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# Effect of the depletion layer capacitance on the mobility determination using transient current extraction of doping-induced charge carriers

Oskar J. Sandberg, Mathias Nyman, Staffan Dahlström, and Ronald Österbacka\*

<sup>a</sup>Åbo Akademi University, Physics/Faculty of Science and Engineering, Center for Functional Materials, Porthaninkatu 3, Turku, Finland, 20500

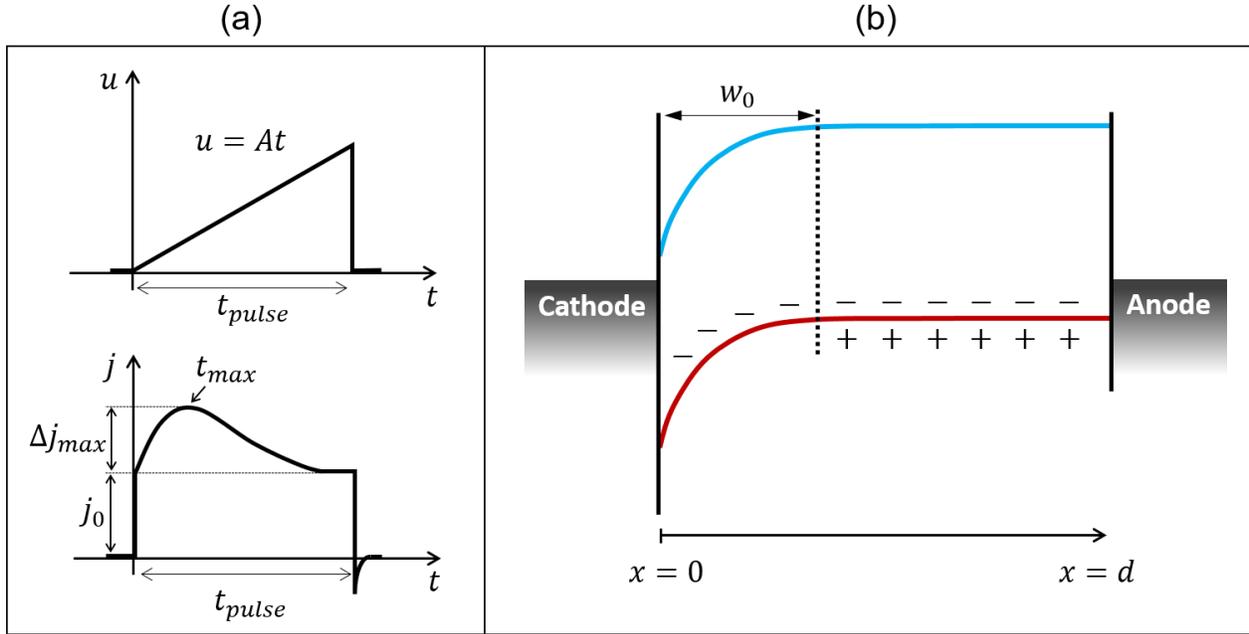
**Abstract.** We use drift-diffusion simulations to clarify the effect of a steady-state depletion layer on the mobility determination using the charge extraction by linearly increasing voltage (CELIV) technique in case of extraction of doping-induced charge carriers. Previous expressions used to extract the mobility from CELIV neglects the effect of the displacement current from the steady-state depletion layer. Accounting for the steady-state depletion layer give rise to a saturation of the extraction current transients to a capacitive regime limited by the depletion layer capacitance. As a consequence of this saturation effect, the standard mobility formulas can overestimate the mobility by several orders of magnitudes if the voltage ramp up rate is not sufficiently large. Based on the simulations, we present a new expression to extract the mobility from CELIV, that takes the displacement current of the depletion layer into account.

**Keywords:** CELIV, mobility, doping, organic solar cells, thin films, drift-diffusion.

\*Ronald Österbacka, E-mail: [rosterba@abo.fi](mailto:rosterba@abo.fi)

## 1 Introduction

Doped organic semiconductor layers are an indispensable component in many organic electronic devices such as organic light emitting diodes (OLEDs) and solar cells.<sup>1,2</sup> Doped layers are frequently used to improve the charge selectivity of contacts by blocking the extraction (or injection) of one charge carrier, and facilitating extraction (or injection) of the other charge carrier. Most OLEDs are based on such an architecture, with the (intrinsic) recombination layer sandwiched between highly n- and p-doped layers, at the cathode and anode respectively, in a so-called p-i-n or n-i-p structure.<sup>3</sup> Charge selective interlayers are also very important in solar cells since poor charge selectivity of the contacts results in losses in performance due to surface recombination.<sup>4-9</sup> Highly selective contacts are particularly important for devices with low bulk recombination, such as perovskite solar cells, as surface recombination is the main loss channel in this case.<sup>5-7</sup>



**Fig. 1** (a) Schematic picture of the CELIV method showing the applied linearly increasing voltage and the corresponding current transient response. (b) Band diagram of a p-doped organic semiconductor layer sandwiched between a low work function cathode and a high work function anode.

The conductivity  $\sigma$  of a doped layer is given by  $\sigma = en\mu$ , where  $e$  is the elementary charge,  $n$  is the charge carrier density and  $\mu$  is the charge carrier mobility. For optimal device performance, it is desirable that the doped interfacial layers have as high a conductivity as possible, which means that the carrier concentration and mobility should be maximized. Thus, in order to improve the quality of charge selective layers further, reliable characterization techniques that can decouple the carrier concentration and mobility are needed.

Charge extraction by linearly increasing voltage, or CELIV, has become one of the most frequently used technique for determining mobility and recombination in thin film devices based on low mobility materials, most notably organic solar cells.<sup>10-12</sup> Moreover, we recently showed that CELIV in the doping-induced capacitive regime (doping-CELIV) can be used to determine the doping-induced charge carrier concentration and the built-in potential.<sup>13-16</sup> In CELIV, a ramp up voltage pulse is applied in reverse bias (or with blocking contact) to extract charge carriers from the device, the voltage ramp up rate  $A$  is given by  $A = u_{max}/t_{pulse}$  where

$u_{\max}$  is the amplitude applied voltage pulse and  $t_{\text{pulse}}$  is the length of the pulse. A schematic of the CELIV method is shown in Fig. 1(a). When the voltage ramp up rate is low enough, the extraction current transient will be directly proportional to the inverse square of the depletion layer capacitance allowing for determination of the doping concentration.<sup>13</sup> The mobility can be determined from the time the extraction current transient reaches its maximum value,  $t_{\max}$ , as shown in the theory section below.

In accordance with the previously presented doping-CELIV theory,  $A$  needs to be high enough ( $t_{\text{pulse}}$  short enough) in order for the mobility determination to be reliable.<sup>13</sup> However,  $t_{\max}$  has to be much larger than the RC time constant of the outer circuit, which limits how large  $A$  can be used (larger  $A$  results in smaller  $t_{\max}$ ). Especially in the case of highly doped layers, or in materials with high mobility, it is experimentally challenging to achieve a high enough  $A$  for a reliable determination of the mobility. In this paper we use drift-diffusion modelling to show that the extraction current transient is ultimately limited by the depletion layer capacitance, leading to a saturation of the extraction current at low voltage ramp up rates. In this saturation regime it is not possible to determine the mobility. We present an analytical expression for determining the mobility when approaching the saturation regime, which greatly expands the measurement regime for mobility determination.

## 2 Theory

We consider a p-doped layer with mobile holes of density  $p$  and immobile negative charges of density  $N$ , which in this case corresponds to ionized dopants. At  $t > 0$ , a linearly increasing voltage is applied, resulting in extraction of holes at the collecting contact ( $x = d$ ). The extracted holes leave a negatively charged space charge layer behind; the charge density is given by

$$\rho(x, t) = e[p(x, t) - N] = \begin{cases} -eN, & x < w(t) \\ 0, & x \geq w(t) \end{cases}, \quad (1)$$

where  $w(t)$  is the extraction depth, corresponding to the thickness of the depleted layer. Note that  $p = N$  for  $x \geq w$ . By the continuity equation, the conduction current at the extracting contact  $x = d$  need to equal the rate of charge carriers leaving the device:  $j_c(d, t) =$

$ep\mu E(d, t) = ep dw/dt$ , where  $E(x, t)$  is the electric field. Under these conditions, the total transient current density  $j(t) = \epsilon\epsilon_0 \partial E/\partial t + j_c(x, t)$  becomes equal to

$$j(t) = j_0 + \Delta j(t), \quad (2)$$

with  $j_0 = \epsilon\epsilon_0 A/d$  and

$$\Delta j(t) = ep \frac{dw}{dt} \left(1 - \frac{w}{d}\right), \quad (3)$$

where in accordance with the Poisson equation  $dE/dx = \rho(x, t)/\epsilon\epsilon_0$ , the extraction depth is related to the applied voltage  $At$  as

$$At + u_0 = \int_0^d E(x, t) dx = \frac{d}{\mu} \frac{dw}{dt} + \frac{eNw^2}{2\epsilon\epsilon_0}, \quad (4)$$

where  $u_0$  is the total potential difference prior to the pulse. Here, the term  $eNw^2/2\epsilon\epsilon_0$  on the right side originates from the space charge of the immobile charges, inhibiting the extraction of the mobile holes.

In the original derivation of the CELIV theory, first presented by Juska *et al.*<sup>11,12,17</sup> and later revisited by others,<sup>18-20</sup> only the special case  $u_0 = 0$  was considered, which corresponds to the case when the built-in voltage is either zero or exactly cancelled by an offset voltage. Under these considerations, the conductivity  $\sigma = eN\mu$  can be obtained via<sup>12,17</sup>

$$\Delta j_{max} = \frac{2}{3} \sigma \frac{At_{max}}{d} = j_0 \frac{2t_{max}}{3\tau_\sigma}, \quad (5)$$

where  $\tau_\sigma \equiv \epsilon\epsilon_0/eN\mu$  is the dielectric relaxation time (within the neutral region), and  $\Delta j_{max} = \Delta j(t_{max})$ . Moreover,  $t_{max}$  is related to the mobility via

$$t_{max} = \sqrt{\frac{2d^2}{3\mu A \left[1 + \chi \frac{\Delta j_{max}}{j_0}\right]}}, \quad (6)$$

where  $\chi$  is a numerical correction factor; Juska *et al.* originally found  $\chi = 0.36$ .<sup>12,17</sup> This correction factor was later revisited by other groups,<sup>18-20</sup> for example, Deibel proposed  $\chi = 0.21$ .

In general, however,  $u_0 \neq 0$  and in the case of doping, a steady-state depletion layer, of thickness  $w_0$  and adjacent to the blocking contact ( $x = 0$ ), is present in the active layer (prior to the voltage pulse); see Fig. 1(b). This depletion layer is formed by diffusion to compensate for the work function difference (the built-in potential) of the contacts, the device being equivalent to a Schottky junction. Accounting for diffusion, Eq. (4) can then be re-expressed as<sup>13</sup>

$$\frac{dw}{dt} = \frac{\mu A t}{d} - \frac{e N \mu}{2 \epsilon \epsilon_0 d} (w^2 - w_0^2), \quad (7)$$

$$w_0 = \sqrt{\frac{2 \epsilon \epsilon_0}{e N} \left( u_0 - \frac{k T}{e} \right)}, \quad (8)$$

for  $u_0 \gg kT/e$  and  $w_0 < d$ . As a part of the mobile carriers have already been extracted prior to the pulse due to the presence of a steady-state depletion layer  $w_0$ , the current maximum in the low conductivity-limit ( $\Delta j_{max} \ll j_0$ ) is in this case given by

$$\Delta j_{max} = j_0 \frac{2 t_{max}}{3 \tau_\sigma} \left( 1 - \frac{w_0}{d} \right), \quad (9)$$

being the analogous expression to Eq. (5) for  $w_0 \neq 0$ . Correspondingly, Eq. (6) is modified as<sup>13</sup>

$$t_{max} = \sqrt{\frac{2 d (d - w_0)}{3 \mu A \left[ 1 + \chi \frac{\Delta j_{max}}{j_0} \right]}}, \quad (10)$$

Note that, in accordance with Eq. (6) and Eq. (10), we expect  $t_{max}/t_{tr} = 1/\sqrt{3}$ , in the limit when  $\Delta j_{max}/j_0 \rightarrow 0$ , where  $t_{tr} \equiv \sqrt{2 d (d - w_0) / \mu A}$ .

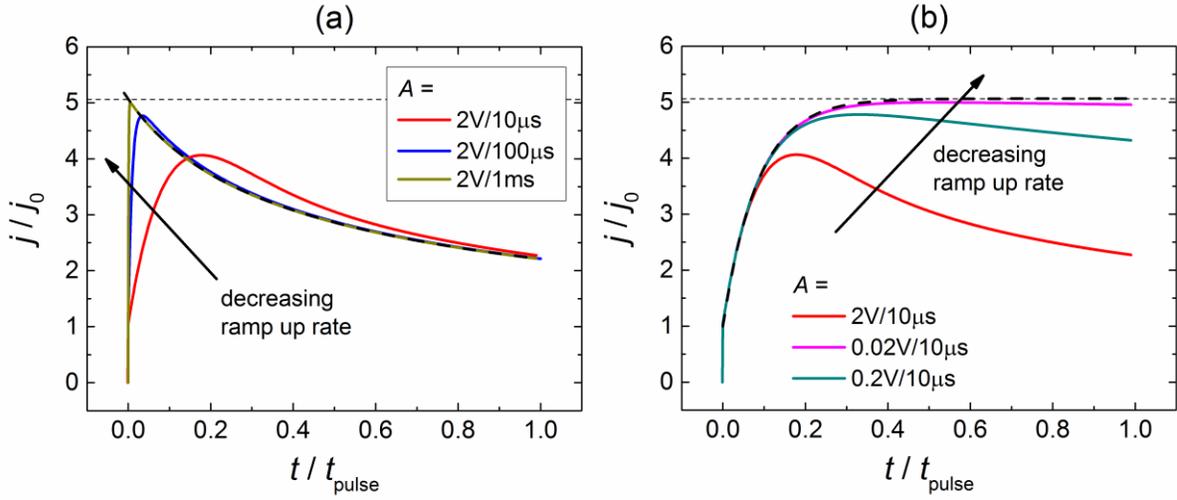
The above expressions Eq. (9) and Eq. (10), being the generalizations of Eq. (5) and Eq. (6), respectively, which are used to determine the mobility in CELIV, neglects the impact of the displacement current of the depletion layer. In the following, the impact of the depletion layer capacitance on the CELIV current transients and the mobility determination is investigated by means of drift-diffusion simulations.

### 3 Methods

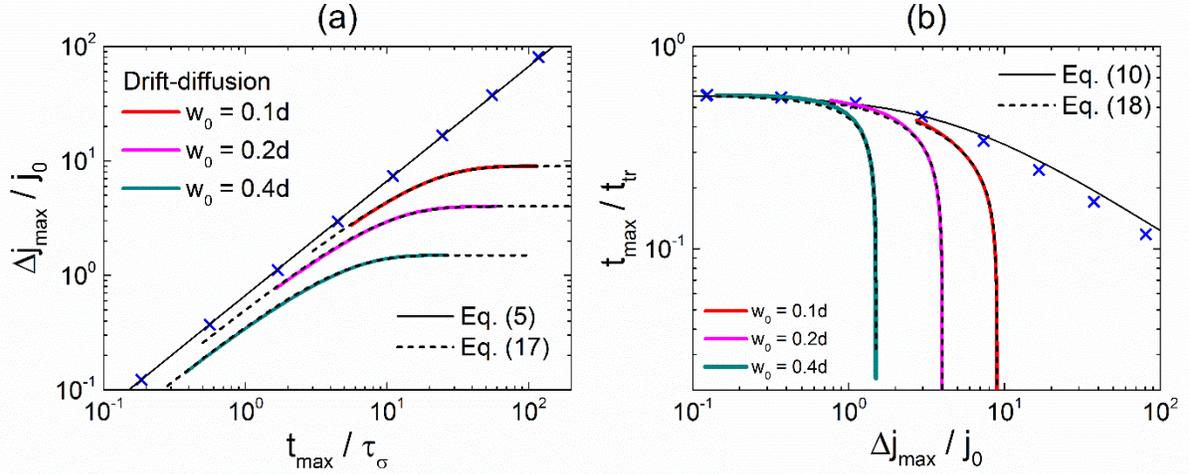
A numerical drift-diffusion model is used for the simulations of the extraction current transients. The device model solves the time-dependent current, with the conduction current given by the drift-diffusion equation, in conjunction with the Poisson equation. The series resistance from the external circuit is omitted. The details of the model can be found in Refs. 21 and 22.

### 4 Results and Discussion

We assume a p-doped active layer with  $\mu = 10^{-4} \text{ cm}^2/\text{Vs}$  and  $d = 200 \text{ nm}$ . In Fig. 2, simulated CELIV current transients are shown at different voltage ramp-up rates for a p-doped active layer of  $N = 10^{17} \text{ cm}^{-3}$ . It can be seen that a saturation of the CELIV current transients takes place at small  $A$ , both in the limit of long pulses and low amplitudes, as shown in Fig. 2(a) and (b), respectively. Fig. 3(a) shows the current transient maximum  $\Delta j_{max}/j_0$  as a function of  $t_{max}/\tau_\sigma$ , as extracted from the simulated current transients by varying  $A$ , at different  $w_0$  (different  $N$ ). The corresponding  $t_{max}$  as function of  $\Delta j_{max}/j_0$  is shown in Fig. 3(b), where  $t_{max}$  have been normalized by  $t_{tr}$ . A good agreement between the analytical approximations and the drift-diffusion simulations is found at low  $\Delta j_{max}/j_0$ . At larger  $\Delta j_{max}$ , however, a saturation of  $\Delta j_{max}$  can be seen, leading to a serious deviation between the analytical approximations, Eq. (9) and Eq. (10) (or Eq. (5) and Eq. (6), respectively), and the full drift-diffusion simulations. Clearly, the impact of the depletion layer becomes significant in this regime.



**Fig. 2** Simulated extraction current transients for varying voltage ramp up rates: (a) increasing voltage pulse and (b) decreasing voltage amplitude. The dashed line in (a) and (b) correspond to the analytical prediction [Eqs. (11) and (14)], respectively. The thin short-dashed lines corresponds to the upper limit set by the depletion layer capacitance.



**Fig. 3** The time of the current maxima  $t_{max}$  and the corresponding current value  $\Delta j_{max}$  extracted from the simulations are shown for different  $w_0$  in (a) as  $\Delta j_{max}/j_0$  versus  $t_{max}/\tau_\sigma$ , and (b) as  $t_{max}/t_{tr}$  versus  $\Delta j_{max}/j_0$ . The thin solid line in (a) and (b) correspond to Eqs. (5) and (10), respectively. In Eq. (10), we assume  $\chi = 0.21$ ; for comparison, however, the exact solution to the drift-only model for  $u_0 = w_0 = 0$  (see Lormann *et al.*<sup>20</sup>) is indicated by the crosses. In the drift-diffusion simulations  $w_0 = 0.4d$ ,  $0.2d$ , and  $0.1d$  correspond to  $N = 5 \times 10^{16} \text{ cm}^{-3}$ ,  $2 \times 10^{17} \text{ cm}^{-3}$ , and  $8 \times 10^{17} \text{ cm}^{-3}$ , respectively.

To understand the reason for this saturation, we first need to clarify the transient behavior occurring in the limit of small  $A$  in Fig. 2. At slow pulses  $t_{pulse} \gg t_{max}$ , the change in the voltage is slow enough for the electric field redistribution to occur and  $E(x, t) = 0$  within neutral region. In this case, the  $dw/dt$  term in Eq. (7) becomes negligibly small (compared with the other terms); the current in this limit becomes (see Appendix A)

$$j(t) = \frac{\epsilon\epsilon_0 A}{w}, \quad (11)$$

$$w = \sqrt{\frac{2\epsilon\epsilon_0}{eN} \left( At + u_0 - \frac{kT}{e} \right)}, \quad (12)$$

as previously shown in Ref. 13. At low amplitudes,  $u_{max} \rightarrow 0$  (or high  $N$ ), on the other hand, a different situation occurs. In this limit, the induced change  $\Delta w = w(t) - w_0$  in the extraction depth during the CELIV pulse is small compared to  $w_0$ . Under these conditions ( $\Delta w \ll w_0$ ), Eq. (7) can be approximated as

$$\frac{d\Delta w}{dt} \approx \frac{\mu At}{d} - \frac{eN\mu w_0}{\epsilon\epsilon_0 d} \Delta w. \quad (13)$$

After solving for  $\Delta w$  and substituting into Eq. (3) (noting that  $w \approx w_0$ ), we then find for the current transient

$$\Delta j(t) = \Delta j_{sat} \left[ 1 - \exp\left(-\frac{w_0 t}{d\tau_\sigma}\right) \right], \quad (14)$$

where  $\Delta j_{sat} = j_0(d/w_0 - 1)$ . Considering the simulated current transients in Fig. 2(b), it can be seen that the current rise is to an excellent agreement reproduced by Eq. (14) at small time scales and small amplitudes. In this case, the current is limited by the discharging current of depletion layer capacitance  $C_w = \epsilon\epsilon_0/w_0$ , with the current rise of  $\Delta j(t)$  asymptotically approaching the upper value  $\Delta j_{sat}$ , as described by Eq. (14). In this limit, the depletion layer thus acts as an insulator whereas the neutral region effectively behaves as an extension of the electrode (since  $E = 0$ ). We note that this type of saturation is similar to the extraction current saturation (due to the discharging of the insulator) that might occur in CELIV on metal-insulator-semiconductor structures.<sup>23,24</sup>

Equations (11) and (14) implies that the extraction current transients are ultimately limited by the displacement current of the (steady-state) depletion layer given by

$$j_{sat} = \frac{\epsilon\epsilon_0 A}{w_0}, \quad (15)$$

where  $w_0$  is given by Eq. (8) for  $u_0 \gg kT/e$ , explaining the saturation observed in Fig. 3(a). We note that in the special case of  $u_0 = 0$ , the upper limit is instead given  $j_{sat} \rightarrow \epsilon\epsilon_0 A/L_D$ , where  $L_D$  is the (extrinsic) Debye screening length (see Appendix A). The effect of the saturation is to distort the mobility determination, invalidating the standard mobility formulas (Eqs. (9) and (10)) in situations close to saturation. The magnitude of the saturation current  $j_{sat}$  depends on the doping concentration as  $j_{sat} \propto \sqrt{N}$ , increasing with increasing doping level. In contrast, the time scale for the saturation is also strongly dependent on the dielectric relaxation time  $\tau_\sigma$  which decreases with increasing doping concentration. The requirement for Eqs. (9) and (10) to be valid are

$$t_{max} < \tau_\sigma \left[ 1 + \frac{\Delta j_{sat}}{j_0} \right], \quad (16)$$

where  $\Delta j_{sat} \equiv j_{sat} - j_0$ . In case of  $N = 5 \times 10^{16} \text{ cm}^{-3}$  with  $w_0 = 0.4d$ , and assuming a typical mobility of  $\mu = 10^{-4} \text{ cm}^2/\text{Vs}$ ,  $t_{max}$  needs to be smaller than  $\sim 0.8 \mu\text{s}$ . At higher doping concentrations, an accurate mobility determination based on Eq. (10) [or Eq. (9)] consequently becomes challenging from an experimental point of view.

Interestingly, as demonstrated in Fig. 3(a), the extraction current maxima  $\Delta j_{max}$  are well approximated by

$$\Delta j_{max} = \Delta j_{sat} \left[ 1 - \exp\left(-\frac{2t_{max}}{3\tau_\sigma \left[1 + \frac{\Delta j_{sat}}{j_0}\right]}\right) \right], \quad (17)$$

Eq. (17) approaches  $\Delta j_{sat}$  at large  $t_{max}/\tau_\sigma$ , whereas the expected result Eq. (9) is reproduced at small  $t_{max}/\tau_\sigma$  (or  $\Delta j_{max} \ll j_0$ ). Apart from reproducing these two limiting cases, a good agreement is also obtained in the transition region in-between. Based on Eq. (17), an expression for  $t_{max}$  that accounts for the saturation effect, is then directly obtained as

$$t_{max} = \frac{3\epsilon\epsilon_0}{2eN\mu} \left[ \frac{\Delta j_{sat}}{j_0} + 1 \right] \ln \left( \frac{\Delta j_{sat}}{\Delta j_{sat} - \Delta j_{max}} \right), \quad (18)$$

from which the mobility can be calculated. Note that  $\Delta j_{sat}/j_0 = j_{sat}/j_0 - 1 = d/w_0 - 1$ . The doping concentration can be obtained independently of the mobility either directly from the current transient at slow pulses [Eq. (11)] (as demonstrated in Ref. 13) or estimated from  $j_{sat}$ . Upon comparing the simulated values in Fig. 3(b) with the analytical approximation Eq. (18), a good agreement is indeed found. Provided that the extraction current is not fully saturated, Eq. (18) allows for the mobility determination within the region close to saturation. Figure 4 shows the corresponding CELIV mobilities as extracted from the simulated current transients using Eqs. (10) and (18). As expected, not accounting for the saturation caused by the displacement current of the depletion layer might overestimate the mobility by several orders of magnitude. It should be noted that in practice it is experimentally difficult to extract mobilities with Eq. (18) when the extraction current transients  $\Delta j_{max}$  are very close to the saturated value  $\Delta j_{sat}$ . Finally, it should be mentioned that the mobility is generally also dependent on the carrier density. Noting that it is the mobility of carriers extracted from the neutral region that is being measured, the obtained CELIV mobilities correspond to the mobility at  $p = N$ .

## 5 Conclusions

We have shown that the doping-CELIV extraction current is limited by the capacitance of the depletion layer leading to a saturation of  $\Delta j$  at low voltage ramp up rates. This effect can lead to an overestimation of the mobility by several orders of magnitude if the voltage ramp up rate is not sufficiently large (so that  $\Delta j_{max} \ll j_0$ ). However, supported by drift-diffusion modelling we have obtained a new formula for calculating the mobility that takes the saturation effect into account [Eq. (18)], thus making it possible to reliably determine the mobility provided that  $\Delta j_{max} < \Delta j_{sat}$ .

## Appendix A

The Poisson equation for the electrical potential  $\psi(x)$  can be expressed as:<sup>25</sup>

$$\frac{d^2\psi}{dx^2} = -\frac{e}{\epsilon\epsilon_0} [p(x, t) - N] \approx \frac{eN}{\epsilon\epsilon_0} \left[ 1 - \exp\left(-\frac{e\psi(x, t)}{kT}\right) \right], \quad (\text{A.1})$$

where in the last step we assumed  $p(x, t) \approx N \exp(-e\psi(x, t)/kT)$ , taking into account the diffusion of mobile carriers tailing into the depleted region, with the potential taken relative to  $\psi(0, t) = At + u_0$ . Then, upon multiplying both sides with  $E = -d\psi/dx$  and integrating, noting that in the limit of slow pulses we have  $E(d, t) \approx 0$ , yields

$$E(0, t) \approx \sqrt{\frac{2eN}{\epsilon\epsilon_0} \left( At + u_0 - \frac{kT}{e} \left[ 1 - \exp\left(-\frac{e[At+u_0]}{kT}\right) \right] \right)}, \quad (\text{A.2})$$

for the electric field at the blocking cathode contact ( $x = 0$ ). Since the total transient current  $j(t) = j_c(x, t) + \epsilon\epsilon_0 \partial E(x, t)/\partial t$  is independent of position, the total current can be evaluated as

$$j(t) = \epsilon\epsilon_0 \frac{\partial E(0, t)}{\partial t} = \frac{\epsilon\epsilon_0 A \left[ 1 - \exp\left(-\frac{e[At+u_0]}{kT}\right) \right]}{\sqrt{\frac{2\epsilon\epsilon_0}{eN} \left( At + u_0 - \frac{kT}{e} \left[ 1 - \exp\left(-\frac{e[At+u_0]}{kT}\right) \right] \right)}}, \quad (\text{A.3})$$

with the conduction current being negligibly small near the depleted cathode region ( $j_c(0, t) \approx 0$ ). Note that Eq. (A.3) becomes equal to Eq. (11) for  $u_0 \gg kT/e$ . On the other hand, for  $u_0 = 0$ , Eq. (A.3) reduces to

$$j(t) = \frac{\epsilon\epsilon_0 A \left[ 1 - \exp\left(-\frac{eAt}{kT}\right) \right]}{\sqrt{\frac{2\epsilon\epsilon_0}{eN} \left( At - \frac{kT}{e} \left[ 1 - \exp\left(-\frac{eAt}{kT}\right) \right] \right)}}, \quad (\text{A.4})$$

with the upper value given by  $j(t) \rightarrow \epsilon\epsilon_0 A/L_D$  (as  $t \rightarrow 0$ ), where  $L_D \equiv \sqrt{\epsilon\epsilon_0 kT/e^2 N}$  is the extrinsic Debye screening length of the doped active layer.

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## References

1. B. Lüssem, M. Riede, and K. Leo, *Phys. Stat. Sol. A* **210**, 9 (2013)
2. Y. H. Kim, S. Schubert, R. Timmreck, L. Müller-Meskamp, and K. Leo, *Adv. Energy Mater.* **3**, 1551 (2013)
3. R. Meerheim, B. Lüssem, and Karl Leo, *Proc. IEEE*, **97**, 1606 (2009).
4. E. L. Ratcliff, B. Zacher, and N. R. Armstrong, *J. Phys. Chem. Lett.* **2**, 1337 (2011)
5. O. J. Sandberg, A. Sundqvist, M. Nyman, and R. Österbacka, *Phys. Rev. Applied* **5**, 044005 (2016)
6. W. Tress, K. Leo, and M. Riede, *Phys. Rev. B* **85**, 155201 (2012)
7. E. J. Juarez-Perez, M. Wussler, F. Fabregat-Santiago, K. Lakus-Wollny, E. Mankel, T. Mayer, W. Jaegermann, and I. Mora-Sero, *J. Phys. Chem. Lett.* **5**, 680 (2014)
8. E. L. Ratcliff, A. Garcia, S. A. Paniagua, S. R. Cowan, A. J. Giordano, D. S. Ginley, S. R. Marder, J. J. Berry, and D. C. Olson, *Adv. Energy Mater.* **3**, 647 (2013)
9. O. J. Sandberg, S. Sandén, A. Sundqvist, J.-H. Smått, and R. Österbacka, *Phys. Rev. Lett.* **118**, 076601 (2017)
10. A. Pivrikas, N. S. Sariciftci, G. Juška, R. Österbacka, *Progress in Photovoltaics: Research and Applications* **15**, 677-696 (2007)
11. G. Juška, K. Arlauskas, M. Viliūnas, and J. Kočka, *Phys. Rev. Lett.* **84**, 4946 (2000)
12. G. Juska, K. Genevicius, K. Arlauskas, R. Österbacka, and H. Stubb, *Phys. Rev. B* **65**, 233208 (2002)
13. O. J. Sandberg, M. Nyman, and R. Österbacka, *Org. Electron.* **15**, 3413 (2014)
14. A. Sundqvist, O. J. Sandberg, M. Nyman, J.-H. Smått, and R. Österbacka, *Adv. Energy Mater.* **6**, 1502265 (2016)
15. M. Nyman, S. Dahlström, O. J. Sandberg, R. Österbacka, *Adv. Energy Mater.* **6**, 1600670 (2016)
16. M. Nyman, O. J. Sandberg, S. Dahlström, D. Spoltore, C. Körner, Y. Zhang, S. Barlow, S. R. Marder, K. Leo, K. Vandewal, and R. Österbacka, *Sci. Rep.* **7**, 5397 (2017)
17. G. Juška, K. Arlauskas, M. Viliūnas, K. Genevicius, R. Österbacka, and H. Stubb, *Phys. Rev. B* **62**, R16235 (2000)
18. C. Deibel, *Phys. Stat. Sol. A* **206**, 2731 (2009)
19. S. Bange, M. Schubert, and D. Neher, *Phys. Rev. B* **81**, 035209 (2010)

20. J. Lorrmann, B. H. Badada, O. Inganäs, V. Dyakonov, and C. Deibel, *J. Appl. Phys.* **108**, 113705 (2010)
21. O. J. Sandberg, M. Nyman, and R. Österbacka, *Phys. Rev. Applied* **1**, 024003 (2014)
22. S. Sandén, O. Sandberg, Q. Xu, J.-H. Smått, G. Juška, M. Lindén, and R. Österbacka, *Org. Electron.* **15**, 3506 (2014)
23. G. Juška, N. Nekrašas, and K. Genevičius, *J. Non-Cryst. Sol.* **358**, 748 (2012)
24. O. J. Sandberg, M. Nyman, S. Dahlström, S. Sandén, B. Törngren, J.-H. Smått, and R. Österbacka, *Appl. Phys. Lett.* **110**, 153504 (2017)
25. S. M. Sze, *Physics of Semiconductor Devices* (Wiley & Sons, New York, 1981)

**Oskar J. Sandberg** received his MSc degree in physics from Åbo Akademi University (ÅAU) in 2012. He is expected to receive his PhD in physics at ÅAU in June 2018. His primary research interest is modeling of device physics in thin-film solar cells using numerical drift-diffusion simulations.

**Mathias Nyman** received his MSc degree in physics and his PhD in physics from ÅAU in 2008 and 2015, respectively. Currently, he is working as a postdoc in the molecular electronics group at ÅAU. His primary research focus is on charge transport and recombination in organic, perovskite, and other thin-film solar cells.

**Staffan Dahlström** received his MSc degree in physics in 2016 from ÅAU. Currently, he is working as a PhD student at the faculty of Natural Science and Engineering at ÅAU. His primary research focus is on molecular doping and charge transport in solution processed organic semiconductors.

**Ronald Österbacka** is currently a professor in physics at ÅAU, Turku, Finland, where he is the chairman of the Center for Functional Materials and the Doctoral Program in Materials Research. His current research interests include electro-optical properties of disordered organic materials and organic electronics.