Transient Effects on High Voltage Diode Stack under Reverse Bias

V. Papež
Czech Technical University in Prague, Technická 2, Prague 6, CR

B. Kojecký, J. Kožíšek
POLOVODIČE, a.s., Novodvorská 138a, Prague 4, CR

J. Hejhal
student
Czech Technical University in Prague, Technická 2, Prague 6, CR

Abstract

This article deals with a description and analysis of the fast transient processes which can occur during a local non-destructive breakdown in a circuit arranged by serial connection of reverse biased high-voltage silicon diodes. The existence of the non-destructive breakdown was observed at some measurements of reverse current-voltage characteristics of individual diodes. However, the study of this phenomenon is very difficult for many serial connected diodes in stack. That is why, a physical model was created for reflection of individual local breakdown in this case. Validity of this model was verified by means of circuit simulation of the investigated process. Further, statistical significance of this process was considered with respect to reliability and lifetime of high-voltage diode stack (HVDS).

Keywords: silicon diode, local breakdown, microplasma, physical model, circuit simulation

List of symbols

C_D	capacity of space charge region (SCR)	F
i_a	avalanche current	A
i_C	capacitive current	A
i_D	total diode leakage current	A
i_d	diffusion current	A
i_{rg}	generation current	A
N	number of serial connected diodes	-
N_C	number of cycles	-
N_D	density of donors	m^{-3}
n_i	intrinsic density of carriers	m^{-3}
P	probability	-
Q_a	avalanche charge	C
q	electron charge	C
R	resistor	Ω
S_D	PN junction area	m^2
t	time	s
V_A	applied voltage	V
V_D	reverse voltage drop of diode	V
V_n	reverse voltage of diode in chain	V
V_R	voltage drop of resistor	V
v_s	saturation velocity	$m.s^{-1}$
x	coordinate	m
x_0	SCR wide before avalanche	m
x_D	SCR wide as a function of time	m
ε	relative permittivity	Fm^{-1}
ε_0	permittivity of vacuum	Fm^{-1}
λ	parameter of the Poisson distribution	-
τ_{SC}	lifetime of carriers in SCR	s

1. Introduction

The presence of micro-defects and inhomogeneities in semiconductor silicon often affects the behaviour of PN junction under reverse bias. Sufficiently high local maximum of electric field due to an appearance of current filaments (microplasmas) or effects referred as second breakdown (mesoplasmas). Both this effects are known long-time and described in detail [1 - 4].

The origin of microplasma is bound together with local avalanche breakdown. High electric field causes an avalanche multiplication of electrons and holes which traverse through the space charge region (SCR) and transform a distribution of original electric field. Simultaneously, the temperature of breakdown place increases. Both these processes (decreasing of the electric field, increasing of the temperature) evoke switching off of the avalanche and the diode reverse voltage is restored again.

The total process consists of two phases:

- avalanche's origin and switching off (order 1 ns duration)
- restoration of the origin state (order 1 ms duration).

If the reverse voltage does not decrease or, on the contrast, increases, the process described above is repeated after any time.

On the basis of physical analysis it is possible to study processes connected with the microplasma occurrence for one diode and simple electric circuit. A solution of more complicated responses in real circuit requires a means of standard circuit analysis. The device and its microplasma - process are performed by substitute circuit so that possible inaccuracy is generally acceptable.
This way allows to anticipate the behaviour of the circuit consisted of a number of devices. Moreover, a measure of influence of the other components in the circuit can be judged so that results of measurement are correctly interpreted.
Physical model and circuit simulation commonly give a possibility to create a picture of avalanche breakdown response in high voltage diode stacks (HVDS). These devices are often used in electrostatic fly-ash separators at a thermal power plants or at a diagnostics X-ray equipments. Reverse voltage of HVDS exceeds 100 kV usually and direct measurement of some electric parameters is very difficult.
The results of the both physical analysis and circuit simulation yield important information as to the function reliability and lifetime of HVDS.

2. Theory

2.1 Physical model

At first, a local avalanche process and its response will be investigated for an individual diode (see Fig. 1). The generation of avalanche charge, its moving through the SCR and shift of charge neutral boundary is shown in Fig. 2.

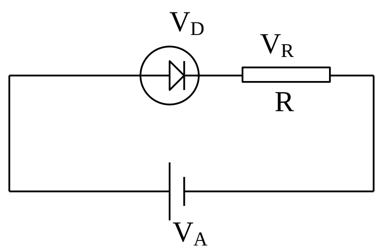

Fig. 1: Simple circuit for physical analysis

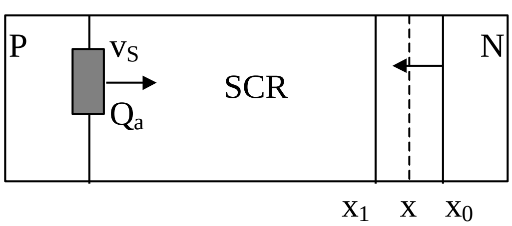

Fig. 2: Scheme of local avalanche breakdown

Avalanche charge Q_a is transported through the SCR and its velocity is v_s (saturation velocity is equal $1.10^5 ms^{-1}$ [5]). A recombination of the carriers is negligible during their transport. Total reverse current of the diode during the avalanche is composed by avalanche current i_a, by generation current i_{rg} and by diffusion current i_d. To simplify situation, we can put $i_a \gg i_{rg} + i_d$. Then equation describing avalanche process has the form

$$\frac{Q_a . v_s}{x} + S_D . q . N_D . \frac{dx}{dt} = \frac{V_R}{R} . \qquad (1)$$

A solution of the Poisson equation for abrupt asymmetrical PN junction can be written like

$$x = \sqrt{\frac{2\varepsilon\varepsilon_o V_D}{qN_D}} . \qquad (2)$$

Further, for any time it must be valid

$$V_A = V_D + V_R , \qquad (3)$$

or

$$\frac{dV_D}{dt} = -\frac{dV_R}{dt} . \qquad (3')$$

Combining Eq. 2 and 3 with Eq. 1 we give

$$-\frac{dV_D}{dt} = \frac{a}{b} - \frac{(V_A - V_D)}{b.R} . \sqrt{V_D} , \qquad (4)$$

where

$$a = Q_a . v_s . \sqrt{\frac{qN_D}{2\varepsilon\varepsilon_o}} , \qquad b = S_D . \sqrt{\frac{\varepsilon\varepsilon_o qN_D}{2}} .$$

The solution of Eq. 4 will be substantially simplified if we put

$$\sqrt{V_D} \approx \sqrt{V_A} . \qquad (5)$$

In other words, the change of the diode voltage is relatively small in comparison with the state before avalanche.
Then, we can write for $\Delta V_D = V_A - V_D$

$$\Delta V_D = \frac{a.R}{\sqrt{V_A}} \left(1 - e^{-\frac{\sqrt{V_A}}{b.R} . t} \right) \qquad (6)$$

with respect to the fact that $V_D \gg V_R$.
After finish of avalanche process, the diode comes back to its former state. Total reverse current may be expressed as

$$i_D = i_C + i_{rg} + i_d , \qquad (7)$$

where i_{rg} is given by known relation

$$i_{rg} = S_D \frac{n_i q . x}{\tau_{sc}} \qquad (8)$$

and diffusion current i_d is constant. Because the change of i_{rg} is also small, then

$$i_r = i_{rg} + i_d = const. \qquad (9)$$

Similar consideration is reasonable for the dynamic capacitance of PN junction (given by the SCR width)

$$C_D = S_D.\left(\frac{1}{2} qN_D \varepsilon\varepsilon_o\right)^{\frac{1}{2}}.V_D^{-\frac{1}{2}} = const. \qquad (10)$$

Restored process can be described by equation

$$C_D.\frac{dV_D}{dt} + i_r = \frac{V_R}{R}. \qquad (11)$$

Solving Eq. 11 we have

$$\Delta V_D = R\left(\frac{V_{RO}}{R} - i_r\right).e^{-\frac{t}{C_D.R}} + i_r R, \qquad (12)$$

where V_{R0} is the voltage drop on the resistor R immediately after finish of the avalanche process. Now, the situation will be discussed when the local reversible breakdown occurs in any diode belonging to a chain of N devices. In other words, (N-1) serial connected diodes are added in Fig. 1.

Avalanche process can be expressed by equation

$$\frac{Q_a v_s}{x} + C_D.\frac{dV_D}{dt} = C_D.\frac{dV_n}{dt} \qquad (13)$$

and for voltage distribution it is valid

$$V_A = V_D + (N-1).V_n, \qquad (14)$$

where V_n is average voltage drop on any diode of the chain and V_D, V_n » V_R.

Then, Eq. 13 may be transformed as

$$-C_D.\frac{dV_D}{dt}\left(1 + \frac{1}{N}\right) = \frac{Q_a v_s}{\sqrt{V_D}}.\sqrt{\frac{qN_D}{2\varepsilon\varepsilon_o}} \qquad (15)$$

and for N » 1 it is

$$\sqrt{V_D}.dV_D = \frac{Q_a.v_S}{C_D}.\sqrt{\frac{qN_D}{2\varepsilon\varepsilon_o}}.dt. \qquad (15')$$

For t = 0 it is $V_D = V_A/N$ and solution of Eq. 15 is in the form

$$\Delta V_D = \frac{V_A}{N} - \left[\left(\frac{V_A}{N}\right)^{\frac{3}{2}} - \frac{3}{2}.\frac{Q_a.v_s}{C_D}.\sqrt{\frac{qN_D}{2\varepsilon\varepsilon_o}}.t\right]^{\frac{2}{3}} \qquad (16)$$

or in simplified relation

$$\Delta V_D = \frac{V_A}{N} - [A - B.t]^{\frac{2}{3}}, \qquad (16')$$

where

$$A = (V_A / N)^{\frac{3}{2}} \quad and \quad B = \frac{3}{2}.\frac{Q_a.v_s}{C_D}.\sqrt{\frac{qN_D}{2\varepsilon\varepsilon_o}}.$$

Immediately after switching off of the avalanche process, the total voltage is divided between the diode after breakdown and other diodes in the chain. This can be expressed by means of SCR widths (resulting from Poisson equation).

$$x_D^2 + (N-1).x_n^2 = N.x_o^2, \qquad (17)$$

where x_D is SCR wide of the diode after avalanche, x_n is SCR wide of any other diode and x_0 is the same parameter before start of breakdown.

Because

$$\frac{dx_n}{dt} = -\frac{x_n}{(N-1).x_o}.\frac{dx_D}{dt} \qquad (18)$$

and the current flowing through all diodes is the same, we can write

$$qN_D.\frac{dx_D}{dt} + \frac{n_i q x_D}{\tau_{sc}} = -\frac{qN_D.x_D}{x_o(N-1)}.\frac{dx_D}{dt} + \frac{n_i q x_o}{\tau_{sc}} \qquad (19)$$

If N » 1, Eq. 19 has the form

$$\frac{dx_D}{(x_o - x_D)} = C.dt, \qquad (20)$$

where $C = \frac{n_i q}{qN_D \tau_{sc}}$.

Solving Eq. 20 we get

$$x_D = x_o\left(1 - e^{-C.t}\right) + x_{D0}, \qquad (21)$$

where x_{D0} is SCR wide immediately after end of avalanche.

Transformation of the x_D to the V_D by means of Poisson equation gives (after small correction)

$$\Delta V_D = \Delta V_{D0}.e^{-C.t}, \qquad (22)$$

where ΔV_{D0} is the voltage difference before start and after end of the avalanche process.

The concrete picture of physical analysis can be made only by means of characteristic parameters of the tested diode chips and relevant physical magnitudes:

$qN_D = 10$ Cm^{-3},	$S_D = 5.10^{-5}$m^2,
$\varepsilon\varepsilon_o = 1.10^{-1}$Fm^{-1},	$qn_i = 1.$Cm^{-3} (125°C),
$C_D = 10$ pF,	$\tau_{SC} = 5.10^{-5}$s,
$v_S = 1.10^5$ms^{-1}	R = 10 kΩ
N = 80	$Q_a = 2.10^{-10}$C

Then, we can calculate the values ΔV_D and time constants in Eq. 6, 12, 16, 22.

For Eq. 6 and t = 2 ns is

$$\Delta V_D = 19{,}8V, \qquad \frac{\sqrt{V_A}}{b.R} = 1.10^7\, s^{-1}.$$

For Eq. 12 is

$$\Delta V_{R0} = 19{,}8V, \qquad \frac{1}{C_D.R} = 1.10^7\, s^{-1}.$$

For Eq. 16 and t = 2 ns is

$$\Delta V_D = 20{,}1V, \qquad B = 6{,}71.10^{11} s^{-1}.$$

For Eq. 22 and τ = 50 μs

$$\Delta V_{D0} = 20{,}1V \qquad C = 2.10^3 s^{-1}.$$

It is evident, the voltage drop is the same for both cases (individual diode or diode chain). The value of voltage drop is about 1 % of the diode reverse voltage, but the time constants of restored process are very different (5.10^3x).

2.2 Circuit simulation

According to the results of physical analysis performed above the breakdown process generates only small change of the diode reverse voltage. Under these conditions, the diode (generally non-linear element) may be approximated by linear substitute circuit created by a parallel combination of a resistor and capacitor. The magnitude of resistor is given by the ratio of reverse voltage and corresponding current in the diode work point, the magnitude of capacitor is near to PN - junction capacitance at choiced reverse voltage. Microplasma forming process is simulated by current source, which generates trapezoidal current pulse. The charge of this pulse - current integral along the time - is equal to microplasma discharge and the duration of discharge is equal to length of pulse.
Convenience of the diode representation by substitute circuit was judged by means of comparison with results of physical analysis.
The circuit in Fig. 1 is replaced by circuit shown in Fig. 3, the shape of initiating current pulse is in Fig. 4. The time dependencies of the breakdown responses received by means of both the physical and circuit analysis for parameters R = 10 kΩ, R_D = 10 MΩ and C_D = 10 pF are shown in Fig. 5. Their maximum mutual deviation is about 3 %.

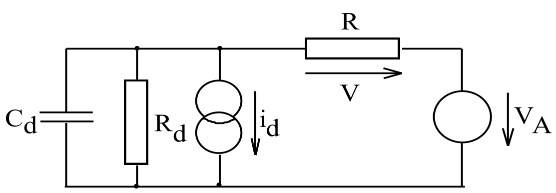

Fig. 3: Individual diode in simulated circuit

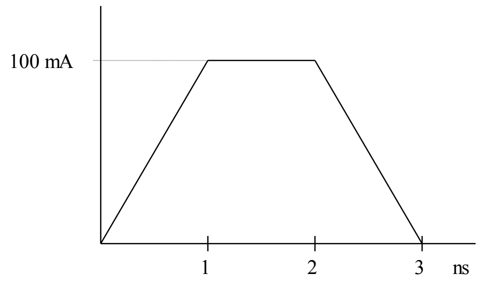

Fig. 4: Simulated shape of the current pulse at breakdown

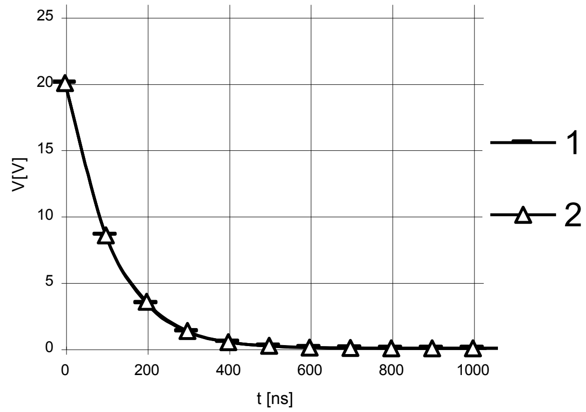

Fig. 5: Calculated dependencies of the voltage change after finish of breakdown (physical analysis 1 vs. circuit computer simulation 2)

3. Experimental

All presented measurements have been carried out on diode chips used for commercial production of HVDS, type DV 808 (made by Polovodiče, a.s., CR). DV 808 contains 80 pcs of serial connected diode chips inside ceramic column and its maximum repetitive reverse voltage is 160 kV. The diode chips are dipped in silicon oil, working temperature of PN-junction is 125°C. The individual diode chip is constituted by silicon slice 370 μm thick, with diameter 5 mm. Specific resistivity of basic silicon is 87 Ωcm, PN junction depth is 85 μm. Silicon wafer is contacted by Mo-electrodes on both sides. This sandwich is soldered to Cu-saucer covered by Ni-layer. Periphery of PN-junction is protected by silicon rubber.
The measurement of reverse characteristics was carried out at 125°C, tested diodes were dipped in thermostatic bath filled by silicon oil. Power supply of dc voltage allowed an regulated rate of rise of total dc voltage in interval 1-100 s, the value of diode serial resistor R was 10 kΩ. The course of reverse current-voltage characteristics was monitored by oscilloscope Agilent 54622A. Examples of reverse current - voltage characteristics are shown in Fig. 6 a, b, a detail of the reversible breakdown is in Fig. 7.

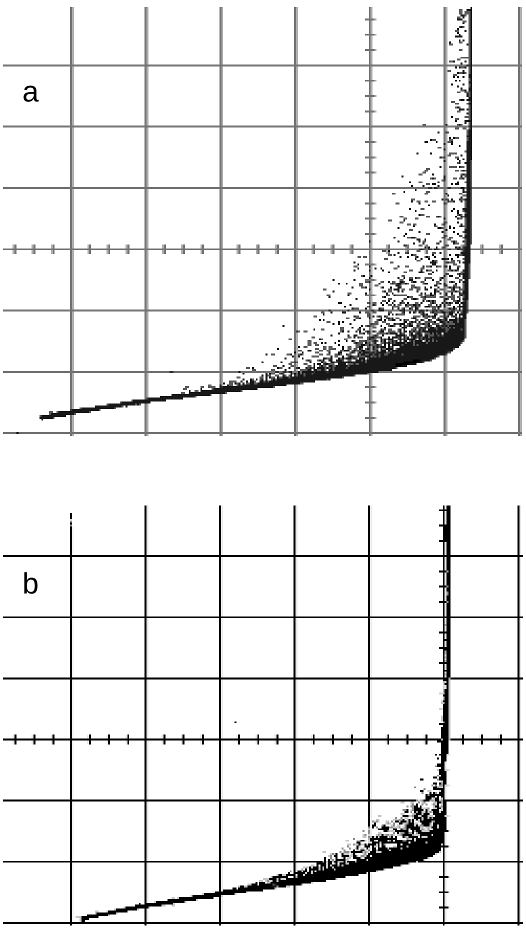

Fig. 6a, b: Examples of experimental I - V reverse characteristics (with breakdown noise); repeated frequency is 0,02 Hz, time measurement about 100 s
x - axe: reverse voltage (500 V/div)
y - axe: reverse current (100 μA/div)

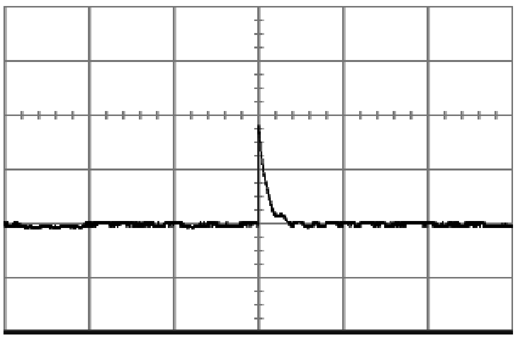

Fig. 7: Detail record of breakdown pulse (I - V characteristics in Fig. 6a)
x - axe: indicated voltage (2 V/div)
y - axe: time (5 μ s/div)

Repeated measurements showed that long time average frequency of current peaks (Fig. 6 a) is about 10 s^{-1} at the reverse voltage 2 000 V. Further, it was confirmed a total disappearance of these peaks if the chips were dried several hours above temperature 200°C immediately before measurement (standard operation made by producer).

4. Discussion

a) <u>Accordance between physical model and circuit simulation</u>

The results of physical analysis indicate that the reverse voltage drop during reversible local breakdown is the same for both individual diode and any diode in serial chain. It is especially evident if the Eq. 16´ is transformed in form

$$\frac{d\Delta V_D}{dt} = \frac{2}{3} B . \left(\frac{V_A}{N} \right)^{-\frac{1}{2}} \qquad (23)$$

for t → 0 and

$$\Delta V_D = \frac{d\Delta V_D}{dt} . \Delta t \, , \qquad (24)$$

where Δt is avalanche charge transit time through SCR. For sufficiently small Q_a (1.10^{-10} - 1.10^{-9}C) the value of ΔV_D is 10 - 100 V and it is not affected by other circuit parameters.
The comparison of time constants in Eq. 16 and Eq. 22 shows the fundamental influence of circuit parameters on restored process. It is many times slower in serial chain of diodes in comparison with one individual diode.
To explain the shape of the pulse in Fig. 5, it is necessary to consider some influence of real circuit. The response of microplasma discharge reflects a parasitic capacitances in circuit, especially the capacitance of connecting shielding cables. Substitute schema of measuring circuit is shown in Fig. 8.

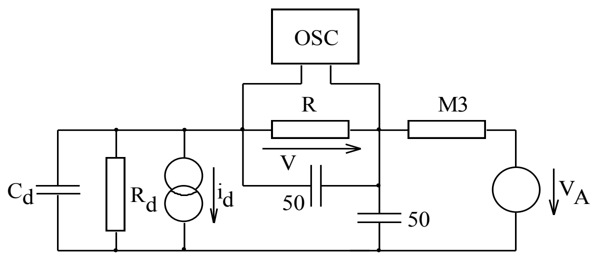

Fig. 8: Substitute scheme of measuring circuit

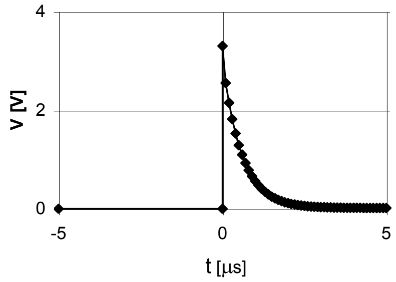

Fig. 9: Calculated dependence of the indicated voltage in measuring circuit (compare with Fig. 7)

The circuit is completed by two capacitors (50 pF) which represent parasitic capacitances. Calculated time dependence of the voltage indicated by oscilloscope input during microplasma breakdown is shown in Fig. 9, the same real dependence recorded by oscilloscope is in Fig. 7. Both dependencies exhibit very good accordance. Comparison between individual diode and the diode in real measuring circuit shows smaller change of voltage and longer time of discharge decay caused by both circuit capacitances.
Substitute schema of the diode chain is in Fig. 10. Simple diode circuit was completed by further diodes. These diodes are represented by parallel combination of resistor and capacitor with the values corresponding to total combination of substitute resistance and capacitance of the diode chain. Resulting course of simulation for 11 diodes in chain is in Fig. 11.

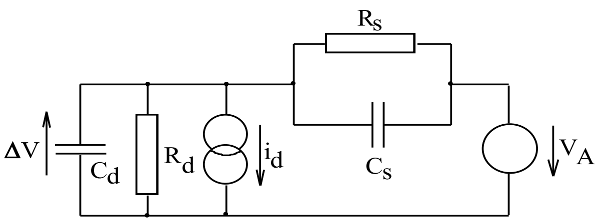

Fig. 10: Substitute circuit for HVDS

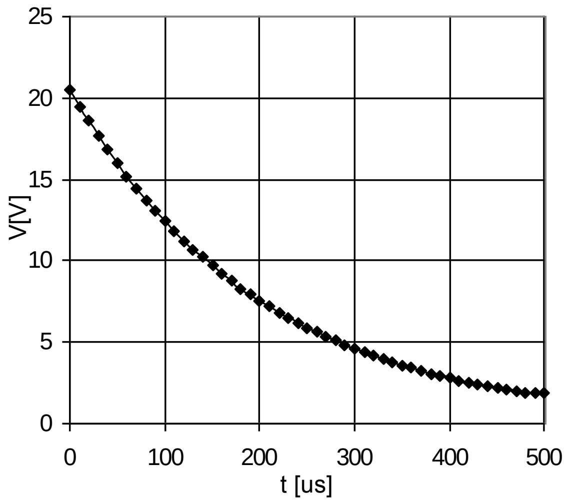

Fig. 11: Resulting course of simulation for 11 diodes in chain.

The time response is relatively long in this case. It corresponds to long time constant in the active diode circuit, which is not influenced by high loading impedance created by other serial diodes. The voltage decreasing is relatively small and it cannot cause any damage of other diodes.

The response course described above is valid for chain combining much more diodes, because the total impedance is determined by parallel combination of individual diode impedance (C_D + R_D) and resulting impedance of remaining passive diodes in chain (C_S + R_S).
The chain impedance is much greater than the impedance of any individual diode (N-times) and its time constant has the same value like time constant of one diode. That is why, the time constant of whole transient process is the same and doesn't depend on number of diodes. Only the value of maximum voltage drop can be variable, its value is increased about 10 % for great number of serial diodes in comparison with Fig. 11.

b) <u>Lifetime and reliability</u>

Many times repeated local breakdown can cause a destruction of device after long time. Material dilatations evoked by fast change of temperature initiate mechanical cracks. A number of temperature cycles N_C causing a damage of device can be expressed in form [6]

$$N_C = \left(\frac{300}{\Delta T}\right)^9 \qquad (25)$$

where ΔT is a local increasing of temperature (°C) during 1 cycle.
If a surface of the microplasma discharge is typically about 50 μm^2 [2], then for V_D = 2 000 V and i_a = 100 mA (situation discussed above), loss energy in silicon is about 4.10^{-7} J and temperature increasing of the avalanche region is about 24,5°C. Using Eq. 25 we receive average lifetime of device - 19,6 years for average frequency of breakdowns 10 s^{-1}.
However this approximate calculation does not include the situation when a next microplasma discharge is initiated sufficiently fast after previous discharge. This is implicated by the statistical nature of process. Then, the value ΔT in Eq. 29 can be increased and, on the other hand, number of cycles N will come down.
To judge a significance of this possibility, it is useful to make a calculation of the time needful for cooling down of microplasma region back to temperature of the surrounding Si.
Let us consider a silicon wafer which has both its sides kept on a constant temperature. Suddenly, very small local heat source - microplasma - appears inside the wafer (during order of 1 ns). A generated heat is conducted out gradually. Let the microplasma region has a cylinder form with a base radius <u>a</u> (see Fig. 12).

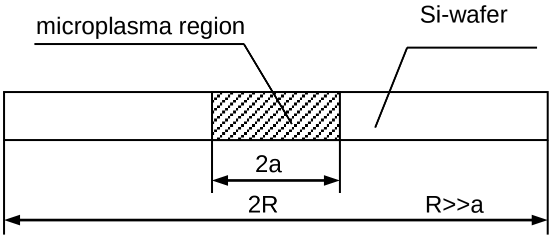

Fig. 12: Silicon wafer with microplasma "hot spot"

The cooling down of microplasma region is described by equation of heat conduction. The solution for this case has following form [7]

$$\frac{T-T_0}{T_m-T_0}=\frac{1}{2}\left[erf\,\frac{a+x}{2\sqrt{(K/\rho.C_P)t}}+erf\,\frac{a-x}{2\sqrt{(K/\rho.C_P)t}}\right] \quad (26)$$

where:

T is actual temperature in x-point for time t
T_m is maximum temperature during microplasma origin
T_0 is the temperature before microplasma origin
K is the thermal conductivity, of Si
C_P is the specific heat of Si
ρ is the density of Si.

Let's estimate the time needful for temperature decreasing to 10 % of maximum temperature value T_m in the centre of microplasma region (x = 0).
Then, there is

$$erf\,\frac{a}{2\sqrt{(K/\rho.C_P)t}}=0{,}100 \quad (27)$$

and

$$\frac{a}{2\sqrt{(K/\rho.C_P)t}}=0{,}089\;. \quad (28)$$

Calculated time t is equal to 6 μs for a =4 μm.
If the microplasma will appear during this time again (in the same place), the number of cycles N necessary for device destruction will be lower.
To estimate the probability P of 6 μs co-incidence of the two discharges, the Poisson distribution can be used

$$P=e^{-\lambda}.\frac{\lambda^k}{k!} \quad (29)$$

where $\lambda = \mu\,.\,t$, μ is average long time frequency of any phenomenon and k is number of this phenomenon during time interval t.
If μ = 10 Hz, t = 6 μs and k = 2, then

$$P=1{,}8.10^{-9}\,. \quad (30)$$

It means, this situation is realised with time period equal to 0,5 year. That is why, an influence of repeated discharge co-incidence on device lifetime may be neglected.

5. Conclusions

The physical analysis and complement circuit simulation were carried out for diode exhibiting transient local breakdown (origin of microplasma) in situations as follows:

- individual diode with serial resistor (analysis and measurement)
- serial chain of many diodes (prognosis).

In the first case, both physical analysis and circuit simulation were compared with experimental dependencies. The very good accordance was found among all these ways. It was shown that

- decreasing of the reverse voltage drop during local breakdown is the same for individual diode or for diode serial chain; the transient reduction of the reverse voltage is about 1 %;
- duration of local breakdown is order of 1 ns, duration of restored process is order of 1 ms for diode situated in serial chain;
- repeated origin of microplasma can lead to a reduction of device lifetime; however, this influence is not significant under conditions discussed above.

Acknowledgement

Authors wish to express the thanks to company Polovodice, a.s. for kind agreement with publication of this article.

References

[1] H. F. John: Proceedings of the IEEE, Vol. 55, No. 8, 1967
[2] S. K. Ghandhi: Semiconductor Power Devices, J. Willey & Sons, N.Y. 1977
[3] K. V. Ravi: Imperfections and Impurities in Semiconductor Silicon, J. Willey & Sons, N.Y. 1981
[4] S. T. Hsu: Solid State Electronics, Vol. 14, pp. 487-497 (1971)
[5] M. Kubát: Výkonová polovodičová technika, SNTL Praha 1978
[6] V. Benda, J. Gowar, D. A. Grant: Power Semiconductor Devices Theory and Applications, J. Willey & Sons, N.Y. 1999
[7] W. M. Rohsenow, J. P. Hartnett: Handbook of Heat Transfer, McGraw-Hill, N.Y. 1973, p. 3-63

Addresses of the authors
V. Papež, J. Hejhal, Czech Technical University in Prague, Technická 2, Prague 6, CR, e-mail: papez@feld.cvut.cz
B. Kojecký, J. Kožíšek, POLOVODIČE, a.s., Novodvorská 138a, Prague 4, CR, e-mail: bkojecky@polovodice.cz