ELECTRICAL TRANSPORT PERPENDICULAR TO SUPERLATTICES BUILT IN BIPOLAR AND PHOTOCONDUCTOR STRUCTURES

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Résumé : Le transport perpendiculaire aux interfaces dans les super-réseaux est étudié au moyen de structures classiques photoconductrices ou transistor contenant une couche active en super-réseau. Les résultats indiquent les limites de validité des modèles classiques de transport surtout pour les trous et montrent une tendance au transport cohérent électronique pour de fines barrières. Les effets de champ électrique particuliers aux super-réseaux sont également présentés et discutés.

Abstract : Perpendicular transport in superlattices is studied by means of classical photoconductor or transistors in which the active layer is made of a superlattice. Results indicate the limits of classical models but clearly show coherent electron transport for thin barriers. High electric field effects particular to superlattices are also shown and discussed.

Transport properties along the growth axis of semiconductor superlattices (perpendicular to interfaces) has not received as much attention as the case of transport parallel to the layers. In addition to intrinsic experimental difficulties, the physical interpretation of the observed effects is far from straightforward. It has been established earlier [1] [2] that charge carriers (electrons or holes) may propagate either in Bloch states as in an ordinary semiconductor (conduction or valence) band, or by other mechanisms specific to the superlattice structure. Among these, two are considered in figure (1). The first one is the phonon-assisted tunneling (hopping) [3]. The second one is the thermoionic emission above the barriers. All those mechanisms are not easily described in a single model. Competition between band transport, hopping, and thermoionic emission is determined by the superlattice parameters, the scattering strength, and the lattice temperature. Moreover, in terms of a local distribution function, the transport parameters of a given carrier are energy dependent. A related situation appears similar in amorphous semiconductors where exists a mobility gap near the band edges, because of a disorder induced localization for low energy states. The competition between a thermoionic emission model and an energy dependent mobility depends on the superlattice period compared to the extended state mean free path.

Fig. 1 : Illustration of band, hopping and thermoionic emission transport.

Fig. 2 : Cross sectional view of processed pin and nin samples.

In other words, the superlattice wells act as giant traps for the charge carriers. The total current is a sum of the hopping contribution and of band transport. Resonant tunneling effects may be observable at applied voltages such that the potential difference between two adjacent wells is of the order of the localized to extended states energy difference. However, the possibility of a total current due to coherent miniband transport cannot be discarded as will be shown by various experimental results. Miniband transport is however limited by the finite miniband width which must be larger than collisional broadening. It must be also larger than the potential drop between two adjacent wells. For superlattices with narrow barriers, transport in the first miniband dominates for electrons and light holes, while localization appears to prevail for heavy holes in all circumstances. Experimental results do not provide clear answers when we use standard transport measurement tools. Thus current-voltage curves alone are not sufficient. They are often strongly non linear even though carrier transport parameters are linear in a wide range of electric fields. The reason lies in band bending due to compensation in undoped SL. It appears therefore interesting to build superlattices inside classical device structures in such a way that perpendicular transport has a key role of the whole device behaviour. That procedure implies we consider the SL active layer as an effective medium. In the case of miniband transport, the minimum thickness required is a few times the mean free path.

The underlying assumption is the existence of a local distribution function involving a well defined mobility versus field dependence. A more sophisticated model with consideration of an energy distribution will be evoked at the end of the paper. With a local distribution of charges, the classical drift-diffusion-Poisson system can be applied in a first approach [4]. Three basic devices with superlattices will be considered hereafter. First the $n^+/SL/n^+$ structure which will provide information on both electron and hole transport [5]. Then the $p^+/SL/n^+$ diode which has also been studied by Larsson et al [6], Capasso et al [7] [8] and Gourley et al [9].

High field effects at low temperatures in those samples will also be described. More recently $n p n$ transistors have been studied in which the base layer has been replaced by a superlattice [10]. This latter structure has a common emitter gain proportional to the electron diffusion length. In a final section we shall propose an improvement to the classical model to take in account both hopping and band transport, in order to provide a tentative explanation of the observed hole mean drift velocity.

1) $n^+/\text{SL}/n^+$ photodiodes

The design of $n^+/\text{SL}/n^+$ photodiodes is shown in figure (2). Electron-hole pairs are generated in brief light pulses through a window AlGaAs layer. That window is n doped in order to have photocurrent lines well perpendicular to layers. Graded layers also improve the electron injection efficiency. The total SL width W is a crucial parameter. It cannot be too large as the photoconductive gain $\sim W^{-2}$. It also cannot be too small as the sample capacitance ($\sim W^{-1}$) must be minimized for broad band detection of the photocurrent.

Consideration of the built-in potential by deep acceptors or compensating impurities is important. In fig (3) the built-in potential effect is shown for two different densities of deep acceptors, $N_A = 8 \cdot 10^{15} \text{ cm}^{-3}$ and $N_A = 2 \cdot 10^{15} \text{ cm}^{-3}$ at an applied voltage $V = 1.5$ volts. The electron Fermi level of the local distribution function is pinned on the major deep acceptor level. Such a structure is not readily usable for DLTS capacitive technique, the whole SL layer being constantly depleted. A. Sibille has developed a new spectroscopy technique well adapted to such structures [11], the Barrier Modulation Deep Level Transient Spectroscopy (BMDLTS). Noticing that the barrier height in fig (3) can be controlled by the amount of trapped electrons on the deep acceptor, a transient current is obtained after excitation of the sample by trap filling. Trap signatures and concentrations obtained by such measurements are extremely useful in order to fit the $I(V, T)$ with as few as possible adjustable parameters.

Fig. 3 : Comparison of two band diagram calculations with different assumed acceptor concentrations in the SL.

One basic result is that, for a given SL thickness, a critical total acceptor concentration N_A^C exists such that, for $N_A < N_A^C$, the space charge cannot be developed at zero volt [case of fig. 3 (a)]. A good photoconductor corresponds to that condition. For $L \sim 1 \mu\text{m}$ $N_A^C \sim 5 \cdot 10^{15} \text{ cm}^{-3}$.

Recent results have been obtained for $n^+/\text{SL}/n^+$ structures when the cathode is on the substrate side in a sample with $N_A \sim 2 \cdot 10^{15} \text{ cm}^{-3}$ and $W = 1.4 \mu\text{m}$. The time dependent photoconduction experiment is described in detail by H. Le Person et al in this conference [12], following earlier studies [13] [14].

Fig. 4 : (a) Variations at different times of the excess carrier density profiles (b) comparison of experimental $I(t)$ at different V with theory.

In figure (4) the observed effects are analysed by a time dependent solution of drift-diffusion-Poisson equations. The main feature is a delayed injection current due to slow hole drift in the SL. The time variations of band bending, see fig 4 (a), during that hole drift causes a contribution of injected electrons. It is nothing else than a dynamic transistor effect. Interesting physical informations can be extracted from the current time dependence. The current surge is obtained at a time of the order of W/V_h where V_h is the mean hole drift velocity. Its amplitude is also closely related to the electron transit time throughout the SL. As evidenced by fig 4 (b) the current surge cannot be clearly separated from the initial burst because of the RC circuit time constant which partly masks the effect. In order to check the consistency of the present analysis, the experimental $I(t)$ curves have been compared with a serie of simulation runs. A quite satisfactory fit could for example be obtained in the case of a sample with 24 Å barriers and 40 Å wells ($x = 0.28$). For low field mobilities $\mu_e \approx 110 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$, $\mu_h \approx 12 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$.

Electron mobility value found by this fit differ by a factor 2 from those obtained in static $I(V)$ and photoconduction experiments. These values will be commented on later.

2) $p^+/SL/n^+$ structures

PIN superlattice or MQW photodiodes have been studied for optoelectronics. Capasso et al have also used such structures to measure the perpendicular mobilities in InGaAs/AlInAs SLs [7]. Larsson et al [6] have also observed the time dependent hole drift in a GaAlAs superlattices pin, with rather large barrier widths. The method presented for $n^+/SL/n^+$ samples can partly be applied here. On the other hand, the main advantage of the $p^+/SL/n^+$ structure is an homogeneous electric field in the SL layer, assuming $N_A < N_D$. As already found in [15], the effective hole drift time of flight is shorter than would be expected from hopping calculations [3]. For example in a sample with $b = 67 \text{ \AA}$, $a = 40 \text{ \AA}$ and $x = 0.2$ we found $\mu_h \sim 4 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$ at low applied voltage, compared to a heavy hole hopping mobility $\sim 10^{-3} \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$, and a light hole hopping mobility $\sim 1 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$. Larsson et al have interpreted such results by the thermoionic emission of holes above the barriers [6]. However this interpretation is clearly inconsistent with the field dependence of the mean drift velocity. The hopping theory [3] has been revisited by Weil and Vinter [16]. The field enters both in the envelope states and in the probability of hopping in their theory leading to higher mobilities. However it cannot explain the discrepancy observed for the hole mobility. Low temperature μ_h values found by Lambert et al [15] are also surprisingly high.

3) Strong electric field effects

A miniband mobility exists as long as the applied electric field do not modify too much the Bloch type of conduction. It has been shown by Rabinovitch and Zak [17] that interband transitions can occur at fields F such that $e F d \Delta$, where Δ is the miniband width. This contrasts with the simple argument of the ladder sequential resonant tunneling. In $n^+/SL/n^+$ structures we can use the classical band diagram to determine the electric field F profile at a given applied voltage V . Near the anode at $V = 6 \text{ V}$, the condition $e F d = \Delta$ is clearly obtained. For the corresponding sample, a sharp negative drop in the sharp negative drop in the current has been observed at $T = 4.2 \text{ K}$ (fig 5).

Fig. 5 : NDR in a $n^+/SL/n^+$ at $T = 4.2 \text{ K}$

Fig. 6 : Peaks in the conductance versus voltage in a large barrier $p^+/SL/n^+$ at $T = 77 \text{ K}$

Such a negative differential resistance (NDR) could at first thought result from an inter-miniband transfer as well as from a transfer to L or X valleys (Gunn effect). The latter mechanism has however been discarded by consideration of the pressure dependence of the critical voltage [18]. Instead, the above NDR is reminiscent of the pioneering experiments of Esaki and Chang [19] and, more recently, Davies et al [20], Choi et al [21]. In fig 6) the successive intersubband tunneling at $T = 77$ K is shown for a $p^+/SL/n^+$ photodiode, the diode being polarized in the forward bias. Negative differential conductivity peaks are also clearly observed and interpreted in terms of sequential resonant tunneling effects which involve different zones of the superlattice when the electric field is decreased. No such structure is observed in the photocurrent of the reverse bias diode, which supports, to some extent, the speculations of section 2 on the importance of high field effects in the same sample.

4) Superlattice Bipolar Transistors (SBT)

An alternative transport study in minibands has been demonstrated recently [10] [22]. Noticing the inhomogeneous field in the $n-i-n$ structure obscures, to some extent, the pure drift of carrier effects, the diffusion constant of injected electron has been merely pointed as a possible test for miniband transport. In the structure we replace the whole base (generally p type in a $n-p-n$ transistor) by a superlattice. The perpendicular transport of injected electrons in a $n-p-n$ transistor is essentially governed by the electron diffusion constant and the hole lifetime in the base as well as at the emitter-base interface. In all the SBT under study we have endeavoured to vary only one SL parameter, namely the barrier width b . The implicit assumption is that the hole lifetime remains constant and independent from the sample. For a miniband electron conduction, the Einstein relation is assumed, $D_n = k_B T \mu_e / e$, D_n being the electron diffusion constant. The transistor common emitter gain h_{FE} is given by :

$$\frac{1}{h_{FE}} = \frac{1}{\gamma} + \frac{W_B^2}{2 D_n \tau_h} \quad (3)$$

in which W_B is the base width, τ_h the hole lifetime in the base and γ the emitter-base injection ratio :

$$\gamma = \frac{\mu_e^B}{\mu_p^E} \frac{N_{DE}}{N_{AB}} \frac{W_E}{W_B} \exp \frac{E_q^E - E_q^B}{k_B T} \quad (4)$$

in which a (E) symbol is related to emitter parameters and a (B) symbol to base parameters. It is preferable to design a transistor in which the second term of (3) limits h_{FE} and not γ . So N_{AB} is maintained as low as possible, W_B not too small ($\sim W_E$) and E_q^E such that $\gamma \sim 10^4$ at $T = 300$ K. It is also worthwhile noticing the formulae (3) (4) are not valid if the interface recombination dominates the emitter base current. Variations of h_{FE} for three SBTs having the same $N_{AB} \sim 5 \cdot 10^{16} \text{ cm}^{-3}$, and their superlattices only differing by the barrier thickness b is shown in fig (7). For a Bloch miniband conduction we have shown the intraband collision time did not vary much with b [23]. The effective mass along z varies like :

$$M_z \sim \exp 2b \sqrt{\frac{2m^*(W-E)}{\hbar^2}} = \exp (\chi b) \quad (5)$$

Assuming $1/\gamma$ negligible in (3) the Bloch mobility would give $\mu_{FE} \sim M^{-1} \exp(-\chi b)$. In fig (7) that exponential variation of μ_{FE} with b is compared to the data. It is clear that the observed variations of μ_{FE} cannot be described by the single diffusion miniband theory. It is suggested that a transition from Bloch to the hopping (or a more complex regime) occurs for $30 \text{ \AA} < b < 40 \text{ \AA}$. To go further a fit of I_C (V_{CE} , I_b) has to be done. The procedure must be limited to large I_b as surface and interface recombination currents are important for low I_b values.

Fig. 7 : SBT's variations of μ_{FE} with b compared with $\exp(-\chi b)$.

Fig. 8 : Electron experimental mobilities ; sample references are those of table 1.

5) Discussion

In table (1) the electron low field mobility deduced from three n^+SL/n^+ structures and three SBT's with different SL parameters are compared to theoretical room temperature values (Bloch and hopping) [see also fig (8)].

Sample	a Å	b Å	x	N_A cm^{-3}	μ_e exp.	μ_e Bloch	μ_e hopping	μ_h exp.
n i n (a)	45	22.5	0.3	$8 \cdot 10^{15}$	~ 500	2000	20	20
n i n (b)	40	45	0.27	$4 \cdot 10^{15}$	5	200	1.	10
n i n (c)	40	24	0.28	$2 \cdot 10^{15}$	110	1000	12	12.5
p i n (a)	45	67	0.27	$2 \cdot 10^{15}$		2.	0.05	4
T R 1	45	18	0.25	$4 \cdot 10^{16}$	500-1000	3000	25	
T R 2	45	38	0.28	$4 \cdot 10^{16}$	~ 10	300	3.	
T R 3	45	28	0.28	$6 \cdot 10^{16}$	~ 50	700	8	

Table (1)

Comparing $n/\text{SL}/n$ and SBT results, they appear to have consistent μ_e versus b dependences. For the hole drift mobility the observed values are not consistent with any known model. We propose the following comment. When the mobility is high, i.e. $> 50 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$ the mean free path is larger than a few SL periods. If the applied electric field is such that $e F d < \Delta$ and if Δ is larger than the collisional broadening, the drift diffusion model can be applied. If not, the whole basis of our interpretation must be revisited. If we suppose that the mobility is energy dependent, the measured value is :

$$\bar{\mu}_n = \frac{1}{N} \int_{E_c}^{\infty} f(\epsilon) \rho(\epsilon) \mu(\epsilon) d\epsilon \quad (6)$$

This can lead to a very simple expression when separated into two contributions, one for localized states, the other for extended ones.

$$\bar{\mu} = \mu_{\text{hop}} + \mu_{\text{ex}} \exp - E/k_B T \quad (7)$$

A detailed theory for such effects has been proposed by Lyo [24].

In order to interpret time-dependent effects we must also keep in mind the hopping processes are rather slow for large barriers ($W^{-1} \sim 100 \text{ psec}$). When the hopping time comes close to the electron-hole recombination time the separate conservation of both charges cannot be asserted. This is one of the reasons why the value $\mu_h \sim 4 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$ for $p^+ \text{ SL } n^+$ (a) of table (1) is rather large with respect to any theoretical value (hopping or thermoionic). In order to conclude we point that the present results may give good agreement with classical theories for true miniband transport (small b values). It will be interesting to go further in interpreting the results by multi-band drift diffusion equations and in taking into account the specific role of carriers trapped in the lowest energy subband.

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