The optical performance of microwave transistors

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ABSTRACT

This paper renders a thorough analysis of the optical properties of microwave transistors, HBT, MESFET and HEMT. The principal photoresponse mechanisms are identified and compared in terms of gain, frequency response and sensitivity. The paper highlights newly observed effects in the HBT, where high speed and gain are realizable.

INTRODUCTION

The optical properties of microwave devices and circuits have intrigued engineers for many years, and various optically controlled microwave subsystems, such as phase shifters[1], amplifiers [2] and switches[3] have been demonstrated. More recently, spurred by rapid developments in fiberoptic based networks (MAN and LAN), the chip level integration of photonic and microwave components for high performance optical receivers have gained attention. PIN-amplifier configurations, such as PIN-HEMT [4] have been reported, and lately high performance PIN -HBT combinations have been realized by Aitken et. al. [5]. However the integration of the PIN diode with microwave transistors requires additional processing steps. For this reason, the idea of using three terminal microwave devices as photodetectors as well as amplifiers in receiver front-end are being studied [6]. This configuration enhances receiver performance by reducing parasitics, requires less pre-amplification due to intrinsic gain of transistors, and has lower power consumption and less costly fabrication.

The key to these developments and related applications in communications and control of microwave systems is the understanding of the optical properties of microwave devices. Seeds and Salles gave an excellent overview on this topic in 1990 [7]. However fresh developments, particularly pertaining to the HBT, warrant the need for a thorough re-examination of the subject. Accordingly, this paper concerns the photoresponse of microwave transistors: HBT, MESFET and HEMT. The inherent photodetection mechanism is identified for each device and analyzed in terms of gain, sensitivity (detectivity) and bandwidth. The analysis is based on detailed models supported by experimental validation. The information contains new results on the HBT, the "internal photoconductivity" effect with gain, which is compared to photo effects observed in the MESFET and HEMT. Finally, we discuss how the optical performance of these devices can be enhanced in relation to different applications.

STATIC ANALYSIS

Effects contributing to the photoresponse of the HBT, MESFET, HEMT as well as the PIN photodiode, are summarized in Table I. Both, gain and speed asso-

	Ipvi		Ipvx		Ipc		Ipci		Ipd		Microwave
	gain	speed	gain	speed	gain	speed	gain	speed	gain	speed	speed
PIN	------	------	------	------	------	------	------	------	< 1	> 10 GHz	------
HBT	------	------	------	------	------	-----	5 to 20 (prop. β)	> 10 GHz	< 1	> 10 GHz	> 10 GHz
Mesfet	~10⁴ logarithmic	5 to 10 MHz	~10⁴ logarithmic	< 5 MHz	< 1	> 10 GHz	------	------	------	------	> 10 GHz
Hemt	~10⁴ logarithmic	5 to 10 MHz	~10⁴ logarithmic	< 5 MHz	< 1	> 10 GHz	------	------	------	------	> 10 GHz

Table I : Different photocurrent components. Ipvi and Ipvx are the internal and external photovoltaic effects, respectively. Ipc is the photoconductor effect, Ipci is the internal photoconductor effect in HBTs and Ipd is the photodiode effect. Also shown is the electric characteristic of the transistors.

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ciated with each effect are shown. The PIN diode, the most commonly used photodetector in high speed applications, is used as a reference. The summary contains simplified expressions which are reinforced by more explicit equations in Appendix A and B.

PIN For the pin-diode the photoresponse, Ipd (see eq.(A1)), is determined by the carriers generated in the high field i-region. There is no gain and the photocurrent varies sub-linearly with optical intensity.

HBT The photoresponse of the HBT, studied for a self-aligned structure (that precludes absorption in the base and emitter regions) is:

$$I_{HBT} = I_{pci} + I_{pd} \qquad (1)$$

where the first term is due to an internal photoconductive effect, an increase in the effective base current due to the drift of photogenerated holes from the collector depletion region to the base. This effect, under constant external bias current, results in gain. The source of this increase is the "readjustment" of the base potential to increase the electron injection rate. The second term is the photodiode component, which consists of the electrons generated at the collector depletion region. The analytic expressions corresponding to these two effects were derived and included in Appendix A. Base and collector photoresponses were calculated using eq(A1) and (A2), respectively.

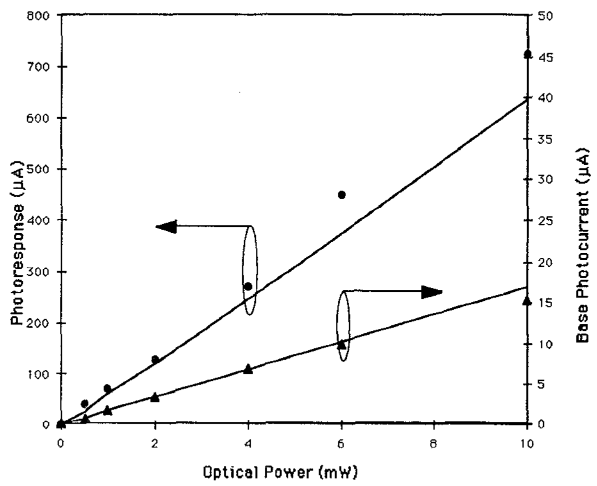

Fig.1 - HBT photoresponse and base photocurrent. Experimental results are represented by discrete points and theoretical by solid lines.

A comparison with experimental values, depicted in Fig.1, shows good agreement with small discrepancies (<6%) at high optical intensities. The photoresponse of the HBT is a linear function of optical power and produces a gain which is proportional to the transistor gain β.

FETs The photoresponse in both field effect transistors (MESFET and HEMT) is attributed to three mechanisms [8]:

$$I_{ph} = I_{pvx} + I_{pvi} + I_{pc} \qquad (2)$$

The photogenerated carriers collected at the gate yield a photovoltage Vphx, when passing through an external resistor. Thus the external photovoltaic effect, an increase in gate bias, opens the channel and results in a photocurrent Ipvx = gm Vphx. High gain can be obtained (Table I) depending on the value of the external resistor.

The internal photovoltaic component is Ipvi = gm Vph. For the MESFET [8] Vph is a light-induced modulation of the channel height. In the case of the HEMT Vph represents a shift in the quasi-Fermi level [9]. The expressions for the equivalent photovoltage, Vph, are in Appendix A. The photoconductive effects are very small and will be neglected.

The responsivity for these devices is compared in Fig. 2. No external resistor was used for the curves shown.

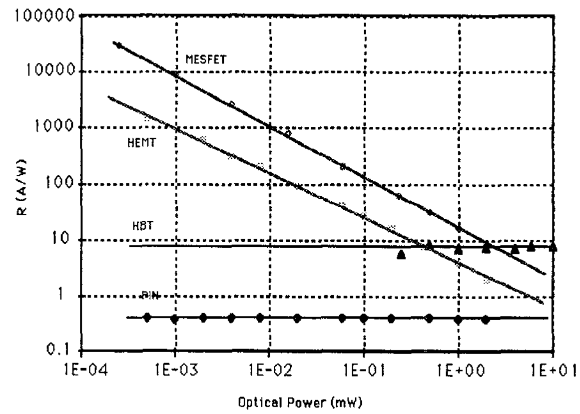

Fig.2 - Comparison of the responsivity for microwave devices

At low illumination the logarithmic response of FET devices provides large gain (Table I). However, photoresponse saturates rapidly, which limits their dynamic range. The HBT, which has relatively large dark current, but low noise[11], presents a diode-like responsivity curve and performs best at moderate and high illuminations.

DYNAMIC RESPONSE

PIN The frequency response of a PIN is limited by the carrier transit time. A shorter intrinsic region yields a faster device, but at the expense of responsivity.

HBT The speed of the HBT is governed by a time constant $\tau = \tau_e + \tau_b + \tau_c + \tau_{sc}$, where τ_e is the charging time of the B-E junction, τ_b is the base transit time, τ_c is the charging time of the B-C junction and τ_{sc} is the transit time across the collector depletion region. The complete expression for it is given in Appendix B. Since these time constants are the same as those which determine the microwave response, the optical response of the HBT is fast (Table I).

FETs For the FET devices the external photovoltaic effect is very slow because of the long charging time of the gate external circuit. For the MESFET the time constant associated with the internal photovoltaic effect is defined by the substrate resistance (R) and the epilayer/substrate junction capacitance (C) [11]. For the HEMT, on the other hand, the RC time constant is determined by the buffer resistance and the change in electron concentration in the 2-DEG channel [9]. It is important to note that the speed of photoresponse of the FETs is independent of their microwave speed, as evidenced by the last column in Table I.

The measured and estimated frequency response for all devices is depicted in Fig. 3. At low frequencies FETs are extremely sensitive, showing optical gains in excess of 20dB with respect to the PIN, depending on the bias. However, the slow photovoltaic effect yields a small gain-bandwidth product, limiting such devices to 20 to 30 MHz, typically . Because of poor optical coupling (<0.5%) HBTs exhibit small low-frequency gain, 15-20dB below PIN diodes. However, HBTs can be substantially improved by proper design of transistors and enhancement of the coupling efficiency. An increase in optical coupling to 5 or 10% raises the response by 20dB, which is already equal or above that of the PIN. Moreover, using devices with larger β's (e.g. 250 instead of 25) give additional advantage to the HBT. The linear response provides a larger dynamic range.

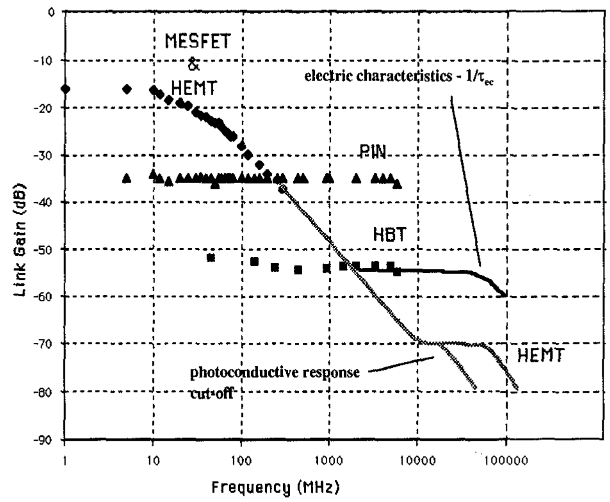

Fig.3 - Frequency response of microwave devices, measured data is represented by discrete points and theory by solid lines. The optical coupling efficiencies were: less than 1% for the HBT, 4% for the MESFET and the HEMT and 60% for the PIN.

CONCLUSIONS

The optical performance of microwave transistors was discussed and compared. From the application point of view, each of these devices has its advantages. For example, chip level optical interconnects require low optical input powers, low driving voltages and moderate speeds (below 1GHz), making the MESFET and HEMT well suited. For mixing of optical and microwave signals, the nonlinearity of the FETs can be exploited. For high speed receiver, on the other hand, the HBT is favored.

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Appendix A- DC expressions

Photodiode current :

$$I_{pd} = q\phi_0 A_i (1-R)[1-\exp(-\alpha W_i)] \qquad (A1)$$

HBT Photocurrent :

$$I_{HBT} = (\beta' - \beta) I_{Bex} + \beta' I_{Blight} + I_{pd} \qquad (A2)$$

The first term, in eq.(A2), is a correction due to change in β with illumination. Contribution of the diffusion of photocarriers in the subcollector is neglected.

External photovoltaic effect : Eq.(A1) can be applied to the MESFET gate photocurrent provided that Wi is considered the length of depletion region not masked by the gate contact, Ai is the area between electrodes and carrier diffusion from the channel is neglected.

Internal photovoltaic effect : Eq. (A1) is applied to the channel substrate junction, in MESFET to calculate the primary photocurrent, I_{pp}. Then $V_{ph}=R_{sub}I_{pp}$. For the HEMT the photovoltage is approximated by $Vph=kT/q \ln(1+\phi_0/\phi_{sat})$.

Photoconductive effect in the MESFET[8]:

$$Ipc = \frac{1}{2} q\phi_0 A_i (G_n + G_p) e^{-\alpha(a-W_i)} \alpha L_p \left(\frac{W_i}{L_p}\right)^3 \left(1 - \frac{e^{-\alpha W_i}}{2}\right) \qquad (A3)$$

where Wi is the channel width and G_n and G_p are the photoconductive gain for electrons and holes respectively. In HEMTs the increase in channel conductivity is a result of migration of photo-excited carriers generated at the buffer and calculated using eq.(A1).

Appendix B - Frequency Response and time constants

The transit-time limited primary photocurrent has similar characteristics for diodes and transistors :

$$I_{pp} = q(1-R)A_i m\phi_0 \frac{[1-e^{-\alpha W}]}{(1+j\omega\tau_r)} \qquad (B1)$$

Transport in HBTs is characterized by the following time components :

$$\tau = \frac{kT}{qI_C}(C_e + C_c) + \frac{W_b^2}{2.4D_n} + R_c C_c + \frac{v_{sat}}{W_{sc}} \qquad (B2)$$

The cut-off frequency of the photoconductive effect in microwave FETs is :

$$\omega_c = \frac{(\alpha L_p)^2}{\tau_p} \qquad (B3)$$