Research Highlights
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Physics Division
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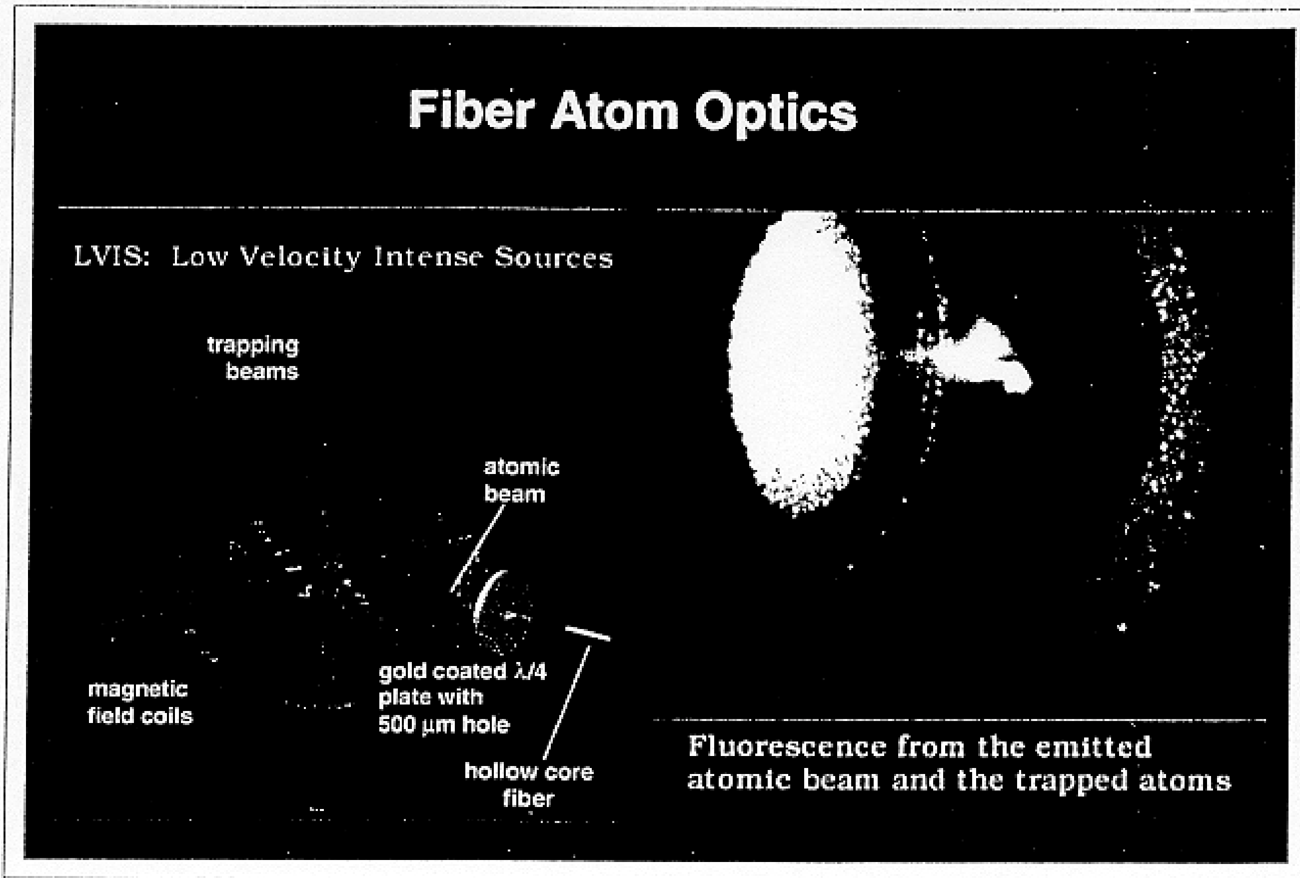

Physical Sciences Directorate
Army Research Office

INTRODUCTION

Research Highlights is the seventh in a series of annual reports of significant research accomplishments supported by the Physics Division of the Army Research Office. Several months ago, the Division's Principal Investigators were solicited to submit a succinct description of exciting research accomplishments. The research results described here were selected from those submissions. We feel these brief descriptions provide excellent examples of significant scientific advances.

ARO publishes a number of program descriptions: the *ARO in Review, ARO–Science to Shape the Future of the Army,* and a *Division Report of Active Projects List.* The *Research Highlights* has a format and utility unique among these publications. *Research Highlights* provides a detailed, but understandable, exposition of a handful of the most exciting accomplishments sponsored by the ARO Physics Division during the preceding year. It is distributed at the annual Physics Division Program Review, sent to the Army laboratories, and mailed to all current Physics Division Principal Investigators. The number of accomplishments described in *Research Highlights* is intentionally limited to a small number; however, we utilize excerpts from all of the submissions to construct briefing materials for the upper levels of Army and DoD management and Congress.

We would like to thank all the Principal Investigators who contributed submissions for this document.

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High Power InAsSb/InAsSbP Laser Diodes Emitting in the 3 ~ 5 μm Range

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Mid-infrared laser diodes (λ= 3 to 5 μm) are the attractive source for a wide range of applications ranging from chemical spectroscopy, free-space and optical fiber communication. A number of III-V semiconductor alloys, benefiting from stronger covalent bonding and advanced growth and device processing technology, have been investigated as alternatives to the IV-VI and II-VI material systems. The InPAsSb quaternary material system is a suitable material for the high power mid-infrared lasers with emission wavelengths of 3 to 5 μm. It provides a very favorable condition for the carrier and optical confinement due to its favorable type-I band alignment and lower refractive index of the higher band gap materials, and excellent dopant incorporation [1], thereby providing efficient injection and carriers confinement. Additionally, extensive research has been aimed to the realization of high power, room temperature operation of the lasers based on InPAsSb [2 ,3]. In this article, we present the recent achievement of the high-power InAsSb/InAsSbP double heterostructure and multiple quantum well laser diodes grown by low-pressure MOCVD (LP-MOCVD) for emission wavelengths of 3 to 5 μm.

Double-heterostructure (DH) [4 ,5 ,6] and MQW [7 ,8] InAsSbP/InAsSb/InAs laser diodes were grown on (100) oriented InAs substrate by LP-MOCVD in an EMCORE MOCVD reactor. The DH structure consists of a 1.0 μm thick undoped ternary active region InAsSb centered between two 1.5 μm thick InAsSbP cladding layers: Sn-doped (10^{18}cm^{-3}) and Zn-doped (10^{18} cm^{-3}), respectively, and a p^+-doped InAs cap layer. The active region of the MQW lasers consists of 10 compressively strained quantum wells of $InAs_xSb_{1-x}$ embedded in a 1 μm thick InAs layer which is surrounded by 1.2 μm thick *n*- and *p*-$InAs_xSb_yP_{1-x-y}$ cladding layers. All layers except for the compressively strained $InAs_xSb_{1-x}$ layers are lattice-matched to the substrate. Broad-area laser diodes were fabricated using lift-off process, in which the cap layer is etched away between the metal contact stripes composed of Ti/Pt/Au. Thermal treatment of the ohmic contacts was performed at elevated temperatures to obtain

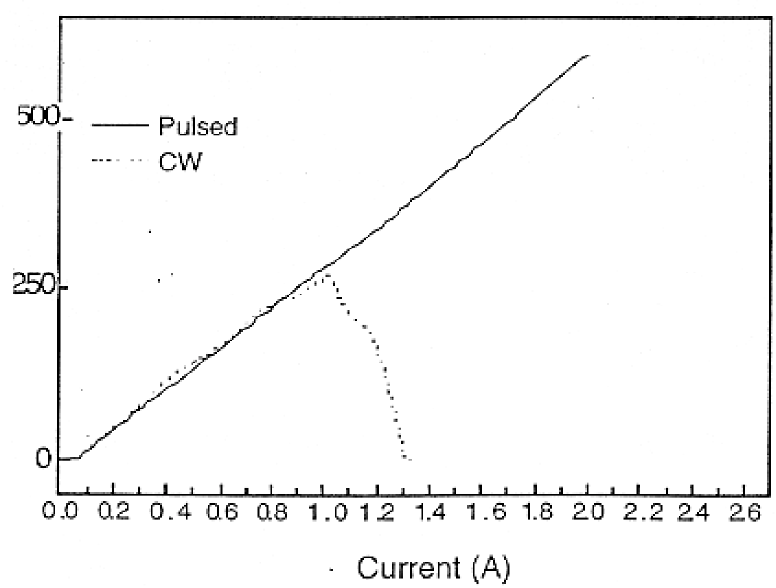

Figure 1. P-I curve for CW and pulse mode of InAsSb/InPAsSb DH laser (λ = 3.2 μm). W=100μm, L=1,205 μm, and power in mW.

a low-resistance of 0.2 Ω at 79K. This represents the lowest contact resistance reported by 3.2 μm lasers. Light-current characteristics were measured in both continuous wave (CW) and pulse-mode operations with lasers mounted inside a cryostat to facilitate a range of temperature operation.

Figure 1 shows the current-light characteristics of the InAsSb/InPAsSb DH lasers. Peak output powers of 540 mW and 240 mW were obtained from the DH lasers at pulsed mode and CW operations, respectively, at λ = 3.2 μm. It shows no significant difference between differential efficiencies η_d in CW and pulse mode operations for the optical power lower than 230 mW. The differential efficiency η_d for this wavelength was determined by to be 83 %, with *P-I* curve showing no sign of any nonlinearities or kinks. The maximum power in most of the devices was limited by our automated current driver. The laser operated up to 220 K with an output power of 1 mW (at I ~ 9.5 A). The internal loss of these InAsSb/InAsSbP DH lasers is determined by measuring the differential quantum efficiency of the diodes at several cavity lengths and was determined to be 3.3 cm^{-1}, which is to the best of our knowledge the lowest ever reported. Additionally, DH InAsSbP/InAsSb/InAs high power laser array bars have been demonstrated in pulse for 3.2 μm lasers (Figure 5a) with far-fields as narrow as 12° (FWHM) as shown in Figure 2c. (Highest output power reported at this wavelength).

Figure 3 shows *P-I* curves of the InAsSb/InPAsSb MQW lasers with emission wavelength of 3.6 μm measured between T = 78 and 155 K. The differential efficiency remains above 70 % up to 155 K. Such high values of differential efficiency for the wide range of temperatures up to 155 K, to the best of our knowledge, had not been obtained from lasers based on conventional inter-band transition for λ > 3.5 μm. Maximum output power (from two facets) up to 1 W was obtained from a MQW laser with stripe width of 100 μm and cavity length of 700 μm for emitting wavelength of 3.65 μm at 90 K (Figure 3). The output power is, to the best of our knowledge, the highest power reported from laser diodes for the wavelength range. The lasers were bonded *p*-side-up because of lack of available current confining technologies for low energy gap materials. Current confinement by deposition of SiO_2 layers is expected to enable *p*-side down bonding and consequently even

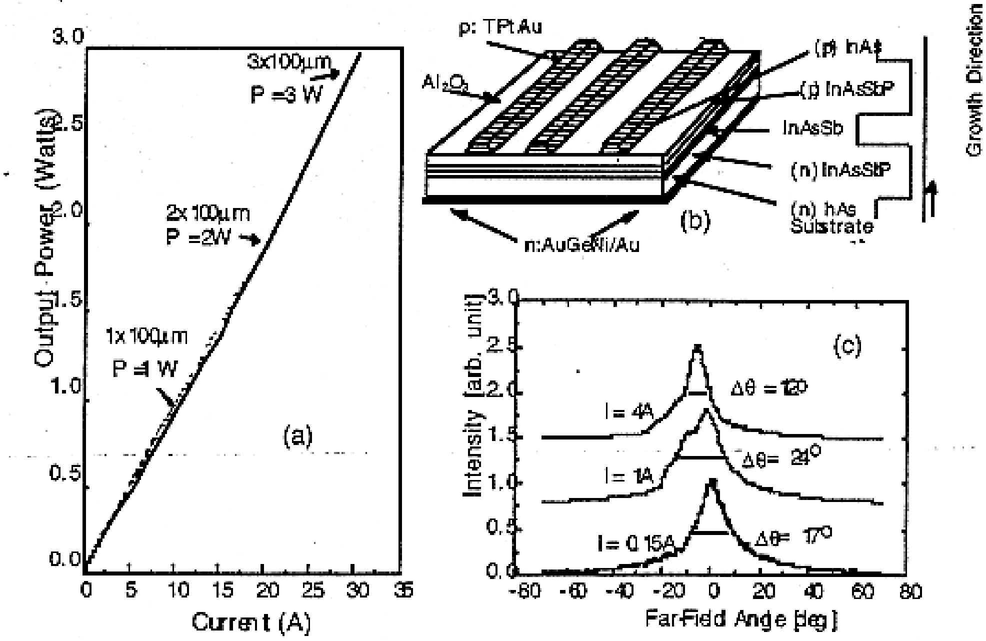

Figure 2. (a) P-I curve for laser bar array with L = 700μm and λ = 3.2μm showing 3 W. (b) Schematic of laser bar array. (c) Far-Field for laser bar array.

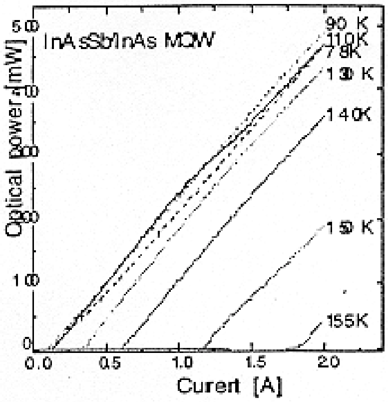

Figure 3. P-I curves of InAsSb/InAs/InPAsSb MQW lasers. L=1200 μm, W=100 μm. Pulsed: 6 μs, 200 Hz.

higher-power and/or higher-temperature operation.

For wavelengths longer than 4 μm, we have extended the emission wavelength by increasing Sb composition in the quantum well. The resultant increase in compressive strain of the quantum wells makes the growth of high quality InAsSb active region even more difficult. Nevertheless, high luminescence-efficiency light sources were grown. Figure 4 shows the electroluminescence spectra of primary MQW InAsSb/InAs/InPAsSb structures with emission wavelengths of 5 μm, with maximum powers of around 1 μW. The bright and narrow-width electroluminescence from the primary MQW structures present the promising potentials of the MOCVD-grown InAsSb/InPAsSb heterostructures for the mid-infrared lasers for deep mid-infrared ranges.

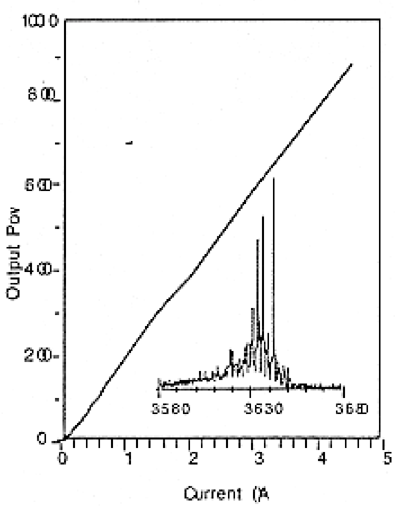

Figure 4. P-I curve and emitting spectrum of an InAsSb/InAs/InPAsSb MQW laser.

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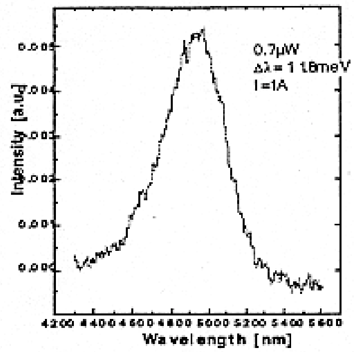

Figure 5. Electroluminescence spectrum of an InAsSb/InAs MQW structure with λ = 5 μm.