Organic Electronics 16 (2015) 212–220

Contents lists available at ScienceDirect

Organic Electronics

journal homepage: www.elsevier.com/locate/orgel

Space-charge limited surface currents between two semi-infinite planar electrodes embedded in a uniform dielectric medium

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A R T I C L E I N F O

Article history:
Received 23 June 2014
Received in revised form 10 September 2014
Accepted 25 October 2014
Available online 6 November 2014

Keywords:
Photoconductor
Interdigitated electrode
Space-charge limited current
Photocurrent
Complex potential
Conformal transformation

A B S T R A C T

We extend the one-dimensional space-charge limited current theory to a two-dimensional geometry where current flows in a thin layer between two coplanar semi-infinite electrodes. It is shown that the surface charge density in the gap between the electrodes is the finite Hilbert transform of the in-plane component of the electric field. This enables us to derive analytical expressions for the field and charge density for single carrier injection and for photo-carrier extraction by solving a non-linear integral equation for the field. The analytical expressions have been verified by numerical calculations. For the in-plane geometry, the one-dimensional Mott–Gurney equation $J = \frac{9}{8}\mu\epsilon\frac{V^2}{L^3}$ is replaced by a similar $K = \frac{2}{\pi}\mu\epsilon\frac{V^2}{L^2}$ equation. For extraction of photo-generated carriers the one-dimensional $J \sim g^{3/4}V^{1/2}$ dependence is replaced by a $K \sim g^{2/3}V^{2/3}$ dependence, where g is the generation rate of photo-carriers. We also extend these results to take into account trapping. We show experimental evidence obtained with an organic photoconductor confirming the predicted voltage, width and generation dependencies.

1. Introduction

Space-charge limited currents have always played a pertinent role in electronic devices, starting with the vacuum tube [1,2], subsequently in solid-state electronic devices [3] and more recently in organic electronic devices [4,5]. In a vacuum tube the space-charge limited electron current is found based on energy conservation and Poisson's equation and leads to the Child–Langmuir equation

$$J = \frac{4}{9}\sqrt{\frac{2e}{m}}\epsilon_0\frac{V^{3/2}}{L^2} \tag{1}$$

with e and m the electron charge and mass, ϵ_0 the dielectric constant of vacuum and L the gap between the parallel electrodes and V the applied voltage. If only a single type of carrier is injected in an insulator without traps, a similar theory leads to the Mott–Gurney equation

$$J = \frac{9}{8}\mu\epsilon\frac{V^2}{L^3} \tag{2}$$

where μ is the mobility of the carrier and ϵ the dielectric constant. If a photoconductor with non-injecting contacts shows a large asymmetry in the mobilities of electrons and holes then a space-charge develops mainly near one electrode when extracting the photo-carriers by applying a bias voltage. In the past one has applied (2) to this space-charge region [6] but a more precise calculation (mentioned later) yields a numerical factor 4 instead of 9/8

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http://dx.doi.org/10.1016/j.orgel.2014.10.036
1566-1199/

$$J \approx egW = 4\mu\epsilon \frac{V^2}{W^3} \tag{3}$$

where g is the volume generation rate of photo-carriers and W the width of the space-charge layer. The difference stems from the hole and electron currents not being constant in the space-charge layer. Eliminating W from (3) yields

$$J \approx (4\mu\epsilon)^{1/4}(eg)^{3/4}\sqrt{V} \tag{4}$$

with a square root dependence on the voltage and a $g^{3/4}$ dependence on the irradiance.

If $W = L$ then the current saturates and this occurs for a voltage

$$V_{\text{sat}} = \frac{1}{2}\sqrt{\frac{eg}{\mu\epsilon}}L^2 \tag{5}$$

These are the simplest models known for space-charge limited currents but modeling real devices usually becomes more complicated because e.g. both types of carriers are injected, or because traps are present [3,7,8] or because the mobility is field dependent [9] and/or carrier density dependent [10] and so on.

All formulas mentioned and possible extensions have been derived for a planar one-dimensional structure. Langmuir [2] also considered cylindrical electrodes, and noted that the $V^{3/2}$ dependence in (1) does not depend on the shape of the electrodes, using a scaling argument. Only recently the Child–Langmuir law was extended to electron emission over a finite patch on a planar cathode [11–13].

Whereas the geometry of many practical devices is indeed one-dimensional, there are exceptions, as just mentioned. Another example are photoconductors, which often have an in-plane geometry with interdigitated electrodes. With inorganic photoconductors usually no space-charge limitation occurs due to the relatively high mobility-lifetime product [14], but with organic photoconductors [15,16] space-charge limited currents have been reported several times [17–20].

In this paper we extend the theory of space-charge limited currents to the geometry of two semi-infinite coplanar electrodes, where the current flows in an infinitesimally thin channel between the electrodes, where it will be assumed that the structure is embedded in a uniform dielectric medium. This is applicable to the mentioned organic photoconductors that use finger electrodes, assuming the width of the fingers is much larger than the gap width and the structure is sealed between two glass plates. In this case the current flow is confined to the channel and is still one-dimensional but the electric field in the channel and in the dielectric medium is two-dimensional. Thin film transistors (TFTs) and in particular OTFTs have a very similar geometry but due to the extra gate electrode the field can be calculated approximately using the well-known gradual channel approximation [21]. This holds also for the photoconductive structures reported by Lombardo et al. [22] and Ooi et al. [23].

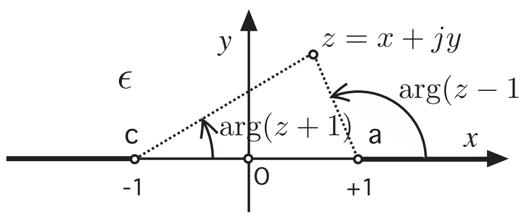
The rest of the paper is organized as follows. In Section 2 we calculate the electric field using a conformal transformation. In the next sections this result is combined with the drift and continuity equations and the overall problem is reduced to solving a non-linear integral equation for the electric field in the gap. In Section 3 we consider single carrier injection and in Section 4 photo-carrier extraction. The details of the calculations are given in Appendix A. In Section 5 some experimental evidence is presented for the theory.

2. Two-dimensional electrostatic problem

The electrostatic problem to be solved consists of two semi-infinite coplanar electrodes, with an applied potential difference V, and separated by a gap with width L. In the plane between the electrodes an unknown surface charge density ρ [C/m^2] is present and the structure is embedded in a uniform medium with dielectric constant ϵ. Since only one length parameter is involved we normalize the width of the gap with $L/2$ and choose a coordinate system as shown in Fig. 1, with the anode $-\infty < x < -1$, the cathode $+1 < x < +\infty$ and the thin conducting layer $-1 < x < +1$. Likewise the potential is normalized with V and with these conventions the electric field and the surface charge density are both normalized with $2V/L$. The field is split into a contribution due to the applied voltage without space-charge being present and the contribution of the space-charge density $\rho(x)$ with no voltage difference applied between the electrodes $E(x) = E_a(x) + E_\rho(x)$. For the first problem the Laplace equation must be solved in the whole 2D-plane except for two cuts along the electrodes and this problem can be solved by transforming this region into the upper halve plane using a complex Schwarz-Christoffel transformation [24–26]

$$w = z + \sqrt{z^2 - 1} \tag{6}$$

where $z = x + jy$ and $w = u + jv$ and with $0 < \arg(z-1) < 2\pi$ and $-\pi < \arg(z+1) < \pi$. In the transformed w-plane the complex potential is easily found as $W_a(w) = -j\frac{1}{\pi}\ln w$



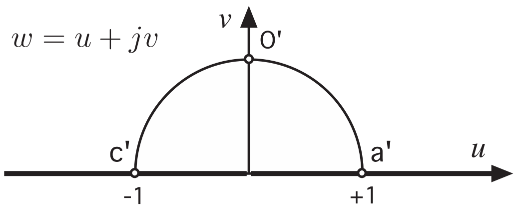


Fig. 1. (top) Geometry used for solving the electrostatic problem. (bottom) The conformally transformed geometry, with the anode $-\infty < u < 0$ and the cathode $0 < u < +\infty$. The gap cOa is transformed into the semicircle c'O'a'.