The suppression by pressure of negative differential resistance in GaAs/GaAlAs double barrier structures

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High-pressure measurements of thermionic emission (TE) and of resonant tunneling in $Ga_{1-x}Al_xAs$/GaAs double barrier structures are reported, where $x = 1$ or 0.33. For $x = 1$, TE in a structure with a very narrow well yields a direct measurement of ~ 150 meV for the Γ-X barrier height, and a shift of ~ -11 meV/kbar. For a structure with a well width of ~ 70 Å and barriers of ~ 40 Å, negative differential resistance (NDR) is observed, which is suppressed at a pressure of ~ 8 kbar, when the height of the Γ-X barrier is approximately equal to the confinement energy of the state in the well. For $x = 0.33$, and in samples with spacer layers, the same criterion for suppression of the NDR applies as for $x = 1$. When spacer layers are absent, anomalies occur in the variation of the first NDR resonance with pressure, and for sufficiently large samples, the threshold for loss of NDR is much lower than expected. The anomalous behavior is related to the higher concentration of impurities in the barriers. The low-pressure threshold of the anomaly, and the dependence of the anomaly on sample size, suggest that impurity correlation may play a significant role in the suppression of NDR. At low pressures, or in the absence of anomalies, the pressure dependence of the peak and valley currents of all resonances which are always in the range -1% to -3%/kbar, indicates that the Γ profile controls the tunneling, through the pressure dependence of the effective mass.

I. INTRODUCTION

Negative differential resistance (NDR) in double barrier resonant tunneling devices (DBRTD) has been studied for a number of years since the effect was first proposed by Tsu and Esaki.[1] Ricco and Azbel analyzed the phenomenon in terms of the coherent interference of the electronic wave function, akin to the operation of a Fabry–Perot resonator with monochromatic light.[2] Such a model, for a device with barriers having transmission coefficients T_1 and T_2 ($T_1 < T_2$), predicts a peak transmission of $\sim T_1/T_2$, and a "valley" transmission of $\sim T_1T_2$, provided that the electron energy is not too close to the top of either barrier. A severe shortcoming of this picture of resonant tunneling devices is the requirement of monoenergetic electrons. In real devices, electrons residing in the emitter have a range of energies up to the Fermi energy. Luryi[3] showed that the resonant behavior of a device could be explained by considering the number of electrons in the emitter "Fermi sphere" which could tunnel in sequential fashion via the resonant state in the well. It was shown by Payne,[4] and by Weil and Vinter[5] that this picture is equivalent to the "coherent" picture when the transmission coefficient for the device is integrated over a range of incident electron energies up to the Fermi energy of the emitter.

In DBRTDs based on GaAs/$Ga_{1-x}Al_xAs$ it has been observed that NDR can be suppressed in some cases by the application of hydrostatic pressures below 10 kbar.[6–8] These results strongly suggest the involvement of the barrier associated with the offset between the Γ edge in GaAs and the X edge in $Ga_{1-x}Al_xAs$. The relative alignments of the various band edges in GaAs and AlAs are shown in Fig. 1, based on the data of Ref. 9 and assuming a Γ-Γ offset ratio of 60:40.[10,11] It can be seen from the figure that the lowest barrier is indeed Γ-X (0.1–0.3 eV, for choices of offset ratio between 60:40 and 70:30), and since the Γ-Γ offset has been shown to be essentially independent of pressure,[10] the Γ-X barrier is expected from the data of Adachi[9] to fall at the rate

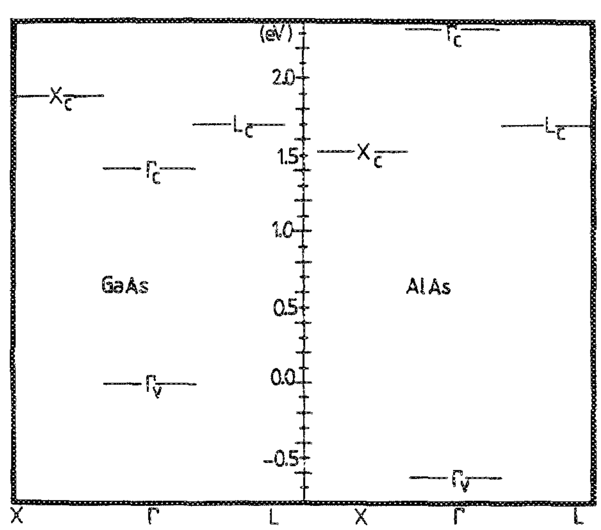

FIG. 1. Relative positions of the Γ-, X-, and L-band extrema in GaAs and AlAs assuming a 60:40 band offset ratio, and the band gaps given in Ref. 9.

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of ~11 meV/kbar. In contrast, the Γ-Γ and the Γ-L barriers are much larger, with the latter expected to fall at the rate of ~8 meV/kbar.

In this work, we attempt an improved characterization of the influence of pressure on the peak and valley currents in DBRTDs based on GaAs/$Ga_{1-x}Al_xAs$, and in particular to study the role of barrier composition. Our results are complementary to the results of Mendez and co-workers.[8] who have investigated the role of well and barrier dimensions on GaAs/AlAs DBRTDs, and found a rapid decrease of pressure threshold for wider barriers and narrower wells. We also report a direct measurement of the Γ-X barrier height for AlAs barriers, and its variation with pressure, from thermionic emission studies.

The GaAs/AlAs structures were grown by atmospheric pressure MOCVD using methyl metalorganic sources and silicon-doped (100) GaAs wafers misoriented by 3° towards (110). A 1.0-μm-thick buffer layer of GaAs *n*-doped to $\sim 2\times 10^{17}$ cm^{-3} was grown first. The sequence of growth was then a further 25 Å of undoped GaAs (spacer layer), the first AlAs barrier, the GaAs well, the second AlAs barrier, a second 25 Å spacer layer, and 2.0 μm of GaAs, *n*-doped to $\sim 2\times 10^{17}$ cm^{-3}. Two different structures were prepared in this way in consecutive growth runs, the first (sample A) with dimensions of barrier-well-barrier (checked by TEM[12]) of 45 Å-15 Å-50 Å, and the second (sample B) with dimensions of 43 Å-72 Å-40 Å. These were fabricated into 200-μm-diam mesa devices with ohmic contacts attached to the top and substrate.

The GaAs/$Ga_{0.67}Al_{0.33}As$ devices (samples C1, C2, and D) were grown by molecular-beam epitaxy and are essentially identical in design to the others, except in the well and barrier region. For C1 and C2 the well and barrier widths are nominally 68 and 85 Å, respectively, and no spacer layers were included. For D, the well and barrier widths are nominally 79 and 85 Å, and spacer layers of undoped GaAs, 102 Å thick, were grown between each barrier and the emitter or the collector. These structures were fabricated into 400- (C1), 200- (D) or 100-μm- (C2) diam devices.

High pressures were applied with a Unipress ($P<10$ kbar) or a homemade teflon sheath ($P<20$ kbar) piston and cylinder cell, using petroleum spirit as the hydrostatic medium and using a degenerate InSb manometer, with an accuracy of better than 1 kbar at all temperatures. Full details of the high-pressure techniques are given elsewhere.[7,13]

We first consider the thermionic emission measurements. This is followed by a discussion of the results for AlAs and $Ga_{0.67}Al_{0.33}As$ barriers, respectively.

II. THERMIONIC EMISSION

Sample A showed no sign of NDR whatsoever in its current voltage (*I-V*) characteristic, or in the first derivative characteristic $dI/dV - V$. Simple effective mass calculations yield an energy for the first quasi-bound state of ~0.43 eV for Γ-Γ barriers ($m^*_{\rm GaAs} = 0.067$ m$_e$, $m^*_{\rm AlAs} = 0.15$ m$_e$), and ~0.057 eV for Γ-X barriers ($m^*_{\rm GaAs} = 0.067$ m$_e$, $m^*_{\rm AlAs} = 1.9$ m$_e$). The total absence of NDR suggests, not surprisingly, that Γ-Γ is more appropriate for determining the resonant states, and that these must lie above the top of the Γ-X barriers. Measurements of current, at a fixed voltage (greater than k_BT/e), as a function of temperature, therefore allow a determination of the Γ-X barrier height according to the Richardson formula: $J/T^2 = A^* \exp[-e\phi_B/k_BT]$, where A^* depends only on fundamental constants and the effective mass of the barrier material.[14] Results for the barrier height as a function of bias voltage and pressure are shown in Fig. 2, and were determined from Arrhenius plots between 300 and 150 K. Note that a pressure change of ~1 kbar occurred over the measured temperature range, so the results for 5 kbar, which was the average pressure over the range, are only approximate. Hase *et al.*[15] show that the actual barrier height is typically about 30 meV greater than that estimated from similar thermionic emission measurements, because when carriers are thermally excited close to the top of the barrier, they are then able to tunnel efficiently. Thus the actual barrier height is approximately 0.15 eV at 1 bar and 0.095 eV at 5 kbar. The rapid fall of barrier height with bias is due to electron accumulation and band bending. One apparent inconsistency is the values of the Richardson constant which were all in the range between 3 and 9 A m^{-2} K^{-2} (there does not appear to be a strong variation of the Richardson constant with bias[7]), approximately four orders of magnitude smaller than the value predicted by the Richardson formula. The reason is almost certainly due to the change from Γ to X character as the electrons traverse the barrier. Our result is consistent with thermionic emission measurements of Solomon, Wright, and Lanza[16] on a $Ga_{0.2}Al_{0.8}As$ barrier, where a value of 400 A m^{-2} K^{-2} was reported, and where by extrapolation, a value of about 10 A m^{-2} K^{-2} is to be expected for an AlAs barrier.

The size of the barrier and its pressure shift are the first direct measurements for a barrier formed between GaAs and AlAs. The results, when compared with Fig. 1, are consistent with a Γ-Γ conduction-band offset of about 63%, which is independent of pressure. These conclusions are also in good agreement with the results of photoluminescence mea-

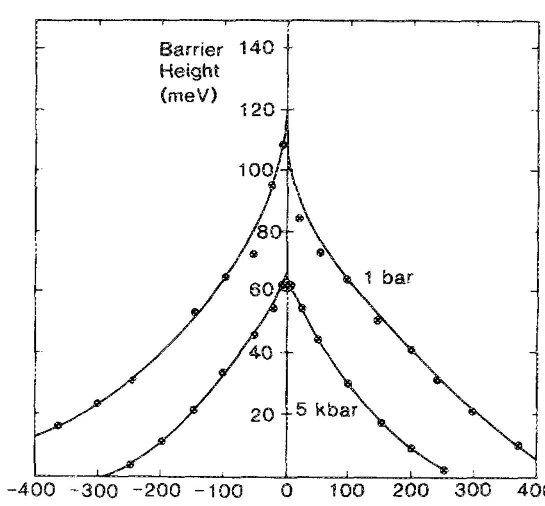

FIG. 2. Barrier height determined from thermionic emission measurements on a 45 Å-15 Å-50 Å GaAs/AlAs structure, as a function of bias and pressure.

surements by Wolford *et al.*,[10] who deduced the band offset and its pressure independence by observing the type-I to type-II transition pressures of a number of superlattices. In what follows, we show that the observed Γ-X barrier height and its pressure variation are consistent with the pressure threshold for loss of NDR in the 43 Å-72 Å-40 Å GaAs/AlAs device.

III. SUPPRESSION OF NDR IN GaAs/AlAs DBRTD

Sample B exhibited a peak-to-valley ratio at 4.2 K of 9.8 in the forward direction (thinner barrier positive with respect to the thicker barrier) and 14.9 in the reverse direction. The asymmetry is consistent with the theory of Ricco and Azbel,[2] but could also be influenced by slight differences in the doping of the n^+ layers, which were measured with a Polaron plotter to be 1.4×10^{17} cm^{-3} near the thinner barrier and 1.7×10^{17} cm^{-3} near the thicker. In forward bias, a second weak resonance is observed at 4.8 V and 1 A (measured with a pulsed voltage source).

The effect of pressure on the characteristic is shown in Fig. 3, for pressures of 1 bar and 5 kbar. The suppression of the size of the resonance with pressure can clearly be observed. Note that the 1-bar characteristic shows complex structure in the NDR region, while this is absent in the other case. Such complex structure has been shown to be related to spontaneous oscillation of the circuit due to stray inductance, and can be suppressed by connecting a large capacitance in parallel with the device.[17] The true characteristic should thus look like that indicated by a dashed line in Fig. 3(a). Oscillation will take place in the circuit between voltages V_{peak} and V_0, where V_{peak} is the voltage of the resonance (i.e., the current peak) and V_0 is the voltage above the resonance where the slope of the true *I-V* curve starts to increase significantly above zero. In Fig. 3(b), it can be seen that V_0 is only slightly above V_{peak}, so no complex behavior is observed and the resonance has a shape close to that expected from theory.[18] We have been unable to observe the true characteristic in Fig. 3(a) because the magnitude of the negative resistance is small for GaAs/AlAs structures and a larger value capacitor than is practical would be needed. The above considerations show, however, that even in the absence of a suitable capacitor, measurements of the peak and valley currents will be very close to the true values, because as soon as the current starts to rise with increasing voltage above the resonance, the oscillations will stop.

The peak and valley currents measured at 77 K are plotted against pressure in Fig. 4. (Both show only a weak temperature dependence below 77 K[7]). The main effect of pressure is to cause a large increase of the valley current. The peak current exhibits a much weaker pressure dependence, rising only slightly in reverse bias and a little faster in forward bias. In both cases, the resonance is almost entirely lost by 8 kbar. If we assume that the energy of the resonant state in the well is determined by the Γ-Γ profile, then a confinement energy of 65 meV is obtained. For the barrier height and shift determined above, 150 meV and − 11 meV/kbar respectively, the pressure threshold of 8 kbar would correspond almost exactly to alignment of the top of the Γ-X barrier with the confined state.

Recent results on related GaAs/AlAs structures by Mendez and co-workers (referred to hereafter as MCW)[8] confirm the greater sensitivity to pressure of the valley current compared to the peak current, and demonstrate a threshold for loss of NDR close to 10 kbar for a nominally 23 Å-60 Å-23 Å structure, a result consistent with our own, particularly in view of significant uncertainties in layer thicknesses. However, for a 40 Å-50 Å-40 Å structure, a threshold of only ~2 kbar was reported.[8] The narrower well and wider barriers would give rise to a significantly higher confinement energy in the well, but this effect alone would be unlikely to be the sole cause of such a large reduction in the pressure threshold, unless the well were considerably narrower than the figure quoted. Perhaps the larger confinement energies of the X-like states in narrower barriers may also play an important role. The explanation proposed by MCW is in terms of a larger X contribution to the current in

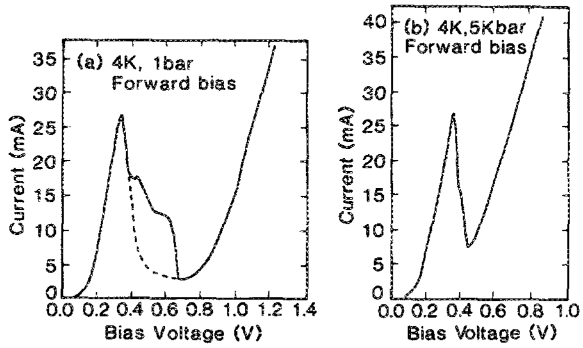

FIG. 3. The *I-V* characteristic (forward bias) at 4.2 K of a 43 Å-72 Å-40 Å GaAs/AlAs DBRTD at a pressure of (a) 1 bar, and (b) 5 kbar. In (a) the dashed line indicates the form of the expected characteristic in the absence of circuit oscillations.

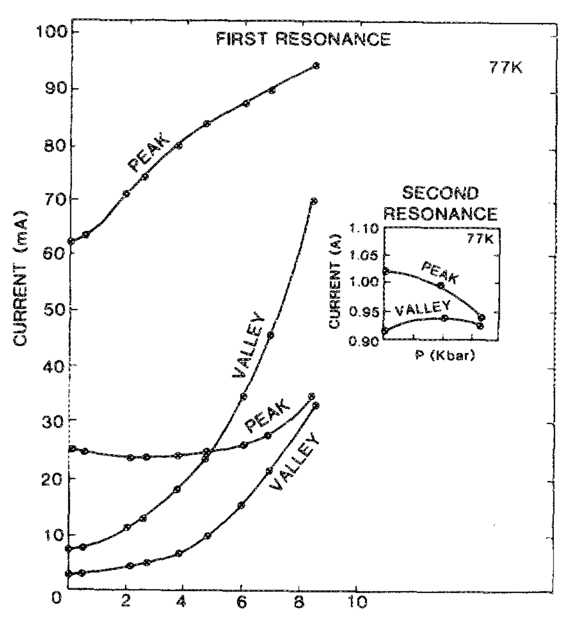

FIG. 4. The peak and valley currents at the first resonance for a 43 Å-72 Å-40 Å GaAs/AlAs DBRTD (sample B) in forward and reverse biases at 77 K as a function of pressure. The smaller peak and valley currents are for forward bias. (Inset: second resonance. 0–4 kbar.)

structures with wider AlAs barriers, compared to the Γ contribution. This mechanism only operates if the low effective mass is invoked, of the four X minima lying in the plane of the layers, in which case inelastic processes will destroy the resonance. This may well be the case for the GaAs/AlAs resonance. This may well be the case for the GaAs/AlAs structures. However, in the case of GaAs/$Ga_{0.67}Al_{0.33}As$ structures, the Γ-X barrier is greater than the Γ-Γ barrier. The inelastic processes of Mendez and co-workers would be expected to play a minor role, unless pressures in excess of 20 kbar are applied, at which point the product of barrier height (relative to the first confined state) and effective mass for Γ-Γ and Γ-X would be comparable (see Fig. 7). This product determines the value of the decay length of a wave function propagating in the barrier. The decay lengths for X-like and Γ-like states in the barrier would thus only be comparable above ~20 kbar. We have therefore investigated such structures, and observe that in some cases the first resonance can be suppressed considerably below 20 kbar. Thus a mechanism different to that found by MCW must control the suppression in this case.

IV. SUPPRESSION OF NDR IN GaAs/$Ga_{0.67}Al_{0.33}As$ DBRTD

Samples C1 and C2 exhibited a strong first resonance with a peak-to-valley ratio of 9 at 77 K, and a weaker second resonance at higher voltage with a ratio at 77 K of 1.3. The appearance of all resonances at all pressures was very similar to the form shown in Fig. 3(b), with a near vertical drop in current immediately after the resonance, and no evidence for hysteretic, or "complex," behavior, in contrast to Fig. 3(a). The pressure dependencies of the peak and valley currents for sample C1 are shown in Fig. 5 and 6 for the first and second resonances, respectively. For C2, the behavior of the second resonance with pressure was identical to that of C1. However, the behavior of the first resonance was different for the two samples, so data for C2 are also included in Fig. 5. In Fig. 5, the smaller current values for C2 are a consequence of the smaller mesa size.

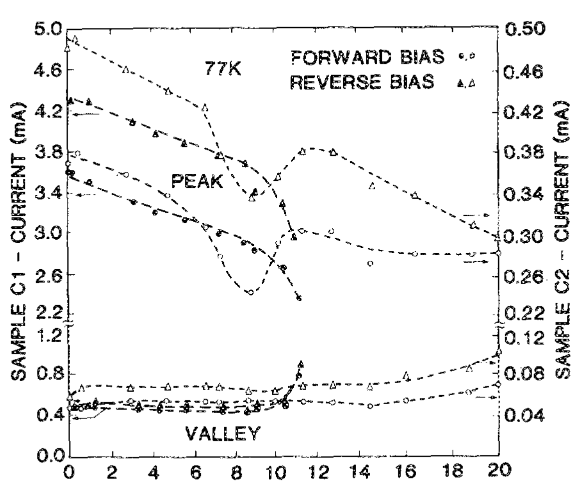

FIG. 5. The peak and valley currents at the first resonance for a 400-μm- (sample C1: solid symbols) and a 100-μm- (sample C2: open symbols) diam mesa of an 85 Å-68 Å-85 Å GaAs/$Ga_{0.67}Al_{0.33}As$ DBRTD, in forward (dots) and reverse (triangles) biases at 77 K as a function of pressure.

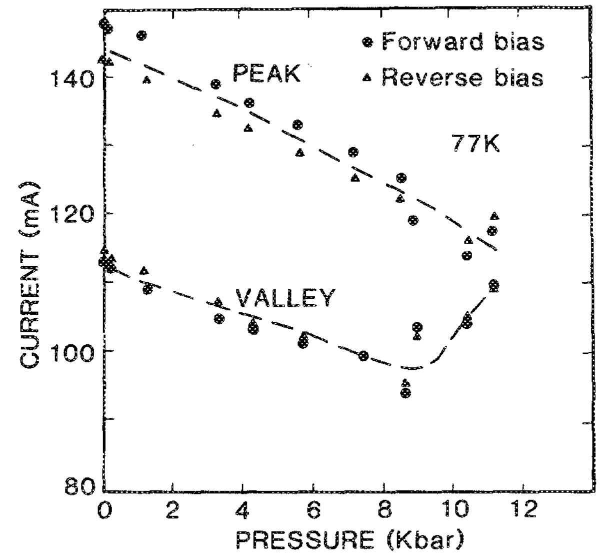

FIG. 6. The peak and valley currents at the second resonance for a 85 Å-68 Å-85 Å GaAs/$Ga_{0.67}Al_{0.33}As$ DBRTD (sample C1), in forward and reverse biases at 77 K as a function of pressure.

The pressure behavior for samples with alloy barriers is clearly quite different to that for samples with binary barriers. Below 8 kbar, both resonances show a decrease of peak current with pressure, at the rate of ~ −3%/kbar and ~ −2%/kbar for the first and second resonances, respectively. The valley currents also show similar decreases, at the rate of ~ −2%/kbar in each case. For C1 above 10 kbar, in contrast to the weak variations at lower pressures, both resonances show much stronger effects. For both resonances, the peak current falls, and the valley current undergoes a rapid increase, with a threshold for complete suppression of ~12 kbar in each case. This threshold is surprising, particularly for the first resonance, in view of the discussions above in terms of Γ-Γ and Γ-X barriers, where a threshold in excess of 20 kbar would be expected for the first resonance. The relative alignment of the Γ and X edges, and of the Γ confined state, is shown in Fig. 7, at 1 bar and 12 kbar, based on a Γ-Γ conduction-band offset ratio of 60% and on the energies and pressure shifts given in Ref. 9. The pressure shift of −11 meV/kbar used for the Γ-X barrier, is in agreement with the thermionic emission measurements described above for the Γ-X barrier in AlAs. The positions of the L minima are also marked at 1 bar. Since the X minima rapidly fall beneath the L minima in the $Ga_{0.67}Al_{0.33}As$ barriers for pressures above 10 kbar, the L minima are not thought to play a major role in the pressure threshold for loss of NDR and are not considered further. It can be seen from the figure for the situation at 12 kbar, that while the Γ-X barrier height is small relative to the second level in the GaAs well, and is not inconsistent with the pressure threshold for loss of NDR for the second resonance (bearing in mind that some uncertainties exist in the exact values to use to construct Fig. 7), the same cannot be said for the first resonance, where the Γ-X barrier height is still considerably larger than that for GaAs/AlAs samples at 1 bar which show excellent resonances as demonstrated above. The result of such a low threshold as ~12 kbar for the first resonance is therefore

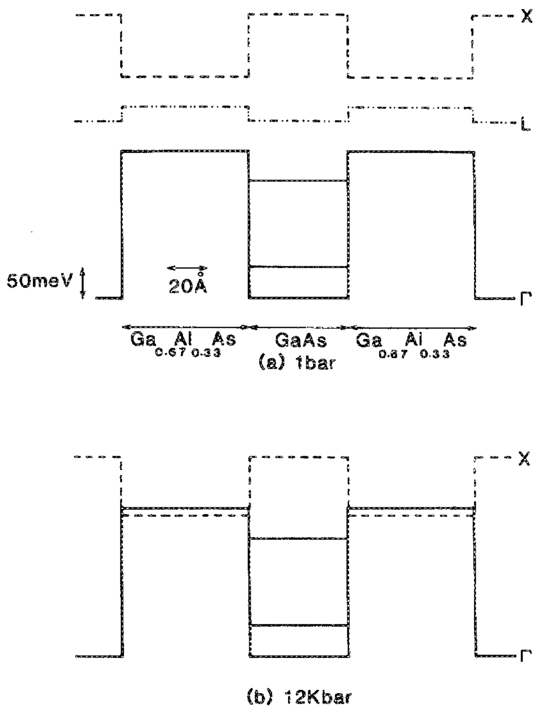

FIG. 7. The Γ-and X-band profiles for the 85 Å-68 Å-85 Å DBRTD (a) at 1 bar, and (b) at 12 kbar, as determined from the data of Ref. 9, and assuming a pressure-independent band offset ratio of 60:40.

most surprising. It should also be pointed out that Mendez and co-workers[6] observed a single resonant state in a 100 Å-40 Å-100 Å GaAs/$Ga_{0.6}Al_{0.4}As$ DBRTD in which NDR at 77 K was suppressed at a pressure of ~ 11 kbar. A lower threshold (~ 22 kbar) would be expected for this sample compared with ours because of the larger confinement energy associated with the narrower well, but the observed value is still too low.

One possibility which should be considered to explain the low threshold pressure for loss of the first NDR resonance in the GaAs/$Ga_{0.67}Al_{0.33}As$ DBRTD is the existence of deep levels probably associated with the X minima, which could align with the first energy level in the GaAs well at lower presures than that required for alignment between this level and the X minima themselves. Perhaps a small number of such centers might have considerably more influence on the first resonance than on the second, due to the much smaller current flowing. Evidence for the involvement of such levels has already been observed for GaAs/AlAs DBRTDs,[7] where it was found that such effects could lead to a decrease of the peak-to-valley ratio, but the pressure threshold for loss of NDR was relatively unaffected. However, in the present case the current density is about 50 times smaller, so the pressure threshold may be far more sensitive to impurities.

In contrast to C1, the first resonance in C2 and D was not suppressed up to the highest pressure (20 kbar) that could be applied. The variation of the peak and valley currents of D are not shown because the curves are very similar to those for C2, but without the dip in the peak current at ~ 8 kbar. For D, the peak current decreased steadily up to 18 kbar at the rate of $\sim -1.8\%$/kbar and $\sim -2.1\%$/kbar for the first and second resonance, respectively. The corresponding changes for the valley currents were $\sim -0.7\%$/kbar (reverse bias) and $\sim -2.0\%$/kbar (forward bias) for the first resonance, and $\sim -1.7\%$/kbar for the second. Both resonances were still observable at 18 kbar, with 77 K peak-to-valley ratios of 4.3 and 1.06, respectively. The second resonance is almost suppressed at 18 kbar. This higher threshold is related to the wider well which lowers the confinement energy by ~ 30 meV relative to the C samples. The rapid loss of the second resonance in the C samples above 12 kbar suggests that for these samples, this threshold might be slightly anomalous; by comparison with D, a threshold of ~ 15 kbar might be expected.

The difference between C1 and C2 is that the samples were processed from different parts of the same wafer, and the mesa for C2 is approximately one tenth of the area of C1 (judging by the ratio of the currents). If the effect described above is correctly ascribed to impurities in the barriers, it is possible that the concentration of impurities in the barriers of C2 is less than a critical amount to suppress the first NDR resonance, and a dip in the peak-to-valley ratio is seen instead of a complete loss of NDR, as some band of levels associated with impurities in the barrier comes into resonance with the Γ-confined state in the well. As the peak in the density of states for the band moves down further with pressure, the resonance appears to recover. Reference to Fig. 7 suggests that this peak would have to be about 200 meV below the X edge in the alloy. The chemical independent effective mass approximation gives a typical binding energy in $Ga_{1-x}Al_xAs$ of ~ 40 meV for an X-related impurity level.[19,20] Chemical (central cell) effects for a silicon impurity could increase this value by up to a factor of two (e.g., Theis reports a value of 75 meV for the lowest silicon hydrogenic level),[21] but would be most unlikely to cause deepening of the energy to ~ 200 meV. However, an effect such as pair correlations of the impurities might cause the necessary deepening (confinement effects might also play a small role, although the diameter of the wave function is only expected to be about 20 Å, which is somewhat smaller than the alloy layer width). Indeed, Henning, Ansems, and Roksnoer[22] observe a level about 200 meV below the X-band edge in Si-doped $Ga_{0.67}Al_{0.33}As$. The fact that this level has only been observed by photoluminescence measurements, and has not been reported in electrical studies, may be an indication that its concentration is significantly less than the total concentration of silicon atoms. Silicon is the impurity most likely to be present, because no spacer was included in the growth of samples C. On the other hand, large spacers were included for sample D; this is consistent with there being no anomalous behavior in the pressure variation of peak and valley currents in D. The presence of the spacer will ensure that far fewer silicon atoms, used to dope the emitter and collector, diffuse into the alloy layers during growth.

It is interesting to estimate the number of impurities in the barrier for the C samples. If we assume that the silicon concentration in the barrier is about 1 order of magnitude down on its value in the emitter and collector layers, then for C2 there will be about 10^6 impurities in each barrier. If a single impurity can create a significant leakage path to shortcircuit the NDR at ~ 12 kbar, it is hard to understand why the anomaly is much stronger in C1, which is only about 10 times the area of C2. However, if some form of correlation of impurity positions in the barrier is necessary to destroy the effect of the barrier, perhaps pairing as suggested above, then it becomes easier to understand why such a marked difference in behavior exists for the two samples. For example, if we assume that only those pairs for which their wave functions overlap have a significant effect, i.e., impurities with nearest-neighbor distances of less than 20 Å, then for C2 less than 100 pairs will fulfill this criterion (calculated using the standard Poisson distribution). With such a small number of significant impurity centers, perhaps it is easier to understand why the anomaly in C1 is much stronger than in C2. Recent measurements on InP/InGaAs DBRTDs have shown that a relatively larger number of impurities are needed in the barriers before anomalous behavior is observed; 50-μm-diam mesas show close to ideal behavior, while 150-μm-mesas show anomalous behavior.[23]

While the mechanism for the NDR anomalies of the C samples remains an open question, the pressure coefficients for the peak and valley currents below 8 kbar for the C samples, and over the full range of 18 kbar for sample D, can be explained in terms of the increase in the Γ effective mass with pressure, as has been done previously for nonresonant tunneling through single barriers.[24] It would suggest that in this regime, the resonance is determined purely by the Γ conduction-band profile. From the theory of Payne,[4,18] and using the approximations of Ricco and Azbel,[2] we expect the valley current I_v to be proportional to T_1T_2, while the peak current I_p, will vary as $(T_1/T_2)\times N$ where N is the number of "channels" in the emitter contact which are in resonance with the state in the well. We use the term "channels" to mean the number of states in the Fermi surface of the emitter with energy and wave vector equal to those of the two-dimensional confined states in the well. Only these states can contribute to the current. If we assume no significant band bending in the emitter, then N is proportional to the volume of an equatorial slab of the Fermi surface whose width is equal to the width of the state in the well, i.e., $N\propto(\delta E/E_F)^{1/2}$. The width of the state in the well may be homogeneous, in which case $\delta E\propto T_2$, or inhomogeneous, in which case $\delta E=$ constant. Alternatively, if we allow for band bending in the emitter, then a two-dimensional electron gas will form at an accumulation layer in front of the first barrier. In this case, N will again be a constant. We can therefore write: $N\propto T_2^{\epsilon}$ where $0<\epsilon<0.5$. Thus the peak current will vary as T_1/T_2^{σ} where $0.5<\sigma<1$. Since for each resonance, the energy of the resonant level is significantly below the top of the Γ barrier, we can write the transmissions[2] as $T_i\sim\exp(-2K_ia)$, in which a is the width of each barrier, $K_i=\sqrt{(2m^*V_i)}/\hbar$, and m^* and V_i are the effective mass and height of the barrier, where the height is measured relative to the energy of the electrons in the emitter contact, and for simplicity the barrier is treated as square and of "average" height.

To start with, let us consider the second resonance. In this case, close to resonance we can write $K_2\ll K_1$ so $I_p\propto\exp(-2K_1a)$ and $I_v\propto\exp(-2K_1a)$. Thus on differentiating we have, for both currents,

$$d\ln I_{p,v}/dP\sim -K_1a[(d\ln m^*/dP)+(d\ln V_1/dP)]\,. \quad (1)$$

Considering the Γ-Γ barrier, the second term takes a value[9] of approximately -0.1%/kbar, for a square barrier of height 0.25 eV. Since the second resonance occurs at a large voltage, such that the first barrier is almost triangular, perhaps a value of -0.2%/kbar would be more appropriate, since the average barrier height is about half its value in zero field. These values are assuming that the band offset ratio is entirely independent of pressure. Even a very weak pressure dependence of this ratio could change the value and even the sign of the second term. However the dominant contribution in Eq. (1) is clearly from the first term, which has a value of 0.62%/kbar for GaAs,[25,26] so a similar value can be expected for $Ga_{0.67}Al_{0.33}As$. For a barrier height of 0.25 eV, an effective mass in the barrier of 0.084, and a barrier width of 85 Å, we find a value $(K_1a)\sim 6.3$. Substituting this value into Eq. (1), a variation for the peak and valley currents is predicted of -2.6%/kbar, which compares reasonably well with the observed values which all lie within the range 2%–3%/kbar. Any discrepancy can easily be accounted for by the uncertainty discussed above for the value of the second term. While the foregoing analysis is simple, and does not take into full account the triangular nature of the top of the barrier, the order of magnitude of the predicted pressure dependencies of peak and valley currents does provide strong support for the dominant role of the Γ-Γ barriers in the second resonance.

Considering now the first resonance, the values of K_1 and K_2 are more closely comparable than for the case of the second resonance. However the value of the peak current depends more strongly on T_1 than on T_2, depending on the mechanism and hence on the value of σ as discussed above. The larger the value of σ, the weaker the pressure dependence. Against this is the effect of the second term in Eq. (1), which for the first resonance will be several times smaller than for the second, due to the smaller confinement energy of the first resonance. A decrease of this term could markedly increase the size of the pressure dependence. The fact that the peak current shows a decrease and exhibits a pressure dependence fairly similar to that observed for the second resonance is therefore to be expected. For the valley current, a variation of between -0.7% and -2%/kbar has been observed in every case. Since the valley current depends on the product T_1T_2, and since the value of the second term in Eq. (1) is now quite small compared to the value of the first, perhaps a slightly larger value for the pressure dependence of the valley current equal to $-(0.0062\text{–}0.001)\times 6.3\times 2=-6.5\%$/kbar is to be expected. However, since the valley current for the first resonance is so small, our observed value for its pressure dependence will be particularly sensitive to any extrinsic or leakage currents with a very weak pressure dependence, and these could possible account for the discrepancy.

We have shown above that the decrease of the peak and valley currents in the low-pressure regime for samples without spacers, and across the full pressure range for those with spacers, is quite consistent with a resonance determined by a

Γ-Γ band profile in a $GaAs/Ga_{0.67}Al_{0.33}As$ DBRTD, and is in contrast to the more complex behavior in GaAs/AlAs devices, where peak and valley currents increase with pressure over the whole pressure range.

V. SUMMARY

We have used thermionic emission measurements as a function of pressure to determine directly the value of the barrier height, and its variation with pressure of ~ 0.15 eV and ~ -11 meV/kbar, in a GaAs/AlAs device. The low values of the Richardson constant (~ 3–9 A m^{-2} K^{-2}) are consistent with a transfer from Γ to X character as the barrier is crossed, and are a measure of the inefficiency of this transfer process. The values of barrier height and shift are also indicative of a Γ-X barrier, and are consistent with a pressure-independent band offset ratio of $\sim 63:37$. They are also consistent with the threshold observed for loss of NDR in GaAs/AlAs DBRDTs, which occurs when the state in the well and the top of the Γ-X barrier are approximately degenerate. The exact value for the threshold however has been shown to exhibit a significant dependence on well and barrier widths,[8] and merits further investigation.

For $GaAs/Ga_{0.67}Al_{0.33}As$ DBRTDs, grown without spacer layers, the behavior can be divided into two regimes. In the low-pressure regime, the peak and valley currents decrease slightly with pressure, behavior which has been shown to be consistent with a Γ-Γ band profile which must therefore control the resonance in this regime. In the high-pressure regime, however (above 10 kbar), a much more rapid variation of peak and valley currents is observed, with a threshold for loss of NDR close to 12 kbar for the second resonance. The first resonance also shows a total loss of NDR in one case at ~ 12 kbar, and a partial loss of NDR and subsequent recovery at ~ 8 kbar in the other case. While the threshold for the second resonance can be understood in terms of the proximity in energy of the state in the well and the top of the Γ-X barrier, as for the main resonance in the GaAs/AlAs device, the anomalous behavior of the first resonance is surprising, since the Γ-X barrier heights at the 8 or 12 kbar pressures of the anomalies are larger than in the GaAs/AlAs devices at 1 bar. These anomalies may be related to the involvement of deep impurity levels. A binding energy of about 200 meV with respect to the X minima is predicted, a value which is not too unreasonable, and from the dependence of the strength of the anomaly on mesa size, may perhaps be related to correlated impurity complexes. The contrast between anomalous behavior for the samples grown without spacer layers, and the well-behaved samples grown with such layers, is thought to arise through the role of the spacer layers in preventing a sizable concentration of silicon dopant atoms from diffusing during sample growth into the alloy barriers.

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