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# Gunn effect in heterojunction bipolar transistors

V. A. Posse and B. Jalali

*Indexing terms: Heterojunction bipolar transistors, Gunn effect*

The Gunn effect in III-IV heterojunction bipolar transistors is investigated using hydrodynamic simulations. It is shown that Gunn domains nucleate and propagate in the collector drift region of an *npn* AlGaAs/GaAs transistor in which the electric field at the base-collector space charge region is properly engineered.

The transferred-electron (Gunn) effect in direct bandgap semiconductors has been of interest for some time [1, 2]. Gunn diodes exploit the negative differential mobility which results from the transfer of electrons from the central Γ valley to large effective mass L and X satellite valleys under a sufficiently high electric field. The instability resulting from the nonlinear field-velocity dependence manifests itself in electron accumulation and the creation of charge domains which move with the saturated drift velocity. On annihilation in the anode, these domains produce current pulses with period corresponding to the length of the transit region and the saturated drift velocity. The diodes serve as low-cost solid-state micro- and millimetre wave sources in radars, intrusion alarms, microwave test instruments and other systems. From a circuit design point of view the two terminal structure of Gunn diodes is a major drawback. This has fuelled work on the transferred electron effect in three-terminal unipolar devices similar to MESFET structures [3, 4]. In this Letter we report our investigation of Gunn effects in III-V heterojunction bipolar transistors (HBTs). We find that in a device with a properly engineered electric field profile, Gunn domains do indeed form and propagate in the collector drift region of a GaAs HBT.

In our numerical simulations we calculated the transient device response using the hydrodynamic model of electron transport. In these simulations the Poisson equation and the first three velocity-moments of the Boltzmann transport equation (which are commonly known as the continuity, current-density and energy balance equations) are solved self-consistently for both types of charge carrier [5]. For simulation of the Gunn effect, the requisite nonlinear velocity-field relation is implemented through a field dependent mobility model. The potential, carrier densities, currents, electric field and other parameters are extracted from the final solution. Recently, Zybura *et al.* [6] have successfully used the hydrodynamic model to simulate conventional Gunn diodes.

Fig. 1 shows the potential energy diagram of the *npn* GaAs HBT structure under bias in the forward active region. The emitter consists of an $n^+$ GaAs contact layer, a 500Å graded Al$_x$Ga$_{1-x}$As transitional layer and a 1500Å Al$_{0.3}$Ga$_{0.7}$As layer with $5 \times 10^{17}$cm$^{-3}$ doping. The $p^+$ GaAs base is 1000Å wide and doped to $1 \times 10^{19}$cm$^{-3}$. The drift region of the collector is 3µm long and doped to $2 \times 10^{16}$cm$^{-3}$. The collector length was chosen to ensure enough distance for a charge domain to emerge and develop if other conditions are met. Transient simulations are performed with step voltages of 1.5 and 5V applied to the base and collector terminals, respectively.

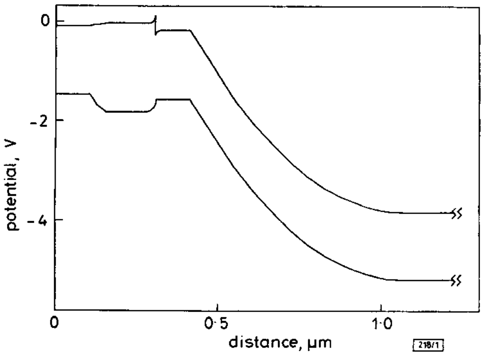

**Fig. 1** *Band diagram of AlGaAs/GaAs npn HBT under forward active bias in common emitter scheme*

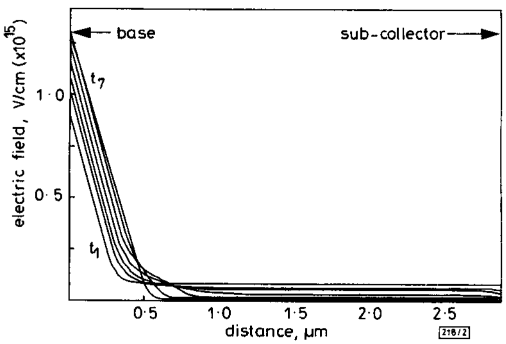

**Fig. 2** *Time evolution of electric field profile in collector drift region of conventional HBT*

$t_1$ = 0.2ps, $t_7$ = 4ps after application of bias at $t$ = 0

Fig. 2 shows the time evolution of the electric field profile in this structure. As expected, the device reaches a steady state which corresponds to the depletion region of the base-collector *pn* junction under the given bias. This occurs in spite of the fact that the electric field is high enough for the onset of negative differential resistance. Although a small charge fluctuation is observed at ~0.6µm into collector, it is quickly annihilated leading to the formation of the conventional depletion region. The Gunn effect is clearly suppressed by the space-charge-region (SCR) electric field of the base-collector *pn* junction. Such a field is obviously absent in a conventional Gunn diode.

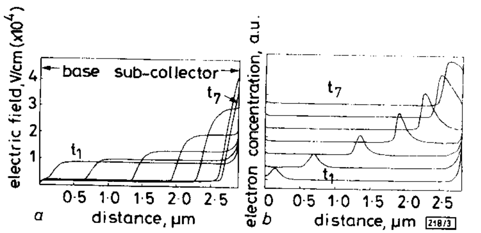

**Fig. 3** *Time evolution of electric field profile and electron concentration in collector modified with $n^+$ doping spike*

$t_1$ = 2ps, $t_7$ = 27.5ps after application of bias at $t$ = 0

*a* Electric field profile
*b* Electron concentration

To prevent the SCR field from extending into the drift region, a thin $10^{14}$cm$^{-2}$ $n^+$ doping spike was introduced at the base edge of the $n^-$ collector. The SCR is contained by this spacer layer, leading to a significantly different initial electric field profile in the drift region. Fig. 3 shows the evolution of the field profile and the electron concentration under the same bias conditions as in Fig. 2. The electric field profile in Fig. 3*a* is clearly unstable and indicates the presence of the Gunn effect. This is supported by the electron concentration shown in Fig. 3*b*, which clearly shows nucleation, growth and propagation of an accumulation layer. We have verified that this phenomenon is a direct consequence of the nonlinear velocity-field relation. Without the nonlinear mobility model the device exhibits a stable behaviour. At the anode the accumulation layer reaches a stable configuration, caused by a back diffusion of charge which counterbalances the drift process. Diffusion stabilised Gunn domains have been discussed and observed in conventional Gunn diodes [7]. Random electric field fluctuations, caused by defects and doping inhomogeneities, absent in our simulations, cause retriggering and oscillations in an actual device.

In summary, we have presented an investigation of the Gunn effect in *npn* heterojunction bipolar transistors. Numerical simulations show that in a conventional transistor with a collector doping concentration of $2 \times 10^{16}$cm$^{-3}$, instabilities are suppressed by the SCR electric field of the base-collector *pn* junction. Nucleation, propagation and growth of Gunn domains are observed in a modified HBT structure in which the SCR field is contained by an $n^+$ doping spike at the beginning of the collector drift region.

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# InP-based single heterojunction bipolar transistors with improved breakdown characteristics

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*Indexing terms: Heterojunction bipolar transistors, Molecular beam epitaxial growth, Indium phosphide*

InP-based heterojunction bipolar transistors (HBTs) have been fabricated from material grown by metal organic molecular beam epitaxy (MOMBE) using InGaAsP with a bandgap of 0.95eV as both the collector and base material. The 4000Å collector was undoped with an electron concentration of $6 \times 10^{16}$cm$^{-3}$ and the 850Å base layer was doped with Mg to a hole concentration of $10^{19}$cm$^{-3}$. The DC gain for 90μm diameter emitter dimension devices was measured to be 340 with a base sheet resistance of 760 Ω/□. The collector and base ideality factors were 1.1 and 1.4, respectively. The breakdown voltage $V_{CEO}$ of 7.5V represents a significant improvement over similar devices with conventional InGaAs collector and base layers.

*Introduction:* Over the past five years, great progress has been made in the performance of InP-based heterojunction bipolar transistors (HBTs). Most of the devices reported thus far are single heterojunction structures which employ InGaAs as both the base and collector material. Although this configuration produces excellent current gain and I-V characteristics, the breakdown is rather low, typically 3 – 4V, due to the small bandgap of the InGaAs [1]. Attempts to increase the breakdown by replacing the InGaAs collector with either InP or AlInAs, thus creating a double heterojunction (DH), usually lead to degradation of the I-V characteristics due to the band discontinuity between the InGaAs base and the wide-bandgap collector [2–4]. In addition the capacitance of the device is increased leading to reduced speed. In this Letter we describe the performance of devices in which the InGaAs collector layer, with a bandgap of 0.74eV, is replaced with InGaAsP with a bandgap of 0.95eV. To avoid the problems associated with the DH structure, we have also used InGaAsP (0.95eV) as the base material.

Changing the composition of the base necessitates a change in the base dopant as well. To date, most of the InP-based devices grown by MOMBE have relied primarily on Be effusion ovens for *p*-type doping. However, in InP, the maximum hole concentrations which can be attained are only 5 – $6 \times 10^{18}$cm$^{-3}$ due to poor activation and severe segregation of the Be. Thus alloys which contain significant mole fractions of InP are severely limited in hole concentration when doped with Be. In addition, gaseous sources are highly desirable for use in MOMBE to avoid the problem of cell degradation often encountered when using gaseous and elemental sources in the same chamber. Zn doping from diethylzinc (DEZn) has been studied [5,6], though Zn typically exhibits a high diffusion coefficient that can lead to diffusion during growth [6] or even degradation of device performance during post-growth processing. Even at growth temperatures below 500°C, Zn concentrations in InP above ~$1.5 \times 10^{18}$cm$^{-3}$ lead to smearing of the dopant profile. In addition, high concentrations of Zn at the growth surface also appear to reduce the In incorporation rate, which leads to a decrease in the InP growth rate and reduction in the In content in InGaAs and InGaAsP. The utility of Zn doping for InP in MOMBE, therefore, appears to be limited to levels $< 10^{18}$cm$^{-3}$.

One candidate which appears promising, particularly for doping of InP and InGaAsP, is Mg. Biscyclopentadienylmagnesium ($Cp_2Mg$) has been shown to yield excellent electrical activation up to ~$2 \times 10^{18}$cm$^{-3}$ in InP [7]. Above this level, the Mg continues to incorporate, but the activation drops until at a level of ~$10^{19}$cm$^{-3}$ only 40% of the Mg is active. By analogy with other *p*-type dopants in III-V materials, we would expect this non-substitutional Mg to diffuse rapidly from the growing layer. However the Mg profiles remain relatively sharp even at the highest doping level. As expected, higher levels can be achieved in InGaAs than in InP, with well-confined hole concentrations up to $10^{19}$cm$^{-3}$ reported [7]. Thus Mg was chosen as the *p*-type dopant for the InGaAsP base layers.

| | |
|---|---|
| **2000Å** | **InGaAs:Sn** |
| **1500Å** | **InP:Sn** |
| **1000Å** | **InP:Sn** |
| **25Å** | **InGaAsP (0.95eV)** |
| **850Å** | **InGaAsP:Mg (0.95eV)** |
| **45000Å** | **InGaAsP (0.95eV)** |
| **200Å** | **InP:Sn** |
| **3000Å** | **nGaAsP:Sn (0.95eV)** |
| **Fe: InP substrate** | |

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**Fig. 1** *HBT layer structure grown by MOMBE*

HBT structures of the type shown in Fig. 1 were grown in an INTEVAC gas source Gen II on 2″ diameter (100) semi-insulating Fe:InP substrates using In-free mounting. Growth temperatures were maintained at 530°C until growth of the InP emitter was initiated. At this point the temperature was reduced to 490°C for the remainder of the run. Temperatures were measured with the substrate thermocouple. InP layers were grown from trimethylindium (TMI) while InGaAs and InGaAsP layers were grown from tri-