Laser oscillation from quantum states in very thin GaAs-$Al_{0.2}Ga_{0.8}As$ multilayer structures

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We report optically pumped laser oscillation from multilayer heterostructures consisting of alternating layers of GaAs and $Al_{0.2}Ga_{0.8}As$. Very thin GaAs layers (50–500 Å) exhibit one-dimensional bound states above the band gap of bulk GaAs. The laser oscillation occurs at energies which are slightly below the exciton associated with the lowest energy $n = 1$ bound state.

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Recent developments in the molecular beam epitaxy (MBE) technique have enabled us to grow multiple very thin alternating layers of GaAs and $Al_xGa_{1-x}As$ in a highly reproducible manner.[1,2] The band gap of $Al_xGa_{1-x}As$ increases with x so that a thin GaAs layer sandwiched between $Al_xGa_{1-x}As$ layers acts as a one-dimensional potential well for electrons and holes. Tunneling between the GaAs layers is strongly dependent on the $Al_xGa_{1-x}As$ layer thickness, and in the structures studied here the GaAs layers are electrically isolated from each other. The characteristics of the multilayer structures are then determined by the widths of the individual GaAs layers and the aluminum content of the isolation layers. Such layers have interesting optical[3] and electrical characteristics.[4] In this letter we report the initial observation of optically pumped laser oscillation from multilayered structures as shown in Fig. 1(a). This work was stimulated in part by the observation that the quantum effects modify the density of states.[5]

The energy levels of electrons and holes in very thin GaAs layers sandwiched between the larger-band-gap $Al_{0.2}Ga_{0.8}As$ layers consist of a discrete number of bound states within the well, and a continuum for energies above the well [Fig. 1(b)].[3] The energies of the bound states of a particle of mass m^* in a well of depth V, of width L_z in the crystal direction, are given by the solution of

$$[(V - E_{zn})/E_{zn}]^{1/2} = \tan[(m^* E_{zn} L^2/2\hbar^2)^{1/2}]$$

$$= -\cot[(m^* E_{zn} L^2/2\hbar^2)^{1/2}], \qquad (1)$$

where E_{zn} is measured from the bottom of the well, and the tan (cot) term yields states, identified by the quantum numbers $n = 1, 2, \ldots,$ which have even (odd) parity with respect to the center of the well.[6] In other directions the particle remains free, and the total energy is

$$E_n = E_{zn} + (\hbar^2/2m^*)(k_x^2 + k_y^2). \qquad (2)$$

The low-temperature absorption spectrum of bulk GaAs consists of a strong exciton line at 1.515 eV and continuum band-to-band absorption above the 1.5192-eV band gap. For very thin layers, the electron-hole interaction yields an exciton for each E_{zn} with a binding energy of 4–7 meV. These excitons appear as peaks in the absorption spectrum and have been used to study the nature of the potential wells.[3] From measurements on a large number of GaAs layers separated by $Al_{0.2}Ga_{0.8}As$ the depths of the potential wells for electrons and holes were found to be 0.22 and 0.03 eV, respectively [Fig. 1(b)]. Thus, for example, with an electron mass ~0.0665m an 80-Å-thick GaAs layer contains two bound electron states. There are also two hole bands, having effective masses ~0.45m and ~0.08m, so that an 80-Å-thick layer contains two heavy-hole and a single light-hole bound states.

The electron and hole bound states with the same n have the largest wave-function overlap. Consequently, the strongest transitions obey the selection rule $n_e = n_h$. At relatively low temperatures photoexcited electrons condense into the lowest energy $n = 1$ state, and the holes condense in the $n = 1$ heavy-hole state. For a (001) layer the heavy and light holes correspond to the $j_z = \pm\frac{3}{2}$ and $\pm\frac{1}{2}$ valence bands, respectively, and the

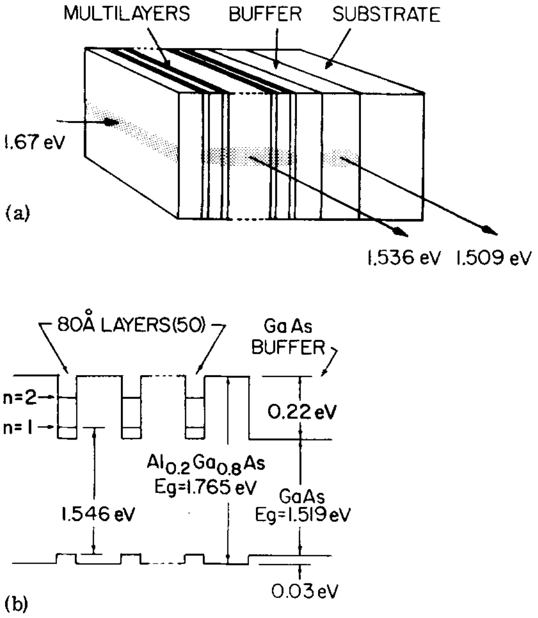

FIG. 1. (a) Configuration used to obtain laser oscillation from the multilayer film. The 1.67-eV pump radiation is absorbed in the GaAs multilayers and the buffer layer. Oscillation is detected from the end faces at 1.536 and 1.509 eV. (b) Band structure of 80-Å-thick GaAs layers separated by 240-Å $Al_{0.2}Ga_{0.8}As$ layers. There are two one-dimensional bound electron states labeled $n = 1$ and 2. The potential well for holes contains three hole states which are discussed in the text, but are not shown.

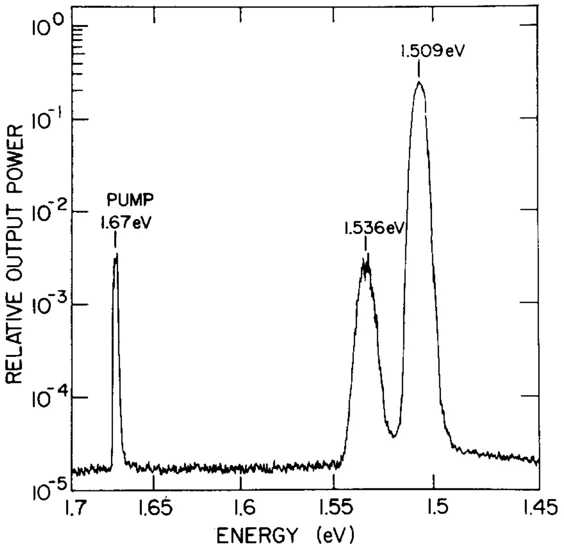

FIG. 2. Emission spectrum from the (110) cleaved end face for a pump intensity 50% above the multilayer threshold. Shown in order of increasing energy are the oscillation from the buffer layer at 1.509 eV, multilayer emission at 1.536 eV, and scattered pump radiation at 1.67 eV.

electrons to the $j_z = \pm\frac{1}{2}$ conduction band. As a consequence, the selection rule for recombination of an electron and a heavy hole requires the emission to be polarized in the plane of the layer. The spontaneous emission from the multilayers is dominated by a single band,[2] of appropriate polarization, which lies just below the $n=1$ excited absorption peak, but above the exciton energy of bulk GaAs for sufficiently thin GaAs layers. At the high level of excitation required for laser oscillation the situation is in some ways analogous to a high doping level and it is unlikely that a simple isolated exciton system exists. Thus, the laser emission is loosely associated with recombination via energy band tails.

The electrons in bound states which are well below the continuum are highly confined to the GaAs layers. On the other hand, the lowest-order optical mode of an 80-Å-wide waveguide penetrates deeply into the surrounding material. Thus, in the multilayer region the optical fields are shared essentially equally by all of the layers, but confined by the 2-μm $Al_{0.2}Ga_{0.8}As$ cladding layers. Hence, the multilayer structure provides in a natural way for the separate confinement of the electrical carriers and the optical wave.[7,8]

The multilayers were grown on GaAs substrates as described in Ref. 1. To assure a flat growth surface, an initial 2-μm GaAs buffer layer is first grown on the (001)-oriented substrate after sputter cleaning. As shown in Fig. 1(a), this is followed by a 2-μm-thick cladding layer of $Al_{0.2}Ga_{0.8}As$, the alternating GaAs and $Al_{0.2}Ga_{0.8}As$ multilayers, and a final 2-μm-thick cladding layer of $Al_{0.2}Ga_{0.8}As$. The structures were optimized for optical absorption work, and had a total GaA layer thickness of ~4000 Å.[3] The structure discussed in detail here consisted of 50 GaAs layers each 80 Å thick and $Al_{0.2}Ga_{0.8}As$ layers 240 Å thick.

The laser cavities were 0.75–1.5 mm long with end reflectors consisting of cleaved (110) faces. The samples were attached to a Cryotip refrigerator and cooled to ~15 °K. For optical pumping tunable radiation from a Chromatix optical parametric oscillator was focused by a cylindrical lens to a strip ~60 μm wide on the (001) face as shown in Fig. 1(a).[9]

The output spectrum from the end of a 1.5-mm-long sample which exhibited laser action in both the multilayers and the buffer layer is shown in Fig. 2. The pump power is 50% above the multilayer threshold, and the data were obtained with a $\frac{1}{4}$-m Bausch and Lomb spectrometer. The oscillation at 1.536 eV is identified with the multilayers, and is about 10 meV lower in energy than the $n=1$ exciton line of the layer structure as seen in absorption. Oscillation from the buffer layer is observed at 1.509 eV which is 6 meV below the 1.515-eV energy of the intrinsic exciton. The substrates are heavily doped and show negligible luminescence under laser excitation. Figure 2 also shows some scattering of the pump radiation at 1.67 eV.

The following additional tests on this sample confirm that laser oscillation of the multilayers has been observed: (i) In the region of threshold the light power from the multilayers and the buffer layer develops a characteristic spiking behavior when excited with a fluctuating pump intensity. (ii) The measured linewidth at threshold is limited by the ~1 meV resolution of the spectrometer, and in some cases broadens to as much as ~9 meV at the highest pump power, a width which is characteristic of semiconductor lasers well above threshold. (iii) The multilayer intensity is polarized in the plane of the layer, thus indicating heavy holes are involved in the recombination process. The buffer layer emission was not polarized. (iv) By translating the magnified image of the output face of the crystal across

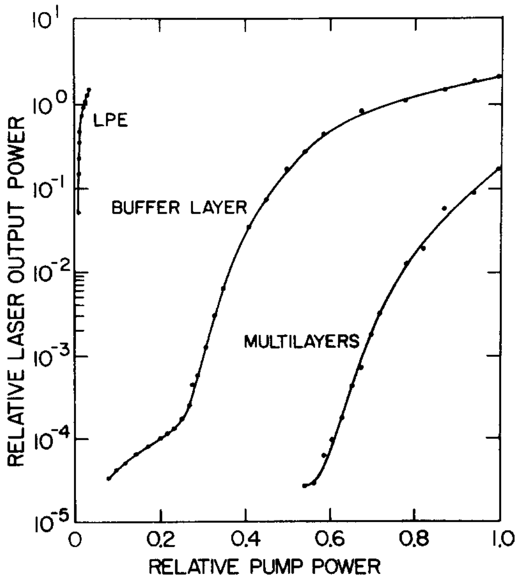

FIG. 3. Dependence of the output power on pump intensity. Also shown is the dependence of a LPE-grown n-type double heterostructure waveguide which has a significantly lower threshold and higher gain than the MBE material.

the spectrometer slits, we found that the multilayer emission originates closer to the front surface than the buffer layer emission as in Fig. 1(a), and had qualitatively the correct spacing (v) A variation of the pump energy from 1.65 to 1.75 eV changed only the scattered wavelength, but did not affect the oscillation wavelengths. (vi) A thick MBE-grown GaAs layer with $Al_{0.2}Ga_{0.8}As$ cladding shows only the 1.509-eV emission.

Figure 3 shows the dependence of the peak output power as a function of pump power from a 0.76-mm-long laser. The pump intensity was varied by means of a Glan-Thompson prism polarizer, and the peak pump power at 0.74 μm just inside the sample was 200 kW/cm^2 with a pulse length of 10^{-7} sec. For total absorption this is equivalent to a current of 120 kA/cm^2. For our multilayer thickness the pump intensity is approximately equally absorbed by the multilayers and the buffer layer and the equivalent thresholds are 36 and 15 kA/cm^2, respectively. When plotted on a linear scale the emission intensities below and above threshold are linear functions of pump power with the slope of the stimulated emission region being significantly larger than that of the spontaneous emission. The threshold appears to be highly dependent on the quality of the multilayers. For some samples the threshold for the multilayers was less than the buffer layer threshold.

For comparison we also show the power dependence of a 1-μm-thick n-type GaAs double heterostructure waveguide with $Al_{0.5}Ga_{0.5}As$ cladding which was grown by liquid phase epitaxy (LPE). The threshold for this unit, 0.2 kA/cm^2, was smaller than that observed with any of the multilayer-buffer layer structures. We attribute the higher thresholds of the multilayer and the buffer layer, as compared to the LPE laser, mainly to the very low luminescent quantum efficiency of p-type MBE grown GaAs which is more than an order of magnitude less than the LPE material, and the thinner active layer thickness of the LPE laser. A qualitative study of passive guiding in the MBE structures used for Figs. 2 and 3 with a 1.06-μm laser indicates that the losses in the multilayers and buffer layer are comparable. Thus, in this case, the presence of the multiple layers in an otherwise similar material suggests that the reduction in gain may be due to recombination centers at the interfaces.

The rectangular potential well is perhaps the simplest structure to fabricate. The MBE growth technique, however, allows for a programmed variation of the Al content, and hence and essentially arbitrary potential well can be repeatedly deposited.[2] As an example we have grown triangular potential wells by first growing an $Al_{0.2}Ga_{0.8}As$ isolation layer, switching rapidly to GaAs growth, and then increasing the rate of Al deposition linearly in time until the $Al_{0.2}Ga_{0.8}As$ composition is reached and then depositing the second isolation layer. The exciton corresponding to the lowest $n=1$ bound state of a 300-Å-wide triangular well is found at 1.61 eV in absorption. Laser oscillation identified with this exciton is observed at 1.60 eV.

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[1] A.Y. Cho, J. Vac. Sci. Technol. 8, S31 (1971).

[2] R. Dingle and W. Wiegmann (unpublished).

[3] R. Dingle, W. Wiegmann, and C.H. Henry, Phys. Rev. Lett. 33, 827 (1974).

[4] L. L. Chang, L. Esaki, and R. Tsu, Appl. Phys. Lett. 24, 593 (1974).

[5] C.H. Henry, R. Dingle, and W. Wiegmann (private communication).

[6] L.I. Schiff, *Quantum Mechanics* (McGraw-Hill, New York, 1955), p. 34.

[7] M.B. Panish, H.C. Casey, Jr., S. Sumski, and P.W. Foy, Appl. Phys. Lett. 22, 590 (1973).

[8] H.C. Casey, Jr., M.B. Panish, W.O. Schlosser, and T. L. Paoli, J. Appl. Phys. 45, 322 (1974).

[9] This pumping scheme has been described by J.A. Rossi, S.R. Chinn, J.J. Hsieh, and M.C. Finn, J. Appl. Phys. 45, 5383 (1974); S.R. Chinn, J.A. Rossi, C.M. Wolfe, and A. Mooradian, IEEE J. Quantum Electron. QE-9, 294 (1973).

Push-pull thin-film optical modulator

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An electro-optic amplitude modulator was made by placing two channel-defined waveguide phase modulators in the legs of a Jamin interferometer. Using a novel detection method, modulation was observed up to 1.8 GHz, although the roll-off in the modulator response started at about 750 MHz. Full amplitude modulation was produced by 17 V, giving a power bandwidth characteristic for the separate phase modulators of 200 μW/MHz for a modulation index of 1 rad.

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Modulation in optical waveguides has been shown in several systems, such as out-diffused $LiNbO_3$,[1] solid solutions of $LiNbO_3$-$LiTaO_3$,[2] and single-crystal films of $LiNbO_3$ on $LiTaO_3$.[3] This letter presents results on a modulator in which the light is guided in a passive material (Nb_2O_5) and the modulation is obtained by an