Current Applied Physics 16 (2016) 170–174

Contents lists available at ScienceDirect

Current Applied Physics

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

Tunneling processes and leakage current mechanisms of thin organic layer sandwiched between two electrodes

Chanho Yoo, Tae Whan Kim[*]

Department of Electronics and Computer Engineering, Hanyang University, Seoul, 133-791, South Korea

ARTICLE INFO

Article history:
Received 2 October 2015
Received in revised form
17 November 2015
Accepted 19 November 2015
Available online 23 November 2015

Keywords:
Electrical characteristics
Space-charge-limited current
Trap-assisted tunneling
Leakage current
Organic layer

ABSTRACT

The current density-voltage (J-V) characteristics of an organic layer sandwiched between two electrodes were simulated by using the space-charge-limited current (SCLC) model and the trap-assisted tunneling (TAT) model taking into account the leakage current paths. The experimental J-V curves of the Al/Alq_3/indium-tin-oxide (ITO) and the Al/mCP/ITO devices fabricated by thermal evaporation were in reasonable agreement with the simulated results calculated by the SCLC and TAT models. The tunneling process in an organic layer was significantly related to the nature traps of disordered organic semiconductors. The leakage current of an organic layer was dominantly attributed to the TAT mechanism.

1. Introduction

Organic materials have been used in various fields, such as organic light-emitting devices (OLEDs) [1,2], organic bistable devices (OBDs) [3,4], and organic solar cell [5,6]. Among these devices, OLEDs and OBDs have been particularly attractive due to their potential applications in next-generation flexible electronic and optoelectronic devices that offer the excellent advantages of low driving voltage, low power consumption, high contrast, wide viewing angle, high flexibility, low cost, and fast response [7–10]. Several numerical models, such as a mobility model using a Monte Carlo simulation, a drift-diffusion (DD) model, and a space-charge-limited current (SCLC) model, have been suggested to analyze the carrier transport mechanisms of the organic layer for organic semiconductors [11]. The Monte Carlo simulation utilizes the Miller and Abraham equation to determine the carrier hopping rate between the randomly-distributed neighboring sites in an organic layer with energy disorder [12,13], which is extensively used for the simulation of the bulk organic materials. The DD model used in organic materials is necessary to modify from that used in inorganic materials [14,15]. Because the carrier transport in organic semiconductors is dominantly assumed to occur via hopping, the density of state for organic semiconductors can be described by the extended Gaussian disorder model (EGDM) [16,17]. The Gaussian density of state in EGDM affects the diffusion of carriers. Therefore, the generalized Einstein diffusion coefficient is used in the EGDM instead of the classical Einstein relation [18]. The carrier transport mechanism of organic semiconductors with a low mobility is described by using the SCLC model. The SCLC model typically takes into account three main equations: Poisson's equation, the drift equation, and a field-dependent trap distribution [19]. However, most models have a weak point, resulting in the disagreement between the theoretical and the experimental current density-voltage (J-V) characteristics at low voltages. Even though some studies on the electrical properties in organic layers have been carried out [16–19], investigations about accurate theoretical analyses for the J-V characteristics and carrier transport mechanisms of organic devices at low voltages have not been conducted yet. Furthermore, studies on the electrical characteristics taking into account of the leakage current paths through the trap sites in organic layers for OBDs sandwiched between two electrodes are necessary to understand clearly their carrier transport mechanisms, resulting in the enhancement of the device performance.

This paper reports the tunneling processes and leakage current mechanisms of thin organic layer sandwiched between two electrodes. The simulation data were obtained by using a SCLC model and a trap-assisted tunneling (TAT) taking into account the leakage current paths [20–23]. The trap distribution in the organic layer is

---

[*] Corresponding author.
E-mail address: twk@hanyang.ac.kr (T.W. Kim).

http://dx.doi.org/10.1016/j.cap.2015.11.015

assumed to be a double Gaussian distribution consisting of shallow and deep traps, as shown in Fig. 1(a). The carrier transport in low fields such as those used in this work is attributed to the TAT current. When the carriers in this device are injected from the electrode at low electric fields, rather than being transported through the organic layer, they occupy traps, as shown in Fig. 1(b). The J-V curves of the Al/Alq$_3$/indium-tin-oxide (ITO) and the Al/mCP/ITO devices were investigated to compare with the simulation J-V results calculated by the SCLC and TAT models. The electrical characteristics at low electric fields for the Al/Alq$_3$/ITO and the Al/mCP/ITO devices were described on the basis of the J-V curves simulated by the SCLC and TAT models.

2. Experimental details

The sheet resistivity and the thickness of the ITO-coated glass substrates were 15 Ω/square and 150 nm, respectively. The organic layers were deposited at room temperature and a system pressure of 1.6×10^{-8} Pa. The deposition rates of the organic layers and the metal layers, as determined from a quartz crystal thickness monitor, were approximately 0.5 and 1 Å/s, respectively. After the tris(8-hydroxyquinolinato)aluminum (Alq$_3$) or the 1,3-bis(N-carbazolyl)benzene (mCP), each with a thickness of 100 nm, had been deposited on the substrate, Al top electrodes were deposited by using a shadow mask on the Alq$_3$ or the mCP, respectively. Because the Alq$_3$ and the mCP, small molecule organic materials, have been typically used in the fabrication of the OLEDs, the Alq$_3$ and the mCP organic materials were chosen as the organic layers in the devices. The J-V measurements were performed by using an HP 4140B I–V meter at room temperature.

3. Theoretical consideration

3.1. SCLC model

The organic memory devices have generally one organic layer sandwiched between two electrodes. When the carriers are injected from electrodes into the organic memory devices, the emitted carriers from the electrodes have generally a distribution of the energy and the organic material has traps of various distributions. The injected carriers are trapped into the organic material and become net positive or negative charges. It is referred to the space charges. The space charges limit the injection current, so that it leads to the space charge limited current SCLC.

Because the effective mass of the hole is larger than that of the electron [24], a single-carrier device was used in this work. The Pöisson equation and the transport equation are given as follows [20];

$$\frac{\partial E(x)}{\partial x} = -\frac{q}{\varepsilon\varepsilon_0}[p(x)+p_t(x)], \tag{1}$$

$$J = q\mu E(x)p(x), \tag{2}$$

along with the boundary condition

$$V = \int_0^d E(x)dx, \tag{3}$$

where p(x) is the concentration of free holes, $p_t(x)$ is the concentration of trapped holes, E(x) is the electric field, q is the electronic charge, ε_0 is the permittivity, ε is the dielectric constant, J is the current density, μ is the hole's mobility, and d is the thickness of the device. A combination of Eqs. (1)–(3) yields a differential equation for the electric field:

$$\int_0^d dx = \int_{E(x=0)}^{E(x=d)} \frac{dE}{\frac{J}{q\mu E}+p_t}. \tag{4}$$

In this work, the trap distribution in the organic layer is assumed to be a double Gaussian distribution consisting of shallow and deep traps, as shown in Fig. 1(a) [25]. The trap distribution for the double Gaussian trap model is given by

$$H_d(x) = \frac{N-N_T}{\sqrt{2\pi}\sigma}\exp\left(-\frac{E^2}{2\sigma^2}\right) + \frac{N_T}{\sqrt{2\pi}\sigma_T}\exp\left(-\frac{(E-E_T)^2}{2\sigma_T^2}\right), \tag{5}$$

where H_d is the density of traps, N is the total density of states, σ is the energy width of the highest occupied molecular orbital, N_T is the concentration of traps, E_T is the average trap energy, and σ_T is the energy width of the trap distribution. The trapped carrier density is determined by multiplying the double Gaussian trap distribution by the Fermi-Dirac occupation probability function and is given by

$$p_t = \int_0^\infty \frac{H_d}{1+\exp[(E-E_F)/kT]}, \tag{6}$$

where E_F is the energy of the Fermi level.

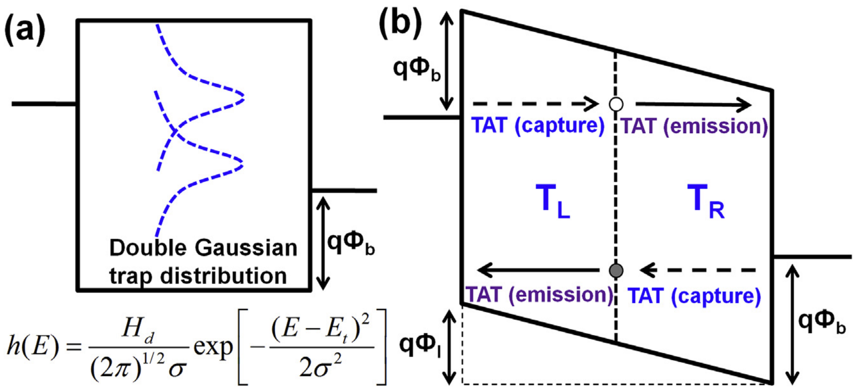

Fig. 1. (a) Schematic diagram of an organic layer with a double Gaussian trap distribution between the anode and the cathode. (b) Schematic representation of tunneling barriers and the transmission coefficients of the barrier.