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PHOTO-ENHANCED CONDUCTION IN INHOMOGENEOUS THIN FILM SPACE CHARGE LIMITED CONDUCTING SYSTEMS

Photo-enhancement of space-charge limited currents in deliberately modified thin-film structures is studied using numerical methods. The obtained results suggest that it should be possible to obtain optically induced increase in current density of the order of 10^7 in modified thin film structures as a result of deliberate modification of trap density at the emitter consisting in formation of high density of traps at the emitter.

Keywords: space charge limited currents, optical switching.

1. INTRODUCTION

Space charge limited (SCL) currents are registered in many inorganic and organic thin film systems potentially useful for microelectronics [1-8]. In the case of simple trap-free SCL conducting system the total current density is given by:

$$j = \frac{9}{8}\varepsilon\varepsilon_0\mu\frac{V^2}{d^3} \tag{1}$$

where e is the electron charge, μ is the mobility, d the sample thickness, ε and ε_0 are the dielectric constant and the permittivity of free space respectively, V is the voltage applied. When the concentration of thermally generated free carriers is greater than the concentration of injected charge from emitter, the current follows Ohm's law; otherwise the current becomes proportional to V^2. The voltage at which the transition from Ohm's law to SCL regime occurs depends on concentration of thermally generated charge and the transition can occur in a wide range of voltages. For an insulator containing a mono-energetic trapping level of shallow traps of charge carriers the expression for SCL currents is similar to that given by eq. (1) but the equation is multiplied by a practically voltage-independent constant Θ being the free-to-total charge concentration ratio.

$$j = \frac{9}{8}\theta\varepsilon\varepsilon_0\mu\frac{V^2}{d^3} \qquad (2)$$

Most papers refer to spatially homogeneous distribution of charge traps even if the SCL theory is used to describe SCL currents in thin inhomogeneous layers. The problem of SCL currents in films with non-uniform spatial distribution of shallow traps was discussed by Nicolet [9] and Sworakowski [10]. Numerical solutions of dark and photo-enhanced SCL currents in some inhomogeneous polycrystalline structures of organic molecular films were also presented in [11,12]. Recently the problem of SCL currents in inhomogeneous films was studied by Dacuna and coworkers [13,14]. Delannoy and coworkers [15] discussed the problem of photoenhanced SCL currents in homogeneous insulators under inhomogeneous excitations. The main conclusions resulting from the papers are as follows:

- Traps at the emitter can influence substantially the current-voltage characteristics. The influence of traps on shape of current-voltage characteristics can be used to estimate both the value of surface concentration of trapping states and the decay of the concentration at the emitter [14]. Both the above parameters can be also estimated using photo-enhanced SCL currents [12].
- In the case of shallow traps a non-uniform trap distribution should not influence the current-voltage characteristics substantially, but in the case of non-uniform spatial distribution of deep traps the current-voltage characteristics changes significantly, especially if the traps are close to the emitter.
- Photo-enhancement of SCL current leads to photo-excitation of charge carriers out of deep trapping states and finally leads to substantial increase of current if the light flux is strong enough. This should enable to switch optically from low-conducting to high-conducting state in some thin-film systems with spatially non-uniform charge trap distribution on condition that injection of charge from electrodes is strong enough to obtain SCL electrical conduction.
- Inhomogeneous excitation (with strongly absorbed light for instance) of homogeneous thin film insulator containing traps leads to rather small increase in current, approximately does not exceeding 20% [15]. However, if the sample is not homogeneous and the trap concentration in the vicinity of emitter is high, much larger increase in current value under excitation is possible.

The non-uniform trap distribution in polycrystalline or any other inhomogeneous thin-film structures may be not easy to control. However, nowadays it is technologically possible to control spatial trap distribution of reproducible crystalline thin-film structures by intentional doping. The purpose of this paper is to solve numerically photo-enhanced SCL currents in thin film insulators with a number of deliberately chosen rectangular charge trap distributions in order to confirm the possibility of optical switching in such SCL thin-film systems and to estimate the increase in electrical current density resulting from photo-excitation.

2. BASIC ASSUMPTIONS AND DESCRIPTION OF NUMERICAL PROCEDURE

On the assumption that diffusion current can be neglected (usually acceptable for voltages higher than a few kT/e) unipolar SCL currents in solid thin film dielectrics can be described by Poisson equation and the continuity equation [16]:

$$\frac{\mathrm{d}F}{\mathrm{d}x} = \frac{e}{\varepsilon\varepsilon_0}\left(n_f + n_t\right) \tag{3}$$

$$j = e n_f \mu F \tag{4}$$

where F is the electric field intensity, n_f and n_t are concentrations of free and trapped charge, j is the current density. For the purpose of the numerical procedure the later equation was used in the form:

$$\frac{\mathrm{d}n_f}{\mathrm{d}x} = -\frac{n_f}{F}\frac{\mathrm{d}F}{\mathrm{d}x} \tag{5}$$

The concentration of trapped charge carriers is given by:

$$n_t(x) = \frac{N_t(x)}{1 + \dfrac{N_c}{g n_f}\exp\left(\dfrac{-\left(E_c - E_t\right)}{kT}\right)} \tag{6}$$

where $N_t(x)$ is the spatial distribution of traps, N_c is the effective density of states in the conduction band, g is the degeneracy factor. E_c and E_t are the energies of the bottom of the conduction band and the trapping level. The occupation of traps in the case of photo-enhanced SCL currents additionally depends on the light intensity $I(x)$ and is given by [17]:

$$n_t(x) = \frac{N_t(x)}{1 + \frac{N_c}{gn_f}\left\{\exp\left(\frac{-(E_c - E_t)}{kT}\right) + \frac{A\kappa I(x)}{\nu}\right\}} \tag{7}$$

A is the quantity transforming the light intensity into free charge carriers (photo-detrapping efficiency), κ is the absorption coefficient and ν is the thermal collision factor. The wavelength has to be short enough to excite the trapped carriers to the conduction band. The incident light intensity I_0 decays exponentially as:

$$I(x) = I_0 \exp(-\kappa x) \tag{8}$$

Fig. 1 shows a schematic view of sample taken for the calculations. The trap concentration in the system was taken as follows:

$$N_t(x) = N_1 \qquad \text{for } 0 < x \le x_d \tag{9a}$$

$$N_t(x) = 0 \qquad \text{for } L \ge x > x_d \tag{9b}$$

MATLAB mathematical software was used to solve the two equations. The values of charge concentration for $x = 0$ $N(0) = 10^{28}$ m^{-3} was assumed (the typical value for metals, the greater values do not influence the results), the mobility of carriers was assumed to be 10^{-6} m^2/Vs, $N_c = 10^{25}$ m^{-3}, $\nu = 10^{12}$ Hz and $\varepsilon = 3$ were taken for the calculations. The numerical procedure used to solve the above problem has been tested for $N_1 = 0$ and solutions identical with analytical expression for unipolar SCL currents in the trap-free case have been obtained.

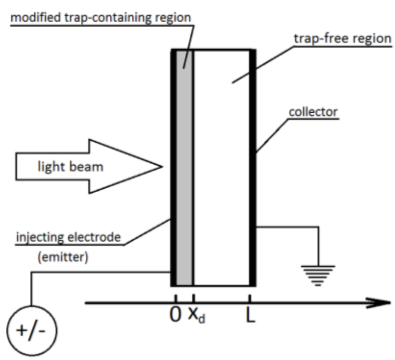

Fig. 1. Sample structure. The concentration of traps in the modified region is independent of the distance x, the concentration of traps in the rest of sample is assumed to be negligible. The thickness L = 6 μm is taken for the calculations. The emitter is polarized either negatively or positively depending on the injecting properties of the electrode

3. RESULTS

The calculations were carried out for the following values of parameters: sample thickness $L = 6$ μm; four values of thickness of the modified layer at the emitter containing traps: 0.2 μm, 0.5 μm, 1 μm and 2 μm; the concentration of traps N_1: 10^{19} m^{-3}, $3 \cdot 10^{19}$ m^{-3}, 10^{20} m^{-3}, $3 \cdot 10^{20}$ m^{-3}. The values of the absorption coefficient κ and the quantity A transforming the light intensity into free charge carriers are strongly dependent on material properties. Four values of the absorption coefficient corresponding to consecutive values of thickness was taken: $5 \cdot 10^6$ m, $2 \cdot 10^6$ m, 10^6 m and $5 \cdot 10^5$ m. The value of A was assumed to be 10^{-22} m^3. Such a value is typical for some organic molecular materials [18], but the value is not crucial for the calculations because it is possible (and necessary to obtain desirable result) to find such an intensity of incident light for which nearly all the traps are empty due to excitation of trapped charge to the conduction band and the current becomes close to the current characteristic of trap-free case. Assuming the accepted value of A the illumination I_0 between 10^{17} quanta/cm^2/s and 10^{22} quanta/cm^2/s is required to change the occupation of traps at illuminated electrode and influence the current values [12]. Five values of the trap depth E_t in the range between 0.35 eV and 0.75 eV were taken for the calculations. Such trap depth is quite typical for many dopants and structural disorder in both organic and inorganic crystals.

Fig. 2 shows solutions of SCL dark currents for the 7 values of trap depth. The shape of current-voltage curve is typical for SCL currents in thin-film dielectrics with monoenergetic trapping level. At the voltage equal to V_{TFL} (voltage of trap-filled limit) the traps become filled and the current rapidly increases normally by a few orders of magnitude. As expected, the influence of traps increases with increasing trap depth. For the voltage 1 V the increase in current value under illumination is equal to a few orders of magnitude for the higher values of trap-depth.

In order to estimate the influence of illumination of the considered structures on their conducting properties we have to compare the photo-enhanced and dark currents. Fig. 3 shows the SCL currents in a sample characterized by the thickness of trapping layer $x_d = 2$ μm and the concentration of traps $N_1 = 10^{20}$ m^{-3}.

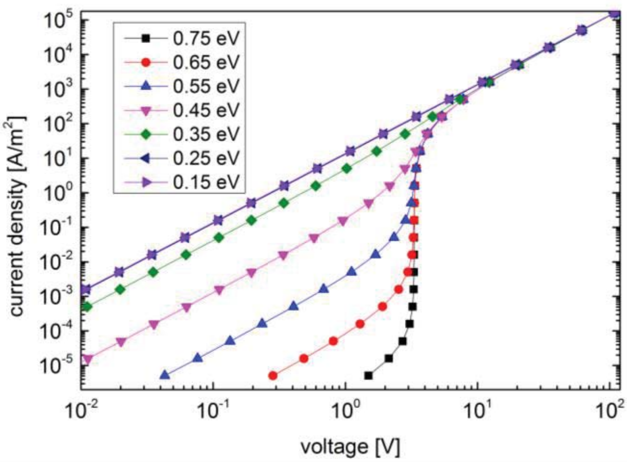

Fig. 2. SCL dark current-voltage characteristics for 5 different values of trap depths $N_1 = 10^{20}$ m^{-3}, $x_d = 1$ μm, $\kappa = 10^6$ m^{-1}

As results from the figure the increase in current density for the voltage equal to 0.8 V exceeds 6 orders of magnitude. Table 1 shows the ratio of photo-enhanced current density to the dark current density for the trap depth $E_t = 0.75$ eV for three various voltages.

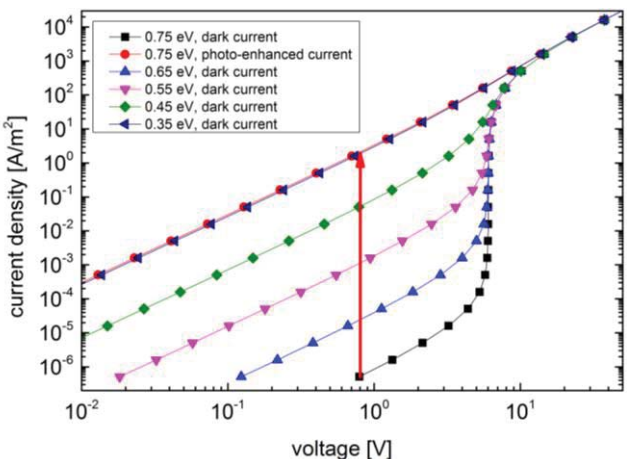

Fig. 3. Comparison of SCL current-voltage characteristics of photo-enhanced and dark currents for a few values of trap depth $N_1 = 10^{20}$ m^{-3}, $x_d = 2$ μm. The arrow shows the increase in current value resulting from photo-enhancement.

The voltages greater than 0.06 V are taken into account because neglecting the diffusion current we assume that the voltage is greater than a few kT. As we see the increase in current density $j_{photo\text{-}enhanced}/j_{dark}$ changes in the range between $3\cdot10^4$ and 10^7 depending on both the concentration of traps and on the width of the trapping layer at the emitter.

Table 1

Values the ratio $j_{photo\text{-}enhanced}/j_{dark}$ for trap depth E_t = 0.75 eV and for various values of the concentration N_1 and the thickness of trapping layer x_d

x_d N_1	voltages	$2\cdot10^{-7}$ m	$5\cdot10^{-7}$ m	10^{-6} m	$2\cdot10^{-6}$ m
10^{19} m^{-3}	U_1=0.06 V	$3.57\cdot10^4$	--	--	--
	U_2=0.1 V	--	$2.6\cdot10^5$	--	--
	U_3=0.2 V	--	--	$4{,}61\cdot10^5$	10^6 (1)
$3\cdot10^{19}$ m^{-3}	U_1=0.11 V	$4\cdot10^5$	--	--	--
	U_2=0.3 V	--	$6.18\cdot10^5$	$2\cdot10^6$	--
	U_3=0.5 V	--	$6.2\cdot10^4$	$1.5\cdot10^6$	$2.75\cdot10^6$
10^{20} m^{-3}	U_1=0.3 V	$1.33\cdot10^6$	--	--	--
	U_2=0.5 V	$8\cdot10^5$	$3.75\cdot10^6$	--	--
	U_3=1.0 V	--	$2.4\cdot10^6$	$7.14\cdot10^6$	$3.75\cdot10^6$
$3\cdot10^{20}$ m^{-3}	U_1=0.5 V	$3.83\cdot10^6$	--	--	--
	U_2=1.0 V	$3.03\cdot10^6$	$1.11\cdot10^7$	10^7	--
	U_3=2.0 V	--	$8\cdot10^6$	10^7	$9\cdot10^6$

(1) For U_3=0.21 V

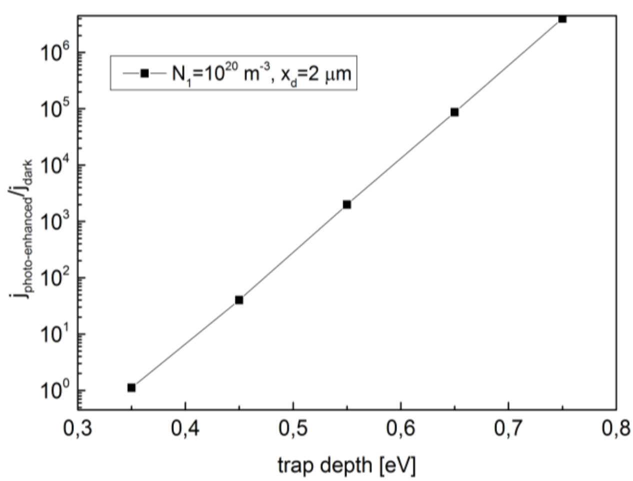

Fig. 4. The ratio $j_{photo\text{-}enhanced}/j_{dark}$ resulting from illumination of the sample as a function of trap depth for the concentration $N_1 = 10^{20}$ m^{-3} and the thickness x_d = 2 μm. The incident light intensity was taken high enough to obtain photo-enhanced current very close to trap-free current

The ratio depends also on the trap depth. Fig. 4 shows the relation between the ratio $j_{photo\text{-}enhanced}/j_{dark}$ and the trap depth for the concentration $N_1 = 10^{20}$ m^{-3} and the width $x_d = 2$ μm. It results from the figure that it may be possible to change substantially the value of SCL current in thin-film system with non-uniform spatial trap distribution using optical excitation of charge carriers in the modified trap-containing region at the injecting electrode.

4. CONCLUSIONS

The analysis presented above suggests that it is possible to develop thin-film structures dominated by SCL conduction which enables strong optical enhancement of their electrical conductivity. It might be also possible to modulate electrical conduction of such structures, but this is quite a complex problem additionally involving kinetics of trapping-detrapping phenomena.

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FOTOWZMOCNIONE PRZEWODNICTWO W NIEJEDNORODNYCH UKŁADACH CIENKOWARSTWOWYCH ZDOMINOWANYCH PRZEZ PRĄDY OGRANICZONE ŁADUNKIEM PRZESTRZENNYM

Streszczenie

Badane są metodami numerycznymi prądy ograniczone ładunkiem przestrzennym w świadomie modyfikowanych strukturach cienkowarstwowych. Otrzymane wyniki sugerują, że powinno być możliwe uzyskanie optycznie indukowanego wzrostu gęstości prądu rzędu 10^7 w układach z modyfikacją koncentracji pułapek przy emiterze, polegającą na wytworzeniu cienkiej warstwy o dużej koncentracji pułapek.