THE INFLUENCE OF DEGENERACY ON THE EMITTER EFFICIENCY OF A BIPOLAR TRANSISTOR

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N O T I C E

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Abstract.

A new expression for the emitter efficiency is derived taking the degeneracy of the emitter into account. It is found that, even if there is no recombination of minority carriers in the emitter, degeneracy reduces the emitter efficiency.

In addition this first order theory explains experimental results on temperature dependence of current gain and predicts an optimum emitter design for a fixed type of emitter profile.

The emitter efficiency is defined as:

$$\gamma = \frac{J_{nb}}{J_{nb} + J_{pe}} \qquad (1)$$

where J_{nb} is the electron current injected into the base and J_{pe} is the hole current injected into the emitter. In a modern transistor the emitter efficiency is the major limitation on the current gain [1]. If β_γ is the current gain of a transistor where emitter efficiency is the only limitation to the current gain, it can be written as:

$$\beta_\gamma = \frac{\gamma}{1 - \gamma} = \frac{J_{nb}}{J_{pe}} \qquad (2)$$

The emitter efficiency for a diffused transistor was first calculated by Tannenbaum and Thomas [2]. In their treatment they neglected recombination in the emitter and their calculation resulted in values for β_γ of almost one or two orders of magnitude larger than measured. Kennedy and Murley [1] took recombination in the emitter into account but still predicted higher

values than measured. In order to explain this discrepancy Whittier and Downing [3] postulated that the phosphorus atoms act as very low lifetime recombination centers at concentrations higher than $10^{19} cm^{-3}$, thus considerably increasing J_{pe}.

On the other hand, Kauffman and Bergh [4] and Buhanan [5] found that the decrease in the forbidden energy gap, due to degeneration and Coulomb interaction of the free carriers in the emitter can explain the temperature dependence of current gain.

This decrease in energy gap was indeed measured by Vol'fson and Subashiev [6] by absorption experiments. They found that the decrease in bandgap energy ΔE_g for n-type silicon can be described by:

$$\Delta E_g = \alpha (N_D^{1/3} - N_d^{1/3}) \quad (eV) \qquad (3)$$

where $\alpha = 3.4 .10^{-8}$ eVcm

$N_d = 1.35.10^{19} cm^{-3}$

are derived from their experimental data and

N_D is the concentration of the donor dopant.

This formula is in qualitative agreement with the Bonch-Bruevich [7] theory of Coulomb inter-

action of free carriers in degenerate semiconductors.

Based on these results Buhanan [5] presented a simple emitter model whereby the uniformly doped but degenerate emitter changes abruptly into a uniformly doped, non-degenerate base so that at the edges of the depletion layer:

$$\frac{p_{ne}}{n_{pb}} = \frac{n_{ie}^2 N_A}{n_{ib}^2 N_D} = \frac{N_A}{N_D} e^{\Delta E_g/kT} \qquad (4)$$

where n_{ie} and n_{ib} are the intrinsic concentrations in the emitter and base respectively. N_A and N_D are the doping levels of base and emitter respectively. As a result:

$$\beta_\gamma = \frac{D_{nb} L_{pe} N_D}{D_{pe} w_b N_A} e^{-\Delta E_g/kT} \qquad (5)$$

D_{nb} and D_{pe} are the electron and hole diffusivities in the base and emitter, L_{pe} is the diffusion length in the emitter and w_b is the base width.

Although this model predicts a lower gain and a strong temperature dependence due to the band-gap decrease, it has some major shortcomings in that it does not take the diffused nature of the device

into account. For most diffused devices the emitter base junction is not degenerate so that (4) does not hold. According to (3) the decrease in bandgap energy starts only at $N_D \geq 1.85.10^{19} cm^{-3}$ so that this effect only takes place in the highly doped part of the emitter.

In this letter a new expression for β_γ will be derived taking degeneracy into account. Fig. 1(a) represents the donorprofile $N_D(x)$ in an n^+ emitter. The emitter-base junction depletion layer boundary is located at $x = 0$ and $x = x_e$ represents the emitter contact.

Bandgap decrease sets in at $x = x_d$ as shown in Fig. 1(b). If the density of states is not strongly affected by the band tailing effect we can write:

$$n_i^2(x) = N_c N_v \exp\left(-\frac{E_{go} - \Delta E_g(x)}{kT}\right) = n_{io}^2 \exp\left(\frac{\Delta E_g(x)}{kT}\right) \geq n_{io}^2 \qquad (6)$$

According to (6) and assuming complete ionization of the donor impurities [8], the equilibrium hole density is given by:

$$p_o(x) = n_i^2(x)/N(x) \qquad (7)$$

where

$$N(x) = N_D(x) - N_A(x) \qquad (8)$$

In equilibrium the hole current is zero so that:

$$J_{pe_o} = -qD_p \frac{dp_o}{dx} + q\mu_p p_o \mathcal{E}(x) = 0 \qquad (9)$$

where $\mathcal{E}(x)$ is the electric field in the emitter.

Since the material is degenerate for $x > x_d$, the generalized Einstein relation [9] :

$$\frac{D_p}{\mu_p} = \frac{kT}{q} \frac{\mathcal{F}_{\frac{1}{2}}(\eta)}{\mathcal{F}_{-\frac{1}{2}}(\eta)} = \frac{kT}{q} \varphi(\eta) \qquad (10)$$

has to be used. $\mathcal{F}_j(\eta)$ is the Fermi-integral of index j and

$$\eta = \frac{q}{kT} (E_F - E_c) \qquad (11)$$

From (7), (9) and (10) it follows that:

$$\mathcal{E}(x) = \frac{kT}{q} \varphi(\eta) \left[\frac{2}{n_i} \frac{dn_i}{dx} - \frac{1}{N} \frac{dN}{dx} \right] \qquad (12)$$

It follows from (12) that the space-dependent n_i introduces a correction to the electric field expression, described as a quasi-electric field by Kroemer [10] .

If $V_{EB} > 0$ a hole current J_{pe} is injected into the emitter. In order to emphasize the degeneracy

effect and to keep mathematics simple, no recombination is assumed and thus J_{pe} is constant throughout the emitter i.e.

$$J_{pe} = -qD_p \frac{dp'}{dx} + q\mu_p p' \mathcal{E}(x) \qquad (13)$$

where $p' = p - p_o$ is the excess hole density.

From (12) and (13):

$$-\frac{J_{pe}}{qD_p} = \frac{dp'}{dx} - \left[\frac{2}{n_i}\frac{dn_i}{dx} - \frac{1}{N}\frac{dN}{dx}\right] p' \qquad (14)$$

Note that at this stage the modified Einstein relation dissapears if $D_p(N)$ is known.

Integration of (14), with $p'(x_e) = 0$ as boundary condition, yields:

$$p'(x) = \frac{J_{pe}}{q} \frac{n_i^2(x)}{N(x)} \int_x^{x_e} \frac{N(\xi)\, d\xi}{D_p(\xi) n_i^2(\xi)} \qquad (15)$$

If it is assumed that the emitter-base junction is not degenerate, it follows from (15) that:

$$p'(0) = p_{ne}\left(e^{qV_{EB}/kT} - 1\right)$$

$$= \frac{J_{pe}}{qN(0)} \int_0^{x_e} \frac{N(\xi)}{D_p(\xi)} \frac{n_{io}^2}{n_i^2(\xi)}\, d\xi \qquad (16)$$

or:

$$J_{pe} = \frac{qn_{io}^2 \left(e^{qV_{EB}/kT} - 1\right)}{\int_0^{x_e} \frac{N(\xi)}{D_p(\xi)} \frac{n_{io}^2}{n_i^2(\xi)} d\xi} \qquad (17)$$

Using the Moll-Ross [11] relation for J_{nb} we finally find:

$$\beta\gamma = \frac{\int_0^{x_e} \frac{N(\xi) n_{io}^2}{D_p(\xi) n_i^2(\xi)} d\xi}{\int_0^{w_b} \frac{N(\xi) d\xi}{D_n(\xi)}} = \frac{\overline{D}_n \int_0^{x_e} N(\xi) \frac{n_{io}^2}{n_i^2(\xi)} d\xi}{\overline{D}_p \int_0^{w_b} N(\xi) d\xi} \qquad (18)$$

Where $\overline{D}_n$ and $\overline{D}_p$ represent appropriate mean values for D_n and D_p.

Eq. (18) represents the main result of this letter and it is interesting to compare it with the Tannenbaum-Thomas expression which is exactly the same except for the fact that in the new expression, for $x \geqslant x_d$, the effective emitter charge is decreased by the factor:

$$\frac{n_{io}^2}{n_i^2(x)} = e^{-\frac{\Delta E_g}{kT}} = e^{-\frac{q\alpha}{kT}(N_D^{1/3} - N_d^{1/3})} \leqslant 1 \qquad (19)$$

Expression (19) follows from (3). As a result the gain is decreased and becomes sensitive to the temperature.

This effect is clearly shown in Fig.2. Curve I represents a Gaussian donor profile with a surface

concentration $N_o = 5.10^{20} cm^{-3}$ and a diffusion depth $x_e = 2 \mu m$.

According to Tannenbaum and Thomas the whole area beneath this profile adds effectively to the emitter charge Q_E.

Curves II, III and IV represent the "effective" emitter profiles corrected by expression (19) for 250, 300 and 350°K respectively. These fictive doping profiles enter the expression (18) for calculation of the effective emitter charge Q_E. It is obvious from this figure that the effective emitter charge is significantly reduced. The reduction decreases with increasing temperature and is relatively more important if the surface concentration is higher. From these facts it follows that for a fixed type of diffusion profile, emitter width x_e and base charge Q_B a surface concentration exists where the emitter efficiency is optimum. This is illustrated in Fig. 3 where the gain $\beta\gamma$ is calculated as a function of N_o for a Gaussian profile, an emitter depth of $2 \mu m$ and $\overline{D}_p Q_B / \overline{D}_n = 10^{12} cm^{-2}$. According to Tannenbaum and Thomas, the gain should increase monotonically with N_o. If degeneracy is taken into account the gain is optimum for $N_o = 4.10^{19} cm^{-3}$ for

this type of profile . For other profile types this value may be different. For larger values of N_o the effective emitter charge Q_E decreases and the gain becomes more and more temperature sensitive, in agreement with the experiments described in ref. [4] and [5] . It is also in agreement with the postulate of Whittier and Downing [3] that the emitter charge for $N_D > 10^{19}$ cm^{-3} is not effective anymore. However, the reason here is not a low lifetime but the degeneracy effect which creates a large aiding electric field, thereby increasing the hole current J_{pe}. It is possible that both effects act together.

More recent computer calculations taking recombination and anomalous diffusion profiles into account [12] confirm the results described in this letter.

In conclusion we can say that an accurate calculation of β_γ is only possible by taking the degeneracy effect into account. Expression (13) indicates that an optimum emitter doping profile exists and confirms the experimental result that a low temperature dependence of β_γ requires a lightly doped emitter.

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Captions to the Figures

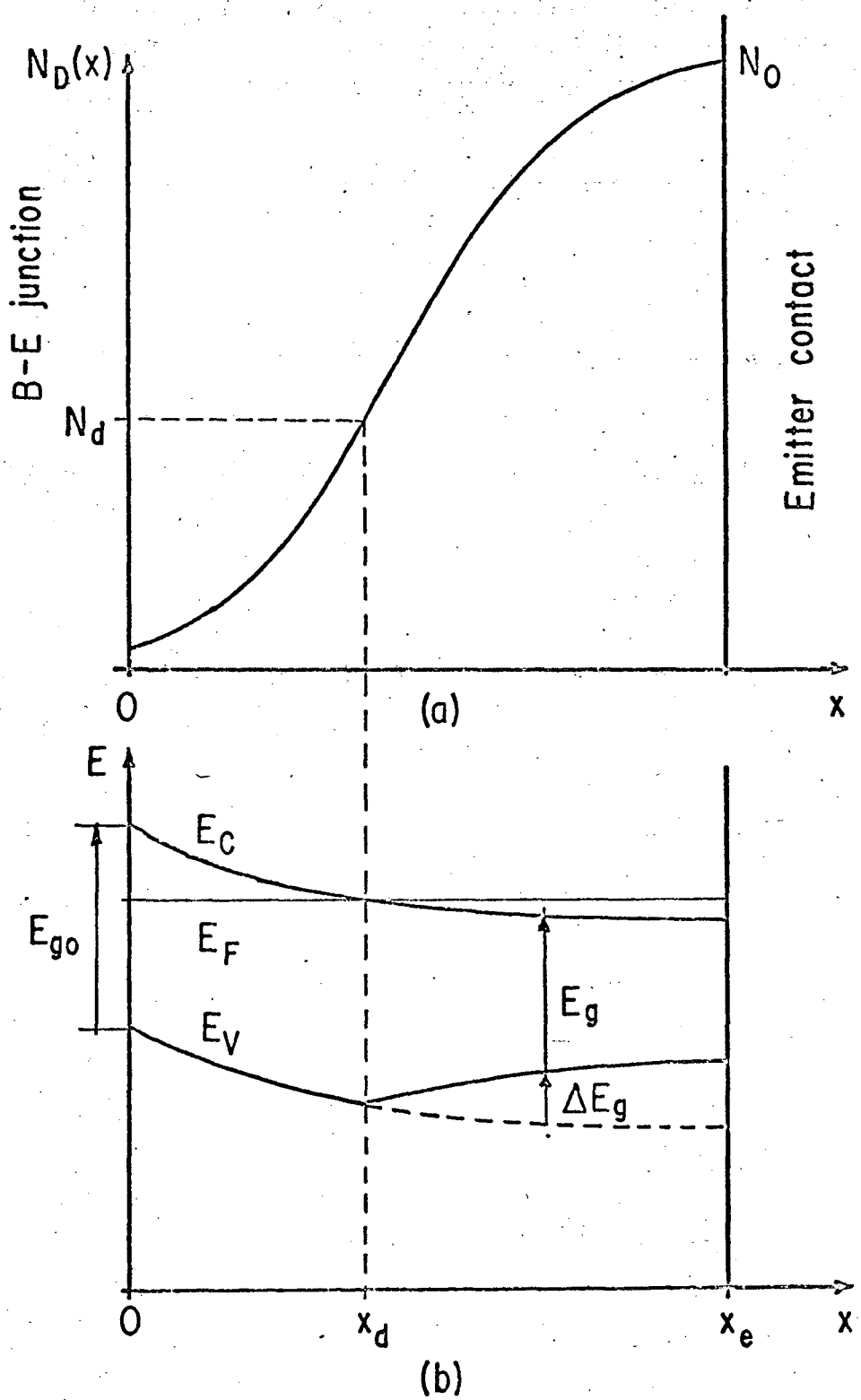
Fig. 1 (a) Donorprofile $N_D(x)$ in an emitter. $x = 0$ corresponds to the base emitter depletion layer boundary and $x = x_e$ to the emitter contact.

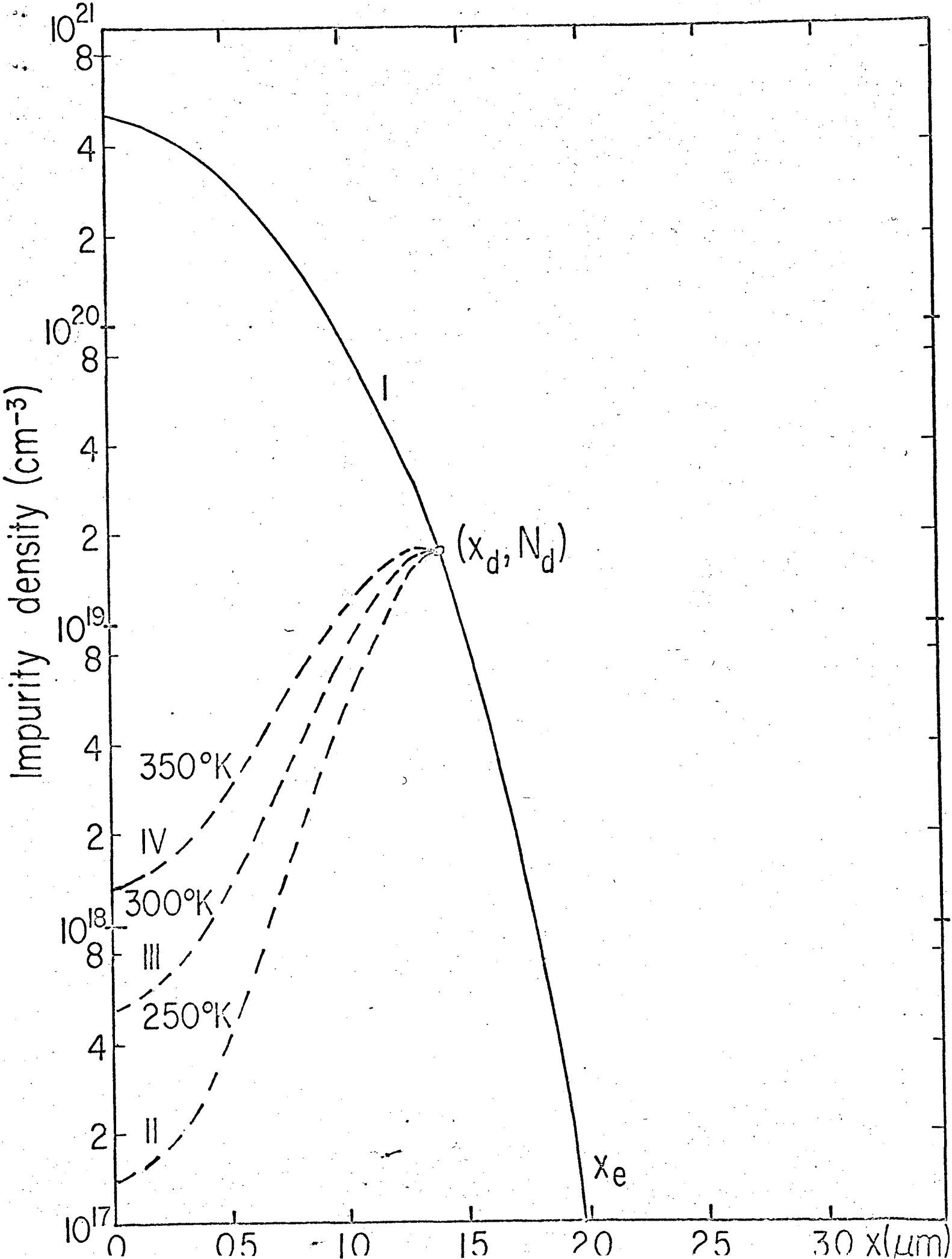
(b) Bandstructure in the emitter. For $N_D(x) > N_d$ the bandgap width E_g becomes smaller than E_{go}.

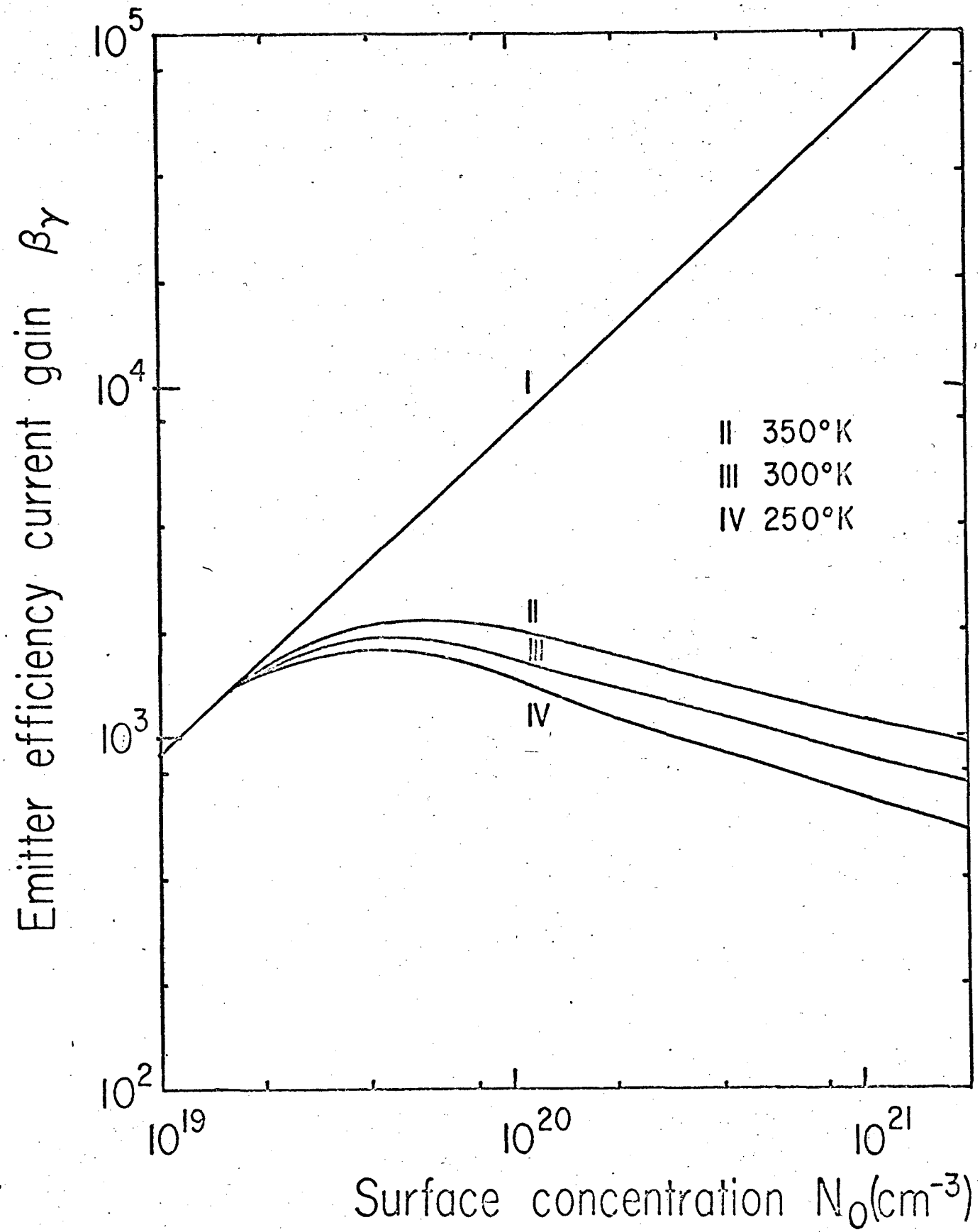
Fig. 2 Curve I: Gaussian emitter profile. Curves II, III and IV represent the "effective" emitter profiles corrected by expression (19) for 250, 300 and 350°K respectively.

Fig. 3 Curve I: emitter efficiency current gain β_γ as calculated from the Tannenbaum-Thomas formula vs. surface concentration N_o for a Gaussian emitter profile.

Curves II, III and IV: calculated from (18) for 350, 300 and 350°K respectively. Emitter depth $x_e = 2\ \mu m$ and $\bar{D}_p Q_B / \bar{D}_n$.


$N_D(x)$
N_0
B-E junction
N_d
Emitter contact
0
(a)
x
E
E_C
E_{go}
E_F
E_g
E_V
ΔE_g
0
x_d
x_e
x
(b)


Impurity density (cm⁻³)
10²¹
8
4
2
10²⁰
8
4
2
10¹⁹
8
4
2
10¹⁸
8
4
2
10¹⁷
I
(x_d, N_d)
350°K
IV
300°K
III
250°K
II
x_e
0
05
10
15
20
25
30 x(μm)


Emitter efficiency current gain β_γ
10^5
10^4
10^3
10^2
I
II 350°K
III 300°K
IV 250°K
II
III
IV
10^{19}
10^{20}
10^{21}
Surface concentration $N_0(cm^{-3})$