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A Study on Hole Transport in p-Type GaInAsP/InP Multilayer Reflectors

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The current-voltage characteristic of a *p*-type GaInAsP/InP multilayer distributed Bragg reflector (DBR) is calculated by taking the light- and heavy-hole transmission tunneling current at hetero-interface into account. It is found that the light-hole current contributes mainly to the reverse bias current which flows from GaInAsP to InP. A high hole concentration in wide energy-gap materials is more effective to realize a low absorption and high reflectivity DBR with low excess bias at DBR region. It is experimentally confirmed that the surface emitting laser structure containing a 5-pair *p*-GaInAsP/InP DBR grown by chemical beam epitaxy is only a 0.5V excess bias.

1. Introduction

A long wavelength surface emitting (SE) laser is one of the important light sources in large capacity parallel networks and optical interconnects. In recent few years, although the performance of GaInAsP/InP SE lasers has been improved [1][2][3][4], however, the temperature characteristic is still poor beyond room temperatures. The reason of this is caused by high optical losses, Auger non-radiative recombination and inter-valenceband absorption. To obtain high performance long wavelength SE lasers, it is required to realize high reflectivity mirror to reduce the threshold. A GaInAsP/InP multilayer distributed Bragg reflector (DBR) is one of high reflectivity mirrors. The GaInAsP/InP DBR applied to the n-side mirror of SE lasers is reported [1][5][6][7], but the *p*-type GaInAsP/InP DBR has not been applied to SE lasers yet. The *p*-type GaInAsP/InP DBR has some difficulties. One is inter-valence band absorption, which reduces the mirror reflectivity. Another is its high electrical resistance at the heterojunction. This electrical resistance at the *p*-type DBR is also a serious problem in GaInAs/GaAs SE lasers using AlAs/GaAs DBRs. Some methods to reduce the excess bias at DBR have been reported, for example, using a graded layer, and high delta doping at the hetero-interface [8][9]. However, the theoretical modeling of carrier transport in *p*-type DBRs has not been fully discussed yet. In this study, we have investigated the current-voltage characteristic of *p*-type GaInAsP/InP DBR structure taking the light- and heavy-hole transmission tunneling into account.

2. Theoretical Calculation

Figure 1 is a schematic diagram of a part of *p*-type GaInAsP/InP DBR. The doping concentration in each layer is assumed to be uniform and the interfaces are abrupt. In this figure, two kinds of heterojunctions marked forward- and reverse-bias is shown. The distinction of the two heterojunctions is a result from the direction of current flow. In the forward-bias interface, holes move from the wide energy-gap material to narrow one. The reverse-bias means the opposite situation. A hetero-spike may exist at this hetero-interface and those spikes obstruct the transport of holes. In the *n*-type DBR, the hetero-spikes also exist, but the electrons distribute in wide energy width at near room-temperature due to small effective mass. On the other hand, holes distribute at near valence-band edge due to

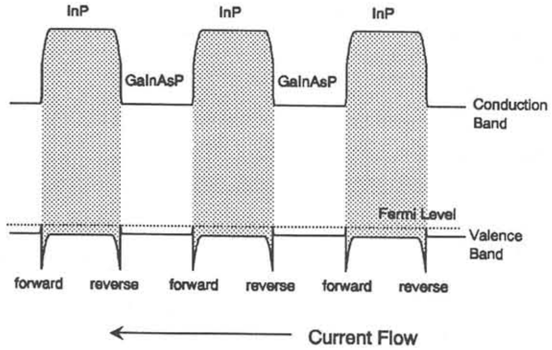

FIG. 1 Schematic band-diagram of a portion of *p*-type GaInAsP/InP DBR. Two kinds of hetero-spikes exist depending on the direction of current flow.

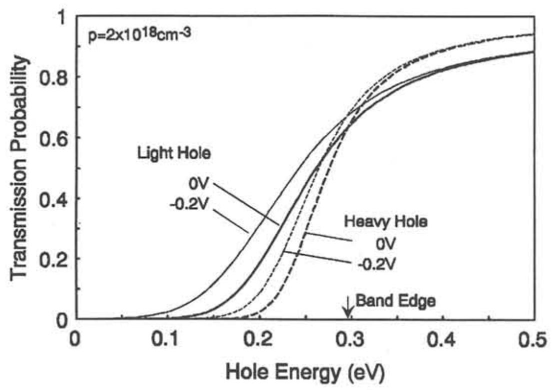

FIG. 2 Transport probability of light- and heavy-hole at GaInAsP/InP hetero-spike for zero and reverse (-0.2V) bias condition. Hole concentration of both materials is $p=2\times10^{18}$cm^{-3}.

a large effective mass. Therefore, both the thermionic emission and tunneling transport should be considered for the hole current.

The hole tunneling transmission current was calculated by Zeeb and Ebeling [10], however, they dealt with only the heavy-hole tunneling and the light-hole transmission tunneling is neglected. Then we consider a new carrier transport model of p-type GaInAsP/InP DBRs which include both light- and heavy-hole tunneling effects. Figure 2 shows the transport probability of light- and heavy-hole at GaInAsP/InP hetero-interface for 0V and -0.2V bias condition. The composition of GaInAsP is $\lambda g=1.45\mu m$ and the hole concentration of GaInAsP and InP is 2×10^{18}cm^{-3}. The valence-band offset energy is assumed to be 0.297eV. The zero energy level is the valence-band edge of GaInAsP. For both bias condition, the increase of transmission probability for the light-hole start at smaller hole energy than that of the heavy-hole and the energy difference is about 50mV. From the comparison of zero and -0.2V bias condition, the transmission probability shifts toward lower energy, and the amount of the energy reduction for the light-hole is larger than that for the heave-hole. These phenomena are caused by small effective mass of the light-hole.

The current-voltage characteristics are calculated using the transmission probability [11]. Figure 3 shows theoretical current-voltage characteristics for the light- and heavy- hole transmission current and the total current means the sum of these two currents. The doping concentrations of both GaInAsP and InP are $p=2\times10^{18}$cm^{-3}. It is noted that the light-hole transmission current is larger than the heavy-hole current, and is dominant in the total current for the reverse bias condition. The density of states of the heavy-hole is larger than that of the light-hole. So the thermionic emission hole current is large for the heavy-hole, however the tunneling transmission probability is large for light-holes at near band edge, where there is large carrier concentration. Then the tunneling transmission current for the light-hole is larger than that of the heavy-hole. The dominant current for the forward bias condition is the heavy-hole current, because the applied bias reduces the hetero-spike height and the thermionic emission current is larger than the tunneling current.

The current-voltage characteristic of p-DBR is calculated by considering the stacks of the same number of forward- and reverse-bias heterojunction. The calculated current-voltage characteristic for the set of one forward- and one reverse-bias heterojunction, which means one-pair DBR, is shown in Fig. 4 for some doping concentrations. From the figure, two lines, which are the same hole concentration of 5×10^{18}cm^{-3} in InP, show nearly same current-voltage characteristics, though the hole concentrations in GaInAsP are different. On the other hand, the hole concentration of 1×10^{18} cm^{-3} in InP shows larger excess bias than the previous two lines. Figure 5 shows theoretical reflectivity of GaInAsP/InP DBR for 25-pair and 100-pair. The horizontal axis is the hole concentration of GaInAsP and the hole concentration of InP is fixed to 5×10^{18}cm^{-3}. The absorption coefficient of InP is 100cm^{-1} and that of

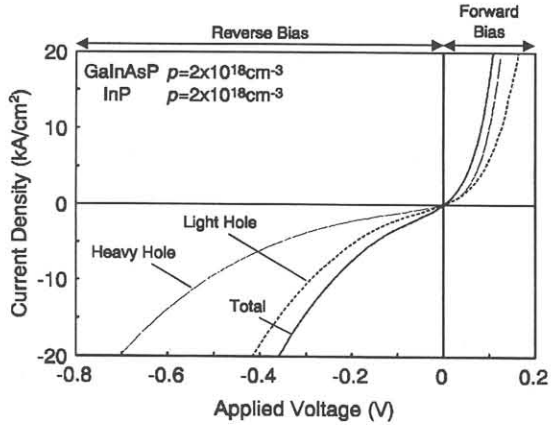

FIG. 3 Theoretical current-voltage characteristics of light- and heavy-hole for GaInAsP/InP heterojunction.

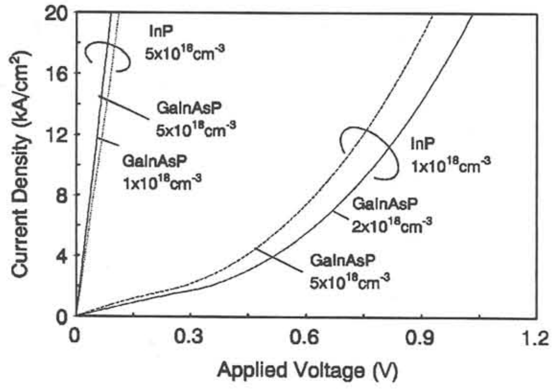

FIG. 4 I-V characteristics of one-pair GaInAsP/InP DBR for different p-doping structure.

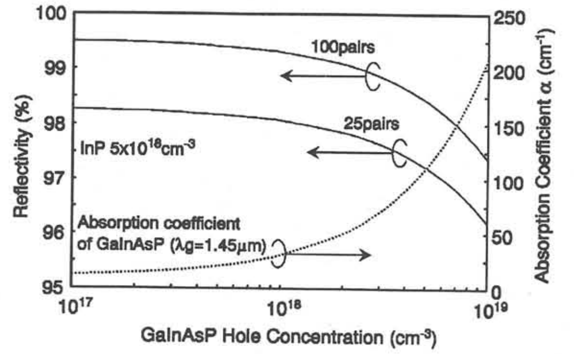

FIG. 5 Theoretical reflectivity of p-type 25-pair and 100-pair GaInAsP/InP DBR considering the absorption loss versus GaInAsP hole concentration. (for InP, p=5× 10^{18}cm^{-3}, α=100cm^{-1})

GaInAsP is calculated using experimentally defined absorption cross-section [12)7)]. If the doping is uniform for both InP and GaInAsP at 5×10^{18}cm^{-3}, the reflectivity for 25-pair-DBR is about 97%, however, the reflectivity for 1×10^{18}cm^{-3} doped GaInAsP shows over 98% with nearly same excess bias. From the calculated result, the modulation doping of high hole concentration in wide energy-gap material may be effective for the reduction of excess bias and high reflectivity mirror.

3. Experiment

Three types of SE laser structures are grown by chemical beam epitaxy (CBE) [13)14)]. One has no DBR structure. The second structure consists of an 8-pair GaInAsP (λg=1.45μm)/InP DBR for the n-side. The third structure has an 8-pair DBR for the n-side and a 5-pair DBR for the p-side. The doping levels of the p-DBR are 1×10^{18}cm^{-3} for InP and 2×10^{18}cm^{-3} for GaInAsP. These wafers were processed to make low-mesa-type SE lasers [7)]. Figure 6 shows the current-voltage characteristics of each structure. The two structures, without DBR and with only n-side DBR, show very similar characteristics. The obtained result indicates that the n-type DBR does not affect the electric characteristics so much. However, the p-side DBR causes an excess bias of 0.5V at 5kA/cm^2. This value is equivalent to a 0.1V excess bias for one DBR pair. This excess bias is somewhat smaller than the value estimated in the previous section. The difference between experimental and theoretical results may be influenced by the tunneling probability, which is sensitive to the band discontinuity and fermi levels.

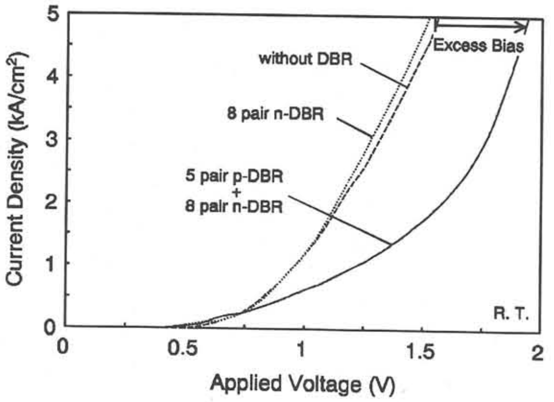

FIG. 6 Experimental current-voltage characteristics of different SE laser structures with/without GaInAsP (λg=1.45μm)/InP DBR.

4. Conclusion

The current-voltage characteristic of a p-type GaInAsP/InP heterojunction is calculated by considering the light- and heavy-hole transmission tunneling current. The light-hole current is dominant for the reverse-bias heterojunction. The calculated results of I-V characteristics for the p-DBR show that the modulation doping in highly hole concentration in InP is effective for low excess bias and high reflectivity. The CBE grown p-DBR structure indicates 0.1V excess bias for one DBR pair. These results may be helpful for the design of the high performance p-DBR and also high performance GaInAsP/InP surface emitting lasers.

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