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High-Speed InGaAs/InP Double Heterostructure Bipolar Transistor with High Breakdown Voltage *

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We design and fabricate an InGaAs/InP double heterostructure bipolar transistor (DHBT). The spike of the conduction band discontinuity between InGaAs base and InP collector is successfully eliminated by insertion of an InGaAs layer and two InGaAsP layers. The current gain cutoff frequency and maximum oscillation frequency are as high as 155 and 144 GHz. The breakdown voltage in common-emitter configuration is more than 7 V. The high cutoff frequency and high breakdown voltage make high-speed and high-power circuits possible.

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InP-based HBTs have been extensively studied due to their advantages of the materials for high-speed devices. In an InGaAs/InP HBT, n-type InP is used as emitter, p^+-type InGaAs is used as base, n-type InGaAs or InP is used as collector. If InGaAs is adopted as collector, the HBT is called single HBT (SHBT); if InP is adopted as collector, the HBT is called double HBT (DHBT). SHBT has typically higher speed due to the higher saturation velocity of electron in InGaAs. The highest current gain cutoff frequency f_t of SHBT reaches as high as 847 GHz.[1] However, the breakdown voltage in SHBT is small due to the small band gap of InGaAs, which limits the application of SHBTs. To improve the breakdown voltage, DHBT is used because of the higher band gap of InP. The conduction band of InP is higher than that of InGaAs. This will result in the current blocking effect, which degrade the current gain and high-frequency performances. Thus the collector should be designed carefully to reach high breakdown voltage and high-frequency performance. In our previously designed DHBT, a highly doped n-type thin InP layer is used to eliminate the spike.[2] However, in this structure, the electrons injected from the emitter have to go through the thin highly doped InP layer by tunnelling, which decreases the velocity of electrons in the collector. Here f_t is only 80 GHz and maximum oscillation frequency $f_{\max}$ is only 60 GHz. A successful method to remove the spike is to use an InGaAs setback layer, an InGaAs/InAlAs superlattice and a δ-doped InP layer.[3] However, in this structure, the electrons are accelerated in the setback layer and go through the superlattice by tunnelling. The tunnelling will reduce the velocity of the electrons in the collector. Furthermore, the thicknesses of the wells and barriers in the superlattice are not constant. It is very difficult to grow such structure. In this study, an optimized collector structure of DHBT is used. An InGaAs setback layer and two InGaAsP layers are used to eliminate the conduction-band spike. The structure eases the difficulty of the layer growth. Here ft and $f_{\max}$ are as high as 155 and 144 GHz, respectively. The breakdown voltage is more than 7 V.

Table 1. Layer structure of InGaAs/InP DHBT.

Layers	Thickness (nm)	Dopant	Doping density (cm^{-3})
$In_{0.53}Ga_{0.47}As$	60	Si	2×10^{19}
InP	130	Si	1.2×10^{19}
InP	40	Si	2×10^{17}
$In_{0.53}Ga_{0.47}As$	65	C	3×10^{19}
$In_{0.53}Ga_{0.47}As$	50	Si	1×10^{16}
InGaAsP	20	Si	1×10^{17}
InGaAsP	20	Si	1×10^{17}
InP	200	Si	1×10^{17}
InP	200	Si	1.2×10^{19}
$In_{0.53}Ga_{0.47}As$	50	Si	2×10^{19}
InP	400	Si	1.2×10^{19}
InP substrate			

The DHBT structure was grown by gas source molecular beam epitaxy (GSMBE) on a semi-insulating InP substrate. The layer structure of our HBT is shown in Table 1. The structure consists of a 400-nm InP (Si: $1.2 \times 10^{19}\,cm^{-3}$) and a 50-nm $In_{0.53}Ga_{0.67}As$ (Si: $2 \times 10^{19}\,cm^{-3}$) and a 200-nm InP (Si: $1.2 \times 10^{19}\,cm^{-3}$) as subcollector, a 200-nm InP (Si: $1 \times 10^{16}\,cm^{-3}$) as the collector, the grade layer is composed of a 20-nm InGaAsP ($E_g = 1.15$ eV), a 20-nm InGaAsP ($E_g = 0.95$ eV) and a 50-nm $In_{0.53}Ga_{0.67}As$ (Si: $1 \times 10^{16}\,cm^{-3}$), a 65-nm InGaAs base layer (C: $3 \times 10^{19}\,cm^{-3}$), a 40-nm InP emitter (Si: $2 \times 10^{17}\,cm^{-3}$), and a 130-nm InP (Si: $1.2 \times 10^{19}\,cm^{-3}$) and 60-nm $In_{0.53}Ga_{0.67}As$ cap layer(Si: $2 \times 10^{19}\,cm^{-3}$).

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The structure was designed according to our recent study.[4] The 50-nm $In_{0.53}Ga_{0.67}As$ grade layer in the collector is the setback layer, to accelerate the electrons injected from the base. The two InGaAsP layers in the collector have two purposes: one is to smooth the conduction band discontinuity between InGaAs and InP, the other is to lower the spike of InP by the higher doping density. The HBTs were fabricated by contact-mode photolithography, conventional wet etching and metal deposition with 3-mesa design. The non-alloyed Ti/Pt/Au was used as n-type Ohmic contact and the non-alloyed Pt/Ti/Pt/Au was as p-type Ohmic contact. The sheet resistance of the base is 620Ω/square and the specific contact resistance is $7 \times 10^{-7}\,\Omega{\cdot}\mathrm{cm}^2$. InP was etched by the HCl-based etchant, InGaAs was etched by the H_3PO_4-based etchant. The planarization of the device was carried by a dielectric film, which makes the contact connections with pads without micro-air bridges to avoid the micro-air-bridge-related parasitics. The dielectric film is then etched back to expose the top of the emitter contact and the base and collector posts. The emitter width is 1.8 μm, the length of the emitter is 15 μm. The dc and rf characteristics of the HBTs were measured by a HP 4515B semiconductor parameter analyser and a HP 8510C vector network analyser, respectively.

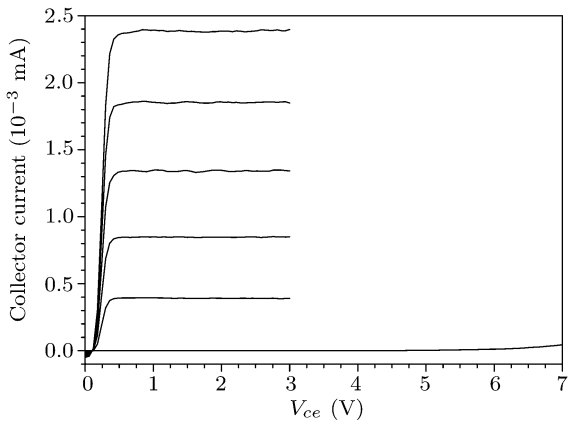


Fig. 1. Common-emitter $I-V$ characteristics of DHBT. The base current is 10 μA/step.

The common-emitter $I-V$ characteristic is shown in Fig. 1. The collector current I_C increases uniformly with the increasing base current I_B. The current gain of 50 can be obtained from the figure. The offset voltage is only 0.1 V and the knee voltage is less than 0.5 V. The value of the knee voltage is related to the current blocking effect. If the electrons injected from the emitter are blocked by the conduction band discontinuity between InGaAs and InP, the electrons must acquire more energy to overcome the conduction-band barrier of InP. This results in a slower increase in I_C with the increasing collector-emitter bias V_{CE}. Thus a higher knee voltage occurs. The low knee voltage and the sharp increase in I_C indicate that the current blocking has been eliminated successfully. The breakdown voltage is more than 7 V, as can be seen in Fig. 1. The high breakdown voltage benefits from the high band gap of InP. The low knee voltage and high breakdown voltage enlarge the linear operation area of the transistor and make a higher output power of an amplifier.

In order to study further the base-collector junction, the reverse Gummel plot of the device has been measured. Figure 2 shows the emitter current in the reverse Gummel plot as a function of the base-collector bias. In the reverse Gummel plot measurement, the electrons are injected from the collector, a part of the electrons recombine in the base region, the left are collected by the emitter. The emitter current I_E actually reflects the properties of the base-collector junction.[5] If the ideality factor of I_E is unity, the base-collector spike is eliminated successfully.[5] The ideality factor of 1 can be derived from the curve in Fig. 2. This confirms that the conduction band spike was eliminated by our design and that no current blocking occurred in our DHBT.

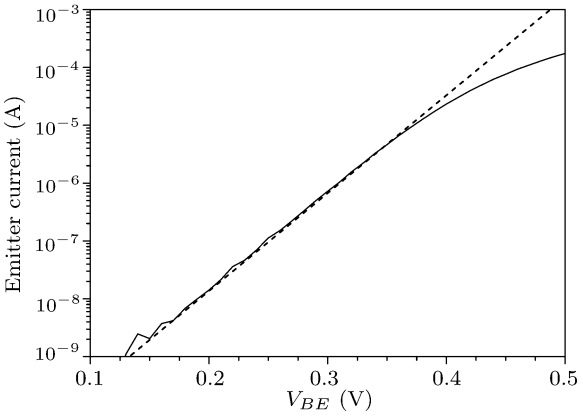


Fig. 2. Emitter current in the reverse Gummel plot as a function of the base-collector junction bias.

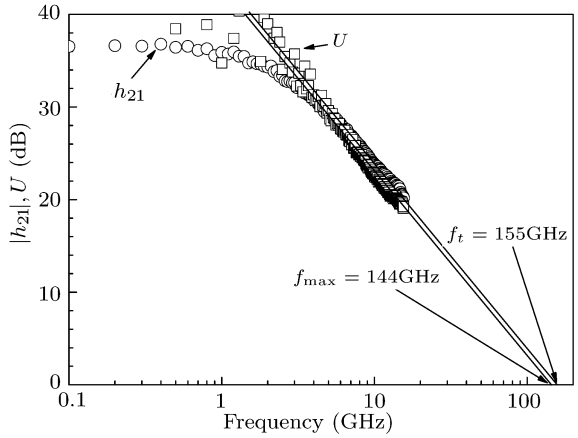


Fig. 3. Behaviour of $|h_{21}|$ and U as a function of the measurement frequency at $I_C = 22.5$ and $V_{CE} = 1.7$ V.

Figure 3 shows the current gain $|h_{21}|$ and the unilateral gain U as a function of the measurement frequency. More than 35 dB current gain was obtained at low frequency, it then decreases slowly with the increasing frequency. Here $|h_{21}|$ finally rolls off along the -20 dB/decade line. The extrapolated current gain cutoff frequency f_t is 155 GHz. The open squares show the relationship between the unilateral gain and the measurement frequency. U has the same trend as that of $|h_{21}|$. The maximum oscillation frequency fmax of 144 GHz is obtained when derived by the -20 dB/decade line. In superlattice graded and -doping structure,[3] when the collector thickness is 300 nm, f_t is 165 GHz, which is comparable to our result. However, the width of the emitter is only 0.4 μm in their case,[3] compared with our emitter width of 1.8 μm. From the scaling law of HBT, our DHBT should have much higher f_t at the same emitter width.[6] This indicates the superiority of our structure.

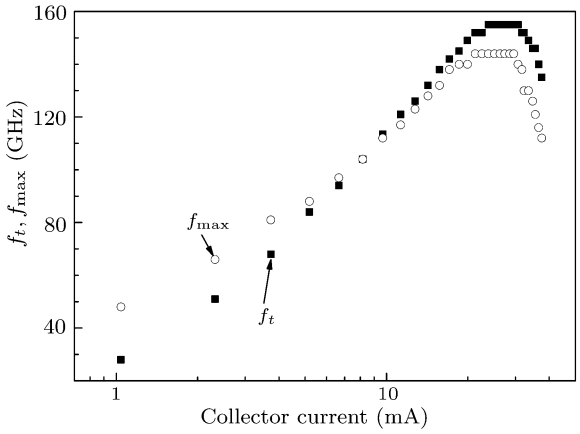


Fig. 4. Behaviour of f_t and $f_{\max}$ as a function of the collector current at $V_{CE} = 1.7$ V.

Figure 4 shows f_t and $f_{\max}$ as a function of I_C at $V_{CE} = 1.7$ V. Both f_t and $f_{\max}$ first increase with an increase in the collector current, they then reach a flat region and finally decrease with an increase in the collector current. Here f_t can be expressed as[7]

$$f_t = \frac{1}{2\pi}\left[\frac{nkT}{qI_C}(C_{BE}+C_{BC}) + \frac{X_B^2}{\nu D_n} + \frac{X_{dep}}{2\nu_{sat}} + (R_E+R_C)C_{BC}\right]^{-1}.$$

From the equation, the increase in f_t with increasing I_C actually reflects the first term in the bracket on the right side. The decrease in f_t with I_C is due to the Kirk effect.[8] The Kirk current is as the maximum operation current. To increase the speed of the circuit and to increase the output power, the Kirk current should be as high as possible. From the curve of f_t vs I_C, the Kirk current of more than 1 mA/μm^2 can be derived. This is a high value at such wide emitter. Further research is going on to improve the Kirk current. The methods to increase the Kirk current include the reduction of emitter width and the optimization of the collector structure.

In summary, the composite graded DHBT has been designed and fabricated successfully. An InGaAs layer and two InGaAsP layers were used to eliminate the conduction band spike between InGaAs base and InP collector. The low offset voltage and low knee voltage has been demonstrated. The breakdown voltage is more than 7 V. The emitter current in the reverse Gummel plot shows an ideality factor of unity, indicating the elimination of the base-collector conduction band spike. High f_t and $f_{\max}$ of 155 GHz and 144 GHz have been demonstrated in our DHBT. The Kirk current can reach more than 1 mA/μm^2.

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