Compensation for RC-effects in organic photodiodes with large sheet resistances

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***Abstract*—Transient measurements on semiconductor devices are distorted by parasitic effects due to the geometric capacitance of the device and the impedance of the attached measurement circuit. Together they form an RC-circuit. Ideally, the transient decay of the pulse response generated by such an RC-circuit follows an exponential function. We investigate the differential equations of the case of an oblong rectangular photodiode with significant sheet resistance of one electrode. We find that under a specific illumination profile the ideal RC-decay can be obtained which is an useful result for RC-compensation in organic photodiodes.**

I. Introduction

Organic photodiodes are of great interest for research on organic solar cell materials. In this research, the charge carrier movement inside the semiconductor layer is investigated. Real devices, however, show parasitic effects due to the displacement current of the intrinsic geometric capacitance. Due to the comparably low layer thicknesses the RC time constant of such devices reaches values where RC-effects dominate the pulse shape [1]. These RC effects can easily be compensated for in devices with small sheet resistances in order to investigate the charge carrier movement in semiconductors [2]. Devices with large sheet resistances show an exponential RC-decay with a modified time constant for long times. For very short times, however, there can be some deviations from the exponential decay [3]. In order to achieve a good RC-compensation in oblong devices with significant sheet resistances we investigate the interplay of the illumination profile of pulsed excitation with the transient RC-decay in the extended electrodes.

II. Optimum illumination profile

In order to derive the optimum illumination profile we need to investigate the relationship between the shape of the pulse response, the device parameters and the illumination profile.

A simple model for a photodiode with a small electrode resistance is shown in Fig. 1a. Here, the total current i_{tot} measured in the load resistance R_{L} can be divided into two parts, the displacement current i_{dis} and the conduction current i_{cond}. The conduction current is the quantity of interest for semiconductor phenomena. The displacement current in the geometric capacitance of the device, however, leads to a pulse deformation. Here, the RC-time τ gives a measure below which value transients will be severely deformed. For a device with a small electrode resistance it is

$$\tau_{\mathrm{small}} = R_{\mathrm{L}} C \tag{1}$$

with R_{L} being the external resistance and C being the device capacitance. The conduction current i_{cond} from the measured current i_{tot} and its derivative $\dot{i}_{\mathrm{tot}}$ as

$$i_{\mathrm{cond}} = i_{\mathrm{tot}}(t) + \tau \dot{i}_{\mathrm{tot}}(t) \tag{2}$$

thereby compensating for the RC-effects [2].

For devices with significant sheet resistances, however we find that the initial pulse decay does not follow an exponential [3]. Instead we need to model the system as an RC-network shown in Fig. 1c. For simulation the continuous line resistance R' and capacitance C' is divided in a number of discrete resistances ΔR and ΔC over the device length l. The total electrode resistance is $R_{\mathrm{E}} = R' l$. We find that the time constant for this system depends on the combination of line resistance, capacitance and the load resistance [3]. It is given by

$$\tau_{\mathrm{extended}} = \frac{R' C'}{\alpha^2} \tag{3}$$

where α is a correction factor given by the solution of the nonlinear equation

$$\frac{R_{\mathrm{L}}}{R'} \alpha \tan(\alpha l) = 1. \tag{4}$$

In Fig. 2 we show the simulated pulse decay of the RC-network under uniform illumination. Here, we see a deviation from the ideal exponential decay needed for perfect RC-compensation according to Eq. 2 at short times. Illumination

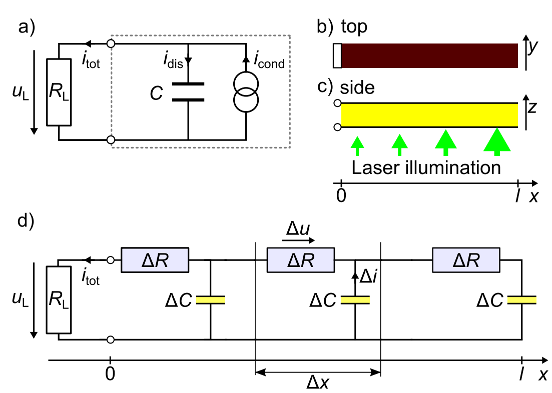

Figure 1. a) The simplified RC-circuit [2]. b) top view and c) side view of the geometry of the photodiode with extended electrodes. The laser profile is graded along the long side of the device. d) Discretized equivalent circuit of a photodiode with extended electrodes [3].

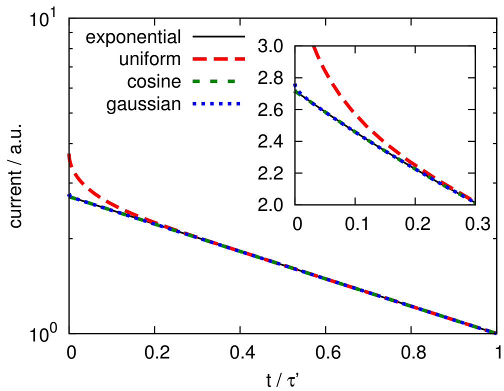

Figure 2. Transient RC-response for different illumination profiles for the case of $R_{\mathrm{E}} = R_{\mathrm{L}}$. Uniform illumination causes some deviation from the ideal exponential decay. Illumination with a properly truncated cosine shape reproduces the exponential decay very well. The Gaussian profile fitted to the cosine shape only causes minor deviations. The inset shows a detail with the vertical axis in linear scale.

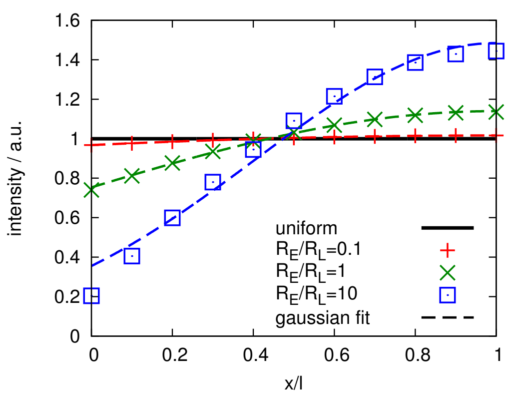

Figure 3. Uniform illumination profile (solid line), truncated cosine illumination profiles (symbols) for different ratios of $R_{\mathrm{E}}/R_{\mathrm{L}}$, and the corresponding Gaussian fits (dashed lines).

close to or far from the electrode contacts leads to a vastly different pulse response in the time domain below $0.5 \cdot \tau$ [3].

The reason for this behavior is the initial charge redistribution inside the network in Fig. 1c. For later times, the curves all follow an exponential decay with the time constant according to Eq. 3 and 4. Therefore if we can avoid this initial charge redistribution, we can provide a better pulse decay allowing for better RC compensation.

In order to find this profile, we can look at the dynamic equilibrium voltage distribution for long time scales

$$u(x) = U_0 \cos(\alpha x) \tag{5}$$

which has a cosine shape [3]. From this we conclude that a cosine shaped illumination profile

$$I(x) \propto \cos(\alpha x) \tag{6}$$

provides the perfect initial charge distribution inside the device to compensate for the RC-effects.

The value of x ranges form 0 to l and the value of αl is smaller than $\pi/2$ [3]. This means that the ideal illumination profile is a truncated cosine. With $\gamma = \alpha l$ we can rewrite Eq. 4 as

$$\gamma \tan(\gamma) = \frac{R_{\mathrm{E}}}{R_{\mathrm{L}}}. \tag{7}$$

From Eq. 7 it becomes obvious that the value of γ and therefore the truncation point of the cosine function solely depends on the ratio of load to electrode resistance.

III. Results and Discussion

The simulated results are shown in Fig. 2 for a device with $R_{\mathrm{E}}/R_{\mathrm{L}} = 1$. For uniform illumination we obtain a significant deformation of the pulse shape for short time spans.

We therefore solve Eq. 7 and calculate the corresponding illumination profile using Eq. 6 for different values of $R_{\mathrm{E}}/R_{\mathrm{L}}$. The truncated cosine profile is shown in Fig. 3 along with the corresponding Gaussian fit which is chosen as a typical laser beam profile [4]. The cosine profile for a low electrode resistance is almost flat. For the case of $R_{\mathrm{E}}/R_{\mathrm{L}} = 1$ we see a significant drop in illumination close to the extraction electrode. This drop compensates for the initial peak under uniform illumination in the transient in Fig. 2. The corresponding simulation results verify that for the cosine profile, this compensation works perfectly. The fitted Gaussian curve, emulating a laser light beam profile, is very close to the cosine shape and results in a very tiny initial peak in the transient simulation.

IV. Conclusion

We analytically investigated the transient behavior of an oblong photodiode with significant sheet resistance. We showed that the non-ideal pulse decay which may negatively impact RC-compensation can be avoided by using a better illumination profile. The perfect solution is a truncated cosine profile. A fitted Gaussian illumination profile also produces very good results. From this we conclude that fitting illumination profiles is a useful tool for measurements on devices with electrodes which have significant sheet resistance.

References

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