http://dx.doi.org/10.5573/JSTS.2013.13.5.516 JOURNAL OF SEMICONDUCTOR TECHNOLOGY AND SCIENCE, VOL.13, NO.5, OCTOBER, 2013

Study of Switching and Kirk Effects in InAlAs/InGaAs/InAlAs Double Heterojunction Bipolar Transistors

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Abstract—**This paper investigates the two dominant but intertwined current blocking mechanisms of Switching and Kirk Effect in pure ternary InAlAs/InGaAs/InAlAs Double Heterojunction Bipolar Transistors (DHBTs). Molecular Beam Epitaxy (MBE) grown, lattice-matched samples have been investigated giving substantial experimental results and theoretical reasoning to explain the interplay between these two effects as the current density is increased up to and beyond the theoretical Kirk Effect limit for devices of emitter areas varying from 20x20 μm^2 to 1x5 μm^2. Pure ternary InAlAs/InGaAs/InAlAs DHBTs are ideally suited for such investigations because, unless corrective measures are taken, these devices suffer from appreciable current blocking effect due to their large conduction band discontinuity of 0.5 eV and thus facilitating the observation of the two different physical phenomena. This enhanced understanding of the interplay between the Kirk and Switching effect makes the DHBT device design and optimization process more effective and efficient.**

Index Terms—**DHBT, current blocking, Kirk effect, switching effect**

I. INTRODUCTION

Double Heterojunction Bipolar Transistors (DHBTs) are preferred over Single Heterojunction Bipolar Transistors (SHBTs) because they offer higher breakdown and larger Early voltage which are required for high power microwave and precision analog and mixed signal applications [1, 2]. These characteristics are achieved in InP-based DHBTs by using a large band gap material in the collector region to reduce the deleterious effect of impact ionization in the otherwise low band gap material ($In_{0.53}Ga_{0.47}As$) in the collector region of SHBT. This, however, introduces a large energy barrier at the base-collector interface which impedes carrier flow across the junction appreciably reducing the current gain. This reduction is usually referred to as collector current blocking [3] and it is directly proportional to the conduction band discontinuity (ΔE_c) at the base-collector heterojunction. Many researchers [2, 4-6] investigated current blocking in InP, $In_{0.52}Al_{0.48}As$ or quaternary InAlGaAs collector based DHBTs. McAlister et al. [7] and others [2, 4, 5] used a combination of dipole doping [8] and setback layer in DHBTs of different materials to reduce current blocking. Despite elimination of current blocking under low current conditions, this phenomenon resurfaces at higher current densities due to the electron pile-up at the BC heterointerface and its screening effect on the electric field [9] and results in a very large offset voltage and a sudden rise in the output current; this characteristic behavior is called the switching effect [9, 10].

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Another dominant mechanism causing loss of current gain in bipolar transistors is the Kirk Effect [11]. As the current density increases in bipolar transistors, the electric field across the BC junction is reduced to zero due to the screening effect of the mobile carriers crossing the BC junction. This absence of electric field allows the majority carriers from the base to diffuse into the collector causing base push out, which results in the loss of current gain; this phenomenon is called Kirk effect [1]. More recently the Kirk Effect has been thoroughly investigated for non-uniformly-doped, multi-layered collector or small feature size device designs [1, 12, 13] to enable device operation at higher current densities which is required to achieve very high cut-off frequencies.

There has been a renewed interest in the pure ternary InAlAs/InGaAs/InAlAs DHBTs due to their high breakdown and favorable high frequency characteristics [6, 14]. This paper uses simple DC measurements to single out the actual current blocking mechanism in various InAlAs/InGaAs/InAlAs DHBT device designs. Furthermore the technique is completely general and is equally applicable to uniformly doped and multi-layer collector designs.

II. EPITAXIAL STRUCTURE GROWTH AND DEVICE FABRICATION

Wafers were grown on a RIBER V100+ solid source Molecular Beam Epitaxy (MBE) on <100> oriented, semi-insulating Fe-doped InP substrates. In Sample 1 a heavily Be-doped $In_{0.53}Ga_{0.47}As$ base of thickness 650 Å and doping $2x10^{19}$ cm^{-3} is sandwiched between $In_{0.52}Al_{0.48}As$ emitter and collector of thickness 500 Å and 2000Å respectively. The salient features of the epitaxial structure are the insertion of an InGaAs setback layer of thickness 500 Å between the base and the collector with $1x10^{16}$ cm^{-3} n-type doping. Furthermore, a dipole of thickness 2x100 Å and $3x10^{18}$ cm^{-3} doping across the base-collector (B-C) heterointerface is introduced. The base-emitter (B-E) heterojunction is abrupt with a spacer layer of 100 Å thickness with no intentional doping. The entire epitaxial structure comprises only $In_{0.52}Al_{0.48}As$ and $In_{0.53}Ga_{0.47}As$ layers lattice-matched to InP and no quaternary alloys are used. Sample 2 has similar epilayers, however, instead of a dipole it only has an n-spike of thickness 50 Å and doping of $2x10^{18}$ cm^{-3} at the BC interface; detailed study on epitaxial structures and current blocking elimination have already been reported by the authors [6].

Devices of emitter areas varying from 20x20 down to 1x5 μm^2 were fabricated using a triple mesa, wet etching process.

III. DYNAMICS OF SWITCHING AND KIRK EFFECT

1. Switching Effect

The SILVACO ATLAS 2-D physical simulator [15] is used to calculate the equilibrium band diagrams of Fig. 1, which illustrate that the large band gap discontinuity of the B-C junction can be reduced partially by the introduction of a setback layer of thickness 500Å. The amount of band bending on both sides of a heterojunction is in inverse proportion to their doping [16]. Fig. 1(A) shows the band diagram of InAlAs-InGaAs DHBT without the setback layer. Since the interface is between a very heavily doped base and a lightly doped collector region, it results in a large B-C junction spike as shown in Fig. 1(A). However, insertion of a setback layer increases band bending on the $In_{0.53}Ga_{0.47}As$ side of the B-C heterointerface, forcing the band spike down resulting in the start of carrier flow across the B-C junction as shown in Fig. 1(B).

Despite appreciable reduction in the band spike relative to the conduction band edge at the base, the barrier for electrons still remains at the B-C heterojunction. The use of Composite Collector (CC) reduces and transforms the step barrier into a triangular quantum well; under forward bias conditions, electrons exiting the base experience the supportive electric field and are swept across. However, due to the presence of the triangular well, most of the electrons cannot cross the BC heterojunction and rather get trapped in the well and start piling up as shown in Fig. 1(B). This electron pile up screens out the field across the B-C junction and due to this effective reduction in electric field electrons acquire less energy from the BC reverse bias voltage. At this stage there are very few electrons that make it to the collector and the predominant transport mechanism across the BC junction is tunneling. As the base collector

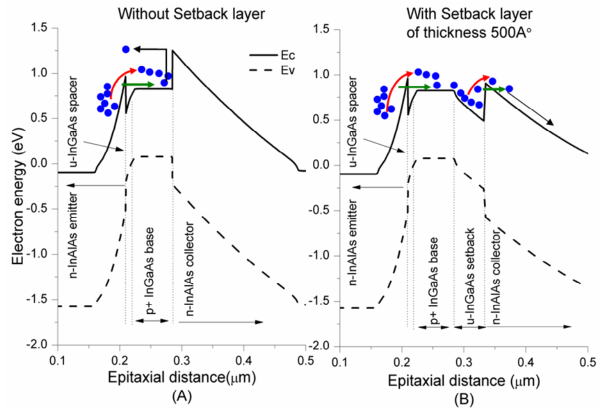

Fig. 1. Equilibrium band diagram model of an InAlAs/ InGaAs DHBT with and without a setback layer.

bias is increased further, this leads to increased tunneling across the BC heterointerface influencing current flow across the BC heterointerface in two ways:

(1) Increased tunneling directly raises the current flow across the BC junction leading to larger collector current and

(2) As the electrons escape the quantum well, their screening effect on the original electric field (due to B-C reverse bias) is also reduced. With the reappearance of the larger electric field across the BC junction, electrons attain higher energy as they go downhill across the junction leading to enhanced thermionic emission across the BC energy barrier [9, 17].

This positive feedback causes a switching of transport mechanism from predominantly tunneling to thermionic emission across the BC heterointerface and gives rise to precipitous increase in the collector current; this phenomenon is called switching effect in DHBTs [3, 7, 9, 17].

2. Kirk Effect

For HBTs with cut-off frequencies of 100 GHz and above, Kirk Effect is the dominant performance limiting mechanism because these devices operate at current densities very close to the Kirk Effect limit derived from equations given by [18]:

$$J_{kirk} = qN_C v_{sat}\left(1+\frac{2\varepsilon\left(\left|V_{BC}\right|+V_{bi(BC)}\right)}{qN_C X_C^2}\right) \qquad (1)$$

where N_C is the collector doping, v_{sat} is the saturation velocity, $V_{bi(BC)}$ is the built-in potential at the BC heterojunction, X_C is the collector thickness, q and ε are electron charge and permittivity. Eq. (1) takes into account the mobile carriers that cross the BC depletion region and gives the current density at which the electric field profile in the BC depletion region starts to invert and the base push out occurs. Unlike the Switching effect, the Kirk effect occurs in both Single and Double HBTs.

IV. RESULTS AND DISCUSSION

Fig. 2 compares I-V curves of samples 1 and 2 illustrating the switching effect. Sample 1 incorporates a doping interface dipole (DID) and that is why its I-V curves show no signs of current blocking for a current density of 5 kA/cm^2 whereas sample 2 (which does not have a dipole) shows characteristic sharp rise in the collector current indicating the presence of switching effect even for a moderate current density of 5 kA/cm^2.

The first order calculation of J_{kirk} using Eq. (1) is ~40 kA/cm^2 assuming saturation velocity of electrons in the collector (v_{sat}) to be 5x10^6 cm/s for sample 1. To elucidate the interplay between Switching and Kirk effect, the current density for the sample 1 devices is varied by an order of magnitude i.e. from 5 kA/cm^2 (Fig. 2) to about 50 kA/cm^2 (Fig. 3(C)). At lower values of the current density, no current blocking is observed in sample 1 devices (Fig. 1), however as the current density reaches values in excess of 20-30 kA/cm^2 even for sample 1 devices, characteristic switching phenomena is observed as is evidenced by the sharp rise in the collector

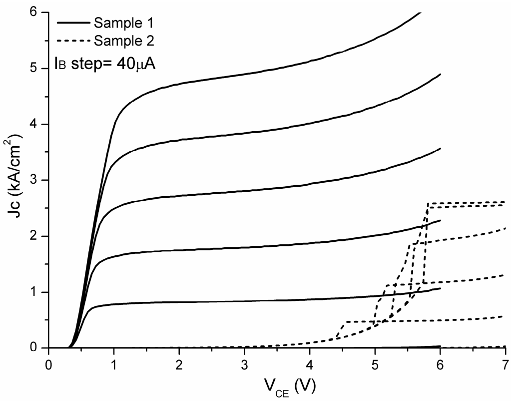

Fig. 2. DC I-V curves of Samples 1 and 2 devices with emitter area of 20x20 μm^2.

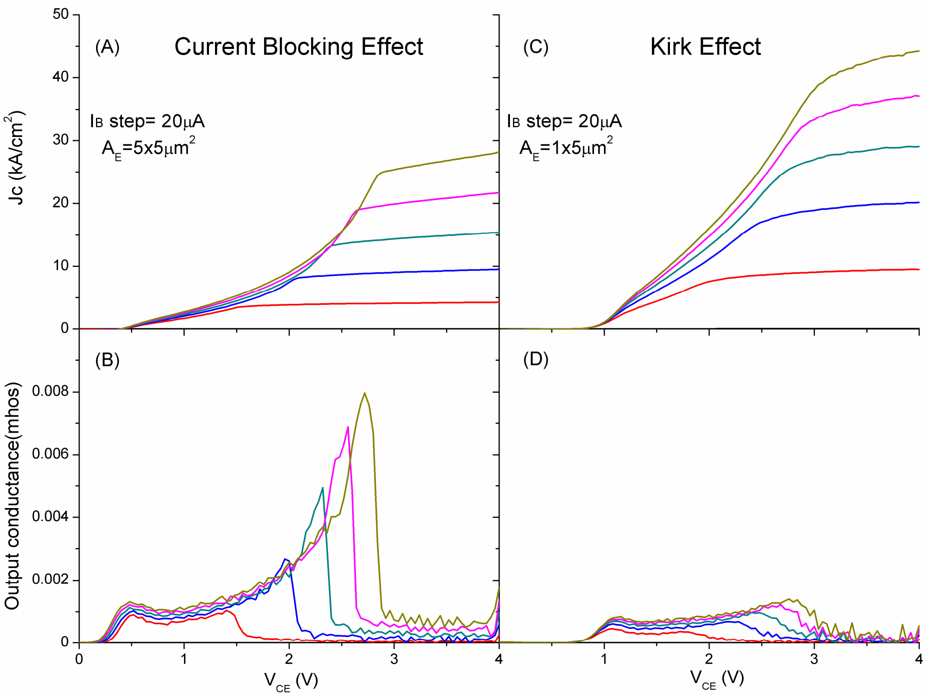

Fig. 3. DC I-V (A & C) and output conductance (B & D) curves of Sample 1 devices with 5x5 μm^2 and 1x5 μm^2 emitter area.

current in the current-voltage characteristics shown in Fig. 3(A); however, as the current density is further increased to about the J_{kirk} limit (40 kA/cm^2), the precipitous rise in the collector current changes to the soft knee characteristics as shown in Fig. 3(C). This is a very important phenomenon, which is consistently observed in other samples (not reported here) as well. It highlights first the straightforward way of distinguishing between Kirk and Switching effect by way of measuring output conductance and looking for the distinctive peaks as shown in Fig. 3(B). Furthermore it reflects the overwhelming influence of the Kirk effect on a sample already showing current blocking effect such that the signature of the output conductance curves change from showing sharp peaks to almost constant value of the output conductance.

This is a very simple technique to distinguish between the two dominant current blocking mechanisms and is independent of the material system and the collector design.

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