Jurnal Teknologi

Full paper

Performance Characterization of Heterojunction Bipolar Transistor as an Optoelectronic Mixer

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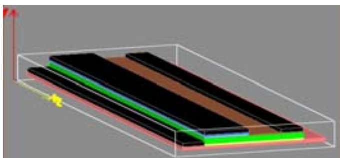
Article history

Received: 8 March 2012
Received in revised form: 10 April 2012
Accepted: 18 July 2012

Graphical abstract



Abstract

This paper explains the development of physical model Heterojunction Bipolar Transistor (HBT) and characterizes its performance as an optoelectronic mixer (OEM). HBT has been identified as a suitable device to be implemented in optoelectronic mixers by simultaneously photodetecting an intensity modulated laser beam at 1550nm and frequency translating the detected signal to a higher or lower frequency which can provide high mixing efficiency and required condition for an oscillator. The HBT OEM was designed, modeled and simulated by using APSYS Crosslight software. Data from the simulation such as the gummel plot, energy band diagram and other characteristics have been generated and analyzed. The device was analyzed considering 1550nm wavelength with up to 30GHz modulating signal frequency. Hence, the designed HBT is found to be possible for the implementation of the broadband RoF system as it can perform the photodetection, amplification and frequency conversion simultaneously as required at RoF remote antenna unit..

Keywords: Heterojunction Bipolar Transistor, Optoelectronic mixer, frequency-up converter, photodetector

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1.0 INTRODUCTION

Millimeter-wave frequencies the are promising RF frequencies for transmitting broadband signal such as video signals and high speed data. Millimeter wave wireless networks should have small cell sizes since millimeter-wave have high transmission loss in air. While the small size cell can offer high frequency reusability and low power consumption, it requires a large number of base stations. Radio over Fiber (RoF) technology is the proposed solution for reducing cost and provides higher reliable communication services which can connect a large number of base stations to one central station trough fiber.

OEM is implemented in RoF system as it performs up-conversion and frequency mixing [1]. In the up-conversion scheme with local oscillator (LO), data is transmitted from central station to base station in optical immediate frequency (IF) and frequency is up-converted to the desired radio frequency (RF) with LO signal. The single HBT is one of the most promising optoelectronic converters for RoF communication systems and is applied at OEM as it perform photodetection and low noise frequency [2].

The aim of this paper is to show performance of physical model device of HBT In addition, the characterization of HBT as an OEM to perform up to 30GHz frequency mixing and performs photodetection that meet 1550nm wavelength will be discussed further in this paper.

2.0 HETEROJUNCTION AS AN OPTOELECTRONIC MIXER

The HBT similar as bipolar junction transistors (BJT), consists of an emitter, base, and collector. Heterojunction bipolar transistors are bipolar junction transistors, which are composed of at least two different semiconductors. As a result, the energy bandgap as well as all other material properties can be different in the emitter, base and collector. In addition, HBT can handle signals of very high frequencies up to several hundred GHz.

The HBT is common in the modern ultrafast circuits, mostly radio-frequency (RF) systems, as well as RoF requiring a high power efficiency, such as power amplifiers in cellular phones. In addition, it becomes a natural choice for very high frequency military applications requiring a high current drive, high voltage handling capability and low noise oscillator. InP/InGaAs HBTs is aimed for optoelectronic circuits for 1.55um fiber optic communications. HBT offers a lot of applications instead of other devices such as HEMT and GaAs FETs [7] when implemented in OEM. HBT can reduce phase noise as the optical injection looking achieved with the injection of an optical signal modulated at the oscillation frequency as [9]. In HBT, there are two internal p-n junctions where the mixing process occurs. The process happens when two junctions exhibit nonlinear exponential current-voltage characteristic.

HBT provides several advantages. Instead, it is suitable to implement in OEM. One of the advantages is provide higher frequency conversion [7]. InGaAs HBT can operate over a broad range of frequencies which are required for many high speed, high

bandwidth applications. Higher operational frequencies enable more data to be transmitted through a fiber or wireless system. HBT improving maximum oscillation frequency, fmax which maximum power gain reach as in (1) is;

$$f_{max} = \frac{\sqrt{f_\tau}}{\sqrt{8\pi R_B C_{BC}}} \quad (1)$$

where RB, is the base resistance, CBC, is the base collector capacitance, and fT is the current gain cutoff frequency.

One of the advantage of HBT is it consist of simple design. HBT only require a single, low-voltage power supply for operation. In addition, HBT consume no power when they are turned off, thereby eliminating the switch components needed for other transistor types. Thus, HBT solutions are easier to design, utilize fewer components and are more compact.

In addition, HBT are not restricted to its dc performance. Microwave devices can also be improved dramatically by using an appropriate heterojunction material system. To illustrate this point the transit frequency, f_T equation.

$$f\tau = \frac{1}{2\pi\tau} \quad (2)$$

Where the total transit time equals is,

$$\tau = \tau_E + \tau_B + \tau_C = \frac{V_t C_{BE}}{I_E} + \frac{W_B^2}{2D_{n,b}} + \frac{X_{d,BC}}{2V_{sat}} \quad (3)$$

Since a HBT have large current gain, even if the base doping density is higher than the emitter doping density, the base can be much thinner even for the same punch through voltage. Therefore, reduce the base transit time without increasing the emitter charging time, while maintaining the same emitter current density. The transit frequency can be further improved by using materials with a higher mobility for the base layer and higher saturation velocity for the collector layer. In HBT, the largest mixing efficiency achieved when HBT in active mode [5].

The maximum oscillation frequency, fmax in (1), can able further improved. The improved transit frequency immediately increases fmax. The higher base doping also provides a lower base resistance and a further improvement of fmax. As in the case of a homojunction BJT, the collector doping can be adjusted to trade off a lower the collector transit time for a lower base-collector capacitance. The fundamental restriction of heterojunction structures still applies, which the materials must have a similar lattice constant so that they can be grown without reducing the quality of the material.

An equivalent circuit of HBT under optical light can be shown in Figure 1. Photodiode located between base and emitter to absorb the optical light with 1550nm wavelength and convert from optical light to electrical energy. An incident light is directed to the optical window of the HBT. Due to the photon absorption of the light, electron-hole pair will be generated and occur in three regions, which are at the base, base-collection depletion and collector regions. They are immediately separated by the strong electric field. Hence, the primary photocurrent, Iprim begins to flow.

The HBT type using is n-p-n junction in which the emitter and the collector are n-type semiconductors, and the base is p-type and operating in common emitter. The two of PN–junctions is base–emitter junction (BE junction) and base–collector junction (BC junction). In the forward active mode the BE junction is forward biased, while BC junction is reverse bias.

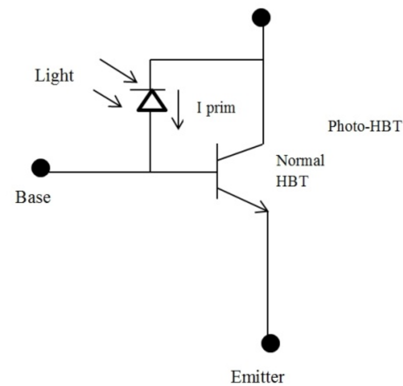

Figure 1 Circuit representation of HBT

■3.0 MODELING-HBT PHYSICAL MODE

APSYS Crosslight is used to build and modeling the structure of HBT OEM. The layer structure of the three-terminal InP/InGaAs normal incident HBT is setup following the parameter include in Table1.

Table 1 HBT physical model design parameter

	Sub collector	Collector	Base	Emitter
Height(µm)	0.4	0.75	0.05	0.15
	0.25			
Width(µm)	13.00	9.00	9.00	4.00
	9.00			4.00
Doping Type	n	n	p	n
Material	InGaAs	InGaAs	InGaAs	InP
	InP			InGaAs
Concentration (m^{-3})	2e+025	2e+021	5e+025	1e+023
	1e+024			1e+025

The optical window located at base to minimize the dimension. In addition, it also avoids current crowding effect as the lights are absorbed at base collector junction as the circuit representation in Figure 1 where the photodetector is located at base-collector terminal. The base-emitter junction determines the turn-on voltage of the transistor and the ideality factor of the base-emitter diode. The emitter made a HBT has a wider bandgap than the base and collector region. To improve the gain dependence of optical power or have a larger gain at lower optical power levels is by adjusting the doping of the emitter and base InP. In the base region, a low base resistance can mainly be traded for high current gain. For a high power gain at high frequencies, the base resistance must be small [16]. This can be reached with a high base doping or a large base thickness. Hence, the base doping should be as high as possible which is additionally advantageous for low base contact resistances. The collector width influences the speed properties of the HBT. High speed devices are often designed with a thin collector. With a thicker collector more photons can be absorbed in the depleted region of the collector and therefore the responsivity of the photodiode is improved.

The design of HBT developed in Apsys in 2D and 3D showed in Figure 2 and Figure 3 as the parameter show in Table 1.

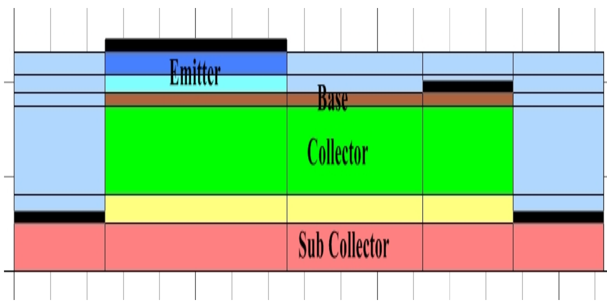

Figure 2 HBT physical model cross section

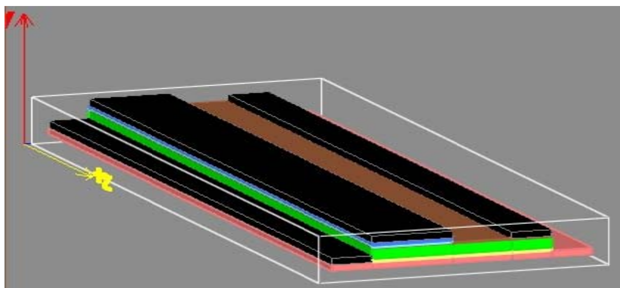

Figure 2 3D HBT model

■4.0 RESULT AND DISCUSSION

In this part is concentrate to the characterization and analysis of physical model that has been design in APSYS Crosslight. The analysis includes the gummel plot and electric filed against distance.

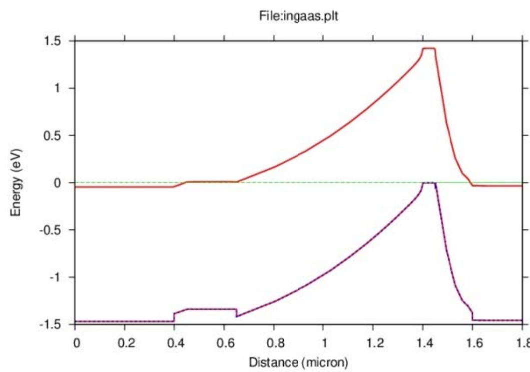

Figure 4 HBT energy band gap

Figure 4 showed energy band diagram versus distance which the upper level of this figure that have plot in red line is conduction band, *Ec* and the lower graph is valance band , *Ev* versus the location was described with a position coordinate or distance in micron. This graph show distance coordinate at x is 4 micron and y from 0 to 1.80 micron where it covers from sub collector to emitter. The band gap difference between emitter and base are larger thus allows a higher efficiency emitter. In addition it leads to forward V_{BE} values. ΔEg is the difference between the bandgap energy in emitter and band gap energy in base and the value shown ΔEg=0eV.It indicates that there is no junction spike at the InP/InGaAs interface which is typically behaviour of ordered InP/InGaAs HBT. In addition, the effect of removing the conduction band spike brought about by the conduction band off-set. At the InP/InGaAs heterojunction, the larger discontinuity in the valence band as compared to that in the conduction band allows a high injection efficiency without compromising the base doping concentration.

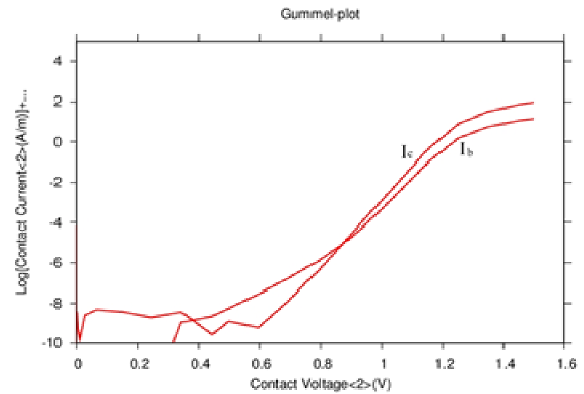

Figure 4 Gummel plot of HBT

Figure 4 shows gummel plot for HBT. Collector current at top curve and base current at bottom curve of a HBT versus the base-emitter voltage. The current due to recombination in the depletion region can be observed as an additional base current between V_{BE} = 0.8V and 1 V. The main nonlinear effect in this bias range was the voltage dependence of the dynamic emitter resistance, re which determined the current gain of the HBT at high frequency. As the result show value of V_{BE} is high, re had a small effect on the high frequency ac current gain, because of its small value hence leads to higher amplification level of RF.

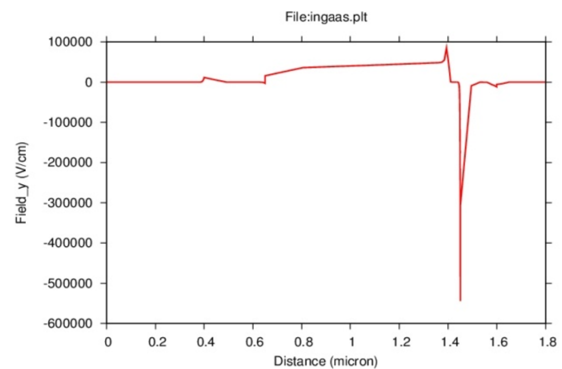

Figure 5 Electric field distribution graph

Peak in Figure 5 showed located between base and collector where electric field corresponding to the depletion region. Basically all the electric field distribution is almost similar but the higher distribution located at between collector and base where it achieve 78903.6V/cm and drop at emitter. In this region, the potential is varying rapidly over a small distance leading high value of electric field. The existence of an electric field requires a significant charge density at each end of the graded regions, which is obtained by a depletion of carriers. This also causes a small cusp in the band diagram. The physical distribution of electric field in HBT is illustrated at figure 6.

■5.0 CONCLUSION

This paper has presented a detailed study on the design, modeling and analysis of characterization of HBT as an OEM. We have shown that the physical model of HBT have meet the characterization as an optoelectronic mixer which can be function as photodetector. In addition, HBT is design in small size. Therefore this device can apply in millimeter wave with RoF as it have high frequency mixing operate, can simplified circuit and high efficiency.

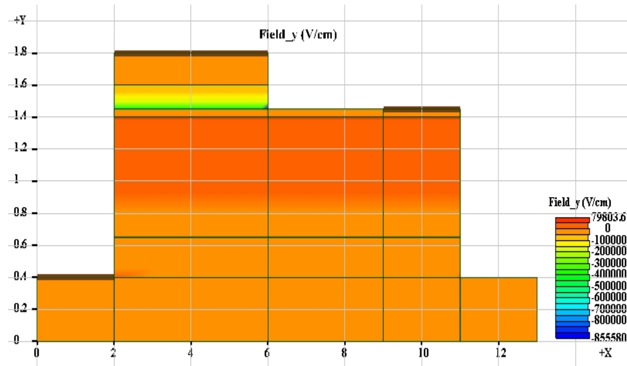

Figure 6 2D Electric field distribution in HBT

Acknowledgement

The authors acknowledge the Ministry of Higher Education Malaysia and the administration of Universiti Teknologi Malaysia (UTM) for the project financial support through Institutional Grant vote number 02H00. The gratitude also goes to the Universiti Teknologi MARA for the financial support through the SLAB funding for the main author.

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