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Technical Note

# Determination of the electronics transfer function for current transient measurements

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ABSTRACT

We describe a straight-forward method for determining the transfer function of the readout of a sensor for the situation in which the current transient of the sensor can be precisely simulated. The method relies on the convolution theorem of Fourier transforms. The specific example is a planar silicon pad diode. The charge carriers in the sensor are produced by picosecond lasers with light of wavelengths of 675 and 1060 nm. The transfer function is determined from the 1060 nm data with the pad diode biased at 1000 V. It is shown that the simulated sensor response convoluted with this transfer function provides an excellent description of the measured transients for laser light of both wavelengths. The method has been applied successfully for the simulation of current transients of several different silicon pad diodes. It can also be applied for the analysis of transient-current measurements of radiation-damaged solid state sensors, as long as sensors properties, like high-frequency capacitance, are not too different.

## 1. Introduction

The analysis of current transients from different sensors is frequently limited by the knowledge of the electronics response, which is also influenced by the sensor properties. Examples for silicon sensors are the determination of the electric fields, carrier lifetimes and charge multiplication in radiation-damaged sensors using the Transient Current Technique (TCT, edge-TCT) [1–3] or charged particles with shallow incident angles [4]. The aim of this Technical Note is to demonstrate that, for an experiment in which the pulse shape from the sensor can be precisely simulated, the electronics transfer function can be obtained from the measured transient using the convolution theorem of Fourier transforms. This transfer function can then be used for analyzing data for which the pulse shape of the sensor is not known. An example is the analysis of measured transients from a radiation-damaged sensor using the known transfer function obtained from the sensor before irradiation, as long as detector properties, like the high-frequency capacitance, do not change too much with irradiation.

## 2. Measurement set-up

The measurement set-up used is described in detail in Refs. [5–7]. The measurements have been performed on $p^+nn^+$ and $n^+pp^+$ pad diodes with different doping, thicknesses of 200 μm and 285 μm, and 4.4 mm$^2$ and 25 mm$^2$ area. In all cases the electronics response function has been successfully determined. Here we present the results from a $p^+nn^+$ pad diode produced by Hamamatsu [8] on a ⟨100⟩ crystal with 204.5 μm mechanical thickness, 4.4 mm$^2$ area, and $2.9\times10^{12}$ cm$^{-3}$ phosphorous doping, which was connected by a 3 m long RG58 cable and a bias-T to an amplifier [9], and read out by a Tektronix DPO 4104 oscilloscope with a bandwidth of 1 GHz and a sampling rate of 5 GS/s. A guard ring was present but not connected for the measurements. The active thickness of the pad diode was estimated to $200\pm1$ μm from dielectric as well as caliper measurements of the physical thickness minus the thickness of the implants from spreading resistance measurements [10]. The depletion voltage was determined to $87.5\pm3.0$ V, from capacitance measurements with a capacitance above the depletion voltage of about 2.7 pF.

The charge carriers were generated by picosecond lasers [11] pulsed at a frequency of 200 Hz with a full-width-at-half-maximum of less than 50 ps and wavelengths of 675 and 1060 nm. For each pulse approximately $10^6$ electron–hole pairs were generated, and for every measurement 512 pulses were averaged. At room temperature the absorption length in silicon for light of 1060 nm is about 1.5 mm. As the attenuation length is long compared to the sensor thickness, the distribution of charge carriers is similar as for charged particles traversing the sensor. At this wavelength the absorption length is a strong function of temperature [12,13]. It is about 650 μm at 40 °C. The absorption length for light of 675 nm is about 3.3 μm at room temperature, and the signal induced in the electrodes of the sensor is essentially due to electrons if the light is injected at the $p^+$ side, and due to holes if injected at the $n^+$ side.

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## 3. Simulations

In the simulations a uniform doping in the active region of the sensor is assumed, resulting in a linear position dependence of the electric field. Using the field simulated with SYNOPSYS-TCAD [14] which includes realistic doping distributions at the $p^+n$ and $n^+n$ transitions [15], it has been checked that the current transients for voltages 50 V above the depletion voltage are hardly affected by the electric field distribution at the transitions.

Electrons and holes are generated on a grid with 100 nm spacing according to exponentials with the light-absorption lengths given above. The charge carriers are then drifted in the electric field in time steps $\Delta t = 10$ ps taking into account diffusion by Gaussians with variances $\sigma_e = \sqrt{(2 \cdot \mu_e \cdot k_B T / q_0)\Delta t}$ for electrons, and similar for holes, with the Boltzmann constant $k_B$, the absolute temperature $T$, the elementary charge $q_0$, and the electron and hole mobilities $\mu_e$ and $\mu_h$. The field dependence of the mobilities of electrons and holes was adjusted to describe our measurements [5,16]. The main difference compared to the standard parametrization [17] is that at high fields ($\approx 50$ kV/cm) the electron and the hole drift velocities are similar. We note that there are hardly any measurements of the drift velocities for ⟨100⟩ silicon available. The current induced in the electrodes in the time interval between $i \cdot \Delta t$ and $(i+1) \cdot \Delta t$ is calculated according to $I_i^{sim} = q_0/\Delta t \cdot \sum_j [(N^e_{i+1,j} - N^e_{i,j}) - (N^h_{i+1,j} - N^h_{i,j})]$, where $N^e_{i,j}$ is the number of electrons and $N^h_{i,j}$ is the number of holes at the grid point $j$ at time $i \cdot \Delta t$. Effects like charge trapping or charge multiplication are not taken into account. The convoluted signal is given by $S_k^{sim} = \sum_l I_{k-l}^{sim} \cdot R_l$, where $R_l$ is the response at $t = l \cdot \Delta t$ to an initial unit current at $t = 0$.

## 4. Transfer function determination

The measurements have been performed for voltages between 100 V and 1000 V in steps of 10 V. For every voltage three sets of data were taken: 1060 nm light injected from the $p^+$ side, called "*IR*", 675 nm light injected from the $p^+$ side, "e", and 675 nm light injected from the $n^+$ side, "h". For "*IR*" holes and electrons contribute equally to the signal, whereas for "e" electrons, and for "h" holes dominate. For determining the transfer function $R$, the *IR* measurement at 1000 V is used. A spline interpolation of the measurement $I^{int}$ is used to obtain values for the same time steps $\Delta t = 10$ ps as in the simulation. Next the Fast Fourier Transforms $\mathcal{F}(I^{sim})$ and $\mathcal{F}(I^{int})$ are calculated, and the transfer function is obtained by $R = \mathcal{F}^{-1}[\mathcal{F}(I^{int})/\mathcal{F}(I^{sim})]$, using the well-known convolution theorem $\mathcal{F}(f \otimes g) = \mathcal{F}(f) \cdot \mathcal{F}(g)$.

Fig. 1 shows the elements used in the determination of the transfer function $R$: the spline-interpolated measured current transient $I^{int}$, the simulated current transient before convolution $I^{sim}$, and $R$ obtained as described. As shown in Fig. 3 the transients for electrons and holes at 1000 V are very similar implying that at high fields around 50 kV/cm the drift velocities of electrons and holes are also similar. As a result, $I^{sim}$ for *IR* at 1000 V, which is a superposition of electron and hole drift, is to a good approximation a straight line without a tail from slower holes. The time step for all curves is 10 ps. The time shift between the simulated and the measured transient is arbitrary. It does not change the shape of $R$, but just its position along the time axis.

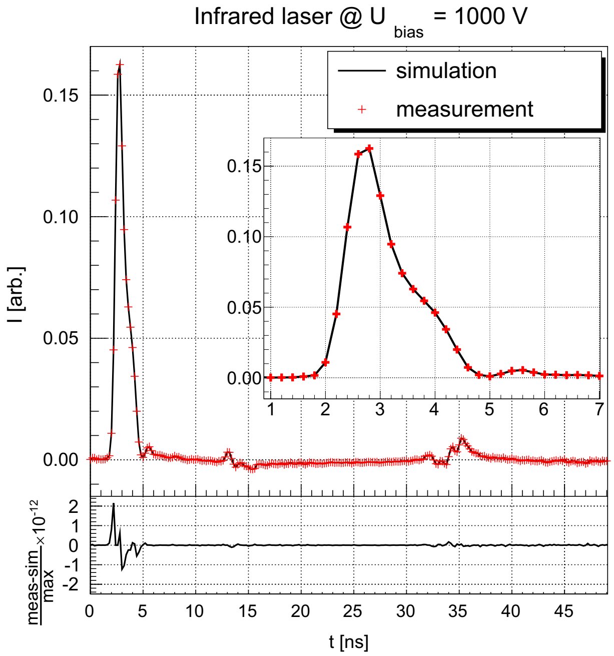

**Fig. 2.** Comparison of the measured current transient (crosses) with the simulated one (solid line) for *IR* at 1000 V. The transfer function used for the convolution has been determined from this measurement.

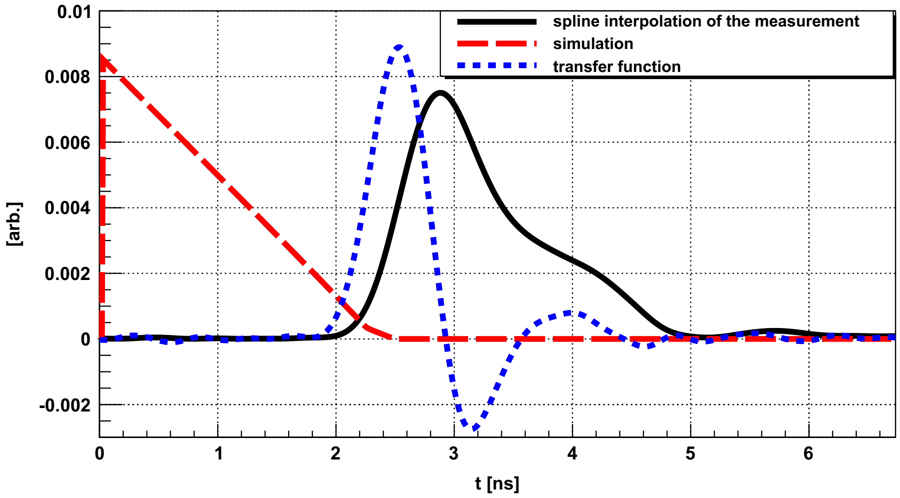

**Fig. 1.** Determination of the transfer function $R$ (dotted) from the spline interpolation of the measured transient $I^{int}$ (solid) and the simulated transient $I^{sim}$ (dashed) for the signal of electrons and holes produced by 1060 nm laser light (*IR*) at 1000 V.