InP Photodetectors for Millimeter Wave Applications

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ABSTRACT

We analyze waveguide InP photodetectors for millimeter wave applications. We start with the PIN waveguide photodetector pointing out key problems like optical coupling, microwave access and maximum available power. To benefit from an internal gain we introduce the waveguide InP heterojunction phototransistor showing its ability to operate up to 60 GHz.

Keywords: waveguide photodiodes, waveguide phototransistors, waveguide photodetectors, millimeter wave optoelectronics.

1. INTRODUCTION

Communication links based on optical fiber and millimeter wave transmission will probably become the basis of tomorrow's wide band network access. Future microcellular and picocellular mobile communication systems could operate at millimeter wave frequencies to exploit the wide transmission bandwidth, and to take advantage of the smaller size of the devices, with a distribution of the millimeter-wave carriers achieved through the optical fiber.

For such systems, high speed InP photodetectors are required. It is now well known that PIN waveguide photodetectors are suitable devices for high cutoff frequency with high quantum efficiency. Several experimental results demonstrated that these components exhibit cutoff frequency higher than 60 GHz with high quantum efficiency[1]. Nevertheless some problems remain: the optical coupling with the optical fiber which needs lens-ended fibers, the maximum available power which is weak due to small size of devices, the microwave access due to strong mismatch between impedance and microwave 50 Ω. In part two, we present how new structures can improve the coupling with cleaved fibers, we discuss the effect of matching networks to get matching to 50 Ω in a small bandwidth, and we examine the theoretical limits of maximum available microwave power.

It is also well known that heterojunction InP/InGaAs phototransistors are good candidates to get gain with low bias voltage and low noise. Part three is devoted to the waveguide InP heterojunction phototransistor (HPT). We discuss design and give experimental results showing that this device is able to work up to millimeter wave frequencies. At last we discuss ultimate performances of such devices and compare to state of the art results.

2. PIN WAVEGUIDE PHOTODETECTOR

It is well known that high speed PIN photodiodes require short transit time in the active layer and small capacitance. As a consequence, for millimeter wave applications the absorbing GaInAs region of InP photodiodes must be thin, typically 0.4 µm and less for cutoff frequency higher than 60 GHz. With vertical illumination so thin absorbing layer leads to small quantum efficiency (less than 30 %). It is the reason why for a long time lot of laboratories try to overcome this trade-off by using lateral illumination. The photodetector is then constituted as a an optical waveguide with an absorbing core. Figure 1 shows schematic of vertical and edge illuminated photodiodes. The advantages are the following: the absorption of light occurs over a sufficient length in order to absorb the totality of the propagating light, with thin absorbing layer, but short enough to get a very small capacitance. Typical values are around 10 to 20 µm for cleaved devices, knowing that the light is absorbed on less than 6 µm. With 3 µm rib waveguide the intrinsic capacitance of such device is around ten fF. Potential cut-off frequencies are then higher than 60 GHz including transit time and capacitance effects[1]. As an example devices fabricated in our laboratory (see figure 2) exhibit 60 % quantum efficiency with lens-ended fiber and without anti-reflection coating at 1.55 µm wavelength. The cutoff frequency depends on the length of the diode after cleaving (to get an input mirror facet) and can be higher than 60 GHz for the shortest devices. The technology[2] was designed to get a small access resistance (1 Ω) and parasitic capacitance (30 fF). The ridge is 4 µm and typical length is 10 µm. Typical capacitance for such a device is 35 fF. The epitaxy was grown by gas source MBE on InP semi-insulating substrate and is the following: a 0.11 µm nid buffer, a 0.7 µm n-type (3.10^{18} cm^{-3}) GaInAsP (λ_g=1.15 µm) confinement layer, a 0.01 µm n-type (3.10^{18} cm^{-3}) GaInAs spacer, a 0.5 µm nid GaInAs intrinsic layer, a 0.01 µm p-type (1.10^{18} cm^{-3}) GaInAs spacer, a 0.15 µm p-type (1.10^{18} cm^{-3}) InP confinement layer and a 0.1 µm p-type (1.10^{19} cm^{-3}) GaInAs contact layer.

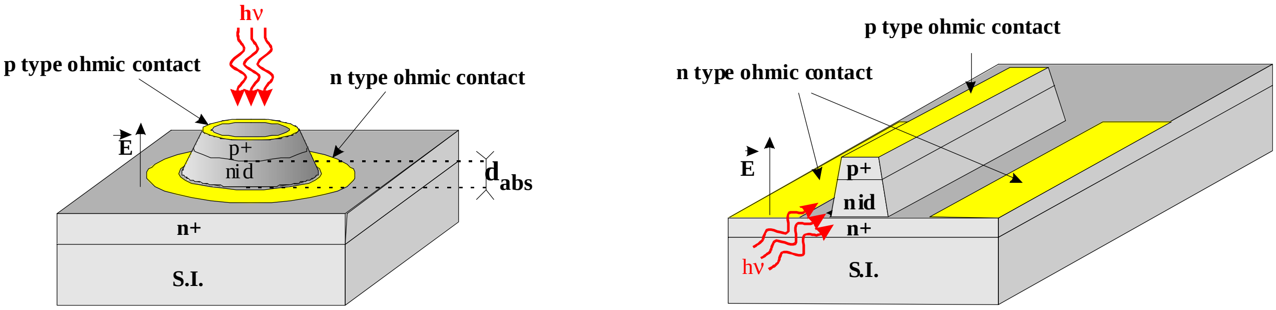


Figure 1: schematic of vertical and edge illuminated photodiodes.

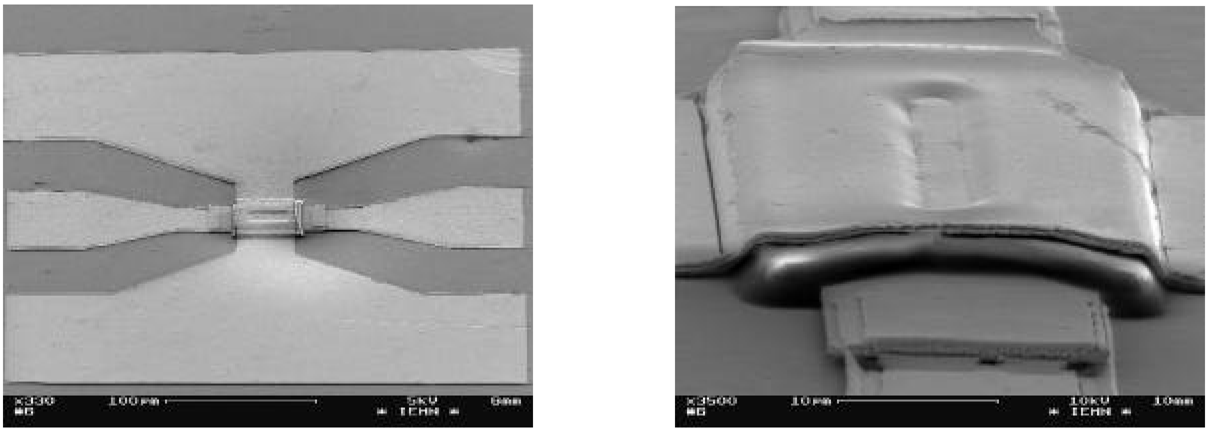


Figure 2: Scanning Electron Microscope photographs of a PIN waveguide photodiode fabricated at IEMN, before cleaving.

But for this kind of devices some problems remain. The first one is the optical coupling with the fiber. The optical mode of the waveguide photodetector is smaller than the fiber one and we know that one solution is a photodiode multimode structure with quaternary layers between GaInAs absorbing layer and InP confinement layer[3] (as we applied for the device fabricated at IEMN). But in this case a lens-ended fiber is required: the mismatch is too large with a cleaved fiber. That means that new structures are needed to get a high coupling with a cleaved fiber. As an example we show below possible epilayers designed to get a lens effect inside the waveguide photodetector. The total thickness of the epitaxy is comparable to the diameter of the core of the fiber, around 10 µm. The epitaxy is constituted of the GaInAs absorbing layer (0.4 µm) and several GaInAsP layers which composition are properly chosen in order to get the lens effect. Symmetrical and asymmetrical structures were studied with a Beam Propagation Method (BPM) in order to predict their quantum efficiency[4]. It turns out that the typical number of quaternary layers is eight for symmetrical structures and four for asymmetrical ones. Parameters under investigation are thicknesses and composition of all the epilayers. Different optimization techniques can be used. One is the Monte Carlo method, which consists in modeling a great number of randomly chosen structures. Another one is the Genetic Algorithm method, which consists in evolving a population of randomly chosen devices by analogy with Darwin's theory. More details on these techniques applied to optoelectronic device optimization can be found in the following reference[4].

We first present examples of structures obtained with Monte Carlo method. To reduce computing time only two different quaternary compositions were used (λ_g=1.1 µm and 1.25 µm). The structures are given in table 1. They are constituted of the GaInAs layer symmetrically surrounded by the two quaternary layers. Different thicknesses of GaInAs layer were tested (0.2 µm, 0.4 µm, 0.6 µm and 1.0 µm) to be compatible with high-speed operation. The corresponding quantum efficiencies are also given in table 1 for 1.55 µm wavelength detection. It appears from this calculation that quantum efficiency higher than 70% can be achieved even for thin GaInAs layer. But Monte Carlo method does not converge towards the optimal structure. To be sure an interesting structure is not missed it is necessary to model a great number of different devices. This leads to a heavy consuming time. A complementary technique is the use of Genetic Algorithm. In this case the calculation evolves towards a structure with optimal quantum efficiency.

	Struct. 1	Struct. 2	Struct. 3	Struct. 4
Q1.1	2.0	2.25	1.3	2.0
Q1.25	1.6	0.6	1.3	1.1
GaInAs	0.2	0.4	0.6	1.0
Q1.25	1.6	0.6	1.3	1.1
Q1.1	2.0	2.25	1.3	2.0
Total	7.4	6.1	5.8	7.2
Quant.Eff	0.75	0.72	0.68	0.84

Table 1: photodiode structures obtained by Monte Carlo method. Quantum efficiencies are given for a 100-µm length.

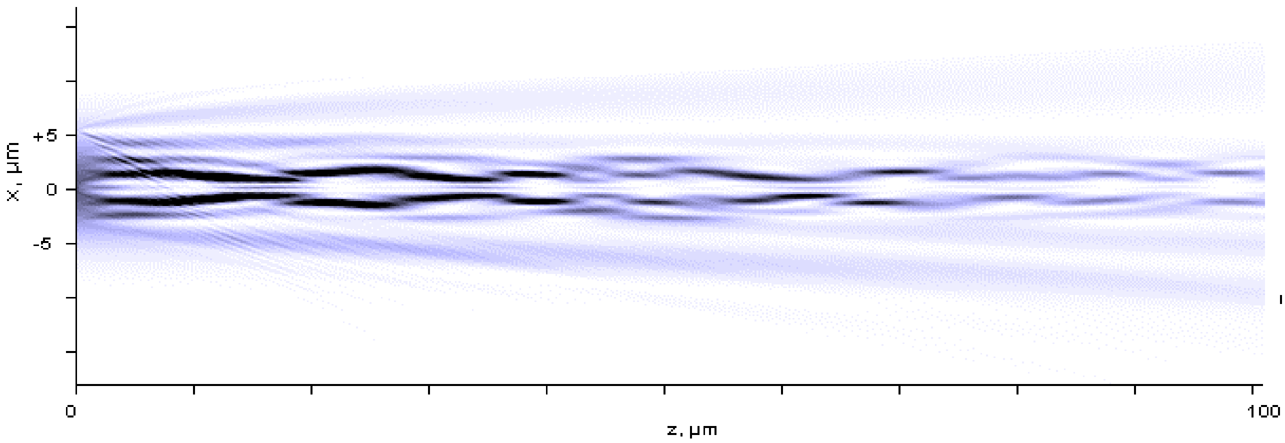


Figure 3: BPM modeling of light propagation in the structure 4.

As a result of this technique it is possible to get improved devices with four quaternary materials, which quantum efficiency can reach 95 % [4]. If now we examine the optical propagation in such structures as shown in figure 2, we observe that light is focused towards the absorbing layer. This lens effect allows achieving a high vertical tolerance of alignment of the fiber (around ± 3 µm). The drawback is the length of device needed to focus the light in the GaInAs layer. This length is more than 100 µm for a cleaved fiber (10-µm mode). This result must be compared to the length needed to absorb light with a lens-ended fiber (6-µm length for 2-µm mode). With a 100-µm length the cutoff frequency of the device is penalized. We expect a relation between the needed length of the device for high quantum efficiency and the optical spotsize. It means that there is a strong link between cutoff frequency and the size of the mode fiber. Consequently the compromise for millimeter wave applications is to work with a device designed for lens-ended fiber with a mode as large as possible for a given cutoff frequency in order to increase the alignment tolerance. Typical values would be 3-4 µm for the mode size giving a cutoff frequency of 30 GHz.

The second problem of millimeter wave photodetectors is the microwave access. As known for a long time is that a good solution is to grow the photodetector on semi-insulating substrate. Such an approach is commonly adopted. Nevertheless remains the problem of matching impedance between the device and the 50 Ω microwave world. More precisely the impedance of the photodetector is high (over several kΩ) compared to the microwave 50 Ω. This results in a strong mismatched impedance and can introduce some penalties in the transmission of the microwave signal to the load or the following circuit. This aspect was already pointed out at lower frequencies[5,6] and was treated as the association of a passive reactive network with the photodiode to get a matching in a small bandwidth. The principle is to associate with the photodetector considered mainly as a capacitance, a passive reactive circuit to compensate the capacitance in a small bandwidth around the operating frequency. Experiments based on hybrid monolithic integration demonstrated the validity of the concept, showing it is possible to get an equivalent impedance close to 50 Ω at the output port in a small bandwidth (10 %) around the operating frequency and improvement of the microwave power transfer thanks to a resonance effect. In the millimeter wave frequency range, the principle of the reactive passive network is the same but the technology is more difficult. Starting from a high bandwidth high quantum efficiency waveguide PIN photodiode[7], Thomson LCR in collaboration with IEMN succeeded in fabrication of matched PIN waveguide for 30 GHz operating frequency[8]. This device was developed in the frame of a European project called "Fiber Radio ATM Network and Services" (FRANS). The matched photodetector developed by Thomson is a basic brick of the fiber radio link of the FRANS project and is a part of the transducer able to transform the optical carrier into a millimeter wave carrier. Both hybrid and monolithic integration were tested. Hybrid circuits were made with coplanar 50 Ω lines and GaAs semi-insulating substrate, and monolithic circuits were constituted of an inductance deposited on the photodiode InP semi-insulating substrate. Both techniques led to microwave reflection coefficient lower than –15 dB in the bandwidth of interest (27-30 GHz), demonstrating the validity of the concept in the millimeter wave frequency range.

The third problem is the millimeter wave power supplied by the photodetector. Because the size of the device is small, the power is obviously limited. Under high optical injection, two effects occur to limit the microwave power[9]. Due to increasing photocarrier density, the electric field in the intrinsic region vanishes close to the I / N+ interface and increases at the P+ / I interface. This phenomenon is cumulative since it reduces the carrier velocity and then increases the carrier density. This results in a bigger capacitance whose value depends upon the input light power introducing non linear effects and to breakdown due to excessive field at P+ / I interface. The second effect is the reduction of the instantaneous photodiode bias voltage due to high photocurrent in the external circuit including parasitics. All these aspects lead, when optical power increases, to saturation of microwave signal, appearance of strong harmonics, and sometimes breakdown. These limits depend upon the volume of the photodetector and hence its cutoff frequency[10] but can be evaluated around a few dBm for a 60 GHz PIN waveguide photodetector. To overcome this problem it would be necessary to increase the volume of the photodetector without degrading its cutoff frequency; the solution can be the use of travelling wave structures with coupling between absorbing optical waveguide and microwave waveguide. If the absorption of light is progressive along the waveguide, we can expect to increase the length and hence the volume of the photodetector; but to avoid a dramatic decrease of the cutoff frequency due to increasing capacitance, the electrodes must be designed to get a 50 Ω microwave line loaded on a 50 Ω impedance. Such structures are in progress in various laboratories and interesting results were recently obtained towards this goal[11].

3. INP WAVEGUIDE HETEROJUNCTION PHOTOTRANSISTOR

Several authors pointed out the potentialities of heterojunction phototransistors for microwave photonic applications. The first experimental demonstration of InP heterojunction phototransistor able to operate in the millimeter wave frequency range is, to our knowledge, due to David Wake[12] with a two terminal HPT with no base contact. More recent experimental and theoretical results confirmed the capabilities of InP HPT for millimeter wave applications, either vertical[13] or edge illuminated[14].

An heterojunction phototransistor can be considered as an heterojunction bipolar transistor (HBT) for which the base-collector junction is used as a photodiode. Consequently, it combines the properties of the HBT and the photodiode monolithically in the same device. The first function of an HPT is, obviously, the photodetector with internal gain. The advantages compared to the classical avalanche photodiode are low bias voltage and low noise. Most of the works dedicated to phototransistor were performed in this way. The second function is a transistor optically controlled. The photocurrent acts as a base current, and we could say that the total base current of the transistor is then optically tuned. This aspect can lead to various applications, such as the optical control of microwave oscillators[15]. The last function of these devices was recently experimentally demonstrated[16,17]: thanks to non-linear behavior of the transistor under suitable bias voltage, they can be used as optoelectronic mixers. Two electrical signals can be mixed onto the device through one or two optical carriers; with one optical carrier, the second signal is applied on the transistor. This function can be used, for example, to transmit a microwave carrier and the data with two modulated optical signals impinging on the device. Such a function can be used in fiber-radio systems.

The most difficult question is how to keep high performance for both photodetector and transistor. To try to answer this question we will examine the structure of an InP HPT compared to an HBT and a photodiode. As an HBT the HPT comprises an heterojunction with high bandgap material (InP) for the emitter and low bandgap material (GaInAs) for the base and collector. The emitter, base and collector are n, p+, n type doped respectively. High performance transistors are due to the high conduction band discontinuity (InP/GaInAs) and to a base as thin as possible with high doping level to reduce parasitic resistance. Photodetection occurs in the GaInAs collector, and the p+ GaInAs base – n- GaInAs collector – n+ InP subcollector act as a PIN photodiode. High-speed transistor and photodetector are obtained with short transit time in

GaInAs layers. Following this way vertical illumination will reduce the quantum efficiency and edge illumination would be appreciated. Edge illumination is possible since the different layers of the phototransistor are compatible with an optical waveguide including an absorbing core. As for waveguide PIN photodiode, good coupling is achieved with multimode structure obtained with quaternary layers between GaInAs collector and InP subcollector. No quaternary layer is introduced in the emitter-base junction to keep its electrical properties. By doing this, the quantum efficiency is improved from 40 % to 60 % without antireflection coating with a lens-ended fiber[14]. A good compromise to get short transit time is 0.5 µm total thickness of GaInAs (as for PIN waveguide photodiode) with 1000 Å for the thickness of the base. Thinner GaInAs layer increases the length for total photodetection and limits the bandwidth due to emitter-base junction capacitance. It was also shown that a good compromise for the quaternary layer thickness is 0.7 µm. Following these indications a three contacts waveguide HPT was fabricated at IEMN[18]. The epitaxy is given in table 2 and was grown by gas-source MBE on InP semi-insulating substrate. A self-aligned base technology was used to reduce parasitic access base resistance. The rib of the waveguide is 3 µm. A SEM photograph of the device is given in figure 4 before cleaving. These components exhibit high current CW gain (β=150), 5 dB gain around 40 GHz when mounted on a 40 GHz microwave submount (figure 5). Under cascade probe, the electrical cutoff frequency is 60 GHz. All these experimental results demonstrate their ability to operate in the millimeter wave frequency range with high quantum efficiency (60 % without antireflection coating).

Layer	Material	Doping / Type (at/cm³)	Thickness (nm)
Contact	GaInAs	1.10^{19} / n++	100
Emitter	InP	5.10^{17} / n+	150
Spacer	GaInAs	nid	50
Base	GaInAs	2.10^{19} / p++	100
Collector	GaInAs	nid	400
Spacer	GaInAs	3.10^{18} / n+	10
Subcollector	$GaInAsP_{1.15}$	3.10^{18} / n+	700
Buffer	InP	-	100
Substrate	InP	SI	400 µm

Table 2: Epitaxy of the waveguide phototransistor.

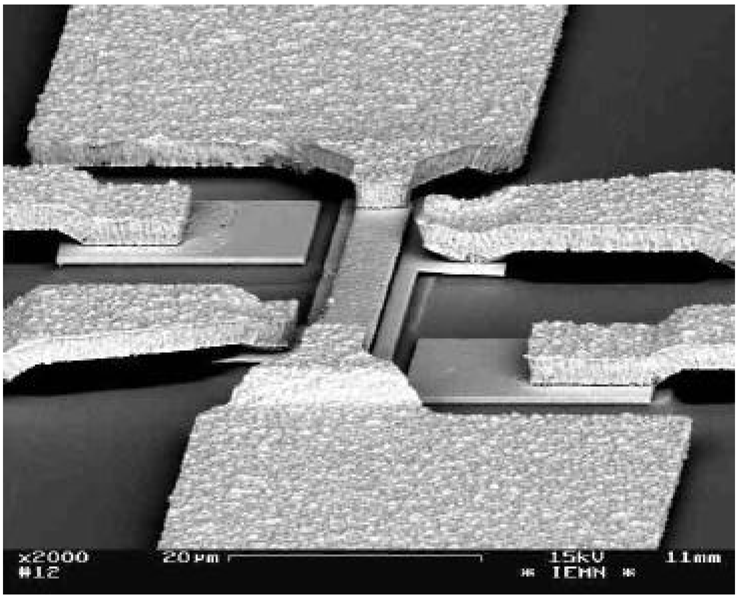


Figure 4: SEM of the homemade phototransistor before cleaving.

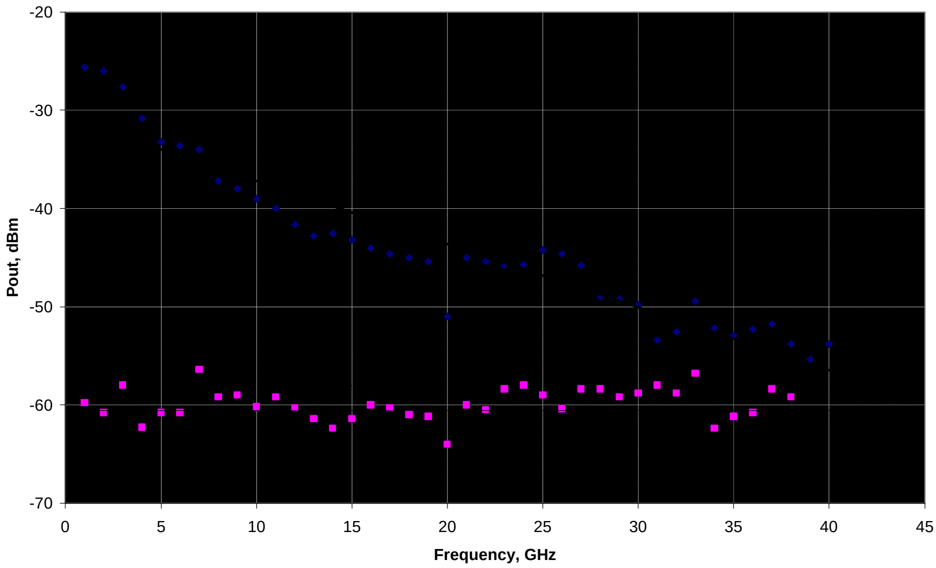
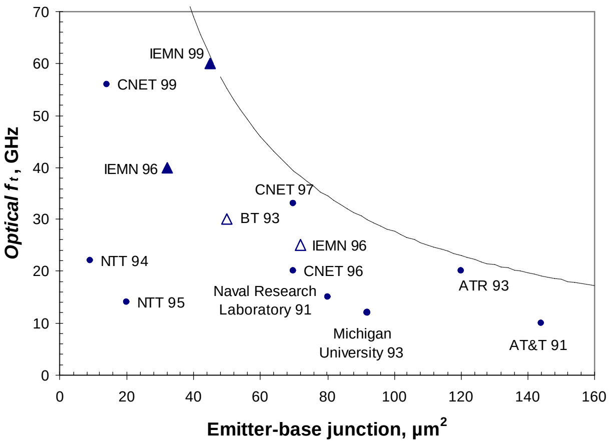


Figure 5: frequency response of the phototransistor compared to the response of the PIN base-collector junction measured by optical heterodyning.

We present in figure 6 the states of the art cutoff frequencies of HBTs and HPTs. These results are presented versus thickness of collector for HBTs and versus surface of emitter-base junction for HPTs. They show with evidence:

- the cutoff frequency of HBTs is very high compared to HPTs
- the main parameter of cutoff frequency is the thickness of collector (transit time) for HBTs, and emitter-base junction surface for HPTs.



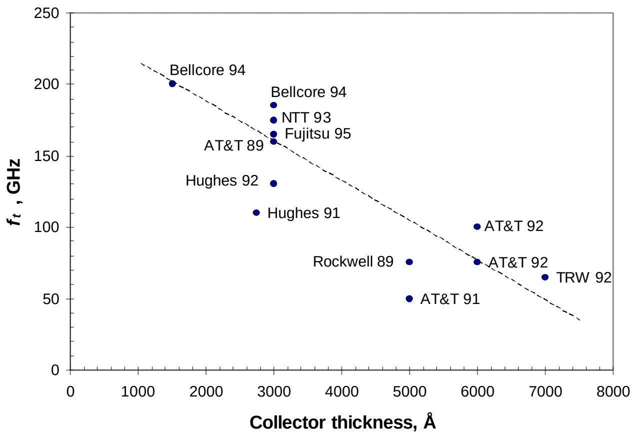


Figure 6: comparison of states of the art of HPTs at left and HBTs at right. For HBTs the figure is based on Chau *et al.* article[19]. For HPTs the dashed curve is inversely proportional to the surface junction.

This is a consequence of the volume of device needed to detect the light, which limits the reduction of its size. This reduction is possible for HBTs, so that the capacitances become second order parameters compared to transit time in the collector. In HPTs the size of the device, needed to detect the light (around 3 µm x 10 µm) leads to (emitter-base) capacitances which are still high (around 150 fF) and mainly govern the cutoff frequency of the device. Several ways then are possible to improve the dynamic response of the device:

- the size reduction down to the limit probably with the drawback of inducing penalties in the quantum efficiency.
- the use of travelling wave phototransistor[20], as for PIN waveguide photodiodes with the expected advantage to be more suitable for power applications.

- The monolithic integration of photodiode with HBT, in order to reduce the dimensions of the HBT without degrading the optoelectronic performance.

4. CONCLUSION

The PIN waveguide photodiode remains a suitable device for photodetection in the millimeter wave frequency range. Optical coupling and microwave access which are still difficult problems, become to be solved. Limitations occur for high optical illumination but correspond to specific applications requiring around 100-mW optical power into the device. (Waveguide) heterojunction phototransitors are attractive and capabilities in the millimeter wave frequency range are demonstrated, but their gain, high in the low frequency range, dramatically decreases in the millimeter wave frequency range. They suffer from their size needed to detect the light, introducing high junction intrinsic capacitance, and it seems difficult to overcome this fundamental limitation. Possible future ways could be travelling wave structures or photodiode-HBT monolithic integration.

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