Induced Base Transistor Fabricated by Molecular Beam Epitaxy

CHUN-YEN CHANG, SENIOR MEMBER, IEEE, W. C. LIU, M. S. JAME, Y. H. WANG, SERGE LURYI, SENIOR MEMBER, IEEE, AND SIMON M. SZE, FELLOW, IEEE

Abstract—**A novel three-terminal hot-electron device, the induced base transistor (IBT), has been fabricated by molecular beam epitaxy (MBE). Two-dimensional electron gas (2-DEG) induced by the applied collector field in an undoped GaAs quantum well is used as the base of the IBT. The common-base current gain α has been achieved as high as 0.96 under a collector bias of 2.5 V and an emitter current of 3 mA.**

I. INTRODUCTION

THE CONCEPT of the induced base transistor (IBT) has been proposed by Luryi [1], [2]. In this letter an experimental realization of this new device is reported for the first time. Our device fabrication sequence is based on the previously reported technologies of the *V*-groove and *U*-groove barrier transistors [3], [4].

The conduction band diagram of the device is depicted in Fig. 1. In thermal equilibrium, the Fermi level lies below the bottom of the lowest subband E_0 in the quantum-well base, as shown in Fig. 1(a), and therefore the base is not conducting. When a positive bias V_{CB} is applied to the collector (Fig. 1(b)), a two-dimensional electron gas (2-DEG) is induced in the base. The principle of operation of the IBT is similar to that of the well-known metal-base transistor [5] with the essential difference that the base "metal" is two-dimensional (the 2-DEG). This permits a significant improvement in the transfer ratio α (the common-base current gain) [1], [2], [6]. Compared to the previous all-semiconductor hot-electron transistors, which used doped base layers (see, for example, references in [6]), the key advantage lies in the fact that the sheet conductivity of the induced base is virtually independent of the base-layer thickness.

II. DEVICE FABRICATION

The cross-sectional view of our experimental IBT is shown in Fig. 2. In order to make contact to a 100-Å GaAs quantum-well base layer, the *V* groove was etched along the emitter periphery, and Au–Ge was deposited to the *V*-groove region by evaporation. The epitaxial layers were grown in an NCKU Anelva MBE-830S molecular beam epitaxial system on a (100)-oriented Si-doped n^+GaAs substrate supplied by Wacker Chemitronic Co. Silicon was used as n-type dopant. The growth was at 620°C and under As-stabilized conditions.

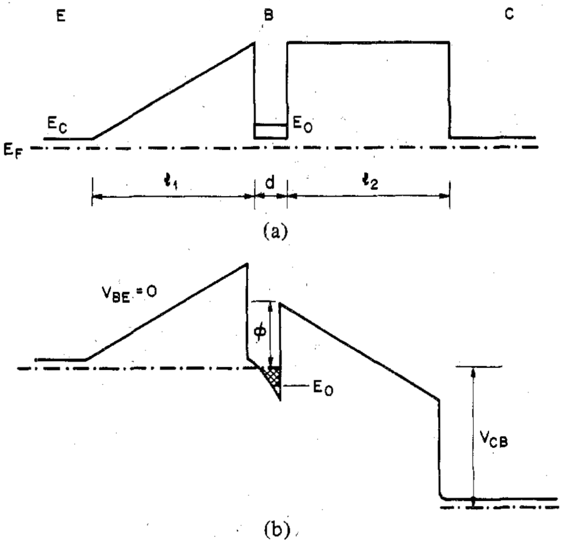

Fig. 1. Schematic band diagram of an induced base transistor [1] (a) in equilibrium and (b) under a positive bias V_{CB} applied to the collector.

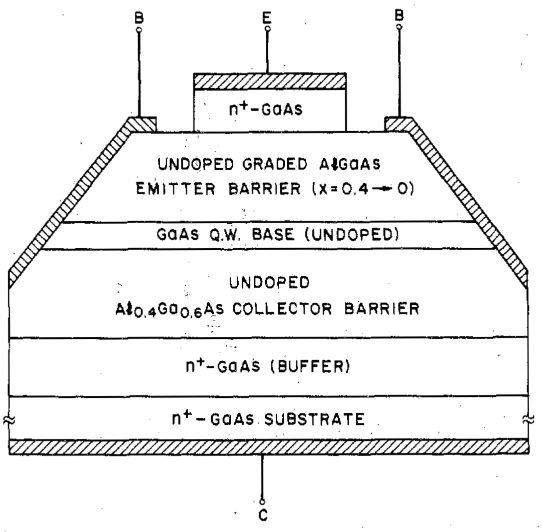

Fig. 2. Cross section of the IBT device fabricated in this work.

First, a 1-μm-thick n^+GaAs buffer layer with a donor concentration of 2×10^{18} cm^{-3} was grown, followed by a 1800-Å-thick undoped $Al_{0.4}Ga_{0.6}As$ collector-barrier layer and a 100-Å undoped GaAs quantum-well base layer. The

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C.-Y. Chang, W. C. Liu, M. S. Jame, and Y. H. Wang are with the Semiconductor and System Laboratories, National Cheng Kung University, Tainan, Taiwan, Republic of China.

S. Luryi and S. M. Sze are with AT&T Bell Laboratories, Murray Hill, NJ 07974.

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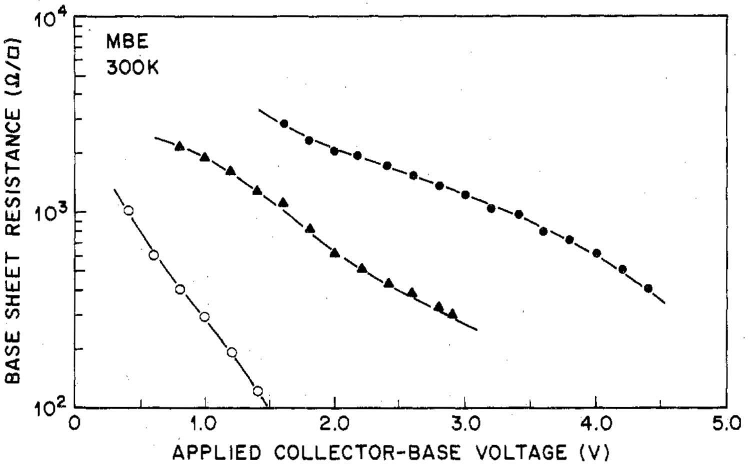


Fig. 3. Sheet base resistance as a function of the collector-base voltage V_{CB}. Triangles correspond to $V_{BE} = 0$, solid circles to $V_{BE} = +0.2$ V, and open circles to $V_{BE} = -0.2$ V (positive V_{BE} means a negatively biased emitter relative to the base).

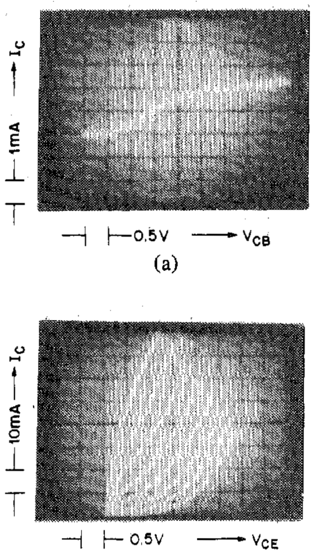
fourth layer (emitter barrier) was formed by a 1500-Å-thick undoped $Al_xGa_{1-x}As$ graded from $x = 0.4$ to 0 by changing the Al cell temperature. Finally, an n^+GaAs (0.3 μm thick, 2 × 10^{18} cm^{-3}) layer was grown for ohmic contact. Emitter and base regions were delineated by a selective etching technique. A *V* groove was etched along the emitter periphery using an H_2SO_4:H_2O_2:H_2O (1: 8: 10) solution, and Au-Ge was applied as the ohmic contact material for all the three terminals—the emitter, the base, and the collector.

III. RESULTS

Fig. 3 shows the measured base sheet resistance $\rho_\square$ which was obtained by measuring two Al pads on both ends of the base as a function of the collector-base V_{CB} and base-emitter V_{BE} biases. At a fixed V_{BE} the $\rho_\square$ decreased with increasing positive V_{CB} indicating the effect of base induction. A negative bias on the emitter relative to the base depletes the latter, whereas a positive bias enhances the sheet charge density σ in the base. The value of the induced charge sheet density and base sheet resistance are limited by the breakdown field in the AlGaAs barrier; in this device $\sigma_{\max} \approx 3 \times 10^{12}$ q/cm^2, and $\rho_{\square\min} \approx 310$ Ω.

The dependence of the collector current I_C on V_{CB} with emitter open is shown in Fig. 4(a). At first, I_C rises rapidly with V_{CB} indicating an increased injection of room-temperature electrons as the height of the collector barrier decreases. When V_{CB} exceeds ≈ 2 V, this rapid dependence ceases and I_C approaches a quasi-saturation. We believe this corresponds to the formation of a conducting sheet in the base, whereupon the only further barrier lowering is due to the 2-DEG image force [7] and the Fermi degeneracy.

When a negative bias is applied to the emitter relative to the base ($V_{BE} > 0$), the triangular emitter-base barrier is biased in the forward direction. This injects hot electrons through the base and into the collector. The current-voltage characteristics $I = f(V_{CE}, V_{BE})$ of the IBT are shown in Fig. 4(b). The base-emitter bias is changed 0.2 V per step from zero. The I_C versus V_{CE} curves are shifted to higher currents with the increasing V_{BE} bias. This is due to the reduction of the barrier height for thermionic emission into the base.



(a)

(b)

Fig. 4. (a) The I_C versus V_{CB} characteristics with emitter open. Note the quasi-saturation effect for $V_{CB} \gtrsim 2$ V. (b) Common-emitter characteristics of the IBT: I_C versus V_{CE} for different values of V_{BE} stepped by 0.2 V from zero ($V_{BE} = 0$ corresponds to the curve on the right).

The highest common-base current gain measured in our IBT device was $\alpha \simeq 0.96$ at $V_{CB} \approx 2.5$ V and the emitter current was ≈ 3 mA. This correlates well with the predicted [1], [2] values. However, when the emitter current increases beyond 10 mA, α decreases rapidly due to base-to-emitter injection across the barrier. This high value of α (for a hot-electron transistor) results from the narrowness of the IBT base (compared to doped-base hot-electron transistors) and from the reduced quantum-mechanical reflection off the collector barrier (as compared to metal-base transistors).

To summarize, we have successfully fabricated by MBE the induced base transistor, a novel hot-electron device which preserves the main attractive feature (high speed) of a metal-base transistor, without sacrificing a high transfer ratio α. The key new idea of IBT is that of an induced—rather than doped—base, which can be fabricated as thin as 100 Å without a loss in its sheet conductance. The undoped barrier structure is also an advantage of the IBT, as it eliminates the variations in the potential barrier height owing to dopant fluctuations. The *V* groove etched down to the base layer to make base contact provides an easy fabrication of IBT.

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