Proposed new resonant tunneling structures with impurity planes of deep levels in barriers

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Theoretical calculations of the transmission coefficient and the current density using a transfer matrix method are presented for several resonant tunneling structures in which impurity planes of deep levels (IPDL) are incorporated. Increases of several orders of magnitude in the width of the resonant peak, as well as in the peak current density, are obtained as compared to conventional double barrier resonant tunneling structures. Furthermore, an optimal position of the IPDLs is obtained in order to maximize the width of the resonant peak. Our results suggest that the incorporation of impurity planes of deep levels can considerably improve the characteristics of resonant tunneling devices.

I. INTRODUCTION

Double barrier resonant tunneling (DBRT) structures have attracted considerable interest in recent years. The negative differential resistance (NDR) observed in these structures make them suitable for application as high-speed oscillators[1] and transistors.[2] Even if Sollner *et al.*[1] have shown that oscillations as high as 2.5 THz can be achieved, it would be technologically interesting to investigate modified structures which could further improve the device characteristics. The intent of this paper is to propose such a modified structure using impurity planes of deep levels.

The transmission of electrons through a DBRT structure can be interpreted as either (a) a coherent resonant tunneling process similar to the optical Fabry–Perot effect, or (b) a sequential tunneling process[3] where electrons tunnel into and out of the well independently and without preserving phase coherence with the incident wave. Several authors[4-6] have investigated the role of scattering in determining which of the two mechanisms prevails. To establish the dominant process, the inherent width, $2\Gamma_r$, of the resonance peak in the transmission probability is compared to the collision broadening, $2\Gamma_c$, of the energy levels in the quantum well due to scattering. The collision broadening is simply $\hbar/\tau_s$ where τ_s is the scattering lifetime of an electron in the well region. If $\Gamma_r \gg \Gamma_c$, coherent resonant tunneling is observable; however, if $\Gamma_r \ll \Gamma_c$, electrons will tunnel incoherently without resonance enhancement of the transmission (i.e., sequential tunneling). The latter process leads to a reduction in both the peak current and the peak-to-valley current ratio (PVR) observed in the I-V characteristics.[4] Therefore, to increase the likelihood of coherent resonant tunneling, Γ_c must be reduced and Γ_r must be increased. The collision broadening is limited mostly by the abruptness and quality (i.e., low interface state density) of the heterointerfaces. However, MBE-grown structures are of exceptional quality as demonstrated by the ultrahigh mobilities observed,[7] and it is not likely that Γ_c can be reduced substantially. To increase Γ_r in a standard DBRT structure, the width and/or the height of the barrier regions must be reduced.[8] However, this would decrease dramatically the PVR and would limit the frequency response of the device.

In this paper, we suggest a new method to increase Γ_r without diminishing the overall characteristics by introducing impurity planes of deep levels within the barrier regions of the DBRT structure (see Fig. 1). These deep levels are considered to be localized in the growth direction by a strong 1D potential but are assumed to be extended in the direction parallel to the interfaces. Beltram and Capasso[9] first suggested incorporating such deep centers within the barrier layers of a conventional heterojunction superlattice. They found an enhancement of several orders of magnitude in the miniband widths, as well as a creation of new Bloch states within the band gap of the superlattice. Similarly, we find that the presence of these deep levels in DBRT structures increases Γ_r by several orders of magnitude when the energies of the deep levels coincide with the resonant energy of the quantum well. These one-dimensional deep levels could be obtained from the incorporation of a high concentration of shallow impurities within a single atomic plane of the host semiconductor, as suggested by the tight binding calculations of Hjalmarson.[10,11] Schubert *et al.*[12] have also shown that spatial local-

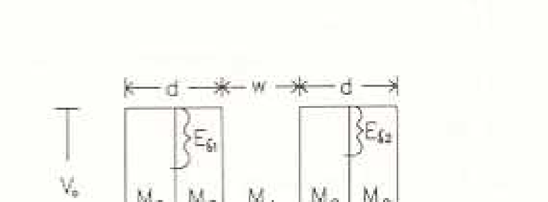

FIG. 1. Schematic of a DBRT structure with IPDL in both barriers. The IPDLs are characterized by their position, z_δ and their binding energy, E_δ. The various transfer matrices [see Eq. (2)] needed to construct the transmission coefficient are also shown.

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ization of impurities on the length scale of the lattice constant can be achieved in MBE-grown GaAs.

In the following section, we present the transfer matrix method used to calculate the transmission coefficient and the current density through the structures considered in this work. Results for four different structures are discussed in Sec. III, and concluding remarks are made in Sec. IV.

II. CALCULATIONS

A. Transmission coefficient

Consider, for example, a DBRT structure with an impurity plane of deep levels (IPDL) in both barriers as shown in Fig. 1. In this figure, d and V_0 are the thickness and height of the barriers, while w is the well width. In order to calculate the transmission coefficient through such a structure, one must specify a model potential which characterizes an IPDL. Beltram and Capasso[9] have verified that only the symmetry and weight (i.e., the integral) of the potential chosen are important so that a δ function potential can be used to qualitatively describe the 1D deep level. We have also verified that a narrow rectangular potential well gives the same qualitative results as the δ potential well. It can easily be shown[13] that the weight of the δ function potential is directly related to the binding energy, E_δ, of the bound state of the isolated δ function well. For this reason, the IPDL is characterized by only two parameters, its binding energy, E_δ, and its position in the barrier, z_δ. The energy of the level with respect to the bottom of the conduction band of the injection region will be given by $V_0 - E_\delta$.

The transmission coefficient, T, for all structures considered in this work is obtained using a transfer matrix approach which was first elaborated by Ricco and Azbel[14] for DBRT structures. However, in their calculations a single effective mass for the entire structure was assumed. Bastard[15] has shown that effective mass differences between the small gap and the large gap semiconductor regions modify the boundary conditions which are imposed on the wave function of the effective mass Hamiltonian. Therefore, to obtain the transfer matrices, one must solve the effective mass Hamiltonian in each region to obtain the wave function Ψ and use the appropriate boundary conditions [i.e., continuity of Ψ and $(1/m^*)$ $(d\Psi/dz)$]. The wave function of an electron with effective mass m_1^* in the allowed regions is expressed in the following form:

$$\Psi = A\, e^{ikz} + Be^{-ikz}, \tag{1}$$

where $k = \sqrt{2m_1^* E/\hbar^2}$ and the energy of the incident electron is taken with respect to the bottom of the conduction band of the region. The wave function in the barrier regions where the effective mass is m_2^* is obtained by replacing k by iK where

$$K = \sqrt{m_2^*(V_0 - E)/\hbar^2}.$$

For a DBRT structure as in Fig. 1, five different matrices are needed to completely describe the transmission of an electron. Defining $X = (m_2^* k)/(m_1^* K)$, we obtain for the first four matrices:

$$M_A = \begin{bmatrix} e^{-ikz_a} & 0 \\ 0 & e^{-ikz_a} \end{bmatrix}, \tag{2a}$$

$$M_B = \begin{bmatrix} e^{Kz_b} & 0 \\ 0 & e^{-Kz_b} \end{bmatrix}, \tag{2b}$$

$$M_{\rm in} = \frac{1}{2}\begin{bmatrix} 1 + i/X & 1 - i/X \\ 1 - i/X & 1 + i/X \end{bmatrix}, \tag{2c}$$

$$M_{\rm out} = \frac{1}{2}\begin{bmatrix} 1 - iX & 1 + iX \\ 1 + iX & 1 - iX \end{bmatrix}. \tag{2d}$$

These matrices are similar to those introduced originally by Ricco and Azbel[14] for a conventional DBRT structure, except that the effective mass difference between the allowed and the barrier regions is included. These four matrices (see Fig. 1) respectively join points within an allowed region (M_A), within a barrier region (M_B), on either side of a potential discontinuity from an allowed to a barrier region ($M_{\rm in}$), and finally on either side of a potential discontinuity from a barrier to an allowed region ($M_{\rm out}$). The quantities z_a and z_b in matrices M_A and M_B represent, respectively, the distance between the points in the allowed region and the points in the barrier region to be joined together.

In order to obtain the final transfer matrix which joins two points on either side of the δ function well, appropriate boundary conditions for the δ function well must be used[13] [i.e., continuity of Ψ but discontinuity of $(1/m^*)$ $d\Psi/dz$].

The matrix, M_δ, which characterizes the IPDL is given by the following:

$$M_\delta = \begin{bmatrix} 1 - \dfrac{K_\delta}{K} & -\dfrac{K_\delta}{K} \\ \dfrac{K_\delta}{K} & 1 + \dfrac{K_\delta}{K} \end{bmatrix}, \tag{3}$$

where the parameter $K_\delta = \sqrt{m_2^* E_\delta/\hbar^2}$.

Once these matrices are individually calculated, they are multiplied following their order of occurrence in the structure from left to right, to obtain the global matrix which describes the entire structure of interest. This global matrix joins the wavefunction in the injection region (far left) to the wavefunction in the collection region (far right), so that

$$\Psi_{\rm inj} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \Psi_{\rm col}. \tag{4}$$

The transmission coefficient, T, is given by the ratio of the transmitted probability flux to the incident probability flux and is written in general as

$$T = \frac{k_{\rm col} m_{\rm inj}^*}{m_{\rm col}^* k_{\rm inj}} \frac{1}{|M_{11}|^2}. \tag{5}$$

Note that, for our calculations, we assume that the injection region and the collection region are the same semiconducting material so that $m_{\rm inj}^* = m_{\rm col}^* = m_1^*$.

B. Current density

The tunneling current density J through the structure as a function of applied voltage V is obtained by numerically integrating the following expression[16]:

$$J = \frac{em_1^* k_B T_a}{2\pi^2 \hbar^3} \int_0^\infty dE\, T(E) \times \ln\left(\frac{1 + \exp[(E_F - E)/k_B T_a]}{1 + \exp[(E_F - E - eV)/k_B T_a]}\right), \quad (6)$$

where k_B is the Boltzmann constant, E_F is the Fermi level in the contact regions, V is the applied voltage, and T_a is the absolute temperature. In order to integrate Eq. 6, $T(E)$ must be calculated for each applied voltage. The exact solution for a DBRT structure in the presence of an applied electric field would involve using Airy functions which are quite cumbersome to compute. However, approximate solutions for $T(E)$ can be obtained using a multiple step technique.[17] This technique consists in subdividing the potential energy profile into several potential steps and calculating the global matrix for the structure under an applied electric field using the same transfer matrix method described above. The transmission coefficient is then obtained from Eq. (5).

It is important to note that the expression for the current density [Eq. (6)] assumes a transmission coefficient that is independent of the electron motion in the transverse direction (i.e., xy plane). This result follows directly from the use in Sec. II A of a 1D Hamiltonian to calculate the transmission coefficient. Vassell *et al.*[15] have used a transfer matrix formulation to obtain the dependance of the transmission coefficient on the transverse component of the electron energy. By assuming a constant transverse energy equal to the thermal average, $k_B T_a$, they showed that the energy of the resonant transmission peaks are slightly shifted. Note that their expression for the current density reduces to Eq. (6) when a constant transverse energy is assumed. Since we are mostly interested in a qualitative discussion of the effects of incorporating IPDLs in DBRT structures, these slight shifts in energy ($\sim 0.1\%$ in our case) are not important.

In this calculation of the current density, we have neglected, for simplicity, all charging effects[19] and phonon-assisted transmission[20,21] which can significantly alter the shape of the $J(V)$ characteristics. Nevertheless, we expect our results for the current density to be qualitatively correct since we are mainly interested in the effect of incorporating IPDLs in DBRT structures.

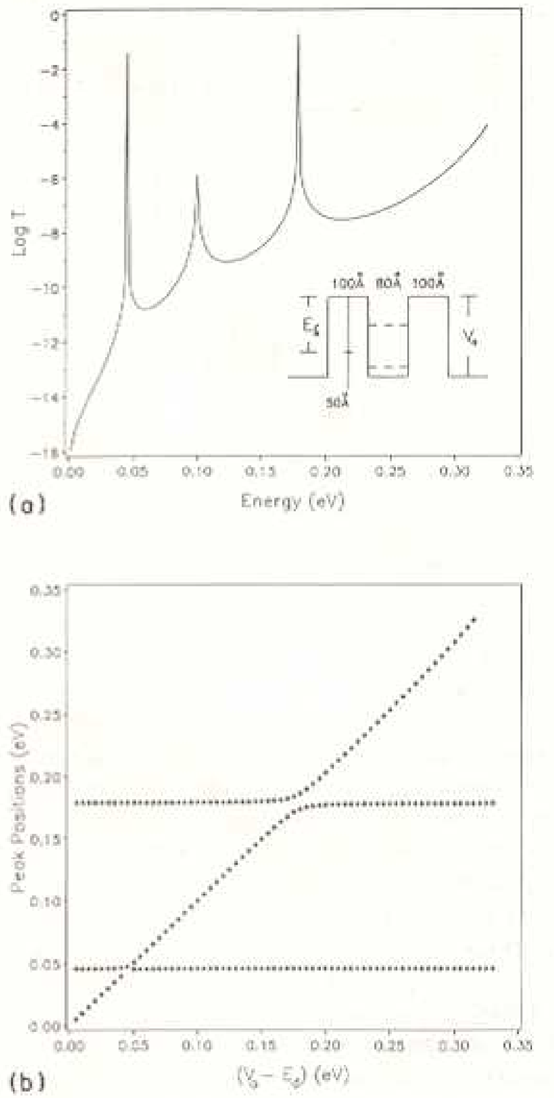

FIG. 2. (a) Logarithm of the transmission coefficient as a function of the energy of the incident electron for the structure shown in the inset with $V_0 - E_\delta = 0.1$ eV. (b) shows the energy position of the peaks as a function of $V_0 - E_\delta$. The position of the IPDL is taken to be 50 Å from the first interface.

III. RESULTS AND DISCUSSION

A. Transmission coefficient for $V=0$

The basic DBRT structure considered here, as an example, consists of a $GaAs/Ga_{0.7}Al_{0.3}As$ heterostructure which gives $V_0 = 0.33$ eV, $m_2^* = 0.092\ m_0$, and $m_1^* = 0.067\ m_0$.[22] The barrier thickness is chosen to be 100 Å while the well width is 80 Å. These parameters yield two resonances for the DBRT structure without IPDL at energies of $E_0 = 45.6$ meV and $E_1 = 178.1$ meV.

Let us now consider the transmission coefficient at zero applied voltage for a structure with an IPDL in only one of the barriers [see inset of Fig. 2(a)]. By varying z_δ and E_δ, it was found that the coupling between the IPDL and the levels in the quantum well could be separated into two regimes. For $z_\delta < 50$ Å, the coupling is very weak except for $V_0 - E_\delta \sim E_0$ and E_1. In this region ($z_\delta < 50$ Å), the presence of the IPDL contributes a third, weak transmission maximum to the $T(E)$ curve as shown in Fig. 2(a), where the transmission coefficient is calculated for $z_\delta = 50$ Å. The transmission maxima at E_0 and E_1 are lowered from their maximum value of unity because the presence of the deep level in only one barrier breaks the symmetry needed to obtain a transmission maximum of unity.[14] Figure 2(b) shows the energy position of the transmission maxima as function of the binding energy, E_δ, of the IPDL for $z_\delta = 50$ Å. As can be seen, the coupling is very weak and the energies of the three maxima correspond to E_0, E_1, and $(V_0 - E_\delta)$. Only for $V_0 - E_\delta \sim E_1$ is the coupling strong enough to split the degeneracy between the levels.

As the deep level further approaches the quantum well ($z_\delta > 50$ Å), the strength of the coupling gradually increases. Figures 3(a) and 3(b) show the results for $z_\delta = 90$ Å. All three maxima have a large transmission coefficient, and the energy of these maxima do not coincide with E_0, E_1,

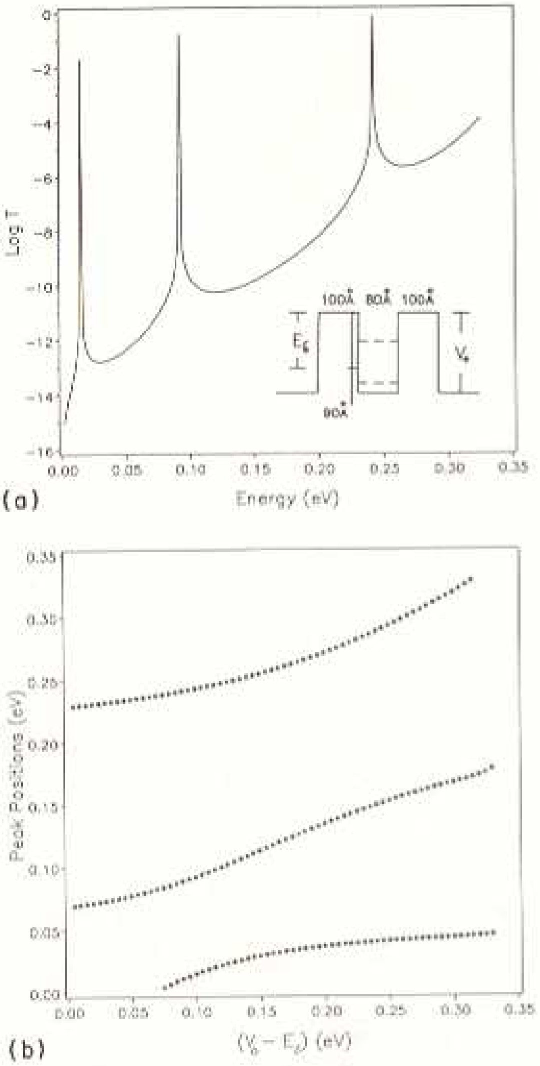

FIG. 3. Same as Fig. 2 except the position of the IPDL is 90 Å from the first interface.

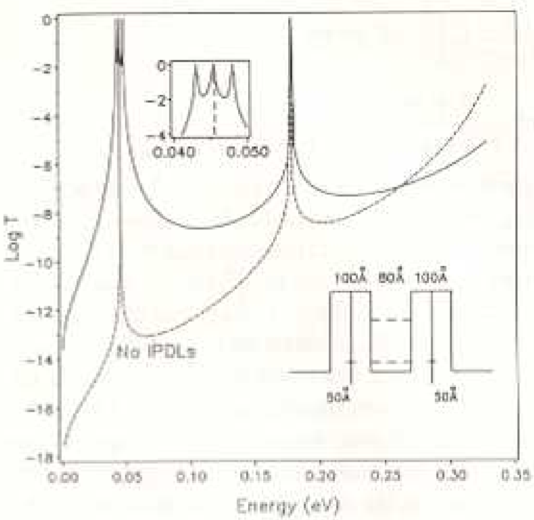

FIG. 4. Logarithm of the transmission coefficient as a function of the energy of the incident electron for a DBRT structure with IPDLs in the middle of both barriers (solid line). The binding energies of the IPDLs are chosen so that the energy of the IPDLs coincide with the lowest energy level of the quantum well. Also shown is the transmission probability for an equivalent DBRT structure without IPDL (dashed line). The upper inset shows the splitting of the three fold degenerate level at $E = E_0$.

and $V_0 - E_\delta$, as seen in Fig. 3(b). It is also interesting to note that, as the binding energy of the deep level increases (i.e., $V_0 - E_\delta$ becomes smaller), the energy of the lowest transmission maximum drops continuously and reaches $E = 0$ for $V_0 - E_\delta \sim 0.07$ eV. For larger values of the binding energy, this maximum is not present. This result is similar to Beltram and Capasso's observation of new Bloch states within the band gap of a superlattice containing IPDL.[9] We see that the incorporation of IPDL close to the quantum well can lead to large resonances at energies very different from the characteristic energy levels E_0 and E_1 of the quantum well.

Let us now consider a DBRT structure with an IPDL in both barriers. Figure 4 shows the $T(E)$ curve for a symmetric DBRT structure with the IPDLs positioned in the middle of each barrier ($z_\delta = 50$ Å). For comparison, the transmission coefficient for a similar structure without the IPDL is also shown [(dashed line in Fig. 4)]. Following Beltram and Capasso,[9] the maximum broadening of the transmission peaks will occur when the energy of the deep levels coincides with the energy of a level in the quantum well. Therefore, we chose $E_{\delta 1} = E_{\delta_2} = V_0 - E_0$ in order to observe large transmission widths, $2\Gamma_r$. The upper inset of Fig. 4 shows the three maxima near $E = E_0$ which result from the splitting of the threefold degenerate energy level. The energy separation between the maxima depends on the position of the deep levels, z_δ, because of the variation of the strength of the coupling between the three degenerate levels.

Figure 5 shows the HWHM, Γ_r, of the three transmission peaks with energies close to E_0 as a function of the position of the IPDLs, z_δ. As before, we take $E_{\delta 1} = E_{\delta 2} = V_0 - E_0$. We observe an initial exponential increase in Γ_r when the IPDLs are far from the quantum well (i.e., z_δ small). For these values of z_δ there is very little coupling between the three degenerate states so that only one maximum is observed. However, the proximity of the IPDLs to the injection and collection regions allow their wave functions to penetrate deeper within the barrier regions. It is easily shown that, on resonance (i.e., $E = E_0$), the amplitude of the wave function at the position of the IPDL (i.e., $z = z_\delta$) is $e^{K_0 z_\delta}$ times larger than the amplitude at the first interface ($z = 0$). Furthermore, the amplitude to the right of the IPDL ($z > z_\delta$) decreases as $e^{-K_0(z - z_\delta)}$. Consequently, at $z = 2z_\delta$, the wave function will have the same amplitude as the wave function at the first interface. The presence of the IPDL at $z = z_\delta$ is therefore equivalent to reducing the effective barrier thickness by[23] $2z_\delta$. The HWHM for DBRT structure without IPDL is found to be proportional to[24] $e^{-2K_0 d_{\rm eff}}$ where K_0 is K evaluated at E_0 and $d_{\rm eff}$ is the effective barrier thickness (for the DBRT structure without IPDL, $d_{\rm eff} = d$). By taking $d_{\rm eff} = d - 2z_\delta$, this expression for Γ_r becomes

$$\Gamma_r = \Gamma_0 e^{4K_0 z_\delta}, \qquad (7)$$

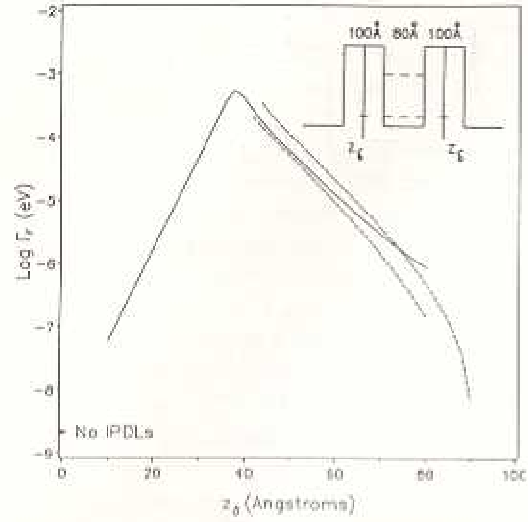

FIG. 5. Logarithm of the HWHM, Γ_r of the transmission peaks as a function of the position of the IPDLs, z_δ. For $z_\delta < 38$ Å, only one peak is observed, while for $z_\delta > 38$ Å three peaks are obtained. The solid line represents the HWHM for the central peak and the dashed lines are the HWHM for the two other peaks when $z_\delta > 38$ Å.

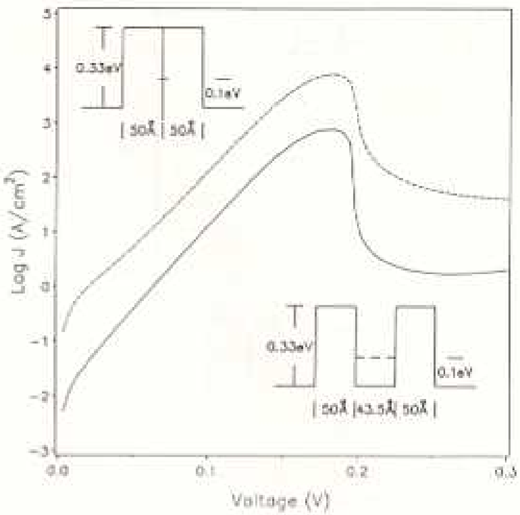

FIG. 6. Logarithm of the current density as a function of applied voltage for a single barrier with an IDPL (dashed line) and for a DBRT structure (solid line). The energy level in the quantum well of the DBRT structure is equal to the energy level of the IDPL.

where Γ_{0r} is the HWHM for the DBRT without IPDL. Equation (7) agrees very well with the curve shown in Fig. 5 for values of z_δ less than the critical position, $z_{\delta c}$, where Γ_r is maximum.

As the IPDLs approach the quantum well, the increased coupling between the three degenerate states leads to an increase in the energy splitting between the three levels (see Fig. 4). The critical position of the IPDLs $z_{\delta c}$ (~ 38 Å in our example) characterizes the position where the energy splitting becomes larger than Γ_r so that three strong transmission peaks are now observed in the $T(E)$ curve. The presence of three separate and strong transmission peaks suggests that we can now consider the resonant tunneling process as the tunneling of an electron through a state of an *effective* well formed by the coupled δ functions and quantum wells. As z_δ increases, the width of this *effective* well diminishes so that the effective barrier thickness between the injection (or collection) region and the *effective* well increases. This increase in d_{eff} leads to a decrease of Γ_r for $z_\delta > z_{\delta c}$ as observed in Fig. 5. Therefore, the position $z_{\delta c}$ characterizes the position where the coupling between the deep levels of the IPDLs and the states of the quantum well becomes important. For IPDLs at this optimal position, the HWHM reaches a maximum value which is more than five orders of magnitude larger than Γ_r for a structure without IPDLs.

The characteristic time for a coherent resonant tunneling process is related to the half width of the transmission maximum, as[25] $\tau_r = \hbar/2\Gamma_r$. This implies that the large increase in Γ_r corresponds to an equivalent decrease in the characteristic tunneling time. Furthermore, this suggests that the speed of a DBRT structure can be greatly improved by the incorporation of IPDL in the barrier regions. Also, since the current density (Eq. 6) depends on the integral of $T(E)$, the broader peak in the transmission coefficient will lead to a larger current density in the structure with IPDLs. This last point is discussed in the next section.

B. Current density

In this section we present the tunneling current density results using the method described in Sec. II B for three different structures. Calculations were performed using $E_F = 0.02$ eV and $T_a = 77$ K.

The first structure, shown in the inset at the top of Fig. 6, consists of a single barrier with one IPDL. The barrier thickness is 100 Å and the IPDL is positioned in the middle of the barrier ($z_\delta = 50$ Å). The binding energy, E_δ, is taken as 0.23 eV so that the energy of the level with respect to the bottom of the conduction band of the injection region, $V_0 - E_\delta$, is 0.10 eV. All other parameters are as before. This structure is compared to an equivalent DBRT structure (inset at bottom of Fig. 6) where each barrier is 50 Å thick. The thickness of the well region is taken as 43.5 Å in order to obtain an energy level at $E_0 = 0.10$ eV. We have given elsewhere[24] analytical expressions for the HWHM, Γ_r, and the energy position of the transmission maximum for such a single barrier structure, and showed that Γ_r for this structure is almost one order of magnitude larger than Γ_r for an equivalent DBRT structure without IPDL. In Fig. 6, we present the $J(V)$ characteristics calculated for both structures. As expected, the larger Γ_r leads to a peak current density for the single barrier (SB) structure which is almost one order of magnitude larger than that of the double barrier (DB) structure. However, for $V > V_{max}$, J_{SB} continues to be greater than J_{DB} because the transmission coefficient through the SB structure, T_{SB}, is larger than T_{DB} so that the larger peak current would not necessarily lead to a larger PVR. For this reason, the SB structure would not be interesting for device applications. However, this structure does offer the possibility to obtain experimentally the binding energy of the IPDL as $\sim eV_{max}/2$.

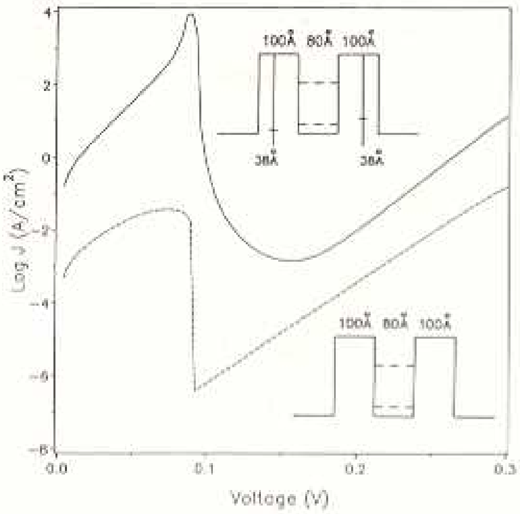

FIG. 7. Comparison of the current density for DBRT structures with (solid line) and without (dashed line) IPDLs. The position of the IPDLs with respect to the electrodes is 38 Å. The energy of the IPDLs are chosen so that they align with the lowest energy level of the quantum well at $V = 89.1$ mV.

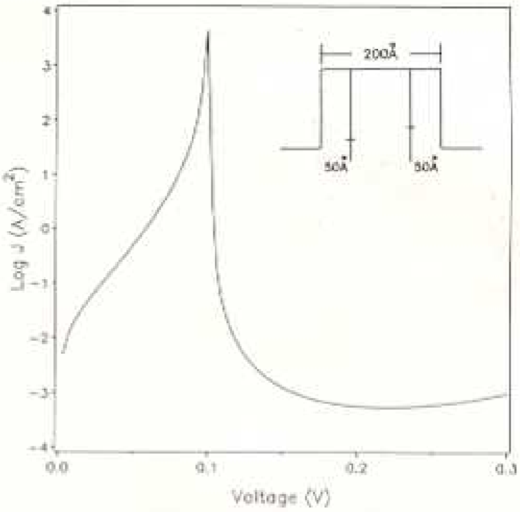

FIG. 8. Logarithm of the current density as a function of applied voltage for a single barrier structure with two IPDLs (see inset). The energies of the IPDLs are chosen to align at an applied voltage of 0.1V.

The second structure considered is a DBRT structure with one IPDL in both barriers (see upper inset of Fig. 7). As suggested by Fig. 5, the IPDLs were positioned at $z_\delta = z_{\delta c} = 38$ Å in order to optimize Γ_r. Furthermore, the binding energies of the IPDLs, $E_{\delta 1}$ and $E_{\delta 2}$, were chosen so that the deep levels aligned with the quantum well level at a particular applied voltage. In order to achieve the largest possible peak current density, the energy alignment of the three levels must occur when the maximum number of carriers can participate in the resonant tunneling process. This will happen when the levels align at an energy approximately equal to E_c in the injection region. For the structure considered here, this alignment is realized at an applied voltage of 89.1 mV. The solid line in Fig. 7 shows the $J(V)$ curve obtained for this structure. Also shown as the dashed line is the current density for the equivalent DBRT structure without IPDLs. As expected, the incorporation of the IPDL has increased considerably (by a factor of $\sim 10^5$ in this example) the peak current density of the DBRT structure because of the large increase in Γ_r. Furthermore, the valley current density is increased by $\sim 10^3$ due to the increased transmission coefficient for energies larger that the resonant energy (see Fig 4). This leads to a calculated PVR for the structure with IPDL of approximately 10^7, as opposed to 10^5 for the structure without IPDLs. As mentionned before, many factors which contribute to the total valley current density have been neglected. However, if the contributions of these factors to the valley current are not increased by the presence of the IPDL, the large increase in the peak current could still lead to a noticeable increase in the PVR.

The last structure studied (see Fig. 8) is similar to the previous one except that the quantum well has been eliminated (i.e., $w = 0$). As mentioned for the previous case, the deep levels must align at an energy which is close to E_c of the injection region to obtain a large peak current density. The binding energies $E_{\delta 1}$ and $E_{\delta 2}$ were chosen so that they align at $E = 0.5$ meV when $V = 0.100$ V. At this voltage, a strong resonance in the transmission is built up between the incident electron and the two aligned levels. The transmission coefficient increases to $\sim 10^{-1}$ and becomes very broad ($\Gamma_r \sim 10^{-4}$ eV). These conditions are valid only when the levels are aligned, and lead to a sharp increase in the current density near $V = 0.100$ V with a J_{peak} of $\sim 5 \times 10^3$ A/cm². When $V > 0.100$ V, the levels are no longer aligned and T through the thick barrier ($d \sim 200$ Å) becomes very small so that the valley current is also quite small. Therefore, this new resonant tunneling structure could also produce interesting J-V characteristics (large J_{peak}, large PVR).

Note that different binding energies for IPDLs could be achieved experimentally by using different types of impurity atoms in the impurity planes of both barriers. Hjalmarson[11] has also suggested that the binding energy of the IPDL can be varied by changing the concentration of impurities in the impurity plane.

IV. CONCLUSION

The coupling between an IPDL and a quantum well increases as the deep level approaches the quantum well, and produces strong resonances at energies which do not necessarily coincide with the binding energy of the deep level or the resonant levels of the quantum well. For a very deep IPDL close to the quantum well, the resonant level of lowest energy disappears. This is similar to the theoretical results of Beltram and Capasso who observed new Bloch states within the band gap of a superlattice containing very deep IPDLs.

We have also shown that the incorporation of IPDLs in DBRT structures leads to an increase of several orders of magnitude in the width of the resonant peak when the energy of the IPDLs coincides with an energy level of the quantum well. In order to optimize the increase of Γ_r in such a structure, the IPDLs must be positioned at a critical distance from the quantum well corresponding to the appearance of three separate transmission peaks in the $T(E)$ curve (i.e., when the energy splitting due to the coupling between the three degenerate levels is larger than Γ_r). This increase in Γ_r has three interesting consequences: (a) coherent resonant tunneling is more likely since Γ_r which is increased by several orders of magnitude could become larger than Γ_c, the broadening due to collisions; (b) the tunneling time, τ_r, is reduced substantially which could increase the operation frequency of the device; and (c) the peak current density is increased by several orders of magnitude (5 in our example). The calculated PVR is also increased; however, many factors which contribute to the valley current have been neglected in this model (e.g., charge effects, phonons).

Advances in the techniques of depositing atomic planes of dopants in semiconductor layers (δ doping) suggest the possible experimental realization of such IPDL structures. Our results suggest that the incorporation of IPDL can considerably improve the characteristics of resonant tunneling devices.

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[1]T. C. L. G. Sollner, W. D. Goodhue, P. E. Tannenwald, C. D. Parker, and D. D. Peck, Appl. Phys. Lett. **43**, 588 (1983).
[2]F. Capasso, K. Mohammed, and A. Y. Cho, IEEE J. Quantum Electron. **QE-22**, 1853 (1986).
[3]M. Büttiker, IBM J. Res. Develop. **32**, 63 (1988).
[4]R. Gupta and B. K. Ridley, J. Appl. Phys. **64**, 3089 (1988).
[5]P. J. Price, Phys. Rev. B **36**, 1314 (1987).
[6]A. D. Stone and P. A. Lee, Phys. Rev. Lett. **54**, 1196 (1985).
[7]J. H. English, A. C. Gossard, H. L. Störmer, and K. W. Baldwin, Appl. Phys. Lett. **50**, 1826 (1987).
[8]See, e.g., K. Araki, J. Appl. Phys. **62**, 1059 (1987).
[9]F. Beltram and F. Capasso, Phys. Rev. B **38**, 3580 (1988).
[10]H. P. Hjalmarson, J. Vac. Sci. Technol. **21**, 524 (1982).
[11]H. P. Hjalmarson, Superlattices Microstructures **1**, 379 (1985).
[12]E. F. Schubert, J. B. Stark, B. Ullrich, and J. E. Cunningham, Appl. Phys. Lett. **52**, 1508 (1988).
[13]See, e.g., I. I. Goldman and V. D. Krivchenkov, *Problems in Quantum Mechanics* (Pergamon, New York, 1961).
[14]B. Ricco and M. Ya. Azbel, Phys. Rev. B **29**, 1970 (1984).
[15]G. Bastard, Phys. Rev. B **24**, 5693 (1981).
[16]R. Tsu and L. Esaki, Appl. Phys. Lett. **22**, 562 (1973).
[17]A. K. Ghatak, K. Thyagarajan, and M. R. Shenoy, IEEE J. Quantum Electron. **QE-24**, 1524 (1988).
[18]M. O. Vassell, J. Lee, and H. F. Lockwood, J. Appl. Phys. **54**, 5206 (1983).
[19]M. Cahay, M. McLennan, S. Datta, and M. S. Lundstrom, Appl. Phys. Lett. **50**, 612 (1987).
[20]L. I. Glazman and R. I. Shekhter, Solid State Commun. **66**, 65 (1988).
[21]N. S. Wingreen, K. W. Jacobsen, and J. W. Wilkins, Phys. Rev. Lett. **61**, 1396 (1988).
[22]S. Adachi, J. Appl. Phys. **58**, R1 (1985).
[23]Note that this is true only if the IPDL is far enough from the quantum well so that the overlap between the wave functions from the IPDL and the quantum well is negligible.
[24]C. J. Arsenault and M. Meunier, Phys. Rev. B **39**, 8739 (1989).
[25]P. J. Price, Phys. Rev. B **38**, 1994 (1988).