THz SOURCES BASED ON INTERSUBBAND TRANSITIONS IN QUANTUM WELLS AND STRAINED LAYERS *

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ABSTRACT

The feasibility and potential of laser sources based on intersubband transitions in quantum wells and strained layers will be presented. The basic schemes and proposed structures for both electrically and optically pumped devices are discussed. Both conduction band and valence band quantum wells as well as strained layers may be used as the active layer of these lasers. These sources can be either optically or electrically pumped with each having its own advantages. Various material systems which are appropriate for these applications will be described.

I. INTRODUCTION

Recent advances in crystal growth techniques such as MBE, CBE, and MOCVD have enabled us to grow thin layers of semiconductor materials on top of bulk materials. Depending on the thickness and the material properties of the grown layers, one can realize either a bulk like or a quantum well layer. If the thickness of the grown layer is less than the de Broglie wavelength and the energy gap of the layer is different from the surrounding layers, a quantum well can be realized in which quantum size effects become easily observable. When the carriers are confined in the valence band of the layer, the well is referred to as "valence band quantum well" while when the carriers are confined in the conduction band of the layer the well is referred to as "conduction band quantum well." The confinement of carriers in one direction and the lack of confinement in the other two directions in the structure lead to the formation of subbands of bound states. The energy separation of subbands is inversely proportional to the square of the well width. In the strained system, the lattice constant of the grown layer does not match the lattice constant of the substrate which leads to lifting the degeneracy of the of light- (LH) and heavy-hole (HH) subbands at the Brillouin zone center. If the strain is compressive, i.e., the lattice constant of the epilayer is larger than that of the substrate, the induced non-degeneracy gives rise to a smaller energy difference between the HH subband and the conduction band compared to the LH subband to conduction band energy separation. If, however, the strain is tensile, i.e., the lattice constant of the

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* This work is supported by the NASA Center for Space Terahertz Technology under contract No. NAGW-1334 and the Army Research Office the URI program under contract No. DAAL03-92-G-0109.

epilayer is smaller than that of the substrate, the non-degeneracy leads to a closer LH subband to the conduction band. The energy difference between the top of the LH and HH subbands is proportional to the strain in the system. Energy separation between subbands in both quantum well and strained layers therefore can be designed properly to be in the THz range (10-20 meV) making these layers a suitable material system for detectors, modulators, and lasers in this range of frequency.

II. PROPOSED STRUCTURES

1) Intersubband Conduction Band Quantum Well Lasers

Recently, several research groups [see e.g. 1-14] have reported studies on intersubband transitions in quantum wells with applications such as infrared lasers, light modulators (switches), and detectors. Strong optical absorption [8] and spontaneous emission [9] due to intersubband transitions have been observed experimentally. Although these observations are encouraging, in order to realize intersubband lasers, enough photon gain should be achieved to compensate all the photon losses in the quantum well. The gain in a laser system is directly proportional to the population inversion in the active layer. To achieve population inversion in the quantum well, both optical and electrical pumping schemes have been suggested [1-7]. Figure 1a shows the band diagram of the simplest electrically pumped intersubband laser suggested by Mehdi *et al.* [1] and Loehr *et al* [2]. Carriers are injected from the left contact and by tunneling through the left barrier, reach to subband 2 and radiatively relax to subband 1 and finally, after tunneling through the right barrier, they are collected by the right contact. Another proposed electrically pumped intersubband laser is shown in Figure 1b. To improve population inversion in the quantum well (the active layer of the laser), resonant tunneling filters have been utilized in the structure to selectively inject carriers into subband 2 and remove carriers from subband 1 [4,5].

The major problems associated with the electrically pumped laser schemes is that the confinement factor in the system, which accounts for the reduction in gain that occurs because of the spreading of the optical energy beyond the active layer, is very low. The net gain therefore is too small which makes the laser action very difficult. This factor can be improved by utilizing the optically pumped laser scheme where one period of its active layer is shown in Figure 2. The structure may utilize 10-20 periods of the well shown in the figure to enhance the confinement factor about a factor of 100-400. The proposed scheme uses a heavily n-doped layer to provide carriers in subband 1 where a pumping laser excites carriers from the subband into subband 4. After relaxing to subband 3, these hot electrons radiatively relax to subband 2, and finally return to subband 1 and the carrier cycle completes.

In conduction band quantum wells, the symmetry of the subbands is the same. Therefore, the tunneling and relaxation rates in the well only depend on the relative energy difference of the subbands. Population inversion, which is a crucial requirement for laser action, may be created when the injection and removal rate of the carriers from the subbands are not identical. Therefore, inverting the population of two different subbands in these wells is rather difficult.

2) Intersubband Valence Band Quantum Well Lasers

Instead of using conduction band quantum wells, one can use valence band quantum wells in similar structures. In these structures, the tunneling and relaxation rates of the hole from one subband to the other is not only dependent on the energy difference of the two subbands, but it also depends on the symmetry of the subbands. This additional feature of the subbands in valence band quantum wells, makes them an excellent choice for inter-subband quantum well lasers. The origins of different transition rates of the hole from different subbands are briefly expressed in the following:

a. The tunneling rate is a function of the carrier mass in the growth direction. The different masses of the holes in the growth direction, therefore give rise to different tunneling rates for light and heavy holes.
b. Under the application of a strong magnetic field parallel to the interface, the motion of holes passing through the barrier is altered [14]. This can be considered as a decrease of the kinetic energy in the tunneling direction or an effective increase of the tunneling barrier. The additional voltage needed, to obtain the same tunneling rate as in the case of zero magnetic field, is inversely proportional to the effective mass of the hole in the growth direction.
c. In strained systems, the barrier seen by the light hole is different from the barrier seen by the heavy hole due to the induced non-degeneracy in the system. Since the tunneling rate decreases exponentially as the barrier increases, the tunneling rate would have different values for the heavy-hole and light-hole.
d. Depending on the symmetry, namely, LH or HH, of the subband, the tunneling rate of the carriers may be different. This provides another feature which can be utilized in designing systems to obtain a better population inversion. The non-radiative relaxation rate between two subbands in the same well also might be reduced if the subbands have different symmetry.

Any of a-d or some combinations thereof may be exploited in designing structures for intersubband lasers where achieving the population inversion between the two subbands involved in the radiation is a vital requirement. The conclusion reached from the above argument suggests that the threshold of the input power (or carrier density) for lasing should be lower in properly designed valence band quantum wells compared to a similar structure but based on conduction band quantum wells. Despite the aforementioned potential of the valence band quantum well, it has not been studied as extensively as conduction band quantum wells. White *et. al.* [15] have observed population inversion with a ratio of 300/1 between LH1 and HH1 in a p-i-n structure. The energy separation between the two subbands is 21 meV which is less than the LO phonon energy. Since the population inversion has been achieved in this simple quantum well, one can consider a simple quantum well, similar to the one shown in Figure 1a, as a potential structure for THz sources.

Figure 3 shows an electrically pumped laser scheme proposed by our group. The structure is the valence band quantum well version of the scheme shown in Figure 1b. In this structure, the transition between subband 3 and subband 1, as well as the transition between subband 2 and subband 0 are undesired and detrimental to the population inversion between subband 2 and subband 1. In the electron version, we do not have much control over reducing these rates except for adjusting the energies of the subbands. In the hole version of the proposed scheme, however, one can make use of the properties mentioned before to reduce these rates more. Figure 3 is an example of a design where due to the different symmetry between subband 3 (HH band symmetry) and subband 1 (LH band symmetry), the transition rate between these two subbands is reduced. The same argument holds for the transition from subband 2 (HH band symmetry) to subband 0 (LH band symmetry). In addition, the lighter effective mass of the carrier in subband 1 provides a higher tunneling rate for holes in this subband. This further improves the population inversion between subband 2 and subband 1.

Optically pumped laser schemes can take advantage of the relaxation properties of the holes in quantum wells. Figure 4 shows a valence band quantum well version of the optically pumped laser structure discussed earlier (see Figure 2). To invert the populations of subband 3 and subband 2, the non-radiative relaxation of holes from subband 4 to 2 as well as from subbands 3 to 1 should be as slow as possible while the non-radiative relaxation of holes from subband 4 to subband 3, as well as from subband 2 to subband 1 should be as fast as possible. A desired symmetry for the subbands of the laser is shown in the figure where unwanted relaxation corresponds to different symmetry transitions while desired relaxation occurs between the subbands with the same symmetry.

In all these proposed structures, in order to have coherent light, we would like to retain carriers in the higher energy subband as long as possible and let photons stimulate their radiation coherently. In addition, to maintain population inversion in the structure, the carriers in the lower energy subband should be emptied out as soon as possible. Consequently, relaxation times between different subbands in a quantum well, as well as tunneling rates between different subbands in adjacent quantum wells are the key factors in determining the achievable population inversion due to a certain current density or pumping rate in an intersubband quantum well laser. Several studies have previously been devoted to intersubband or interwell scattering [see e.g. 16, 17]. These studies mostly have addressed the case of simple quantum wells and transition from subband 2 to subband 1.

In order to enhance the confinement factor of the laser, the use of optically pumped structures was suggested earlier. Although, a considerable improvement may be obtained, however, the factor is still far below unity in the frequency range of interest.

3) Bulk Strained Lasers

As has been mentioned earlier, the energy separation between LH and HH subbands in a strained layer is proportional to the amount of strain in the layer. By adjusting the strain, one can design the desired energy separation of the subbands. Depending on the strain, hoewever, the thickness of the strained layer may not exceed a certain thickness called critical thickness for the pseudomorphic or coherent layer, i.e., a layer without any dislocations. The critical thickness is *inversely* proportional to the strain on the system. For the energy separations that lead to THz radiation (around 10 to 20 meV), this thickness is more than 100 nm which can be a great advantage for THz lasers based on these systems as will be discussed later. Figure 5 shows the critical thickness for InGaAs alloys as a function of the frequency which can be radiated due to the transition of the hole from one subband to the other.

The far-infrared (FIR) amplification of the electromagnetic waves due to direct transition of the hot holes in *strong* electric and magnetic field (larger than 1 kV/cm and 1 T, respectively, induced by a voltage greater than a few kilovolts and a few Amperes) has been under investigation [see e.g. 18, 19]. The observed stimulated emission covers a broad wavelength range 80-210 μm with a line width of about 20 1/cm and with pulse emitted power up to 10W. The FIR radiation from uniaxially stressed p-type Ge in the absence of a magnetic field and at lower electric fields also has been observed [see e.g. 20, 21]. The uniaxial strain in the Ge layer split the degenerate valence band edge at the Brillouin zone center into two subbands separated by the energy Δ. In the measured structure which is a bar of the semiconductor, at zero electric field essentially all of the holes occupy the lower energy band with small effective mass in the stress direction. When an electric field is applied to the sample, the light holes heated by the field are transferred to the upper band with larger effective mass and higher density of states. The direct optical transitions may take place only due to the holes with energies above the band-split energy Δ.

Instead of using external uniaxial strain, one can use biaxial strained layers which are grown on a lattice mismatched substrate. An electrically pumped p-i-p laser structure based on strained bulk systems proposed by our group is shown in Figure 6. The active layer, which is intrinsic, is under tensile strain. When an electric field is applied to the system, the top of the emitter valence band is aligned to the top of the active layer HH band while the top of the collector valence band is aligned to the top of the active layer LH band. The applied field moves holes from the emitter valence band to the active layer HH band where holes radiatively relax to the active layer LH band. Holes are then collected by the collector layers. If the structure is designed for the light radiation with the photon frequency of 4 THz (~16 meV energy separation), the thickness of the active layer may be as high as 200 nm as can be extracted from Figure 5. Therefore, in these structures the confinement factor of the laser gain can be improved by a factor about 40 compared to that of the quantum well system.

An optically pumped laser which is based on strained bulk layers is shown in Figure 7. The active layer is under tensile strain and is p-doped. A laser pump is used to excite electrons from split-off band to LH band. Hot electrons in this band radiatively relax to HH band which create photons at a THz frequency. The relaxed holes to HH band then relax back to split-off band and complete the circle. The relaxation time between LH band and HH band will be long, if the energy separation between the HH band and the LH band at $k = 0$ (where k is the wave number) is less than LO phonon energy. However, the energy separation between the split-off band with the LH and HH bands are more than LO phonon energy leading to shorter transition rates between these bands.

III. MATERIAL SYSTEM

Figure 8 shows different layers used to realize the strained electrically pumped laser structure shown in Figure 5. The substrate is InP and the alloy used in the injector and collector layers is $In_{0.53}Ga_{0.47}As$ which is lattice matched with the substrate. The alloy used in the strained layer is $In_{0.49}Ga_{0.51}As$ which is not lattice matched with the substrate and other layers. Since the lattice constant of the active layer is less than that of the substrate, therefore the layer is under tensile strain. The advantage of using InGaAs/InP systems is that by changing the composition of Ga (or In) in the alloy, one can have a lattice matched, compressive or tensile strained layer.

The choice of materials in none of the proposed structures is restricted to direct band gap semiconductors and indirect band gap materials, like Ge and Si, also can be utilized in the laser structure. Therefore, these system have the potential to be integrated eventually with other semiconductor devices in silicon based integrated circuits.

IV. SUMMARY

The potential application of the transition between subbands in both conduction band and valence band quantum wells as well as the transition between HH and LH subbands in strained layers for THz sources was discussed. Both electrically and optically pumped lasers based on quantum well and strained systems were proposed. The optically pumped schemes offer a larger confinement factor compared to electrically pumped structures in the same system. At present time, the strained system seems to be the most promising system in both electrically and optically pumped lasers among the proposed structures. The confinement factor in the optically pumped laser based on strained layers can be as high as 1. In addition, the factor is higher in the proposed electrically pumped scheme compared to similar structures based on quantum wells. The choice of materials in these structures is not limited only to the direct band gap semiconductors and indirect band gap semiconductors such as Si and Ge may be used in the active layer of these systems. To asses the performance and characteristics of the proposed structures further study is being carried out both theoretically and experimentally.

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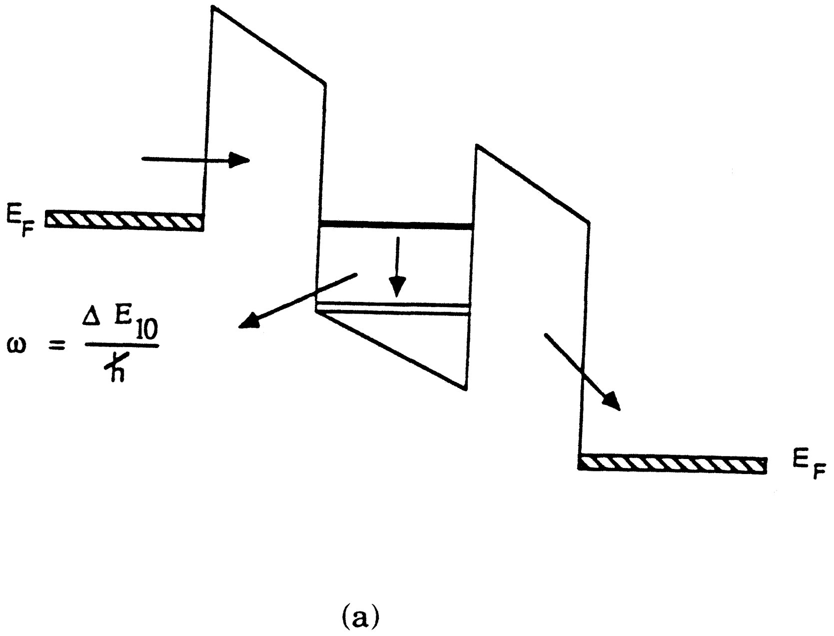


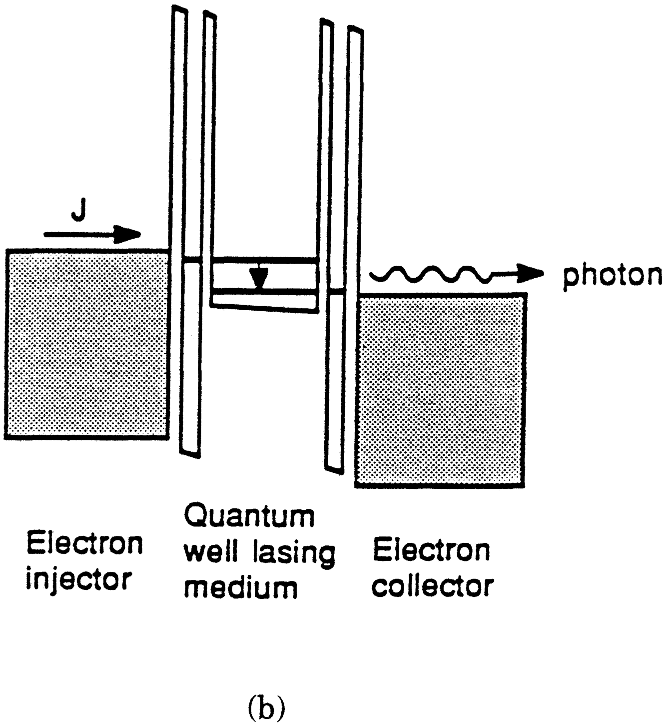


Figure 1. Electrically pumped laser based on conduction band quantum wells a) single quantum well [1,2] b) coupled quantum well [4,5].

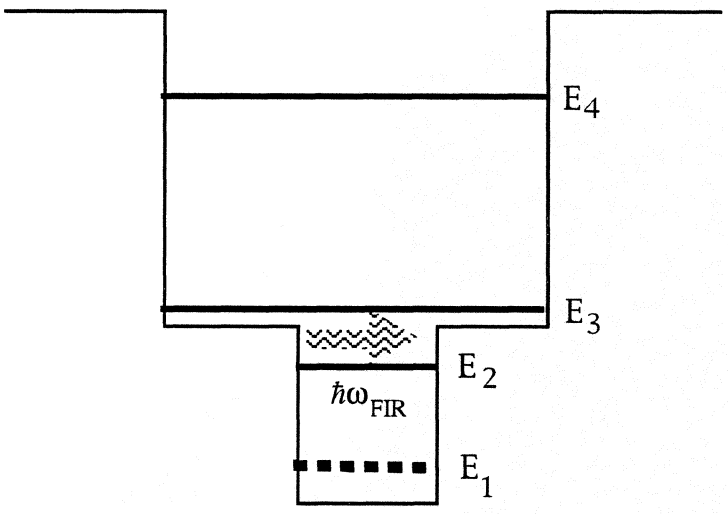


Figure 2. Optically pumped laser structure based on conduction band quantum wells.

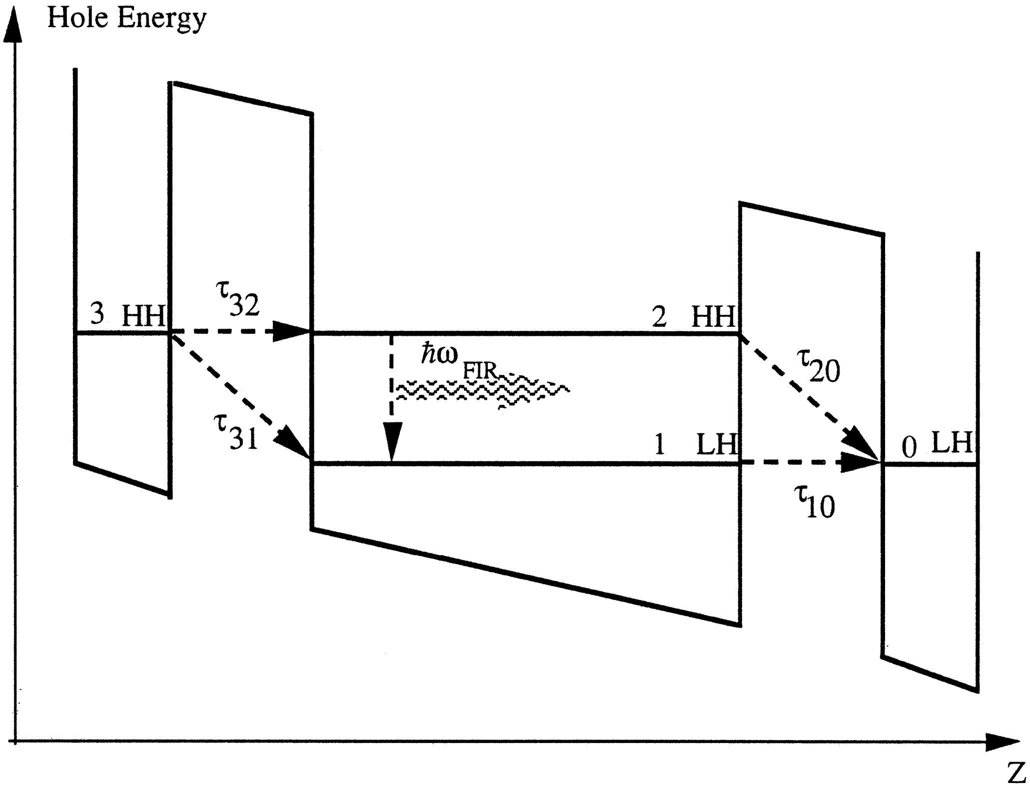


Figure 3. Electrically pumped laser based on valence band quantum wells

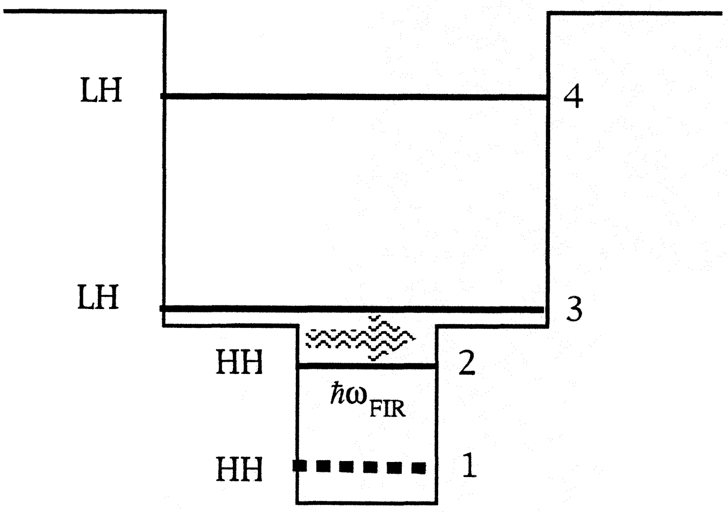


Figure 4. Optically pumped laser structure based on valence band quantum well lasers

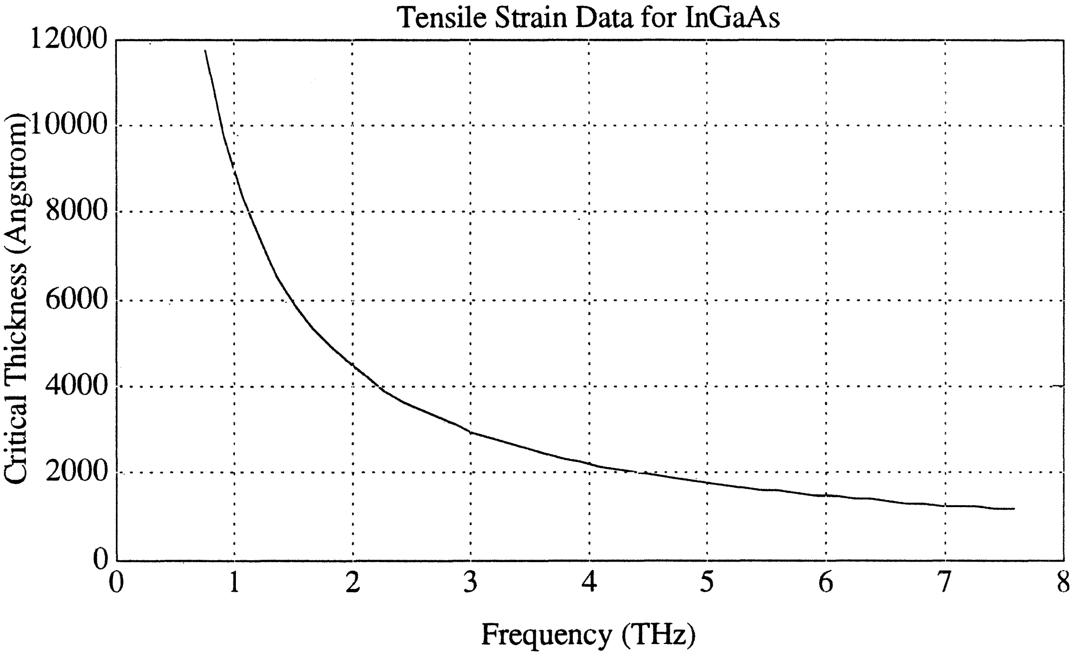
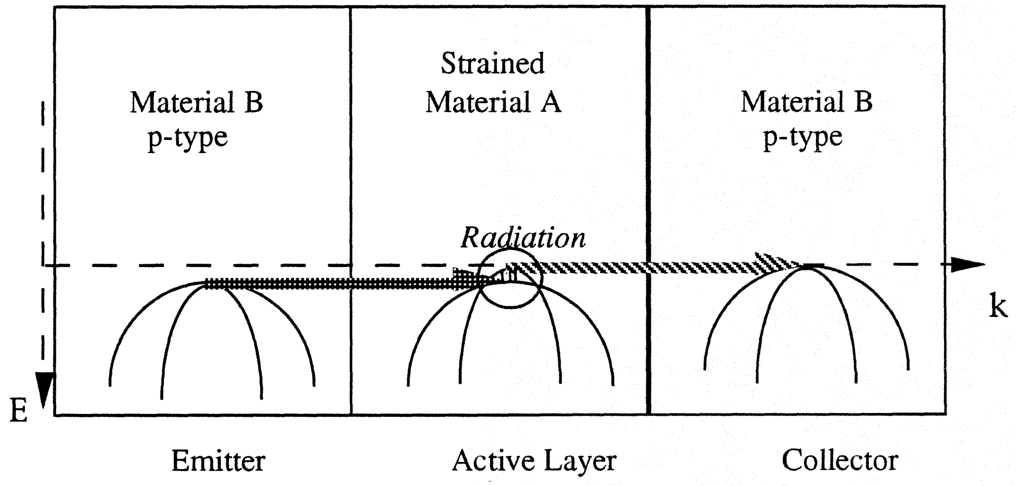


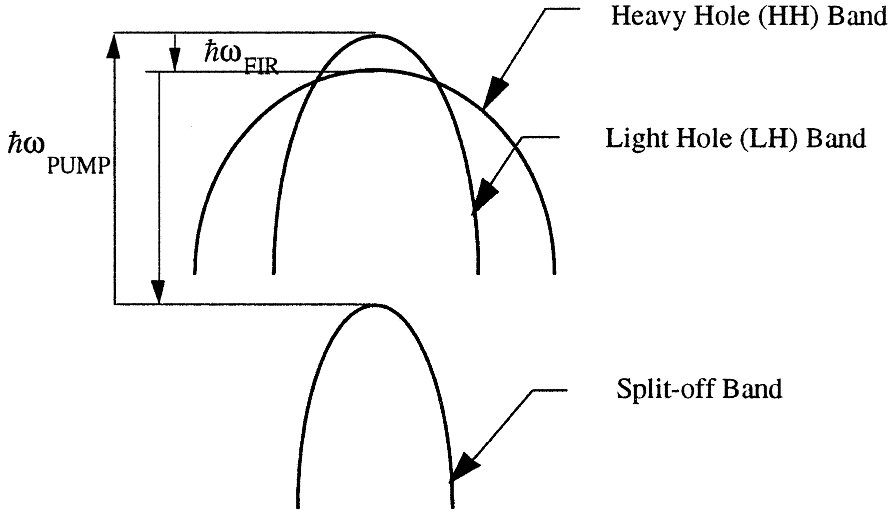
Figure 5. Critical thickness of InGaAs/GaAs systems as a function of frequency which can be radiated due to transition of holes from one subband to the other.



$a_{\text{substrate}} = a_B$

$a_{\text{substrate}} > a_A$ Tensile Strain

Figure 6. Electrically pumped laser structure based on strained layers



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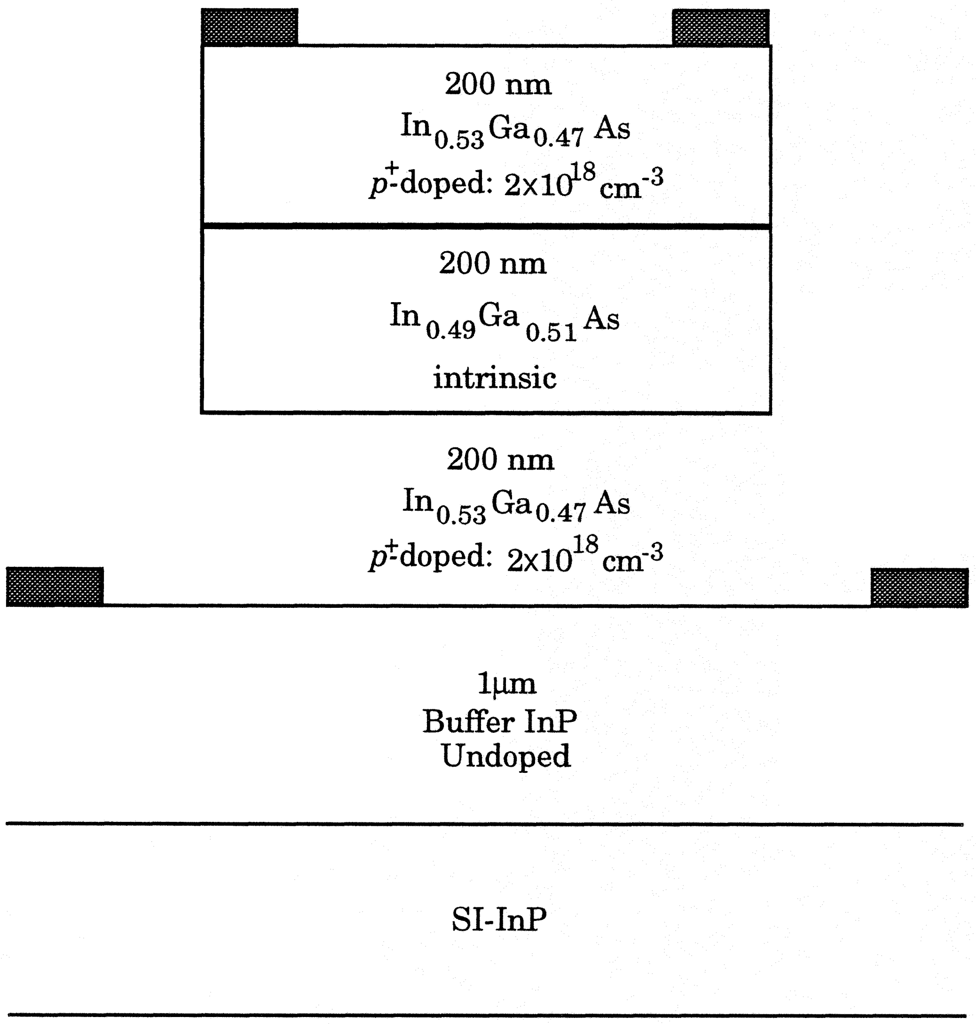

Figure 8. A realization of electrically pumped laser proposed in Figure 5.