THE D.C. MODELING OF THE I^2L GATE WITH THE NON-LINEAR CIRCUIT ANALYSIS PROGRAM TRANZ-TRAN

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Since the presentation of integrated injection logic (I^2L) [1, 2] and later published review articles [3, 4] several investigations have been done in the field of modeling of the I^2L structures [5—10].

All previously mentioned models did not take into account a lot of physical effects (for example τ_n, τ_p concentration dependence and so). Also the most part of the models need measured model parameters, and because of it is impossible to give physical explanation to turn over process or to explain which factors determine, for example, the transfer characteristic behaviour.

The model described here is based on ideas of Ebers-Moll transport model [11].

The strategy of building up the model is following:

For the I^2L structure the circuit diagram (physical-topological model, Figure 1), corresponding to cross section AÁ was built up and is shown in Figure 2. In such "two-dimensional" model the model parameters (saturation currents, base resistance, current gains) have been determined from doping levels, technological and electrophysical parameters. The model is examined with the non-linear circuit analysis program TRANZ-TRAN [12].

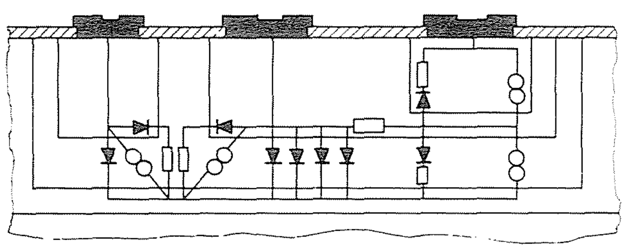

Fig. 1. Structure oriented model of the I^2L gate

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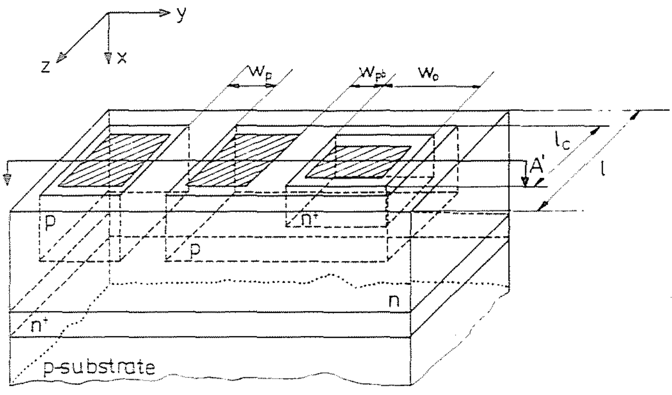

Fig. 2. Conventional I^2L structure

The dimensions of model structure are in agreement with those in literature (see for example [13, 14]. The doping profile is determined by exponential function [15, 16].

The mathematical model

The model, described here, is constructed so, that the currents in junctions are represented by different diodes. For the diode the following equation is valid:

$$J = J_0\left[\exp\left(\frac{U}{mU_T}\right) - 1\right] \tag{1}$$

where J_0 — saturation current density, which depends on various physical and technological parameters and temperature;

m — bulk recombination factor ($1 \leqq m \leqq 2$).

At first one must determine the different saturation currents. For the saturation currents the following equations have been developed.

The lateral pnp part of the I^2L structure (Figure 3)

$$J_{ilo} = (qn_i^{-2}\bar{D}_p)/(N_{epi}w_p)\,, \qquad m=1, \tag{2}$$

$$J_{ivo} = q \,/\, \Big\{ \int_0^{x_{jb}} [N_a/(n_i^2 D_n)]\, \mathrm{d}x \Big\}\,, \qquad m=1\,. \tag{3}$$

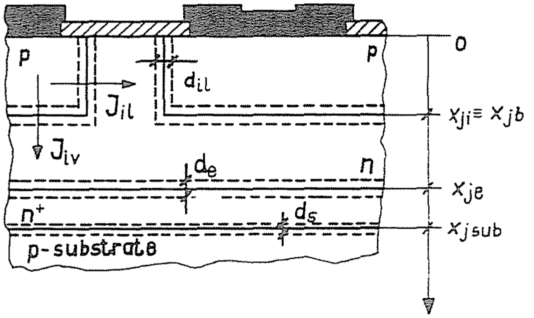

Fig. 3. Lateral *pnp* part of the I^2L gate

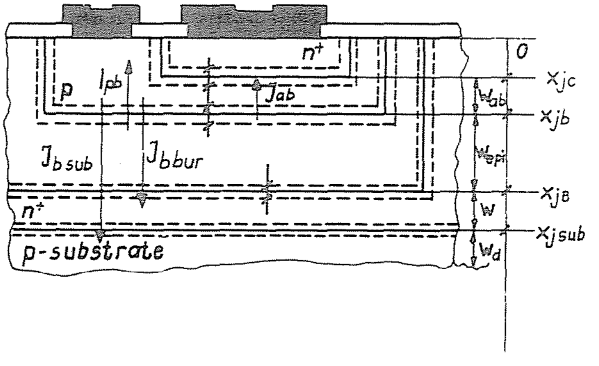

Fig. 4. Vertival *npn* part of the I^2L gate

The vertical npn part of the I^2L structure (Figure 4)

$$J_{bmo} = q / \left\{ \int_0^{x_{jb}} [N_a/(n_i^2 D_n)]\, \mathrm{d}x \right\}, \qquad m = 1, \tag{4}$$

$$J_{boxo} = (q n_i^{-2} v_{ox}) / N_{as}, \qquad m = 1, 12, \tag{5}$$

$$J_{abo} = q / \left\{ \int_{x_{jc}}^{x_{jb}} [N_a/(n_i^2 D_n)]\, \mathrm{d}x \right\}, \qquad m = 1, \tag{6}$$

$$J_{bburo} = (q n_i^{-2} v_{nn}^{+}) / N_{epi}, \qquad m = 1, 15, \tag{7}$$

$$J_{bsubo} = (q n_i^{-2} U_T / \bar{\mu}_p) / (N_d \cdot w), \qquad m = 1, \tag{8}$$

$$J_{Go} = (q \bar{n}_i d) / \tau_e, \qquad m = 2. \tag{9}$$

In Equations (2—9) the following effects were neglected:

1. High level injection, which should be taken into consideration with so called "knee" voltage factor in formula (1) [9].

2. The geometrical effects of the junctions (cylindrical or spherical), which should be taken into consideration with correction factor in formula (1), but which changes considerably by high injection levels [15].

The temperature dependence of the saturation current densities is shown in Figure 5.

The current gains have been modeled with the help of the current generators (Figure 1). For the current gain one can write

$$\alpha = \gamma \kappa \delta \,, \tag{10}$$

where δ is the collector efficiency which is practically 1. For lateral *pnp* transistor the normal and inverse current gains have not been calculated. The data are taken from literature [17], $\alpha_{pnp}^{n} = 0.85$ and $\alpha_{pnp}^{i} = 0.75$.

To calculate the current gains in vertical *npn* part, the emitter and collector junction areas equality is assumed, which is not typical for I^2L structures, but in case of one collector this assumption is satisfactory. In the case of many collectors the following formulae must be improved.

The current gains

$$\gamma_n = \frac{1}{1 + \dfrac{\int_{x_{jc}}^{x_{jb}} (N_a/D_n)\, \mathrm{d}x}{\int_{x_{jb}}^{x_{je}} (N_d/D_p)\, \mathrm{d}x}} \,, \tag{11}$$

$$\gamma_i = \frac{1}{1 + \dfrac{\int_{x_{jc}}^{x_{jb}} (N_a/D_n)\, \mathrm{d}x}{\int_{0}^{x_{jc}} (N_d/D_p)\, \mathrm{d}x}} \,, \tag{12}$$

$$\kappa_n = \frac{1}{1 + \left(\dfrac{W_{ab}}{L_n}\right)^2 F_-(N)} \,, \tag{13}$$

$$\kappa_i = \frac{1}{1 + \left(\dfrac{W_{ab}}{L_n}\right)^2 F_+(N)} \,. \tag{14}$$

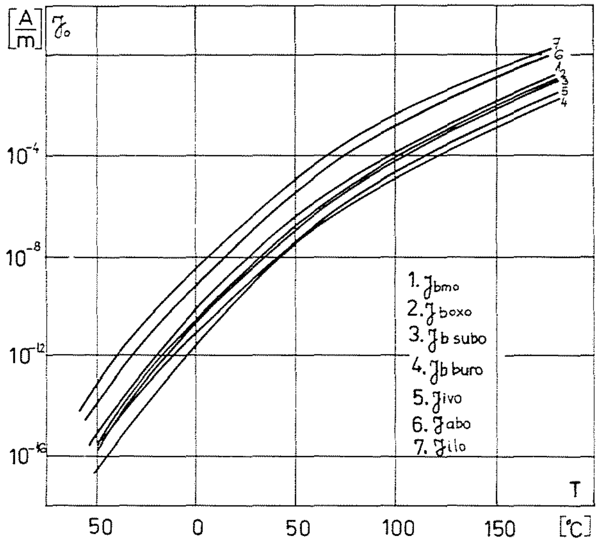

Fig. 5. Saturation currents (J_o) dependence on temperature (T)

The breakdown voltage of the junctions have been determined by calculations given in literature [18], because in I^2L structures the breakdown and multiplication properties are not important. The temperature dependence of breakdown voltage described for example in [19] was left out of consideration.

The base resistance consisting of active and passive base resistances is determined and so is the collector contact resistance.

The resistances:

$$R = R_{ab} + R_{pb}, \tag{15}$$

$$R_{pb} = \frac{w_{pb} \cdot 1}{\int\limits_0^{x_{jb}} q\mu_p N_a \, dx}, \tag{16}$$

$$R_{ab} = \frac{R_{pb}}{1 - \frac{I_c}{I}\left(1 - \frac{\int\limits_0^{x_{jb}} q\mu_p N_a \, dx}{\int\limits_{x_{jb}}^{x_{jc}} q\mu_p N_a \, dx}\right)}. \tag{17}$$

$$R_C = \frac{b\bar{D}_p L_p}{[\bar{D}_p \operatorname{sh}(x_{jc}/L_p) + w_p L_p \operatorname{ch}(x_{jc}/L_p)] S_c}. \tag{18}$$

To determine the model parameters (Equations (2)...(18) the following equations are needed:

$$n_{io}=A_1T^{3/2}\exp(-A_2/U_T), \tag{19}$$

where $A_1=3.1\cdot10^{22}m^{-3}$, $A_2=0.603$ V, $U_T=kT/q$,

$$\Delta V_{go}=A_3[\ln(N/A_4)+\sqrt{[\ln(N/A_4)]^2+1/2}], \tag{20}$$

where $A_3=9.10^{-3}$, $A_4=10^{23}m^{-3}$,

$$n_i=n_{io}[\exp(\Delta V_{go}/U_T)]^{1/2}, \tag{21}$$

$$\mu_{n.p}=\mu_{no.po}\cdot A_5^{(n.p)}\cdot N^{[A_6^{(n.p)}\cdot T-A_7^{(n.p)}]}\cdot\exp[A_8^{(n.p)}-A_9^{(n.p)}\cdot T], \tag{22}$$

where μ_{no}, μ_{po}, $A^{(n.p)}_{5..9}$ found in [20],

$$D_{n.p}=\frac{D_{no.po}}{1+(N/A_{10})\Theta_{n.p}}, \tag{23}$$

where $D_{no.po}=\mu_{no.po}\,.\,U_T$, $A_{10}=7.5\cdot10^{23}m^{-3}$, $\Theta_n=0.55$, $\Theta_p=0.68$,

$$\tau_n=\frac{\tau_{on}}{1+N/A_{11}}, \tag{24}$$

where $\tau_{on}=1.5\ \mu s$, $A_{11}=5.10^{24}m^{-3}$,

$$\tau_p=(A_{12}\cdot N^{A_{13}})^{-1} \tag{25}$$

where $A_{12}=2.25\cdot10^{-19}$, $A_{13}=1.36$,

$$\tau_e=\frac{1}{2\sqrt{\tau_{po}\tau_{no}}\,\mathrm{ch}\,[(\Delta W_t/kT)\ln\sqrt{\tau_{po}/\tau_{no}}]}, \tag{26}$$

where τ_{po}, τ_{no} – carrier lifetime in junctions,

$$\rho=1/(q\bar{\mu}_nN_d), \tag{27}$$

$$b=\bar{\mu}_n/\bar{\mu}_p, \tag{28}$$

$$L_{n.p}=\sqrt{\bar{\tau}_{n.p}\cdot\bar{D}_{n.p}}, \tag{29}$$

$$F_{\pm}(N)=\frac{\pm\eta-1+e^{\pm\eta}}{\eta^2}, \tag{30}$$

$$\eta=\ln\frac{N_{be}}{N_{bc}}. \tag{31}$$

More detailed informations about the model can be found in [21].

The results of calculations

At first the transfer characteristic dependence on the change of the base surface concentration (N_{as}) has been investigated. The results are shown in Figure 6. As one can see, to larger surface base concentration (N_{as}), greater input voltage is needed for the turn over. The reason is, that the increase of the base surface concentration (N_{as}) causes the increase of the base integral, due to the active base current decrease. Due to it higher input current is needed to turn over the gate. Larger input current is reached by increasing the input voltage. Conclusionally it means, that the turn over level of the transfer characteristic of the I^2L gate moves to right.

In Figure 7 one can see transfer characteristic dependence on the change of the epitaxial layer concentration (N_{epi}). Similarly to the previous case, the increase of the epitaxial layer concentration (N_{epi}) pushes the turn over level of the transfer characteristic to right. The change of epitaxial layer concentration (N_{epi}) influences the lateral and n^+ layer current in explicite way while the

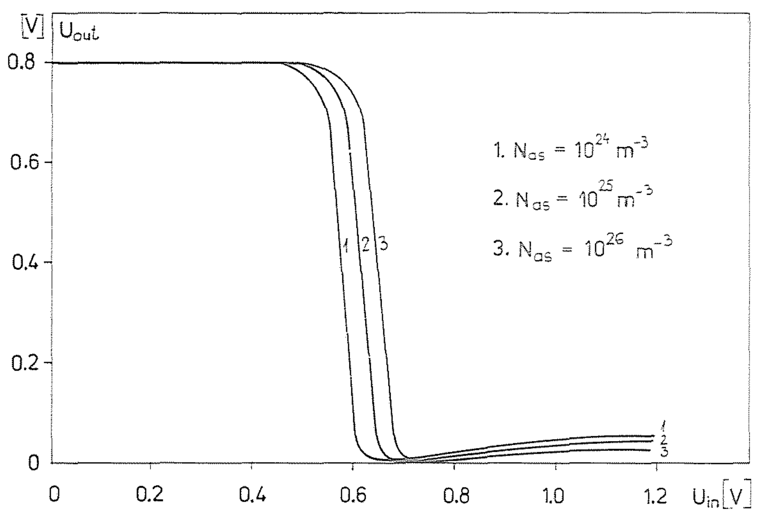

Fig. 6. Transfer characteristic dependence on the change of the base surface concentration (N_{as})

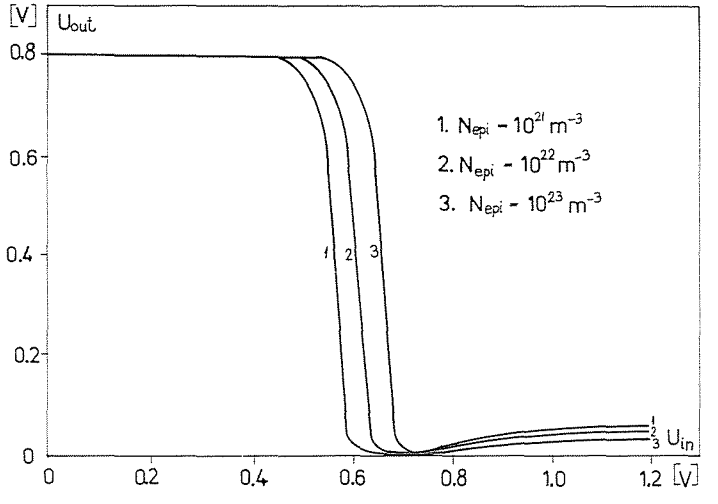

Fig. 7. Transfer characteristic dependence on the change of the epitaxial layer concentration (N_{epi})

active base, injector vertical and substrate current in implicite way. The increase of epitaxial layer concentration (N_{epi}) causes the increase of base integral due to the active base current decreases, and the transfer characteristic turn over level shifts toward greater input voltages.

The calculations show, that the increase of base surface concentration (N_{as}) and decrease of epitaxial layer concentration (N_{epi}) cause the decrease of normal current gain (α^n_{npn}) of I^2L gate. The decrease of normal current gain (α^n_{npn}) causes decrease of the curvature of the transfer characteristic, but the change is not so considerable that it should be followed on transfer characteristics.

On Figure 8 the transfer characteristic dependence on the change of active base thickness (w_{ab}) is shown. The increase of active base thickness (w_{ab}) yields the increase of base integral due to the active base current decreases. Also small increase of injector lateral current was observed.

Consequently the transfer characteristic moves toward larger input voltages.

Increasing the active base thickness causes decrease in base transport factors ($\kappa^{n,i}_{npn}$) due to the current gains $\alpha^{n,i}_{npn}$ decrease. The increase of α^n_{npn} causes the increase of curvature of the transfer characteristic of the I^2L gate. From the calculations one can conclude that the transistor technological condition ($w_{ab} < L_n$) should remain.

The calculations also show that other geometrical parameters (passive base thickness w_{pb}, lateral base thickness w_p, epitaxial layer thickness w_{epi}, structure wideness 1. and some other parameters (for example nn^+ junction

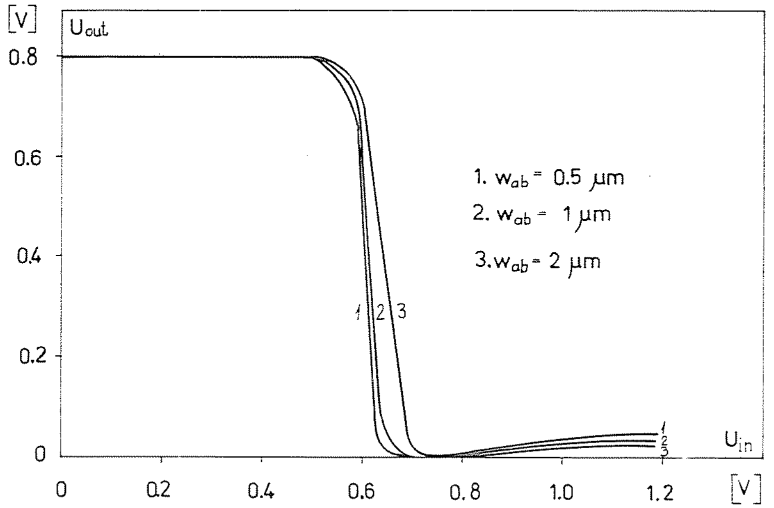

Fig. 8. Transfer characteristic dependence on the change of the active base thickness (w_{ab})

recombination speed v_{nn}·, Si—SiO_2 surface recombination speed v_{ox}) practically do not influence the transfer characteristics of the I^2L structure.

In the model, the model parameters depend on temperature. The temperature dependence of the carrier lifetime is described by the following formula [22]

$$\tau_{n,p} = \tau_{n,p}(T_o)\,(T/T_o)^{A_{14}}, \tag{32}$$

where

$$A_{14} = 2.5\,, \qquad T_o = 25\ ^\circ C\,.$$

The influence of neutron irradiation is presented with the following formula [23]:

$$\tau_{n,p}^{-1} = \tau_{n,p}^{-1}|_{\Phi=0} + \Phi/K_o\,, \tag{33}$$

where

$$K_o = 3 \cdot 10^{10}\,\frac{\text{neutron}}{m^2} \cdot s\,.$$

In Figure 9 the transfer characteristic dependence on the change of the temperature (T) is shown. The change of temperature has strong influence on the transfer characteristic of the I^2L gate. The increase of the temperature causes the increase of the whole currents in the structure, due to it the I^2L gate comes nearer to turn over level. Because of it the turn over level of the transfer characteristic moves toward smaller input voltages. The high temperature

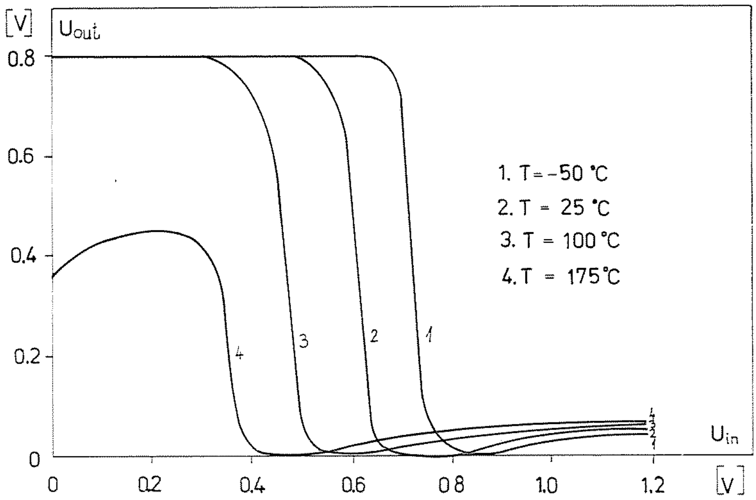

Fig. 9. Transfer characteristic dependence on the change of the temperature (T)

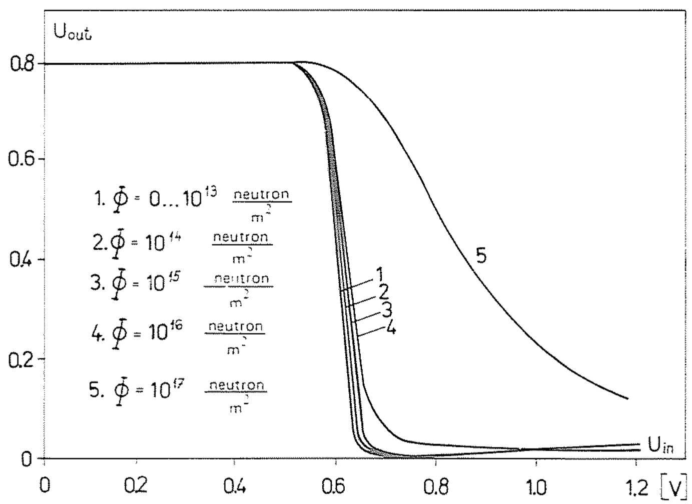

Fig. 10. Transfer characteristic dependence on the change of the neutron irradiation (Φ)

($T \geqq 175$ °C) causes the loose of the high output level on the transfer characteristic of the I^2L gate.

In Figure 10 the transfer characteristic dependence on the change of the neutron irradiation (Φ) is shown. The dependence is quite strong. The increase of neutron irradiation (Φ) causes the decrease of α^n_{npn} and α^i_{pnp} due to the curvature of the transfer characteristic decreases. In the case of modeling the neutron irradiation the transistor technological condition ($w_{ab} < L_n$) should remain.

Conclusion

The structure oriented "two-dimensional" model of I^2L structure is presented. The transfer characteristic dependence on main technological parameters, temperature and neutron irradiation has been examined.

The calculations show, that the change of the active base thickness (w_{ab}), temperature (T) and neutron irradiation (Φ) have the strongest influence on the transfer characteristic, while the changes of base surface concentration (N_{as}) and epitaxial layer concentration (N_{epi}) have weaker influence. Other geometrical and physical parameters do not affect the transfer characteristic of the I^2L gate.

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Summary

A structure oriented physical-topological model of the I^2L gate is described. The model parameters (saturation currents, base resistance, current gains) have been calculated from doping levels, geometrical and electronic parameters.

The model is examined by the non-linear circuit analysis program TRANZ-TRAN.

The transfer characteristic dependence on main technological parameters, temperature and neutron irradiation, has been investigated. It has been shown that active base thickness (w_{ab}), temperature (T) and neutron irradiation (Φ) have strong influence to transfer characteristic of the I^2L gate. Weaker affect is followed from base surface concentration (N_{as}) and epitaxial layer concentration (N_{epi}) to transfer characteristic of the I^2L gate. Other technological parameters (w_p, w_{pb}, w_{epi}, w, l) practically do not affect the transfer characteristic of the I^2L gate.

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