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Transverse magnetic field effects on the resonant tunneling current

L. A. Cury ⁽¹⁾, A. Celeste ⁽¹⁾, B. Goutiers ⁽¹⁾, J. C. Portal ⁽¹⁾, D. L. Sivco ⁽²⁾ and A. Y. Cho ⁽²⁾

⁽¹⁾ INSA-CNRS, Avenue de Rangueil, 31077 Toulouse Cedex, France et SNCI-CNRS, Avenue des Martyrs, 38048 Grenoble Cedex, France

⁽²⁾ AT & T Bell Laboratories, Murray Hill, New Jersey 07974, U.S.A.

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Résumé. — Un système à double barrière à semiconducteurs basé sur les alliages (InGa)As-(InAl)As est étudié sous un fort champ magnétique transverse B_{\perp} (perpendiculaire au courant). On étudie plus particulièrement la variation expérimentale de la tension V_p associée au courant pic en fonction du champ magnétique B_{\perp} . A très fort champ, le comportement attendu de V_p en B_{\perp}^2 est observé. Dans le domaine des bas champs magnétiques une déviation du comportement quadratique est mise en évidence. Le comportement plus compliqué de V_p en fonction de B_{\perp} est obtenu au travers d'un lissage numérique. Nous proposons une discussion qualitative, de ces résultats, fondée sur notre travail antérieur (L. A. Cury, A. Celeste, J. C. Portal, *Solid-States Electron.* **32** (1989) 1689) ainsi qu'une comparaison avec les résultats d'autres auteurs.

Abstract. — Resonant tunneling process in an (InGa)As-(InAl)As symmetric double-barrier structure subjected to a transverse magnetic field B_{\perp} (perpendicular to the current) is investigated. We particularly focus on the experimental behaviour of V_p , the voltage at the current peak position, as a function of the magnetic field B_{\perp} . For strong magnetic fields a clear dependence on B_{\perp}^2 is observed, as expected. However, an original result is obtained at small magnetic fields where a deviation from the parabolic behaviour is observed. The more complicated dependence on B_{\perp} of V_p is obtained from a numerical fit. A qualitative discussion is proposed on the basis of a previous publication (L. A. Cury, A. Celeste, J. C. Portal, *Solid-States Electron.* **32** (1989) 1689) and the differences with the results of other authors are pointed out.

(InGa)As-(InAl)As double-barrier devices [1-4] have recently attracted considerable interests. High peak to valley ratios have been reported recently [5] on double-barrier diodes based on (InGa)As-(InAl)As lattice matched to InP and even better results were found in strained layer structures [6]. The presence in this system of low effective masses in both (InAl)As-barrier [7] and (InGa)As-well [8], high conduction band discontinuities [9] and conduction band non-parabolicity [10] makes it appropriate to the study of vertical transport.

In this letter, we analyse the transverse magnetic field effects on the current-voltage characteristics (Fig. 1). In figure 2 we show the experimental behaviour of the voltage at the current peak position V_p as a function of the applied transverse magnetic field B_{\perp} . At the

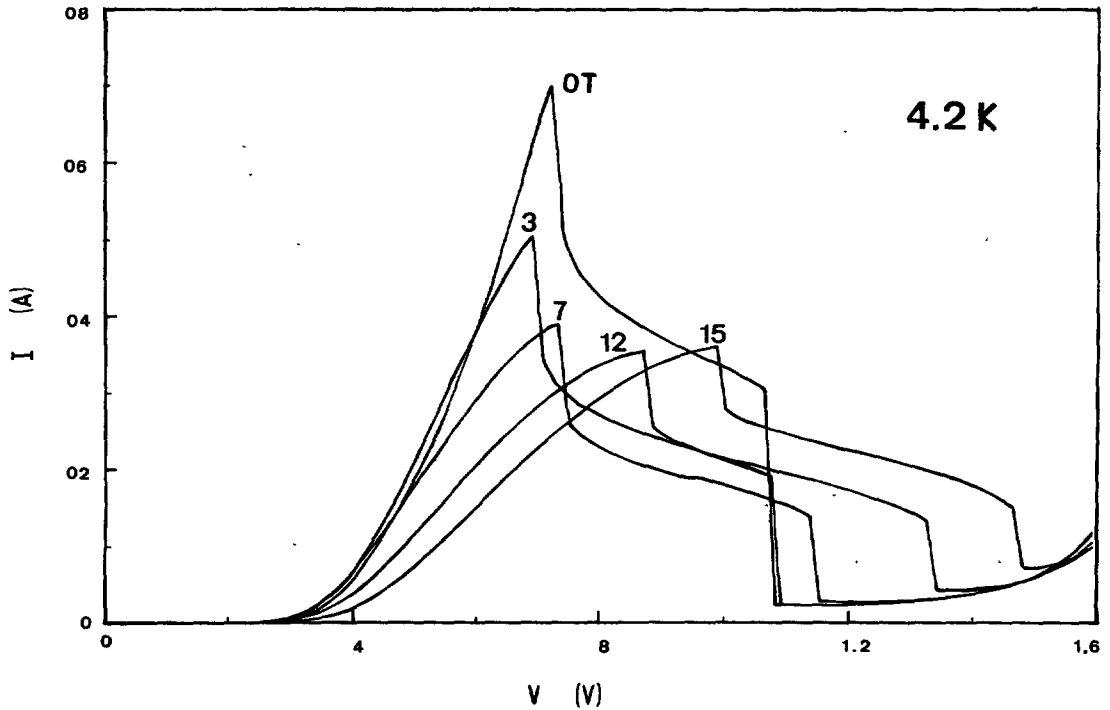


Fig. 1. — I versus V characteristics for several transverse magnetic fields.

high magnetic fields the expected B_{\perp}^2 behaviour is obtained [11] whereas at low magnetic fields, a more dependence on B_{\perp} is observed in agreement with our previous theoretical work (Ref. [14]). A numerical fit of the experimental V_p versus B_{\perp} curve (Fig. 2a), reveals a polynomial behaviour up to the fourth order in B_{\perp} . The terms proportional to B_{\perp}^3 and B_{\perp}^4 are the adjustment terms which we believe indicate the non-parabolicity effects in our structure. A comparative analysis with other experiments is done. We conclude that the behaviour at small magnetic fields is mainly connected with the effective Fermi energy E_{fe} in the region adjacent to the emitter barrier.

The sample studied has two 50 \AA with (InAl)As barrier and the enclosed 50 \AA width (InGa)As well between them. The complete structure, in order of growth from the $n^+ - \text{InP}$ (100) substrate is: (i) 0.5 \mu m of $n = 1 \times 10^{18} \text{ cm}^{-3}$ $\text{In}_{1-y}\text{Ga}_y\text{As}$; (ii) 25 \AA of undoped $\text{In}_{1-y}\text{Ga}_y\text{As}$ spacer layer; (iii) 50 \AA of undoped $\text{In}_{1-x}\text{Al}_x\text{As}$ barrier; (iv) 50 \AA of residually doped $n = 8 \times 10^{15} \text{ cm}^{-3}$ $\text{In}_{1-y}\text{Ga}_y\text{As}$ well; (v) 50 \AA of undoped $\text{In}_{1-x}\text{Al}_x\text{As}$ barrier; (vi) 25 \AA of undoped $\text{In}_{1-y}\text{Ga}_y\text{As}$ spacer layer; (vii) 0.5 \mu m of $n = 1 \times 10^{18} \text{ cm}^{-3}$ $\text{In}_{1-y}\text{Ga}_y\text{As}$ top contact. The Al and Ga concentrations are $x = 0.48$ and $y = 0.47$, respectively, 50 \mu m mesas were fabricated using standard lithography techniques.

Our current-voltage characteristics are shown in figure 1 corresponding to several transverse magnetic fields. The following features are observed when B_{\perp} is increased: (i) the current peak is shifted to high voltages; (ii) the negative differential resistance region broadens; (iii) the magnitude of the peak current I_p is first decreased at small B_{\perp} , and increases at higher magnetic fields. These effects have been observed by Ben Amor and colleagues [2] and they are well explained qualitatively in the respective reference. The main difference between the previous results and ours, is that we observe a singular behaviour

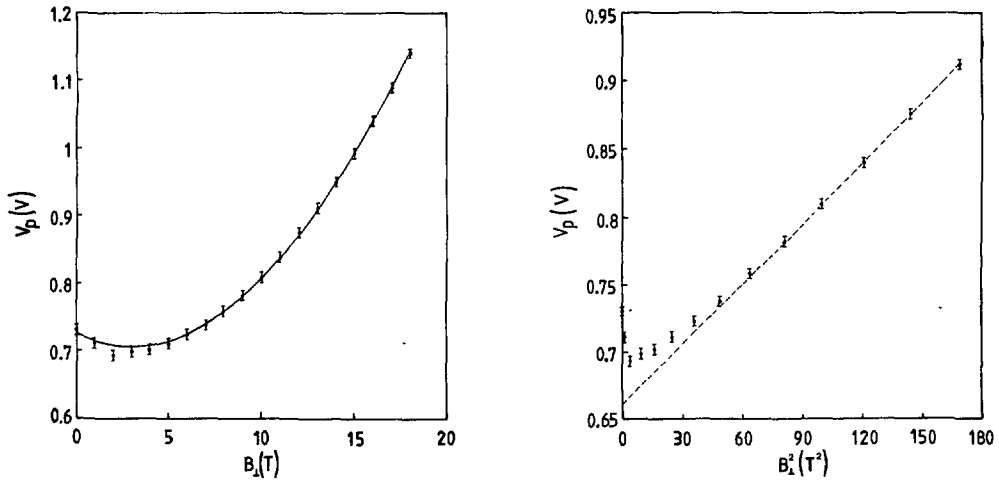


Fig. 2. — a) V_p versus B_{\perp} curve. The full line is the numerical fit obtained from equation (1); b) V_p versus B_{\perp}^2 curve. The linear behaviour is observed for $B_{\perp} > 8$ T. For $B_{\perp} \leq 8$ T the deviation of the linear behaviour is clearly verified. The dashed line is a guide for the eyes.

at small magnetic fields (Figs. 2a and 2b) which was not observed before. The following of this paper attempts to give a qualitative explanation of this original effect.

For comparison we will analyse some results obtained by Ben Amor and colleagues in reference [2] and [12] where the two magnetic field geometries $\mathbf{B} \perp \mathbf{J}$ and $\mathbf{B} \parallel \mathbf{J}$ are studied, respectively. The same sample studied in these references, has a large 400 \AA (residually doped 10^{15} cm^{-3}) spacer layer separating the wide ($0.5 \text{ }\mu\text{m}$) very doped ($n = 2 \times 10^{18} \text{ cm}^{-3}$) $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ layer to the barrier. Calculations of the Fermi energy considering non-parabolicity corrections to first order [13] give $E_f = 122 \text{ meV}$ in their very doped (InGa)As contact layer ($n = 2 \times 10^{18} \text{ cm}^{-3}$) at 4.2 K. The equilibrium condition between the Fermi energies guaranties that the conduction band minimum in the spacer layer region will roughly have an energy $E = \frac{1}{2} E_{g\text{InGaAs}} + E_f$ above the conduction band minimum in the doped region.

E_g is the energy gap in the (InGa)As bulk layer. Under bias, the spacer layer will give rise to a roughly triangular quantum barrier separating the Fermi sea to the accumulation layer and associated quasi-two dimensional electron gas (2DEG) in the region adjacent to the emitter barrier.

The magnetoquantum oscillations in the current for $\mathbf{B} \parallel \mathbf{J}$ observed in reference [12] revealed the presence of one electric subband in the accumulation layer. The effective Fermi energy E_{fe} in this region, relative to this electric subband, can be calculated by $E_{fe} = \hbar e B_f / m$. B_f is the fundamental field defined from the periodicity of the oscillations. In reference [12] B_f has a linear behaviour from 12 T up to 33 T corresponding to voltages above the threshold for resonant tunneling. A saturation is present around 15 T, slightly below V_p . At V_p , the fundamental field abruptly increases to 18.6 T. An estimate, using $m = 0.041 m_e$ [8] and $B_f = 18.6 \text{ T}$, gives $E_{fe} \approx 52 \text{ meV}$ at the peak voltage which is smaller than the Fermi energy in their heavily doped contact region (122 meV).

Our sample has a very thin (25 \AA) spacer layer. Under bias no accumulation layer is formed. The effective Fermi energy corresponding to the doped region ($0.5 \text{ }\mu\text{m}$ of $n = 1 \times 10^{18} \text{ cm}^{-3}$ $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$) is 80 meV [13] sensibly higher than in the Ben Amor's sample. The resonant tunneling process implies directly 3D-electrons of the Fermi sea in the

emitter. For magnetic fields smaller than 8 T (Figs. 2a) a minimum is observed for a non-zero magnetic field position indicating that the voltage V_p has a more complex behaviour than the B_\perp^2 one in this range of fields. This effect has not been observed in precedent works [2, 11]. In our previous paper [14], it was predicted that a large enough Fermi energy is necessary to observe a deviation of the quadratic behaviour of V_p with B_\perp . Our present results seem to be in a good qualitative agreement with this statement, since our sample presents a higher effective Fermi energy necessary to observe this effect.

Ben Amor and colleagues in reference [2] have not studied directly the behaviour of V_p as a function of B_\perp . They claimed that this behaviour is comparable to that of the turn-off voltage which is defined as the bias at which the valley current reaches an absolute minimum. Their V_{off} versus B_\perp curve does not show the same behaviour at small magnetic fields than ours in figure 2a. We believe this is caused by the lower value of the effective Fermi energy in the 2D accumulation layer of their structure.

A deviation of the B_\perp^2 behaviour, as observed in figure 2b at small magnetic fields, was interpreted in the previous work [14] by an increase of the coefficient of the term in B_\perp contained in the V_p expression. At small fields and if the effective Fermi energy in the region adjacent to the emitter barrier (E_{fe}) is large enough, the K_y electron wave-vector contained in this coefficient could take values such that the term in B_\perp could become more important than the B_\perp^2 one.

A larger dependence on K_y wave-vector for a larger E_{fe} which increases the term proportional to B_\perp , as interpreted in our previous work (Ref. [14]), is reinforced by our numerical fit (Fig. 2a) where the experimental points are well described by the fourth order polynome

$$V_p = 0.7260 - 0.01347 B_\perp + 0.0022 B_\perp^2 + 0.0000001 B_\perp^3 - 0.0000005 B_\perp^4 . \quad (1)$$

As we can see in equation (1), the coefficient on B_\perp is about 6 times larger than the B_\perp^2 one in absolute value. At small magnetic fields the term on B_\perp must predominate. This is in a good agreement with the qualitative discussion in reference [14]. However, the dependence on B_\perp^3 and on B_\perp^4 has not been predicted. The coefficients of these terms in equation (1) are much smaller in comparison with the coefficients on B_\perp and on B_\perp^2 but they turn out to be important for larger magnetic fields. We believe that these terms can come from the conduction band non-parabolicity, which is stronger in the (InGa)As-(InAl)As structures and that was not taken into account in the previous work (Ref. [14]).

The formalism developed by Ekenberg [15], based on the conduction band dispersion in the bulk of a direct-gap III-V semiconductors expanded up to fourth order in K , seems to be a common way to introduce the non-parabolicity effects in the envelope function method as well as the effects of the transverse magnetic field. However, it is not trivial from an analytical point of view. We believe this is a possible solution to explain our experimental fourth order polynomial behaviour of V_p as a function of B_\perp . This will be the subject of a future work.

In summary, we have investigated the current versus voltage characteristics as a function of the transverse magnetic field B_\perp . We have observed a deviation from the expected effect on the voltage V_p at the current peak position, in the range of small magnetic fields, that had not been observed in precedent works. We associate our results to the growth parameters of our sample where a large enough effective Fermi energy is present in the region adjacent to the emitter barrier. This is in a good qualitative agreement with reference [14], where the deviation from the linear behaviour of V_p versus B_\perp^2 has been predicted in this case. Our experimental results reinforce the statement in reference [14] that the K_y wave-vector of the incident electron is an important factor to establish the behaviour of V_p as a function of B_\perp .

Although our results give a good qualitative agreement with the predictions in reference [14], a more complete theory, including conduction band non-parabolicity corrections, is necessary to explain analytically the fourth order polynomial behaviour of V_p versus B_{\perp} obtained from our numerical fit.

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$$n = \int_0^{\infty} g(\alpha', \varepsilon) f(\varepsilon, E_f) d\varepsilon$$

where $f(\varepsilon, E_f)$ is the Fermi function, $g(\alpha', \varepsilon) = \frac{\sqrt{2} m^{3/2}}{\pi^2 \hbar^3} (1 + 2\alpha' \varepsilon) \sqrt{\varepsilon(1 + \alpha' \varepsilon)}$ is the density of levels. $\alpha'_{(\text{InGa})\text{As}} = 1.243 (1/\text{eV})^{(10)}$ is the non-parabolicity coefficient.

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