論　文

A New Structure Design 'Multiple-Quantum Barrier in Active Region' for High Temperature Operation of AlGaAs Superluminescent Diode*

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A multiple-quantum barrier (MQB) structure has been applied to AlGaAs superluminescent diode (SLD) to suppress the electron overflow from active to cladding region at elevated temperatures. It was found that the presence of MQB in the p-cladding region leads to stagnant hole transport to the active region. To improve the hole transportation, we propose a new quantum structure for active region. In this design, the superlattice structure MQB is located in the middle of active region which allows smooth hole injection to the active from cladding region. Carriers can reach both side of the MQB structure in the active region by tunneling phenomenon which critically depends on the barrier thickness. Simulation results show that low energy electrons can tunnel through the MQB barriers, while high energy electrons are reflected back by effective barrier. Finally, multiple-quantum well (MQW) structure is integrated at each side of MQB to minimize the possible over-flow of tunneled electrons and to improve the radiative efficiency of the SLD device. Experimental data support the visibility of the proposed 'MQB+MQW in Active' structure at elevated temperatures.

Key Words : Superluminescent Diode, SLD, AlGaAs, Multiple-quantum Barrier, MQB Multiple-quantum Well, MQW, Quantum Efficiency, High Temperature, Superlattice.

1. INTRODUCTION

An ideal SLD is an incoherent light source with only internal gain and no optical feedback. In other words, SLD is basically a single-pass semiconductor amplifier for spontaneous emission which emits at a large number of frequencies, rather than certain preferred frequency. From a technological standpoint, the SLDs are attractive candidates for applications requiring higher radiance levels, coupled with low temporal coherence. Such applications include fiber optic gyroscopes1) and multimode fiber optic communication systems where low coherence eliminates noise found in laser diode (LD) based systems due to model interference. SLD requires high single pass optical gain coupled with effective lasing suppression within the device. To realize high temperature operation of SLD device above 100℃ for automobile applications, we must suppress the excess electron overflow from the active layer into the p-cladding layer at elevated temperatures, which results in poor performances. To overcome the problem of carrier overflow, superlattice structure MQB in the p-cladding region has been employed, which was predicted by Iga et al.2) This design artificially increase the effective barrier height over the bulk potential barrier to enhance the electron wave confinement as a result of electron wave interference through MQB structures. In this work, we report the introduction of MQB structure into SLD device for the first time, to our knowledge, to deduce whether or not the MQB structure is efficacious in AlGaAs system. Finally, we propose a new quantum structure design of active region for high temperature cw operations.

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2. MQB DESIGN : THEORETICAL CONSIDERATION

The calculation of electron wave reflectivity is based on the transfer matrix method (TMM) proposed by Tsu and Esaki.[3] A 1-D Schrodinger equation in the effective mass approximation was applied to the 1-D potential model for the multilayer structure. Marsh[4] analyzed electron transport through GaAs-AlGaAs-GaAs tunnel junctions with an empirical pseudo potential formulation and effective mass approximation. The calculated result showed fairly good agreement for thin barriers ($0.56\ \mathrm{nm} < L_B < 4.23\ \mathrm{nm}$) using effective mass approximation. However, there exists some scatter on what should be the correct values. Therefore, critical parameters in these calculations are the relative effective masses of the wells and barriers in the MQB structure and the band offsets of $Al_XGa_{1-X}As$, relative to the band gap of GaAs. In our work, we used the values reported by Miller et al.[5] The conduction band offset is assumed to be 60% and the effective band edge masses in the Γ valley are taken as:

$$m_c/m_o = 0.0665,\ m_{hh}/m_o = 0.34,\ \text{and}\ m_{lh}/m_o = 0.094$$

where, m_c is the conduction band electron mass, m_{hh} is the valence band heavy hole mass, and m_{lh} is the valence band light hole mass. The composition dependent effective masses in $Al_XGa_{1-X}As$ are taken as:

$$m_c/m_o(x) = 0.0665 + 0.0835x,$$
$$m_{hh}/m_o(x) = 0.34 + 0.175x,\ \text{and}$$
$$m_{lh}/m_o(x) = 0.094 + 0.069x$$

The bandgap of undoped bulk GaAs is taken as 1.424eV. The bandgap of $Al_XGa_{1-X}As$ (undoped) depending on the mole fraction of Al is taken as:

$$E_g(Al) = 1.424 + 1.247x\ (0 < x < 0.45),\ \text{and}$$
$$E_g(Al) = 1.900 + 0.125x + 0.143x^2\ (0.45 < x < 1.0)$$

The MQB structure calculated in this work is consists of periodically alternating thin layer of the AlGaAs barrier and GaAs well with a thickness of L_B & L_W respectively. If L_B & L_W matches the interference condition of the reflected electron wave at the boundaries of the MQB, an incident electron is reflected by the effective potential barrier enhanced by MQB. The interfering electron energy is inversely proportional to the square of L_B or L_W. It is assumed that an electron behave as a coherent wave in the entire MQB. Mendez et al.[6] reported that the electronic coherence is maintained for nine period of GaAs-AlGaAs superlattice, even at room temperature. This implies that the electron wave coherence can be maintained in the entire MQB, if the number of period is limited to less than 10. Also, to avoid electron tunneling to the MQB, the first barrier thickness is designed to be rather thick compared to other layers. We analyzed L_B & L_W dependence of electron wave reflectivity using 70 monolayers (ML) thick first barrier. The number of pairs, barrier and well thickness are optimized and fixed to 5 pairs, 6ML, and 8ML, respectively. Fig. 1 shows the electron wave

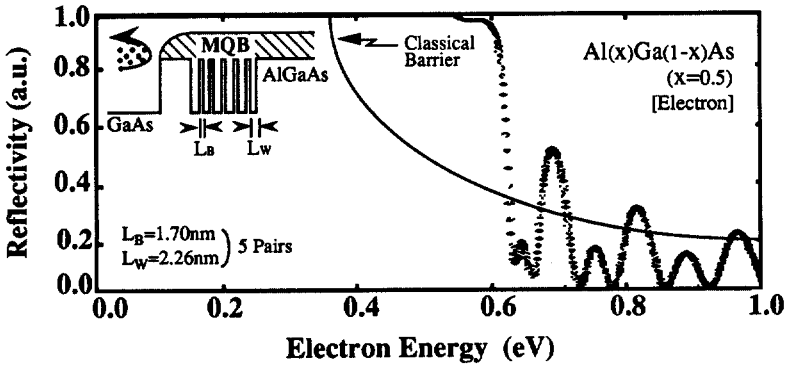

Fig. 1 The electron wave reflectivity of the superlattice designed 'MQB in clad' structure.

reflectivity of the designed 'MQB in Clad' structure with first tunneling stop layer. Calculated electron wave reflectivity of bulk classical barrier is also shown for reference. The introduction of first thick barrier suppress the electron tunneling efficiently and does not affect the characteristics of electron wave reflectivity at the higher energy side. The effective potential barrier height is artificially increased by 1.6 times compare to classical barrier height. Simulation work was also performed to estimate the modulated reflectivity of heavy holes for different Al content (x) viz., $x=0.3$, 0.5, and$=0.7$ and to check the adverse effects of MQB structure on the hole transport mechanism. The hole wave reflectivity of the designed 5 pair MQB structure with tunneling stop layer for $x=0.3$ &$=0.5$ is shown in **Fig. 2**. It was found that in AlGaAs/GaAs system, effective barrier height for hole transport is very sensitive to the x and increases with the increasing x, along with a shift toward the low energy side. Accordingly, if the thermalization energy of $\geqq$100meV is assumed then the injected holes will be reflected back by effective hetero-barrier in the case of MQB structure with $x=0.5$. These results reveal that a sufficient effective barrier can retards the hole injection when hetero barrier structures with $x \geq 0.3$ are employed. Here, the MQB barrier height which holes experience in the cladding region is calculated under the thermal equilibrium conditions. In the actual device, electrons and holes are injected from the opposite sides of the active region and any physical separation of these two type of carriers will create a very large electric field to force the highly mobile electrons to redistribute them selves and maintain charge neutrality. Thermally activated high energy electrons are reflected back in the active by the artificially enhanced MQB hetero-barrier. The entire carrier injection process is dominated by holes because of their low mobility and recombines through stimulated and spontaneous emission. However, simulation results suggest that the existence of MQB structure introduce additional resistance to the hole transportation viz., (i) The modulated reflectivity of the hole barrier results in the stagnant hole transport to the active region, and (ii) The existence of thick electron tunneling stop layer leads to holes accumulation in the cladding region.

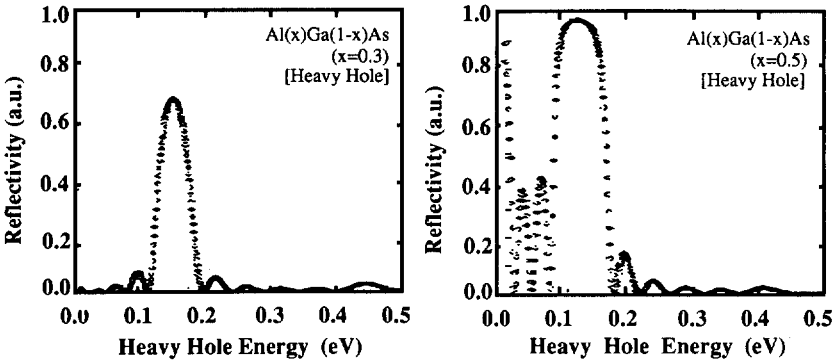

Fig. 2　The heavy hole wave reflectivity of the superlattice designed 'MQB in clad' structure.

To overcome the demerits of MQB design in cladding region, a new concept structure is proposed for active region as shown in **Fig. 3**. The main points of this design are as follow : (i) The superlattice structure MQB is located in the middle of active region which allows smooth hole transportation in to the active region from cladding region, and (ii) Thick electron tunneling stop layer is removed to avoid hole accumulation. The carrier can reach both side of the MQB structure in the active region by tunneling phenomenon which critically depends on the barrier thickness. **Fig. 4** shows the simulated electron reflectivity of proposed 'MQB in Active' design. It can be seen that low energy electrons can tunnel through the MQB barrier, while high energy electrons are reflected back by effective barrier. The tunneled low energy electrons are stopped by the classical barrier of the cladding region. Finally, MQW structure is integrated at each side of MQB to minimize the possible over-flow of tunneled electrons. A dramatic improvement in SLD performance is expected by the combination the MQW with 'MQB in Active' structure. In SLD device, emitted light consists of amplified spontaneous radiation. This causes the shape of the emission spectrum to be directly related to the gain spectrum. The optical gain spectrum is much wider in MQW structures than bulk DH SLDs at a given current density. This leads to reduction of operational current of the SLD device with improved radiative efficiency. The proposed 'MQB+MQW in Active' structure is shown in Fig. 5.

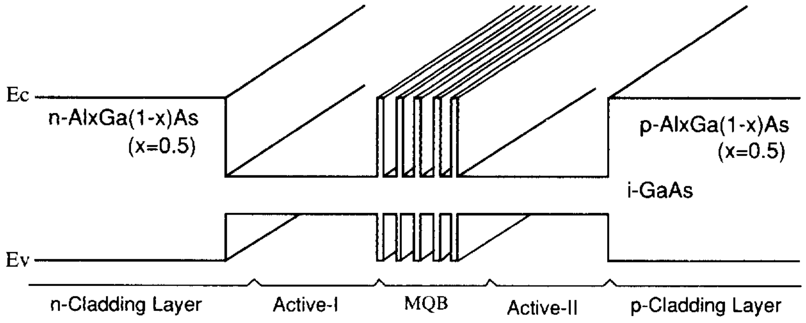

Fig. 3 Schematic 3-D diagram of new proposed 'MQB in Active' structure.

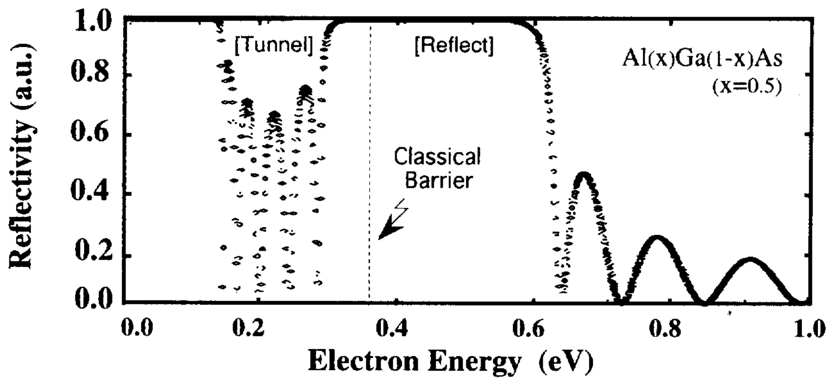

Fig. 4 The electron wave reflectivity of proposed 'MQB in Active' structure.

3. EXPERIMENTAL DETAILS

An index guided ridge waveguide SLDs with an internal absorber were fabricated to check the basic characteristics at elevated temperatures. The layer structure was grown by metalorganic vapor phase epitaxy (MOVPE) on a (100) oriented n-GaAs substrate has the following layers : n^+buffer(N_d=1.0x10^{+18}cm-^{3}), 1μm thick n-$Al_{0.5}Ga_{0.5}As$ cladding (N_d=1.0x10^{+18}cm^{-3}), a GaAs active layer (undoped), MQB consisting of a 2.26nm (8ML) thick GaAs well/1.70nm (6ML) thick $Al_{0.5}Ga_{0.5}As$ barrier with 19.8nm (70ML) thick first barrier ; 5 superlattice pairs, 1μm thick p-$Al_{0.5}Ga_{0.5}As$ cladding (N_a=1.0x10^{+18}cm^{-3}), and 1μm thick p^+ GaAs contact layer (N_a=2.0x10^{+19}cm-^{3}). MQWs of active region consisting of three 6.22nm (22ML) thick GaAs wells (undoped) sandwiched between 3.96nm (14ML) thick $Al_{0.2}Ga_{0.8}As$ barrier & guide layers of 26.8nm (95ML) thick $Al_{0.2}Ga_{0.8}As$ segments. 4μm wide ridge waveguide SLD were processed. An absorber was integrated at the non-output end of the active region. The absorber length is about 300μm, which corresponds to effective reflectivity of about<0.001%, to achieve high power cw operations with low spectral modulation. The SLD facets are (011) oriented and was formed by cleaving in air. The front output facet was coated with $\lambda/4$ thick Al_2O_3 antireflection film (R=2%). The purpose of AR coating is to minimize the optical feedback to the active region. Finally, SLD devices were cleaved to a chip-length of 600μm and soldered junction side down on a c-BN submount and Cu block heatsink. Planar gain guided lasers (LD) were also fabricated for a comparison of the active layer structure. Photoluminescence (PL) spectra were recorded to confirm the character of proposed active region structures at elevated temperature upto 150℃. This was done by exciting the samples, through the p-cladding layer, before the ridge structure was formed, with an Ar^+ laser 488nm line at 500mW excitation power.

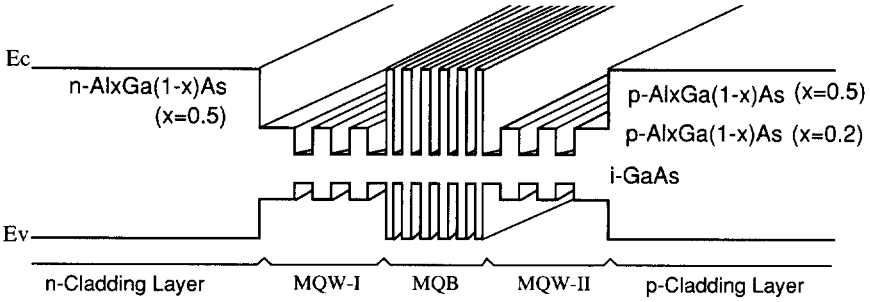

Fig. 5 Schematic 3-D diagram of new proposed 'MQB+MQW in Active' structure.

4. RESULTS

To confirm the basic characteristics of the proposed structure, three type of planar gain guided LDs were fabricated using different layer structures viz., (i) DH, (ii) MQB in clad, and (iii) MQB in active. The stripe width and length of the laser chip were fixed at 20μm and 300μm, respectively. The current-output power (I-L) and differential quantum efficiency (I-η_d) characteristics under cw operation is shown in **Fig. 6**. It can be seen that introduction of superlattice structure MQB in the cladding region results in the increase of threshold current (I_{th}) by≈13% and decrease of η_d by≈5%. This implies that the inclusion of the MQB in cladding region has a significant adverse impact on the device character because of its many hetero-interfaces, although effective in reducing the thermionic emission of carriers over the MQB into the cladding region. On the other hand, MQB in the active region leads to decrease in the I_{th} by≈12% and increase in the η_d by≈7%. This improvement can be attributed to the additional carrier transport effect of superlattice structure in the active region. These results indicate that the proposed 'MQB in Active' structure can counter the demerits of 'MQB in clad' structure by improving the hole injection efficiency.

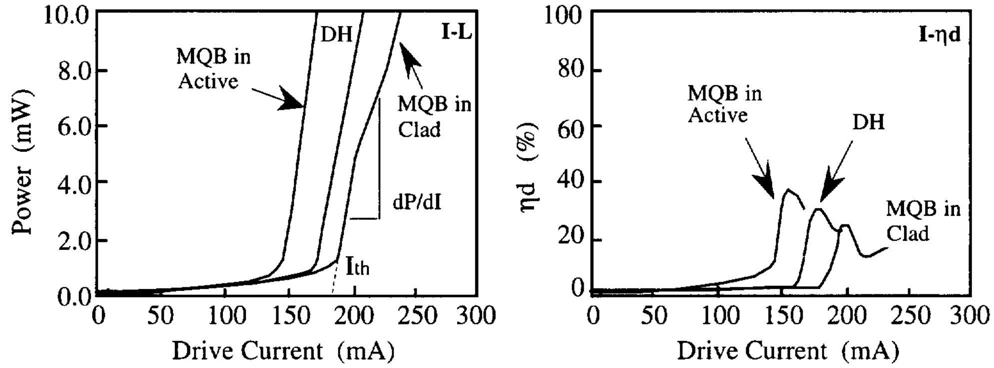

Fig. 6 Comparison of I-L and I-η_d characteristics of planar gain guided LDs with (i) DH, (ii) 'MQB in Clad', and (iii) 'MQB in Active' structure.

The temperature dependence of the I-L character of index guided ridge waveguide SLD with 'MQB in Active' structure under cw operation is shown in **Fig. 7**. The I-L data is measured in the temperature range of 20～100℃. For comparison, the I-L character of the DH SLD at 100℃ is shown in the figure. The improved character of the proposed structure at elevated temperatures can be seen clearly in the figure. The I-L data shows that SLD device is capable of emitting>10.0mW at 20℃ ambient temperature. At 100℃ temperature,

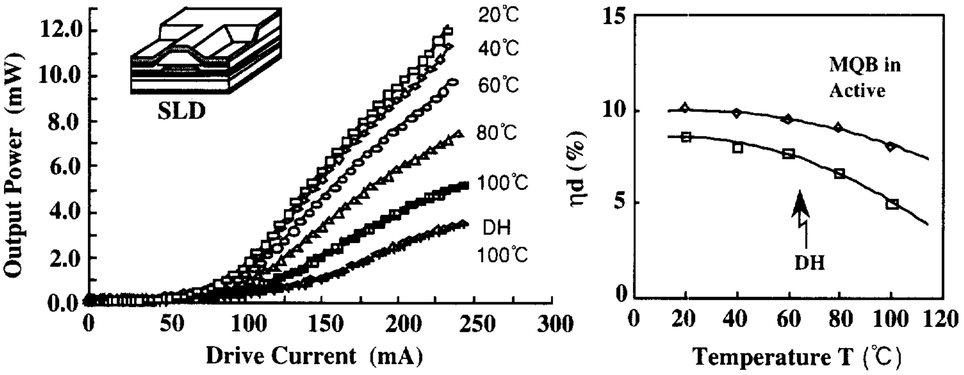

Fig. 7 Temperature dependence of I-L and η_d characteristics of 'MQB in Active' and DH structure index guided ridge waveguide SLD.

the output power of ≥5.0mW is obtained. This indicates an increase of 50% in the output power compare to DH SLD devices. The reduction in output power at elevated temperatures is mainly due to quantum efficiency losses due to electron overflow. The temperature dependence graph of η_d shows that the η_d is significantly reduced in the case of the DH SLD over the whole temperature range with a greater reduction in the high temperature side, compare to 'MQB in Active' SLD. This may be expected, in that, at elevated temperatures the carrier overflow would be expected to becomes worse, and thus we expect the 'MQB in Active' structure to have greater effect at such temperatures. Finally, to minimize the possible over-flow of tunneled electrons, MQW structure is integrated at each side of the MQB in active region. In this design, carriers are exchanged between separate confinement hetero-structure (SCH) 3-D continuous states and 2-D confined quantum well states through quantum mechanical capture and escape process involving longitudinal optical photons. To observe the character of the 'MQB+MQW in Active' structure at elevated temperatures, PL spectrum was measured. The temperature dependence of the PL spectra in the temperature range of 23℃ to 150℃ is shown in Fig. 8(a). Fig. 8(b) shows the comparison of PL peak intensity for MQB+MQW in Active', MQB in Active', and DH structure. It can be seen that with increasing temperature, there is no significant change in the shape of emission spectra. However, the full width at half maxima (FWHM) showed an increase with increasing temperature. The strong emission can be observed even at temperature as high as 150℃. These superior PL characteristics of 'MQB+MQW in Active' structure is due to MQW efffect and the additional suppression of carrier overflow at elevated temperatures. These results ensure the high temperature cw operations of SLD devices with proposed 'MQB+MQW in Active' structure.

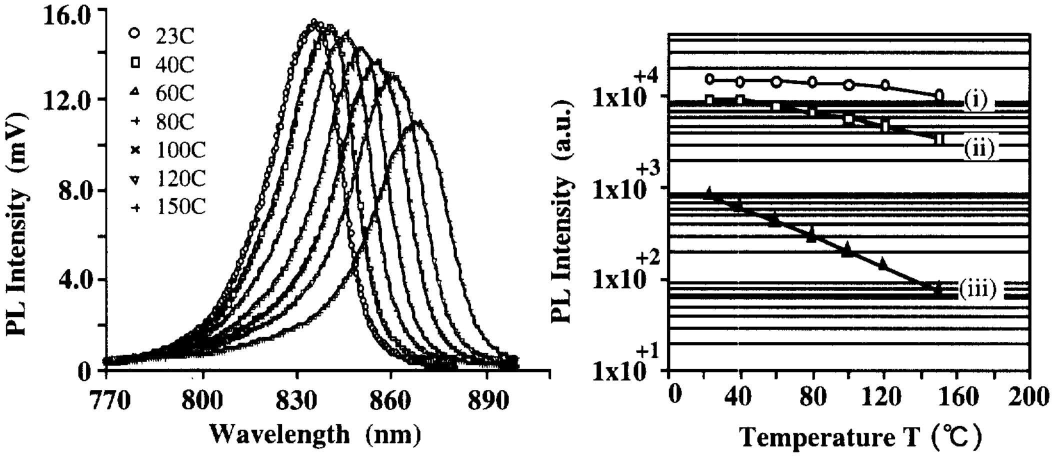

Fig. 8 (a). Temperature dependence of PL spectra of 'MQB+MQW in Active' ; (b). PL temperature dependence of (i). 'MQB+MQW in Active', (ii) 'MQB in Active', and (iii). DH structure.

5. CONCLUSIONS

In conclusion, index guided ridge waveguide SLD with an internal absorber are fabricated using proposed active layer structure and operated successfully under cw operation. Our simulation results in line with experimental data shows that 'MQB in Clad' structure, which was designed to overcome the problem of carrier overflow is not suitable for AlGaAs system, because of stagnant hole transportation. The reflectivity results reveal that a sufficient effective barrier can retards the hole injection when $GaAs/Al_xGa_{1-x}As$ superlattice structure with $x \geq 0.3$ are employed. The MQB design plays the crucial role as it controls the hole transport mechanism. To overcome the demerits of MQB design, new quantum structure for active region is proposed. The I-L temperature dependence of the SLD device endorse the improved characteristics, which can be attributed to the reduction of the overflow current and is directly related to the inclusion of the MQB in the active region. PL data supports the visibility of the 'MQB+MQW in Active' structure SLD at elevated temperatures. This structure is an ideal candidate for LD/SLD devices requiring high temperature operations or even for short wavelength devices.

REFERENCES

1) K. Bohm, P. Marten, K. Petermann, E. Weidel and R. Ulrich : Elect. Lett., 17 (1981), p. 352
2) K. Iga, H. Uenohara and F. Koyama : Electron Lett., 22 (1986), p. 1008
3) R. Tsu and L. Esaki : Appl. Phys. Lett., 22 (1973), p. 562
4) A. C. Marsh : IEEE J. Quantum Electron., QE-23 (1987), p. 371
5) R. C. Miller, D. A. Kleinman and A. C. Gossard : Phys Rev. B, 29 (1984), p. 7085
6) E. E. Mendez, F. Agullo-Rueda and J. M. Hong : Appl. Phys. Lett., 56 (1990), p. 2545

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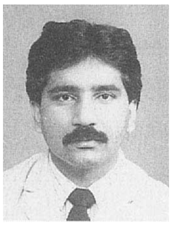

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