Effect of band mixing on hole-tunneling times in GaAs/AlAs double-barrier heterostructures

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We examine the influence of band mixing on hole-tunneling times in GaAs/AlAs double-barrier heterostructures using the eight-band effective bond-orbital model. We find that mixing of heavy-hole and light-hole states in the valence subbands can substantially reduce hole-tunneling times from the values predicted by the Kronig-Penney model, which does not account for band mixing. These results are in agreement with the experimental measurements of Jackson *et al.* [Appl. Phys. Lett. **54**, 552 (1989)], indicating that hole-tunneling times are much shorter than predicted by the Kronig-Penney model, and comparable in fact to electron-tunneling times. We also compare our calculation with an earlier phenomenological model for incorporating band-mixing effects in the calculation of hole-tunneling times.

I. INTRODUCTION

Resonant tunneling in double-barrier heterostructures (DBH) has been a subject of intense investigation since its original proposal by Tsu and Esaki.[1] Devices utilizing quantum-mechanical resonant tunneling through quasibound states in double-barrier heterostructures are of great interest in the field of high-speed electronics. An important area of application is in the fabrication of high-frequency oscillators, where double-barrier resonant-tunneling diodes oscillating at a fundamental frequency greater than 700 GHZ have recently been achieved.[2] As the performance of resonant-tunneling diodes has improved, it has become apparent that their high-frequency characteristics depend critically on the quasibound-state lifetimes.[3] A number of theoretical[4-8] and experimental[9-11] studies of quasibound-state lifetimes in double-barrier heterostructures have been reported. In a recent experiment, Jackson *et al.*[9] measured quasibound-state lifetimes by studying the decay of electron and hole populations in GaAs/AlAs double-barrier heterostructures. In this experiment, electrons and holes created in the GaAs quantum-well region by photoexcitation were assumed to relax rapidly to the lowest conduction subband and the highest valence subband, respectively, and then escape from the quantum well by tunneling through the AlAs barriers. According to the Kronig-Penney model, the highest valence subband is heavy-hole-like. The holes should therefore escape from the quantum well much more slowly than the electrons, due to the large heavy-hole mass. Surprisingly, however, in the samples studied by Jackson *et al.*,[9] the electron- and the hole-tunneling times were found to be indistinguishable. Jackson *et al.*[9] discussed effects, such as diffusion and quantum-well charging, that may conspire to make the electron and hole tunneling escape times exactly equal, but it was felt that these effects alone were not sufficient to explain the enormous discrepancy between the measured and the calculated heavy-hole tunneling times.

To explain the rapid hole-tunneling escape rates, Yu, Jackson, and McGill proposed a phenomenological model[12] based on the notion of band mixing.[13,14] It is well known that, while the zone-center quantum-well valence-subband states are purely heavy-hole-like or light-hole-like, the $\mathbf{k}_\parallel \neq 0$ states ($\mathbf{k}_\parallel$ being the component of the wave vector parallel to the heterostructure interfaces, given in units of $2\pi/a$ throughout this paper) contain mixtures of both heavy-hole and light-hole components.[13,14] The phenomenological model asserts that the mixed-hole states should have tunneling escape times that fall between the long heavy-hole-tunneling times and the short light-hole-tunneling times. When averaged over all populated $\mathbf{k}_\parallel$ states, the resulting hole-tunneling time can therefore be substantially shorter than the time predicted by the Kronig-Penney model.

The key approximation used in the phenomenological model is that $\tau(\mathbf{k}_\parallel)$, the tunneling time for a hole state with an arbitrary $\mathbf{k}_\parallel$, can be estimated from the zone-center heavy- and light-hole tunneling times $\tau^0_{\rm hh}$ and $\tau^0_{\rm lh}$ according to the amount of heavy- and light-hole character contained in the quasibound-state wave function. Since $\tau^0_{\rm hh}$ and $\tau^0_{\rm lh}$ can be computed easily due to the decoupling of the heavy-hole and light-hole bands at the zone center, this provides a relatively simple method for estimating $\tau(\mathbf{k}_\parallel)$.

In this paper we reexamine the problem by using a realistic band-structure model that correctly treats the coupling among the hole bands, the coupling of the hole bands to conduction bands, and the spin-orbit interaction. With this band-structure model, we calculate $\tau(\mathbf{k}_\parallel)$ explicitly from the widths of the transmission resonances for the double-barrier heterostructures. The purpose of this calculation is twofold: (i) to determine if the fundamental assumption of the phenomenological model, that mixed hole states have "mixed tunneling times," is valid, and (ii) to provide a more rigorous basis for the calculation of hole-tunneling times and obtain quantitatively more accurate results. In Sec. II we describe our calculation and compare it with the phenomenological model. The results are presented in Sec. III, and then summarized in Sec. IV.

II. METHODS

We discuss briefly the phenomenological model for comparison with the calculation used in this work. In the phenomenological model, the lifetime for a quasibound valence-subband state with an arbitrary $\mathbf{k}_{\parallel}$ is estimated by examining the amount of heavy-hole–light-hole mixing in its wave function. To obtain a quantitative measure of hole mixing, the quasibound-state wave function for the highest valence subband in the double-barrier structure is approximated by the bound-state wave function of the corresponding quantum-well structure (i.e., AlAs-GaAs-AlAs), given by

$$|\psi(\mathbf{k}_{\parallel},z)\rangle = \sum_m F_m(\mathbf{k}_{\parallel},z)|J,m\rangle \ , \tag{1}$$

where $\{|J,m\rangle\}$ is the 4×4 Luttinger-Kohn Hamiltonian[15] basis set, with $J=\frac{3}{2}$ and $m=-\frac{3}{2},-\frac{1}{2},\frac{1}{2}$, and $\frac{3}{2}$. $|\frac{3}{2},\pm\frac{3}{2}\rangle$ and $|\frac{3}{2},\pm\frac{1}{2}\rangle$ are the zone-center heavy-hole and light-hole states, respectively. F_m is the mth component of the hole envelope function.

In the same way that a $\mathbf{k}_{\parallel}\neq0$ quantum-well hole state can be thought of as a mixture of zone-center heavy-hole and light-hole states, the phenomenological model assumes that the tunneling rate for a $\mathbf{k}_{\parallel}\neq0$ quasibound-hole state can be considered as an average of zone-center heavy-hole and light-hole tunneling rates:

$$\frac{1}{\tau(\mathbf{k}_{\parallel})} \approx \sum_m \int |F_m(\mathbf{k}_{\parallel},z)|^2 dz \frac{1}{\tau_m^0} \ . \tag{2}$$

In the above equation $\tau_{3/2}^0$ and $\tau_{1/2}^0$ are, respectively, the zone-center heavy-hole and light-hole tunneling time; they can be calculated using simple one- and two-band models due to the decoupling of the heavy-hole state from the light-hole and conduction-band states at the zone center.

In this work, we determine the tunneling times by explicitly computing the hole transmission coefficients for the double-barrier tunnel structures. The tunneling times $\tau(\mathbf{k}_{\parallel})$ are calculated from the full width at half maximum (FWHM) of the transmission resonances using the relation

$$\tau(\mathbf{k}_{\parallel}) \approx \frac{\hbar}{\Delta E_{\mathrm{FWHM}}(\mathbf{k}_{\parallel})} \ . \tag{3}$$

To include the band-structure effects properly, we use the eight-band effective bond-orbital model,[16] which includes the heavy-hole, light-hole, and splitoff valence bands and the lowest conduction band. This model, a reformulation of Kane's eight-band $\mathbf{k}\cdot\mathbf{p}$ model[17] in the tight-binding framework, provides a realistic description of the relevant band structure needed for treating hole tunneling in double-barrier structures. Computing hole transmission coefficients using the effective bond-orbital model requires some care. It is well known that the standard transfer-matrix method[18,19] for computing transmission coefficients is numerically unstable when used in conjunction with realistic multiband band-structure models.[20] Recently, Frensley[21] pointed out that by following the approach taken by Lent and Kirkner[22] in solving the two-dimensional (2D) effective-mass Schrödinger equation for quantum waveguides, and formulating the heterostructure tunneling problem as a system of sparse linear equations, numerical stability can be achieved. For our calculation of hole transmission coefficients, we have generalized this method to multiband tight-binding models; the details are described elsewhere.[23]

For comparison with the experimental data by Jackson *et al.*,[9] we need to compute the average tunneling time for a distribution of photoexcited carriers. This is done by averaging $\tau(\mathbf{k}_{\parallel})$ over all occupied $\mathbf{k}_{\parallel}$ states. Assuming that the barriers are sufficiently thick so that the transmission resonances are much narrower than the intersubband spacing, the two-dimensional hole density in the quantum well can be written as

$$\rho^{2\mathrm{D}} = \sum_n \int \frac{d\mathbf{k}_{\parallel}}{2\pi^2}[1-f(E_n(\mathbf{k}_{\parallel}),\mu_p,T)] \ , \tag{4}$$

where n labels the valence subbands, $E_n(\mathbf{k}_{\parallel})$ is the quasibound hole state energy, μ_p is the quasi-Fermi level for holes, T is the hole population temperature (which can differ from the lattice temperature), and f is the Fermi-Dirac distribution function. The average hole-tunneling time is then obtained by averaging the hole-tunneling rates over all occupied $\mathbf{k}_{\parallel}$ states:

$$\frac{1}{\tau_p} = \frac{1}{\rho^{2\mathrm{D}}} \sum_n \int \frac{d\mathbf{k}_{\parallel}}{2\pi^2}[1-f(E_n(\mathbf{k}_{\parallel}),\mu_p,T)]\frac{1}{\tau(\mathbf{k}_{\parallel})} \ . \tag{5}$$

Typically, the hole population only occupied the highest valence subband, and the summation is taken over the highest band only.

III. RESULTS AND DISCUSSION

Figure 1 shows the hole transmission coefficients for a (001) symmetric double-barrier structure with well and barrier widths of 21 and 10 monolayers, respectively. Since both the incident and the transmitted states can be in either the light-hole or the heavy-hole band, the transmission coefficient has four components. In this figure, we present only the hh-hh (heavy hole to heavy hole) and the lh-lh (light hole to light hole) components. Results for three different values of $\mathbf{k}_{\parallel}$ are presented. For $\mathbf{k}_{\parallel}=(0,0,0)$, the hh-hh and lh-lh transmission coefficients peak at two distinct energies. Since heavy-hole and light-hole states do not couple at $\mathbf{k}_{\parallel}=0$, the $n=1$ peak is a pure heavy-hole resonance, while the $n=2$ peak is a pure light-hole resonance. At $\mathbf{k}_{\parallel}=(0.015,0,0)$, both the hh-hh and lh-lh transmission coefficients show the $n=1$ and $n=2$ resonances, indicating that, as a result of band mixing, the quasibound states associated with these resonances have both heavy-hole and light-hole characteristics. Further away from the zone center, at $\mathbf{k}_{\parallel}=(0.03,0,0)$, the hh-hh curve shows both the $n=1$ and the $n=2$ resonances, while the lh-lh curve terminates at -0.049 eV, showing only the $n=2$ resonance. The explanation is as follows: At a given $\mathbf{k}_{\parallel}$, the lh-lh transmission coefficient is obtained by considering the transmis-

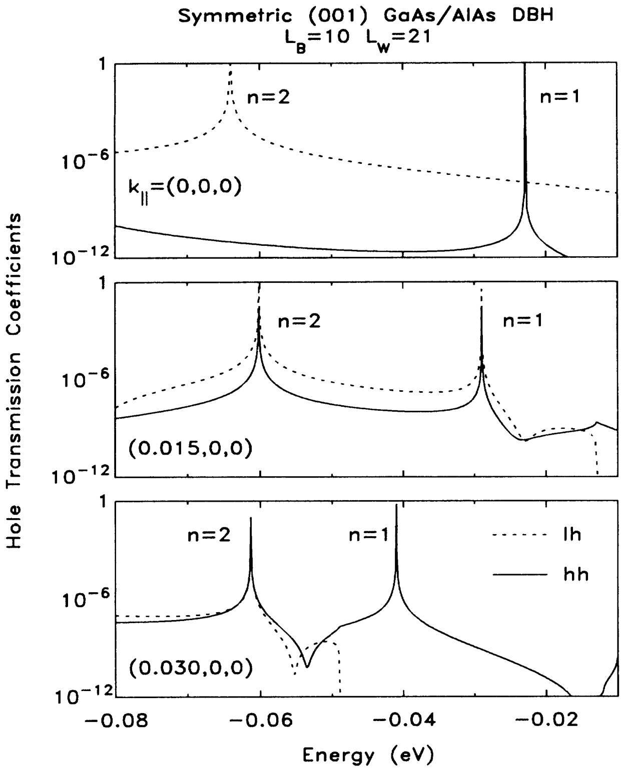

FIG. 1. Hole transmission coefficients for a (001) GaAs/AlAs symmetric double-barrier heterostructure with $L_W=21$ (monolayers) and $L_B=10$ at three $\mathbf{k}_{\|}$ values. Solid and dashed lines denote the hh-hh and lh-lh components, respectively.

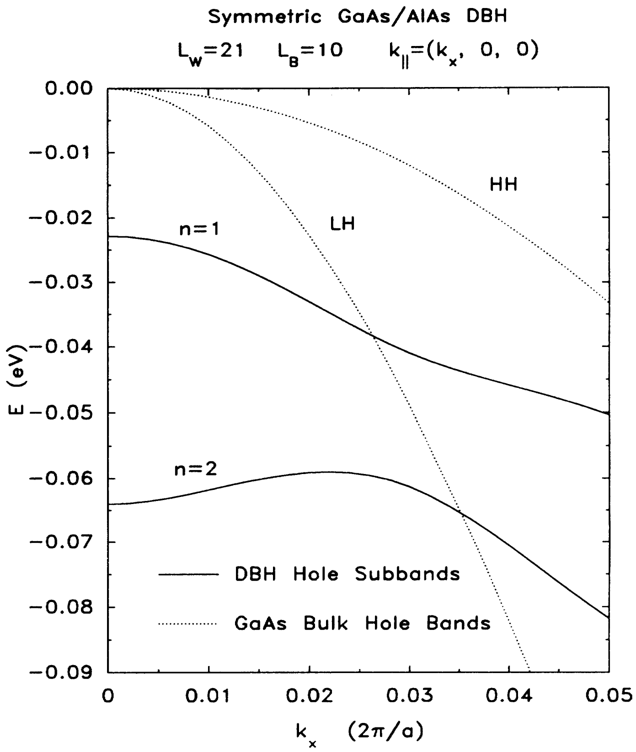

FIG. 2. Valence subband structure for a (001) GaAs/AlAs symmetric double barrier heterostructure with $L_W=21$ and $L_B=10$ (solid lines). Bulk GaAs heavy-hole and light-hole bands are also shown (dotted lines) for comparison.

sion properties of incoming light-hole states with the same $\mathbf{k}_{\|}$ in the GaAs electrode. [In this case, this means all GaAs light-hole states with $\mathbf{k}=(0.03,0,k_z)$.] Since no GaAs light-hole state with $\mathbf{k}_{\|}=(0.03,0,0)$ has energy higher than -0.049 eV, the lh-lh transmission coefficient is simply undefined for energy greater than -0.049 eV.

In Fig. 2 we plot the peak positions of the $n=1$ and $n=2$ resonances as functions of $\mathbf{k}_{\|}$ along [100]. For comparison, the GaAs bulk heavy-hole and light-hole bands are also shown. Due to band mixing, the $n=1$ and $n=2$ quasibound-state subbands are highly nonparabolic, and do not follow the same trends as either of the bulk bands (as would be the case if band mixing were not taken into consideration). In fact, the $n=1$ and $n=2$ subbands cross the bulk light-hole band at $\mathbf{k}_{\|}=$ (0.0263,0,0) and $\mathbf{k}_{\|}=$ (0.0352,0,0), respectively. The importance of these crossings will become apparent when we discuss tunneling times. Here we comment briefly on their significance. A resonance at a given $\mathbf{k}_{\|}$ is constructed from bulk states with $\mathbf{k}=\mathbf{k}_{\|}+\mathbf{k}_{\perp}$ [$\mathbf{k}_{\perp}=$ $(0,0,k_z)$ in this case]. The bulk light-hole band curve in Fig. 2 shows the energies of the $k_z=0$ states, which are the bulk GaAs light-hole states with the highest energy at each given $\mathbf{k}_{\|}$. It should be viewed as a boundary, below which lies a continuum of light-hole states that can contribute to a resonance having the same $\mathbf{k}_{\|}$, but above which no light-hole states are available. Since the resonance widths are typically very narrow in the cases under consideration, if a resonance level is above the bulk light-hole curve in Fig. 2, it cannot contain significant contributions from the light-hole states.

From the widths of the transmission resonances, we can estimate the quasibound-state lifetimes using the uncertainty principle. As seen in Fig. 1, a transmission resonance can be found in different components of the transmission coefficient. We have verified that if a resonance is seen in more than one component of the transmission coefficient, then each of the components yields the same resonance width ΔE_{FWHM}. This confirms that ΔE_{FWHM} is an intrinsic property of the quasibound-state, and does not depend on the choice of incoming and outgoing states. Figure 3 shows the quasibound-state lifetimes for the $n=1$ and $n=2$ quasibound states calculated from transmission resonance widths (solid curve). Since heavy- and light-hole states are decoupled at the zone center, the $n=1$ and $n=2$ tunneling times at $\mathbf{k}_{\|}=$ (0,0,0) represent the pure heavy- and light-hole tunneling times, respectively. The pure light-hole tunneling time is found to be more than three orders of magnitude shorter than the pure heavy-hole tunneling time—shorter, in fact, than the electron-tunneling time for the lowest conduction-band quasibound state. In sharp contrast with the Kronig-Penney model, which predicts that tunneling times are approximately independent of $\mathbf{k}_{\|}$, our calculation shows a complex $\mathbf{k}_{\|}$ dependence. Moving away from the zone center along [100], the $n=1$ subband tunneling time rapidly decreases until

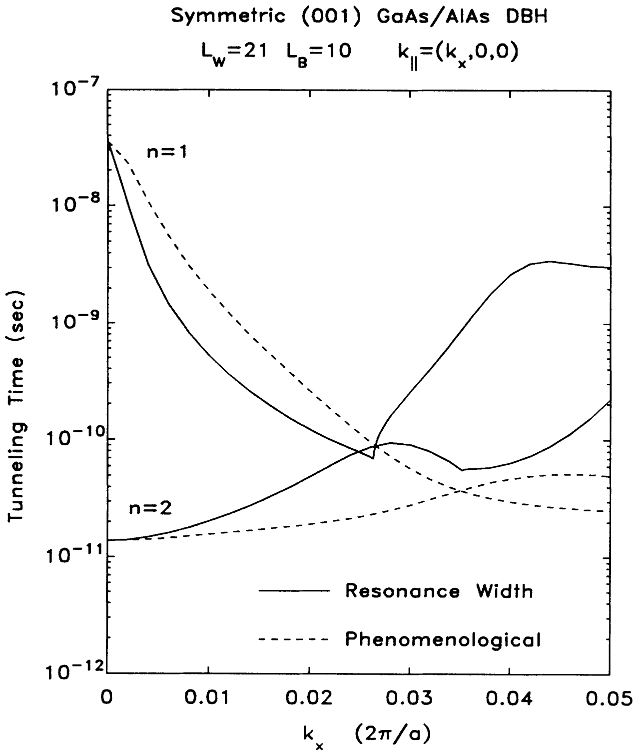

FIG. 3. Hole quasibound-state lifetimes as functions of $\mathbf{k}_{\parallel}$ along [100] for the first two hole subbands in a (001) GaAs/AlAs symmetric double-barrier heterostructure. The results from the exact calculation and from the phenomenological model are shown by solid and dashed lines, respectively.

reaching a minimum at $\mathbf{k}_{\parallel}=(0.0263,0,0)$; the trend is reversed as the tunneling time increases after the minimum. At the minimum, the tunneling time is more than 500 times shorter than the zone-center pure heavy-hole time. The $n=2$ subband tunneling time curve also exhibits large variations; it follows a generally increasing trend with $\mathbf{k}_{\parallel}$, although a local minimum is found at $\mathbf{k}_{\parallel}=(0.0352,0,0)$. We shall show that the seemingly complex behavior of the tunneling time curves is, in fact, consistent with the simple idea that resonances with more light-hole characteristics have shorter tunneling times. We focus our attention on the $n=1$ curve. The initial decreasing trend in this curve is simple to explain. At $\mathbf{k}_{\parallel}=(0,0,0)$, heavy-hole and light-hole states do not couple for symmetry reasons, and the $n=1$ resonance has a long heavy-hole-like tunneling time. With increasing $\mathbf{k}_{\parallel}$, the $n=1$ resonance gains light-hole characteristics, resulting in the shorter, more light-hole-like tunneling times. The minimum at $\mathbf{k}_{\parallel}=(0.0263,0,0)$ and the subsequent increase in the $n=1$ curve may seem puzzling at first. However, noting that the minimum occurs at exactly the same $\mathbf{k}_{\parallel}$ value where the $n=1$ subband crosses the bulk light-hole band (see Fig. 2), we are led to the following explanation. Recall that after the crossover, the $n=1$ resonance rises above the energy range of available bulk light-hole states, and does not contain significant light-hole contributions. Therefore, we can attribute the increase in tunneling time beyond $\mathbf{k}_{\parallel}=(0.0263,0,0)$ to the loss of light-hole characteristics.

We have attempted to show that tunneling times depend critically on whether the quasibound states are heavy-hole-like or light-hole-like. But thus far we have only discussed the character of the quasibound states in a very qualitative manner. Here we will try to obtain a more quantitative description. In computing transmission coefficients, we specify an incoming plane wave with a fixed energy E_{in}, and calculate the wave function to obtain the coefficients of the outgoing plane waves. In the case of resonant tunneling, the wave function in the quantum well can also reveal information about the quasibound state involved in the resonant tunneling process. We can decompose the wave function in the quantum well in terms of GaAs bulk complex band states. Let C_j^{hh} and C_j^{lh} be the coefficients of the bulk heavy-hole and light-hole band states, respectively. The relative contributions from the bulk heavy-hole and light-hole bands can be obtained by forming the following ratios:

$$f_{\text{hh}}=\frac{S_{\text{hh}}}{S_{\text{hh}}+S_{\text{lh}}}\ , \tag{6}$$

$$f_{\text{lh}}=\frac{S_{\text{lh}}}{S_{\text{hh}}+S_{\text{lh}}}=1-f_{\text{hh}}\ , \tag{7}$$

where $S_{\text{hh}}=\sum_j |C_j^{\text{hh}}|^2$ and $S_{\text{lh}}=\sum_j |C_j^{\text{lh}}|^2$. We have found that if the energy of the incoming state E_{in} is within approximately ΔE_{FWHM} of the resonance peak energy, f_{lh} and f_{hh} are insensitive to E_{in}. They are also insensitive to the type of incoming state—we obtain the same answer for both heavy-hole and light-hole incoming states. This is taken as an indication that f_{lh} measures the property of the quasibound state, and not of the incoming state. It is very important to note that the quantities f_{hh} and f_{lh} only measure the contributions from the heavy-hole and light-hole bands relative to each other, since the quantum-well wave function can contain contributions from evanescent states as well as the heavy-hole and light-hole states. Thus, $f_{\text{lh}}=0$ should not be taken to mean that the quantum-well wave function contains heavy-hole band contributions exclusively. Figure 4 shows f_{lh} for both the $n=1$ and $n=2$ resonances as functions of $\mathbf{k}_{\parallel}$ along [100]. The $n=1$ ($n=2$) subband shows no light (heavy) -hole contribution at the zone center, but becomes increasingly light (heavy) -hole-like as $\mathbf{k}_{\parallel}$ increases along [100]. Each curve show a cutoff of f_{lh} as the hole subband energy drops below the bulk GaAs light-hole band. The behavior of the f_{lh} curve are consistent with the qualitative arguments we presented earlier.

Comparing Figs. 3 and 4, it is apparent that the hole-tunneling time is strongly related to the quasibound-state composition. Specifically, quasibound states with more light-hole contributions are found to have shorter tunneling times. This result validates the fundamental assumption used in the phenomenological model, that the quasibound mixed-hole states have lifetimes that fall between the long pure heavy-hole state lifetimes and the short pure light-hole state lifetimes. To make quantitative

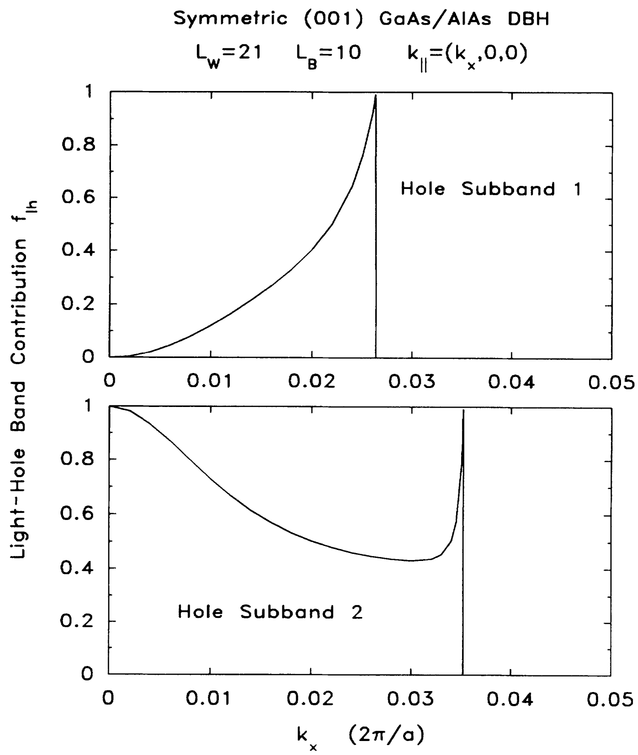

FIG. 4. The relative light-hole contribution (see text) in the wave functions of the first two hole quasibound states as functions of $\mathbf{k}_{\parallel}$ along [100].

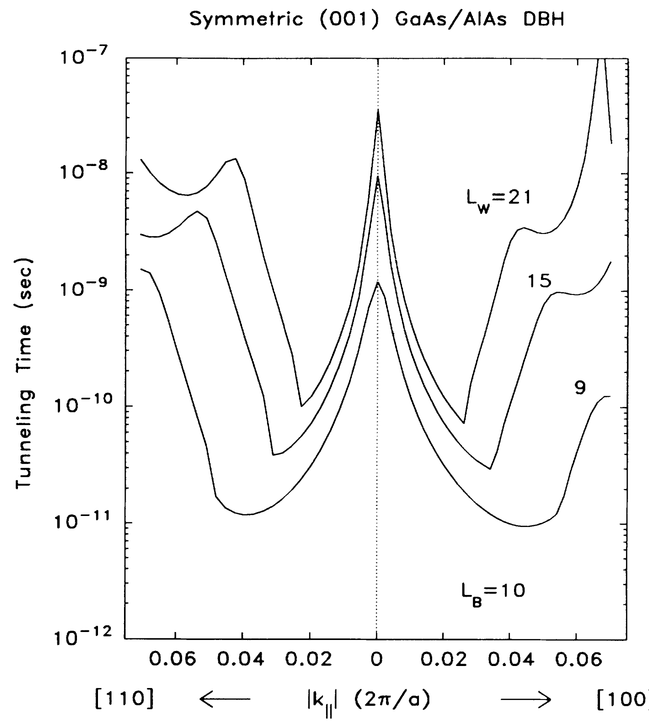

FIG. 5. Hole quasi-bound-state lifetimes for the $n=1$ subband as functions of $\mathbf{k}_{\parallel}$ along [100] and [110]. Results for well widths of 9, 15, and 21 monolayers are shown.

comparisons with the phenomenological model, hole-tunneling times calculated using Eq. (2) are also shown in Fig. 3 (dashed lines). To be consistent with our current calculation, the quantities needed for computing tunneling times in Eq. (2), such as τ_m^0 and F_m, are all taken from the eight-band effective bond-orbital-model calculation; this ensures that the results from the two calculations agree at $\mathbf{k}_{\parallel}=0$. Comparing the two calculations, we see that the phenomenological model predicts that the $n=1$ subband tunneling time decreases monotonically with k_x, while the exact results shows a minimum at $k_x = 0.0263$. This is because the phenomenological model uses the zone-center hole basis set, and does not take into account the fact that the bulk GaAs light-hole band drops below the $n=1$ hole subband beyond $k_x = 0.0263$. For $k_x < 0.0263$, the phenomenological model predicts $n=1$ ($n=2$) subband tunneling times which are longer (shorter) than the exact calculation. Since band mixing decreases the $n=1$ subband tunneling times from the pure heavy-hole tunneling time, and increases the $n=2$ tunneling times from the pure light-hole tunneling time, our results indicate that the phenomenological model underestimates the effect due to hole mixing. However, the general conclusion of the phenomenological model, that band mixing effects sharply reduce the hole-tunneling time in the first subband compared to the pure heavy-hole tunneling time, is confirmed by these calculations.

Figure 5 shows the tunneling time calculated for the $n=1$ state as function of $\mathbf{k}_{\parallel}$ along [100] and [110] for

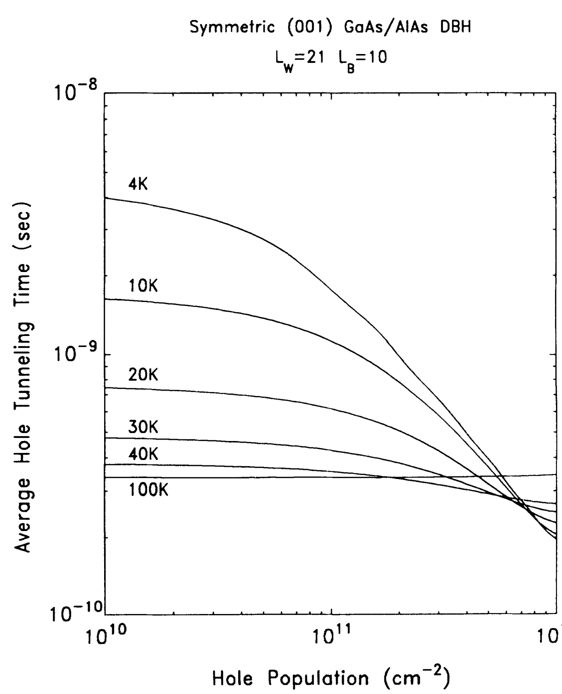

FIG. 6. Average hole-tunneling escape time for a (001) GaAs/AlAs symmetric double-barrier heterostructure as a function of 2D hole population distribution in the quantum well. The dependence on hole population and temperature is illustrated.

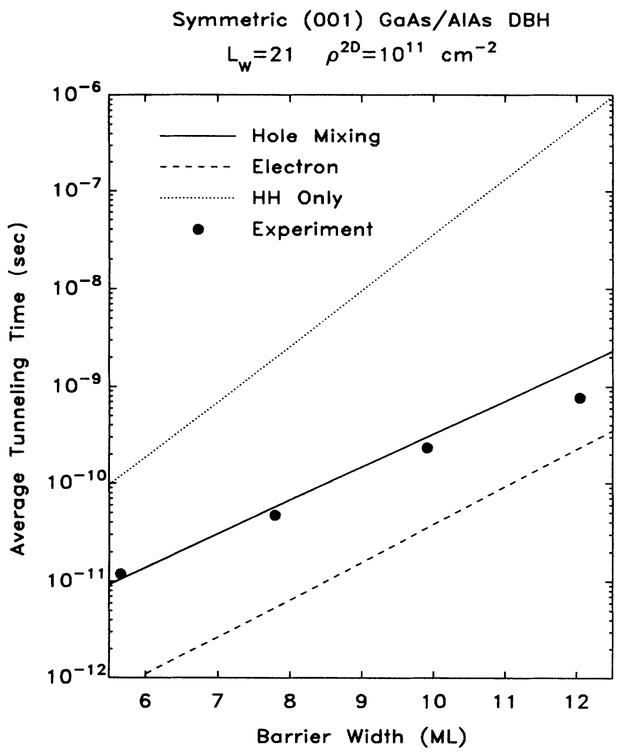

FIG. 7. Average tunneling escape time for electrons (dashed line) and holes (solid line) as functions of barrier width. Well width is 21 ML and the 2D hole density in the quantum well is 10^{11} cm^{-2}. The pure heavy-hole quasi-bound-state tunneling time is shown by the dotted line. Experimental tunneling times are shown as closed circles.

several well widths. The dependence of the hole-tunneling time on $\mathbf{k}_{\parallel}$ is found to be qualitatively similar for all well sizes, although tunneling times are shorter for narrower wells. In addition, the calculated hole-tunneling time is found to be fairly isotropic for $|\mathbf{k}_{\parallel}| \lesssim 0.03$.

In Fig. 6 we plot the average hole-tunneling time as a function of hole concentration and hole temperature. At low hole temperatures and concentrations, only the $n=1$ subband states very near the zone center are populated. Since these states are almost entirely heavy-hole-like in character, the resulting averaged tunneling time is relatively long. At higher hole temperatures or concentrations, states with more light-hole character are also occupied, leading to shorter mean hole-tunneling times. Note that at 100 K, the average hole-tunneling time actually increases slightly with increasing hole concentration due to the occupation of states with $|\mathbf{k}_{\parallel}| > 0.0263$.

Figure 7 shows the calculated average electron- and hole-tunneling times as functions of barrier width. The GaAs well width is 21 monolayers, and the 2D hole density in the quantum well is 10^{11} cm^{-2}. Experimental tunneling times taken from Jackson *et al.*[9] are also shown. Since the electron- and the hole-tunneling times were found to be indistinguishable,[9] the data points represent both electron- and hole-tunneling times. To illustrate the influence of the band-mixing effects, pure heavy-hole tunneling times are plotted for comparison. The tunneling times, as expected, are found to increase exponentially with increasing barrier width, although hole-mixing effects reduce the rate of increase in the hole-tunneling time. Comparing our calculation with the Kronig-Penney model, we find that incorporating band-mixing effects can reduce hole-tunneling times by more than two orders of magnitude, bringing them much closer to electron-tunneling times, and in much better agreement with experimental values.

IV. SUMMARY

We have examined the effect of band mixing on the average hole-tunneling times for GaAs/AlAs double-barrier heterostructures using the eight-band effective bond-orbital model, which includes the heavy-hole, light-hole, and splitoff valence bands and the lowest conduction band. The calculation shows that, at sufficiently high hole temperature or concentration, mixing of heavy-hole and light-hole states in the valence subbands can decrease the average hole-tunneling times by more than two orders of magnitude from the values predicted by the Kronig-Penney model. In agreement with reported experimental observations, our model brings the hole tunneling times much closer to the electron-tunneling times. These results support the basic conclusions of an earlier study on the same subject using a phenomenological model. However, we find that the phenomenological model underestimates the effect of band-mixing on hole-tunneling times, and fails to predict the more complex $\mathbf{k}_{\parallel}$ dependence of hole-tunneling times as seen in our calculation.

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[1]R. Tsu and L. Esaki, Appl. Phys. Lett. **22**, 562 (1973).

[2]E. R. Brown, J. R. Söderström, C. D. Parker, L. J. Mahoney, K. M. Molvar, and T. C. McGill, Appl. Phys. Lett. **58**, 2291 (1991).

[3]E. R. Brown, C. D. Parker, and T. C. L. G. Sollner, Appl. Phys. Lett. **54**, 934 (1989).

[4]M. Büttiker and R. Landauer, Phys. Rev. Lett. **49**, 1739 (1982).

[5]N. Harada and S. Kuroda, Jpn. J. Appl. Phys. **25**, L871 (1986).

[6]S. Collins, D. Lowe, and J. R. Barker, J. Phys. C **20**, 6213 (1987).

[7]H. Guo, K. Diff, G. Neofotistos, and J. D. Gunton, Appl. Phys. Lett. **53**, 131 (1988).

[8]D. Z.-Y. Ting and T. C. McGill, J. Vac. Sci. Technol. B **7**, 1031 (1989).

[9]M. K. Jackson, M. B. Johnson, D. H. Chow, T. C. McGill, and C. W. Nieh, Appl. Phys. Lett. **54**, 552 (1989).

[10]M. Tsuchiya, T. Matsusue, and H. Sakaki, Phys. Rev. Lett. **59**, 2356 (1987).
[11]J. F. Whitaker, G. A. Mourou, T. C. L. G. Sollner, and W. D. Goodhue, Appl. Phys. Lett. **53**, 385 (1988).
[12]E. T. Yu, M. K. Jackson, and T. C. McGill, Appl. Phys. Lett. **55**, 744 (1989).
[13]J. N. Schulman and Y. C. Chang, Phys. Rev. B **31**, 2056 (1985).
[14]Y. C. Chang and J. N. Schulman, Appl. Phys. Lett. **43**, 536 (1983); Phys. Rev. B **31**, 2069 (1985).
[15]J. M. Luttinger and W. Kohn, Phys. Rev. **97**, 896 (1955).
[16]Y. C. Chang, Phys. Rev. B **37**, 8215 (1988).
[17]E. O. Kane, in *Semiconductors & Semimetals,* edited by R. K. Willardson and A. C. Beer (Academic, New York, 1966), Vol. 1, p. 75.
[18]E. O. Kane, in *Tunneling Phenomena in Solids,* edited by E. Burstein and S. Lundqvist (Plenum, New York, 1969), p. 1.
[19]See, for example, J. N. Schulman and Y. C. Chang, Phys. Rev. B **27**, 2346 (1983).
[20]C. Mailhiot and D. L. Smith, Phys. Rev. B **33**, 8360 (1986).
[21]W. R. Frensley, Rev. Mod. Phys. **62**, 745 (1990); (private communication).
[22]C. S. Lent and D. J. Kirkner, J. Appl. Phys. **67**, 6353 (1990).
[23]D. Z.-Y. Ting, E. T. Yu, and T. C. McGill, Phys. Rev. B **45**, 3583 (1992).