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 preyly. 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 \(h_{\tau_0}\) in low and high current region are due to the surface recombination and conductivity modulation respectively. 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, \(10^{19}\) to \(10^{20}\) from \(^{235}\) reactor source, γ-ray dose, \(10^{14}\) to \(10^{16}\) R/cm\(^2\) from \(^{60}\) 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 irrations were made in Union Research Institute of Ministry of Economics.

II. Surface recombination and conductivity modulation

According to Sah et al\(^{12}\) and Webster\(^{13}\) the current amplification factor for abrupt junction is related as
\[
\frac{1}{h_{fe}} \approx \frac{S A_B X_B}{A_E D_{eb}} g(Z) + \left[ \frac{\mu_{pB} \mu_{nB} N_{pB}}{\mu_{nB} N_{pB}} \frac{X_B}{L_{oB}} + \frac{1}{2} \left( \frac{X_B}{L_{oB}} \right)^2 \right] (1+Z)
\]  

(1a)

where

\[Z = \frac{x ul_{E}}{A_E A_{E}} = \frac{x_n / \mu_{pE} I_{E}}{D_{eb} A_{E}}\]

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

\(s\) = surface recombination velocity
\(A_e\) = the effective area of surface recombination
\(x_n\) = base width
\(A_e\) = effective emitter area
\(D_{eb}\) = electron diffusion constant of Base region
\(\mu_{pB}\) = hole mobility in emitter region
\(\mu_{nB}\) = electron mobility in base region
\(p_{nB}\) = emitter hole concentration
\(n_{nB}\) = base electron concentration
\(L_{oB}\) = hole diffusion length in emitter region
\(L_{oB}\) = electron diffusion length in base region

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

\[
\frac{1}{h_{fe}} \approx \left( \frac{R_{eB}}{R_{eb}} + \frac{x_B^2}{4L_{oB}^2} \right) f(Z) + \frac{S A_e x_B}{A_{B} D_{eb}} g(Z)
\]  

(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 \(I_n\). 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,

\[
\frac{1}{h_{fe}} \approx \frac{\mu_{nB} D_{eb}}{\mu_{pB} N_{pB}} \frac{X_B}{L_{oB}} \left( 1 + \frac{I_{E} X_{B}}{q D_{eb} A_{E} N_{A}} \right) + \frac{X_B^2}{4L_{oB}^2} + \frac{S A_e X_B}{2A_{B} D_{eb}}
\]  

(2)
here, it is equivalent to consider $D_{ns}$ 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 $I_b$ and thus decreases $h_{ie}$ 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 $s$, greatly depends upon surface treatment. Incomplete cleaning and etching process may cause the fast falloff of $h_{ie}$ at lowering the base current as well as the decreasing of the overall gain. Hot cleaning solution ($\sim 50^\circ C$) and etching solution ($\sim 80^\circ C$) 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
The carrier concentrations are increased by increasing temperature before the semiconductor becomes intrinsic, at the impurity concentration of $10^{19}$ cm$^{-3}$, (base doping)

at $200^\circ$C, $\mu_v = 200$ cm$^2$/v-sec

at $30^\circ$C, $\mu_v = 500$ cm$^2$/v-sec

$10^{19}$ $\mu \sim$ constant after Gartner$^{(3)}$

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

$$\frac{(h_{re})_{200^\circ C}}{(h_{re})_{30^\circ C}} \approx \frac{\mu_{at 30^\circ C}}{\mu_{at 200^\circ C}} = \frac{500}{200} = 2.5$$

in Fig. 3, $(h_{re})_{200^\circ C}/(h_{re})_{30^\circ C} = \frac{800}{250} = 3.2$.

However, there are some other factors which affects the $h_{re}$, 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 $0^\circ$C to $100^\circ$C than the smooth curve we have drawn.

At the temperature above $200^\circ$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 mechanism.

V. Radiation effects:

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

(1) Frenkel defect in the crystal and produce localized energy states$^{(4)}$ and acts as recombination centers.

(2) lattice damage
(3) concentration change
(4) radiation induced positive ions in the SiO₂ layer and hence induce inversion and instability.

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, the ionization potential of each of its valence electrons was estimated from the relation

\[ \epsilon_i = \frac{i^2 \epsilon_{ii}}{(k_i')^2} \]

where \( i \) refers to the ionization potential in question and is therefore the effective nuclear charge, \( \epsilon_{ii} \) 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)

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**Fig. 4. LOCALIZED LEVELS FOR VACANIES 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 $\gamma$-RAY IRRADIATION

**Fig 6.** $h_{fe}$ VS NEUTRON IRRADIATION

Neutron dose from $10^{14}$ to $10^{15}$ nv made the current gain decreases from 80% to 7% correspondingly. Temperature annealing is made on $10^{14}$ 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 7-ray doses are ranged from $7.75 \times 10^4$ to $7.75 \times 10^6$ R and the falling off effect is much smaller than that of neutrons.

Radiation effects on $I_{c30}$, the collector cutoff current, 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 $I_{c30}$ 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, controlling 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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