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Experimental Analysis and Modeling of the Electrical and Thermal Transients of the Diode-By-pass for the LHC- Magnet Protection at Cryogenic Temperatures

R. Denz and D. Hagedorn

Abstract

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1 INTRODUCTION

For the protection of the superconducting dipole and quadrupole magnets of the LHC by-pass diodes will be used besides current breakers, dump resistors, heaters. The by-pass diodes will be installed in the magnet cryostat subjecting them to superfluid helium temperatures and radiation flux. They are high current silicon rectifier diodes connected in parallel to the superconducting magnets thus creating an electrical bypass in case the magnet quenches. In that case, the turn on voltage of the diode in parallel will be exceeded and the current will automatically commute from the quenched magnet into the diode during the discharge of the still superconducting magnets.

All superconducting lattice magnets will be equipped with by-pass diodes, one bypass diode across each twin-aperture dipole and one diode across each single quadrupole aperture. Inside the quadrupole diode package the two diodes are galvanically separated, since focusing and de-focusing quadrupoles will be powered separately. Before installation, all diode packages will be tested at liquid helium temperature. As the differences of the electrical characteristics between 1.9K and 4.2K are rather small, nearly all tests will be carried out at 4.2K. Only a few of the series diode assemblies need to be tested at 1.8K to verify their turn-on characteristics.

Each diode package must be able to conduct an ultimate current pulse of 13kA peak with a nominal decay time constant of about 100s for the dipole diode and of about 50s for the quadrupole diode respectively. The heat sinks for the dipole diode package have to absorb a nominal energy of about 1.5MJ, the heat sinks for one quadrupole diode a nominal energy of about 0.7MJ. The diodes have to operate within temperature range of 1.8K - 450K, withstand the associated thermal stresses, and to continue to operate reliably after several cold-warm cycles (endurance tests) before final installation.

In addition the quadrupole diodes have to support safely an estimated dose of about 200Gy and neutron fluence of about 1.2 10^{12}n/cm^2 during 10 years of operation and the dipole diode a dose of about 30Gy and a neutron fluence of about 1.5 10^{11}n/cm^2. During irradiation the forward voltage of the diode junction will increase resulting in higher energies to be absorbed by the heat sinks. Before submitting the diode assemblies to ten endurance test cycles at 4.2K, the forward current-voltage characteristic $I_f(U_f)$ of each diode is measured at 77K and at 300K by applying short (200µs) half sine current pulses up to 15kA peak and measuring the forward voltage U_f at current peak (dI/dt=0).

2 FORWARD BIAS CHARACTERISTICS OF THE DIODE JUNCTION VERSUS TEMPERATURE

One of the main reasons for a diode failure is excess temperature (T_j > 450K), followed by a burnout of the silicon wafer. The wafer temperature is determined by the combined effects of power dissipation ($P_j = U_f * I_f$) at the junction and heat diffusion through adjacent materials inside the diode capsule to the heat sinks. The forward voltage drop U_f for a given diode depends on forward current I_f, wafer temperature T_j, and radiation damage.

Figure 1 shows the measured current-voltage characteristic $I_f(U_f)$ at different temperatures. A monotonic increase of the dynamic resistance at lower temperatures can be observed. The I_f-U_f-characteristics of the diode below 50K could not be measured due to the too high self-heating of the wafer during the high current measuring pulse. Also plotted in Figure 1 is the monitored I_f-U_f-characteristic of the diode during an endurance test run. The current turns on at a V_{to} of about 8V (not visible) and reaches after about 0.8s a maximum of about 13kA. The maximum wafer temperature of about 240K occurs after about 30s.

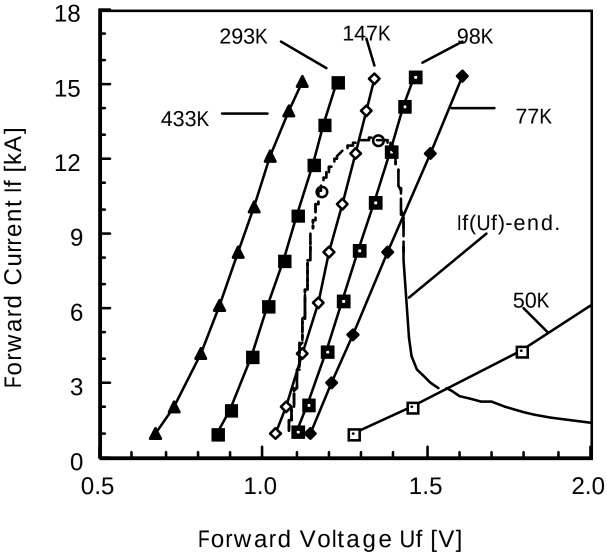

Figure 1 Measured I_f-U_f-characteristics of an EUPEC diffusion type diode at different temperatures and moni- U_f and I_f during endurance testing

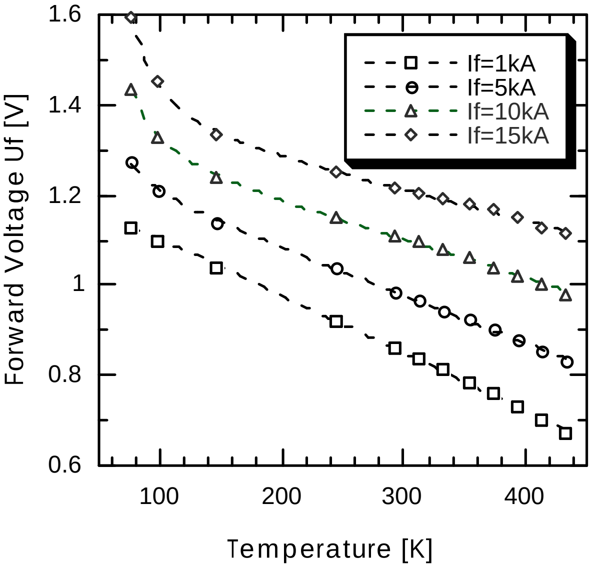

Figure 2 Forward voltage U_f versus temperature at different forward currents I_f

Using a simple interpolation algorithm for the current I_f, the dependence of the forward voltage U_f on temperature with I_f as a parameter can be determined as shown in Figure 2.

The data in Figure 2 were fitted to the following formula:

$$U_f \ (T,I=\text{const.}) = R_o I_f \exp(\varepsilon_1 / 2k_B T) + C_1 T + C_0 \qquad (1)$$

The first term describes the temperature dependence of the series resistance of the diode. The series resistance, which arises from the bulk resistivity of the quasi-neutral regions of the device, increases exponentially with lower temperatures due to the starting of carrier freeze-out. The activation energy is close to the ionization energy of a single donor or acceptor respectively [1], e.g. in silicon 0.045eV for the donor phosphorous and the acceptor boron[2]. The linear term is a result of the Shockley theory for a pn-junction, which gives:

$$\delta U_f / \delta T \bullet \ (U_f - \eta E_{go} / e) / T \qquad \text{or} \qquad U_f (T,I = \text{const.}) \bullet \ C_1 T + \eta E_{go}/e \qquad \text{with } 1 \le \eta \le 2$$

Here is the charge of the proton and E_{g0} the band-gap linearly extrapolated to T=0 (the real $E_g(T=0)$ is smaller) [3]. For small diode currents (I_f<500A), the contribution of the first term is negligible and the constant C_o can be derived from the experimental data, thus reducing the unknown parameters to R_o and C_1, which both depend on the diode current I_f. This offers the possibility to use only the two calibration points at T=77K and T=293K. By interpolation of the diode current-voltage characteristics at T=77K and T=293K, the above algorithm provides a set of U_f (T,I=const.)-curves, which enable the use of the device itself as thermometer. This is especially interesting, as during the series testing of LHC-diodes the internal parts of the device are not accessible. For non-irradiated diodes this calibration turned out to be valid from 77K=T=450K. The use of the device as a thermometer at temperatures below T=77K is difficult, as the measurement itself produces significant heat.

In case of radiation damage, in Equation (1) a term must be added to take into account the increase of dynamic resistance of the diode. The evaluation of this term requires additional data from irradiation experiments which are just under way [4].

3 ELECTRO-THERMAL MODELING OF THE DIODE PACKAGE

Besides thermal contact resistances, the heat sink is the limiting factor in the wafer temperature increase. How much U_f can increase due to radiation without exceeding the maximum wafer temperature, is strongly related to the heat sink design. The diodes are mounted between cylindrical copper blocks acting as heat sinks. Three insulated steel rods and eight Cu-Be alloy spring washers are used to press the copper blocks against the diodes.

3.1 Approximations and assumptions

For the thermal model we considered as a first approximation a one-dimensional cylindrical symmetry since the components of the diode and the heat sinks are cylinders. The volume of the groves for the interconnecting bus bars and tie rods on the heat sinks has been subtracted - resulting in a smaller outer diameter - so that a realistic copper volume was obtained. Any heat transfer to the clamping system is neglected as well as any heat transfer to the liquid helium (pure adiabatically conditions). This assumption is justified since the diodes are housed in a cylindrical box in which the small amount of liquid helium is evaporated within the first few seconds after applying the current pulse. In the model the interconnecting bus bars are attached to the external faces of the heat sinks, so that the influence of their dimensions could be studied. Concerning material properties, the specific heat and thermal conductivity versus temperature of ETP-Copper, Molybdenum, and Silicon were used. For the electrical resistivity of Copper a residual resistance ratio RRR= 100 was assumed.

The whole package was subdivided into 37 cylindrical disks of different thickness for each of the material components. For each of these disks the diffusion equation for thermal transients was solved by the finite difference method. Contact thermal resistances were introduced in the model between the electrodes of the diode and the heat sinks. In the model some asymmetries had to be taken into account, the thickness of the Mo-disks inside the diode and also the length of the diode interconnections are different for anode and cathode. For the electric power dissipated in the wafer the electrical characteristics of the diodes according to equation (1) were applied.

3.2 Results

In Figure 3 the measured wafer temperature T_w and heat sink temperatures T_{hsa} and T_{hsc} are plotted versus time during an endurance test of a dipole diode package. The dotted lines represent simulation results. The simulated wafer temperature decreases less rapidly compared with measured temperature which is mainly due to the assumption that the thermal impedance (R_{tha}= R_{thc}= 0.006K/W) between heat sinks and diode is constant. In reality the thermal contact resistance decreases with temperature [5].

As there is still some heat exchange with the environment, the modeled heat sink temperatures are higher than measured. The higher temperature on the anode heat sink is mainly caused by the longer interconnecting bus bar which also heats up and creates an additional thermal impedance. The agreement between modeled and measured maximum wafer temperature is good enough to study other effects which can influence the wafer temperature.

The maximum wafer temperature T_w versus heat sink copper volume is plotted in Figure 4. The dotted curve represents the variation of the copper volume length at constant copper cross section A_{cu}, the solid curve the variation of the copper cross section at constant length d. With the actually foreseen copper volume of about $3000cm^3$ per dipole diode package, there is still some reserve in volume, which will be necessary to absorb higher energies caused by in increase of forward voltage due to radiation damage. For the quadrupole diode package the agreement between measured and modeled results is similar to the results for the dipole diode package.

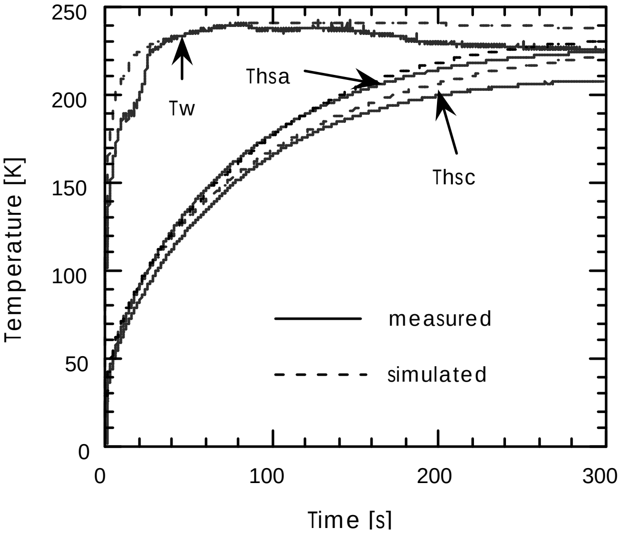

Figure 3 Measured and simulated wafer-and heat sink temperatures versus time

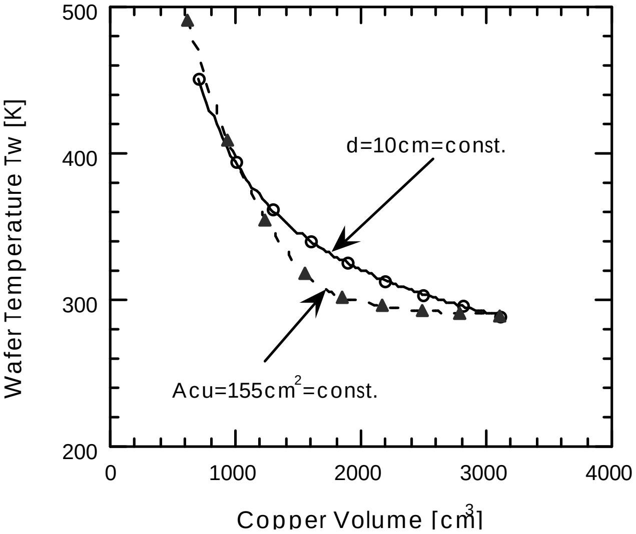

Figure 4 Simulated wafer temperature versus copper volume of the heat sinks

4 CONCLUSIONS

For a power diode an electrical model for the forward current-voltage characteristics in the temperature range between 77K and 450 K has been developed based on the pn-junction theory. The electrical model is part of a developed electro-thermal model of the diode package, which allows to simulate the temperature transients inside the diode and adjacent heat sinks. The modeled maximum diode wafer and heat sink temperatures agree well with measured results from endurance tests. As soon as more results from ongoing irradiation experiments are available the model can be extended, and it will be possible to estimate the lifetime of the diodes under radiation. The present heat sinks have a sufficient reserve to absorb the additional energy caused by radiation damage on the diode.

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