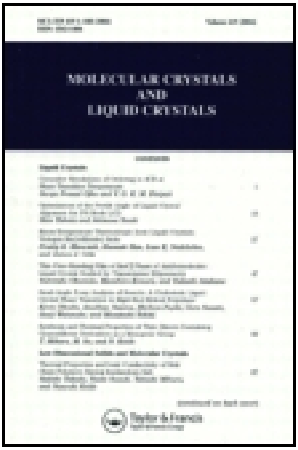

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EQUIVALENT CIRCUIT MODELING OF BILAYER ORGANIC LIGHT EMITTING DIODES

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EQUIVALENT CIRCUIT MODELING OF BILAYER ORGANIC LIGHT EMITTING DIODES

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The ac and dc equivalent circuit models of small molecule-based bilayer organic light emitting diodes are discussed. In order to model the devices under ac bias application, the frequency-dependent properties of bilayer organic light emitting diodes have been studied using admittance spectroscopy. The equivalent circuit models of bilayer diodes, for which the interface properties between the organic layers are included, are suggested. The dc model of the organic light emitting diodes is also presented, and will be compared with the experimental current-voltage characteristics. The simulated results of these equivalent circuit models are in good agreement with the measured results and these models can be used for the ac and dc modeling of small molecule-based organic light emitting diodes.

Keywords: admittance spectroscopy; current-voltage characteristics; equivalent circuit model; frequency dependence; organic light emitting diode

INTRODUCTION

The organic light emitting diodes based on the small molecules or conjugated polymers have been paid much attention due to their possible applications for flat panel displays [1,2]. They are attractive because of multicolor emission capability, low operating voltage, low power consumption, and low cost. A lot of investigations for the commercial applications have been pursued, but some of the important electrical characteristics have not been revealed yet.

We have investigated ac and dc equivalent circuit modeling of bilayer organic light emitting diodes with indium tin oxide (ITO)/N,N′-diphenyl-N,N′-(3-methylphenyl)-1,1′-biphenyl-4,4′-diamine (TPD)/tris(8-hydroxyquinoline) aluminum (Alq_3)/aluminum bilayer structures.

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EXPERIMENTAL DETAILS

The bilayer device was fabricated on ITO-patterned glass substrates. The TPD is used as a hole transport layer, and Alq_3 is for electron transport and light emitting layer. The substrates were ultrasonically cleaned in acetone, isopropyl alcohol, and deionized water in succession, and then dried in a vacuum oven. ITO film has a sheet resistance less than 20 Ω/□ and is about 100 nm thick. The organic materials were thermally evaporated on the patterned ITO under 2×10^{-6} Torr. The aluminum cathode was evaporated under the same vacuum condition. During the evaporations, the substrates were held at room temperature. The thickness of the organic layers for the bilayer structure is about 50 nm. The cathode is around 100 nm thick. All the thicknesses were confirmed with the ellipsometry (Plasmos, SD-2100) and α-step profilemeter (Tenkor, 200). The effective cell area is defined with the overlap region between anode and cathode, as $9 \times 10^{-4}\,mm^2$.

For all the electrical measurements, the aluminum cathode has served as a reference electrode. The admittances of the devices for the ac equivalent circuit modeling were measured using Hewlett Packard 4192A LF impedance analyzer. The amplitude of the test signal was 50 mV, which was superimposed on the operating dc bias, and the measurement frequency was in the range from 100 Hz to 10 MHz. The steady-state current-voltage characteristics are measured with Keithley 238 source-measurement unit. All the measurements were carried out in the dark and shielded environment. The admittance spectroscopic characteristics and current-voltage relationship of the devices were simulated using the equivalent circuit models extracted from the measurements and compared with the measurements to confirm the validity of the models.

RESULTS AND DISCUSSIONS

The equivalent circuit model of the bilayer organic light emitting diode is suggested in Figure 1, where the realistic equivalent circuit model with the influences of the interface between organic layers, is presented in Figure 1. In the bilayer light emitting device, TPD is used for hole transport, and Alq_3 acts as electron transport and light emitting layer. The holes and electrons are transported from the each electrode to and recombine in the region of the Alq_3 layer close to the interface between the TPD and Alq_3 layers. The accumulation region is built up in the Alq_3 layer close to the Alq_3-TPD interface, where the recombination of electrons and holes occur. The R_i and C_i enact the influences of the interface between organic layers. The C_i is calculated from the device geometry as $\varepsilon_0 \varepsilon_r A/d$, where A is the effective cell area and d is the charge accumulation region width. The accumulation

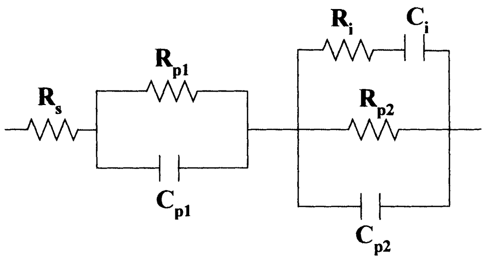

FIGURE 1 ac equivalent circuit model of the bilayer organic light emitting diode.

region width is optimized to be about 3 nm through the conductances vs. frequency simulations of the bilayer device for different accumulation region widths (Fig. 2). The R_i is extracted from the relaxation time ($\tau = R_iC_i$) of the devices. The relaxation time is the reciprocal of the relaxation frequency, which is simply extracted from the capacitance-frequency data of the bilayer devices [3]. The relaxation frequency is the center region of the abrupt reduction part of the capacitance with frequency. If the relaxation time and interfacial capacitance are assumed to be independent of the bias, the R_i and C_i are nearly constant even though the high bias is applied. Therefore, the equivalent circuit branch represented the TPD-Alq_3 interface properties at low bias can be applied even when the high bias is applied. It is expected that the charge carrier accumulation region at low bias is similar with the radiative region at high bias. The contact resistance (R_s) was estimated as 90 Ω. The bulk resistance (R_{p1} and $_{p2}$)

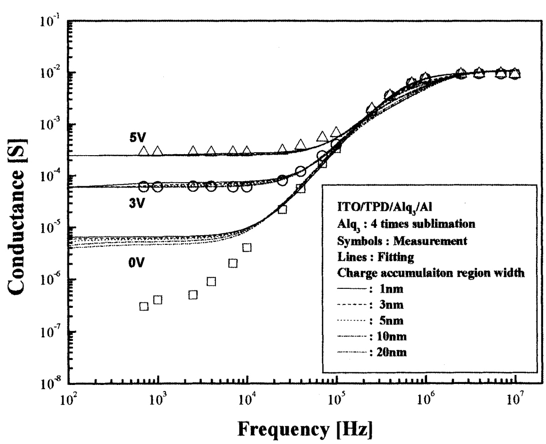

FIGURE 2 Conductances variation with different bias of the bilayer light emitting diodes.

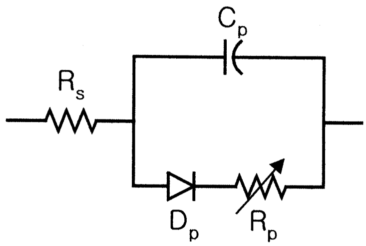

FIGURE 3 dc equivalent circuit model of the bilayer organic light emitting diode.

and capacitance values (C_{p1} and C_{p2}), extracted from the TPD and Alq_3 single-layer device measurements, were used for the simulations [4,5].

The simulated conductances of the bilayer device by the model of the Figure 1 provide a good agreement with the measured results as shown in Figure 2, where the measured and simulated conductances are compared. In Figure 2, the conductance variations of the ITO/TPD/Alq_3/Al device with frequency for different accumulation region widths are also presented.

The dc equivalent circuit model to simulate steady-state current-voltage characteristics is shown in Figure 3 [6]. The R_s is the contact resistance between anode and hole transport layer, C_p the organic bulk capacitance, R_p the organic bulk resistance, and D_p the diode model, respectively. The R_s and C_p are similar with the case of the ac equivalent circuit model. The R_p is strongly dependent on the applied bias. Therefore, the R_p variation as a function of bias relationship extracted from the admittance measurement is used for the dc equivalent circuit model. The R_p variation

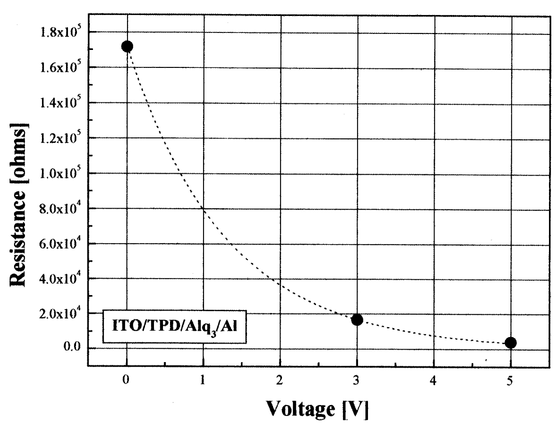

FIGURE 4 Organic bulk resistance variation as a function of the dc bias.

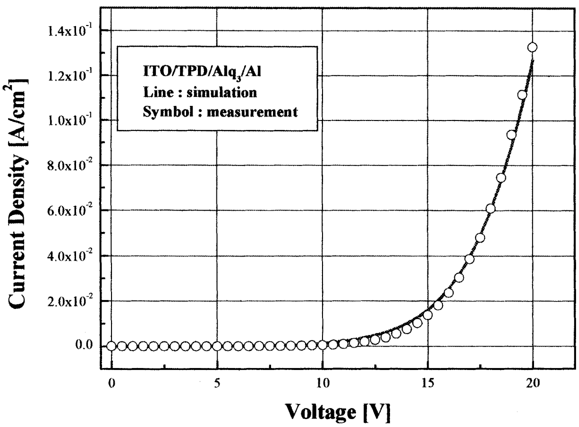

FIGURE 5 Linear I-V curves.

with the bias is shown in Figure 4. From the single exponential decay fitting, the following relationship can be obtained:

$$R_p = A \cdot \exp\left(-\frac{V_d}{B}\right) \tag{1}$$

where, R_p is the organic bulk resistance, V_d the dc bias, A and B the constants, respectively.

The linear and semilogarithmic current-voltage characteristics of ITO/TPD/Alq_3/Al device are shown in Figure 5 and Figure 6. The empty circles are the measured values, and the lines are the simulated results.

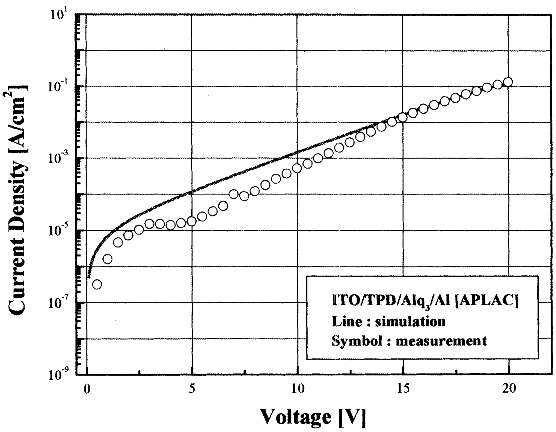

FIGURE 6 Semilogarithmic I-V curves.

The simulation of the current-voltage characteristics is performed with APLAC™ [7]. The Eq. (1) is used for the bias-dependent bulk resistance properties. The saturation current, IS, is 1×10^{-6} A, and the ideality factor, N, is 79, respectively. This very large ideality factor is very different with the inorganic-based diodes, such as pn junction diode and Schottky diode. This is due to the amorphous properties and very low mobility of the organic materials. The simulated results are in good agreement in the experimental results. In Figure 6, at low biases, however, a little inconsistency is obtained between the simulated and measured data. This is due to the additional factor, such as the charge carrier injection, in low bias region. This behavior is being studied in progress.

SUMMARY

The ac and dc equivalent circuit modeling of the small molecule-based bilayer organic light emitting diodes are discussed. The bilayer diodes can be modeled as two parallel resistor-capacitor circuits in series, one of which includes the serially connected resistance and capacitance elements in parallel to account for the interfacial and light emitting behaviors. The dc model of the organic light emitting diodes is also presented, and will be compared with the experimental current-voltage characteristics. The simulated results of this equivalent circuit models are in very good agreement with the experimental results and this model can be used for an ac and dc modeling of bilayer organic light emitting diodes.

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