AlGaAs/GaAs HBT with Enhanced Forward Diffusion

Personnel

K. Konistis and Q. Hu, in collaboration with M. Melloch at Purdue University, and C. G. Fonstad

Sponsorship

AFOSR

One of the key limits of high-frequency operation of bipolar transistors is the base transient time, which is proportional to the square of the base width when the base transport is dominated by diffusion. Consequently, high-frequency bipolar transistors tend to use thin bases (<100 nm) that results in a short base transient time and a high cut-off frequency f_T. However, for high frequency operations, it is not the current gain that matters most. Rather, it is the unilateral power gain that determines the operating frequency of any three-terminal devices. The frequency f_{max}, at which the power gain is unity, is determined by both f_T and RC time constant. Because of the peculiar geometry of bipolar transistors, the electrical contact to the base is always made from the side. Thus, a thin base, which is important to yield a high f_T, will inevitably result in a high sheet resistance and a lowering of f_{max}. It is this difficult trade-off between f_T and f_{max} that lead Prof. S. Luryi and his co-workers to propose a novel heterostructure bipolar transistor, whose band diagram is shown in Figure 26.

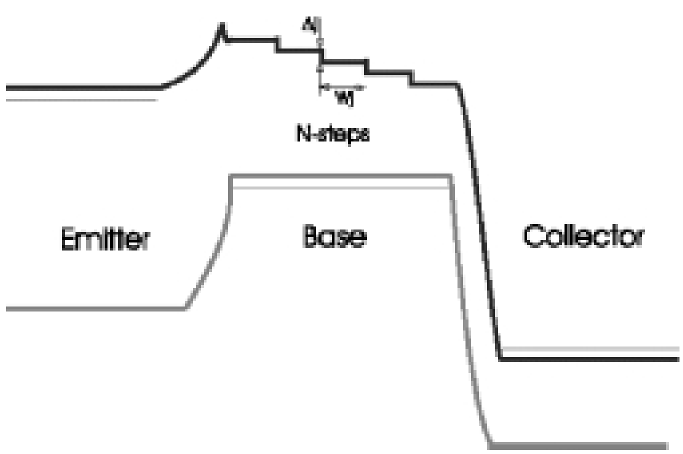

Fig. 26: Energy band diagram of an HBT with stepwise base. The energy drop Δ at each step is slightly greater than the LO-phonon energy (36 meV) in GaAs. Thus, electrons encounter very fast LO-phonon emission scattering (with a time ~0.1 ps) when they go over the edge of a step. Consequently, backward diffusion is significantly reduced and forward diffusion is enhanced.

The main feature of this novel HBT is that its base is graded like a staircase. The height of each step Δ is slightly greater than the LO-phonon energy in GaAs (36 meV). Thus, electrons will encounter very fast LO-phonon emission scattering (with a time ~0.1 ps) when they go over the edge of a step. Consequently, backward diffusion is significantly reduced. In a way, the edge of each step resembles and performs a similar function as the base-collector interface: any injected excess minority carrier will be quickly swept down the energy potential. As a result, each step acts like a minibase, as far as the diffusion transport is concerned. The resulting minority carrier concentration assumes a nearly periodic distribution, provided that the energy drop is greater than the sum of LO-phonon and thermal energy to ensure a fast scattering and prohibit backward diffusion. The total base transient time is therefore approximately N times the transient time of each step, whose width can be as narrow as 30 nm, yielding a high f_T. On the other hand, all the N steps are connected in parallel for the base contact, reducing the base resistance by an approximate factor of N. The combination of a thin effective base and small base resistance will yield a high f_{max}.

The use of LO-phonon scattering as a resetting mechanism introduces the concept of independent cascade of base transport factors. In our analysis, the intrinsic part is modeled by device physics whereas the extrinsic are treated as lumped circuit elements. A simple approach that captures most of the physics is to define the transport as the product of the individual base steps assuming perfect resetting LO mechanism. As a result, the total base transport factor is a simple product of the transport factor of each step, as shown in Figure 27. It can be seen clearly, as the number of steps N increases, the amplitude of the base transport factor increases, resulting in a higher cut-off frequency.

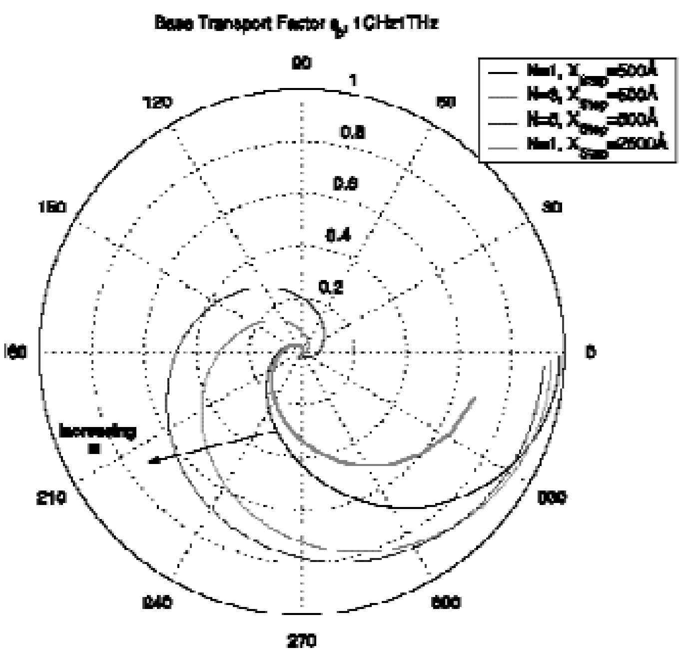

Fig. 27. Polar plot of base transport factor in frequency, for N steps and XStep step size.

One interesting result of our analysis is the existence of resonances of the unilateral power gain. Their physical mechanism is closely linked with the current-phase delay. A base structure introduces both phase delay and magnitude attenuation of current. As the frequency of operation increases, the phase delay increases and at a certain frequency the voltage and current acquire opposite phases, which will yield a resonance if the amplitude attenuation is not too overwhelming. A short base offers small phase delay and resonance occurs at high frequencies where the magnitude attenuation is strong. On the other hand, a long base may provide a large phase delay but the heavy attenuation at low frequencies smoothes out the unilateral gain peaks. For a multi-step base, the total phase delay is the sum of each step, while the total attenuation is the product of each step, enhancing the possibilities of achieving resonance. As can be seen in Figure 10, the base transport factor of multi-step base HBTs crosses the real axis with an appreciable amplitude, Figure 28 shows both the current gain and unilateral power gain as a function of frequency for N =1-6. Clearly, even though f_T decreases somewhat as the number of steps N increases, f_{max} barely changes due to the reduced base resistance of high-N bases. Furthermore, resonance can be achieved above 100 GHz by using multi-step base HBTs, which is promising for the development of high-frequency fundamental oscillators.

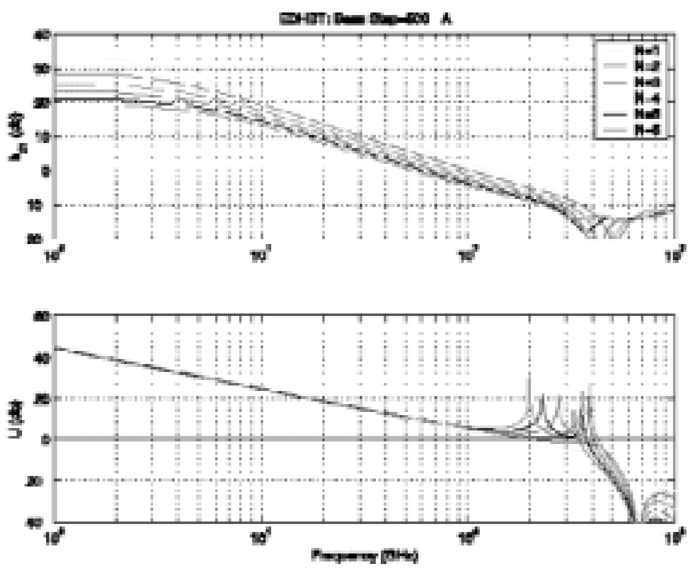

Fig. 28: Current gain h_{21} and Unilateral power gain U in frequency for X_{Step} =500 Å and variable number of steps. The resonance (peaks in U) is clearly shown above 100 GHz, which is promising for the development of high-frequency fundamental oscillators.