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MISCELLANEA

MODELING OF THE PARAMETERS OF BIPOLAR TRANSISTORS

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A model for calculation of the parameters of a bipolar transistor has been proposed and the regularities of their change in fast thermal treatment of ion-doped silicon layers have been established.

Speed and packing density are the main performance figures of very large-scale integrated circuits. One basic method of increasing these parameters is the principle of proportional scaling, when we have a decrease in both the topological and vertical dimensions of microcircuits, namely, the depth of the base and the emitter and the thickness of dielectric, epitaxial, and current-conducting layers [1].

Since practical implementation of vertical scaling requires a considerable decrease in the depth of *p–n* junctions formed, it is clear that to do this requires a reduction in the diffusional redistribution of the impurity of an ion-doped layer in the process of its electric activation. The use of fast thermal treatment (FTT) in creating very large-scale integrated circuits is preferred for this purpose [2].

The basic limiting factors in vertical scaling are the base-to-collector and collector-to-emitter *p–n* junction electric breakdowns and the punch-through in the *n–p–n* transistor; these phenomena are caused by the avalanche multiplication of carriers in the epitaxial film and by the joining of depletion layers in the base region. Since these phenomena are determined by the doping level and thickness of the corresponding layers, certain requirements are imposed on them.

One basic parameter determining the operating capacity of a transistor is its direct current gain, which must be no less than 80 for an *n–p–n* transistor. This brings up limitations on all the remaining electrical and geometric parameters of the transistors formed. It is well known that such parameters as $U_{\text{c.e}}$, $U_{\text{c.b}}$, and β_{p} are related as follows [3]:

$$U_{\text{c.e}} = U_{\text{c.b}} \left(\frac{1}{1 + \beta_{\text{p}}} \right)^{1/4} . \quad (1)$$

Calculation carried out on the basis of expression (1) has shown that the minimum required value $\beta_{\text{p}} = 80$ is attained under different combinations of $U_{\text{c.e}}$ and $U_{\text{c.b}}$, e.g., for $U_{\text{c.b}} = 9$ V and $U_{\text{c.e}} = 3$ V or $U_{\text{c.b}} = 12$ V and $U_{\text{c.e}} = 4$ V. However, the use of transistors with $U_{\text{c.e}} < 3$ V leads to a degradation of such circuit's parameters as the output voltage and the supply current. This means that the minimum possible breakdown voltages of the *p–n* junctions of a transistor ensuring $\beta_{\text{n}} = 80$ must have the following values: $U_{\text{c.b}} = 9$ V and $U_{\text{c.e}} = 3$ V (Fig. 1).

Using the numerical-simulation method, we consider the influence of the FTT process on the parameters of a bipolar transistor. It is well known that an electric field of strength $E(x)$ appears in the transistor under the action of the voltage applied. Upon the attainment of the maximum value $E_{\max}$ dependent on the voltage applied and the concentration of the carriers in the epitaxial film or in the region of formation of a basic *p–n* junction, an avalanche

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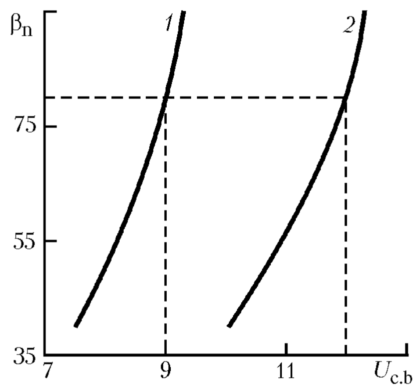


Fig. 1. Direct current gain of the *n–p–n* transistor vs. collector-to-base breakdown voltage: 1) $U_{c.e}$ = 2 and 2) 4 V. $U_{c.b}$, V.

breakdown of a reverse-biased collector-to-base junction occurs. The electric-field strength is described by a Poisson equation which, in a one-dimensional approximation, has the form

$$\frac{\partial E(x)}{\partial x} = e\varepsilon^{-1}\rho(x) . \quad (2)$$

Near the point x of the *p–n* junction, we have a disturbance in the neutrality of charge due to the movement of mobile carriers to the points of application of external stress; in the region of the *p–n* junction, a depletion region appears, in which expression (2) takes the form

$$\frac{\partial E(x)}{\partial x} = e\varepsilon^{-1}N(x) . \quad (3)$$

Since the field strength vanishes at the boundaries of the depletion region (x_u, x_{low}), and the ionization integral is equal to unity, expression (3) may be written in the form

$$\frac{\partial^2 \varphi(x)}{\partial x^2} = e\varepsilon^{-1}N(x) . \quad (4)$$

Multiplying both sides of (4) by x and integrating from x_u to x_{low} on condition that the field strength at the boundaries of the depletion region is equal to 0 and the voltage drop is equal to the potential difference applied, we obtain the expression for the breakdown voltage of the collector-to-base junction

$$U_{c.b} = e\varepsilon^{-1}\int_{x_u}^{x_{low}} xN(x)\,dx . \quad (5)$$

However, despite the simplicity of the integrand of the integral

$$\int_{x_u}^{x_{low}} A\exp\left\{-B[E(x)]^{-1}\right\}dx = 1 , \quad (6)$$

it is poorly specified, has a very sharp maximum at a point of the collector *p–n* junction (x_c), and is fast decreasing with distance from the point x_c. To semianalytically compute the integrand with a high degree of accuracy and in minimum time we expand the exponent in a Taylor series near x_c, restricting ourselves to its first terms:

$$\exp\left\{-B\,[|E\,(x)|]^{-1}\right\} = \exp\left(-BE_{\max}^{-1}\right)\left\{1 + [N'(x_c)\,(x - x_c)]\,(2E_{\max})^{-1}\right\}. \tag{7}$$

Substituting (7) into (6) and integrating from minus to plus, which is possible in view of the very fast drop in the integrand, we obtain the transcendental equation for determination of the maximum strength $E_{\max}$

$$A \exp\,(-BE_{\max}^{-1}) = E_{\max}^{-1}\left\{[B\ |N'(x_c)|\,]\,(2\pi)^{-1}\right\}^{1/2}. \tag{8}$$

After the iterative solution of (8) and determination of $E_{\max}$ by integrating in both directions from the point x_c, we determine the boundaries of the depletion region x_u and x_{low} so that the condition

$$\left|\int_{x_u}^{x_c} N\,(x)\,dx\right| = \left|\int_{x_c}^{x_{low}} N\,(x)\,dx\right| = E_{\max} \tag{9}$$

is fulfilled.

Using (5) we find the avalanche-breakdown voltage; to determine this in the case of the basic *p–n* junction, we must know the impurity distribution in the depletion region and the position of its boundaries in breakdown. Since the first is dependent on the regimes of ion doping of the base, FTT, and epitaxial growth, we consider the influence of these parameters on $U_{c.b}$.

An analysis of the experimental distributions of boron in the base region and antimony in the latent layer by the least-squares method has shown that in the first case the distribution obeys the Gaussian distribution, whereas in the second case it obeys the Fermi distribution:

$$N_{Sb}^{0}\,(x) = \frac{N_{\max} \exp\,[(x - z)\,b^{-1}]}{1 + \exp\,[(x - z)\,b^{-1}]}, \tag{10}$$

$$N_{Sb}\,(x)\Big|_{b=0} = N_{\max} x \geq z\,;\quad N_{Sb}\,(x)\Big|_{b=0} = 0\,,\quad x < z\,. \tag{11}$$

For the chloride-hydride technology of epitaxial growth, which is used in producing thin epitaxial films, we have experimentally determined the value $b = 0.073$ μm. The impurity distribution after the FTT was determined by solution of the equation

$$N\,(x) = D\left\{[2\pi\,(2D^* + \Delta R_p^2)]^{1/2}\,\mathrm{erfc}\,[-R_p\,(\sqrt{2}\,\Delta R_p)^{-1}]\right\}^{-1} \times$$
$$\times \sum_{i=\pm} \exp\left[-(x - iR_p)^2\,(4D^* + 2\Delta R_p^2)^{-1}\right]\mathrm{erfc}\,(-\theta_i)\,, \tag{12}$$

where $\theta_\pm = \left\{\pm x[\Delta R_p^2(2D^*)^{-1}]^{1/2} + R_p[2D^*(\Delta R_p^2)^{-1}]^{1/2}\right\}(4D^* + 2\Delta R_p^2)^{-1/2}$ and $D^* = \sum_{i=1}^{m}\int_0^{t_i} \check{D}\,[T(t)]dt;\ t_i = \tau_i + \tau_i'.$

For boron after ionic doping it is described by the expression [2]

$$N_B^0\,(x, t = 0) = D\,(2\pi\Delta R_p^2)^{-1/2} \exp\left\{-[(x - R_p)\,(\sqrt{2}\,\Delta R_p)^{-1}]^2\right\}, \tag{13}$$

where $R_p = 85.6E^{0.777}$ and $\Delta R_p = 1760E^{0.106} - 1990E^{0.0192}$.

In FTT with M pulses, the impurity distribution in the case of boron takes the following form:

$$N_B(x) = D\,[2\pi\,(\Delta R_p^2 + 2\check{D}M)]^{-1/2} \exp[-(x - R_p)^2\,(2\Delta R_p^2 + 4\check{D}M)^{-1}] \int_0^{\infty} F(z', x)\,dz' +$$

$$+ \exp[-(x + R_p)^2\,(2\Delta R_p^2 + 4\check{D}M)^{-1}] \int_0^{\infty} F(z', -x)\,dz' , \quad (14)$$

where $\check{D} = \int_0^t D(t')dt'$ and $F(z', x) = \exp\left\{-z' + [(x\Delta R_p)(2\check{D}M)^{-1/2} + R_p\,(2\check{D}M\Delta R_p^{-2})^{1/2}](4\check{D}M + 2\Delta R_p^2)^{-1/2}\right\}$, whereas in the case of antimony it appears as

$$N_{Sb}(x) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{+\infty} \exp(-y^2)\,N_{Sb}^0(\gamma y + x)\,dy\,, \quad \gamma = 2\left[M \int_0^t D_{Sb}(t')\,dt'\right]^{1/2} . \quad (15)$$

Since γ is a small quantity, the product γy may be disregarded if the variable x lies in the region not adjacent to z. This condition is fulfilled for $E \geq 60$ keV and an epitaxial-film thickness less than 1.0 μm, and expression (15) may be written as follows:

$$N_{Sb}(x) = \frac{1}{\sqrt{\pi}} N_{Sb}^0(x) \int_{-\infty}^{+\infty} \exp(-y^2)\,dy = N_{Sb}^0(x) . \quad (16)$$

This means that FTT virtually does not change the antimony-distribution profile and consequently we may disregard it.

Thus, the total impurity distribution may be represented as

$$N(x) = N_B(x) - N_{Sb}(x) - N_{e.f} . \quad (17)$$

To study the distinctive features of change in the gain of a common-emitter β_n and common-collector n–p–n transistor β_i in its creation with the use of FTT we consider one-dimensional continuity and transfer equations for minority carriers: holes in the emitter and in the latent layer and electrons in the base for outer potentials not leading to avalanche multiplication. In this case the transfer physics is determined by the slight deviation of the configuration of carriers from a uniform concentration, and the equations have the form

$$\frac{dI}{dx} = e\tau^{-1} f_{min}(x) , \quad (18)$$

$$I = -eD_{min} F \frac{d}{dx}\left\{f_{min}(x)\,[F(x)]^{-1}\right\} , \quad (19)$$

where $F(x) = \left\{n_{intr}^2 \exp[\Delta E_g (kT)^{-1}]\right\}^2 [N(x)]^{-1}$, $n_{intr}^2 = 9.61 \cdot 10^{32} T^3 \exp[-E_g (kT)^{-1}]$.

Equations (18) and (19) must be supplemented with two boundary conditions that will be different for each transistor region (emitter, base, or collector) and for direct and inverse connections. For transistors with micron and submicron depths of p–n junctions, the minority-carrier lifetime may be assumed to be very long, i.e., the right-hand side of Eq. (18) may be considered as a perturbation and the solution of the system of equations (18) and (19) may be sought by the perturbation-theory method with a small parameter τ^{-1}. Then, in the zero approximation in τ^{-1} I = const and with allowance for the fact that the concentration of excess minority carriers is expressed in terms of the voltage U applied to the p–n junction by the relation

$$f_{\min}(x) = F(x)\left\{\exp\left[eU(kT)^{-1}\right] - 1\right\}, \tag{20}$$

we obtain that, in direct connection, the density of the hole current in the emitter is

$$|I_p| = e\left\{\exp\left[eU_{\text{e.b}}(kT)^{-1}\right] - 1\right\} n_{\text{intr}}^2 \left\{\int_0^{x_{\text{e.b}}} \left[(N_p - N_n) D_p^{-1}\right] \exp\left[-\Delta E_{\text{g}}(kT)^{-1}\right] dx\right\}^{-1}, \tag{21}$$

and the density of the electron current in the base is

$$|I_n| = e\left\{\exp\left[eU_{\text{e.b}}(kT)^{-1}\right] - 1\right\} n_{\text{intr}}^2 \left\{\int_{x_{\text{e.b}}}^{x_{\text{c.b}}} \left[(N_n - N_p) D_n^{-1}\right] \exp\left[-\Delta E_{\text{g}}(kT)^{-1}\right] dx\right\}^{-1}. \tag{22}$$

Consequently, the current gain in the common-emitter circuit will be

$$\beta_n = \frac{I_n}{I_p}. \tag{23}$$

In inverse connection, the density of the electron current in the active base is equal to

$$|I_{na}| = en_{\text{intr}}^2 \exp\left[eU_{\text{c.b}}(kT)^{-1}\right]\left\{\int_{x_{\text{e.b}}}^{x_{\text{c.b}}} \left[(N_n - N_p) D_n^{-1}\right] \exp\left[-\Delta E_{\text{g}}(kT)^{-1}\right] dx\right\}^{-1}, \tag{24}$$

and in the passive one, it is

$$|I_{np}| = en_{\text{intr}}^2 \exp\left[eU_{\text{c.b}}(kT)^{-1}\right] \times$$

$$\times \left\{\int_0^{x_{\text{c.b}}} \left[(N_n - N_p) D_n^{-1}\right] \exp\left[-\Delta E_{\text{g}}(kT)^{-1}\right] dx + N_n(0) \exp\left[-\Delta E_{\text{g}}(kT)^{-1}\right] V_{\text{b}}^{-1}\right\}^{-1}. \tag{25}$$

The density of the hole current in the transition region of the latent layer is determined by the expression

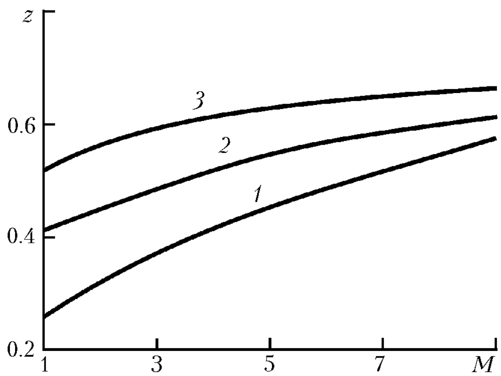
$$|I_{p\text{lat.layer}}| = en_{\text{intr}}^2 \exp\left[eU_{\text{c.b}}(kT)^{-1}\right] \times$$

$$\times \left\{\int_{x_{\text{e.b}}}^{x_{\text{c.b}}} \left[(N_p - N_n) D_n^{-1}\right] \exp\left[-\Delta E_{\text{g}}(kT)^{-1}\right] dx + N_p(h) \exp\left[-\Delta E_{\text{g}}(kT)^{-1}\right] (V'_{\text{lat.layer}})^{-1}\right\}^{-1} \times$$

$$\times \left\{1 + N_p(h) \exp\left[-\Delta E_{\text{g}}(kT)^{-1}\right] (V'_{\text{lat.layer}})^{-1} \int_{x_{\text{e.b}}}^{x_{\text{c.b}}} \exp\left[-\Delta E_{\text{g}}(kT)^{-1}\right] \left[\tau(x) N_p(x)\right]^{-1} dx\right\}. \tag{26}$$

In this case the gain in the common-collector circuit will be described by the expression

$$\beta_{\text{i}} = S_{\text{e.b}} I_{na} \left[(S_{\text{c.b}} - mS_{\text{e.b}}) I_{n\text{p}} + S_{\text{c.b}} I_{p\text{lat.layer}}\right]^{-1}. \tag{27}$$



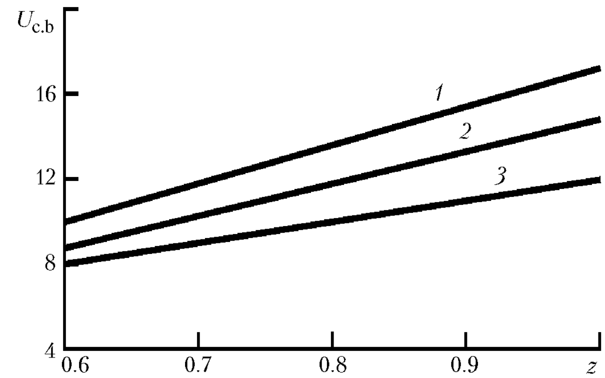


Fig. 2. Depth of the base vs. number of FTTs for different energies of its doping (D_d = 6.5 μC/cm^2): 1) 20, 2) 60, and 3) 80 keV. z, μm.

Fig. 3. Collector-to-base breakdown voltage vs. epitaxial-layer thickness for different energies of boron doping of the base (D_d = 6.5 μC/cm^2): 1) 20, 2) 60, and 3) 80 keV. $U_{c.b}$, V. z, μm.

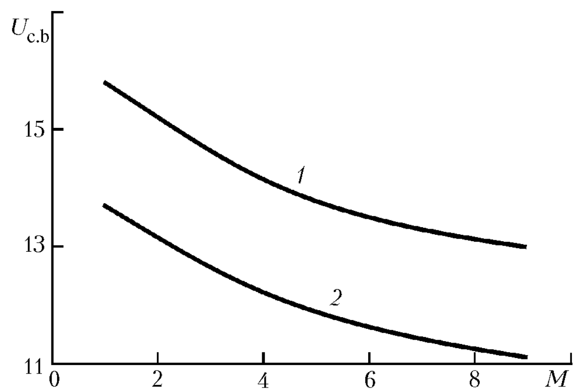


Fig. 4. Collector-to-base breakdown voltage vs. number of FTTs for different energies of boron doping of the base (D_d = 6.5 μC/cm^2): 1) 60 and 2) 80 keV. $U_{c.b}$, V.

It is noteworthy that (21)–(26) involve the parameter ΔE_g which characterizes the narrowing of the energy gap for high doping layers and is a quantity determinable experimentally and dependent on the impurity concentration. In our case the narrowing of the energy gap correlated with the Mott transition.

Numerical modeling has enabled us to establish the following regularities. When thin epitaxial layers (0.6–1.0 μm) are used, the base p–n junction is formed in the transition layer epitaxial film–latent n^+ layer; increase in both the energy and the doping dose leads to an increase in the depth of formation of the p–n junction. Decrease in the thickness of the epitaxial film causes the p–n junction depth to decrease for constant regimes of doping of the base. The reason is that, when the impurity distribution in the base is preserved, the concentration of the carriers in the region of formation of the base junction grows and consequently its depth decreases. Increase in the number of FTTs leads to growth in the depth of the base (Fig. 2); the energy of its doping increases with decrease in the impurity redistribution. The reason is that the concentration of the carriers in the region of the p–n junction grows with doping energy; as a consequence, the diffusion coefficient of boron decreases, which causes the impurity redistribution to decrease. The regularities enumerated above lead to a reduction in $U_{c.b}$.

The main reason for such a functional dependence of the base-to-collector breakdown voltage on the technological parameters is the proximity of the latent n^+ layer to the base, since in this case a charge gradient exists in the depletion region, which leads to the presence of strong electric fields affecting $U_{c.b}$. These calculations have enabled us to establish that to ensure $U_{c.b} \geq 9$ V the carrier concentration in the epitaxial layer or in the region of the base

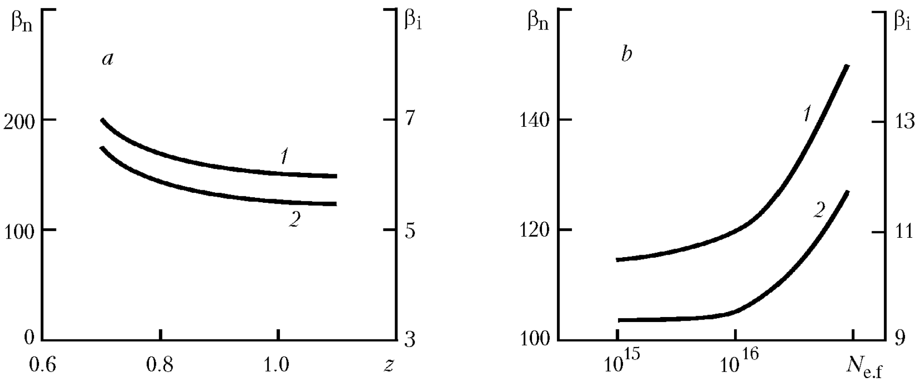


Fig. 5. Direct (1) and inverse (2) current gains of the *n–p–n* transistor vs. thickness of the epitaxial film (a) and concentration of charge carriers in it (b). μm; $N_{e.f}$, cm^{-3}.

p–n junction must satisfy the condition $N \leq 10^{17}$ cm^{-3} (Fig. 3), and the minimum thickness of the epitaxial film must be 0.6 μm (Fig. 4) for an energy of doping of the base of 50 keV.

Calculation of the gains β_n and β_i as functions of the thickness of the epitaxial layer and the layer of its doping and the regimes of formation of the base and the emitter with the use of FTT has enabled us to draw the following conclusions. Increase in the thickness of the epitaxial film (Fig. 5a) and decrease in the concentration of carriers in it (Fig. 5b) lead to a reduction in the gain of a bipolar transistor, which is caused by the decrease in the concentration of carriers in the region of the base *p–n* junction. For an epitaxial-film thickness of more than 1 μm the base *p–n* junction is in the epitaxial film with a constant concentration of carriers of 10^{16} cm^{-3}; it is no longer in the transition region of the latent layer; therefore, further increase in the film thickness does not cause the gain to change. Growth in the direct and inverse gains with decrease in the dose and energy of doping of the base and with increase in the dose and energy of doping of the emitter is caused by the decrease in the width of the active base, the increase in the emitter efficiency, and the reduction in the time of transit of the carriers through the base. Growth in the amplifying properties of the *n–p–n* transistor with increase in the density of the incident-radiation power and decrease in the reflection coefficient of the irradiated surface is related to the increase in the temperature of the treated wafer and consequently to the increase in the impurity redistribution, which is the strongest in the emitter region.

NOTATION

A and *B*, constant quantities equal to $7.03 \cdot 10^5$ cm^{-1} and $1.231 \cdot 10^6$ cm^{-1} respectively; *D*, diffusion coefficient, cm^2·sec^{-1}; D_{min}, diffusion coefficient of minority carriers, cm^2·sec^{-1}; D_d, doping dose, μC/cm^2; *E*, electric-field strength, V·m^{-1}; E_g, energy gap width (energy gap), eV; *e*, electron charge; $F(x)$, equilibrium concentration of carriers, cm^{-3}; f_{min}, nonequilibrium concentration of minority carriers, C; *h*, transition-layer thickness, μm; *I*, current density, A·cm^{-2}; *k*, Boltzmann constant, eV/^{o}C; *M*, number of pulses; *m*, number of emitters; *N*, concentration of the impurity, cm^{-3}; $N'(x_c)$, derivative of distribution of the implanted impurity at the point x_c; $N_{e.f}$, concentration of carriers in the epitaxial film, cm^{-3}; n_{intr}, intrinsic concentration of charge carriers, cm^{-3}; R_p, projection of the ion path, nm; ΔR_p, standard deviation of the projection of the ion path, nm; *S*, area of the *p–n* junction, μm^2; *T*, temperature, ^{o}C; t_i, total time of one *i*th treatment, sec; *U*, voltage, V; V_b, rate of recombination of electrons on the base contact, sec^{-1}; $V'_{lat.layer}$, rate of recombination of holes on the latent-layer surface, sec^{-1}; *x*, running coordinate; *y*, integration variable; *z*, thickness of the epitaxial layer, μm; β, gain; ε, dielectric constant, F·m^{-1}; $\rho(x)$, electric charge at the point *x*, C; τ, lifetime of minority charge carriers, sec; τ_i, time of one *i*th treatment, sec; τ'_i, time of cooling of the silicon wafer after the *i*th process of FTT, sec; φ, electric potential, V. Subscripts and superscripts: a, active; b, base, c, collector; c.b, collector-to-base; c.e, collector-to-emitter; d, doping; p, passive; lat. layer, latent layer; intr, intrinsic; min, minority charge carriers; e.b, emitter-to-base; e.f, epitaxial film; i, inverse connection of the transistor; u, upper boundary; low, lower boundary; max, maximum value; n, normal connection of the transistor; *n*, electronic (*n*-type) conduction; *p*, hole (*p*-type) conduction; g, gap.

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