SIMULATION OF HEAT FLOW IN TVS DIODES

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1. Introduction

TVS (Transient Voltage Suppressor) diodes are designed to protect circuits from transient high voltage peaks. To achieve this they make use of the avalanche effect in the reverse polarity which is reversible and non-destructive. The reaction time of TVS diodes, being about several picoseconds, is much smaller than other methods of circuits protections. Hence they are ideal for very short high-voltage peaks caused by lightnings, inductive switches or electrostatic discharges.

In a normal regime in reverse direction, $V < V_{BR}$, the TVS diodes exhibit high impedance and have no effect on the functionality of the circuit. At the break-down voltage electrons and holes entering the depletion region attain large acceleration as a consequence of the strong electric field. If the kinetic energy of the carriers is large enough, their collisions with atoms lead to secondary ionization. Subsequently also the secondary particles are accelerated, the process is repeated and the number of carriers grows exponentially [1,2]. The impedance of the diode drops to almost zero and the high-power pulse is guided into the ground, avoiding the protected circuit.

Part of the kinetic energy of the carriers is passed to the crystalline lattice. The consequence is that the carriers must cross larger difference in potential, or larger voltage for a generation of a single electron-hole pair. This leads to the dominant temperature-dependence of the *I-V* characteristics of the TVS diodes, i.e. the break-down voltage V_{BR} grows with increasing temperature (Fig. 1).

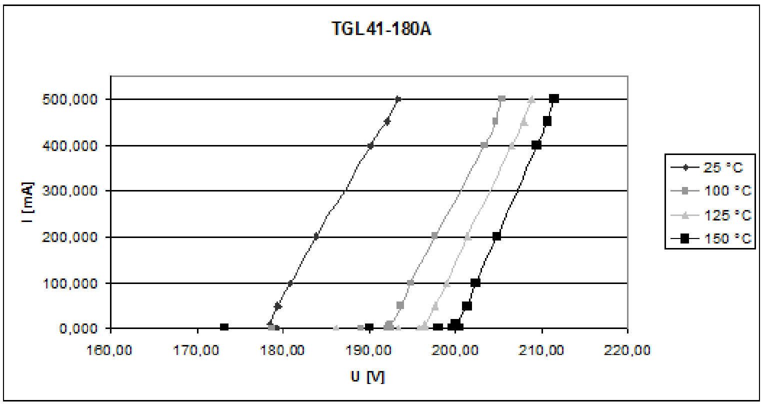

Fig.1: *Temperature-dependent I-V characteristic of the TVS diode . Each curve corresponds to a steady-state regime for which the real temperature of the p-n junction is unknown.*

Fig.2: *Geometrical and material composition of the TVS diode with single p-n junction.*

The avalanche effect is nondestructive and reversible process. Once the voltage peaks drops below the break-down voltage, the avalanche damps out and the diode returns to its normal, high-impedance state. However, the heat produced by the large avalanche current and voltage, if not drained well, may lead to a destruction of the diode. The aim of our work is simulation of the transient heat flow in the diode during the high-power peak and to calculate maximal temperatures on the p-n junction during the avalanche process.

2. The model for the heat flow in TVS diode

Our model for the TVS diode with single p-n junctions is chosen to mimic the commercially produced TVS diode TGL41-180A by SEMIKRON, GmbH. The model consists of layers of copper, solder and silicon chip with p-n junction (Fig. 2).

Since the width of the diode (about 1.5 mm; area of the junction S = 2.5 mm^2) is significantly larger than its extension along the current flow, the heat flow is considered quasi one-dimensional in the direction normal to the p-n junction. In each layer, the transient heat flow in the diode is described by the equation [2]

$$\rho c_p \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2} + \dot{g} \qquad (1)$$

where ρ, c_p and λ are the mass density, specific heat capacity at constant pressure and the thermal conductivity in a given layer. $T(x,t)$ is the temperature in the diode at the position x and time t. $\dot{g}$ stands for the heat generated in the p-n junction per unit time and volume. The latter comes dominantly from the depletion region of the p-n junction where the drop in the voltage appears,

$$\dot{g} = i(t)\,u(t)\,\delta(x - x_{pn})/S, \mathrm{u}(t) = V_{BR}(T_{pn}) + R(T_{pn})\,i(t) \qquad (2)$$

where $i(t)$ is the time-dependent current, $u(t)$ the voltage across the p-n junction and S the area of the junction. The delta-function represents the fact that the heat is generated solely in the depletion region of the p-n junction (at x_{pn}), the width of which is negligible compared to the widths of the layers forming the diode. The *I-V* characteristics of the diode is given by the the temperature-dependent break-down voltage $V_{BR}(T_{pn})$ and its differential resistance $R(T_{pn})$ [3]. It is essential that the dependence of these parameters on the temperature at the p-n junction, $T_{pn} = T(x_{pn}, t)$, is accounted for, particularly during the transient process, when this temperature is changing with time according to Eq.(2). This is modelled in a linear form ,

$$V_{BR}(T_{pn}) = V_{BR}(T_{pn}^0)\left(1 + \alpha\left(T_{pn} - T_{pn}^0\right)\right) \qquad (3)$$

where α is the thermal coefficient of the break-down voltage and ,

$$R(T_{pn}) = R(T_{pn}^0)\left(1 + \beta\left(T_{pn} - T_{pn}^0\right)\right) \qquad (4)$$

where β is thermal coefficient for the differential resistance at the reference temperature T_{pn}^{0} . The values of these parameters were obtained from the stationary characteristics of the diode (Fig. 1) and are listed in Section 3.

At the interfaces between different layers the continuity of the heat flow is imposed using the conditions

$$\lambda_1 \frac{\partial T}{\partial x}\bigg|_{x=x_i-0} = \lambda_2 \frac{\partial T}{\partial x}\bigg|_{x=x_i+0} \tag{5}$$

where λ_1 and λ_2 are thermal conductivities of the neighbouring layers, the ends of the diode where modelled using open boundary conditions, e.g. at its right-most end we impose

$$-\lambda \frac{\partial T}{\partial x}\bigg|_{x=x_{end}} = h\left(T\left(x_{end}\right) - T_0\right) \tag{6}$$

where h = 1.0 W/(m^2 °C) is a rough estimate for the heat transfer coefficient between the end of the diode and environment.

The model given by Eqs.(1)-(6) was implemented in a versatile computer program [5] using explicit finite-difference scheme [4], which allows easy modifications for various widths of the layers and variable number of p-n junctions.

3. Comparison of simulations with experimental results

The experimental measurements were realised in the testing laboratories of SEMIKRON in Vrbové. From the static *I-V* characteristics of TVS diode at several temperatures we have obtained values for the parameters $U_{BR}(25°C)$ = 178.22*V*, *R* = 31.44 Ω, as well as their thermal coefficients α = 0,0011 °C^{-1} and β =-0.0021 °C^{-1} [5].

Material parameters of the constituent materials, i.e. its density, thermal capacity and thermal conductivities of silicon, solder (lead) and copper were set to their standard values at room temperature [6]. From these, the most severe dependence on temperature exhibits the thermal conductivity of silicon, which drops by factor of 2 by going from the room temperature to *T* = 125 *°C.* We have checked that this does have noticeable effect on the temperature in the diode, but does not resolve the problem discussed below. Hence, for simplicity, we did not implement the temperature-dependence into our model.

The simulate a high power pulse a current pulse of finite duration, given in Figure 4 by the full grey line, was applied to the diode. As a result, the temperature at the p-n junction first grows to its maximal value and subsequently fades to the temperature of the environment. A series of temperature profiles in the diode is shown in Fig. 3. We see that the maximum temperature, about T_{max} = 200*°C,* is reached 1.2 ms after the current attains its maximum, and lasts for about 1 ms. We have checked that during this time the boundary conditions at the ends of the diode do not play principal role. However, for proper prediction of the temperature of the p-n junction for larger times (> 2 ms) the difference in fixed and open boundary condition may result in the difference in the temperature in the depletion region even 80°C. We can also note that the differences in temperature in the silicon during the transient are about 50°C which means that incorporating the temperature-dependence of the thermal conductivity of silicon into the model might lead to improvement of the quality of the simulations.

Using the time-dependence of the temperature at the p-n junction from the above simulations, and using it within the model I-V characteristics of the diode, Eq. (2), we can compare the measured and calculated voltage response of the diode (Fig. 4). While for times larger than 3 ms the experimental (grey, crosses) and the simulated time-dependence of the voltage (grey, dashed line) are similar, the simulation significantly overshoots the values

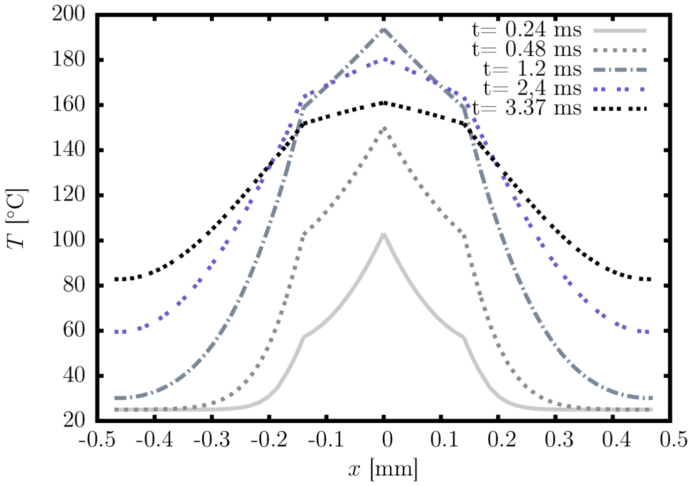

Fig.3: *Temperature profile along the diode at selected times caused by short current pulse. The maximum temperature is reached in the time interval t=0.6-1.4 ms, at the position of the p-n junction.*

of the transient voltage. The third curve (black, dashed line) corresponds to the simulation with modified differential resistance, namely using ten times smaller value, R=3.144 Ω, which follows closely the experimental results.

Indeed, we believe that incorrect values of the differential resistance of the *I-V* characteristic of the diode is the main reason for the observed discrepancy between the experimental data and the simulation. This is also in agreement with previous investigations [2], where it has been found that the differential resistance of the isothermal *I-V* characteristic is much smaller than the steady-state *I-V* characteristic, which even though measured at constant temperature of the environment, exhibits different (and experimentally unknown) temperatures of the p-n junction. In their work they estimated that as much as 80% of the apparent steady-state differential resistance stems from the rise of the temperature of the p-n junction and hence from the temperature dependence of the break-down voltage in Eq. (3). A simple estimate based on steady-state heat transport gives the difference between the temperature of the environment and the p-n junction,

$$T_{pn}=T_0+u(t)i(t)R^T \tag{7}$$

where R^T is the thermal resistance of the diode. Using the geometrical and physical properties of the diode we find

$$R^T=\frac{2}{S}\left(\frac{l_{Cu}}{\lambda_{Cu}}+\frac{l_{Si}}{\lambda_{Si}}\right)\approx 1{,}5\ ^{\circ}\mathrm{C}\ \mathrm{W}^{-1} \tag{8}$$

so that once the diode is in the avalanche regime, the temperature of the p-n junction can be easily 200°C above the temperature of the environment. This complicates the interpretation of the parameters of the diode obtained from the steady-state measurements, particularly the differential resistance and its temperature coefficient. The comparison of our simulations with the experimental voltage response indicate that the true differential resistance is much smaller than the one inferred from the steady-state *I-V* characteristics.

4. Conclusions

In conclusion, we have discussed a model and implementation of a simulation of heat flow in TVS diodes. The resulting program can simulate the time-evolution of the temperature inside

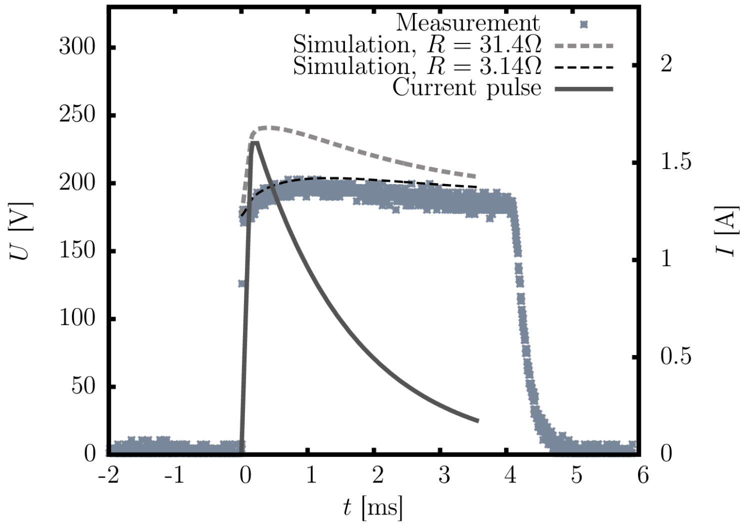

Fig.4: *Experimental (crosses) data, data simulated based on measured differential resistance (grey dashed line) and simulated using small differential resistance (black dashed) responses of the voltage on the current pulse (full black). The agreement is obtained only is the differential resistance is about ten times smaller than the one obtained from steady-state I-V characteristics.*

the diode. Critical to the quality of these simulations is a good description of the *I-V* characteristic of the diode and its dependence on the temperature at the p-n junction. We have confirmed that the steady-state *I-V* characteristics of the diode do not directly give a good estimate of the differential resistance of the diode and more involved analysis is necessary to obtain this parameter. Further improvement of the model can be obtained by incorporating temperature dependence of the thermal conductance in the silicon since the gradients of the temperature in the diode are significant.

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