Heterostructure bipolar transistor with enhanced forward diffusion of minority carriers

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We consider the minority transport in a heterostructure bipolar transistor whose base band gap narrows down toward the collector in N discontinuous steps. Assuming that the potential energy drop at each step is sufficiently large to prevent the reverse flow of minority carriers, we show that the total base propagation delay τ is shorter by a factor of N compared to the diffusive delay in a flat base of the same width. Moreover, if the length of each step is sufficiently narrow, then for large N the magnitude $|\alpha|$ of the base transport factor $\alpha=|\alpha|\exp(-i\omega\tau)$ decreases so slowly with increasing frequency ω that it becomes feasible to obtain an active behavior of the transistor above its own conventional cutoff frequencies.

Almost 40 years ago, Shockley suggested[1] that under certain conditions the delay τ_B in minority-carrier transit across a transistor base can lead to an active device behavior at extended frequencies above the transit-time cutoff $\omega\tau_B=1$. A necessary condition for this to occur is that the directed transport across the base be much faster than the diffusive transport, which tends to wash out any modulated structure of the injected minority-carrier distribution. In principle, this condition can be met in a minority-carrier delay diode (or drift transistor) with an exponentially graded doping profile in the base,[1,2] however, due to a limited possible range of the potential variation, the feasibility of this approach is marginal and it has never been realized. Shockley's argument can be extended to heterostructure bipolar transistors (HBTs) with a graded-alloy base composition;[3-5] to our knowledge, however, the idea has not been developed in that context. As discussed at the end of this letter, achievement of a negative output impedance through base delay in graded-alloy drift transistors is feasible and may lead to a useful device. Similar effects can be obtained[6] in abrupt-junction *ballistic* HBTs; however, that proposal is restricted to low temperatures[7] and, moreover, because of the ballistic requirement it is limited to ultrahigh frequencies (near THz).

In the present letter we propose a new HBT structure, in which the minority transport occurs at room temperature by a *strongly accelerated diffusive process*, adequate for achieving the transit-time resonance both at ultrahigh and conventional frequencies. Moreover, even without the resonance, the proposed transport mechanism is expected to enhance the design flexibility for high-performance HBTs.

Consider a HBT whose base band gap narrows down toward the collector in a stepwise fashion, see Fig. 1. Let the band edge for minority carriers in the base consist of N steps W_j which are high enough, $\Delta_j \gg kT$, that carriers are effectively forbidden to return once they have fallen off a particular step. Moreover, let us assume that all the memory of the previous journey is lost in each step. The latter condition is reasonable if the steps are higher than the threshold for rapid inelastic process, e.g., optical phonon emission: $\Delta_j \gtrsim \hbar\omega_{\text{opt}}$. With this condition fulfilled, we can treat the transport in each step individually, and characterize it by a step transport factor α_j

$$\alpha_j(\omega)=\frac{1}{\cosh[(2i\varphi_j)^{1/2}]}, \tag{1}$$

where $\varphi_j \equiv \omega\tau_j$ is the acquired phase and $\tau_j=W_j^2/2D$ is the step propagation time by diffusion. We assume that the steps are narrow enough that $\varphi_j \ll 1$. In this case, to within quadratic in φ_j terms, Eq. (1) reduces to the form

$$\alpha_j(\omega)\approx e^{-\varphi_j^2/3}e^{-i\varphi_j}. \tag{2}$$

We see that at small values of the acquired phase φ_j, the magnitude $|\alpha_j|$ deviates from unity *quadratically*[8,9] in φ_j.

This observation enables us to construct a "coherent" $|\alpha_B|$ with a large phase and little decay in magnitude. Indeed, the total base transport factor is the product of α_j's:

$$\alpha_B(\varphi)=\prod_{j=1}^{N}\alpha_j \approx e^{-\varphi^2/3N}e^{-i\varphi}, \tag{3}$$

where $\varphi=\Sigma\varphi_j$ is the overall phase acquired in the base transport; we have assumed for simplicity that all steps are

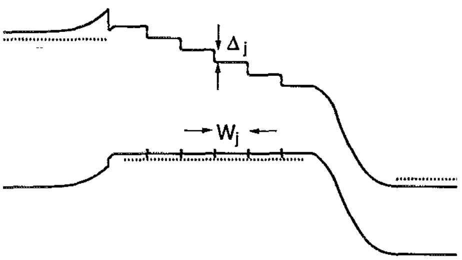

FIG. 1. Schematic band diagram of a HBT with enhanced diffusion of minority carriers.

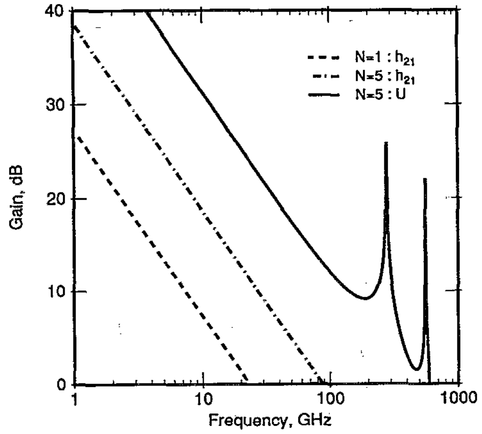

FIG. 2. Common-emitter current gain $|h_{21}|$ and the unilateral gain $|U|$ of HBTs having the same base width $W=0.25$ μm, the same diffusivity $D=50$ cm^2/s, the same collector transit time $\tau_C=1$ ps, and different number N of steps in the base. Assumed parameters: $R_B=R_{Bx}=50$ Ω μm, $R_E=10$ Ω μm, $R_{Ex}=R_{Cx}=20$ Ω μm, $C_C=0.25$ fF/μm, and $C_C=10$ fF/μm.

equal and therefore $\varphi=N\varphi_j$. The intrinsic current gain $\beta_B=\alpha_B(1-\alpha_B)^{-1}$ will have a peak $|\beta_B|>1$ at $\varphi=2\pi$ (i.e., at frequency $f=2\pi f_T$), provided

$$|\alpha_B(2\pi)|>0.5 \tag{4}$$

which, according to Eq. (3), requires $N>N_{2\pi}=(2\pi)^2/3\ln 2\approx 19$.

Physically, the described effect originates from an enhancement of the *forward* diffusion transport. The essential condition is carrier thermalization at every step, which provides the independence of α_j's and restricts particles from returning to a preceding step. The resultant "stepped up" diffusion is a rather peculiar, at first glance even counterintuitive, process. Thus, in a *static* regime, the minority concentration in the base is a *periodic* (rather than decreasing) function of the distance. Indeed, the steady-state current in each step is

$$J=\frac{e[n(0_j)-n(W_j)]}{DW_j}\approx\frac{N\,en(0)}{DW}, \tag{5}$$

where $W=NW_j$ is the total base thickness and $n(0_j)$ is the concentration at the beginning of step j. From the current continuity in the absence of recombination, we have $n(0_j)=n(0)$, independent of j. Equation (5) shows that the diffusion flux is enhanced by a factor of N and so is the effective diffusion velocity, which becomes $2D/W_j$. If we increase the number of steps keeping W constant, the conventional cutoff frequency f_T will increase in proportion to N, cf. Fig. 2. For high enough N, we would see a peaked structure in the current gain $|h_{21}|$ and for $N>N_{2\pi}$ the peak value is greater than unity. However, this situation is difficult to realize in practice, because each step must be high enough ($\Delta_j\gtrsim\omega_{\rm opt}$) to ensure the no-return condition, while the overall potential drop is limited by the band-gap difference.

On the other hand, conditions for the transistor oscillation activity are more relaxed. Consider the intrinsic case first. An extended-frequency peak in the unilateral power gain U appears when the real part of the common-emitter output impedance $r_{22}\equiv\mathrm{Re}(z_{22}^e)$ changes sign.[6,10] In an intrinsic transistor we have $r_{22}=R_\varphi+R_E$, where

$$R_\varphi=\frac{\cos(\varphi)-\cos(\varphi+\theta)}{\omega C_C\theta}|\alpha_B|\approx\frac{|\alpha_B|\sin(\varphi+\theta')}{\omega C_C}. \tag{6}$$

R_E is the emitter resistance, and $\theta\equiv\omega\tau_C=2\theta'$ is the collector transit angle. The phase φ includes the (usually small) delay $\varphi_E=\omega R_E C_E$, due to emitter capacitance C_E. The approximate relation in the right-hand side of Eq. (6) corresponds to $\theta\lesssim 1$. In this case a power gain peak occurs at $\varphi\approx\pi$, provided $|\alpha_B|>\omega C_C R_E$.

The latter condition is relatively easy to accommodate. However, as pointed out by Tiwari,[11] considerations of the phase-shift effects on unilateral gain are rather meaningless without including extrinsic resistances and capacitances. A careful analysis[6] shows that when these "parasitics" are included, the condition for a peak in U near $\varphi=\pi$ is

$$|\alpha_B(\pi)|>\omega\tau_X, \tag{7}$$

where τ_X is a parasitics-limited time constant. For example, in a model which includes extrinsic emitter base, and collector resistances (R_{Ex}, R_{Bx}, and R_{Cx}, respectively, cf. the equivalent circuit[6] of an abrupt-junction HBT) but neglects an extrinsic collector capacitance C_{Cx}, the expression for U is

$$U=\frac{|\alpha_B\alpha_C|^2}{4\omega^2C_C^2(R_B+R_{Bx})}\frac{1}{R_\varphi+R_X}, \tag{8}$$

where $R_X\equiv R_E+R_{Ex}+R_{Cx}+R_{Cx}(R_E+R_{Ex})/(R_B+R_{Bx})$ and $\alpha_C\equiv(\sin\theta'/\theta')e^{-i\theta'}$ is the collector transport factor. The corresponding τ_X in Eq. (7) is $\tau_X=C_C R_X$. Besides the "low" frequency regime, where $U>1$, the transistor will be active in the range of frequencies, where

$$|\alpha_B|\sin(\varphi+\theta')+\omega\tau_X\leqslant 0. \tag{9}$$

In this range $U>0$ and hence one can obtain $U\gg 1$ by adding a series resistance.[10] Obviously, inequality (9) can only be obtained if $|\alpha_B|>\omega\tau_X$; from Eq. (3) this means that the number of steps in the base must exceed the value $N_\pi=(\pi^2/3)|\ln(\omega\tau_X)|^{-1}$. For a transistor not overdamped by the parasitics, say $\omega\tau_X\lesssim 0.5$, we need $N\gtrsim 5$. The solid line in Fig. 2 displays the gain $|U|$, calculated for a model HBT with five steps in the base. The two peaks correspond to a vanishing denominator in Eq. (8); between the peaks U is negative.

It should be emphasized that we are not considering any "ballistic" boosts in the particle speed at the step edges. Such effects may in fact be beneficial; they are not expected to qualitatively modify the results in Eqs. (3) or (5). If we increase N at the expense of making the step height smaller, $\Delta_j<\hbar\omega_{\rm opt}$, then the necessary energy relaxation will not occur at each step and hot electrons will diffuse backward as well as forward. In order to treat this regime quantitatively, a Boltzmann transport model for minority carriers has been developed.[12] It also includes the effects of a finite optical phonon scattering time $\tau_{\rm op}$ and finite exit velocity at each step. Preliminary results[12] obtained in this model indicate that for $\Delta_j > \hbar\omega_{\rm opt}$ the present simplified approach is valid, provided that $\tau_{\rm op}$ is shorter than the elastic collision time of hot carriers exiting a step.

On the other hand, in the limit of $N \to \infty$ and $\Delta_j, W_j \to 0$ the problem becomes equivalent to the case of a graded-gap HBT[3-5] with $\nabla E_C = \lim \Delta_j / W_j$. In such a device, the phase of α_B is acquired with the drift velocity $v \equiv -\mu \nabla E_C / e$, while the magnitude $|\alpha_B|$ is attenuated due to spreading by diffusion. An equation analogous to Eq. (3) can be derived[13] for this case by solving the continuity equation $\nabla \cdot J = e(\partial n / \partial t)$ for the minority current taken in the drift-diffusion form $J = n\mu \nabla E_C + eD\nabla n$. The result is

$$\alpha_B(\omega) = \frac{\exp(r)}{\cosh(\lambda) + (1 + 2i\omega\tau_B / r)^{-1/2} \sinh(\lambda)}, \qquad (10)$$

where $\lambda \equiv \sqrt{r^2 + 2i\omega\tau_D}$ and r is the ratio of the characteristic diffusion time $\tau_D = W^2/2D$ to the drift time $\tau_B = W/v$, viz.,

$$r \equiv \frac{\tau_D}{\tau_B} = \frac{Wv}{2D} \approx \frac{\Delta E_C}{2kT}, \qquad (11)$$

where ΔE_C is the total band-gap variation. The last equation in the right-hand side of Eq. (11) results from Einstein's relation $eD = \mu kT$ (valid for not too high band-gap gradients). In the absence of a grading, $v \to 0$, Eq. (10) reduces to $\alpha_B = \cosh^{-1}[2i\omega\tau_D)^{1/2}]$, which corresponds to Eq. (1) extended to the entire base. For a large grading, $r \gg 1$, one has, asymptotically, $\lambda \approx r + i\omega\tau_B + (\omega\tau_B)^2/2r$ and Eq. (10) reduces to

$$\alpha_B(\varphi) = e^{-\varphi^2/2r} e^{-i\varphi}, \qquad (12)$$

where $\varphi \equiv \omega\tau_B(1 - 1/2r)$. The minority carrier drift effects are qualitatively similar to those resulting from the enhanced forward diffusion. Parameter $2r$ in Eq. (12) plays the same role as $3N$ in Eq. (3). For our example of five steps (Fig. 2) we need $\Delta E_C = 5\Delta_j \gtrsim 5\hbar\omega_{\rm opt} \approx 180$ meV (in GaAs/AlGaAs). Precisely the same effect will be achieved with a graded-gap base with $r = 7.5$, requiring $\Delta E_C = 15\ kT \approx 380$ meV at room temperature. As means for achieving the extended frequency operation at $\varphi \gtrsim \pi$, both approaches appear equally feasible.

The step-based approach offers additional flexibility in the design of ultrahigh speed heterostructure transistors. Perhaps its most obvious practical application is to relieve the stringent trade-off between the requirements of low base resistance and short base propagation time. As discussed above, this can be accomplished even with a small number of steps, e.g., $N = 2$. For higher number of steps, $N \gtrsim 5$, one can obtain an active behavior of the transistor at an extended frequency $f \approx \pi f_{\max}$, provided [cf. Eq. (7)] the device at this frequency is not overdamped by extrinsic elements.

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