Transient Effects on High Voltage Diode Stack under Reverse Bias

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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) $\text{F}$
- $i_a$: avalanche current $\text{A}$
- $i_C$: capacitive current $\text{A}$
- $i_D$: total diode leakage current $\text{A}$
- $i_d$: diffusion current $\text{A}$
- $i_g$: generation current $\text{A}$
- $N$: number of serial connected diodes $\text{-}$
- $N_C$: number of cycles $\text{-}$
- $N_D$: density of donors $m^{-3}$
- $n_i$: intrinsic density of carriers $m^{-3}$
- $P$: probability $\text{-}$
- $Q_a$: avalanche charge $\text{C}$
- $q$: electron charge $\text{C}$
- $R$: resistor $\Omega$
- $S_D$: PN junction area $m^2$
- $t$: time $\text{s}$
- $V_A$: applied voltage $\text{V}$
- $V_D$: reverse voltage drop of diode $\text{V}$
- $V_n$: reverse voltage of diode in chain $\text{V}$
- $V_R$: voltage drop of resistor $\text{V}$
- $v_s$: saturation velocity $m.s^{-1}$
- $x$: coordinate $\text{m}$
- $x_D$: SCR wide before avalanche $\text{m}$
- $x_T$: SCR wide as a function of time $\text{m}$
- $\varepsilon$: relative permittivity $Fm^{-1}$
- $\varepsilon_0$: permittivity of vacuum $Fm^{-1}$
- $\lambda$: parameter of the Poisson distribution $\text{-}$
- $t_{SC}$: lifetime of carriers in SCR $\text{s}$

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](image)

![Fig. 2: Scheme of local avalanche breakdown](image)

Avalanche charge \( Q_a \) is transported through the SCR and its velocity is \( v_s \) (saturation velocity is equal \( 1 \times 10^5 \) \( \text{ms}^{-1} \) [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 \( i_a \approx i_{rg} + i_d \). Then equation describing avalanche process has the form

\[
\frac{Q_a}{x} + S_D qN_D \frac{dx}{dt} = \frac{V_R}{R}.
\]

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

\[
x = \sqrt{\frac{2e_0 V_D}{qN_D}}.
\]

Further, for any time it must be valid

\[
V_A = V_D + V_R,
\]

or

\[
\frac{dV_D}{dt} = -\frac{dV_R}{dt}.
\]

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

\[
-\frac{dV_D}{dt} = \frac{a}{b} \frac{(V_A-V_D)}{b,R} \sqrt{V_D} ,
\]

where

\[
a = Q_a v_s \sqrt{\frac{qN_D}{2e_0}}, \quad b = S_D \sqrt{\frac{e_0 qN_D}{2}}.
\]

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

\[
\sqrt{V_D} \approx \sqrt{V_A} .
\]

In other words, the change of the diode voltage is relatively small in comparison with the state before avalanche.

Then, we can write for \( \Delta V_D = V_A - V_D \)

\[
\Delta V_D = \frac{aR}{\sqrt{V_A}} \left( 1 - e^{-\frac{\sqrt{V_A}}{b,R}} \right) \quad (6)
\]

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

\[
i_D = i_C + i_{rg} + i_d ,
\]

where \( i_{rg} \) is given by known relation

\[
i_{rg} = \frac{S_D qN}{\tau_{sc}} X
\]
and diffusion current \(i_d\) is constant. Because the change of \(i_n\) is also small, then

\[ i_r = i_n + i_d = \text{const}. \]  

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

\[ C_D = S_D \left( \frac{1}{2} qN_D \varepsilon \right) \left( \frac{1}{2} V_D \right)^{\frac{1}{2}} = \text{const}. \]  

Restored process can be described by equation

\[ C_D \frac{dV_D}{dt} + i_r = \frac{V_R}{R}. \]  

Solving Eq. 11 we have

\[ \Delta V_D = \frac{R}{V_R} \left( V_{R0} - i_r \right) e^{-\frac{t}{C_p R}} + i_n R, \]  

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

\[ \frac{Q_n}{x} + C_D \frac{dV_D}{dt} = C_D \frac{dV_x}{dt} \]  

and for voltage distribution it is valid

\[ V_A = V_D + (N-1)V_n, \]  

where \(V_A\) is average voltage drop on any diode of the chain and \(V_0, V_n \rightarrow V_n\).

Then, Eq. 13 may be transformed as

\[ -C_D \frac{dV_D}{dt} \left( 1 + \frac{1}{N} \right) = \frac{Q_n}{V_D} \frac{qN_D}{\sqrt{2\varepsilon}} \]  

and for \(N \gg 1\) it is

\[ \sqrt{V_D} \frac{dV_D}{dt} = \frac{Q_n}{C_D} \frac{qN_D}{\sqrt{2\varepsilon}} dt. \]  

For \(t = 0\) it is \(V_D = V_0/N\) and solution of Eq. 15 is in the form

\[ \Delta V_D = \frac{V_A}{N} \left[ \left( \frac{V_A}{N} \right)^{\frac{3}{2}} - 3 \frac{Q_n}{C_D} \frac{qN_D}{\sqrt{2\varepsilon}} t \right]. \]  

or in simplified relation

\[ \Delta V_D = \frac{V_A}{N} \left[ A - B J \right]^{\frac{3}{2}}, \]  

where

\[ A = \left( V_A / N \right)^{\frac{3}{2}} \text{ and } B = \frac{3}{2} \frac{Q_n}{C_D} \frac{qN_D}{\sqrt{2\varepsilon}}. \]

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).

\[ x_D^2 + (N-1)x_n^2 = N x_o^2, \]  

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

Because

\[ \frac{dx_n}{dt} = -\frac{x_n}{(N-1)x_o} \frac{dx_D}{dt} \]  

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

\[ qN_D \frac{dx_D}{dt} + n_q x_D = -qN_D x_D - \frac{dx_D}{dt} + n_q x_n \]  

If \(N \gg 1\), Eq. 19 has the form

\[ \frac{dx_D}{dx_D} = \frac{C dt}{(x_o - x_D)} \]  

where \(C = \frac{n_q}{qN_D \tau_{sc}}\).

Solving Eq. 20 we get

\[ x_D = x_o \left( 1 - e^{-Ct} \right) + x_D 0, \]  

where \(x_D 0\) 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)

\[ \Delta V_D = \Delta V_{D0} e^{-Ct}, \]  

where \(\Delta V_{D0}\) 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:

\[ qN_0 = 10 \text{ Cm}^{-3}, \quad S_0 = 5 \cdot 10^{-5} \text{m}^2, \]  

\[ \varepsilon \varepsilon_0 = 1.10^{-1} \text{Fm}^{-1}, \quad qn_1 = 1 \text{Cm}^{-3} (125\text{C}), \]  

\[ C_D = 10 \text{ pF}, \quad \tau_{sc} = 5 \cdot 10^{-6} \text{s}, \]  

\[ \nu_5 = 1.10^5 \text{ms}^{-1} \quad R = 10 \text{k}\Omega, \]  

\[ N = 80 \quad Q_n = 2 \cdot 10^{-10} \text{C} \]  

Then, we can calculate the values \(\Delta V_D\) and time constants in Eq. 6, 12, 16, 22.

For Eq. 6 and \(t = 2\) ns is
\[
\Delta V_D = 19.8 \text{V}, \quad \sqrt{\frac{V_A}{bR}} = 1.1 \times 10^7 \text{s}^{-1}.
\]

For Eq. 12 is
\[
\Delta V_{R0} = 19.8 \text{V}, \quad \frac{1}{C_{D_R}R} = 1.1 \times 10^7 \text{s}^{-1}.
\]

For Eq. 16 and \( t = 2 \text{ ns} \) is
\[
\Delta V_D = 20.1 \text{V}, \quad B = 6.71 \times 10^{11} \text{s}^{-1}.
\]

For Eq. 22 and \( \tau = 50 \text{ \mu s} \)
\[
\Delta V_{D0} = 20.1 \text{V} \quad C = 2.1 \times 10^3 \text{s}^{-1}.
\]

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 \times 10^3\).  

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 \( R = 10 \text{k} \Omega \), \( R_0 = 10 \text{M} \Omega \) and \( C_0 = 10 \text{pF} \) are shown in Fig. 5. Their maximum mutual deviation is about 3\%.

![Fig. 3: Individual diode in simulated circuit](image)

<table>
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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)](image)

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 \( \mu \text{m} \) thick, with diameter 5 mm. Specific resistivity of basic silicon is 87 \( \Omega \text{cm} \), PN junction depth is 85 \( \mu \text{m} \). 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 \( R = 10 \text{k} \Omega \). 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. 6a) is about 10 s⁻¹ at the reverse voltage 2000 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) Accordance between physical model and circuit simulation

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

$$ \frac{d \Delta V_D}{dt} = \frac{2}{3} R \left( \frac{V_A}{N} \right)^{1/2} $$

for \( t \to 0 \) and

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

where \( \Delta t \) is avalanche charge transit time through SCR. For sufficiently small \( Q_a (1 \times 10^{-10} - 1 \times 10^{-9} \text{C}) \) the value of \( \Delta V_D \) 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.

![Substitute scheme of measuring circuit](image)

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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.

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) Lifetime and reliability

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]

\[ N_c = \left( \frac{300}{\Delta T} \right)^9 \]  

(25)

where \( \Delta T \) is a local increasing of temperature (°C) during 1 cycle.

If a surface of the microplasma discharge is typically about 50 \( \mu \)m\(^2\) [2], then for \( V_D = 2000 \) 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 \( \Delta T \) 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 \( a \) (see Fig. 12).
The cooling down of microplasma region is described by equation of heat conduction. The solution for this case has following form [7]

$$\frac{T - T_0}{T_m - T_0} = \frac{1}{2} \left\{ \text{erf} \left( \frac{a + x}{\sqrt{2K/\rho Cp}t} \right) + \text{erf} \left( \frac{a - x}{\sqrt{2K/\rho Cp}t} \right) \right\}$$

(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
- $\rho$ 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

$$\text{erf} \left( \frac{a}{\sqrt{2K/\rho Cp}t} \right) = 0.100$$

(27)

and

$$\frac{a}{\sqrt{2K/\rho Cp}t} = 0.089.$$  

(28)

Calculated time $t$ is equal to 6 $\mu$s for $a = 4 \mu m$.

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 $\mu$s coincidence of the two discharges, the Poisson distribution can be used

$$P = e^{-\lambda/\mu} \frac{\lambda/\mu^k}{k!}$$

(29)

where $\lambda = \mu \cdot t$, $\mu$ is average long time frequency of any phenomenon and $k$ is number of this phenomenon during time interval $t$.

If $\mu = 10$ Hz, $t = 6$ $\mu$s and $k = 2$, then

$$P = 1.8 \cdot 10^{-9}.$$  

(30)

It means, this situation is realised with time period equal to 0.5 year. That is why, an influence of repeated discharge coincidence on device lifetime may be neglected.

Fig. 12: Silicon wafer with microplasma “hot spot”

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.

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