ADVANCES IN TUNABLE DIODE-LASER TECHNOLOGY

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SUMMARY

Three major areas of research have been investigated. They are: the improvement of long-term reliability, the purification of mode properties, and the achievement of higher-temperature operation. In reliability studies we observed a slow increase in contact resistance during room temperature storage for lasers fabricated with In-Au or In-Pt contacts. This increase is actually caused by the diffusion of In into the surface layer of laser crystals. By using a three-layered structure of In-Au-Pt or In-Pt-Au, we have reduced this mode of degradation. In characterizing the mode properties, we found that the lasers emit in a highly localized, filamentary manner. For wide-stripe lasers the emission occurs near the corners of the junction. In order to achieve single-mode operation, stripe widths on the order of 8-10 μm are needed. We also found that room temperature electroluminescence is possible near 4.6 μm.

INTRODUCTION

In recent years the technology of fabricating lead-salt diode lasers has advanced rapidly. Progress has been stimulated by the demand for more reliable and well behaved devices for certain applications. For instance, deleterious changes in electrical and optical properties have been overcome.[1,2] This was achieved by improving the crystal growth technique, the diffusion process, and above all the contacting method. We have found that contact reliability is the dominant factor in determining the lifetime of lead-salt diode lasers. Besides long term reliability, better emission characteristics are essential for most applications. We have characterized stripe-geometry $Pb_{1-x}Sn_xTe$ diode lasers with data on near-field measurements. In this paper, the technology needed to fabricate simple single-mode, stripe-geometry lasers will be discussed.

Higher temperature operation is another desirable feature of well behaved lasers. Processes leading to the fabrication of room temperature $PbS_{1-x}Se_x$ light emitting diodes will be discussed.

Contact Reliability

For cw operation at temperatures approaching 40 K, we found that a contact resistance of 10^{-4} ohm-cm^2 or less is necessary. This is attributed to the low thermal conductivity of lead salt materials (typically 0.07 W/cm-K versus 3.0 W/cm-K for GaAs at 77 K).[3] Since lead-salt crystals have very high electron affinities, low resistance and ohmic contact to the n-type side of diodes can be obtained easily by using either Au, In or In-Au combinations. It is the p-type contact that normally causes problems.

For the p-type side In-Au,[4] In-Pt[5] and In-Pt-Au[6] structures have been reported as producing low resistance, ohmic contacts. More recently only In-Au combinations have been used.[7,8] We are not aware of any systematic studies on the long-term reliability of In-Au contacts. However, we found that they are not stable in our devices. During storage at room temperature over periods that range from days to months, the resistance of In-Au contacts can increase. Such increases are typically accompanied by increases in cw threshold current densities and laser emission frequencies, while at the same time laser output powers tend to decrease.

We found that the increase in contact resistance is caused by the diffusion of In into the surface layer of the p-type side. Figure 1 shows an electron microprobe analysis of In and Pb concentration profiles near the metal-semiconductor interface before and after degradation. The samples were prepared with In-Au as the p-type contact. The degradation was accelerated by heating the sample to 100°C for one hour. This test condition is equivalent to room temperature storage of approximately one week. Both the degraded and the control samples were angle-lapped at a 3° inclination to provide a twenty-fold improvement in spatial resolution normal to the interfaces.

The typical electron beam penetration depth is about 1 to 2 μm. The X-rays generated by the E-beam (the signal strength shown in Fig. 1) are absorbed partially by the contact metals before being detected. Au and Pt are good absorbers for the X-rays. We calculated that 70% of the X-rays generated in the crystal are absorbed by Au in a distance of 0.2 μm. This explains the sharp change in the Pb X-ray signal near the interface (and hence the good accuracy in identifying the interface). From Fig. 1 it is also noted that for a degraded sample, traces of In were found in the first few μm of the crystal below the contact. Since In is a donor in lead-salt materials, a reduction in hole carrier concentration near the surface is expected. We think that this is the reason for the increase in contact resistance.[9]

Further study revealed that Au or Pt alone cannot form a barrier against In penetration, but a combination of Pt-Au does.[1,2] It was also noticed that the reliability of the lasers depends on the thickness of the Pt and Au layers. We found that both layers have to be at least 0.2 μm thick in order to form a barrier against In diffusion. After depositing the Au and Pt layers on the p-type side of the diode a 10 μm layer of In is added. The n-type contact consists of a 0.2 μm layer of Au plus 5 μm of In. The p-type side of the crystal surface was purposely oxidized by exposure to air before evaporating the first layer of Au. This increases the hole carrier concentration near the surface and tends to stabilize the contact resistance.

Over a period of ten months, groups of $PbS_{1-x}Se_x$ and $Pb_{1-x}Sn_xTe$ lasers (made with three-layer contacts on the p-type side) have been tested for thermal cycling, room temperature storage and cw operation. For up to sixty thermal cycles and five hundred hours of cw operation, no significant changes in contact resistance, threshold current density or optical properties were observed. The test results are summarized in Table 1. This is a significant improvement over lasers that have been fabricated in the past, whose performance could degrade in a matter of a few days at room temperature.

Mode Control

Diode Lasers with both contact stripes and diffused junction stripes have been studied. Since lead-salt materials generally have very high electrical conductivity, lasers with contact stripes will encounter severe current spreading problems.[10] For this reason, the lasers described here were made with junction stripes by an impurity diffusion process. Both Sb and Cd were used as diffusion sources,[11,12] with MgF_2 and SiO_2 as the diffusion masks.

In lasers with 125 μm wide stripes, the emission originated from the corners of the diffused planar junctions. The near field pattern exhibited two peaks with a separation approximately equal to the width of the stripe (Fig. 2). This is consistent with the tuning curve that was observed with a monochromator. By adjusting the position of a collection lens in front of the laser, each filament could be imaged separately on the entrance slit of the monochromator. As shown in Fig. 3 the two filaments produced two separate, but parallel, tuning curves. The frequency difference was approximately constant at 5.3 cm^{-1}. This difference could be produced by a 0.1% variation in the composition of the $Pb_{1-x}Sn_xTe$ across the 125 μm stripe. When the detector was scanned along the direction perpendicular to the p-n junction plane and near one corner of the stripe, the near field pattern showed only one peak. This suggested that the photon confinement perpendicular to the junction was quite good for these impurity-diffused junctions.[13] Proper confinement parallel to the junction was then expected to produce single-filament operation. We estimate that a stripe width on the order of 10 μm is needed to achieve single-mode operation.

From Fig. 2 it is noted that the spot size of the filaments is quite broad. Since a simple BaF2 lens was used in this experiment, the resolution is set by aberration. By using the third-order approximation of a perfectly centered thin-lens aberration theory, we estimated that the image of an infinitely distant axial point source would be approximately 44 μm. This is in good agreement with the spot size observed in Fig. 2. In order to see any fine structure, a diffraction-limited lens has to be used.

OPERATING TEMPERATURE

In an effort to predict the highest temperature of operation for lasers at long wavelengths, we have made an empirical plot as shown in Fig. 4. From this plot, it is seen that the longest wavelength for a room temperature semiconductor laser is 2.5 μm. Although laser sources are desirable for many applications, room temperature, long wavelength incoherent light sources are of interest for low resolution applications, as well as for low loss optical fiber communication systems.[14,15] The narrow band gap, lead-salt materials are suitable for fabricating emitters in the 3-16 μm spectral range. Photoluminescence[16] and cathodoluminescence[17] have been observed at room temperature, but not electroluminescence. We report here the first recorded electroluminescence from lead-sulfide-selenide at room temperature.

The diodes were fabricated from high quality lead-sulfide-selenide single crystals grown from the vapor phase. A two-step diffusion-annealing process produced a graded carrier concentration region[18] for photon confinement transverse to the junction. No attempt was made to confine the carriers or photons along the junction plane. These results represent a further improvement in the two-step diffusion-annealing process which produced low temperature diode lasers in lead-sulfide-selenide.[18]

High temperature spontaneous emission spectra were recorded as shown in Fig. 5. Notice that the 330 ppm atmospheric CO_2 absorption band near 4.2 μm appears in the 260 K and 300 K spectra (Figs. 5(e) and 5(f)).

The power output for this (laser) diode geometry is low, on the order of a few hundred nW. This is attributed to the high index of refraction (4.6) for lead-sulfide-selenide, which produces substantial internal reflection at the semiconductor-air interface. The critical angle for total internal reflection (i.e., the largest angle which incident radiation can subtend with the normal and still exit the crystal) is 12°. A large fraction of the randomly oriented junction radiation is totally reflected back into the semiconductor and absorbed. By using a hemispherical structure and extracting light from the top surface rather than the side, a factor of 1000 improvement in power is possible. This will allow these diodes to emit 200 μW at room temperature.

CONCLUDING REMARKS

In conclusion, we found that the slow degradation of contact resistance for lead-salt diode lasers fabricated with In-Au contacts is due to the migration of In into the surface layer of the p-type side of the lasers. By using combinations of Au-Pt or Pt-Au as barriers to prevent In migration, we have substantially increased the lifetime of these lasers. For laser mode control, we found that narrow stripe (∿ 10 μm) diode lasers are needed for single-mode operation. Finally, for high temperature operation, we have shown that although lasing action at room temperature is possible only up to 2.5 μm, spontaneous emission at room temperature has been observed near 4.6 μm.

REFERENCES

1. Lo, W.: The Elimination of Contact Degradation in Lead-Salt Diode Lasers. Jap. J. Appl. Phys., Vol. 18, Suppl. 18-1, 1979, pp. 367-369.

2. Lo, W.; and Gifford, F. E.: Contact Reliability Studies on Lead-Salt Diode Lasers. J. of Electrochemical Society, June 1980.

3. American Institute of Physics Handbook. McGraw Hill, 1975, pp. 4-156.

4. Ralston, R. W.; Melngailis, I.; Calawa, A. R.; and Lindi, W. T.: Stripe-Geometry $Pb_{1-x}Sn_xTe$ Diode Lasers. IEEE, J. Quant, Electron., Vol. QE-9, 1973, pp. 350-356.

5. Antcliffe, G. A.; and Parker, S. G.: Characteristics of Tunable $Pb_{1-x}Sn_xTe$ Junction Lasers in the 8-12 μm Region. J. Appl. Phys., Vol. 44, 1973, pp. 4145-4160.

6. Ralston, R. W.; Walpole, J. N.; Calawa, A. R.; Harman, T. C.; and McVittie, J. P.: High cw Output Power in Stripe Geometry PbS Diode Lasers. J. Appl. Phys., Vol. 45, 1974, pp. 1323-1325.

7. Walpole, J. N.; Calawa, A. R.; Harman, T. C.; and Grove, S. H.: Double Heterostructure $Pb_{1-x}Sn_xTe$ Lasers Grown by Molecular-Beam Epitaxy. Appl. Phys. Lett., Vol. 28, 1976, pp. 552-554.

8. Linden, K. J.; Nill, K. W.; and Butler, J. F.: Single Heterostructure Lasers of $PbS_{1-x}Se_x$ and $Pb_{1-x}Sn_xSe$ with Wide Tunability. IEEE J. Quant. Electron., Vol. QE-13, No. 8, 1977, pp. 720-725.

9. Lo, W.: Te-Rich Growth and Laser Fabrication of $Pb_{1-x}Sn_xTe$ with $0.06 < x < 0.08$. J. Electron. Mater., Vol. 6, 1977, pp. 39-48.

10. Dumke, W. P.: Current Threshold in Stripe-Contact Injection Lasers. Solid State Electron., Vol. 16, 1973, pp. 1279-1281.

11. Lo, W.; Montgomery, G. P., Jr.; and Swets, D. E.: Ingot-Nucleated $Pb_{1-x}Sn_xTe$ Diode Lasers. J. Appl. Phys., Vol. 47, 1976, pp. 267-271.

12. Lo, W.: Cd-Diffused $Pb_{1-x}Sn_xTe$ Diode Lasers with High Output Power. Appl. Phys. Lett., Vol. 28, 1976, pp. 154-156.

13. Lo, W.: Homojunction $Pb_{1-x}Sn_xTe$ Diode Lasers with Increased Frequency Tuning Range. IEEE J. Quant. Electron., Vol. QE-13, 1977, pp. 591-595.

14. Pinnow, D. A.; Gentile, A. L.; Standlee, A. G.; Timper, A. J.; and Hobrock, L. M.: Polycrystalline Fiber Optical Waveguide for Infrared Transmission. Appl. Phys. Lett., Vol. 33, 1978, pp. 28-29.

15. VanUitert, L. G.; and Wemple, S. H.: $ZnCl_2$ Glass: A Potential Ultralow-Loss Optical Fiber Material. Appl. Phys. Lett., Vol. 33, 1978, pp. 57-59.

16. Galeski, F.; Drozd, L.; Lebedeva, L. Y.; Ten, V. P.; and Yunovich, A. E.: Stimulated Emission From Thin PbSe Films at Room Temperature. Sov. Phys. Semicond., Vol. 11, 1977, pp. 327-328.

17. Kurbatov, L. N.; Britov, A. D.; and Karavaev, S. M.: Cathodoluminescence of Lead-Tin Selenide. Sov. Phys. Semicond., Vol. 9, 1976, pp. 1045-1046.

18. Lo, W.; and Swets, D. E.: Diffused Homojunction Lead-Sulfide-Selenide Diodes with 140 K Laser Operation. Appl. Phys. Lett., Vol. 33, 1979, pp. 938-940.

Table 1. Laser test results
(Ten-month test period)

		R_c (Ohm-cm^2)X10^5 Contact Resistance		J_{th} (A/cm^2) Threshold Current density		P(mW) Total Output Power at I=1 Amp, T=20K		Remarks
		Initial	Final	Initial	Final	Initial	Final	
$PbS_{0.82}Se_{0.18}$	#1	1.10	1.18	260	280	0.85	0.80	•500 hours c.w. operation •Thermal cycling 26 times
	#2	0.87	0.91	365	380	3.2	2.6	•Thermal cycling 45 times
$Pb_{0.86}Sn_{0.14}Te$	#1	0.74	0.80	95	105	0.65	0.58	•300 hours c.w. operation •Thermal cycling 25 times
	#2	0.65	0.73	125	135	0.90	0.86	•420 hours c.w. operation •Thermal cycling 33 times

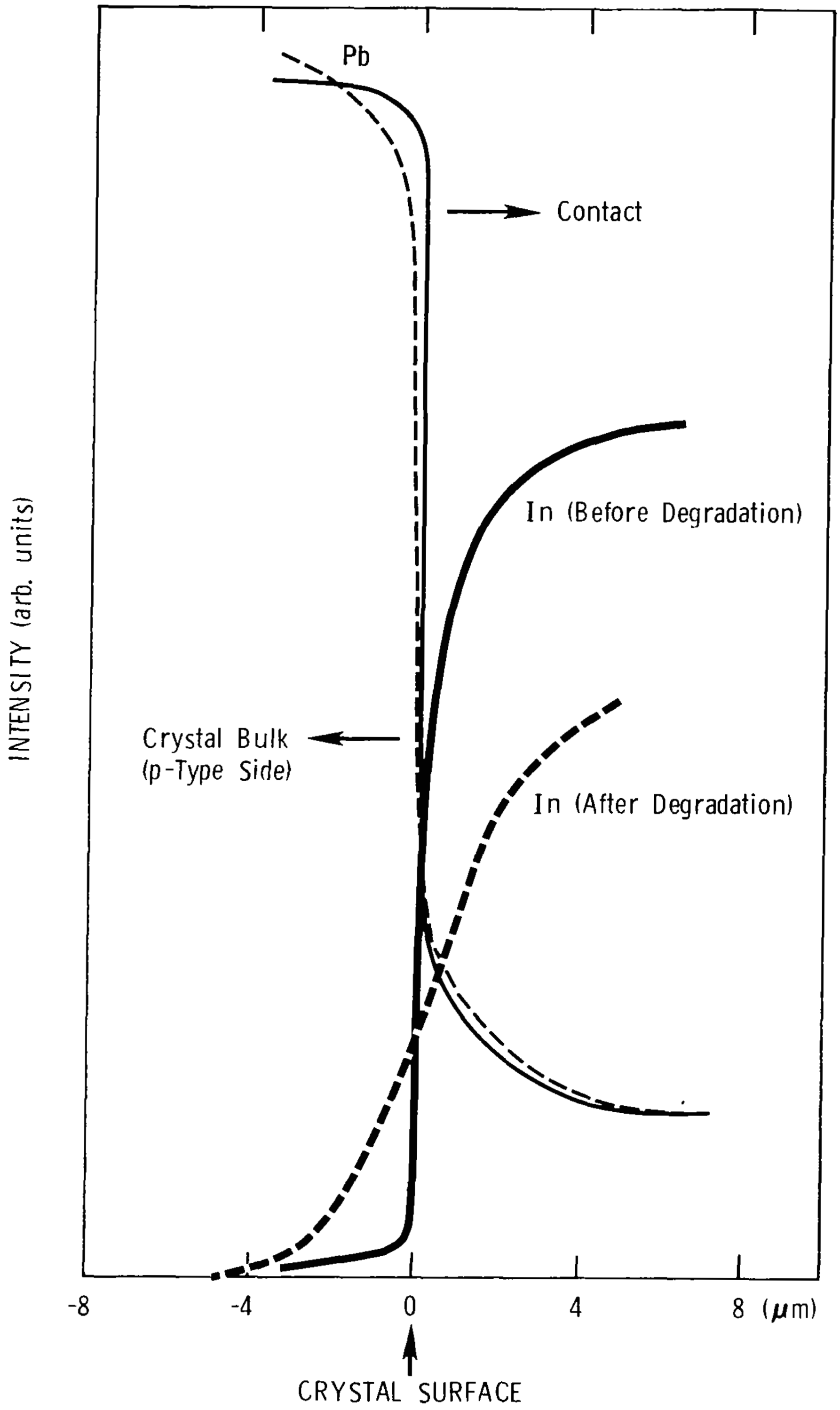

Figure 1.- Electron microprobe analysis of a crystal-contact interface for $PbS_{0.82}Se_{0.18}$.

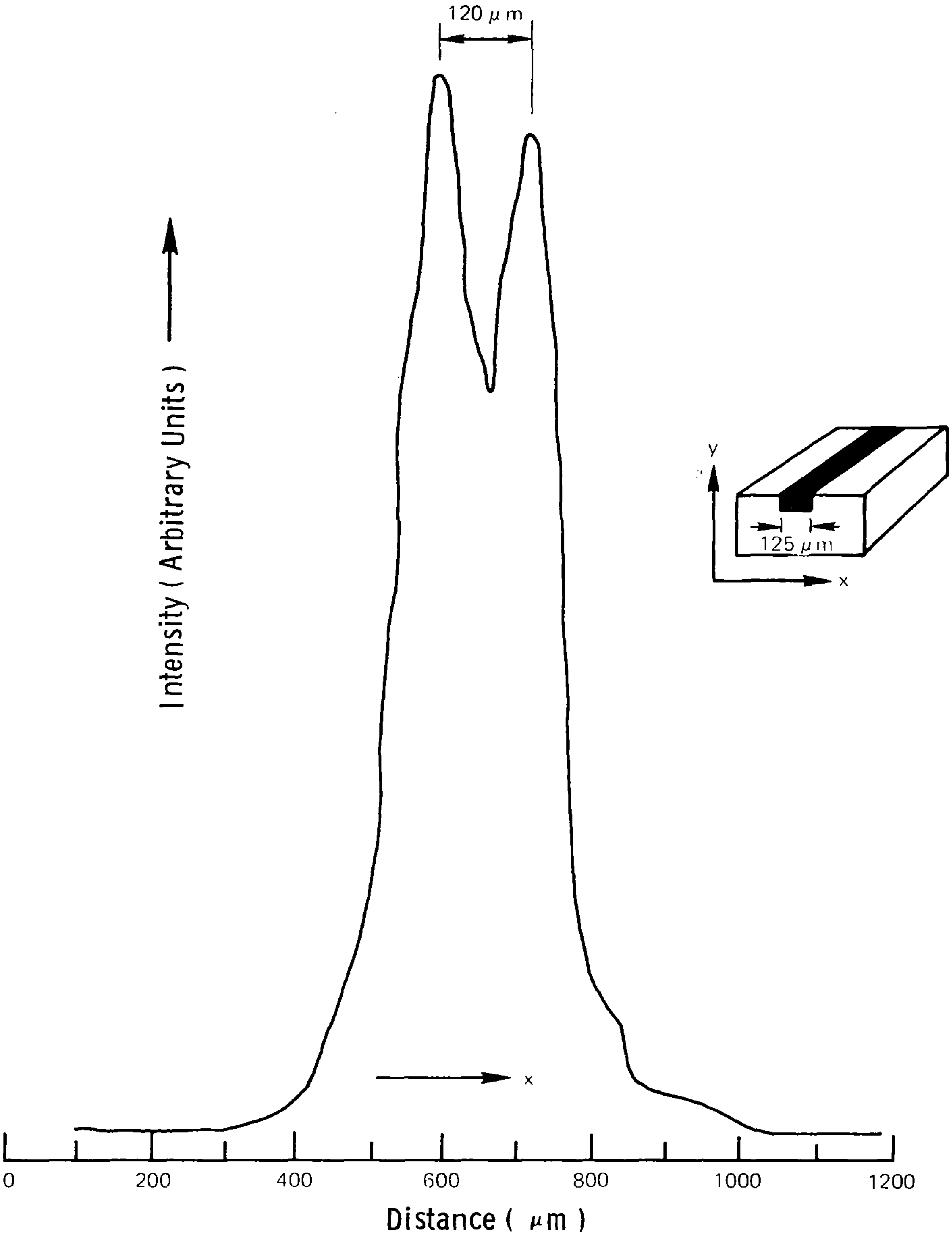

Figure 2.- Near field pattern in the plane parallel to the junction for a 125 μm stripe laser.

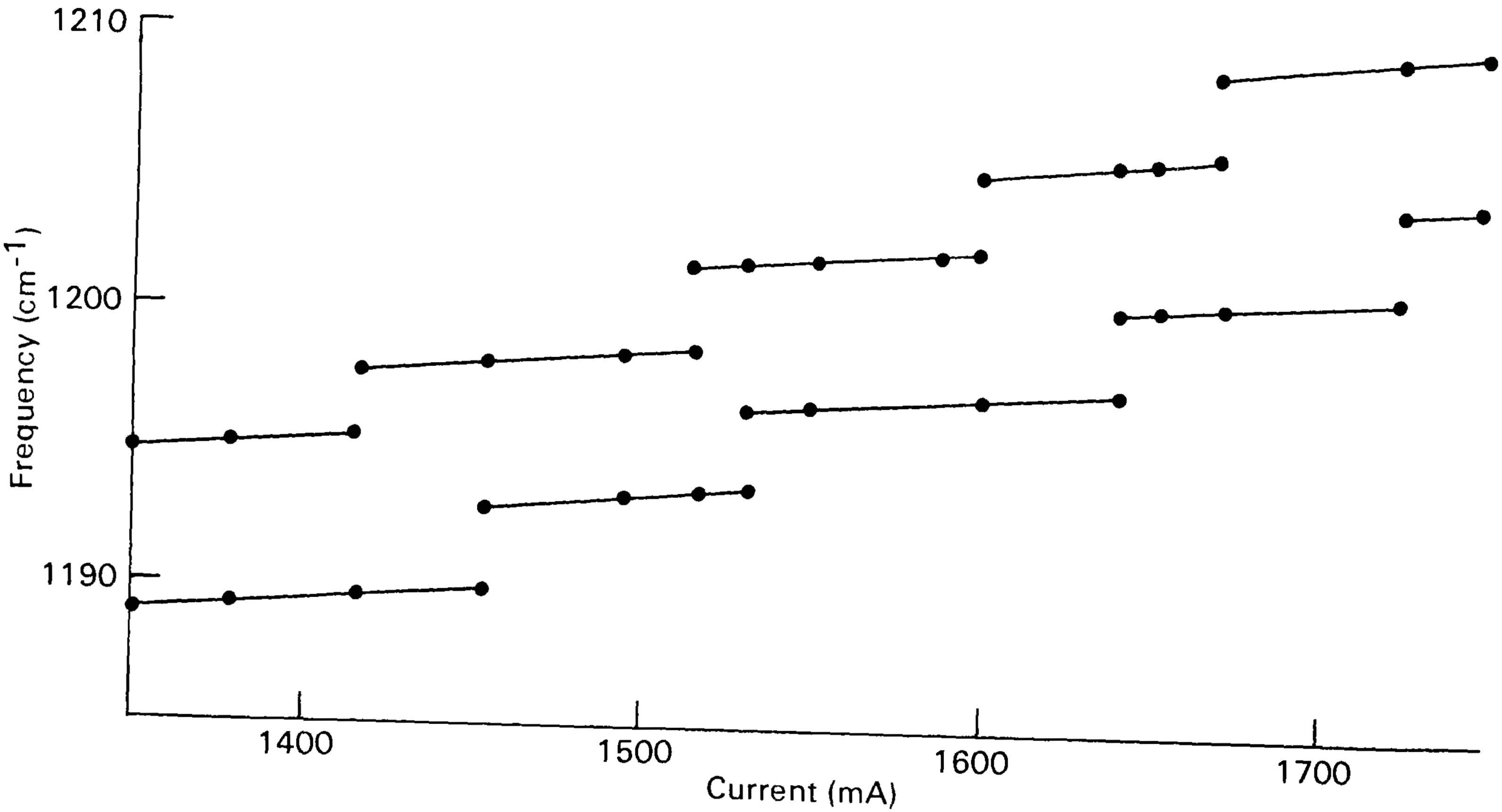

Figure 3.- Tuning curve for a 125 μm stripe laser.

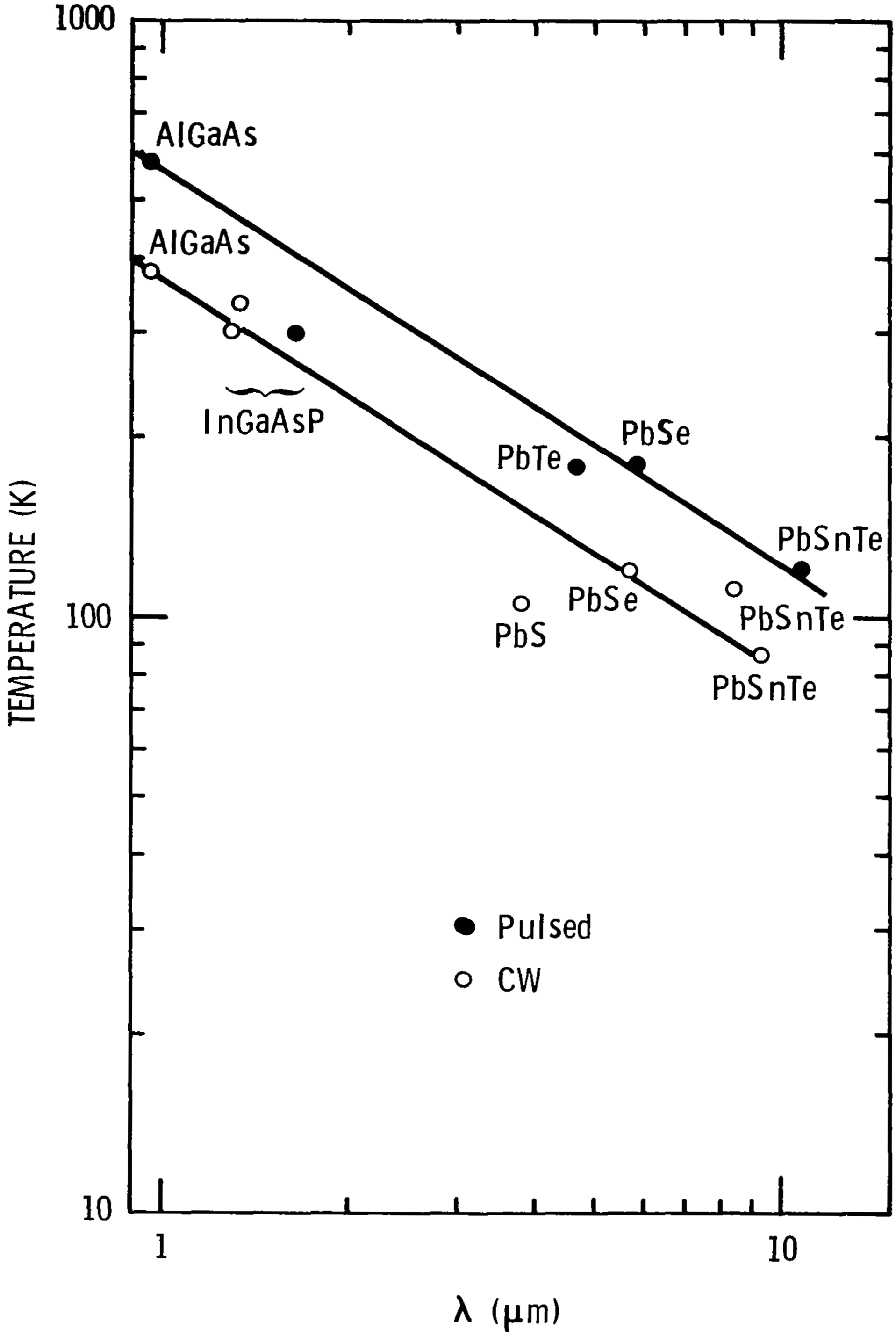

Figure 4.- Empirical plot of the highest observed operating temperatures for semiconductor diode lasers at different wavelengths.

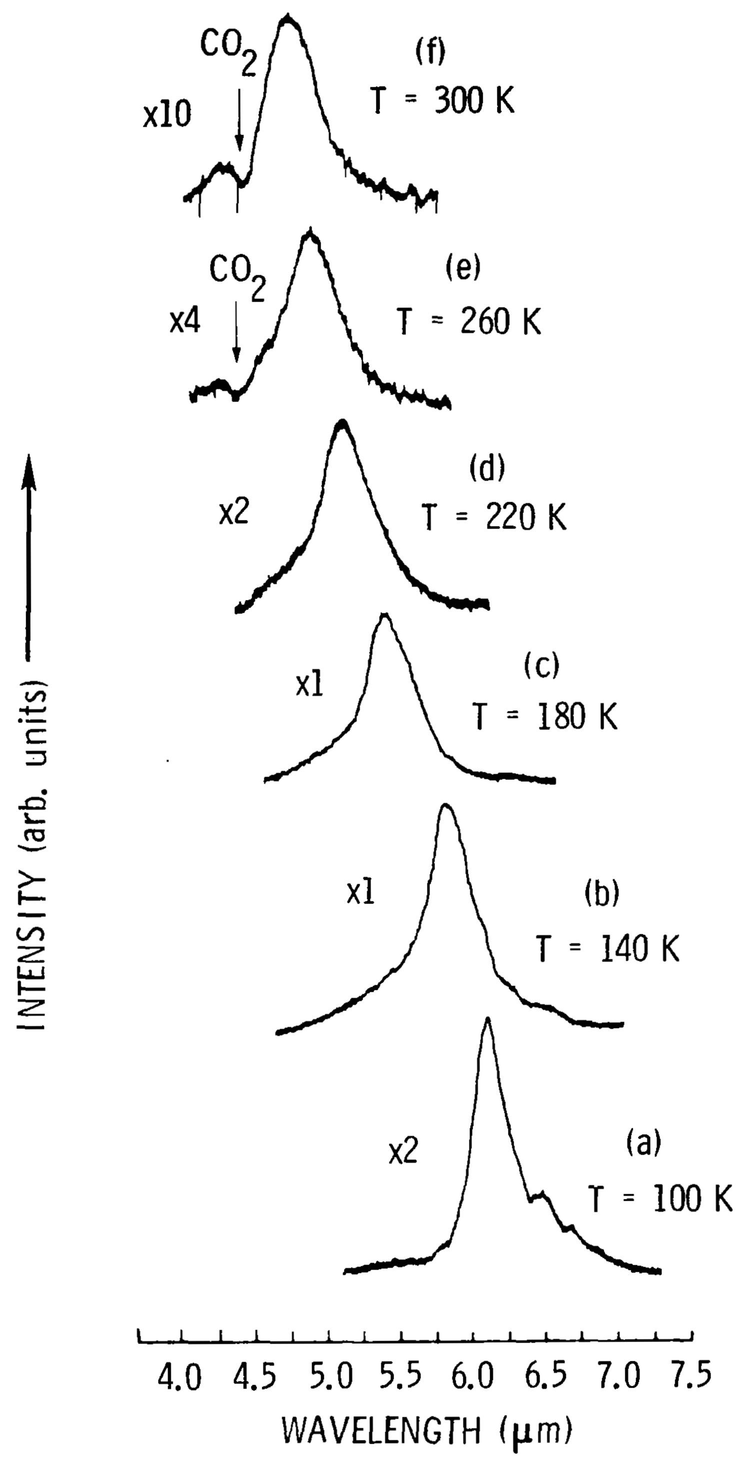

Figure 5.- Spontaneous emission spectra at different temperatures. Also shown is the 330 ppm atmospheric CO_2 absorption band near 4.2 μm in the 260K and 300K spectra.