AlGaAs/GaAs HETEROJUNCTION BALLISTIC BIPOLAR TRANSISTORS (BBT) FOR EHF AMPLIFIERS

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ABSTRACT

This paper presents the theory and design of AℓGaAs/GaAs heterojunction Ballistic Bipolar Transistors(BBTs) which utilize heterojunction injection and ballistic electron motion in GaAs. Key factors for the successful realization of this new 3-terminal EHF solid-state device are identified and discussed. We present for the first time an ideal emitter junction structure with suitable Aℓ concentration and doping profile as well as an "inverted" heterojunction bipolar device structure. The proposed inverted BBT structure has the advantages of reducing both the base current and the important emitter-base capacitances. The performance of this new device makes it an attractive candidate for the first realizable 3-terminal solid-state device capable of amplification in the EHF frequency range (60 GHz and above) as well as GaAs gigabit logic building block. It is believed that BBT represents a new 3-terminal device of tremendous promise for both analog and digital MMIC and M^3IC applications.

INTRODUCTION

Heterojunction transistor has been proposed by Shockley [1] and Kroemer [2] over twenty-five years ago. Its high frequency performance is expected to be excellent because its emitter junction capacitance does not increase while the base resistance decreases. Dumke, Woodall and Rideout [3] were the first to present a practical design of an AℓGaAs/GaAs heterjunction transistor. A series of papers on heterojunction transistors [4]-[10] have been published recently and Kroemer [11] has written an excellent paper on the basic theory of the heterojunction bipolar transistor and its implication to future high-speed IC applications. However, up to now, no microwave GaAs bipolar with RF performance better than the conventional silicon microwave transistors has been reported, and no successful GaAs bipolar with electrode dimensions less than 5 μm has been reported. The reasons for these are due to the basic fabrication and design difficulties encountered and some important device design considerations are neglected.

Recently, a ballistic bipolar transistor (BBT)-bipolar transistor utilizing heterojunction injection and ballistic electron motion was proposed by Zhu and Ku [12]. In this paper, some key steps for the successful realization of BBT are identified and discussed. These are (a) Ideal emitter-base junction structure, (b) Reduction of emitter transit time and delay time, (c) "Inverted" structure, (d) Reduction of contact resistance.

ELECTRON BALLISTIC MOTION AND THE ESSENTIAL PRINCIPLE OF BBT

Electron ballistic motion is investigated recently by Eastman et al [13][14]. Even though some questions have been raised [15]-[19], we can state the basic theory as: the electrons moving in a bulk GaAs could be accelerated rapidly by a potential drop along the [100] direction to obtaining a kinetic energy of 0.3 eV, they will have a mean free path of 0.15μ at room temperature. If collisions occur for some of them, their energy will be reduced by little more than 10%. In addition, the deflection angle range can be small (5°-10°). These electrons may travel a much longer distance near ballistically.

As evidence of electron ballistic motion, an experimental planar doped barrier transistor with a CE D.C. current gain of about 20 was reported [20]. This fact indicates that electrons can cross the base of thickness 0.1∿0.4μ, which is an energy band valley between two barriers, so the only way the electrons could cross it is moving ballistically. Thus supporting conclusive evidence for the statement mentioned above.

Our proposal is that we can realize a ballistic bipolar transistor if the injecting electrons through the neutral base of a conventional bipolar transistor have an initial kinetic energy. This is possible if we notice that when the material composition varies abruptly there will be a potential drop at the heterojunction interface due to the difference in electron affinities [21]-[24]. [See Figure 1]. This discontinuity in conduction band

$$\Delta E_c \cong 0.85\ \Delta E_g = (1.06 \pm 0.03)\ x_{AlAs}, \text{ for } x<0.45 \quad (1)$$

where E_g is the difference in energy gaps. Therefore, electrons injected from an $Al_{0.20}Ga_{0.80}As$ emitter into a GaAs base will have an initial kinetic energy greater than 0.21 eV, and will move through the base and the collector depleted layer near ballistically, thus making possible the realization of a BBT.

It is believed that even higher doping will not seriously interfere with ballistic electron motion, because electrons with energy 0.1∿0.3 eV encounter rather small ion scattering cross-section. The width and doping of the base would be selected experimentally, so that a relatively low value of resistance and high value of cutoff frequency can be obtained [25].

The Trade-off Between Injection Efficiency and Electron Ballistic Motion

As discussed by Kroemer [7], a shortcoming of a barrier at the heterojunction interface is reduction of h_{FE}. However, the trade-off between injection efficiency and electron ballistic motion is possible. Ankri et al [26] have discussed this problem, but in their calculation, hole injection from p+-base near the interface is neglected and the applicability of the drift-diffusion equation for the emitter of a ballistic bipolar transistor is questionable.

It is easy to understand that the potential drop ΔE_C should be large enough to launch the injected electrons, but should not be so large as to cancel the effect of the heterojunction energy-gaps difference ΔE_g, the D.C. gain h_{FE}, which is proportional to $\exp[\Delta E_g - \Delta E_C/nKT]$ will still be higher. For a $Al_{0.3}Ga_{0.7}As$ emitter. A ΔE_C value of 0.18 ~ 0.24 eV is expected.

In order to reach the value of ΔE_C, a structure with suitable Aℓ concentration and doping profile is suggested. [See Figure 2].

Across the emitter n-p^+ junction, the Aℓ concentration is varied gradually, and the doping changes abruptly at the point where the expected Aℓ concentration is reached
[for ΔE = 0.21 eV. $X_{A\ell}$=0.20]

Because the variation of the valence band edge with Aℓ concentration in p^+ region is very small (nearly no change of electrical potential in p^+ base), so that the conduction band edge varies with the variation of Aluminim concentration, a constant potential drop is formed in front of the base near the emitter junction. The depleted layer of E-B junction is mainly in the n-region, where the Aℓ concentration varies gradually, and the electrical potential drops more abruptly, so that the conduction band edge becomes lower. Thus we obtain a barrier at the interface with the necessary constant potential drop and the value of ΔE is determined only by the Aℓ concentration at the interface.

This proposed structure is easier to fabricate and difficulties such as the spike and notch in the energy band, the quantum mechanical tunnel and reflection effect, and the traps at abrupt varied interface, etc., are circumvented.

CUT-OFF FREQUENCY AND EMITTER DOPING

The cut-off frequency f_T of a bipolar transistor is given by [27]

$$f_T = 1/2\pi[\tau_e' + \tau_b' + \tau_c' + \tau_e + \tau_c]. \quad (2)$$

It includes all the transit times and R-C delay times including the emitter, base and collector transit-times, τ_c', τ_b', τ_c', respectively, and the emitter delay time $T_e = r_e c_{eb}$, where $r_e = kT/eI_e$, I_e is the emitter current and c_{eb} is the E-B capacitance, and the collector delay time τ_C is a relatively small quantity in general.

Evidently, if we want to obtain a small total transit and delay time, all terms in (2) should be minimized. When the electron kinetic energy is above 0.20 eV, the ballistic motion velocity is about 10^8 cm/sec and the transit time of electrons crossing the base, τ_b', and the collector depleted layer, τ_c', is very short. For example, if the thickness of base and collector depleted layer is 0.1μ and 0.2μ respectively, the transit time will be $\tau_b' = \tau_c'$=0.1 ps. The emitter transit time τ_e' and the emitter delay time, τ_e will impose the major limitations for the high frequency performance of the BBT.

It should be emphasized that the emitter transit time τ_e' must be considered seriously. It seems that almost all authors have neglected this factor [2]-[7][11][20] and have chosen a very low emitter doping in order to obtain a smaller emitter base capacitance. If diffusion motion is obeyed by the electrons moving in the emitter depleted layer, the emitter transit time, τ_e', will be considerably greater because the electrons travel under a retarded electric field.

According to the calculation results for silicon double-diffused transistors by Retagi et al. [28][29] when the thickness of the emitter depleted layer is altered from about 370 Å to 950 Å, the corresponding emitter transit time changes from 8 ps to 70 ps. This calculation is verified by the fact that when arsenic is used instead of phosphorous for an emitter diffusant and the transit time is significantly reduced [29]. Such a long emitter transit time as mentioned above is not acceptable.

Therefore, it is necessary to ensure that the thickness of the emitter depleted layer, d, is much less than the mean free path of the lower energy electrons; then the value of τ_e' may be less than o.1 ps. In GaAs, the mean free path for lower energy electrons is about 1000Å, and the values in AℓGaAs will not be lower than 500Å. A value of about 300Å for d may be used, corresponding to an emitter doping of $2x10^{17} cm^{-3}$.

The emitter depleted layer is rather thin now and the question is how can we reduce the emitter-delay time τ_e? The emitter delay time is given by

$$\tau_e = r_e c_{eb} = [kT/eI_e] \cdot [\kappa A_e/d] = [\kappa kT/ed] \cdot [I_e/A_e]^{-1} \quad (3)$$

where κ is dielectric constant, τ_e is inverse proportion to the current density. τ_e will be reduced when I_e/A_e is sufficiently large.

Because the ballistic motion velocity is greater, a larger current density is possible; for example, if the doping of collector depleted layer is $1x10^{16}$ cm^{-3}, then I_{max} may be $3.2x10^5$ $/cm^2$. Thus the emitter delay time will be as low as 0.1 ps

Accordingly, even with the reduction of τ_e. once again a heavy emitter doping is necessary. Because the emission velocity of electrons crossing the emitter barrier is rather small, the electron density on the top of barrier is limited by the emitter doping. If the emitter doping is not heavy enough, the emission current density will be small and the loss due to the increase of τ_e is more than the gain of C_{eb} reduction for lower emitter doping. We have shown that the widely adopted low-doping emitter is not a reasonable one and a doping concentration of at least $2x10^{17}cm^{-3}$ should be used. The optimum value of emitter dopoing concentration has recently been calculated by the authors [30] and this conclusion is consistent with that due to Asbeck et al.[31].

INVERTED BBT STRUCTURE

The key to the successful realization of BBT is the reduction of parasitic elements. "Inverted" structures have been proposed by Beneking et al [5] and Kroemer [11] for the conventional heterojunction bipolar transistors and by Zhu and Ku for the ballistic bipolar transistors [12]. In this structure, the substrate is used as an emitter and not as a collector as the conventional structure. The emitter lead inductance is eliminated and the collector-base feedback capacitance is reduced. Both of these parasitics are important for high-frequency operations. In addition this structure is more suitable for monolithic microwave matching and IC applications such as the I^2L.

For the electrode contact to the base, Be^9 is implanted from the collector side to the depth of the GaAℓAs emitter layer. Because the barrier of a GaAℓAs p-n junction is higher than the emitter base injecting barrier, the injection from the emitter to the Be^9 implanted p-region is expected to be blocked [8] [11]. Our experimental work indicated that the blocking effect is not ideal as expected. In fact, the annealing process after Be implantation poses some difficulties [32][33] and a large number of defects still remain in this region resulting in a E-B leakage current which reduces the D.C.gain. This is a major difficulty in doing inverted structure. In order to overcome this problem, an isolation layer is formed beneath the Be implanted region, which improved the D.C. gain and, at the same time, the additional capacitance between emitter and Be implanted region is reduced. A nearly ideal structure is thus obtained by this important fabrication step.

REDUCTION OF OHMIC CONTACT RESISTANCE AND EMITTER LEAD INDUCTANCE

Since a smaller dimension is needed, the reduction of contact resistance is also necessary which is a major difficulty encountered by previous contributions on heterojunction bipolar transistors Up to now, the conventional technologies for small dimension devices still have not been used for the fabrication of GaAs bipolar transistors. As yet, no RF results of these devices have been reported.

Emitter resistance is larger in some earlier devices and is considered as the main limitation of its high-frequency performance. This could be solved by adding a n+-GaAs cap on the AℓGaAs emitter and the resistance due to the AℓGaAs-GaAs interface could be avoided by heavy doping and using a gradual Aℓ concentration. The contact resistance on n+-GaAs layer is no longer a problem and a specific resistivity value of less than $1x10^{-6}$ cm^2 is obtainable [34].

Kroemer has recently discussed in detail the base resistance of a microwave transistor and a digital switching transistor [11]. However, difficulty comes from the contact resistance on the p-layer. Reported values of specific resistivity are of the order of $1x10^{-4}$ to $1x10^{-5}\Omega cm^2$, which is too large. Further work is needed to reduce the contact resistance on p+ GaAs. Instead of GaAs, GaInAs may be used as the base-collector material in our proposed inverted BBT structure to overcome the difficulty discussed above.

As an alternative method, it is noted that there is a capacitance C' at the interface in parallel with the contact resistance, r'. The equivalent series resistance $1/\omega^2c'^2r$ will be small at high frequency if the value of C' is large enough. For example, suppose the depleted larger thickness is 100Å between the metal electrode and p+-surface and c' is 1.10^6pf/cm^2. The value of $1/\omega c'$ is equal to $1.6x10^{-5}$ Ωcm^2 at 10 GHz. A larger parallel contact resistance of $1x10^{-4}$ Ωcm^2 will correspond to a smaller value of series resistance of less than $2.5x10^{-6}\Omega cm^2$. Therefore, we can reduce the high-frequency equivalent interface resistance and a larger low-frequency value of r' is permissive due to the higher DC gain and smaller base current.

EXPERIMENTAL RESULTS

An inverted structure BBT with the electrode width of 2μ is fabricated as shown in Figure 3. The area of the two collector fingers is 2μx10μ and the emitter area is 12μx18μ. It is believed that the dimensions of this device are the smallest reported to date. The material was grown by molecular beam epitaxy on a N^+-GaAs substrate As shown in Figure 4, the emitter doping concentration is $2.5x10^{17}$ cm^{-3}, base doping concentration is 3-$5x10^{18}$ cm^{-3} and the collector N^- - N layer doping concentration is $1x10^{16}$ cm^{-3} and 1-$2x10^{17}$ cm^{-3}, respectively.

Double Be implantation (40 keV, $3x10^{14}cm^{-2}$; 100 keV, $6x10^{14}cm^{-2}$) was used for base contact and a proton implantation in front of the Be-implanted layer is used. Our experimental results on a test diode show that the forward current is blocked by proton implantation. The doping concentration of n-AℓGaAs region is $2x10^{17}cm^{-3}$ and the p+ region is formed by Be-implantation. (40 keV, $1.5x10^{14}cm^{-2}$, 100 keV, 3-$10^{14}cm^{-2}$).

After Be implantation and annealing at 700°C, 30 min., the D.C. gain of the transistor is very low. This is improved by about two (2) orders of magnitude by proton implantation. The surface was covered by sputtering SiO_2 and conventional Au-Ge-Ni electrode is used for the emitter and the collector and alloyed at 450°C. Finally Cr-Au Schottky barrier electrode is used for base contact.

Figure 5 presents the D.C. out-put I-V characteristics of the BBT. The curves are more perfect with a D.C. gain of 20 and rather low value of collector and emitter resistance. It is worthy to note that an operation current as high as $4x10^4 A/cm^2$ could be reached. An emitter-grounded 100 mil package was used. Based on measured equivalent circuit element values and careful RF device model and calculated scattering parameters of the "inverted" structure BBT, a f_{max} exceeding 60 GHz can be predicted. Detailed experimental results will be presented in the paper.

ACKNOWLEDGMENT

The authors are indebted to Professor L. F. Eastman of Cornell University for valuable technical discussions, T.H. Hsu of Harris Microwave Company for packaging and high-frequency measurements and J. Q. He for technical assistance in computer-aided device modelling. Partial support by the Naval Research Laboratory on this work is also acknowledged.

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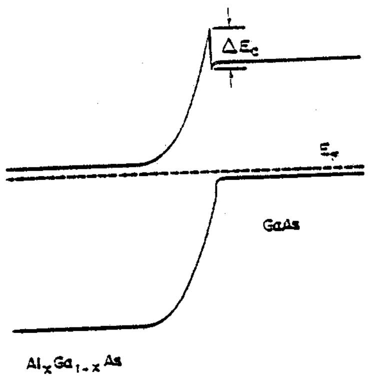

Fig.1. Discontinuity in AℓGaAs/GaAs Heterojunction Energy Band.

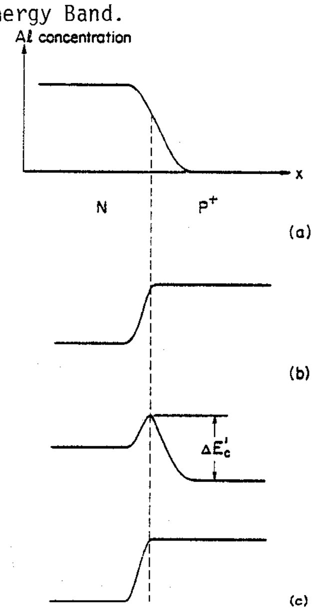

Fig.2. Proposed Aℓ Concentration, Doping Profile and the Energy Diagram at the E-B Junction.

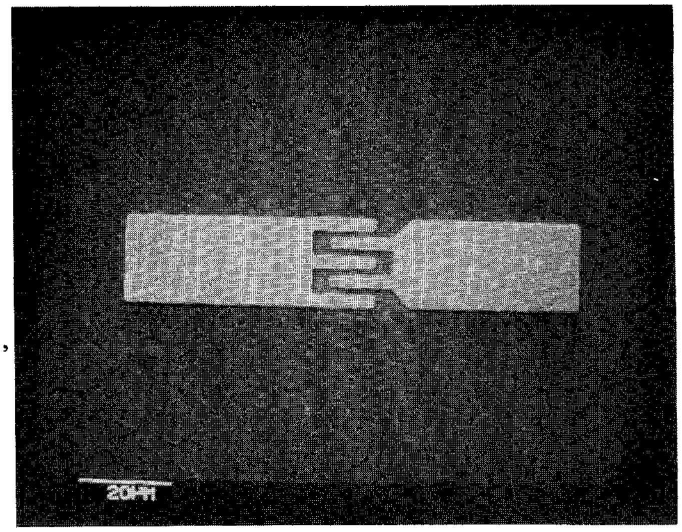

Fig.3.The Inverted Ballistic Bipolar Transistor(BBT).

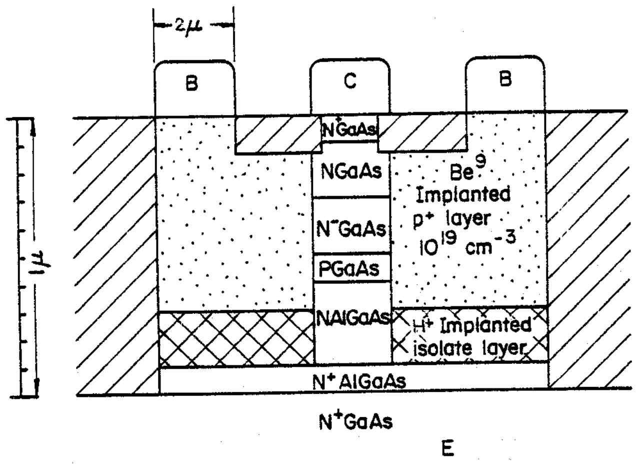

Fig.4.Layer Structure of the BBT.

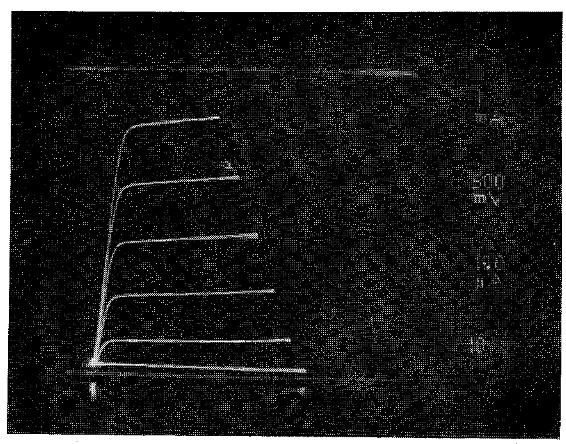

Fig.5. Measured I-V Characteristics of the BBT.