because of their high spectral brightness (compared to thermal sources) and wide spectral coverage (compared to line-tunable gas lasers). While the primary commercial application of these lasers has been for ultra-high resolution (10^{-4} cm^{-1}) laboratory spectroscopy, there are numerous systems applications, including laser absorbtion pollution monitors and laser heterodyne radiometers, for which diode lasers have great potential utility. There are, however, several problem areas related to the wider use of these components. Among these are total tuning range, mode control, and high fabrication cost. A fabrication technique which specifically addresses the problems of tuning range and cost, and which also has potential application for mode control, is reported here.

PROCEDURE

Crystal Growth

($Pb_{.81}Sn_{.19}$)Te homojunctions were grown by multiple source molecular beam epitaxy (MBE). Independently controlled sources of PbTe and SnTe permitted precise composition control, while Bi_2Te_3 and Tl were used as extrinsic n and p dopants, respectively. A fifth Knudsen source was included to provide excess Te, if necessary, to control stoichiometry. The substrate was BaF_2, first used by Holloway (ref. 1). Unlike earlier work which used the (111) cleavage plane, the substrates for this work were chemically polished (100) oriented material, to allow for the preference of the lead salts to grow in the (100) orientation.

Crystal growth took place at temperatures from 400 to 420°C and growth rates of from 2 to 4 μm per hour. The laser's vertical structure was a five-layer homojunction utilizing carrier concentration gradients for both optical and electrical confinement. Structures similar to this have been reported by Lo (ref. 2) using bulk diffused material and by Walpole (ref. 3) using MBE-grown material on a bulk substrate. A typical growth sequence consisted of growing an n-type contact layer 0.5 μm thick and doped to 10^{19} cm^{-3}, an

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n-type buffer layer 2 μm thick and doped to $3x10^{18} cm^{-3}$, an undoped active layer 1.5 μm thick which was typically $1x10^{18}$ p-type, 2 μm of $3x10^{18}$ p-type buffer, and, finally, 0.5 μm of $1x10^{19}$ p-type contact layer. Following growth, the entire multilayer film, which was typically 8mm long, 10mm wide, and 9 μm thick, was metallized and soldered to a copper heat sink, forming electrical contact to the p-contact layer. The BaF_2 substrate was then slowly dissolved off using warm flowing de-ionized water.

Device Fabrication

Standard integrated circuit processes were used to mass-produce mesa diode lasers. The process steps from crystal growth to wire bonding are summarized in figure 1. Following substrate removal, rectangular Fabry-Perot cavities were etched, either wet-chemical or by ion milling. Next, a BaF_2 insulating layer was deposited and a contact window opened to permit electrical contact to the n-type contact layer without creating an electrical short to the copper heat sink. Metal was then deposited over the entire structure and subsequently removed from one face of the laser. The device was completed by wire-bonding to the top contact metal, next to the device, in order to avoid damage due to mechanical stress. Figure 2 shows the finished mesa diode in detail.

A typical structure is 75 μm wide, 250 μm long, and 9 μm high. An array of these diodes prior to final wire bonding is seen in figure 3. The diodes are spaced 500 μm apart in x and y. The dark squares are the photoresist which has been used to pattern the top contact metal, and the smaller rectangles within the squares are the lasers, where one face of the laser is covered by metal and one face extends beyond the metal, permitting radiation to escape.

LASER PERFORMANCE

Diodes fabricated in this way have been operated cw at heat sink temperatures ranging from 12K to 60K, and they operated in 5 μs pulses up to 95K, at which temperature the pulsed threshold current was 10,000A/cm^2. Low tempera ture thresholds were between 500A/cm^2 and 1000A/cm^2, both pulsed and cw. These values for threshold currents compare favorably with those obtained for devices made by more conventional one-at-a-time processes based on the growth of high quality bulk single crystal material.

The emission wavelength of lead salt lasers is varied by changing the temperature at the junction. This tuning is accomplished by varying the heat sink temperature and the current in the laser, together or separately. A laser can operate in either a single mode or multimode, depending upon small changes in the operating point. Figure 4 illustrates both the current tuning and the mode structure of a diode operated at a heat sink temperature of 20K. Since the average emission wavelength is determined primarily by the temperature dependence of the band gap of the semiconductor, one can predict the average wavelength of emission given the I-V characteristics of the laser, the measured thermal resistance, and the known temperature dependence of the band gap.

Figure 5 summarizes both the temperature tuning and the current tuning of a laser which operated in the pulsed mode up to 95K. The cw emission wavelength is taken to be the center frequency for cases of multimode emission. This wavelength is plotted as a function of current and heat sink temperature. The solid lines were calculated from the known electrical and thermal properties of the diode.

Because of difficulties in the thermal package, this diode exhibited quite a high temperature rise at the junction; thus, the cw emission of 10 μm at 1.35A and a heat sink temperature of 15K corresponded to a junction temperature of 95K, the highest temperature for pulsed operation. Significantly, we have obtained, in a single diode, cw emission from 10 μm to 14 μm, a tuning range comparable to the widest reported in the literature.

CONCLUSION

Useful laser performance has been demonstrated in devices fabricated using thin-film and integrated circuit technologies geared toward mass production. The MBE crystal growth technique permits independent and precise control of composition and carrier concentration. The lasers described in this paper were grown on a BaF_2 substrate and exhibited an extremely wide tuning range, despite a 1.4% lattice mismatch. This wide tuning range is probably attributable to excellent optical and electrical confinement, accomplished with the thin active region and sharp concentration gradients achievable with MBE.

On the other hand, these devices did not show good performance in terms of single mode or multimode output power. There are two likely causes for the low output power (typically 10 μW). There is probably non-optimal output coupling due to imperfect and misaligned etched end mirrors. Refinements of the ion-milling process have led to some improvements in this area. More significantly, there may be severe quantum efficiency reduction due to the lattice mismatch. This effect has been demonstrated by Kasemset for (PbSn)Te heterojunctions (ref. 4).

Figure 6 presents the range of lattice constants for some potential substrate materials. The only possibilities for lattice-matching to (PbSn)Te are bulk material or the mixed alkali-halide, which is a very poor thermal match and not a very good substrate. On the other hand, it is possible to lattice-match (PbSn)Se to $(BaSr)F_2$.

In addition to potential cost reduction, the thin-film processing techniques provide the possibility for integrated arrays of diodes differing from each other in a controlled fashion. This would greatly aid in the problem of spectral coverage. The photolithographic cavity definition allows the use of shaped cavities for mode control, and the multi-layer thin film crystal growth permits great flexibility in vertical structure. Thus, standard devices may be obtained with improved properties in terms of both cost and performance.

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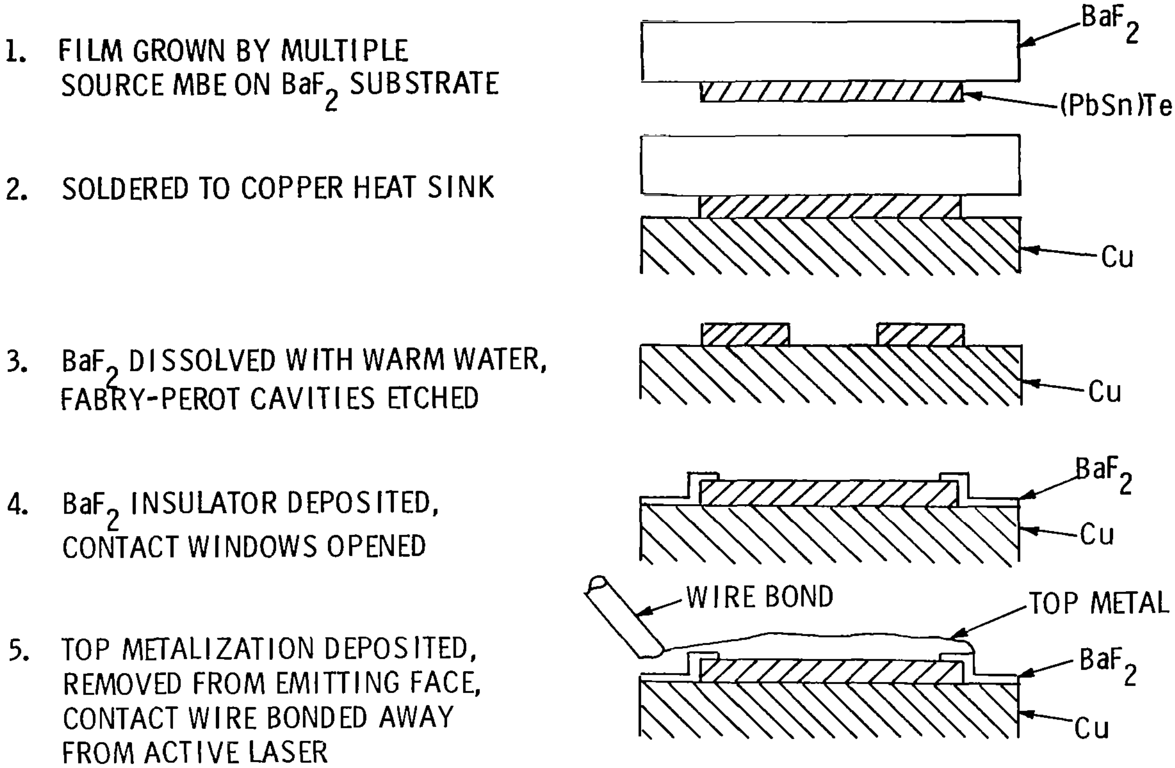

Figure 1.- Processing steps in laser fabrication, from crystal growth to final wire-bonding.

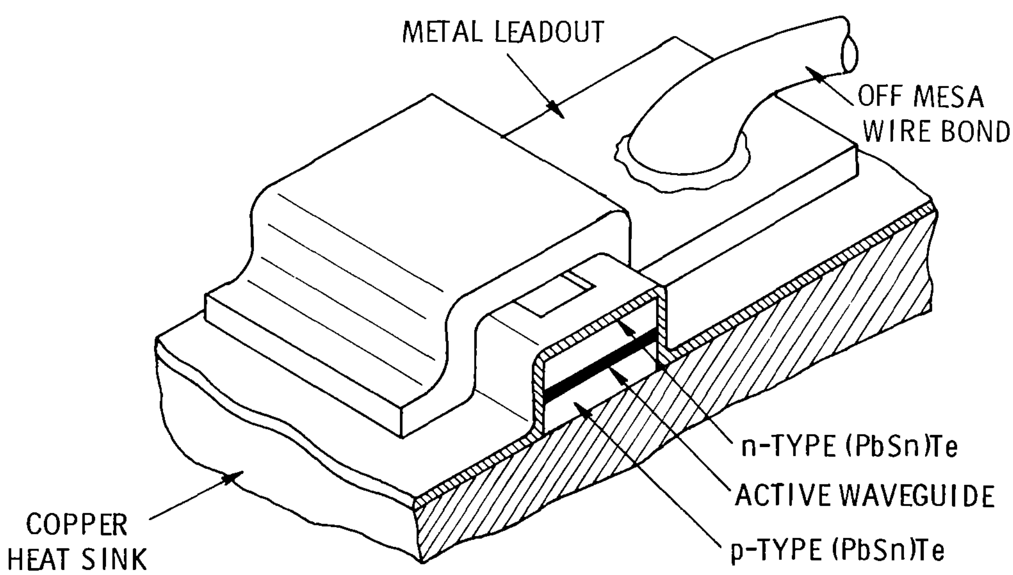

Figure 2.- Detailed illustration of etched mesa diode laser.

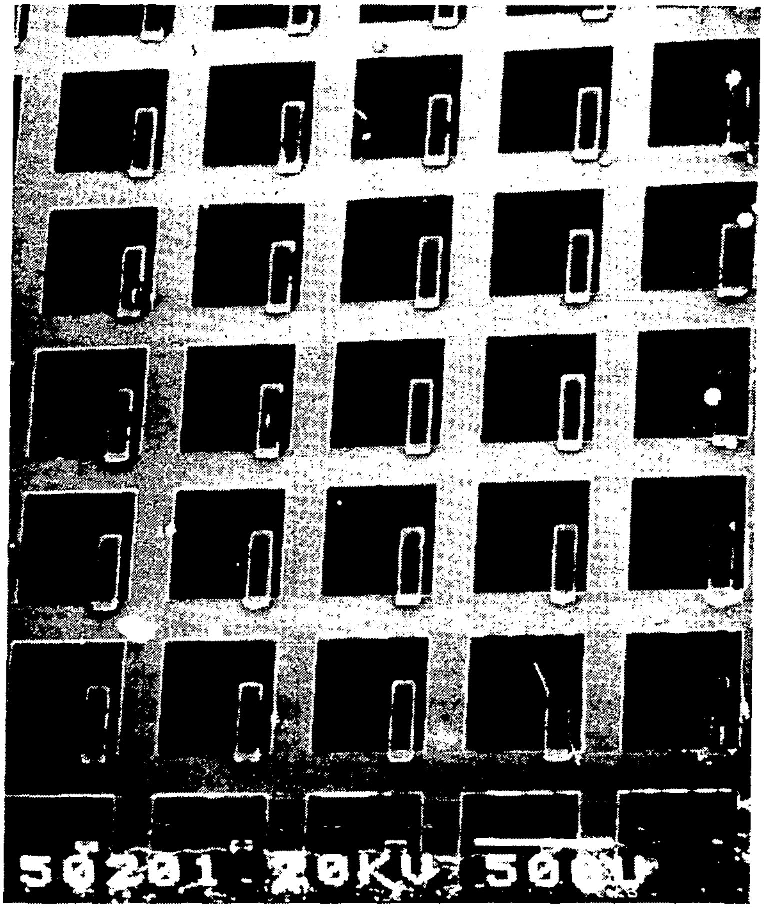

Figure 3.- Scanning electron micrograph of an array of lasers prior to wire-bonding.

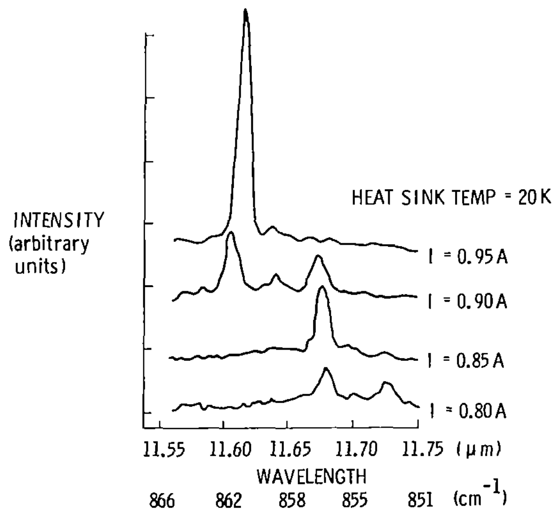

Figure 4.- Output spectrum illustrating complex mode structure and rapid wavelength tuning with current.

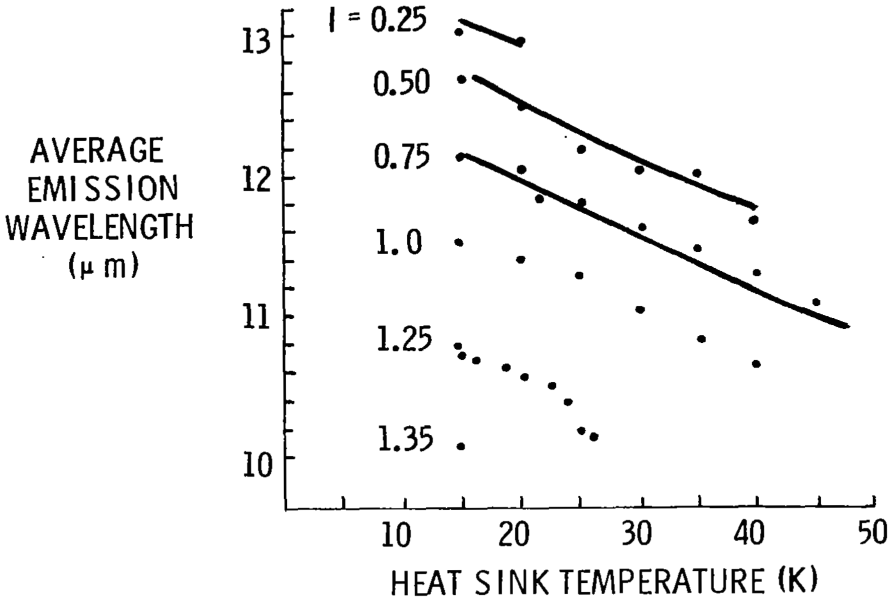

Figure 5.- Range of accessible wavelengths for diode operating cw. Wavelength tuned with temperature and current from 14 μm to 10 μm. Solid lines are theoretical tuning curves derived from temperature dependence of the band gap and known electrical and thermal properties of the diode.

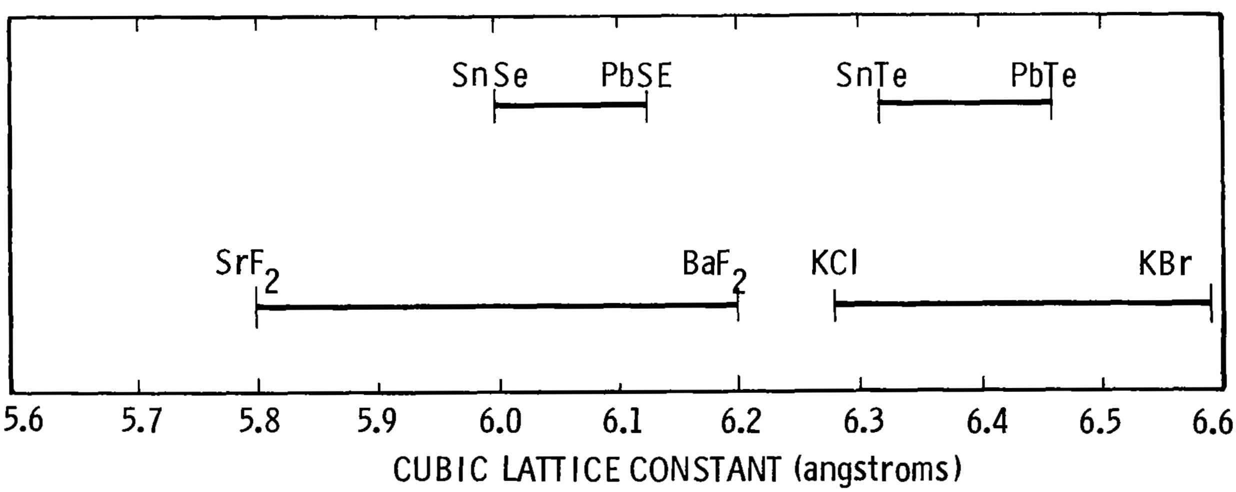

Figure 6.- Range of cubic lattice constants for potential substrate materials for epitaxial growth of lead salt laser material.