Radiation, Temperature and Gain in npn Planar Transistor

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Abstract: The dependence of current amplification factor on emitter current, temperature, resistivities, surface treatments as well as on the radiation effects are investigated. The experiments show that the current amplification factor is more dependent on recombination and scattering mechanism than the other effects. Temperature effect is profound also, high temperature causes high gain (400% at 200°C), low temperature causes very low gain (5% at liquid oxygen). Both the neutron and the γ-ray irradiation cause the Frenkel defect in the crystal and thus also decrease the current gain preatly. Recovery of gain is obtained by heating at 300°C, 150°C etc. in dry nitrogen atmosphere and then followed by quick annealing.

I. Introduction: The variation of current amplification factor on the emitter current has been verified by Webster[1], the falloffs of h_{fe} in low and high current region are due to the surface recombination and conductivity modulation re;pectively. The experimental data show that it fits fairly to Webster's results.

The authors have further investigated the temperature effects, surface treatments as well as the radiation effects. With the temperature range of -182.5°C of liquid oxygen to 200°C, the neutron dose, 10^{13}nv. to 10^{14}nv. from u^{235} reactor source. γ-ray dose, 10^{14} R/cm^2 to 10^{16} R/cm^2 from co^{60} source.

The transistor samples were made by our npn planar transistor process starting from 1Ω-cm, 5 mil thick Si wafer, along 111 direction.

Current amplification and its characteristics were measured by the Tektronics 575 curve tracer. Neutron irradiations were made in Tsing-hwa University reactor. γ-ray irradiations were made in Union Research Institute of Ministry of Economics.

II. Surface recombination and conductivity modulation

According to Sah et al[2] and Webster[1] the current amplification factor for abrupt junction is related as

$$\frac{1}{h_{fe}} \sim \frac{SA_sX_B}{A_ED_{nB}} g(z) + \left[\frac{\mu_{pE}p_{nE}}{\mu_{nB}n_{pB}} \frac{X_B}{L_{pE}} + \frac{1}{2}\left(\frac{X_B}{L_{nB}}\right)^2\right](1+z) \tag{1a}$$

where

$$Z = \frac{xuI_E}{A\sigma_b} = \frac{x_B\mu_{pE}I_E}{D_{nB}A\sigma_b}$$

and $g(z) = \frac{1+p_e/N_d}{1+2p_e/N_d}$ is Webster's $g(Z)$ function, which increases as Z decreases

s = surface recombination velocity

A_s = the effective area of surface recombination

x_B = base width

A_E = effective emitter area

D_{nB} = electron diffusion constant of Base region

μ_{pE} = hole mobility in emitter region

μ_{nB} = electron mobility in base region

p_{nE} = emitter hole concentration

n_{pB} = base electron concentration

L_{pE} = hole diffusion length in emitter region

L_{nB} = electron diffusion length in base region

For linear grade junction, the current amplification is approximately related as

$$\frac{1}{h_{fe}} \simeq \left(\frac{R_{sE}}{R_{sB}} + \frac{x_B^2}{4L_{nB}^2}\right) f(Z) + \frac{sA_sx_B}{A_ED_{nB}} g(Z) \tag{1b}$$

where

$$f(Z) = 1+Z$$

In equation (1a), the first term is the surface recombination term, the first term in the bracket is due to emitter efficiency. The second term is due to the volume recombination. $(1+Z)$ is the conductivity modulation factor which rises as I_E rises. However, at low level injection, the surface recombination is obvious, due to $g(Z)$ increasing at small I_E. The falloff of h_{fe} at low emitter current is shown in Fig. 1. At high level injection, the h_{fe} can be replaced by the following equation,

$$\frac{1}{h_{fe}} \sim \frac{u_{pE}p_{nE}}{u_{nB}n_{pB}} \frac{x_B}{L_{pE}}\left(1 + \frac{I_Ex_B}{2qD_{nB}A_EN_A}\right) + \frac{x_B^2}{4L_n^2} + \frac{sA_sx_B}{2A_ED_{nB}} \tag{2}$$

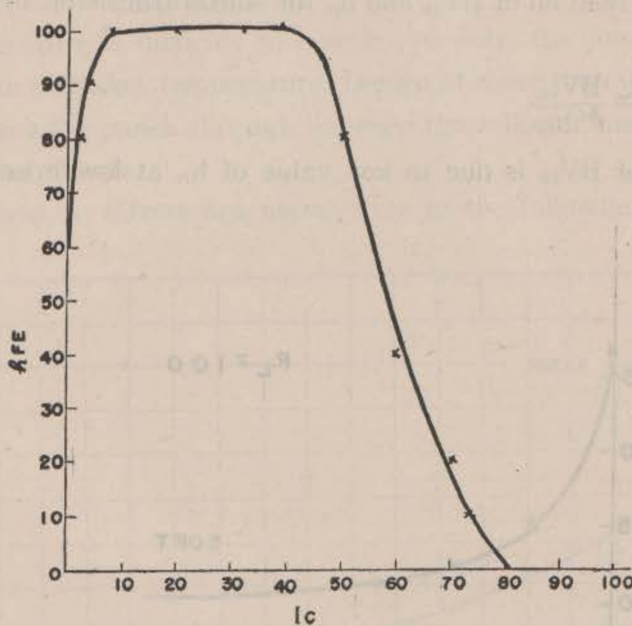

Fig. 1. CURRENT AMPLIFICATION Vs COLLECTOR CURRENT

here, it is equivalent to consider D_{nB} by two times. N_A is the impurity concentration in the base region. The first term in equation (2) also indicates the conductivity modulation effect, which increases with increasing I_E and thus decreases h_{fe} at high emitter current, this is also shown in Fig. (1). And the experiments fairly coincide with what was just discussed.

It has been shown that the periphery of the emitter junction is rather more effective than the effective area A. And it is favorable to design transistor by long thin stripe and overlay type which increases the periphery and promotes the power discipation of the transistor as well.

The surface velocity s, preatly depends upon surface treatment Incomplete cleaning and etching process maycause the fast falloff of h_{fe} at lowering the base current as well as the decreasing of the overall gain. Hot cleaning solution (~50°C) and etching solution (~80°C) may get better results. Sintering process is also good for current gain.

The experiment also shows that the breakdown voltage is related to the base current. The curve starts with a high breakdown voltage at zero base current and then decreases to a nearly constant value as Fig. 2 shown

$$\tau_{nr}=\frac{1}{N_R C_n}$$

N_R=the concentration of center cm^{-3}

C_n, C_p=the capture probabilities of the centers for holes and electrons respectively cm^{-3} sec^{-1}

the carrier concentrations are increased by increasing temperature before the semiconductor becomes intrinsic, at the impurity concentration of 10^{17} cm^{-3}, (base dopping)

at 200°C $\mu_p=200cm^2/v-sec$
approximately linear
at 30°C $\mu_p=500cm^2/v-sec$
10^{19} $\mu\sim$constant after Gartner[3]

Therefore, if the temperature effect of h_{fe} is mainly dependent on emitter efficiency,

$$\frac{(h_{fe})200^\circ C}{(h_{fe})30^\circ C}\simeq\frac{\mu_p at 30_\circ C}{\mu_n at 200^\circ C}=\frac{500}{200}=2.5$$

in Fig. 3, (h_{fe}) 200°C/(h_{fe}) 30°C$=\frac{800}{250}=3.2$,

However, there are some other factors which affects the h_{fe}, the minority carrier lifetime is the next important factor.

Investigation of the equation (4) shows that increasing of the lifetime due to the temperature rise contributes the high current gain too,and the experiments give the fairly satisfactory results.

In Fig. 3, our experiments show that the current gain is rather flat in the region between 0°C to 100°C than the smooth curve we have drawn.

At the temperature above 200°C, the breakdown occurs even at very low collector voltage and shows that the breakdown voltages are temperature dependent and decreases with increasing temperature thus due to the contrary to avalanche breakdown phenomena. The breakdown should be due to another machanism.

V. Radiation effects:

The irradiation of neutron, electron,photon and γ-rays etc. may produce following effects

(1) Frenkel deffect in the crystal and produce localized energy states[6] and acts as recombination centers.

(2) lattice damage

(3) concentration change

(4) radiation induced positive ions in the SiO_2 layer and hence induce inversion and instability[7].

The first, second and fourth factor may decrease the current gain of the transistor, however the concentration change is relatively smaller than the other factors.

According to James and Lork-Horovity model[6], the ionization potential of each of its valence electrons was estimated from the relation

$$\epsilon_i = \frac{i^2 \epsilon_H}{(k_i')^2}$$

where i refers to the ionization potential in question and is therefore the effective nuclear charge, ϵ_H is the ionization energy of the hydrogen atom and k_i' is the effective dielectric constant to which the electron in question is subject.

The localized levels for vacancies and interstitials are shown in Fig. (4)

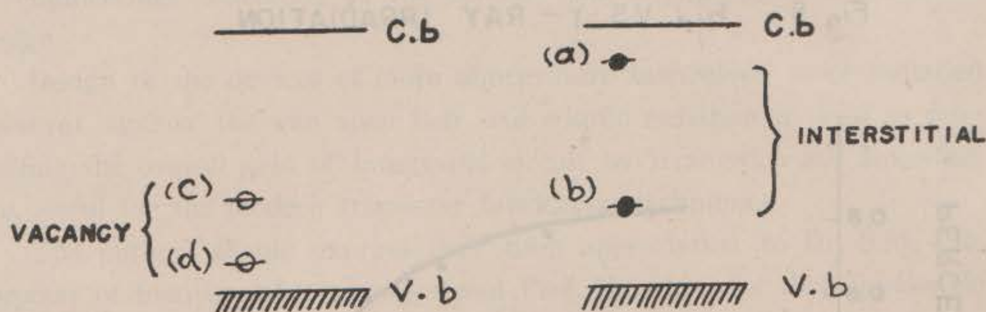

Fig.4. LOCALIZIED LEVELS FOR VACAN IES AND INTERSTITIALS

(a) If occupied, the interstitial atom is neutral

(b) If not occupied, interstitial atom is doubly charged;

(c) If occupied, net charge of two electrons near vacancy,

(d) If not occupied, zero net charge near vacancy.

current amplification is decreased both by neutron and r-ray irradiation. Fig. 5 and Fig. 6 show this effects.

When the irradiated samples are heated up to 400°C in dry nitrogen atmosphere, and then followed by quick annealing in the cool forced air,

the current amplification factor will be recovered to some extent.

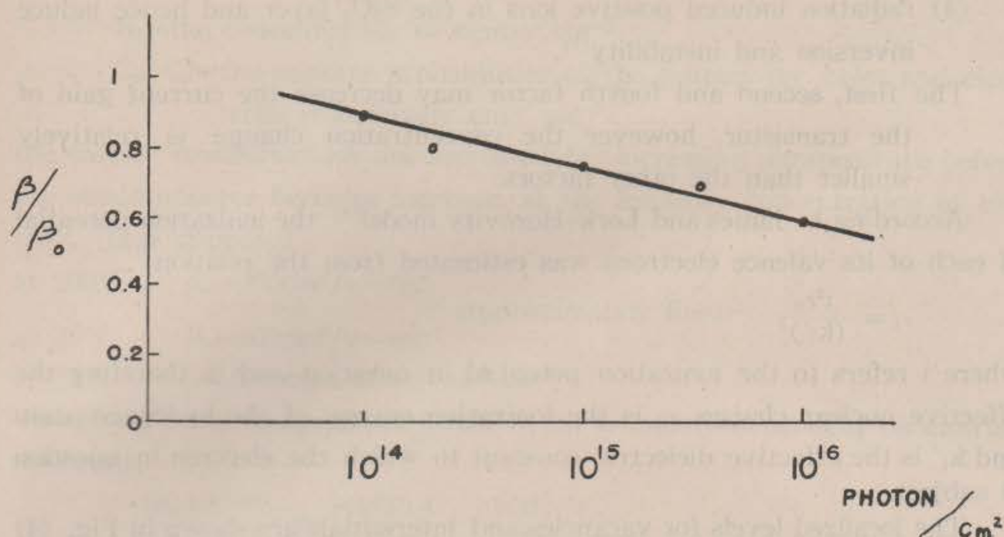

Fig 5. h_{fe} VS γ- RAY IRRADIATION

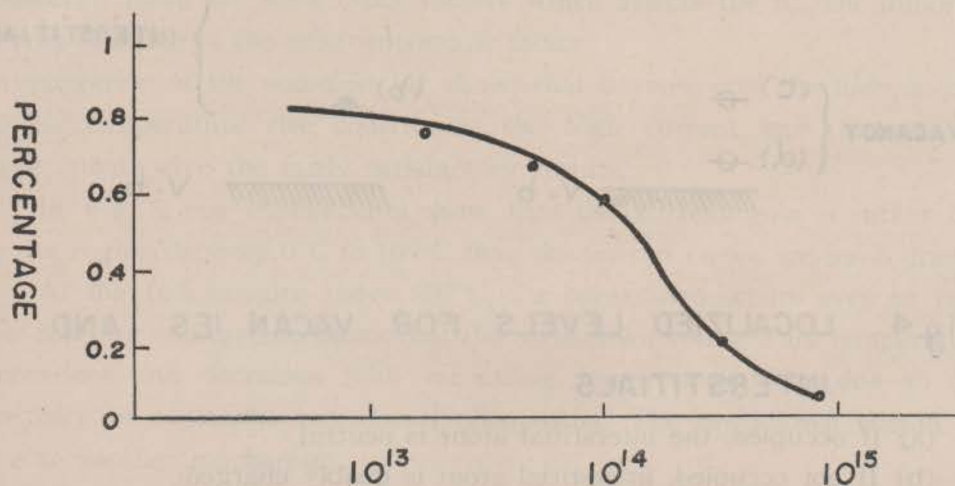

Fig 6. h_{fe} VS NE TRON IRRADIATION

Neutron dose from 10^{14} to 10^{16} nv made the current gain decreases from 80% to 7% correspondingly. Temperature annealing is made on 10^{16} nv

neutron irradiated samples, and at 150°C annealing, the current gain recovered from 7% to 10%. At 300°C annealing, the current gain recovered from 7% to 40%.

The γ-ray doses are ranged from 7.75×10^4 to $7.75 \times 10^{+6}$ R and the falling off effect is much smaller than that of neutrons.

Radiation effects on I_{CBO}, the collector cutoff current,[8] has been studied recently. Neutron irradiation introduces the additional recombination centers within the volume, while the gamma ray irradiation is a surface effect, so that I_{CBO} is increased.

V. Conclusion: The advantage of investigating the temperature, surface, and radiation effects on the current gain is the simple way to study their influences on the semiconductors. The disadvantage is that it is difficult to tell to what extent the respective factor affects the semiconductor alone due to the composite effects of many factors. However, on the point view of engineering, controling of the current gain is important for transistor design.

Design of the devices of more temperature insensitive, more radiation resistant against the van allen belt and cosmic radiation as well as controlling the overall gain of integrated circuit by irradiation and annealing are useful for the modern transistor fabrication techniques.

The authors should express their deep appreciation to Dr. S.M. Lee, Director of Institute of Electronics, and Prof. H.C. Liu, for their invaluable encouragement. The authors are also indebted to Mr. C.P. Wu and Mr. M.S. Tang for their cooporative work. Thanks is due to Mr. U. P. Wang, of Union Research Institute, Mr. K.P. Sun, of Tsing-hwa University who generously offered the irradiation apparatus.

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