Physica 134B (1985) 466-469
North-Holland, Amsterdam

Induced Base Transistor

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The concept of induced-base transistor, a recently proposed novel hot-electron device, is further developed. Alternative structures for the implementation of the device and its speed limitations are discussed.

Recently, I proposed[1] a new hot-electron device called the Induced-Base Transistor or IBT. Conceptually, it belongs to the class of ballistic transistors reviewed in the preceding paper.[2] Figure 1 schematically shows the device cross-section and the energy-band diagram. In the IBT the base represents an undoped quantum well (QW) in a variable bandgap heterostructure. The only doped layers in the structure are the emitter and the collector layers separated from the base by potential barriers. The emitter barrier is of triangular shape, so that it becomes injecting under an application of a forward emitter-base bias. The collector barrier is blocking for the base → collector injection. In equilibrium the base may not be conducting. The base conductivity is provided by a degenerate electron gas induced at the base-collector heterojunction interface by an electric field emanating from the collector electrode. Electrical contacts are provided to the emitter, base, and collector electrodes. The principle of operation of the IBT is similar to that of the well-known metal-base transistor — with the notable difference that the base "metal" is two-dimensional. This permits a dramatic improvement in the transfer ratio α (the transistor common-base current gain). Conservatively estimated α is over 97% — mainly owing to a low quantum-mechanical reflection coefficient R at the collector barrier interface. Model calculations[1] of the above-barrier reflection give $R < 0.02$.

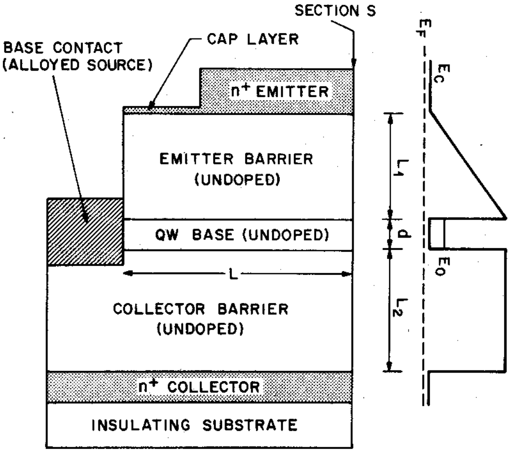

FIGURE 1: Cross-section of the proposed IBT and the conduction-band diagram along line S. Implementation using a GaAs/AlGaAs heterosystem is assumed. Device is symmetric about S to minimize base resistance. A thin (depleted) cap layer protects the base from the surface field.

Compared to the previous all-semiconductor monolithic hot-electron transistors (which used doped base layers),[2] the key advantage lies in the fact that the sheet conductivity of the induced base is virtually independent of the base-layer thickness d — provided the latter exceeds the characteristic transverse extent of the wave-function of two-dimensional electrons. With $d \approx 100$ Å, the lateral base resistance can be as low as 600 Ω/□ at room temperature and still much lower at 77K. The IBT operation requires little or no lateral electric field in the base, so the device can take a direct advantage of the high electron mobility in a two-dimensional metal at an undoped heterojunction interface.[3] The low-field electron mobility parallel to the layers is greatly enhanced (especially at lower temperatures) because of the suppressed Coulomb scattering of electrons by ionized impurities — due to *i)* spatial separation from the scatterers and *ii)* higher than thermal electron Fermi velocity in a degenerate 2-D electron gas, which reduces the scattering cross-section in accordance with the Rutherford formula.

Injected hot electrons, traveling across the base with a ballistic velocity of order 10^8 cm/sec, lose their energy mainly through the emission of polar optic phonons. For $d = 100$ Å the attendant decrease in α is estimated[1] to be about 1%. Energy losses to the collective and single-electron excitations of the two-dimensional electron gas are unimportant.

Let us discuss some alternative possibilities for an implementation of the IBT. An injecting emitter barrier of triangular shape can be organized using either the graded-gap technique[4] (as illustrated in Fig. 1) or using planar-doped barriers.[5] The second alternative is especially attractive when one wishes to employ heterostructure materials in which lattice-matched grading of the gap is difficult to achieve (such as, e.g., the InGaAs/InAlAs system). A possible IBT structure of this type is schematically shown in Fig. 2 (where a GaAs/AlGaAs system is assumed for illustration).

It contains two built-in charge sheets — planar-doped acceptors and donors. The dopant concentration and the geometry must be designed so as to have both sheets depleted of mobile carriers providing a desired barrier height. The 2-dimensional electron gas induced at the heterointerface by the collector field, as shown in Fig. 2, should be separated from the donor sheet by an undoped setback layer of at least 50 Å — to ensure the benefit of enhanced mobility in the base.

A similar — though complementary in the dopant polarity — structure can in principle be implemented using Si/Ge heterojunction technology[6] (provided one is able to achieve a high-quality interface). In this case one should use injection of hot holes because, unlike the conduction-band minima, valence-band maxima are located at the same $k = 0$ point in both semiconductors. The valence band offset in a Si/Ge heterojunction is sufficiently large to confine holes in germanium: there is even an experimental evidence[7] that the bands are staggered in these structures — with Ge conduction band being above that of Si.

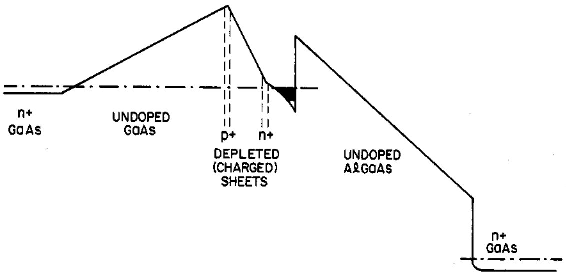

FIGURE 2: Induced-base transistor with a planar-doped emitter barrier.

Some heterostructure combinations may offer a fascinating possibility of employing *different conduction bands* for transporting injected carriers across the base and the lateral conduction in the base.[8] The band offsets in AlGaAs/GaAs heterojunctions at high aluminum concentrations ($x \rightarrow 1$) are not as well established at present as those for $x \leq 0.45$. This gives me the liberty to illustrate the idea with an AlAs/GaAs structure by assuming that the band discontinuities $\Delta E_C^{(\Gamma)}$ and ΔE_V are split in the proportion 83 : 17 (close to the "old" Dingle rule which has been recently revised[9] — at least for $x \leq 0.45$, where the rule is now approximately 60 : 40). Consider a device whose band diagram is illustrated in Fig. 3.

Conduction-band bottom in the AlAs emitter is in the X valleys. If the above band offset rule is obeyed, then there is no discontinuity in the X band at the GaAs interface and, as far as the X electrons are concerned, the structure is not different from a homogeneous *nin* diode. In the absence of a base voltage the emitter to collector current is space-charge limited. Electrons sail through the base QW without noticing it (apart from a finite probability of making an intervalley transfer by spontaneous phonon emission). On the other hand, electrons in the GaAs quantum well (which may or may not be there at equilibrium and, when induced by the collector field, come from the base contact) are in the Γ valley. The collector current can be exponentially quenched by applying a base-emitter reverse bias. The device thus operates much like a bipolar junction transistor (of infinitesimal base thickness but good lateral conductivity) — with carriers in the subsidiary branch of the conduction band replacing the holes of an *npn* structure. It would be very neat indeed if a heterostructure could be found to implement this idea. Unfortunately, the $Al_xGa_{1-x}As$/GaAs combinations would be "ruled-out", if the 60 : 40 proportion (or close to it) is found to persist for $x \rightarrow 1$, since in that case the X-band is strongly discontinuous at all values of x.

Like in most transistor concepts, the ultimate speed limitation of IBT results from intrinsic RC (C/g_m) delays. One such delay (τ_b) arises due to the finite charging time of the base-emitter capacitance through the lateral base resistance. For an optimized device structure simple estimates[1,2] give $\tau_B \lesssim 1$ psec at room temperature and still much lower at 77K due to the enhanced mobility. It should be noted, however, that in a high-speed operation the mobility of 2-D electrons may be substantially degraded due to their heating by the microwave field. This problem certainly requires special consideration. Other limitations[1] arise from the space-charge effects due to the injected carriers in the barrier layers. These effects limit the regime in which the output current is an exponential function of the base-emitter voltage, replacing it at high currents by a linear law. Accordingly, the C/g_m delay (which decreases in the exponential regime as $1/I$) tends to a minimum value given by the time of carrier diffusion and drift across the entire structure.

An optimized IBT will have both the emitter and the collector barriers about 10^{-5} cm thick, which implies a total delay of order 3 psec at room temperature. In order to realize this performance, the critical problem is to develop a technology for producing good ohmic contacts to the 2-D electron gas in a QW separated by only a 1000 Å-thick barrier from another conducting layer of same polarity. Successful resolution of this problem holds the key to the future of the induced base transistor.

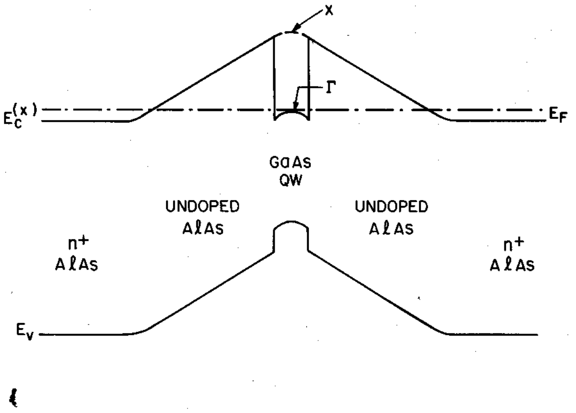

FIGURE 3: Hypothetical band-diagram for an AlAs/GaAs heterostructure in which the discontinuities in the Γ valleys of the conduction band and the valence band are assumed split in the proportion 83 : 17. This rule implies a continuous X-band minimum.

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