The Breakover Condition for the PNPN Structure

1989 Jpn. J. Appl. Phys. 28 L169

(http://iopscience.iop.org/1347-4065/28/2A/L169)

Japanese Journal of Applied Physics
Vol. 28, No. 2, February, 1989, pp. L 169–L 172

The Breakover Condition for the PNPN Structure

David C. Y. Chang

Institute of Electronics, National Chiao Tung University,
Hsin Chu, Taiwan, R.O.C.

(Received September 5, 1988; accepted for publication January 12, 1989)

In this work, the breakover condition of the Shockley diode by the voltage triggering is studied. By replacing the current gain and the multiplication factor with their ac counterparts, an elegant definition of the breakover condition is presented and justified to be more general than previous definitions.

KEYWORDS: PNPN structure, breakover condition, multiplication factor, voltage triggering

§1. Introduction

Recently, the ac triggering of the Shockley diode has attracted much attention due to the serious latch-up problem associated with complementary metal oxide semiconductor (CMOS) VLSI applications.[1,2] Breakover and holding points are two major areas for investigation. Various formulations have been reported to define the breakover condition.[3-6] However, all of them failed to correctly interpret the voltage-related triggering of PNPN diodes. In this work, the inconsistencies between different difinitions are investigated by calculating the current gain variations as a function of the bias voltage of the PNPN diode under the voltage triggering condition. To overcome the deficiencies of the various definitions, the conventional static current multiplication factor is modified by taking the small signal variations into account. Finally, simplified numerical simulations are used to prove that the breakover condition can be consistently defined using a modified expression, which cannot be achieved by any previously reported definitions.

§2. Theory

The schematic diagram of electron-hole flowing across the device is shown in Fig. 1. According to this diagram, if a single charge of hole is injected from the anode in a

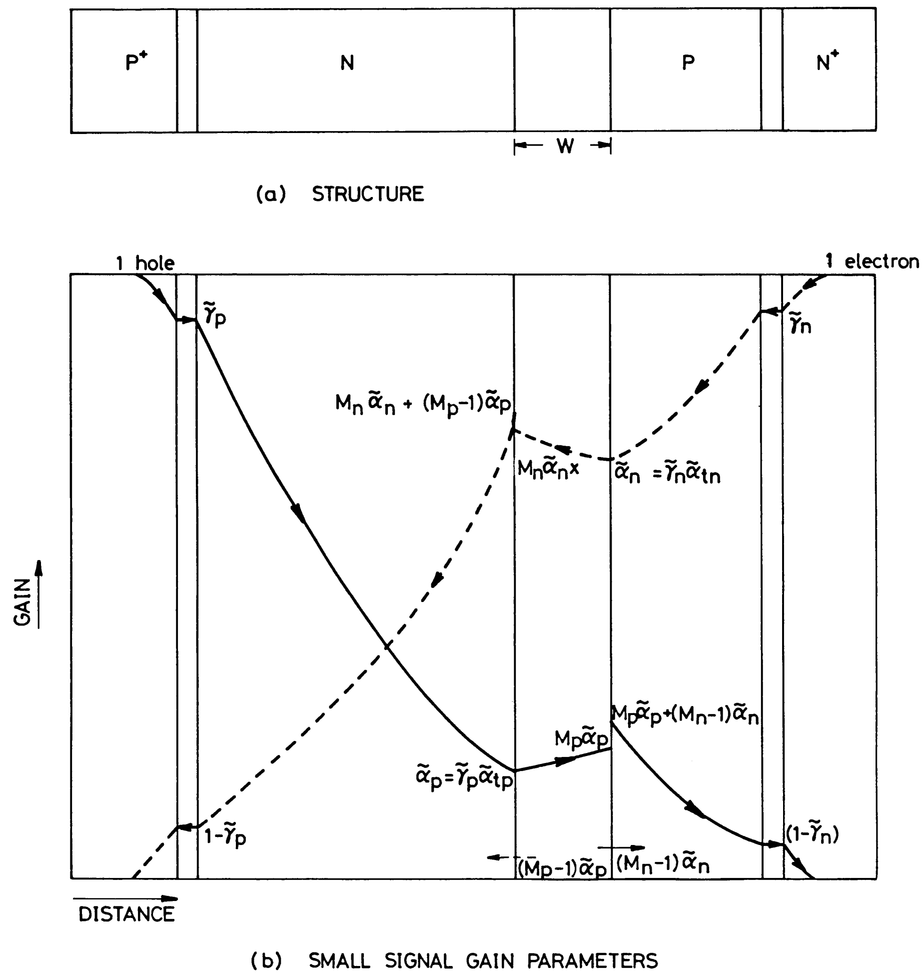


Fig. 1. The single charge carrier flow and small signal current gain parameters in a PNPN structure.

PNPN structure, electrons will be generated at the cathode. When the number of induced electrons is more than that of the injected hole, breakover will occur. Therefore, it can be derived that, when the Shockley diode operates at the current triggering mode, the breakover condition is[6]

$$M_n\tilde{\alpha}_n+M_p\tilde{\alpha}_p=1 \tag{1}$$

where M_i and $\tilde{\alpha}_i$ (i is either n or p) are the multiplication factor at the base-collector junction and the small signal common base current gain, respectively. M_i can be approximated by[7]

$$M_i=\frac{1}{1-(-V_2/BV_{cbo})^n} \tag{2}$$

where BV_{cbo} is the open emitter base-collector junction breakdown voltage, V_2 is the voltage drop across the junction and n is a constant. However, in the case of voltage triggering, due to the voltage dependent depletion width of the collector junction, the static representation of the multiplication factor as shown in eq. (1) will no longer be valid and it should be replaced by its ac counterpart $\tilde{M}_i$, i.e., breakover will occur only when the displacement majority carrier current (which include the recombination loss in the base region and at the emitter junction). The breakover condition should be defined as

$$\tilde{M}_n\tilde{\alpha}_n+\tilde{M}_p\tilde{\alpha}_p=1 \tag{3}$$

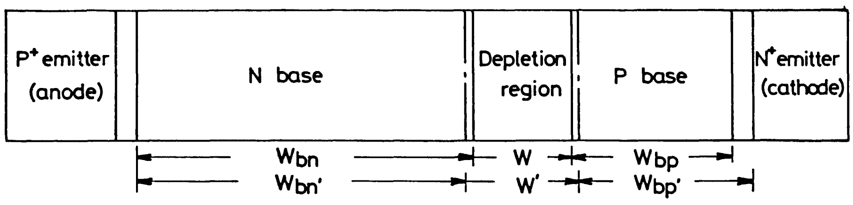
where, refer to Fig. 2(b), $\tilde{M}_i$ is the ac carrier multiplication factor due to the modulation of the depletion width during the voltage triggering and

$$\tilde{M}_i=\frac{\partial J_{di}}{\partial J_{ci}}=\frac{\partial(M_i\alpha_i J)}{\partial(\alpha_i J)} \tag{4}$$

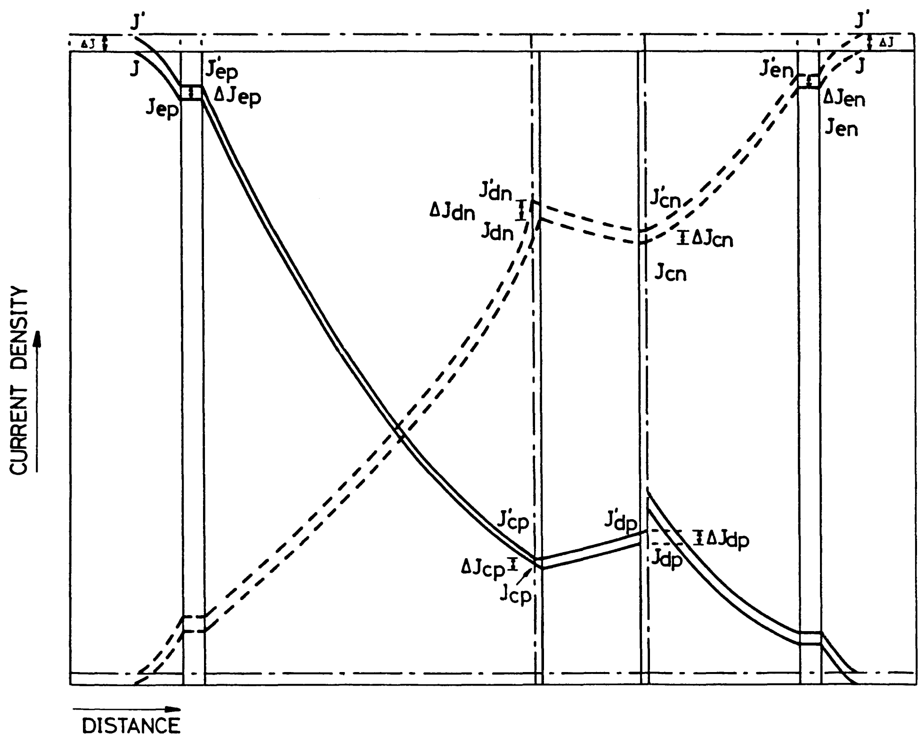
where J, J_{ci} and J_{di} are the total current density, current densities at two edges of the collector junction, respectively. (see Fig. 2) According to eq. (4), $\tilde{M}_i$ can be furtherly derived as

$$\tilde{M}_i=M_i+(\alpha_i J)\frac{\partial M_i}{\partial(\alpha_i J)}. \tag{5}$$

Because of the inherent difference between the incremental and dc parameters, the overall current gain using voltage triggering is substantially different from that obtained by dc parameters.



(a) STRUCTURE



(b) CURRENT DENSITY DISTRIBUTION

Fig. 2. Current density distribution in a PNPN structure. The fluctuation in depletion region indicates the voltage triggering.

§3. Numerical Simulation and Result

To elucidate the differences of the breakover mechanisms between voltage and current triggerings, a simple one-dimensional model as shown in Fig. 2 is used for simulation. In the figure, the unprimed state is the old state and the primed state is the new state when triggering ac voltage is applied. The simulation process is started from the current density equations with boundary condition specified by three junction voltages.[7] Set V_1, V_2 and V_3 to be the three junction voltages as shown in Fig. 2(a), and let V_1 and V_2 as two independent variables. Thus the anode current density and all anode or depeltion region related parameters can be obtained. Since the current density is continuous across the whole device, V_3 and all cathode related parameters can be obtained by Newton-Ralphson iteration method. The steady state is maintained as[3]

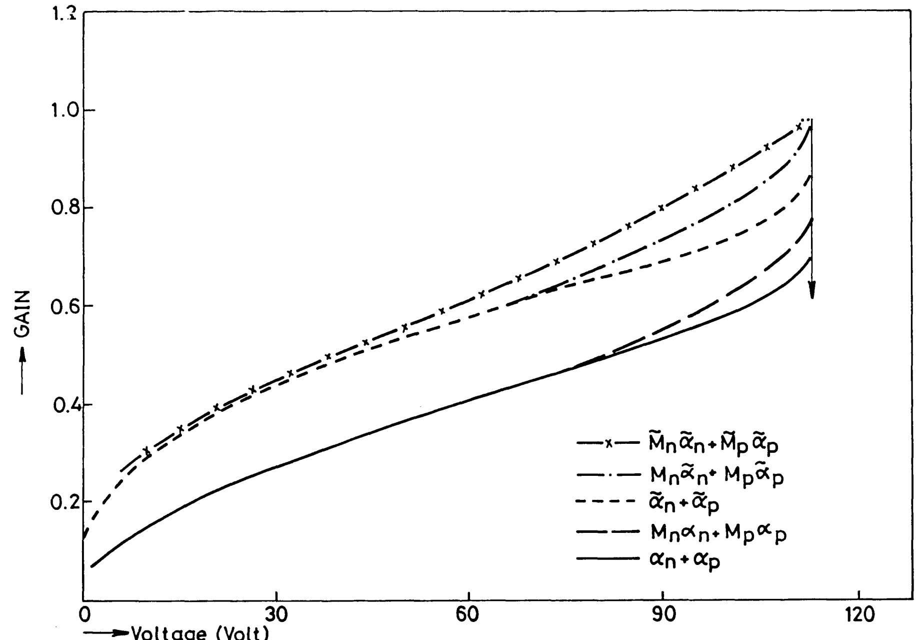
$$M_n\alpha_n+M_p\alpha_p+J_{co}/J=1. \tag{5}$$

Here, the dc multiplication factor of electron and hole is assumed the same for simplicity; J_{co} is the leakage current density at the collector junction which is considered as a multiplicative process[9] and

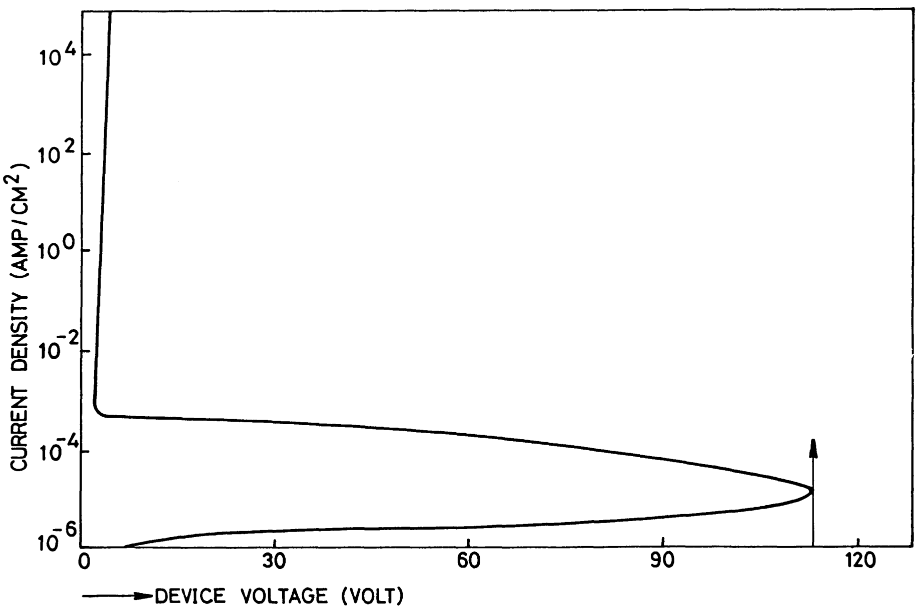
$$J_{co}=qU(W'_nM_n+W'_pM_p) \tag{6}$$

where q is the electronic charge, U is the recombination rate, W'_n and W'_p are the depletion widths of N and P side, respectively. The multiplication factor M_i is calculated according to eq. (2) with $n=3$, and BV_{cbo} is calculated using abrupt junction approximation.[8]

The small signal ac parameters such as injection



(a) The Simulated Current Gain Variations



(b) The Simulated Stable J-V Curve

Fig. 3. Five (5) simulated current gain values along the stable J-V curves, up to the breakover point.

efficiency, $\tilde{\gamma}_i$, transport factor, $\tilde{\alpha}_{ti}$, $\tilde{\alpha}_i$ and $\tilde{M}_i$ can be obtained using following eqs.,

$$\tilde{\gamma}_i=\Delta J_{ei}/\Delta J=(J'_{ei}-J_{ei})/(J'-J)=\gamma_i+\Delta\gamma_i/\Delta J \times J \quad (7)$$

$$\tilde{\alpha}_{ti}=\Delta J_{ci}/\Delta J_{ei}=(J'_{ci}-J_{ci})/(J'_{ei}-J_{ei}) =\alpha_{ti}+\Delta\alpha_{ti}/\Delta J_{ei} \times J_{ei} \quad (8)$$

$$\tilde{\alpha}_i=\Delta J_{ci}/\Delta J=\Delta J_{ci}/\Delta J_{ei}\times\Delta J_{ei}/\Delta J=\tilde{\alpha}_{ti}\times\tilde{\gamma}_i \quad (9)$$

$$\begin{aligned}\tilde{M}_i&=\Delta J_{di}/\Delta J_{ci}=(M'_i\alpha'_iJ'-M_i\alpha_iJ)/(\alpha'_iJ'-\alpha_iJ)\\&=M'_i+(M'_i-M_i)\times\alpha_iJ/(\alpha'_iJ'-\alpha_iJ)\\&=M'_i+\alpha_iJ\times\Delta M_i/\Delta(\alpha_iJ)\end{aligned} \quad (10)$$

where, J_{ei} is the current density at the emitter-base junction.

In the calculations, a non-symmetrical PNPN device with a wide N base and a narrow P base was chosen. This is equivalent to the lateral PNP merged with a vertical NPN transistor to simulate the most commonly used structure appearing in CMOS IC. In this structure, the current gain is dominated by the narrow base width transistor. The major parameters used in our simulation are $P_{e0}=1.0\times10^{19}\,\text{cm}^{-3}$, $N_{b0}=3.0\times10^{15}\,\text{cm}^{-3}$, $P_{b0}=7.5\times10^{17}\,\text{cm}^{-3}$, $N_{e0}=1.0\times10^{19}\,\text{cm}^{-3}$, $W_n=100\,\mu\text{m}$, $W_p=5\,\mu\text{m}$ and $U=10^{16}\,\text{cm}^{-3}\text{sec}^{-1}$. The lifetime is $1\,\mu$ second for both electron and hole. Where P_{e0}, N_{b0}, P_{b0} and N_{e0} are the doping concentrations of the four PNPN regions, respectively. W_n and W_p are the N or P base width, respectively. Five different criteria of the PNPN breakover conditions are calculated. They are $\alpha_n+\alpha_p$,[1] $\tilde{\alpha}_n+\tilde{\alpha}_p$,[5] $M_n\alpha_n+M_p\alpha_p$,[3,6,10] $M_n\tilde{\alpha}_n+M_p\tilde{\alpha}_p$[6,11] and $\tilde{M}_n\tilde{\alpha}_n+\tilde{M}_p\tilde{\alpha}_n$, respectively. For all cases, their values from zero biasing to the breakover points were calculated with the results shown in Fig. 3 for comparsion. The calculated avalanche breakdown voltage is 115 volt which is slightly larger than the breakover voltage as shown in Fig. 3(b). According to the simulation results shown in Fig. 3(a), it is obvious that the current variation obtained from ac multiplication factors is larger than others which are physically incorrect under voltage triggering. A more complete analysis of this phenomenon is underway, in which the effects of bandgap narrowing, Auger recombination, and graded junction, etc. are all included.

§4. Conclusions

In summary, it has demonstrated for the first time, that a completely different definition of the breakover condition is required to correctly interpret the triggering mechanism of the Shockley diode by the voltage method. Compared with other definitions, a correct description of the breakover transition of the Shockley diode can be achieved only when the dc parameters are replaced by their ac counterparts.

Refernces

1) D.B. Esterich: Standford Electronics Labs. Tech Rep. **G-201-9** (1980).
2) M. J. Chen and C. Y. Wu: Solid-State Electron. **29** (1986) 551.
3) J. L. Moll, M. Tanenbaum, J. M. Godley and N. Holonyak: Proc. IRE **44** (1956) 1174.
4) I. M. Macchintosh: Proc. IRE **46** (1958) 1229.
5) W. Fulop: IEEE Trans. Electron Devices **ED-10** (1963) 120.
6) J. F. Gibbons: IEEE Trans. Electron Devices **ED-11** (1964) 406.
7) S. L. Miller: Phys. Rev. **99** (1955) 1234.
8) S. M. Sze: *Physics of Semiconductor Devices* (Wiley Intersicence, New York, 1981).
9) C. T. Sah, R. N. Noyce and W. Shockley: Proc. IRE **45** (1957) 1228.
10) P. Voss: Solid-State Electron. **17** (1974) 655.
11) F. E. Gentry, F. W. Gutzwieler, N. Jr. Holonyak and E. E. Zastrow: *Semiconductor Controlled Rectifiers* (Englewood Cliffs, N. J. Prentice-Hall, 1964).