Theoretical Model for Heterojunction Phototransistor in Optoelectronic Switch Configurations Part II: Speed of Switching Operation

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Abstract

The aim of this paper is to investigate the switching characteristics of hetrojuncation phototransistor (HPT). First, the static characteristics of the HPT are given under ideal conditions to get a physical insight on the main parameters affecting it's response. Then the speed of response of HPT is addressed and supported by simulation results reported for 1.3 µm InGaAs/InP transistor.

نموذج نظري للترانزستور الضوئي ذو المفرق المتباين المستخدم في تراكيب المفتاح الضوئي – الإلكتروني
جزء II : سرعة تشغيل ألا قلاب

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الخلاصة:

الهدف من هذا البحث هو عرض مميزات ألا قلاب للترانزستور الضوئي ذو المفرق المتباين (HPT),قدمت المميزات الاستاتيكية لـ (HPT) تحت الشروط المثالية للحصول على فهم فيزيائي لتأثير البارمترات الرئيسة على سرعة استجابة الترانزستورز.دعم التحليل النظري بنتائج محاكاة للترانزستور InGaAs/InP يعمل بطول موجي 1.3 µm.

1. Ideal Heterojunction Phototransistor

Let us examine the static characteristics of the HPT derived in section 2 under ideal conditions. This is useful to get a simplified picture for the behaviour of the transistor that can be used later as a guideline to explain the switching characteristics of the device. The following assumptions are assumed to be satisfied in ideal HPT, (i) The incident light on the device is absorbed in the base, base-collector depletion region, and collector, (ii) There is no surface recombination.

The base – collector junction acts as a photodiode as shown in Fig. (1). The expressions of the transistor current are simplified as follows [1].

(a) Emitter Region

$$I_{pe} = qA\frac{D_e}{L_e}\left[\exp(V_e / V_T) - 1\right] p_{eo}$$

(b) Neutral Base Region

$$I_{nbe} = -qA\frac{D_b}{L_b \sinh\left(\frac{w_b}{L_b}\right)}[1 + [\exp(V_e/V_T) - 1]$$
$$\cosh\left(\frac{w_b}{L_b}\right) + F_2[\cosh\left(\frac{w_b}{L_b}\right) - \exp(-\alpha w_b)$$
$$-\alpha L_b \sinh\left(\frac{w_b}{L_b}\right)]] \qquad \ldots(2)$$

where $\alpha = \alpha_b = \alpha_c$ is the absorption coefficient.

$$I_{nbc} = -qA\frac{D_b}{L_b \sinh\left(\frac{w_b}{L_b}\right)}[\exp(V_e/V_T) - 1 +$$
$$\cosh\left(\frac{w_b}{L_b}\right) + F_2[1 - \exp(-\alpha w_b)\cosh\left(\frac{w_b}{L_b}\right)$$
$$-\alpha L_b \sinh\left(\frac{w_b}{L_b}\right)\exp(-\alpha w_b) \qquad \ldots(3)$$

$$F_2 = -\frac{\eta\alpha\Phi_o L_b^2}{D_b n_{bo}\left(1 - \alpha^2 L_b^2\right)} \qquad \ldots(4)$$

Further η is the quantum efficiency of the absorption region.

(c) Collector Region

When the collector region is modeled as a photodiode with reverse bias V_{c1}, one can obtain (see Fig. 1)

$$I_{pc} = I_{pH} + I_{co} \qquad \ldots(5)$$

I_{co} = dark current

I_{pH} = photo current generated in the base and collector region due to light absorption. (1)

The incident power increased the collector- base leakage current from dark current I_{co} to ($I_{pH} + I_{co}$)

From the solution of the continuity equation, one can get

$$I_{pc} = qA\frac{D_c}{L_c}\left[\frac{L_c^2\eta\alpha\Phi_o}{D(1 + \alpha L_c)} + P_{co}\right] \qquad \ldots(6)$$

$$I_{co} = qA\frac{D_c}{L_c}P_{co} \qquad \ldots(7)$$

Using eqn. (6) into eqn. (5) yields:

$$I_{pH} = qA\frac{\eta\alpha L_e \Phi_o}{(1+\alpha L_e)} \qquad \ldots(8)$$

The total emitter current is

$$I_e = I_{nbe} - I_{pe} \qquad \ldots(9)$$

$$I_e = \frac{I_{nbe}}{\gamma_e} \qquad \ldots(10)$$

The total collector current is computed as;

$$I_c = (I_{pH} + I_{co}) - I_{nbe}$$

$$= -\gamma_b I_{nbe} + (I_{pH} + I_{co}) \qquad \ldots(11)$$

Since the current is constant through the device and the net base current must be zero, then $I_e + I_c = 0$ .Thus

$$I_{nbe}\left[\frac{1}{\gamma_e} - \gamma_b\right] + \left[I_{pH} + I_{co}\right] = 0 \qquad \ldots(12)$$

which yields

$$\exp(V_e/V_T) = \frac{1}{I_{n1}}\left[\frac{\gamma_e(I_{pH} + I_{co}) + (1-\gamma_e\gamma_b)n_{bo}F_2}{\gamma_e(1-\gamma_e\gamma_b)}\right] + \cosh\left(\frac{W_b}{L_b}\right) - 1 \qquad \ldots(13)$$

In eqn. 13,

$$I_{n1} = qA\frac{D_b}{L_b}\frac{n_{bo}}{\gamma\tan\left(\frac{w_b}{L_b}\right)} \qquad \ldots(14)$$

Enq. 13 shows how the forward bias of emitter junction (Ve) increases in the presence of flux of light Φ_o, through the parameters F2 and I_{pH}.

Substituting eqn. 13 into 11 yields

$$I_c = \frac{1}{(1-\gamma_e\gamma_b)}\left[\gamma_e\gamma_b(I_{pH} + I_{co}) + (1-\gamma_e\gamma_b)(I_{pH} + I_{co})\right]$$

$$= \frac{(I_{pH} + I_{co})}{(1-\gamma_e\gamma_b)} \qquad \ldots(15)$$

Since the DC current gain h_{FE} is expressed as

$$h_{FE} = \frac{\gamma_e\gamma_b}{1-\gamma_e\gamma_b} \qquad \ldots(16)$$

Then

$$I_c = (1 + h_{FE})(I_{pH} + I_{co}) \qquad \ldots(17)$$

2. Speed of Response

It is well known that the basic operation conditions at switching transistor is a large- signal transient process. The most important issue to be addressed for a switching bipolar transistor is the interplay between the current gain the switching time. The small gain- band width product (GBP) of a bipolar transistor is usually computed as $f_T = ½\pi\tau_{ec}$, where τ_{ec} is the total emitter- to – collector signal delay time [2].

$$\tau_{ec} = \tau_e + \tau_b + \tau_D \qquad \ldots(18)$$

In eqn. 18

τ_e = Charging time of the junction capacitance through the emitter dynamic resistant $r_e = kT/qI_e$

τ_b = Base transit time

τ_D = Collector depletion layer transit time.

For the ideal case the emitter current is calculated from

$$I_e = \frac{q\eta P_{in} h_{FE}}{h\nu} \qquad \ldots(19)$$

where

η = Quantum efficiency of the photodiode

P_{in} = incident input power

$h\nu$ = photo energy

The charging time τ_e is calculated from

$$\tau_e = re\,(C_e + C_c) \qquad \ldots(20)$$

where

C_e = Emitter capacitance

C_c = Collector capacitance

The times τ_b and τ_D are given by [3]

$$\tau_b = \frac{w_b^2}{2D_b} \qquad \ldots(21)$$

$$\tau_b = \frac{w_D}{2v_s} \qquad \ldots(22)$$

where v_s is the saturation velocity in the collector.

When the optical power incident on the HPT increases suddenly at $t = 0$ from $(P_{in})_{min}$ to $(P_{in})_{max}$, the general equation that describes the temporal response of the collector current may be expressed as;

$$I_c(t) = I_f + (I_i + I_f)\exp(-t/\tau) \qquad \ldots(23)$$

where I_i and I_f are the initial and final values of the collector current:

$$I_i = (1 + h_{FE})I_{(pH)min} \qquad \ldots(24a)$$

$$I_f = (1 + h_{FE})I_{(pH)max} \qquad \ldots(24b)$$

In eqn. (24)

$I_{(pH)\ min}$ = photogenerated current due to minimum input power

$I_{(pH)\ max}$ = photogenerated current due to maximum input power

The time constant governs the response of the transistor is given by [4].

$$\tau = h_{FE}[\tau_e + \tau_b + \tau_D] \qquad \ldots(25)$$

The rise time (defined as the time required by I_c to change from 10 to 90 percent of its final value) of pulse response is calculated from eqn. (23)

$$t_r = \tau \ln\left[\frac{(O_v - 0.1)}{(O_v - 0.9)}\right] \qquad \ldots(26)$$

where O_v ($\leqq$ actual collector photocurrent / saturation limited collector), measures how far the device is driven into saturation.

3. Illustrative Results

The parameter values used in the calculations are given in Table I [1]. The input power is assumed to be switched from $(P_{in})_{min} = 0$ to a $(P_{in})_{max} = P_{in}$.

The dependence of rise time (t_r) on the incident power (P_{in}) is calculated as shown in Fig. (2a) for different values for base width. When τ_e is the dominant response time constant, the variation of W_b has a negligible effect on t_r. However, when a sufficiently large input signal is used, then $\tau_e < \tau_b + \tau_D$ and the rise time decreases significantly with increasing W_b.

Figure 2a also reveals that the rise time decreases as the input power increases. The rise time t_r is equal to 5 ns,

Figure 2a also reveals that the rise time decreases as the input power increases. The rise time t_r is equal to 5 ns, 2 ns, and 1 ns when W_b = 30 nm, 50 nm, and 70 nm, respectively and Pin = 50 μW. Figure 2b shows the rise time as a function of input power P_{in} and the width of collector depletion region W_D. The base width is taken as 100 nm in these calculations. This figure highlights the following fact. The rise time is less sensitive to W_D than the W_b. For the parameter values used in the simulation, t_r is almost insensitive to W_D for $W_C > 1$ μm.

The dependence of total time delay (Emitter- collector time delay) τ_{ec} on base width is displayed in Figs. 3a and 3b when L_b and P_{in} are taken as independent parameters, respectively. Notice that τ_{ec} less than 1 ns is expected to be achieved in HPT when P_{in}=100 μW and W_b = 0.45 μm (i.e. h_{FE} = 160). Reducing the level of P_{in} reduces τ_{ec} and hence reduces the transistor bandwidth ($1/2\pi\ \tau_{ec}$) and gain bandwidth product $f_T = h_{FE} / (2\pi\tau_{ec})$ as depicted in Figs. 4a and 4b.

The rise time of device has been calculated or different values of the parameter O_V, and the results are shown in fig. 5. The rise time is an decreasing function of O_V and hence to increase the switching speed of the HPT, the value of O_V must be increased.

4. Conclusions

The effect of device parameters on the speed of switching operation of 1.3 μm InGaAs/InP HPT have been characterized. The main findings of this paper are:

(i) The response time constant associated with temporal response is affected by both h_{FE} and incident power. It is more sensitive to the input power than diffusion length L_b at $W_b > 0.5$ μm.

(ii) High gain – bandwidth product f_T can be obtained at high input power and high current gain h_{FE}.

(iii) The effect of the base width on the rise time is more pronounced at higher values of input power.

(iv) To reduce the dependence of rise time on input power and h_{FE}, an external electrical bias current and large value of O_V ($O_V >> 1$) must be used, respectively.

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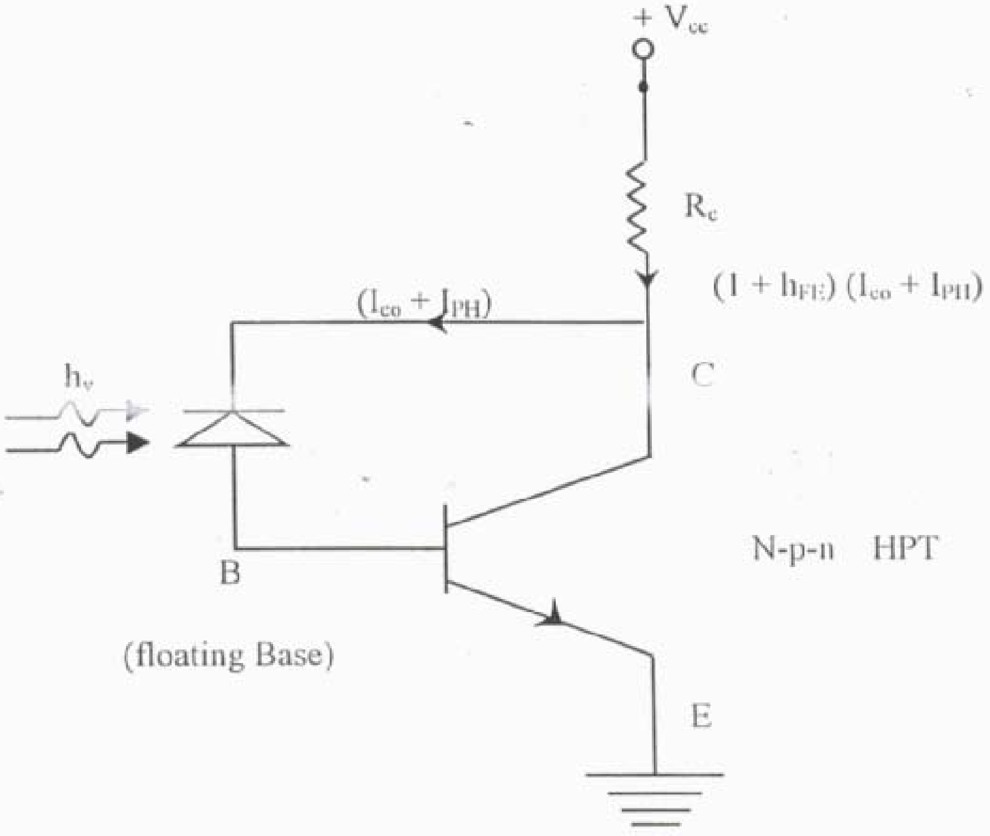

Fig. 2.1 Model of bipolar HPT

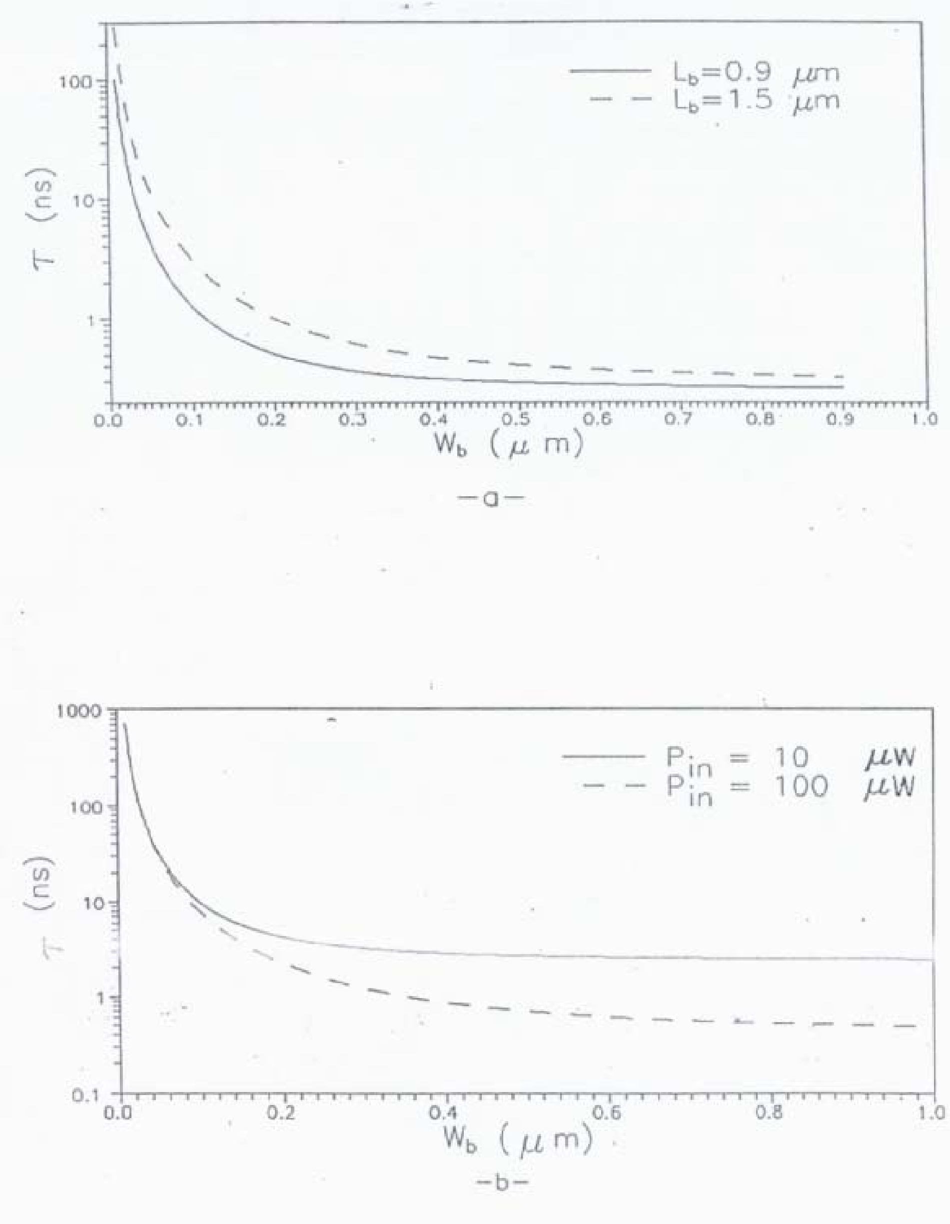

Fig. (2)- Response time constant τ as a function of base width W_b

a- for different values of L_b

b- for different values of P_{in}

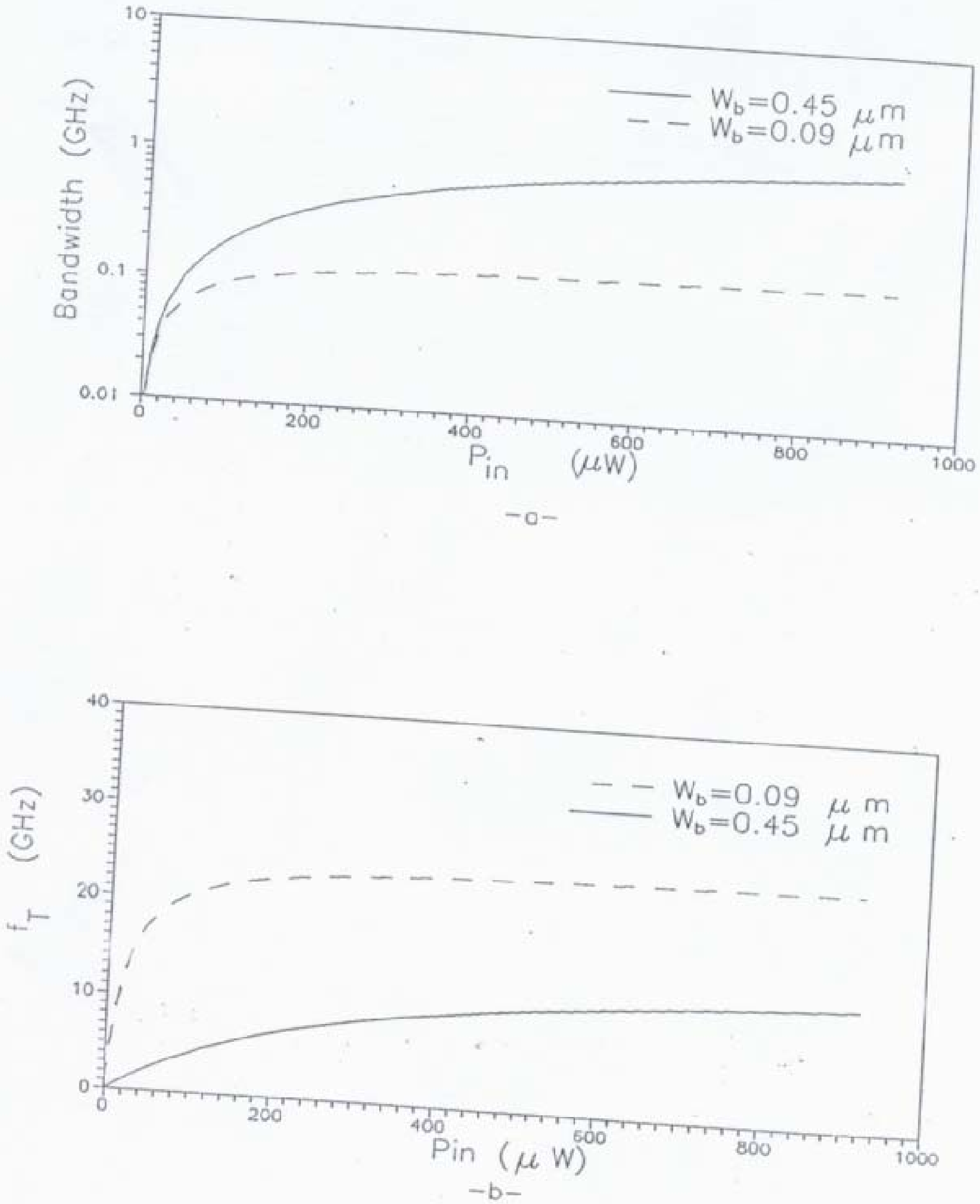

Fig. (3)- Effect of Base width W_b on the, (a) Bandwidth–input power characteristics, and (b) Gain bandwidth product f_T-input power characteristics.

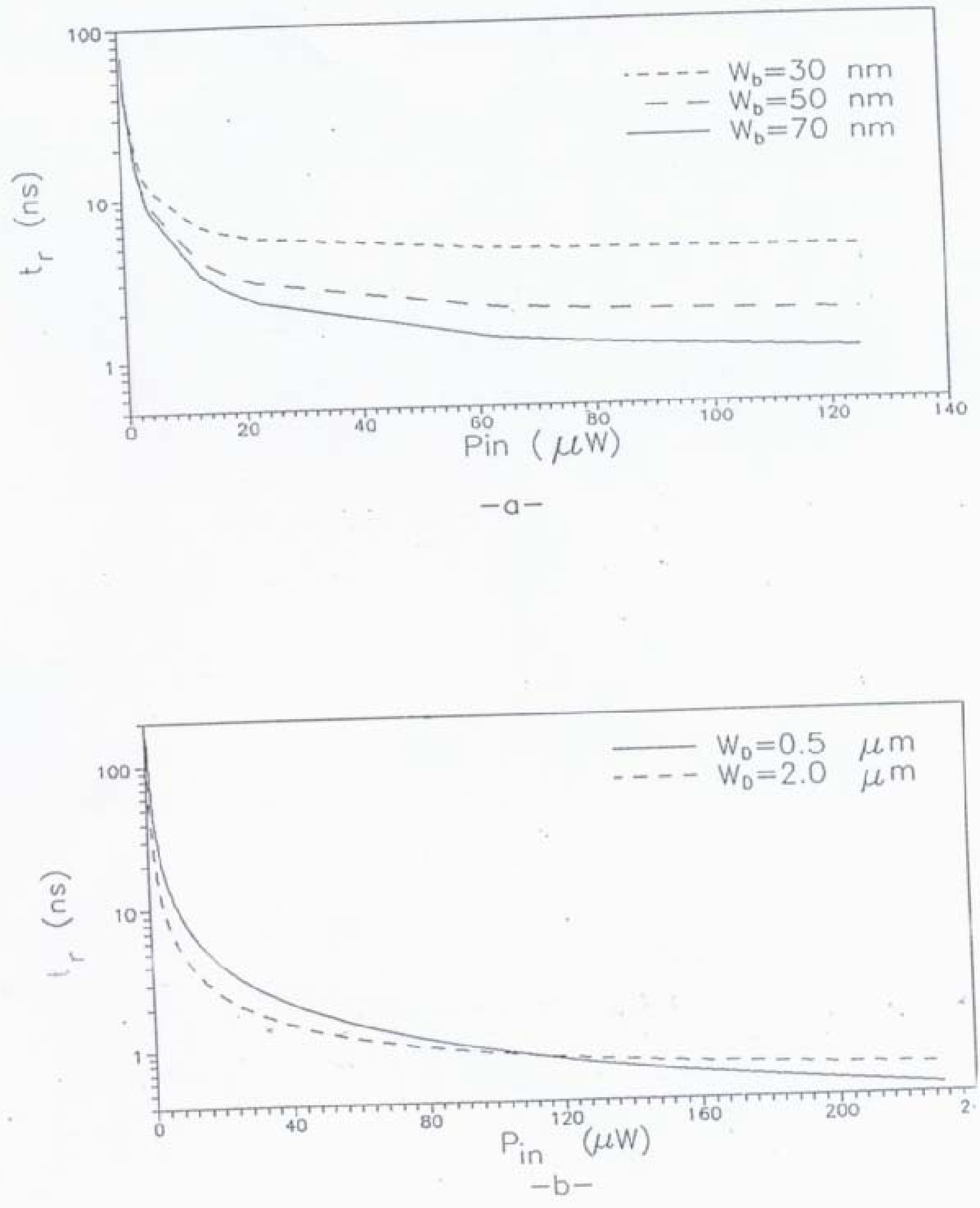

Fig. (4)- Rise time t_r as a function of input power P_{in}

a- Effect of base width W_b

b- Effect of depletion width collector junction W_D

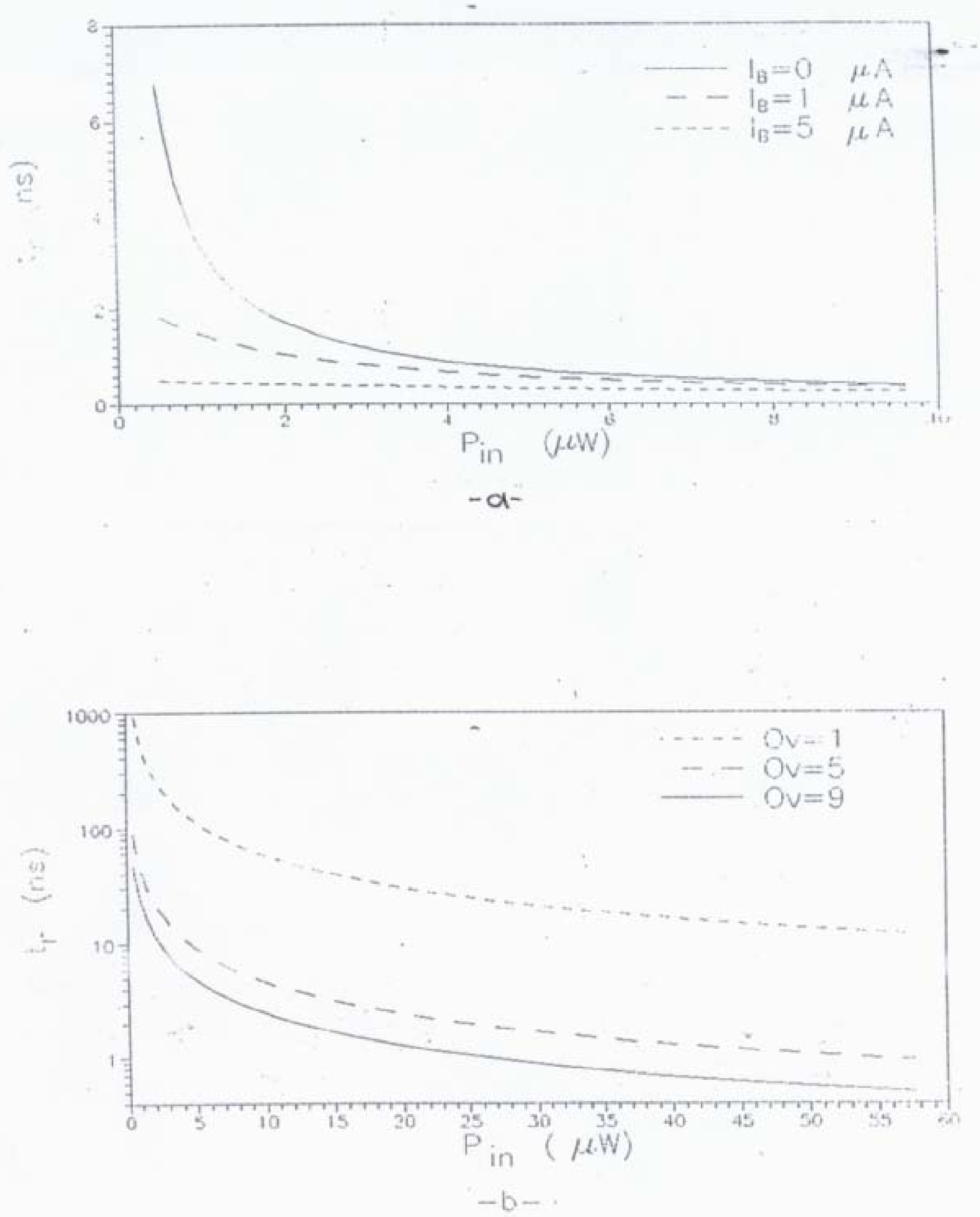

Fig. (5)- Rise time t_r as a function of input power P_{in}

a- Effect an external base current I_B.

b- Effect of factor Q_v (= I_f/I_{cs})