# Transverse magnetic field studies in $Al_{1-y}In_yAs/Ga_{1-x}In_xAs$ quantum-well tunneling structures

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We have studied the current-voltage (*I-V*) characteristics of a double-barrier, lattice-matched $Ga_{1-x}In_xAs/Al_{1-y}In_yAs$ tunneling structure in a transverse magnetic field, **B**, perpendicular to the current (**B**⊥**J**), in fields up to 18 T at temperatures $<4.2$ K. The devices used in this work showed stable dc *I-V* curves for all bias voltages and magnetic field values. This permitted the accurate determination of the bias-voltage position of the valley current and observation of the effect of **B** on the tunneling current in the negative-differential-resistance region. The data show the tunneling current turn-on and turn-off bias voltages behaving quadratically with *B*. We also observed the width of the resonance peak increasing linearly with *B*. All these observations are accurately explained by a simple description that accounts for the *B*-induced redistribution of the tunneling electron's momentum and energy. A fit of this model to the data gives values of maxima in the transverse momentum that agree with values determined from magnetoquantum oscillations in the **B**||**J** configuration on another device from the same wafer.

## I. INTRODUCTION

High magnetic fields are a powerful tool in the study of the electrical properties of quantum-well tunneling structures (QWTS's). Several recently published experimental studies have investigated the effect of parallel[1–3] (quantizing) and perpendicular[4–6] magnetic fields (**B**) on the electrical properties of tunneling structures. Detailed theoretical studies of the effect of transverse **B** have also been conducted.[7,8] This work reports the effect of **B**, applied perpendicular to the current direction, on the current-voltage (*I-V*) characteristics of a *stable* (and not the time-averaged self-oscillatory *I-V*) $Ga_{1-x}In_xAs/Al_{1-y}In_yAs$ QWTS. We investigated the effect of magnetic field on the turn-on and turn-off voltages of the resonant tunneling current as well as on the shape and width of the resonance peak. The stable characteristics meant that the complete *I-V* curve including the bias position of the valley-current minimum and changes in the shape of the negative-differential-resistance region could be observed for all **B**. These results are quantitatively compared to a simple semiclassical model.

The samples in this work show very high peak-to-valley ratios (23:1 at 4.2 K) and very low valley currents. As a consequence (this is confirmed by our **B**||**J** magnetoconductance studies),[3,9] most of the current obeys the basic tunneling selection rules: conservation of energy and transverse momentum $k_\perp$. In the work presented here, the effect of a transverse magnetic field is included within this simple picture. After a description of the sample and measurement techniques, we show the effect of the perpendicular field (**B**⊥**J**) on the *I-V* curve. We discuss the *B*-induced behavior of the peak current and peak bias voltage, and then focus on the magnetic field dependence of the turn-on and turn-off voltages and the resonance-peak width. Then, a very simple model based on the description of Refs. 4–6 is presented. This model is compared with our experimental results and the validity of this description is discussed.

## SAMPLES AND MEASUREMENTS

The tunneling structure was grown by molecular-beam epitaxy, and consisted of an $n^+$-type InP substrate, a 0.5-$\mu$m $n^+$-type (Si doped, $2\times10^{18}$ cm$^{-3}$) $Ga_{1-x}In_xAs$ layer, a 400-Å undoped $Ga_{1-x}In_xAs$ spacer layer (with a residual impurity level in the upper $10^{15}$-cm$^{-3}$ range), a 72-Å undoped $Al_{1-y}In_yAs$ barrier, a 43-Å undoped $Ga_{1-x}In_xAs$ well, a 72-Å undoped $A_{1-y}In_yAs$ barrier, a 400-Å undoped $Ga_{1-x}In_xAs$ spacer layer, and, finally, a 0.5-$\mu$m $n^+$-type $Ga_{1-x}In_xAs$ layer ($2\times10^{18}$ cm$^{-3}$).[10] This was fabricated into devices with sizes ranging from 25 to 400 $\mu$m$^2$. The measurements were performed at 4.2 K in magnetic fields up to 18 T. The resistance of the voltage source and probe leads was kept less than 10 Ω to minimize the effect of the measurement circuit on the stability of the device. Nevertheless, only the 25- and 50-$\mu$m$^2$ structures were intrinsically stable. The data presented here were obtained on devices that were stable throughout the whole range of bias voltage ($V_b$) and magnetic field.

## OBSERVATIONS

Figure 1 displays the *I-V* behavior at several magnetic fields for a 50-$\mu$m$^2$ device. The overall *I-V* curve is

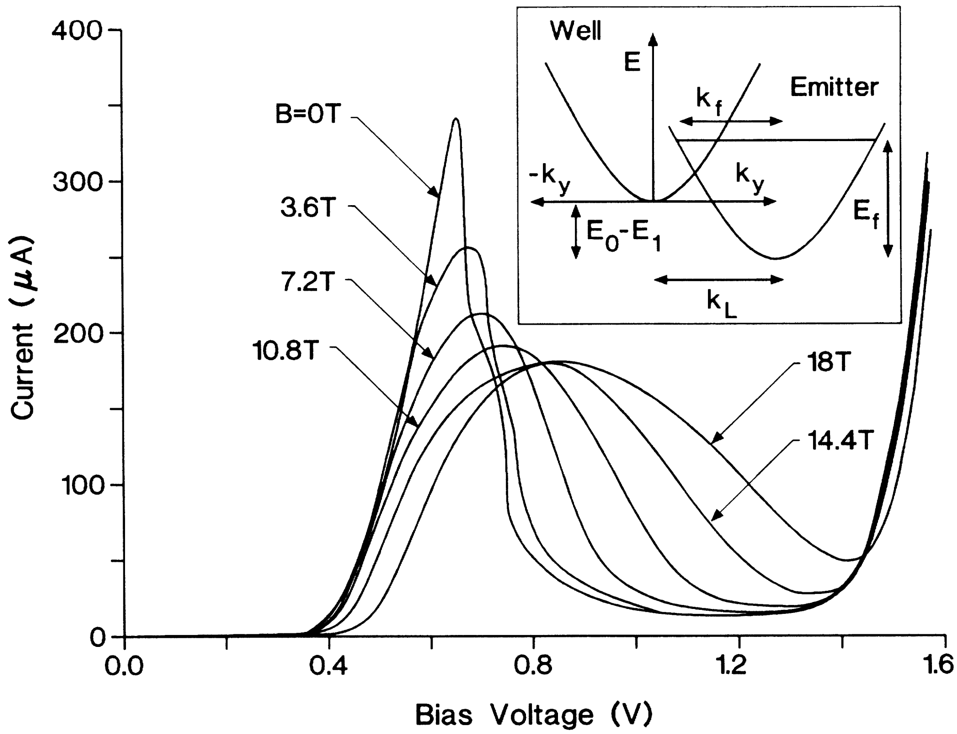


FIG. 1. *I-V* characteristic at different fields (**B**⊥**J**). The inset shows the overlapping of the occupied states in the emitter and states in the quantum well. $E_0 - E_1$ is fixed by the applied bias voltage $V_b$.

strongly affected by the magnetic field. The resonant tunneling peak is broadened by $B$ with the peak-to-valley ratio rapidly decreasing from 23 at $B=0$ to 3.6 at 18.8 T. Initially, the peak tunneling current ($I_p$) decreases, reaching a minimum at ~16 T, and increases for larger values of $B$. The bias-voltage position of $I_p$ and valley-current minimum increase with $B$. This trend is consistent with our other work reported for tunneling with **B**⊥**J**.[6]

We define the turn-on voltage ($V_{on}$) as the bias for the onset of tunneling where the current is 1% of $I_p$. This definition allows us to compare devices of different sizes and peak current, and only negligible variations from device to device were observed, provided that their *I-V* characteristics were stable. The turn-off ($V_{off}$) voltage is defined as the bias at which the valley current reaches an absolute minimum. The change in $V_{on}$ and $V_{off}$ as a function of $B$ are displayed in Fig. 2. Initially, $V_{on}$ decreases and reaches a minimum at ~9 T before increasing for larger $B$, while $V_{off}$ increases quadratically with field. The variation of the peak voltage is comparable to that of $V_{off}$.

We also define the width at half maximum (WHM) of the tunneling peak by analogy with a spectral line. The

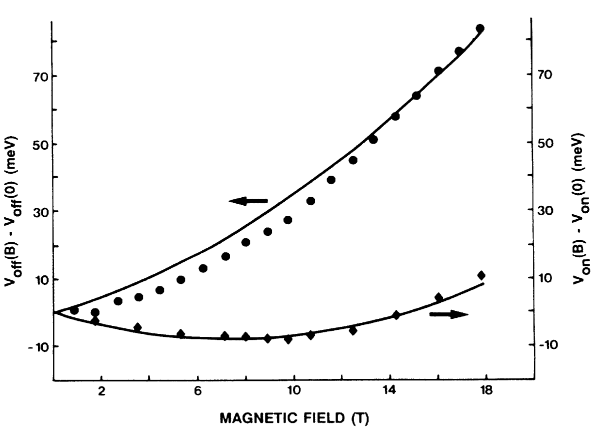


FIG. 2. Turn-on and turn-off voltages of the resonance as a function of $B$. The solid lines are the result of the calculation.

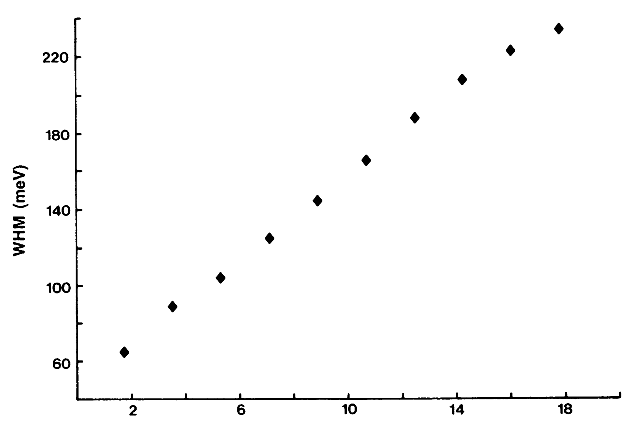


FIG. 3. Width of the resonance peak at half maximum as a function of $B$.

width is determined by the momentum distribution of tunneling electrons and the width of the bound energy level in the well. The $B$-induced broadening of the peak is roughly symmetric and the WHM increases linearly with $B$ (Fig. 3).

In wide-spacer-layer samples only a small fraction of the applied bias is felt across the emitter-barrier, quantum-well, and collector-barrier portions of the device. However, from the analysis of magneto-oscillation data ($\mathbf{B}\|\mathbf{J}$) on these devices, we were able to determine how much of the applied bias was across the well and barrier regions.[2,3] Therefore, we use our earlier results on similar samples to scale the voltages in the present work.[3]

## INTERPRETATION

When a magnetic field is transverse to the current (we choose $\mathbf{z}$ to be the tunneling direction and $\mathbf{B}\|\mathbf{x}$), electrons (with charge $e$ and effective mass $m^*$) will perform classical cyclotron motion due to the Lorentz force. In the $\mathbf{x}$ direction, motion is free-electron-like and independent of $B$ (e.g., $k_x$ is constant). Over a distance $z$, the $y$ component of the electron's momentum $\hbar k_y$ changes to $\hbar k_y' = \hbar k_y + eBz$. There is also a magnetic contribution to the electron's effective potential energy:[5,6]

$$V(z) = (eBz)^2/(2m^*) + eBz\hbar k_y/m^* \ , \tag{1}$$

where $z$ is the length the electron travels in the tunneling direction.

In QWTS's there is a characteristic length $L$, the distance over which an electron travels when tunneling from the near-emitter region through the first barrier and into the well.[4] The potential-energy change described in Eq. (1) for $z = L$ can be considered an addition to the barrier seen by a tunneling electron in a QWTS.

The emitter and well dispersion relations for transverse momentum are shifted with respect to one another along the $k_y$ direction by $\hbar k_L = eBL$ (represented by the inset to Fig. 1). Respectively, the turn-on and turn-off voltages occur when the overlap between the emitter and well parabolas begins and ends. Turn on is set by the $k_y = -k_f$ states and turn off by the $k_y = +k_f$ states, where $\hbar k_f$ is the electron momentum in the emitter, as shown in Fig. 1. This leads to the following expressions:

$$V_{\rm on}(B) = V_{\rm on}(0) + \hbar^2(k_L^2 - 2k_f k_L)/2m^* \ , \tag{2}$$

$$V_{\rm off}(B) = V_{\rm off}(0) + \hbar^2(k_L^2 + 2k_f k_L)/2m^* \ . \tag{3}$$

These two equations explain the behavior of $V_{\rm on}$ and $V_{\rm off}$ shown in Fig. 2. The change of $V_{\rm on}$ is initially negative and then becomes positive for $B > 2\hbar k_f/eL$. The variation in $V_{\rm off}$ should be entirely positive and behave as the sum of terms that are linear and quadratic in $k_L$.

Equations (2) and (3) can be simultaneously fitted to the $V_{\rm on}$ and $V_{\rm off}$ data with $k_f$ and $L$ as the only adjustable parameters (the fits are shown as solid lines in Fig. 2). The best fits occur for $k_f = 1.9\times10^8$ m$^{-1}$ and $L = 85$ Å. This value for $k_f$ is comparable to those obtained independently from $\mathbf{B}\|\mathbf{J}$ experiments on the same QWTS used in this study (but with a different device).[3] Similarly, $L$ falls within $\sim 10\%$ of the sum of the barrier and half-well-width (95 Å). This agreement is very good considering the simple way that $B$ is incorporated into the model. This approach is reasonable, since the magnetic energies are small compared to the barrier height and the energy of the bound level in the well is high so that $B$ acts as a perturbation. At 18 T the cyclotron orbit (60 Å) is still 30% larger than the width of the quantum well, so that we do not expect significant bulklike orbit effects.

We will now focus on the shape of the resonance peak as a function of $B$. The potential in Eq. (1) shows that tunneling electrons with different $k_y$ experience a different $B$-induced potential increase. This redistribution of the electron energies will therefore broaden the resonance peak, both in the positive- and negative-differential-resistance regions (PDR and NDR). For the sake of simplicity, we will describe the resonance peak as a triangle of base $V_{\rm off} - V_{\rm on}$ and of height $I_p$. This description is not very accurate because, at $B=0$, the PDR width depends mainly on the repartition of the energy and momentum of electrons in the emitter side. On the other hand, the NDR width is determined by the width of the bound level in the well. However, this description allows us to make qualitative predictions about the $B$-induced evolution of the resonance-peak width. In this context, we can write the WHM as $(V_{\rm off} - V_{\rm on})/2$,

$$\Delta V_{\rm WHM}(B) = \Delta V_{\rm WHM}(0) + 2\hbar^2 k_f k_L/2m^* \ . \tag{4}$$

The observed linear variation with field, shown in Fig. 3, is indeed predicted by Eq. (4) since $k_L = eBL/\hbar$. Using the previously obtained values of $k_f = 1.9\times10^8$ m$^{-1}$ and $L = 85$ Å in Eq. (4) produces a WHM that is about half the experimental value (Fig. 3). This difference can be simply explained by the argument that the WHM of a rounded peak will always be smaller than that of the triangular shape we have assumed in this description.

## CONCLUSIONS

$I$-$V$ measurements in $Al_{1-y}In_yAs/Ga_{1-x}In_xAs$ tunneling structures were performed in a transverse magnetic field. Our experimental results agree with previous works.[6] However, in this study a large fraction of the current rigorously followed tunneling selection rules, allowing us to successfully use a simple model describing the effect of the transverse magnetic field. Stable $I$-$V$ curves permitted us to accurately study the NDR and valley-current regions. Excellent quantitative agreement is found for the resonance turn-on and turn-off voltage behavior, and the predicted linear broadening of the resonance peak is also observed. The value of $k_f$ determined from the transverse $\mathbf{B}$ results is in good agreement with $k_f$ obtained form magnetoconductivity measurements on another device on the same wafer.

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