Solid-State Electronics Vol. 31, No. 3/4, pp. 625–628, 1988
Printed in Great Britain

0038-1101/88 \$3.00 + 0.00
Pergamon Journals Ltd

ROOM TEMPERATURE OPERATION OF UNIPOLAR HOT ELECTRON TRANSISTORS

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ABSTRACT

In this paper we discuss the kinematic and dynamical constrains involved in the design of useful unipolar hot electron transistors and we demonstrate room temperature operation of a double heterojunction hot electron transistor with a two-dimensional electron gas forming the base region. Our test structure has the narrowest ever reported base width at a mere 100Å and is the first such transistor to show current gain in excess of 10 at room temperature. The device uses an indirect, wide band gap $AlSb_{0.92}As_{0.08}$ emitter and the transistor base is a thin InAs layer.

KEYWORDS

Room temperature operation of double heterojunction unipolar hot electron transistors; extreme nonequilibrium electron transport; kinematic and dynamical constraints on hot electron transport; InGaAsSb.

INTRODUCTION

In principle, a unipolar Hot Electron Transistor (HET) is a fast electronic device. Base resistance, R_b is low due to the high mobility of ambient electrons in the base and the emitter-base capacitance, C_{eb} is low due to the absence of minority carrier diffusion effects. Hence, the R_bC_{eb} time constant is unimportant in a HET and the ultimate speed of the device depends only upon the hot electron emitter-collector transit time.

In this short paper we describe how to design a useful HET.

DESIGN CONSIDERATIONS

For the purpose of discussion we show in Fig. 1(a) a schematic diagram of the conduction band of a (001) oriented, $AlSb_{0.92}As_{0.08}$/InAs/GaSb double heterojunction HET under bias. Fig. 1(b) shows the measured room temperature common emitter current gain, β for the device. For this HET, β is greater than 10 when operated at emitter current desities in the range 10 to 1000 A cm^{-2}. Because details of crystal growth (Chiu and co-workers (1987)), fabrication and measured electrical characteristics of this device (Levi and Chiu (1987)) have been described, in this paper we use our device as the focus for a discussion of general HET design requirements.

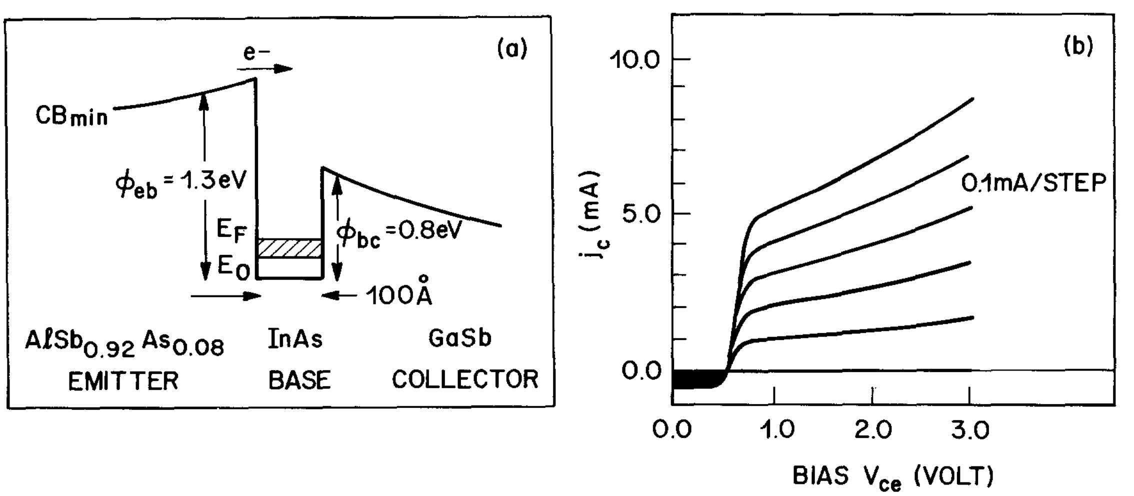

Fig. 1 (a) Schematic diagram of the conduction band of an $AlSb_{0.92}As_{0.08}$/InAs/GaSb double heterojunction unipolar HET under bias. The conduction band minimum, CB_{min} is indicated as is the confinement energy, E_o and the Fermi energy, E_F of the occupied two-dimensional electron states in the InAs base. (b) Room temperature (T = 300 K) common emitter current gain characteristics of the device in (a). Curves were taken in steps of 0.1 mA beginning with an injected base current of zero. Emitter area is 7.8×10^{-5} cm^{-2}, j_c is collector current, and V_{ce} is collector/emitter voltage bias.

We take full advantage of the HET's high current drive capability (useful for high speed applications) by using thermionic emission to inject electrons of energy E_i from the emitter into the base. Space charging effects can occur in the emitter and collector barriers when the device is operated at high current density. This is avoided by doping the barriers to a density $\rho > j/ev$ where v is the average velocity in the barrier, j is the current density and e the electron charge. Reverse current flow from base to emitter and collector to base is minimized by choosing emitter barrier energy $\phi_{eb}(\simeq E_i)$ and collector barrier ϕ_{bc} to be much greater than ambient thermal energy $k_B T \simeq 0.025$ eV (typically $\phi_{bc} \gtrsim 0.5$ eV).

Consider a thermal electron injected from a state close to the X-minimum of the $AlSb_{0.92}As_{0.08}$ conduction band in the emitter into a Γ-state of energy E_i in the InAs base. Because, in the absence of scattering, the injection process conserves energy, E_i and wavevector parallel to the interface, $k_{\parallel}$ band structure considerations dictate that electrons cannot be injected into large $k_{\parallel}$ states. The kinematic constraints giving rise to this type of injection window are illustrated in Fig. 2(a). Only electrons in the shaded X-minimum $AlSb_{0.92}As_{0.08}$ conduction band pockets are injected into the unoccupied Γ-states in the InAs base. An approximate measure of the spread in injection angles is given by $\Delta\theta = \tan^{-1}(k_B T/E_i)^{1/2}$. For our device this gives $\Delta\theta \sim 8^\circ$ at room temperature. The injected electrons therefore traverse the base in the minimum possible time with a large component of momentum in the **z** direction, perpendicular to the interface.

It is important to inject electrons in a narrow range of energies close to E_i. Optimum device performance occurs when quantum reflections from ϕ_{bc} are minimized and this can only be achieved for a limited range of injection energies. This point may be illustrated using the established boundary conditions employed in the effective mass approximation (Ando and Itoh (1987)). Reflections from the abrupt change in potential at ϕ_{bc} approach zero when the hot electron velocity (the slope $\partial\omega/\partial k$ at E_i in Fig. 2(b)) is the same either side of the base-collector junction. This impedance matching condition is $m_1^*/m_2^* = E_i/(E_i - \phi_{bc})$, where m_1^* and m_2^* are the effective electron masses in the base and collector respectively. Therefore, by carefully choosing E_i, ϕ_{bc}, base and collector materials, including the possible use of superlattices, quantum reflections from ϕ_{bc} can be eliminated for a small range (~0.5 eV) of E_i. It is worth mentioning that at a real heterojunction interface, impedance matching also requires that the character of the electron wave function in the base and collector be similar (for example the Γ, s-like states at E_i in Fig. 2(b)).

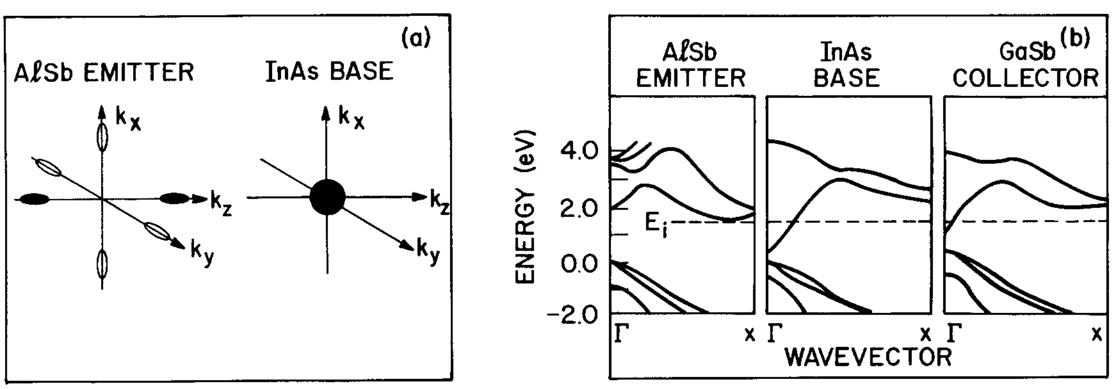

Fig. 2 (a) Kinematic constraints result in only electrons in the shaded X-minimum $AlSb_{0.92}As_{0.08}$ conduction band pockets being injected into the shaded unoccupied Γ-states in the InAs base. (b) Band diagrams illustrating the states used in (001) transmission of an electron energy E_i through an AlSb/InAs/GaSb double heterostructure unipolar HET.

Although quantum mechanical reflection is not a fundamental limit to device performance it is known that inelastic electron scattering is. This dynamical constraint due to electron scattering applies to both unipolar (Levi and co-workers (1986)) and bipolar (Levi and Yafet (1987)) HETs. Calculations indicate that, for a given n-type carrier concentration in a unipolar HET, scattering rates in bulk InAs are almost a factor of two less than in GaAs. This is due to a reduced density of states in InAs compared to GaAs (InAs has an effective electron mass $m^*_{InAs} = 0.021\ m_o$ whereas GaAs has $m^*_{GaAs} = 0.07\ m_o$). In addition to choosing a low effective electron mass material for the base, scattering can be reduced by decreasing the base width.

A transistor base in which ambient electrons occupy two-dimensional electronic states has a number of advantages. For example, it is known that enhanced electron mobility may be achieved in such a system (Dingle and co-workers (1978)) thereby reducing the base resistance, R_b. Of greater significance, however, are the constrains on scattering imposed by the quantization of electronic states in the base.

An injected electron, energy E_i and wave vector $\mathbf{k}_i$, moving in the $\mathbf{z}$ direction is able to scatter into a continuum of high energy states in the base by losing energy $\hbar\omega$ and changing wave vector by $\mathbf{q}$. For example, small angle Coulombic scattering due to emission of longitudinal polar optical phonons is possible and occurs with a probability close to that in the bulk. However, energy and momentum conservation restrict electron-electron scattering in the base. As illustrated in Fig. 3, quantization limits the type of electronic excitations which can occur and, because Coulomb scattering is predominantly small angle, the probability of electron-electron scattering from occupied two-dimensional electronic states in the base is less than the corresponding bulk value.

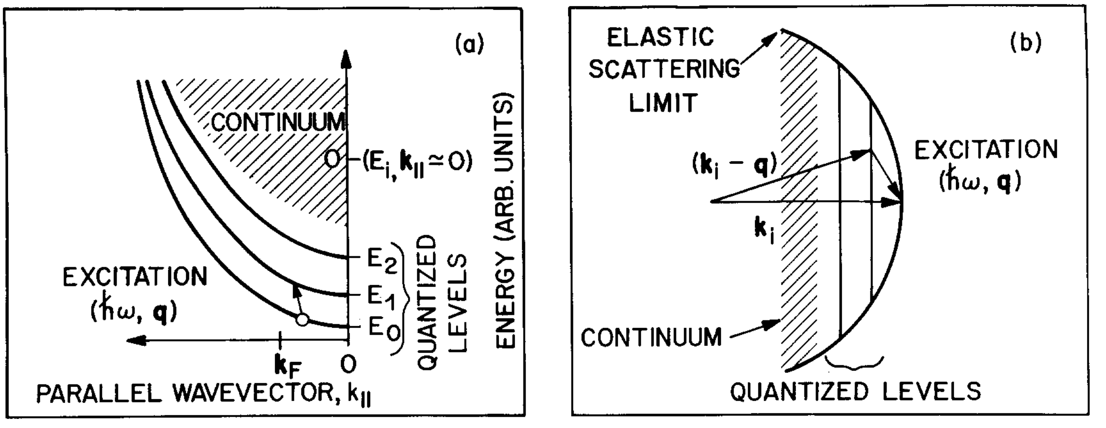

Fig. 3 (a) Schematic diagram showing excitation of a conduction band electron between subbands in the base. The subbands have quantization energies E_0, E_1, and E_2. The excitation is characterized by an energy $\hbar\omega$ and wave vector $\mathbf{q}$. (b) Illustration of restrictions imposed on scattering by quantization of electronic states in the transistor's base. The injected electron has initial energy E_i, wave vector $\mathbf{k}_i$ and is scattered, changing wave vector by $\mathbf{q}$ and losing energy $\hbar\omega$. The elastic scattering limit, in which the injected electron changes wave vector but maintains its energy, is indicated. For the sake of simplicity, we do not consider the small ($\sim$ 30%) contribution to scattering at room temperature in which the injected electron gains energy.

There are other, potentially important scattering mechanisms which can limit performance of a HET. For example, above a critical value of injection energy, E_i there is a high probability of electron transfer into the subsidiary X-minima in InAs (L-minima transfer is less important for an electron moving in the $\mathbf{z}$ direction (Levi and co-workers (1987)). However, as may be seen in Fig. 2(b), in our structure E_i is more than 0.5 eV *below* the energy of the subsidiary X-minimum so this scattering mechanism is unimportant in our device. Another scattering mechanism which should be considered arrises due to the small band gap, E_g of low effective electron mass materials such as InAs. A conduction band electron of energy $E_i >> E_g$ can excite an electron from the valence band into the conduction band (Glicksman and Steel (1958)). However, the confinement energy, E_o and the Fermi energy, E_F of electrons in the 100Å wide base serves to increase the band gap of InAs from 0.36 eV to an effective value of around 0.6 eV while retaining the advantage of the semiconductor's low effective electron mass. This increase in effective band gap greatly reduces the probability of direct excitation from the valence band.

SUMMARY

In this brief report we discussed previously ignored kinetic and dynamic constraints involved in the design of a useful hot electron transistor. A useful device utilizes thermionic emission, two-dimensional electronic states in the base, and careful tailoring of band structure to minimize quantum reflections from the base-collector junction. Applying the design criteria mentioned above we have demonstrated the first room temperature operation of a double heterojunction unipolar hot electron transistor with a current gain greater than 10.

ACKNOWLEDGMENTS

We wish to thank D. R. Hamann and S. Schmitt-Rink for useful discussions.

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