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Electrical properties of the GaAlAsSb/GaSb heterojunctions for lasers and photodetectors application

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Abstract— **The GaAlAsSb alloy is an interesting material for optoelectronic device technology and particularly for the preparation of lasers and photodetectors. Therefore, electrical properties of GaSb/GaAlAsSb heterojunctions are important for the characteristic devices based on them.**

The current-voltage characteristic of $Ga_{0.53}Al_{0.47}As_{0.04}Sb_{0.96}$(p)/GaSb(n+) heterojunction, obtained by liquid phase epitaxy on GaSb substrate, is studied. The current of the heterojunction, which is essentially a thermoionic emission of holes, has a behavior identical than that of the Schottky diode, which have permitted to derive the barrier height V_b = 685 meV for this heterostructure. The Richardson constant of the system is calculated to be 49.1 A.cm^{-2}. K^{-2}.

The band offsets at the interface between the two semiconductors are determined as ΔE_C = 460 meV, ΔE_V = 128 meV, in agreement with other works. The preliminary study of the variation of the valence band offset with Al composition shows a good agreement with the theoretical models proposed by Jaros and Mujica.

Key-Words— GaAlAsSb/GaSb, heterojunction, current-voltage and band offset.

I. INTRODUCTION

$Ga_{1-x}Al_xAs_ySb_{1-y}$/GaSb heterojunction attracts much interest because its possible use in optoelectronic device technology such as photodetectors [1]-[2] and lasers [3]-[4]. These applications are due to the possibility to grow high quality quaternary layers perfectly lattice-matched to the GaSb substrate [5], in interesting wavelength ranges. For example the $Ga_{1-x}Al_xAs_{1-y}Sb_y$ can be tailored in the direct bandgap 1.3 - 1.7 µm region, which covers the low-loss and the low-dispersion region for optical fiber communications in silica fibers. Besides, the quaternary alloy can be used in the mid-infrared region (2 - 2.5 µm) in avalanche photodiodes [2]-[6].

The band discontinuity at the heterojunction interface is an important element for understanding the optical and transport properties. In a previous work [7] we have used capacitance-voltage method to determine band discontinuities at the interface, ΔE_C and ΔE_V for the same GaAlAsSb/GaSb system. In the present work, we report on the current-voltage characteristic of the perfectly lattice-matched GaSb(n^+)/$Ga_{0.53}Al_{0.47}As_{0.04}Sb_{0.96}$(p) heterojunction :

The n-GaSb/p-GaAlAsSb heterojunction is rectifier as expected [8] and the current-voltage characteristic behaves like a Schottky diode; The band offset of the heterojunction acts like a barrier at a Schottky contact. Using this property, we derive from the experimental I-V characteristic the contact potential V_b, and the conduction and valence band-offsets ΔE_C and ΔE_V. The values obtained are in agreement with those determined by capacitance-voltage measurements [7], showing that when the applied bias voltage is not close to the contact potential, the total depletion simple model gives correct results [8]-[9]-[10]-[11].

We study also, in this work, the variation of the valence band offset ΔE_V with the Al composition of the quaternary GaAlAsSb. Our results and other data in the literature show that ΔE_V variations are in good correlation with theoretical predictions of Jaros [12] and Mujica et al [13].

II. CURRENT VOLTAGE (I-V) CARACTIRISTIC

The experimental current-voltage characteristics are performed on a set of mesa diodes of 200 µm diameter achieved from GaSb(n^+)/$Ga_{0.53}Al_{0.47}As_{0.04}Sb_{0.96}$(p) heterojunction, which was grown elsewhere by liquid phase epitaxy on a (100) oriented GaSb substrate[5].

The ohmic contacts were realised with Au-Zn and Te-Au alloys, on the p and n+ sides respectively. The mesa structure is represented in inset of "Fig. 1 ".

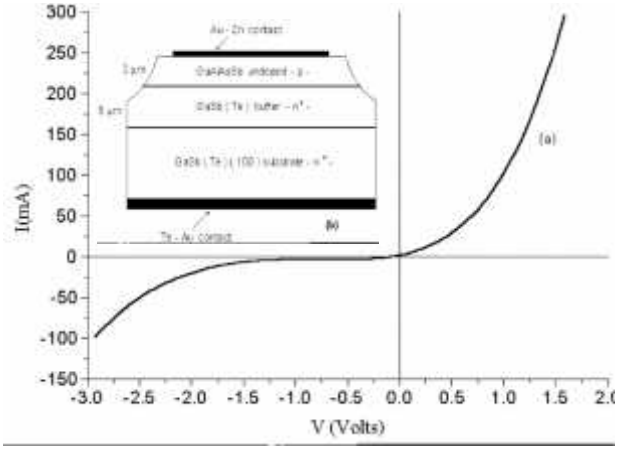

Fig. 1 (a) Typical current-voltage characteristic at T = 300K of GaSb(n^+)/$Ga_{0.53}Al_{0.47}As_{0.04}Sb_{0.96}$(p) heterojunction. In inset: (b) the mesa epitaxied structure.

The typical current-voltage characteristic of a $GaSb(n^+)/Ga_{0.53}Al_{0.47}As_{0.04}Sb_{0.96}(p)$ heterojunction, at room temperature, is represented in "Fig. 1 ". It shows a rectifying behavior: The forward current increases exponentially with voltage, and the reverse bias current presents a slight saturation for low reverse applied voltages and increase slowly, without any breakdown. This is the general aspect of I-V characteristic theoretically expected for an n-p heterojunction between two semiconductors 1 and 2, where the work functions and the net carrier densities are as $eV_1 > eV_2$ and $Nd_1 > Na_2$ [8]. In a previous work [7] we have deduced, using the capacitance voltage technique, the band diagram of the heterojunction which presents a pseudo discontinuity E_C in the conduction band, and a strong discontinuity E_V in the valence band, as observed in ref 14 for the same system. Consequently of the existence of this strong discontinuity in the valence band, the current in such a structure is theoretically due to thermoionic emission of holes over the barrier [8]-[14]-[15], and obeys to the law [8]:

$$I \quad I_S \left[e^{\frac{qV}{nkT}} \quad e^{\frac{qV}{kT}} \right] \qquad (1)$$

$$\text{With} \quad I_S \quad SA^{*}T^{2}e^{\frac{qVb}{kT}} \qquad (2)$$

Is the saturation current and n the ideality factor. The parameter is related to dielectric constants and net carrier densities of the two semiconductors 1 and 2, respectively GaSb and GaAlAsSb, by the following equation [8]:

$$\frac{{}_2 Na_2}{{}_1 Nd_1 \quad {}_2 Na_2} \qquad (3)$$

The calculation gives a coefficient about 0.015.

The reverse current, as it can be seen on "Fig. 1 ", varies slowly with the applied voltage as expected by the second term of the equation (1). Nevertheless, the law (1) could not perfectly fit the experimental curve, as observed for other semiconductor heterojunctions [16]. Probably other transport mechanisms contribute to the current.

The semi-logarithmic plot of the forward I-V characteristic "Fig. 2 " shows different regions of current : Down to 0.6 V the current can be interpreted by a thermoionic emission of holes. For the low polarizations inferior to 0.2 V, a leakage current due to a shunt resistance R_{sh} is added. Above 0.5 V, the characteristic is deviated by the series resistance effect, generally observed for other semiconductor heterojunctions [15]-[17]. In our case the series resistance is due essentially to the GaSb substrate. Besides, one can show that for forward voltages up to 0.7 V, a band to band tunnel effect arises when the bands become opposite each other under the effect of polarization. The current varies with the applied voltage as $V^{3/2}$.

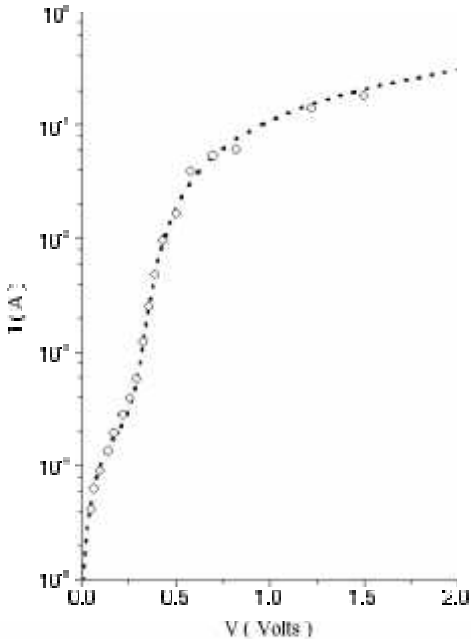

Fig. 2 A semi-logarithmic plot of the typical direct I-V characteristic at T = 300K, for the $GaSb(n^+)/Ga_{0.53}Al_{0.47}As_{0.04}Sb_{0.96}(p)$ heterojunction.

Like that, other kinds of charge transport mechanisms contribute to the current with the thermoionic emission of holes over the barrier, making difficult the determination of accurate values of the heterostructure parameters Is, Rs and n [18]-[19]-[20]. However, the behaviour of the I-V characteristic allows the use of other methods, initially expected for Schottky diodes, to determine Rs and n. Theses techniques are based on the following expressions [21]-[22]:

$$I \quad \frac{kT}{qRs} \quad a \quad n \qquad (4)$$

$$\frac{G}{I} \quad \frac{q}{nkT} \quad 1 \quad GRs \qquad (5)$$

where I and G are respectively the current and the differential conductance of the diode, a is a parameter which can take values from 1 to . The results, R_s = 5 and R_{sh} = 1.2 k , were used to correct the I-V curve and to deduce I_s 10^{-8} A and n 1.1, suggesting a good quality of the heterojunction interface. Then, the experimental I-V curve can be interpreted in direct polarizations by a law of kind :

$$I \quad I_S e^{\frac{q\,V \quad R_s I}{nkT}} \quad \frac{V \quad R_s I}{R_{sh}} \quad I_T \qquad (6)$$

Where I_T is a tunnel component varying proportionally to $V^{3/2}$.

III. BARRIER HEIGHT AT GaSb (n^+) / GaAlAsSb (p) INTERFACE

The Schottky behavior observed on our GaSb (n^+) / GaAlAsSb (p) heterojunction can be easily explained considering the high doping of the n side GaSb ($N_d = 10^{+18}$ cm^{-3}) which locates the space region in the GaAlAsSb side, so that the band bending essentially relates to the quaternary, as derived by the voltage-intercept in capacitance-voltage characteristic [7] .

The structure becomes similar to Schottky diode where the role of the metal is played by the n^+-GaSb semiconductor. This behavior was observed previously for other heterojunctions [15]. Using values given on table 1, the barrier height V_b, characterizing the structure can be deduced from the law giving the saturation current Is (equation 2), V_b = 685 meV.

The Richardson constant of the structure, was calculated $A^* = 49.1$ $AK^{-2}cm^{-2}$, taking into account the positions of the bands in the heterostructure and also values of electron and hole affinities[8].

No Richardson constants values for this structure are given in the literature. Rotelli et al [23] give $A^* = 5.1$ $AK^{-2}cm^{-2}$ for n-GaSb/Au Schottky diode.

We observe that the barrier height found is lower than that obtained by capacitance-voltage measurements, performed on the same heterojunction, Vd_2 = 792 meV [7]. The difference between the two methods is that the capacitance–voltage characteristic is measured in reverse bias whereas the I-V is measured in forward bias so that transport mechanisms which increase the saturation current appear, lowering consequently the barrier height V_b.

Other researchers have reported previously that the capacitance-voltage method gives higher values for the barrier height [16]-[23]-[24]-[25].

TABLE I : Parameters related to GaSb(n+) and GaAlAsSb(p), * values obtained by linear interpolation. ** values calculated in ref [7].

PARAMETERS	SC_1- GaSb(n+)	SC_2- GaAlAsSb(p)
Dielectric constant / o	15.69	13.84 *
Net carrier density (cm^{-3})	10^{18}	$1.2\ 10^{16}$
Energy gap Eg (meV)	725	1313
Energy of the Fermi level (meV)	10 **	178 **
Electron affinity e (meV)	4.06	3 .84 *

Knowing the potential contact $V_{d2} = V_b$ = 685 meV in the wide gap p semiconductor, and using the parameters of the table I, we can draw the heterostructure diagram on "Fig. 3 ", and derive the conduction and valence band-offsets, E_C = 460 meV, E_V = 128 meV. These values are well related to those determined by the intercept (C-V) method on the same heterostructure [7]. The difference is due to the used method in the determination of contact potential V_b and errors on calculations and measurements, estimated generally at 50 meV. By I-V method, Polyakov et al. have found for $Ga_{0.5}Al_{0.5}AsSb$(p)/GaSb(n) E_V = 150 meV [10], and for $Ga_{0.5}Al_{0.5}As_{0.04}Sb$(p)/$Ga_{0.85}In_{0.15}As_{0.13}Sb_{0.87}$(n) close system E_V = 100 meV [11]. Our results are also in agreement with the theoretical correlated predictions of Jaros [12] and Mujica et al [13].

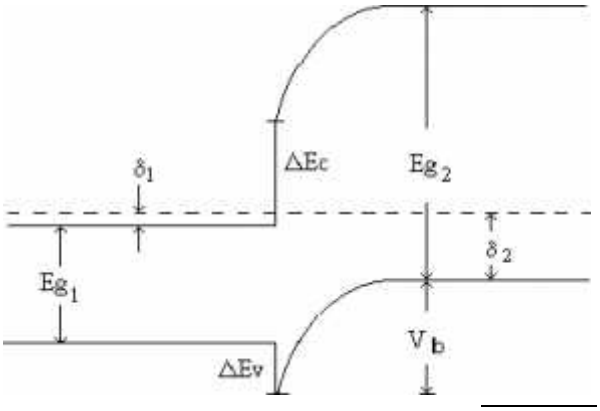

Fig. 3 Band diagram at equilibrium of the $GaSb(n^+)/Ga_{0.53}Al_{0.47}As_{0.04}Sb_{0.96}$(p) structure.

We report on "Fig. 4 " our results and some experimental data for the valence band offsets of $GaSb/Ga_{1-x}Al_xAs_ySb_{1-y}$ heterojunction in order to study the variations of E_V band offset with x_{Al} composition of the quaternary layer. In the figure are also reported the bandgap variation of direct E and indirect E_X and E_L transitions. When we compare with theoretical models [12]-[13]-[26]-[27], we conclude that for Al compositions less than 0.5, where the transport of electrons occurs in the and L valleys of the conduction band, the valence band offset variations with Al composition, are well explained by Jaros [12] and Mujica et al [13] models.

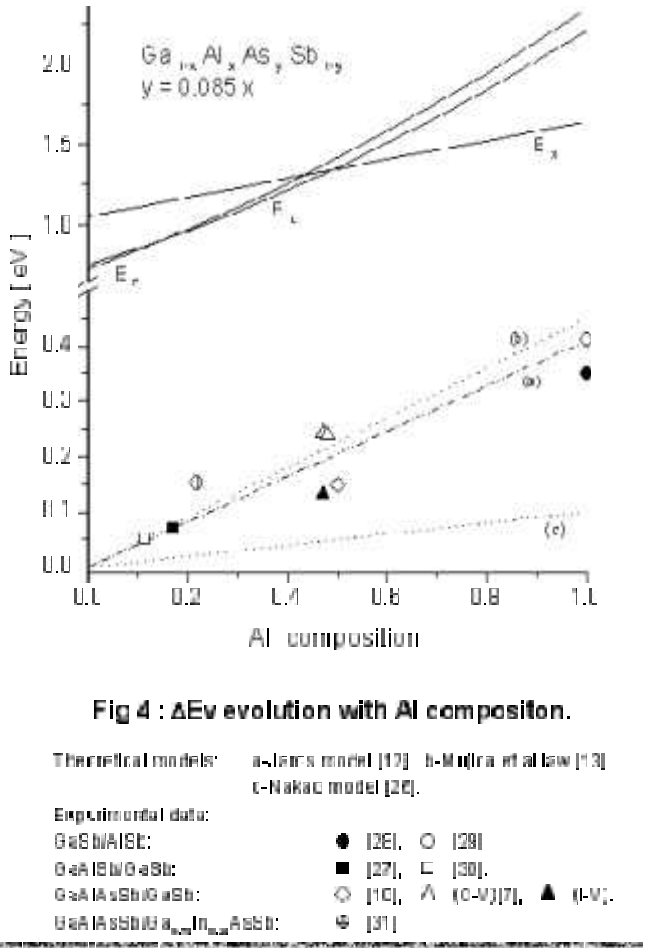

Fig 4 : ΔEv evolution with Al composition.

Theoretical models: a-Jasers model [17] b-Mujica et al law [13] c-Nakao model [26].

Experimental data:
GaSb/AlSb: [28], [28]
GaAlSb/GaSb: [27], [30].
GaAlAsSb/GaSb: [10], (C-V)[7], (I-V).
GaAlAsSb/$Ga_{1-x}In_xAsSb$: [31]

IV. CONCLUSION

We have reported on the current-voltage characteristic of a GaSb(n+)/$Ga_{0.53}Al_{0.47}As_{0.04}Sb_{0.96}$(p) heterojunction in order to understand the physical phenomena at the interface. We show that the transport mechanisms consists essentially of thermoionic emission of holes over the valence band barrier, at which add other effects.

We calculate from the characteristic the barrier height and treat the heterojunction so that the valence band offset plays the role of a Schottky barrier of 685 meV. The Richardson constant is calculated to be $A^* = 49.1\ A.cm^{-2}.K^{-2}$.

The band offsets are derived E_C = 460 meV and E_V = 128 meV, in good agreement with those determined by capacitance-voltage method and with other works. We find also that the models proposed by Jaros and by Mujica are those which relate better the variations of Ev valence band offset versus the quaternary alloy compositions in 0 – 0.5 x_{Al} range.

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