Surface transport and DC current gain in InGaAs/InP DHBTs for THz applications

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InGaAs/InP double heterojunction bipolar transistors (DHBTs) are highly suitable for applications in GHz mixed-signal ICs, >100 GHz digital logic, and millimeter-wave communications and imaging because of their high breakdown voltage and high cutoff frequencies ($f_\tau/f_{max}\approx0.5/1.0$ THz)[1,2]. To extend HBT bandwidth, device dimensions must be reduced and the doping concentration in the InGaAs base must be increased. As a result, surface recombination increases, as does lateral electron transport from the emitter to the base contact, both on the exposed base surface and within the bulk base semiconductor. The DC current gain (β) thus decreases. Experimentally measured β are ~10-25 in THz DHBTs [2]. Because it limits the useful range of circuit applications, it is important to understand the mechanisms causing decreased β in scaled DHBTs. Using TCAD simulation, we had earlier found that lateral carrier diffusion within the bulk of the base contributes significantly to the observed high base currents in THz HBTs [3]. Here we model the surface conduction between the emitter and base contacts resulting from Fermi level pinning at the exposed base semiconductor surface, comparing simulations with experimental data. At bias conditions corresponding to peak f_τ/f_{max}, we find that ~50% of the total base current arises from surface conduction. This finding suggests the need for improved base surface passivation in THz HBTs.

Fig. 1 shows a mesa DHBT cross-section. At the interface between the dielectric (SiN_x) sidewall and InGaAs base, the surface Fermi level is pinned by interfacial trap states, inducing a surface inversion layer. Fig. 2 shows the electron quasi-Fermi level (E_{fn}) and conduction band edge (E_C) across the base, simulated at $J_e\approx25$ mA/μm^2. Under bias, a fraction of electrons injected from the emitter accumulate near the base surface, and are transported to the base contact by the gradient in E_{fn}. This surface conduction can be viewed as a parasitic diode whose width is that of the surface inversion layer and whose length is the base-emitter contact spacing W_{Gap}.

The base of the experimental DHBTs is 20nm-thick with doping graded from $12\text{-}8\times10^{19}$ cm^{-3}. The base-emitter spacing, W_{Gap} is ~10 nm. Fabrication is as in [2]. DC characteristics were measured using an Agilent semiconductor parameter analyzer. HBTs were simulated using Synopsys Sentaurus with settings and carrier transport and bulk base recombination parameters as in [3]. From [4], a 5000 cm/s electron surface recombination velocity ($v_{surf.SRH}$) is assumed. The interface traps are modeled using a Gaussian energy distribution centered 0.2 eV below the InGaAs conduction band edge, with variance σ_e=0.1 eV, and, because this parameter is unknown, with varying density D_{it}.

Given base lateral current density (K_B, mA/μm) from lateral transport of electrons from the emitter to the base contact, both within the bulk base semiconductor and at its surface, β can be written as $1/\beta = 1/\beta_{bulk} + P_{je}K_B/A_{je}J_E$, where J_E is the emitter current density, P_{je} and A_{je} are the perimeter and area of the emitter junction, and β_{bulk} the current gain limited by bulk (Auger, SRH, radiative) recombination processes. Experimentally, K_B and β_{bulk} are determined by plotting $1/\beta$ versus P_{je}/A_{je} and finding the intercept and slope of the fitted data. Fig. 3 shows measured and simulated characteristics at $J_E \approx 25\mu A/\mu m^2$. The experimental results indicate $\beta_{bulk} \approx 45$ and $K_B \approx 72\ \mu A/\mu m$; in the experimental devices with 100 nm wide emitters, i.e. $P_{je}/A_{je} \approx (50\ nm)^{-1}$, 72% of the total base current arises from lateral conduction, both surface and bulk, to the base Ohmic contact, and 28% from bulk processes, primarily Auger.

The HBT is then first simulated with $D_{it} = 0\ cm^{-2}eV^{-1}$ and $v_{surf.SRH}$=0 cm/s, forcing surface conduction and surface recombination to zero, and allowing us to determine from K_B, the component of the base current arising from lateral diffusion, in the bulk base semiconductor, of electrons from the emitter to the base contacts. This is $K_B \approx 20\ \mu A/\mu m$.

In simulations using $v_{surf.SRH}$=5000 cm/s, surface recombination contributes negligible ($K_B < 1\mu A/\mu m$) current.

The HBT is then simulated with $v_{surf.SRH}$=5000 cm/s and with $D_{it} = 5\times10^{12}, 10^{13}$, and $5\times10^{13}\ cm^{-2}eV^{-1}$, giving lateral current densities $K_B = 33, 35$, and $50\ \mu A/\mu m$. Given that 20μA/μm arises from lateral diffusion in the bulk base semiconductor, the lateral current densities arising from surface conduction are then 13, 15, and 30 μA/μm. With $D_{it} = 5\times10^{13} cm^{-2}eV^{-1}$ and W_E=100 nm, approximately 50% of the total base current is attributed to surface conduction.

These simulations indicate that surface transport contributes substantially to base current in THz DHBTs. In simulations, more than half of the base current originates from conduction on the exposed base surface between the emitter and the base contacts. Recently, $D_{it} = 2.5\times10^{12} cm^{-2}eV^{-1}$ has been reported for InGaAs passivated by ALD Al_2O_3 after a nitrogen plasma treatment [5]. If such processes can be incorporated into DHBT process flows, current gain can be significantly improved.

[1] M. J. W. Rodwell, *et al, Proc. IEEE*, vol. 96, no. 2, pp271-286, Feb 2008
[2] V. Jain, *et al*, *69th IEEE Device Research Conference*, Jun 2011
[3] H.-W. Chiang, *et al*, *J. Appl. Phys.*, vol. 115, no. 3, 034513, Jan 2014
[4] E. Yablonovitch, *et al*, *Appl. Phys. Lett.*, vol. 60, no. 3, pp371-373 , Jan 1992
[5] V. Chobpattana, *et al*, *Appl. Phys. Lett.*, vol. 102, no. 2, 022907-1-022907-3, Jan 2013

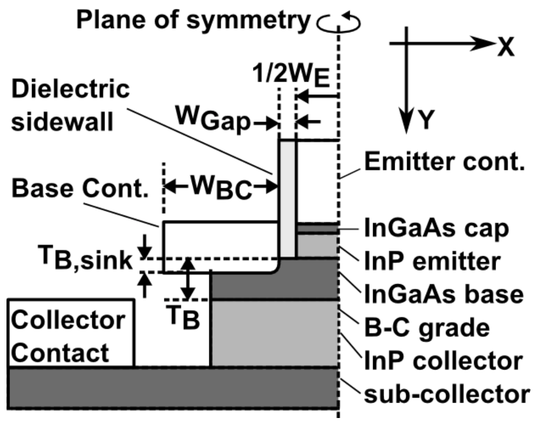

Fig. 1. DHBT schematic cross section (normal to the emitter stripe). The device is symmetric about the indicated line.

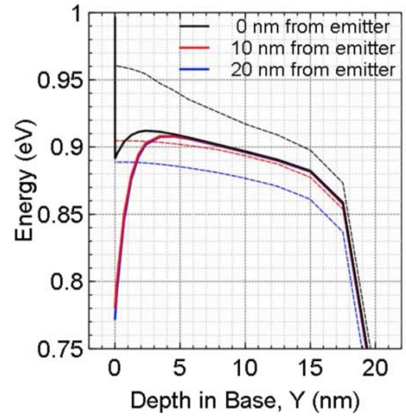

Fig. 2. Conduction band edge (solid) and electron quasi-Fermi level (dashed) vs. depth into the base (Y-direction) simulated for W_{Gap}=30 nm and D_{it}= 5×10^{13} $cm^{-2}eV^{-1}$ at distances of 0, 10, and 20 nm from edge of the emitter contact.

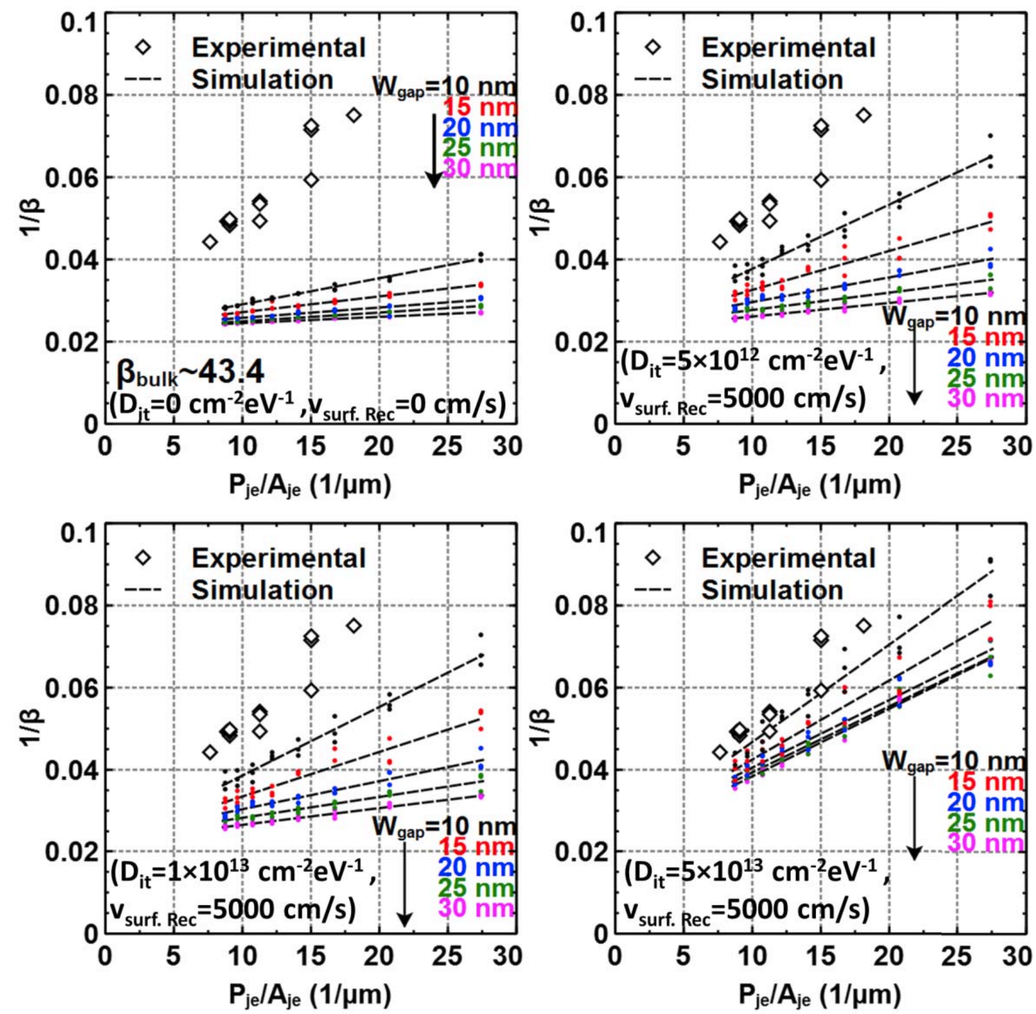

Fig. 3. Inverse DC current gain (1/β) vs. HBT emitter periphery to area ratio (P_{je}/A_{je})for interfacial trap densities (D_{it}) of 0, 5×10^{12}, 1×10^{13}, and 5×10^{13} $cm^{-2}eV^{-1}$ and base-emitter spacings (W_{Gap}) of 10, 15, 20, 25, and 30 nm. Current gain was simulated for base conduction band potential grading (ΔE_C) of 54 meV, base contact penetration of 5 nm, and base contact widths of $1.2W_E$, $1.4W_E$, and $1.6W_E$. Experimental results were measured from DHBTs with W_{Gap}=10~15 nm as determined from TEM analysis.