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Extraction of source functions of surface photovoltage transients at very short times

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ABSTRACT

The measurement of surface photovoltage (SPV) transients over 12 orders of magnitude in time was recently demonstrated [Rev. Sci. Instrum. **88**, 053904 (2017)]. In dedicated experiments, however, a high-impedance buffer shall be placed outside the measurement chamber, which has consequences for SPV measurements at very short times. By varying the LCR circuit of a measurement configuration, applying a multi-parameter fit and simulating the corresponding SPV transients, we show, on the examples of highly doped silicon and a CdS thin film, that the source function of SPV transients can be reconstructed with a resolution time better than 1 ns.

Surface photovoltage (SPV) transients can be measured over 12 orders of magnitude in time starting from the ns range.[1] In those measurements, the high-impedance buffer for coupling out the SPV signals was placed inside the measurement chamber. The incorporation of transient SPV measurements into more complex setups, for example, ultra-high vacuum chambers,[2] is desired. The high-impedance buffer has to be placed outside the chamber in such a case and a minimum length of a wire connecting the reference electrode with an electrical feed-through (d_L) cannot be avoided (see the inset of Fig. 1). Typically, d_L is of the order of 2–20 cm depending on the size and construction of the chamber. In this note, the additional parasitic inductance (L) and capacitance (C) and the role of a series resistance (R) will be considered for the analysis of SPV transients at very short times.

The inductance of a free wire is about 10 nH/cm.[3] The capacitances of a BNC feed-through, a shielded high-impedance buffer, and a measurement capacitor are typically about 2.2, 4–7, and 10–100 pF, respectively (own measurements). Therefore, the voltage pulse of a SPV transient can excite oscillations disturbing SPV transients in the ns range. The extraction of undisturbed SPV transients, also called source functions of measured SPV transients, is important for extending transient SPV measurements to complex setups.

Figure 1 shows SPV transients in the ns range of (a) a highly n-type doped c-Si sample [c-Si(n^{++})] and (b) a CdS thin film measured for different values of d_L (2, 6, 12, and 22 cm). The transients were excited with laser pulses (NT230, duration time 3 ns, wavelength 540 nm, intensity 1 mJ/cm^2) and measured at a sampling rate of 4 GS/s (Rohde & Schwarz HMO3004, bandwidth 1 GHz). The high-impedance buffer was based on the operational amplifier OPA656 (see Ref. 4 for details). The reference electrode with the sample was placed in a shielded box. Damped oscillations were excited and the period of the oscillations decreased with decreasing d_L.

For the shortest d_L, the measured transients were only weakly disturbed. The SPV transient of c-Si(n^{++}) increased to 142 mV within the first 2–3 ns and decreased to 50 mV within the following 10 ns, i.e., the relaxation time constant was of the order of 10 ns. Regarding an Auger recombination coefficient of highly doped c-Si of 3×10^{-31} cm^6/s[5] and an Auger recombination lifetime of 10 ns, the density of free electrons

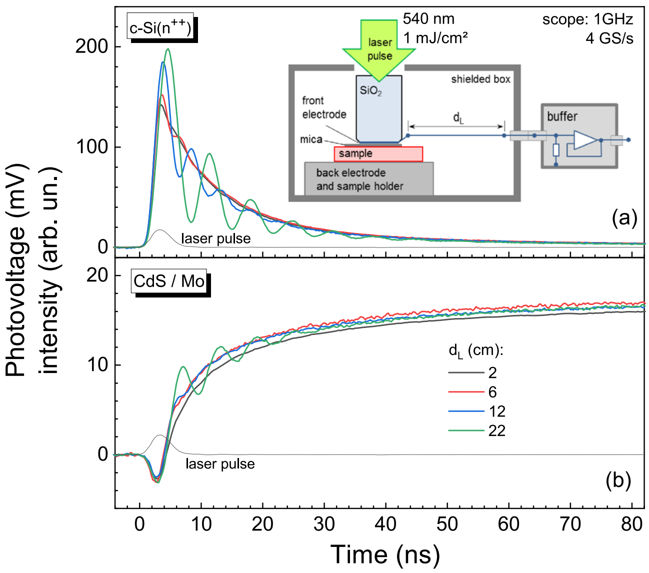

FIG. 1. Surface photovoltage transients of highly n-type doped crystalline silicon (a) and a CdS thin film (b) measured for different lengths of the wire connecting the reference electrode with the electrical feed-through to the high-impedance buffer (d_L equal to 2, 6, 12, and 22 cm: black, red, blue, and green lines, respectively). The thin grey line gives the shape of the exciting laser pulse. The inset shows the schematic measurement configuration.

of 2×10^{19} cm^{-3} is obtained, which is in excellent agreement with the sample (specific resistance 3 mΩ cm). The amplitude of the SPV transient of the CdS thin film increased to negative values of up to −2.6 mV within the first 2.5 ns, became positive at 4 ns, and increased to about 16 mV at longer times. The analysis of such very short overshoots in SPV transients is of interest for the investigation of trapping of charge carriers at electronic states near the surface and charge transport. The extraction of the correct source function of the SPV transient is therefore very important for future experiments.

A measured SPV transient is a superposition of the source function, the function describing the resolution time and the damped oscillations. The product of the source function and the function describing the resolution time is also called the fit function. The function describing the resolution time has been described by a logistic growth function with the time constant τ_{on}. The value of τ_{on} corresponds to the minimum resolution time of the transient SPV measurements and was constant for all transients.

A multi-parameter fit procedure was developed for extracting the characteristics of the damped oscillations, i.e., the effective values R_{eff}, C_{eff}, and L, and of the source function with the function describing the resolution time. In the experiments, the values of R_{eff} and C_{eff} could vary as well for different d_L due to the changing distances of the wires to metal parts in the shielded box. Random rank numbers were introduced for the fit parameters in order to avoid local minima in fitting. The fits were performed for all transients of c-Si(n^{++}) or CdS in one procedure.

The fit function of c-Si(n^{++}) [$f_{fit}(n^{++})$] consisted of the product of a sum of an exponential decay (undisturbed Auger recombination) and a stretched exponential decay (consideration of additional recombination and transport processes) and a logistic growth function

$$f_{fit}(n^{++}) = \frac{A_1 \cdot \exp(-t/\tau_1) + A_2 \cdot \exp\left(-(t/\tau_2)^{\beta}\right)}{1 + \exp(-(t - t_0)/\tau_{on})}. \tag{1}$$

For the CdS thin film, the source function [f_{fit}(CdS)] consisted of the product of a sum of an exponential growth, a stretched exponential growth, a negative exponential decay, and a logistic growth function

$$f_{fit}(\mathrm{CdS}) = \frac{A_1 \cdot [1 - \exp(-t/\tau_1)] + A_2\left[1 - \exp\left(-(t/\tau_2)^{\beta}\right)\right] - A_3 \cdot \exp(-t/\tau_3)}{1 + \exp(-(t - t_0)/\tau_{on})}. \tag{2}$$

The time constants ($\tau_{1,2,(3)}$), stretching parameters (β), and amplitudes ($A_{1,2,(3)}$) were specific for c-Si(n^{++}) and CdS and independent of d_L.

The function of the damped oscillations [f_{fit}(osc)] is well known

$$f_{fit}(osc) = A_0 \cdot \sin\left(\sqrt{\frac{1}{L \cdot C_{eff}} - \left(\frac{R_{eff}}{2L}\right)^2} \cdot t + \varphi\right) \cdot \exp\left(-\frac{t \cdot R_{eff}}{2L}\right). \tag{3}$$

The transients measured for d_L equal to 2, 6, 12, and 22 cm were fitted using Eqs. (1) and (3) for c-Si(n^{++}) or Eqs. (2) and (3) for CdS. Before fitting, the rough values of the phase (φ), $A_{0,1,2,(3)}$, $\tau_{1,2,(3)}$, β, t_0, τ_{on}, L, C_{eff}, and R_{eff} were obtained.

The value of τ_{on} was 0.6 ns which was in excellent agreement with the band width of the high-impedance buffer (OPA656: 500 MHz) and the increase in the intensity of the laser pulse. Therefore, a resolution time below 1 ns was reached with the given setup. Furthermore, the values of L scaled very well with d_L {20, 55, 118, and 203 nH [c-Si(n^{++})] and 27, 61, 144, and 254 nH (CdS) for 2, 6, 12, and 22 cm, respectively}, and the values of R_{eff} and C_{eff} were around 48–60 Ω and 4–7 pF, respectively, for the different samples and d_L. For c-Si(n^{++}), the values of A_1, A_2, τ_1, τ_2, and β were 260 mV, 31.5 mV, 7 ns, 25 ns, and 0.85, respectively. For CdS, the values of A_1, A_2, A_3, τ_1, τ_2, τ_3, and β were 11.1 mV, 6.7 mV, 6.1 mV, 6.5 ns, 13.4 ns, 2.7 ns, and 0.37, respectively.

Due to the transfer of signals through the measurement configuration including the high-impedance buffer, the position of the maximum in SPV transients at very short times is not really well defined since the onset of a measured SPV transient can be shifted in relation to the onset of the laser pulse. In order to get information about shifts of signals at

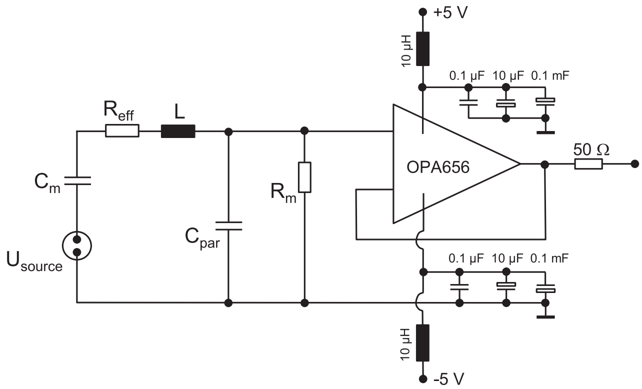

FIG. 2. Equivalent circuit used for the *multisim* (National Instruments) simulations of SPV transients from a source function. C_{eff} results from C_m and C_{par} (measurement and parasitic capacitances resulting mainly from the BNC connectors and electrical feed-throughs). R_{eff} and L are caused mainly by the sheet resistance of the reference electrode and the wire connecting the reference electrode with the feed-through, respectively. C_m and C_{par} can be replaced by C_{eff} which is equal to $C_m \cdot C_{par}/(C_m + C_{par})$.

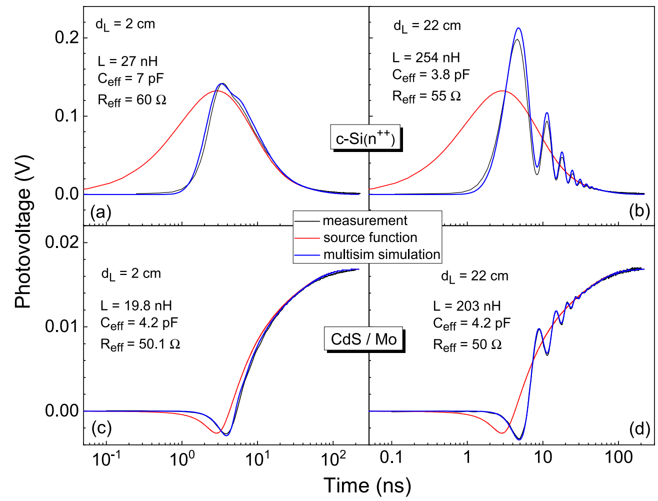

FIG. 3. Measured SPV transients (black lines), extracted source functions (red lines), and with *multisim* (National Instruments) simulated SPV transients (blue lines) of highly n-type doped crystalline silicon [(a) and (b)] and a CdS thin film [(c) and (d)] measured for d_L equal to 2 [(a) and (c)] and 22 cm [(b) and (d)]. The parameters of the effective RCL are given.

very short times and in order to verify self-consistently the fit functions, *multisim* (National Instruments) was used to simulate SPV transients from the source functions and the values of L, C_{eff}, and R_{eff}. For this purpose, an LCR circuit with L, C_{par}, and R_{eff} was added in the equivalent scheme (Fig. 2). R_{eff} was mainly caused by the sheet resistance of the electrode. C_{eff} resulted from C_m (measurement capacitance) and C_{par} (parasitic capacitance due to BNC connectors and the electrical feed-through). R_m was set to 10 GΩ, and the filtering of frequencies from the power supply with an inductance (10 μH) and 3 capacitors (100 nF, 10 μF, 100 μF) was considered. The parameters of the OPA656 were already implemented into the software library of *multisim*. The logistic growth function in Eqs. (1) and (2) resulted from the resolution time of the setup. Furthermore, the onset of a logistic growth function is not well defined from an experimental point of view (parameter t_0 was implemented). Therefore, the logistic growth function in Eq. (1) was replaced by an exponential growth function in the source function for c-Si(n^{++}) with a time constant of τ set to 1.6 ns. For the CdS thin film, the source function was equal to the fit function since SPV transients could not be very well reproduced with an exponential instead of the logistic growth function.

Figure 3 compares the measured SPV transients for c-Si(n^{++}) and CdS with the source functions and simulated transients for d_L equal to 2 and 22 cm. A very good agreement was found between the measured and simulated transients, i.e., the very simple model including L, C_{eff}, and R_{eff} can be very well applied in order to extract the fit or source functions from the measured SPV transients. The resolution time of about 0.6 ns was also confirmed as a limitation of the measurement configuration with the high-impedance buffer. Furthermore, as a result of the simulations, the simulated transients were delayed by about 1 ns in comparison to the source functions. The main peaks of the simulated transients were shifted in relation to the peaks of the source functions by 0.5, 1.9, 1.0, and 1.8 ns for d_L equal to 2 and 22 cm for c-Si(n^{++}) and 2 and 22 cm for CdS, respectively. Therefore, delays, time shifts, and shapes of SPV transients depend on the source function and on the measurement configuration. This shall be considered when comparing transient SPV measurements performed on different samples and at different setups.

Finally, the source transients were extracted from SPV transients with a resolution time of 0.6 ns. With respect to our analysis, resolution times down to 100 ps seem possible for transient SPV measurements if the duration time of laser pulses will be further reduced and the bandwidths of the operational amplifier and of the oscilloscope will be increased. For example, a naked chip of an operational amplifier with a bandwidth higher than 1–2 GHz and a very low input capacitance, such as the OPA859, may be bonded directly to a pcb (printed circuit board) to further reduce parasitic effects. At the same time, it is recommended to keep d_L as short as possible or to vary d_L in order to avoid artifacts in the interpretation. Incidentally, the development of a general algorithm for the extraction of source functions will also be useful for other kinds of transient measurements.

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