An Induced Base Hot-Electron Transistor

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Abstract—**A novel three-terminal device is proposed in which the base represents an undoped quantum well in a graded-gap heterostructure. The base conductivity is provided by a two-dimensional electron gas induced by the collector field. The intrinsic delay time is estimated to be about 1 ps at room temperature with a common-base current gain close to unity.**

THE DEVICE PROPOSED in this work bears a conceptual similarity to the well-known metal base transistor (MBT) [1]-[3], with an important difference being that the base "metal" is two-dimensional. The base is formed by a degenerate electron gas induced at a heterojunction interface by an electric field emanating from the collector electrode, hence the name: induced base transistor (IBT).

I will describe the IBT concept assuming its implementation in GaAs/GaAlAs heterojunction technology. Fig. 1 schematically shows the cross section of the proposed structure and its energy-band diagram. The only doped layers in the structure are the emitter and the collector made of n^+-GaAs. The base layer is an undoped GaAs quantum well (QW) of thickness $d \sim 10^{-6}$ cm. The base is separated from the emitter by a graded AlGaAs triangular barrier of thickness L_1 and from the collector by a rectangular barrier of thickness L_2. Electrical contacts are provided to the emitter, base, and collector layers.

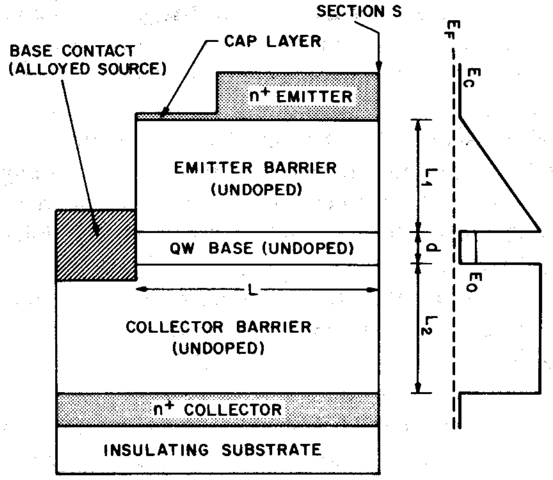

Fig. 1. Cross section of the proposed device structure and the conduction-band diagram along line S. The diagram is very schematic and serves only to illustrate the concept of IBT. Device is assumed to be symmetric about S to minimize the base resistance. A thin (depleted) cap layer protects the base from the surface field. Some modulation doping may be provided in the collector barrier to ensure a "normally-on" base and help lower the base contact resistance. For higher mobility in the base it may be advantageous to place the emitter on the substrate side of the QW and the collector on the top of the structure.

In equilibrium the base may not be conducting. This is emphasized in Fig. 1 by drawing the Fermi level below the bottom of the lowest subband E_0 in the QW. Conducting electron sheet is induced in the base by applying a positive bias V_{cb} to the collector. This situation is illustrated in Fig. 2. First, let the base–emitter voltage $V_{be} = 0$ and consider the energy-band diagram in a section of the device under the emitter. As V_{cb} is increased, the energy level E_0 moves downward with respect to the Fermi level E_F and the number of electrons in the QW rises exponentially. This may be called the subthreshold regime of the IBT. As the base becomes conducting, it shields the emitter from the collector field and the electron concentration in the base becomes a linear function of V_{cb}

$$\sigma = \epsilon(V_{cb} - V_T)/L_2 \tag{1}$$

where σ is the sheet charge density in the base and ϵ the dielectric permittivity. The threshold voltage V_T for the base conduction depends on the geometry of the device (L_1, L_2, d) and the doping levels in the emitter and the collector. In principle, one can have a "normally-on" base, i.e., $V_T < 0$.

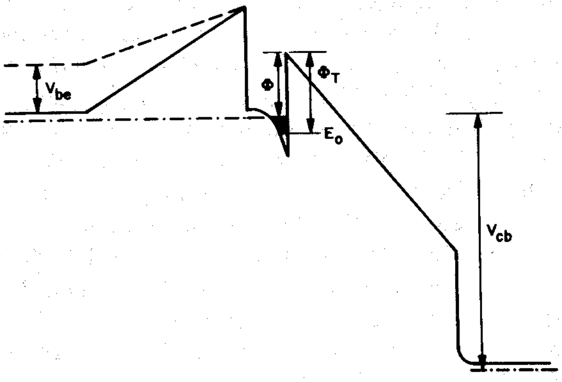

Fig. 2. Band diagram of the IBT in the operating regime. In order to achieve an optimum Φ_T, the equilibrium height of the collector barrier can be made lower than the emitter barrier. The electron injection energy can be enhanced by incorporating a planar-doped sheet of acceptors near the top of the emitter barrier.

At $V_{be} = 0$ the collector current will be determined by thermionic emission over the rectangular potential barrier. The height of this barrier Φ is a weak function of V_{cb}. In addition to the familiar Schottky image force lowering [4], the dependence $\Phi(V_{cb})$ results from two quantum effects [5]—the zero-point-motion energy E_0 and the Fermi energy of a two-dimensional metal, $E_F - E_0 = \pi\hbar^2 \sigma/\mathrm{em}$, both of which are subtracted from the barrier height. To a good approximation, E_0 varies as $F^{2/3}$, where F is the electric field in the collector barrier. Using the variational approach of Fang and Howard [5, p. 466] and the parameters m, ϵ of GaAs, we find $E_0 = (\sigma/\sigma_0)^{2/3} \times 21$ meV, where $\sigma_0 \equiv 10^{11}$

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e/cm^2. Expressing σ from (1), we have

$$\Phi = \Phi_T - (ea/4L_2)(V_{cb} - V_T) \tag{2}$$

where $\Phi_T = \Phi_0 - E_0$, with Φ_0 being the conduction band discontinuity between GaAs and AlGaAs at the collector interface, and $a = 4\pi\epsilon\hbar^2/me^2 \approx 103.5$ Å is the Bohr radius in GaAs. We see that for $L_2 \gg a$ the charge injection due to barrier lowering is unimportant. This ensures a quasi-saturation of the collector current characteristics with respect to V_{cb}.

Transistor action results when $V_{be} > 0$ (emitter biased negatively relative to the base). In this case the triangular barrier between the emitter and the base is biased in the forward direction. This gives rise to a charge injection controlled by V_{be}. The injected carriers ("hot electrons") travel through the thin base and pass over the collector barrier. Of course, a fraction of them will be lost in the base because of scattering and barrier reflection which thus diminish the transistor common-base current gain α. These processes are considered below. First, however, let us make simple small-signal estimates of the IBT speed of operation, assuming an ideal transfer ratio $\alpha = 1$. The graded-gap triangular barriers have been studied in detail over recent years [6]. At not too high current densities $J \lesssim 10^4$ A/cm^2 their forward characteristics obeys a diode law $J \propto \exp(eV_{be}/kT)$. At higher currents the exponential characteristics of a triangular barrier saturates and is eventually replaced by a linear law. This occurs [7], [8] because of: 1) slowing down of the effective diffusion velocity on the uphill slope; and 2) screening of the applied field by the mobile charge on the downhill slope. These effects limit the maximum achievable transconductance g_m per unit area and thus impose speed limitations [8]. Effect 1) gives $g_m < \epsilon v_R/L_1{}^2$, where $v_R = (kT/2\pi m)^{1/2}$ is the mean thermal velocity in a given direction, and leads to a delay $\tau_e = L_1/v_R$. Effect 2) leads to a collector drift delay time $\tau_c = L_2/v_s$ where v_s is the saturation velocity. Another delay occurs due to a finite base charging time. This effect is rather peculiar in IBT: the base responds to a variation δV_{be} like an FET channel to a variation in the gate voltage, viz. $\delta\sigma = \epsilon\delta V_{be}/L_1$. This does not lead, however, to a characteristic time-of-flight delay L/v of an FET. (Here L is the lateral base dimension, i.e., the distance from one of the source contacts to the middle of the base, Fig. 1.) A straightforward RC estimate gives $\tau_b = \epsilon L^2/\mu\sigma L_1$, where μ is the low-field mobility in the base. It is interesting to note that the IBT takes a direct advantage of the high electron mobility in a two-dimensional metal at an undoped heterojunction interface (see the reviews [5] and [9] and references therein).

Which of the above delay times (τ_e, τ_c, τ_b) will dominate, depends on the ambient temperature and the device geometry. Without pushing the limits of technology, e.g. using the rules already employed in fabricating the charge injection transistor at Bell Labs [10] (taking $L_1 \sim L_2 \sim 10^{-5}$ cm, $L \sim 10^{-4}$ cm, and $\sigma[V_{cb} = 2\text{ V}] \sim 10^{12}$ e/cm^2), we estimate that each of the three delays can be made of the order of 1 ps at room temperature.

The above estimates were made assuming an ideal static common-base current gain $\alpha = 1$. Let us now estimate this very important factor. Electrons injected into the base at high energy E (say, 0.36 eV, counting from E_0) will travel initially with a ballistic velocity $v_B \approx 10^8$ cm/s (the highest group velocity in GaAs), traversing the base in time d/v_B. They are losing energy at the rate $r \approx 1.6 \times 10^{11}$ eV/s due to the emission of polar optic phonons [11]. Ignoring (for a moment) quantum mechanical (QM) reflections above the collector barrier, we can estimate the fraction η of electrons lost in the base as follows:

$$\eta = rd/v_B(E - \Phi_T) \sim 0.01. \tag{3}$$

In estimate (3) I assumed $E - \Phi_T \approx 0.16$ eV; a hot electron needs about 1 ps on average to lose this amount of energy, while it spends only ~ 0.01 ps traversing the base.

Next, the probability of a QM reflection off a *rectangular* barrier (Fig. 3(a)) is given by [12]

$$R = \left[\frac{1 - \sqrt{1-\phi}}{1 + \sqrt{1-\phi}}\right]^2 \tag{4}$$

where $\phi \equiv \Phi_T/E$. Taking $\phi = 0.5$, e.g., $E = 0.36$ eV and $\Phi_T = 0.18$ eV, we have $R = 0.03$. A more realistic model (Fig. 3(b)) for our collector barrier of a triangular shape also admits an exact solution [13], expressed in terms of Hankel functions. In the limit $\Phi_T \gg (\hbar^2 e^2 F^2/2m)^{1/3}$ and $\phi \lesssim 0.8$ the exact solution reduces to (4). For the above values of E and Φ_T, taking the triangular barrier thickness $l = 200$ Å (corresponding to $F = 2 \times 10^5$ V/cm), it gives a still lower (by about a factor of 2) value of R. It should be noted that estimates based on (4) are valid only for heterojunction barriers in which the bottom of the conduction band lies in the same valley of the Brillouin zone in both semiconductors. If this condition is not fulfilled, the QM transmission probability will be substantially reduced.

We conclude that in an IBT one can realistically expect $\alpha = (1 - \eta)(1 - R) \gtrsim 0.96$. For comparison, the recent data for a metal-base transistor, achieved with an epitaxial Si/CoSi$_2$/Si structure [14], correspond to $\alpha \lesssim 0.02$. The crucial difference lies in the QM reflection which is much higher in the case of a metal, in part because the values of ϕ one must use in (4) in this case are typically close to unity (the energies are counted from the bottom of the conduction band [15]). The problem of QM reflections becomes even worse if one accurately takes into account the different band structures of the metal and the semiconductor.

Like in the case of IBT, the above-barrier reflection is not a serious problem in other semiconductor analogs of the MBT, such as the monolithic hot-electron transistors based on camel [16], planar-doped [17], or tunnel-emitter [18] barriers. In those devices, however, the doped base layer cannot be made thin because of the increasing resistance. Here is where our two-dimensional metal comes in handy! The induced-base sheet resistance can be easily made less than $R_\square = (\mu\sigma)^{-1} \lesssim 400\ \Omega$ at room temperature (taking the phonon-limited mobility [9] $\mu = 8500$ cm^2/V·s), and still much lower at 77 K. The value of the induced charge sheet density is limited by the breakdown field in the AlGaAs barrier, giving [10] $\sigma_{\max} \approx 2 \times 10^{12}$ e/cm^2. The induced

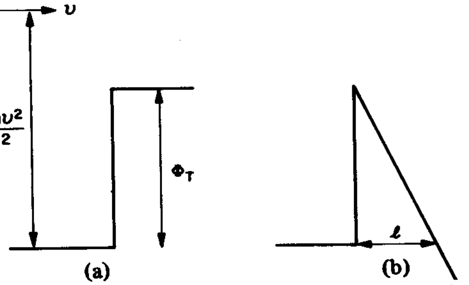

Fig. 3. Exactly calculable models for estimating the above-barrier quantum-mechanical reflection of ballistic electrons. (a) Rectangular barrier. (b) Triangular barrier: $l \equiv \Phi_T/eF$.

base resistance is independent of the base thickness d, provided the latter is larger than the characteristic extent in the tranverse direction of the wave function of two-dimensional electrons [5].

The fundamental limitations of the IBT appear to be similar to those of a bipolar transistor with a thin graded-gap base [19]. The latter device does not benefit from an enhanced mobility in the base, but it compensates by offering the possibility of a larger sheet carrier concentration. It is premature to discuss at this point which of the two devices—the bipolar [19] or the present unipolar—will prove more practical.

To summarize, I have proposed a novel hot-electron transistor which preserves the main attractive feature (high speed) of a metal-base transistor, while avoiding its inherent drawback of a low α. Compared to previous all-semiconductor hot-electron transistors, the key new idea is that of an induced—rather than doped—base, which allows one to design a base layer as thin as 100 Å without a loss in its sheet conductance. Although I discussed it only in the instance of a graded-barrier AlGaAs/GaAs system, the idea can be implemented in a variety of materials. The absence of doping in the barrier structure is an advantage of the IBT, as it should minimize the variations in the potential barrier height owing to dopant fluctuations. However, for certain applications it may be useful to incorporate some modulation doping in the collector barrier. This would provide a base conductance at $V_{cb} = 0$. Moreover, the presence of a positive donor charge in the vicinity of the base may help lower the base contact resistance, and the resultant concave form of the potential barrier can be expected to ease the space-charge limitation of the collector current. One can also incorporate a planar-doped negative charge sheet in the emitter barrier and thus increase the energy at which electrons are injected into the base. Higher injection energy may be desirable, provided this does not lead to a high rate of intervalley scattering. In this regard, it may be advantageous to use materials such as InGaAs/InAlAs which have a higher energy separation of the satellite valleys.

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