

Transferred-electron induced current instabilities in heterojunction bipolar transistors

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Current driven instabilities in the collector of III–V heterojunction bipolar transistors (HBT) are investigated. Numerical simulations indicate that in a modified AlGaAs/GaAs HBT the collector current shows oscillatory behavior due to the transferred-electron (Gunn–Hilsum) effect. Influence of the Kirk effect as well as conditions for oscillation are discussed. © 1995 American Institute of Physics.

Gunn diodes, which utilize the transferred-electron effect in direct band gap semiconductors, represent low-cost, low-complexity sources of micrometer and millimeter wave radiation. They are extensively used for generation, and to lesser extent for amplification and processing of signals in the frequency range from 1 to 100 GHz. Currently, Gunn diodes are used in radars, intrusion alarms, microwave test instruments, and other systems. Furthermore, they are being considered in the development of automotive collision avoidance radars operating at 78 GHz.¹ Recently, second-harmonic InP Gunn diodes producing 7 mW of power at 188 GHz have been demonstrated.²

The operation of Gunn diodes relies upon current driven instabilities due to transfer of electrons from the central Γ valley to large effective mass L and X satellite valleys under a sufficiently high electric field. Such instabilities manifest themselves in formation of space-charge domains which move with the saturated drift velocity. Repeated pulses of current with period corresponding to the time for domains to traverse the length of the transit region are produced in the external circuit upon domain annihilation at the anode. The major drawback of Gunn diodes from a circuit design point of view is the two terminal nature of these devices and the incompatibility with the integrated circuit technology. These deficiencies have stimulated studies of transferred-electron effect in three terminal lateral devices similar to metal–semiconductor field effect transistor (MESFET) structures.^{3,4} The similarity between the collector region of a III–V heterojunction bipolar transistor (HBT) and a Gunn diode has motivated us to explore the Gunn–Hilsum phenomenon in bipolar transistors.^{5–7} In this letter we report of our investigation of Gunn oscillations in III–V HBTs. We analyze non-linear electron transport in the collector and show that collector current instabilities can occur in modified HBT structures.

We begin by reviewing the conditions for observing oscillations in a conventional Gunn diode. First, the electric field must be greater than the threshold for onset of negative differential mobility. A region where the magnitude of electric field has a positive gradient is a prerequisite for the formation of instabilities since the dynamics of an initial charge

accumulation is related to the local electric field gradient through charge conservation, $\partial\rho/\partial t = -\nabla J$, where J is the local current density.⁶ For diodes with a high-field cathode this results in current density threshold condition $J_{th} \geq eN_d v_s$, where $v_s \cong 10^7$ cm/s is the electron saturation velocity, e is the electronic charge, and N_d is the donor concentration.⁸ The acceleration in high electric field and subsequent scattering of Γ -valley electrons into subsidiary valleys occur over a finite distance. This so called “dead-space layer” places a lower limit on the device length. Also, for a charge accumulation to grow the diode length L , and its doping N_d , must satisfy the condition $N_d L \geq \kappa$, where $\kappa = 10^{12}$ cm⁻² for GaAs and InP.⁸

Recently, we have shown that the absence of Gunn effect in a conventional HBT, in which the collector satisfies the above requirements, may be attributed to the electric field profile of the base-collector junction^{5,7} and the Kirk effect.⁶ Modification of the electric field profile, by an n^+ doping spike introduced at the base edge of the collector, was shown to result in nucleation and propagation of a Gunn domain in the collector drift region of an n - p - n AlGaAs/GaAs HBT. An additional benefit of the n^+ spacer is the hot electron injection which results from the abrupt potential drop at the base-collector junction. It is well known that hot electron injection reduces the dead-space layer and enhances the performance of Gunn diodes.⁹ This was recently demonstrated in an AlGaAs/GaAs Gunn diode.^{10,11}

We use the hydrodynamic model of electron transport to simulate the transient device response. The model simultaneously solves for 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, for both types of the charge carriers. The self-consistent algorithm includes a solution of the drift-diffusion (Poisson, current-density, and continuity) equations followed by a solution of the energy balance equations.¹² The latter are solved for the carrier temperatures which are then used in the drift-diffusion equations until convergence criteria are met. The potential, carrier den-

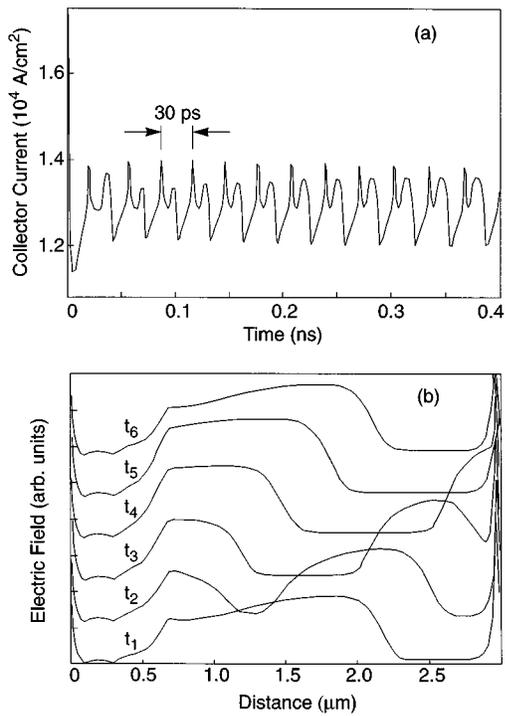


FIG. 1. Collector current density (a) and time evolution of the electric field profile in the collector drift region during one cycle of oscillations (b) in the modified HBT under the bias $V_{be}=1.525$ V, $V_{ce}=4$ V. $t_6 > t_1$, $\Delta t=6$ ps.

sities, currents, electric field, and other parameters are extracted from the final solution. The nonlinear velocity-field relation, required for simulation of Gunn effect, is implemented through a field-dependent mobility model. Recently, it was shown by Tait *et al.* that with a judicious choice of parameters, a hydrodynamic model can accurately simulate conventional Gunn diodes.^{13,14}

The device under investigation is a modified n - p - n AlGaAs/GaAs HBT structure. The emitter consists of an n^+ GaAs contact layer, 500 Å graded $\text{Al}_x\text{Ga}_{1-x}\text{As}$ transitional layer and a 1500 Å $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ layer with $N=5 \times 10^{17} \text{ cm}^{-3}$. The p^+ GaAs base is 1000 Å wide and doped to $1 \times 10^{19} \text{ cm}^{-3}$. The drift region of the collector is 3 μm long and doped to $1 \times 10^{16} \text{ cm}^{-3}$. A thin $1.5 \times 10^{13} \text{ cm}^{-2}$ n^+ doping spike is placed between the base and the collector to alter the electric field profile in the collector drift region. The thickness of this layer must be less than the mean-free path associated with energy relaxation. A doping notch ($5 \times 10^{15} \text{ cm}^{-3}$, 400 nm) is incorporated in the collector drift region 250 nm from the base junction to emulate the effect of random doping inhomogeneities, which are responsible for the triggering of oscillations in conventional Gunn diodes and which are not accounted for in the hydrodynamic model. A similar technique was previously used for simulations of conventional Gunn diodes.^{13,15} Without such a notch our model predicts formation of a stable anode trapped domain, similar to the results of previous Gunn diode studies.¹⁵

Figure 1(a) shows the collector current as a function of time following application of bias at time $t=0$. The transistor is biased at $V_{be}=1.525$ V and $V_{ce}=4$ V. The collector

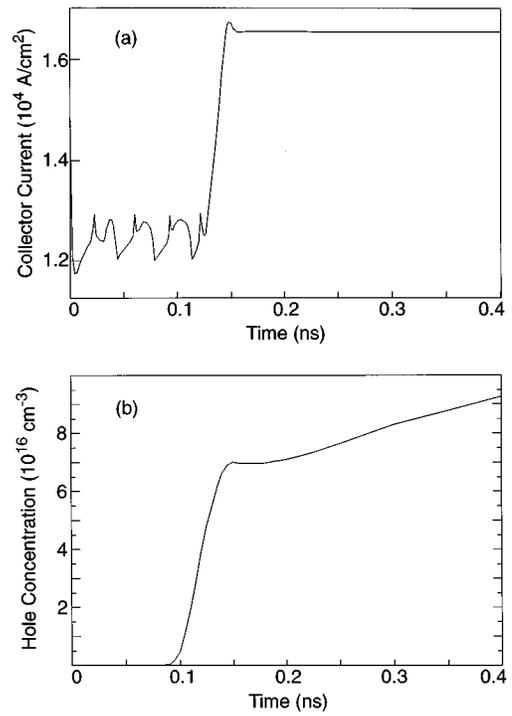


FIG. 2. Collector current density (a) and hole concentration in the collector at 0.1 μm from the cathode (b) in the modified HBT after applying the bias $V_{be}=1.55$ V, $V_{ce}=4$ V.

current is clearly unstable with the expected frequency of oscillation ~ 33 GHz corresponding to Gunn domains traversing the 3 μm drift region at the saturated drift velocity, $v_s \cong 10^7$ cm/s. The detailed shape of the wave form within the cycle period of ~ 30 ps is due to the nonsinusoidal shape of the charge domains and the finite temporal response of the anode. The evolution of the electric field in the collector during one period of oscillation is shown in Fig. 1(b), and illustrates emergence, propagation, and growth of a Gunn domain. Its annihilation at the anode (subcollector) results in a pulse of collector current.

Further insight into the Gunn–Hilsum effect and its complex relation to other phenomena in the HBTs may be obtained by investigating the transient response at higher electron injection levels. Figure 2(a) shows the simulated collector current for $V_{be}=1.55$ V ($V_{ce}=4$ V). While initially Gunn oscillations similar to those in Fig. 1 are observed, the device eventually reaches a steady state corresponding to a stable Gunn domain at the anode. Unsustainable Gunn oscillations may occur during the transient switching of the device. To show the underlying physics we plot, in Fig. 2(b), the time evolution of hole concentration inside the collector at 0.1 μm from the base-collector boundary (cathode). At time $t \cong 100$ ps the carrier concentration in the collector drastically increases in the vicinity of the cathode. This eliminates the electric field in this region and prevents nucleation of the next domain. The effective widening of the base is the well-known Kirk effect which occurs at high collector current density.

In general, the Kirk effect suppresses the transferred-electron phenomenon.⁶ Figure 3 shows qualitative potential

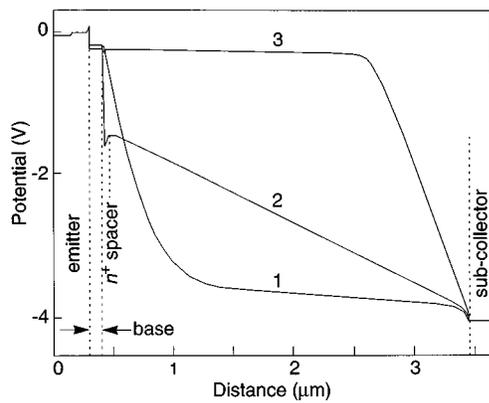


FIG. 3. Potential energy profiles in conventional HBT (1), the modified structure (2) and after the onset of the Kirk effect (3).

energy profiles in conventional HBT (line 1), the modified structure (line 2), and after the onset of the Kirk effect (line 3). It is obvious that the Kirk effect results in a potential profile which is highly incompatible with that required for the Gunn effect. On the other hand, the spacer layer promotes the Gunn effect in the modified device. Its benefits are threefold: First, it confines the diffusion field of the base-collector junction; second, it suppresses the Kirk effect (under nonstationary conditions), and third, it creates a hot electron injector and thus reduces the dead-space layer.

The onset of base widening is associated with a current density at which free-electron concentration surpasses the ionized impurity density in the collector resulting in zero electric field at the base-collector p - n junction. In a conventional HBT this takes place at the collector current density $J_K = eN_d v_s + 2\epsilon v_s \phi / L^2$, where ϵ is the dielectric constant, L is the length of the collector, and ϕ is the total base-collector potential.¹⁶ For conventional HBTs with parameters favorable for the transferred-electron induced oscillations ($N_d L > \kappa$) the second term is negligibly small and $J_K \approx eN_d v_s$. Comparison with the Gunn effect threshold current density J_{th} suggests that charge fluctuations can only

occur at current densities sufficient for the onset of Kirk effect and, therefore, are suppressed by the base widening. However under transient conditions, in the modified HBT structure with an inhomogeneous collector doping profile, the n^+ doping spike increases the Kirk effect threshold current allowing the observation of collector current oscillations as demonstrated in Fig. 1.

In summary, we have presented an investigation of the Gunn–Hilsum effect in the collector of n - p - n HBTs. In a modified AlGaAs/GaAs HBT structure with properly engineered electric field, electron density in collector is unstable resulting in collector current oscillations. At sufficiently high current density the Kirk effect suppresses Gunn oscillations by reducing the electric field and preventing domain nucleation.

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