HBT for THz Bio Sensing

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***Abstract*— This paper reports, analyzes, and discusses the abilities of heterojunction bipolar transistors to be used for terahertz biosensing. We find heterojunction bipolar transistors– in this paper, those made of indium phosphide– to be very useful in this regard, as transistors manufactured in this fashion are be capable of very high cutoff frequencies, allowing images utilizing the terahertz band to be taken.**

***Keywords*— Biological interactions, Biosensors, Heterojunction bipolar transistors, Terahertz radiation**

I. INTRODUCTION

Biosensing in the Terahertz (THz) band is a very promising field of study with high potential of medical benefit. Radiations in this band (which, loosely defined, are waves in the electromagnetic spectrum beginning at 300 GHz ranging as high as 30 THz; these waves lie between microwaves and infrared waves) are non-ionizing and, in specific configurations, capable of penetrating select substances. Usage of the THz band has recently seen advances in areas such as radio frequency communications, spectroscopy, surveillance, and many more. In the medical field, THz biosensing is particularly sought after, as its aforementioned non-ionizing nature allows medical subjects to theoretically be imaged without short-term or even long-term damage. X-rays, the current band for medical imaging, have significantly shorter wavelengths and higher photon energies, which indeed makes it ionizing and thus harmful. The potential of damage is indeed very small for X-rays, however, prolonged exposure to X-rays (such as those by X-ray technicians) does run a huge risk of biological damage.

As previously mentioned, due to the THz band's greater wavelength, it does not have the same penetrating power as X-rays. T-rays, as they are sometimes called, are not able to penetrate Earth's atmosphere and are quickly dissipated by air. The THz band is also typically unable to penetrate liquid water and metals. However, successfully implementing THz band technology into medical imaging could lead to the ability to image certain aspects of the human body with very little damage and no chemical markers necessary [5], only barred by how deep the T-rays are able to penetrate.

Heterojunction Bipolar Transistor (hereinafter referred to as "HBT") technologies are typically chosen for their abilities to handle high frequencies. Naturally, it makes sense to attempt to employ HBTs for THz biosensing.

II. FIGURES OF MERIT

In determining the performance of a particular device, we use certain quantifiable metrics to describe the device in question, making it easier to compare to other devices, and to see the device's internal strengths and weaknesses. What follows are figures of merit for an Indium Phosphide(InP)-based HBT used in the biosensor as proposed by Jongwon et al.

A. Cutoff Frequency (f_t)

Cutoff frequency is the boundary in a system's frequency response at which energy flowing through the system begins to be attenuated (reflected or reduced) rather than passing through (i.e. the frequency at which the corresponding gain is equal to one [Fig.1]). For context, industrial production level transistors using materials such as SiGe have cutoff frequencies around the low 300s [ref. 11], and transistors using only silicon tend to perform even worse, while InP HBTs were reported to have cutoff frequencies of almost 400GHz. [ref.7]

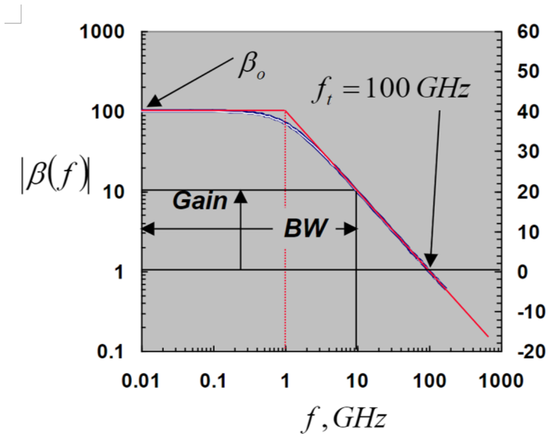

Fig. 1. Bode plot of transistor frequency response [Lecture 5 p.13]

B. *Maximum Frequency of Oscillation*

The Maximum Frequency of oscillation, f_{max}, is the frequency upper bound of a system at which it is still useful for circuit operations. Again, compared to Si based devices, III-V semiconductors have an upper hand when it comes to f_{max}, with 720 GHz reported by Rücker et al. for SiGe HBTs [ref. 11], and frequencies exceeding 1 THz for InP HBTs [ref. 7].

C. *Limit of Detection*

The limit of detection (LOD) is the quantity obtained from the smallest detected signal that can still be apprehended and analyzed. This is also the threshold towards determining what is considered "signal" and what is considered "noise" [6].

D. *Signal-to-Noise Ratio*

The Signal-to-Noise Ratio (SNR) is the ratio between the power of a signal and the power of the noise received when detecting this signal. So the higher the SNR of a device, the better the performance.

E. *Noise Equivalent Power*

The Noise Equivalent Power (NEP) is defined as the signal power required to achieve an unity SNR. It is a useful figure of merit to assess the sensitivity of a detector and is often measured in units of Watts per root of Hertz ($W/\sqrt{Hz}$). Essentially, NEP represents the minimum detectable power of the device, thus, a low NEP is desirable [1]. The NEP varied for different frequencies, according to Yun et al. [Fig. 2] Values ranged from 25 pW/Hz$^{1/2}$ to 45 pW/Hz$^{1/2}$.

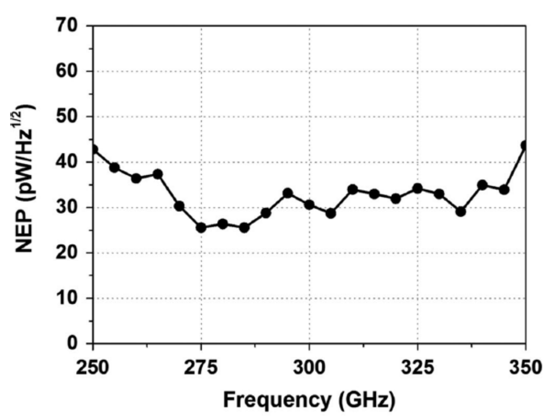

Fig. 2. Measured NEP for InP HBT [ref. 1]

F. Responsivity

Responsivity measures the gain of a detector between input and output signals, typically in V/W or kV/W. Responsivity can also be a good indicator for quantum efficiency since the two are directly proportional. Similarly to NER, responsivity also has a mild dependence on operating frequency as shown in Fig. 3, with numbers ranging from 30 kV/W to 60 kV/W

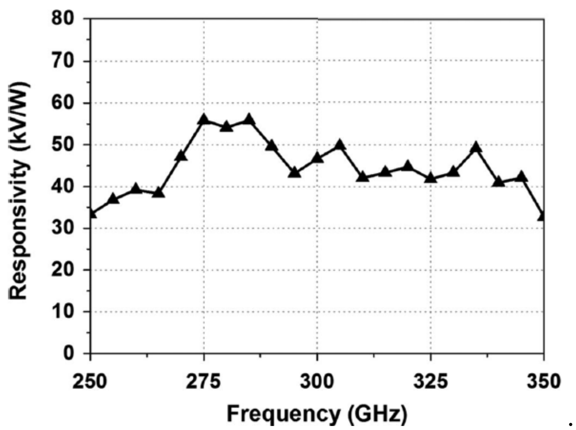

Fig. 3. Measured responsivity for InP HBT [ref. 1]

III. OSCILLATING CIRCUIT AND DETECTOR

Many solid-state oscillators are not compatible with regular commercial semiconductor technologies, thus not suitable for on-chip integrations. Therefore, electronic oscillators are developed to create compact and power-efficient THz signal sources and detectors. Figures 3 and 4 below from Jongwon et al. show a realized 300-GHz oscillator and detector, respectively.

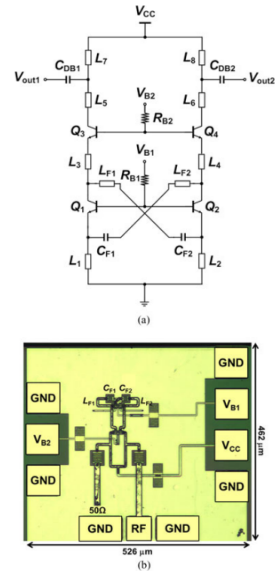

Fig. 3: (a) Schematic and (b) chip photograph of the developed 300 GHz fundamental-mode oscillator, from Jongwon et al.

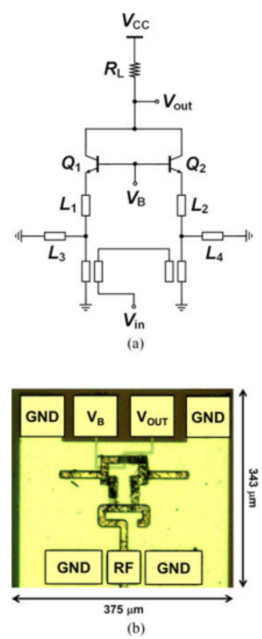

Fig 4: (a) Schematic and (b) chip photograph of the fabricated 300-GHz direct detector, from Jongwon et al.

Figure 3 depicts a 300-GHz high-power oscillator which uses a common-base cross-coupled structure to generate higher frequencies than a typical common-emitter structure [1][7]. Figure 4 depicts a 300-GHz square-law detector, which converts input RF signals into DC output signals [1].

IV. HBT DESIGN BREAKDOWN

For terahertz biosensing, transistor-based signal source and detectors are the core elements that utilize HBT technologies. In the studies that we are reviewing, both the oscillator in the signal source and the direct detector in the director circuit are fabricated in Teledyne's 250-nm InP HBT technologies [2][3].

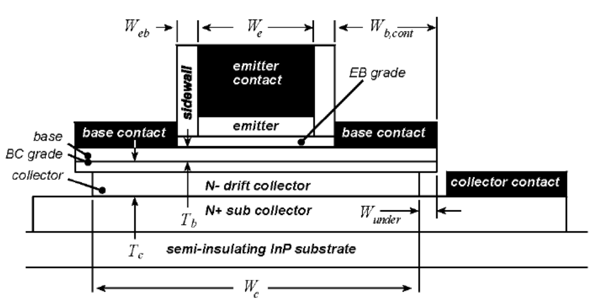

Figure 1: HBT cross-section and critical dimensions. The emitter stripe extends a distance L_e perpendicular to the figure. W_e is the emitter junction width, W_{eb} the base-emitter sidewall spacer thickness, $W_{b,cont}$ the width of the base Ohmic contact, and W_{under} the undercut of the collector junction under the base contacts.

Fig. 5: HBT cross-section and critical dimensions from Rodwell et al.

Figure 5 above shows the cross-section schematic of the HBT design. As of 2007, a 250-nm InP HBT was downscaled from a previously available 500-nm HBT. By reducing the emitter and collector junction area by 4:1, reducing the emitter specific access resistivity by 4:1, and reducing base contact resistivity by 2:1, a high-speed 250-nm InP HBT can be achieved [2]. Furthermore, continuing this trend and scaling further to 125 nm and 62.5 nm could allow for even higher frequencies, up to a theoretical 1.5 THz at 62.5 nm [2].

To achieve better performance after fabrication, some modifications to the design are needed. Since InP and InGaAs have different bandgap energy, they will form type-I heterojunction and will result in abrupt changes in the conduction band. This conduction band discontinuity can be removed by using a superlattice InGaAs/InAlAs grade. The dimension and doping profile of the superlattice structure can be found in detail in Table 1. The energy diagram for such graded doping was simulated by Bandprof [4] and is shown in Figure 6 below.

TABLE I
INP DHBT EPITAXIAL LAYER STRUCTURE

Thickness,nm	Material	Doping, cm^{-3}	Description
5	$In_{0.85}Ga_{0.15}As$	$5 \cdot 10^{19}$: Si	Emitter cap
15	$In_xGa_{1-x}As$	$4 \cdot 10^{19}$: Si	Cap grading
20	$In_{0.53}Ga_{0.47}As$	$4 \cdot 10^{19}$: Si	Emitter cap
80	InP	$3 \cdot 10^{19}$: Si	Emitter cap
10	InP	$8 \cdot 10^{17}$: Si	Emitter
40	InP	$5 \cdot 10^{17}$: Si	Emitter
30	InGaAs	$7 - 4 \cdot 10^{19}$: C	Base
15	InGaAs	$3.5 \cdot 10^{16}$: Si	Setback
24	InGaAs/InAlAs	$3.5 \cdot 10^{16}$: Si	B-C grade
3	InP	$3.5 \cdot 10^{18}$: Si	δ - doping
108	InP	$3.5 \cdot 10^{16}$: Si	Collector
5	InP	$1 \cdot 10^{19}$: Si	Subcollector
6.5	$In_{0.53}Ga_{0.47}As$	$2 \cdot 10^{19}$: Si	Subcollector
300	InP	$2 \cdot 10^{19}$: Si	Subcollector
—	InP	Semi-insulating	Substrate

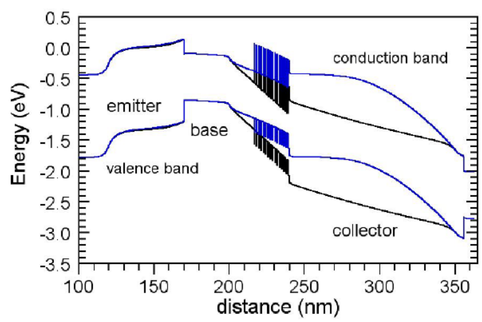

Fig. 1. Simulated energy band diagrams for the 30 nm base, 150 nm collector UCSB type-I InP DHBT at bias V_{cb} = 0.6 V and J_e = 0, 10 mA/μm^2.

Fig. 6: Generated energy diagram from Bandprof

V. GROWTH AND FABRICATION

According to Griffith et al, the epitaxial material was grown on a 3-inch semi-insulating InP wafer, and the HBTs were fabricated in an all wet-etch, triple mesa process [3]. All physical features were defined by I-line lithography. The top-view SEM image of the 250-nm InP HBT was shown in Figure [*2] below.

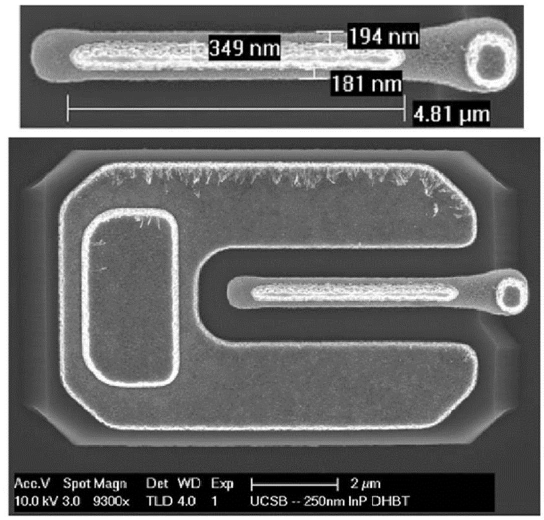

Fig. 2. SEM image of 250 nm UCSB InP DHBT.

VI. INDUSTRIAL APPLICATIONS

As previously mentioned, imaging in the THz band is very appealing due to its non-ionizing nature. However, due to its low penetrating power, it has to be exploited in very particular ways to generate useful data.

Because water absorbs T-rays very efficiently, a T-ray emitter-detector setup as in [1] can be used to transmit and detect changes in T-rays to determine water content of the sample. Furthermore, THz band imaging can be used to detect certain cancers, such as skin cancer, which is not as deep in the body as other organs and does not require as much penetrating power as X-rays [8].

As for practical applicability, THz imaging systems currently use femtosecond lasers coupled with photoconductive switches [8]. To advance into more compact and more advanced THz imaging systems, the HBT technology described in previous sections seems a very promising route. Although [1] is limited to the lowest of the THz band, 0.3 THz, advancing InP technologies as described in [2] can surely push THz biosensors into the ~1 THz frequency range while maintaining its compact form factor.

VII. CONCLUSION

In this paper, we analyzed InP HBTs as they could potentially be used for THz-band biosensing. In particular, we reported a proposal of a 0.3 THz emitter and detector by Jongwon et al, which demonstrates very promising results. As the technology of HBTs, and indeed InP HBTs, continue to advance, so too can this technology only continue to advance. Although T-rays may not entirely eradicate X-ray or other imaging technologies, in the correct contexts, T-rays could stand to be a viable alternative to X-rays.

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