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Operational Calculation of Puncture Voltage of Drift *n-p-n* Transistors in Inverse Mode

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The article deals with the issues of the operational calculation of the breakdown voltages of drift *n-p-n* transistors in the inverse operating mode when calculating the parameters of their structure according to the given electrical parameters and characteristics. When calculating the parameters of the structure of a bipolar drift transistor, the concentrations at the collector-base (N_{CB}) and emitter-base (N_{EB}) *p-n* junctions are determined for a given avalanche breakdown voltage. The limitation of the minimum base thickness ($W_{B.min}$) is determined by the given value of the voltage of the transistor base puncture and by a certain calculated impurity concentration between the concentrations of N_{CB} and N_{EB}. The calculated impurity concentrations in the base of the drift transistor in the forward and inverse modes of operation differ significantly. The technological experiment was carried out on silicon wafers with two different impurity concentrations in epitaxial structures and with different base thicknesses, as indicated by different values of the current amplification factors both in the direct and inverse connections. The concentration values were determined by calculating N_{CB} and N_{EB} according to the known boron diffusion mode to form the transistor base regions. The depths of *p-n* junctions were determined by the ball-thin section method. The electrical parameters of the transistors in direct and inverse connections were measured on an Л2-56 semiconductor device meter. Based on experimental data, the calculated impurity concentration in the base of the drift transistor is determined from the values of N_{CB} and N_{EB}. The resulting calculation expression can also be used to calculate the base voltage of drift *n-p-n* transistors in the inverse operating mode, the base voltage of switching transistors in I^{2}L elements, as well as to calculate the area of the reverse gradient of ultra-sharp varicaps.

Keywords: Drift transistor, Inverse mode, Puncture voltage.

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1. INTRODUCTION

In bipolar microcircuits, along with typical applications of drift *n-p-n* transistors, these transistors are often used in the inverse mode, in which the breakdown voltage is several times lower than the breakdown voltage during direct switching due to the uneven distribution of impurities in the base of the transistor.

Therefore, in the on-line calculation of the structure of the drift transistor according to the given electrical parameters with respect to the method proposed in [1], it is desirable to simultaneously evaluate the breakdown voltage of the drift transistor in the inverse mode.

2. DESCRIPTION OF THE OBJECT AND RESEARCH METHODS

2.1 Analysis of Recent Research and Publications

Considerable attention is paid to the problem of determining the exact characteristics of *p-n* junctions and semiconductor structures based on them. The studies mainly concern combinations of semiconductor materials used to create semiconductor structures and the influence of various external conditions on their characteristics, including breakdown parameters during inverse switching [2-8]. The real value of the breakdown voltage of bipolar transistors, both in direct and inverse switching, is determined by the smaller of the values of the avalanche breakdown voltage and the puncture voltage of the base when the space charge region (SCR) of the collector *p-n* junction, passing through the base, reaches the emitter region.

The avalanche breakdown voltage of the transistor is determined through the avalanche breakdown voltage of the collector-base *p-n* junction and the gain of the transistor. In addition, when calculating the breakdown voltage in the inverse mode of operation with the avalanche mechanism, it is necessary to take into account the ratio of the emitter and collector areas [9]. And the puncture voltage of the base ($U_{pt} \geq U_{CEO}$) is determined by the thickness of the base of the transistor and the concentration of impurities in the base, according to the formula [10]:

$$U_{pt.} = \frac{W_B^2 \cdot e \cdot N_B}{2 \cdot \varepsilon \cdot \varepsilon_o} - \varphi_K , \qquad (1)$$

where W_B is the base thickness of the bipolar transistor, e is the electron charge equal to $1.6 \cdot 10^{-19}$ C, N_B is the impurity concentration in the base, φ_K is the contact potential difference at the collector *p-n* junction.

On the other hand, if the concentration of the impurity in the base of the transistor is known, then for a given breakdown voltage, one can estimate the minimum required thickness of the base by transforming expression (1):

$$W_{B.\min} \geq \sqrt{\frac{2 \cdot \varepsilon \cdot \varepsilon_o \cdot (U_{pt} + \varphi_K)}{e \cdot N_B}} . \qquad (2)$$

Due to the uneven distribution of the impurity in the base of the drift *n-p-n* transistor in formulas (1) and (2) with direct connection, the calculated average value of the concentration of the impurity in the base N_B is used, which can be estimated by the expression [11]:

$$N_B = N_{B.a} = \exp\left[\frac{\ln\left(N_{EB}\cdot N_{CB}\right)}{2-\dfrac{\ln\left(\dfrac{N_{EB}}{N_{CB}}\right)}{2\cdot\ln N_{EB}}}\right] \qquad (3)$$

where N_{EB} is the impurity concentration at the emitter-base *p-n* junction, N_{CB} is the impurity concentration at the collector-base *p-n* junction, $N_{B.a}$ is the average calculated impurity concentration in the base.

2.2 Purpose of the Study

Usually in transistor-transistor logic microcircuits at the inputs, inverse switching of bipolar transistors is used. In addition, in bipolar logic circuits it is convenient to simultaneously use part of the circuit (input and output stages) on drift *n-p-n* transistors, and the logical part on I^2L elements, which can significantly reduce the current consumption of the chip and the chip area. In order not to complicate the manufacturing technology of such microcircuits, *n-p-n* transistors and I^2L elements have the same structure as drift *n-p-n* transistors, but are used in inverse switching.

In addition, if there is data on the average calculated impurity concentration in the base, formulas (1) and (2) become universal, and they can be used to calculate the puncture voltage of the base or calculate the thickness of the base for any type of bipolar transistor with any inclusion.

Studies have shown that the values of the real puncture voltages of the base of drift *n-p-n* transistors in the inverse inclusion using formula (3) gives values that differ greatly from the calculated ones, although, as expected, the denominator becomes more than 2, since the logarithm of the concentration ratio (N_{EB}/N_{CB}) becomes negative. This is due to the fact that when inversion is turned on, the SCR propagates from the region with a high concentration to the region with a low concentration.

The aim of the work is to obtain an expression for determining the average calculated impurity concentration in the base of drift *n-p-n* transistors when inverted.

3. EXPERIMENTAL

To determine the dependence of the puncture voltages of the base of a bipolar drift transistor in inverse switching, batches of plates were carried out in the following modes of creating the base and emitter regions of transistors.

For the experiment, single-layer epitaxial structures of n-n^+ type (plates No. 1, 2, 3, 4, 5 and plates No. 6, 7, 8, 9) were used.

The base regions of the transistors were prepared after the first photolithography by ion doping with boron at a dose of 12 μC/cm^2 and subsequent acceleration at a temperature of 1150 °C in a gas-vapor medium: 5 min – dry O_2; 25 min – water vapor in the O_2 carrier; 50 min in nitrogen (N_2). Then, the 2nd photolithography was performed under the emitter region. The emitters were created simultaneously on all plates with a diffuser of phosphorus (P) at a temperature of 1040 °C.

Additionally, for plate No. 2, phosphorus (P) was further distilled at a temperature of 900 °C for 18 min, for plates No. 3 and 6 within 33 min, for plates No. 4 and 7 within 45 min, for plates No. 5 and 8 within 55 min, and for plate No. 9 within 60 min.

After the 3rd photolithography, we measured the amplification factors of transistors and breakdown voltages, both for direct and inverse switching. Measurement of electrical parameters was carried out on a parameter meter of semiconductor devices – Л2-56, certified with a measurement error of not more than 5 %. The measurement data are shown in Table 1. Also, the depth of the emitter and collector *p-n* junctions was measured on the test crystals of these plates using the ball-section method, the data are shown in Table 1. For a more accurate determination of the depth of *p-n* junctions, the test crystals were located on the cross (Fig. 1).

The depth of the *p-n* junction was determined as the average value of five measurements and was rounded to 2-3 significant digits. The calculated value of the thickness of the base of the transistor was determined as the difference between the depths of *p-n* junctions.

The real breakdown voltage of a bipolar transistor, both in direct and inverse switching, is determined by a lower value from the base puncture voltage and the avalanche breakdown voltage. If the real breakdown voltage of the transistor is determined by avalanche breakdown, then the base transistor puncture voltage was determined by the value of the extrapolation voltage of the output *I-V* characteristics (U_E is the Earley voltage), since according to [10], the Earley voltage and the base puncture voltage are calculated using the same expressions. For this purpose, the real output *I-V* characteristics of transistors connected with a common emitter were recorded on a parameter meter of semiconductor devices Л2-56, by which the extrapolation voltages were determined (see Fig. 2), the obtained measurement data are also listed in Table 1.

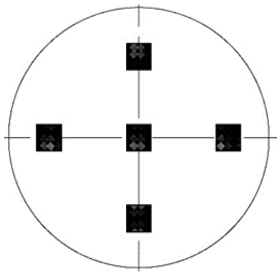

Fig. 1 – Arrangement of test crystals for ball sections on the plate

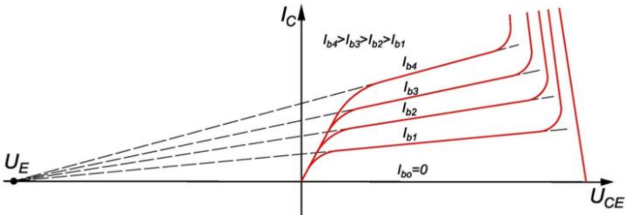

Fig 2 – Determination of extrapolation voltages (Earley voltage U_E) from the output current-voltage characteristics of a bipolar transistor in a circuit with a common emitter

Table 1 – Measurement results

Plate number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
ρ_{el}, Ω·cm	0.3					1.0			
$N_{EB}\cdot 10^{16}$, cm^{-3}	16.6	14.2	11.4	9.0	6.77	11.4	9.0	6.77	4.6
φ_{KE}, V	0.851	0.842	0.833	0.819	0.804	0.833	0.819	0.804	0.784
$N_{Ba(I)}\cdot 10^{16}$, cm^{-3} calculated by (4)	4.1	3.9	3.49	3.32	3.08	1.83	1.6	1.49	1.32
$N_{Ba(I)}\cdot 10^{16}$, cm^{-3} calculated by (5)	4.19	3.93	3.59	3.27	2.93	1.82	1.66	1.46	1.25
Δ, %	+ 2.2	+ 0.8	+ 2.9	– 1.5	– 5.1	+ 0.5	+ 1.2	– 2.0	– 5.6

Table 2 – The results of the calculations

Plate number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
ρ_{el}, Ω·cm	0.3					1.0			
$N_{CB}\cdot 10^{15}$, cm^{-3}	18	18	18	18	18	5.6	5.6	5.6	5.6
x_{jC}, μm	1.76	1.76	1.76	1.76	1.76	2.0	2.0	2.0	2.0
x_{jE}, μm	1.17	1.22	1.29	1.36	1.44	1.29	1.36	1.44	1.55
W_B, μm	0.59	0.54	0.47	0.4	0.32	0.71	0.64	0.56	0.45
Parameters of the transistor in direct connection									
B_N, p.u.	260	350	520	790	1300	480	720	1150	2200
U_{CEO}, V	8.5	7.9	7.1	6.4	3.2	12.5	11.4	8.2	3.6
Inverted transistor parameters									
B_I, p.u.	68	88	136	220	390	45	65	95	180
$U_{CEO(I)}$, V	6.9	6.6	5.4	3.4	1.7	6.5	4.4	2.9	1.35
$U_{E(I)}$, V	10.5	8.2	5.3	3.4	1.7	6.5	4.4	2.9	1.35

If the values of $U_{ECO(I)}$ and $U_{E(I)}$ coincide, the breakdown of the transistor is determined by the puncture effect of the base, and if $U_{ECO(I)} > U_{E(I)}$, then the breakdown of the transistor occurs by an avalanche mechanism.

Using well-known regimes for the formation of base regions and measurements of the depth of *p-n* junctions, the impurity concentrations at emitter-base *p-n* junctions were calculated, and the contact potential difference was determined from the calculated concentration. The calculation data are shown in Table 2.

The average calculated concentration in the base of the drift transistor during inverse switching was determined based on the transformation of expression (1),

$$N_{B.a.(I)} = \frac{2\cdot\varepsilon\cdot\varepsilon_o\cdot(U_{pt(I)}+\varphi_{K(I)})}{e\cdot W_B^2}. \qquad (4)$$

Based on the data shown in Table 1 and Table 2, an expression is determined for calculating the average concentration in the drift of base *n-p-n* bipolar transistor with inverse switching on:

$$N_{B.a.(I)} = \exp\left[\frac{\ln(N_{EB}\cdot N_{CB})}{2+\dfrac{\ln\left(\dfrac{N_{EB}}{N_{CB}}\right)}{3\cdot\left(\ln N_{EB}+4,5\cdot\sqrt{\dfrac{N_{EB}}{\cdot N_{CB}}}\right)}}\right] \qquad (5)$$

$$N_{B.a.I} = \exp\left[\frac{\ln(N_B\cdot N_B)}{2-\dfrac{\ln\left(\dfrac{N_B}{N_B}\right)}{3\cdot\left(\ln N_B+4,5\cdot\sqrt{\dfrac{N_B}{N_B}}\right)}}\right] = \exp\left[\frac{\ln(N_B)^2}{2-\dfrac{\ln(1)}{3\cdot(\ln N_B+4,5)}}\right] = \exp\left[\frac{2\cdot\ln(N_B)}{2-\dfrac{0}{3,3\cdot\ln N_B+4,5}}\right] = N_B \qquad (6)$$

where $N_{B.a.(I)}$ is the calculated average concentration of impurities in the base when the drift *n-p-n* transistor is inverted.

A comparison of the average calculated impurity concentrations in the database calculated by expression (4) and expression (5) shows that the deviation of the calculation results mainly lies within the measurement error (± 5 %). A slight excess of the error is observed for a small base thickness, which is explained by the influence of the SCR of the inverse emitter, the width of which becomes comparable with the base thickness.

With a uniform distribution of impurities in the base, i.e. when $N_{EB} = N_{CB} = N_B$ according to expression (5), it should be obtained: $N_{B.a.(I)} = N_B$ (6). The calculations shown confirm the adequacy of expression (5).

4. CONCLUSIONS

1. The calculated average concentrations of impurities in the base of drift transistors make it possible to use them to create a simple method for the on-line calculation of base puncture stresses, both in direct and inverse operation, even before calculating technological modes and distribution of impurities in the base region.

2. The obtained expression of the average calculated impurity concentration in the base for the inverse switching on of the drift transistor allows one to determine the puncture voltage of the base also for elements of I^2L circuits and other semiconductor silicon structures with an uneven distribution of the impurity in the case when the SCR of the *p-n* junction expands from the region with a higher impurity concentration to an area with a lower concentration. The same impurity distribution is observed in the base of an ultra-sharp varicap with an inverse gradient region.

3. Using expressions (3) and (5), it is possible to estimate the average concentrations of impurities in the region with their non-uniform distribution. This allows the use of simple expressions for calculating the puncture voltage (1) or calculating the minimum base thickness (2) for both bipolar transistors without drift and for transistors with drift, both forward and reverse switching.

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Оперативний розрахунок напруги проколу бази дрейфових *n-p-n* транзисторів в інверсному режимі роботи

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У статті розглянуті питання оперативного розрахунку напруги пробою дрейфових *n-p-n* транзисторів в інверсному режимі роботи при розрахунку параметрів їх структури по заданих електричних параметрах і характеристиках. При оперативному розрахунку параметрів структури біполярного дрейфового транзистора визначаються концентрації на *p-n* переходах колектор-база (N_{CB}) і емітер-база (N_{EB}) по заданій напрузі лавинного пробою. Обмеження на мінімальну товщину бази ($W_{B.min}$) визначається по заданій величині напруги проколу бази транзистора і за деякою розрахунковою концентрацією домішки між концентраціями N_{CB} і N_{EB}. Розрахункові концентрації домішки в базі дрейфового транзистора в прямому і інверсному режимах роботи значно відрізняються. Технологічний експеримент проводився на кремнієвих пластинах з двома різними концентраціями домішки в епітаксійних структурах і з різною товщиною бази, на що вказували різні значення коефіцієнтів посилення по струму як в прямому, так і в інверсному включенні. Величини концентрацій N_{CB} і N_{EB} визначалися розрахунковим шляхом за відомим режимом дифузії бору для формування областей бази транзистора. Глибини *p-n* переходів визначалися методом куль-шліфа. Електричні параметри транзисторів в прямому і інверсному вмиканні вимірювалися на вимірнику параметрів напівпровідникових приладів Л2-56. На основі експериментальних даних розрахункова концентрація домішки в базі дрейфового транзистора визначається за значеннями N_{CB} і N_{EB}. Отриманий вираз розрахунку також може бути використано для розрахунку напружень проколу бази дрейфових *n-p-n* транзисторів в інверсному режимі роботи, напруги проколу бази перемикаючих транзисторів в елементах И^{2}Л, а також для розрахунку області зворотного градієнта надрізьких варікапів.

Ключові слова: Дрейфовий транзистор, Інверсний режим, Напруга проколу бази.