OLED Power Driving Simulation Using Impedance Spectroscopy

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Abstract

Nonlinear parameterization of OLED device from measurements of bias dependence of impedance spectra and parameter extraction using Levenberg-Marquardt complex nonlinear least square regression algorithm based on resistor-capacitor equivalent circuit model enables computer simulation of OLED power driving characteristics in forms of square-wave or sinusoidal output signal at arbitrary conditions. We introduce developed OLED power driving simulation software and discuss transient responses in voltage- or current-controlled operations as well as nonlinear characteristics of OLED, by presenting both the simulation and experimental results. This OLED simulation technique using impedance spectroscopy is extremely useful in predicting performance of the nonlinear device, especially in time-domain analysis of device operation.

1. Introduction

Although the light-emission process in organic light-emitting diode (OLED) shows intrinsically fast electro-optical response, which is promising for the application as the next generation mobile display, actual device performance still has some limitation arising from device configuration. Devices like OLED, operating by solid-state charge transport through multi-layer structure, have several electronic processes, which determine dynamic properties during device operation, and which are generally nonlinear in external field.

Characterization of organic nonlinear devices such as OLED and organic thin film transistor (OTFT), in consideration of time dependence and transient effect, requires special techniques other than standard dc measurements. Parameterization of nonlinear device using impedance spectroscopy [1] is a new technical solution for characterization of nonlinear devices which provides a well-defined procedure to obtain characteristic device parameters using experimentally measured data and equivalent circuit model consisting of physically relevant elements. Model parameters of the equivalent circuit, which are valid at fixed bias voltage, can be determined from an impedance spectrum by fitting it to the equation describing its frequency dependence of impedance [2]. A complete set of parameters in the bias range of device operation is an equivalent numerical representation of a nonlinear device theoretically valid and practically applicable for simulation of device operation with arbitrary forms of power signal at wide range of electrical current densities and time-constants as well as for entire bias range.

In this work, we introduce a generic procedure for nonlinear device parameterization of OLED from bias dependence of complex impedance spectra measured from an ITO/α-NPD/Alq_3:DCM2/Alq_3/LiF/Al device. Using two different sets of impedance parameters extracted from OLED devices with different operating characteristics, we [resent simulated results of pulse power driving performance at various conditions and compare with experimental results.

2. Experimental

The devices are fabricated by using successive vacuum-depositions of α-NPD (500 Å), Alq_3:DCM2 (300 Å), Alq_3 (400 Å), LiF (5 Å), and Al electrode (1200 Å), without breaking vacuum, onto etched and cleaned indium tin oxide (ITO) substrates. The ITO substrates with a sheet resistance of about 10 Ω/€ are supplied by Samsung Corning Inc. The overlap area of the Al and ITO electrodes is about 2 mm^2. The dopant concentration of Alq_3:DCM2 is estimated to be 1 %. The evaporation rates are about 2Å/s, measured by a quartz crystal oscillator, under a base pressure of about $2x10^{-6}$ Torr. For the device characterization at ambient condition, fabricated devices are encapsulated by using SUS plate and UV epoxy glue with inner-filled CaO as desiccant.

The current-voltage (I-V) characteristics were measured by using Polaronix™ M6100 OLED IVL test system. The measurements of complex impedance spectra were carried out by using Autolab PGSTAT 30 with the FRA2 impedance measurement electronic interface module. The voltage-controlled sinusoidal perturbation signals of 50 mV amplitude and variable frequencies from 100 Hz to 1 MHz were applied upon various dc bias in the range of 0 ~ 5 V for device operation.

3. Parameterization Procedure

3. 1. Impedance Measurement

Two selected OLED test cells with similar onset voltage of light emission at 3.5 V and peak intensity at wavelength of 610~620 nm exhibit different I-V characteristics as shown in Fig. 1. One of the cells shows normal diode characteristics with negligible amount of current less than nA below the onset voltage. The other cell shows substantial amount of leakage current below onset voltage, providing additional linear contribution to I-V characteristics. The resistance by leakage current is estimated to be ~120 KΩ.

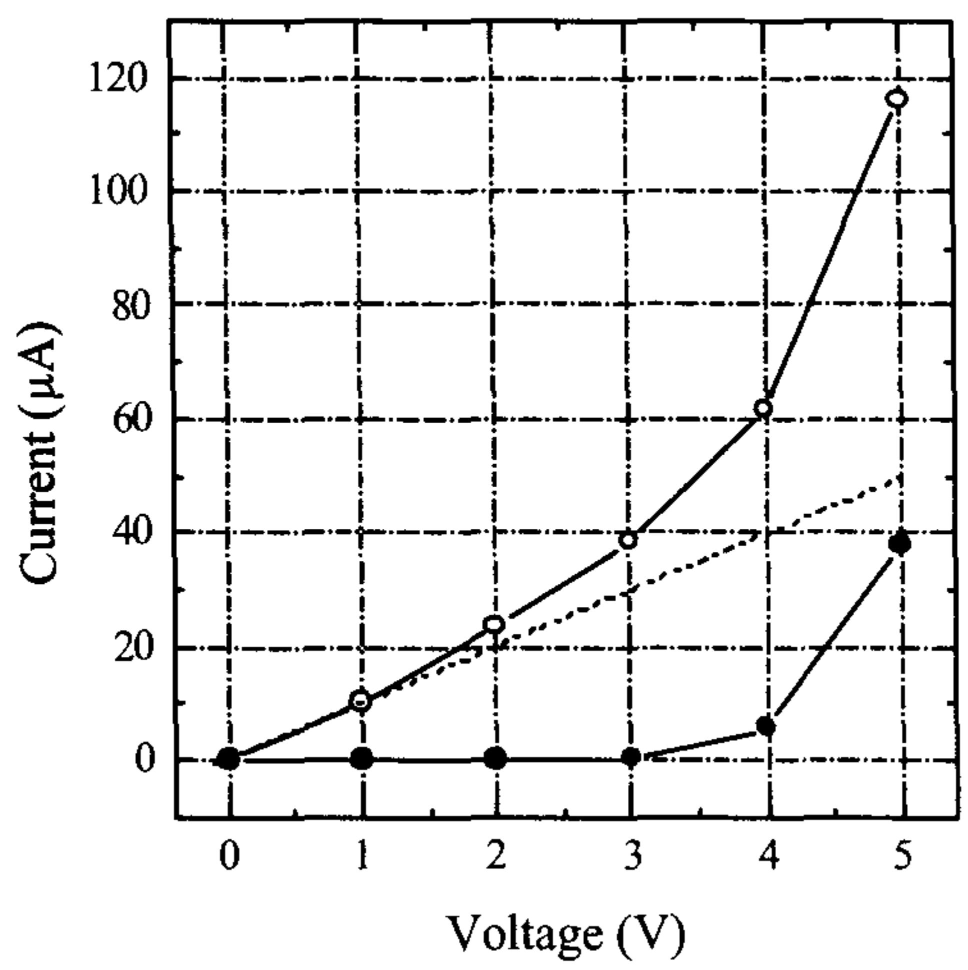

Figure 1 The voltage dependence of current for two ITO/α-NPD/Alq_3:DCM2/Alq_3/LiF/Al OLED test cells: A normal cell (●) and a cell with leakage current (○), A dotted line representing linear contribution by leakage current is drawn to guide eyes.

Two sets of complex impedance spectra measured as a function of frequency and bias voltage are shown as 3-dimensional Nyquist plots in Fig. 2. All spectra have semicircle shape in general, the real parts of which have two zero-crosses. The values for lower zero-crosses (high frequency limit) are small and comparable to ITO resistance. The values for higher zero-crosses (dc limit) are substantially changing upon bias voltage, in accordance with the results of dc measurement of nonlinear I-V characteristics.

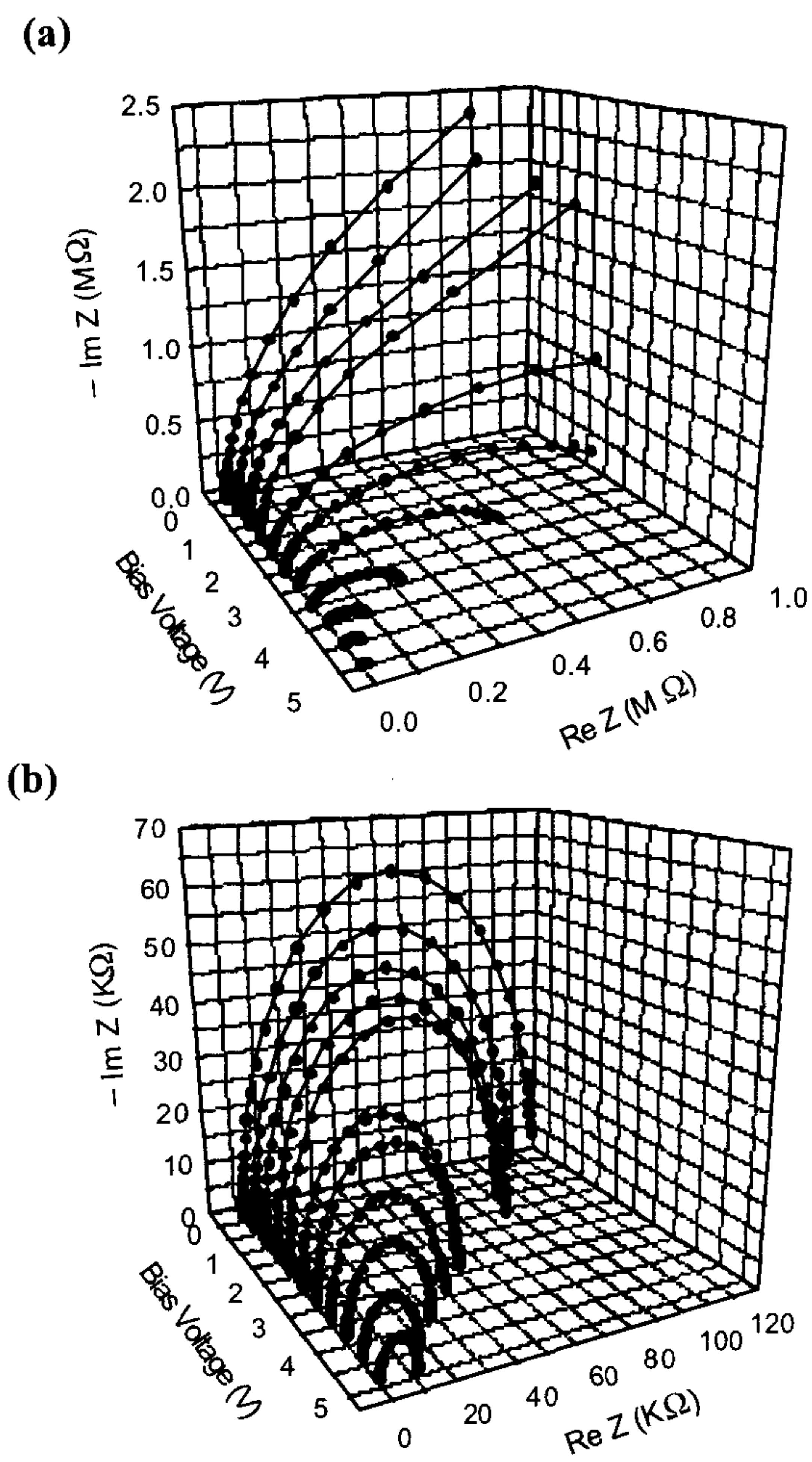

Figure 2 Complex impedance spectra of OLED test cells measured as a function of bias voltage: (a) a normal cell, and (b) a cell with leakage current.

3. 2. Equivalent Circuit Model

Process of charge transport in OLED, independent of particular chemistry involved, includes several common steps. The most important of these are (a) field-dependent carrier injection through metal-semiconductor interface, (b) charge carrier conduction through transporting medium, and (c) capacitive charging/discharging at the interface. The semicircle shape impedance spectra of OLED indicates that, in measured frequency (f) range of 1 Hz ~ 1 MHz, the impedance characteristics can be interpreted by the simple equivalent circuit model consisting of a RC pair connected in parallel (R_p and C_p) with a serial resistance (R_s), as shown in Fig. 3. In this case, the complex impedance can be expressed as,

$$Z = R_s + \frac{R_p}{1+\omega^2\tau^2} - j\omega\tau\frac{R_p}{1+\omega^2\tau^2} \qquad (1),$$

where ? $= 2\pi f$, and $t = R_pC_p$ is the time constant.

At high perturbation frequency the real part of complex impedance is several orders if magnitude smaller than that of low frequency with little variation upon bias voltage, indicating that contribution of serial resistance to complex impedance in the device such as ITO and Al electrode [3]. The parallel components of the equivalent circuit R_p and C_p, which contribute to the complex impedance as a semicircle with radius $R_p/2$ in the Nyquist plot, can be interpreted as nonlinear transport properties of semi-conductive emission and transporting layers in the device. These parameters are the most nonlinear elements, and substantially dependent upon bias voltage. The conductivity through the layer increases due to high carrier injection at higher electric field, consistent with the decrease of R_p with increasing bias voltage.

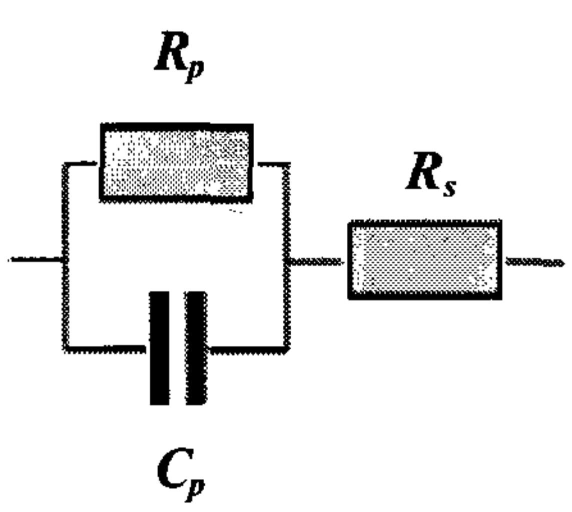

Figure 3 A simple equivalent circuit model for the complex impedance spectrum analysis of OLED (R_p: parallel resistance, C_p: parallel resistance, and R_s: serial resistance).

3. 3. Nonlinear Parameterization

The fitting of experimental data was performed using SpectroMaster™ impedance analysis software with built-in complex nonlinear least square (CNLS) fitting algorithm [4]. All nonlinear parameters given in Eq. (1) are used as fixed parameters in the fit. The relative standard deviations obtained by the fit for all parameters did not exceed 5 %. Two sets of nonlinear parameters fitted from bias dependence of impedance spectra for normal test cell and the cell with leakage current are listed in Table 1 and Table 2, respectively. The obtained R_p shows strong bias dependence, whereas C_p increases about 10 %, and R_s shows relatively small change.

Table 1 Parameter set of normal OLED test cell.

Bias (V)	R_s (Ω)	R_p (MΩ)	C_p (pF)	τ (μsec)
0.0	48.5	8.86	443	3920
0.5	43.7	7.34	410	3010
1.0	45.7	5.78	414	2394
1.5	47.1	4.93	418	2060
2.0	46.3	1.84	467	860
2.5	46.3	1.06	479	508
3.0	44.1	0.605	488	295
3.5	39.4	0.241	475	114
4.0	38.8	0.102	467	47.4
4.5	37.2	0.0439	471	20.7
5.0	37.1	0.0209	470	9.83

Table 2 Parameter set of OLED test cell with leakage current.

Bias (V)	R_s (Ω)	R_p (KΩ)	C_p (pF)	τ (μsec)
0.0	48.5	8.86	443	3920
0.5	43.7	7.34	410	3010
1.0	45.7	5.78	414	2394
1.5	47.1	4.93	418	2060
2.0	46.3	1.84	467	860
2.5	46.3	1.06	479	508
3.0	44.1	0.605	488	295
3.5	39.4	0.241	475	114
4.0	38.8	0.102	467	47.4
4.5	37.2	0.0439	471	20.7
5.0	37.1	0.0209	470	9.83

4. Power Driving Simulation

Prediction of electrical operation of OLED under the specific condition of pulse power signal can be achieved by representing the model as nonlinear electric circuit which can be easily solved by using formalism developed in theoretical electronics or using finite-difference electronic circuit simulator like SPICE. The OLED power driving simulation program shown in Fig. 4, developed in our laboratory, is designed to select a set of nonlinear parameters obtained from impedance spectra measurements and corresponding equivalent circuit model, as described previously, and to perform numerical simulation based on custom-designed waveform in voltage or current control mode using built-in SPICE engine.

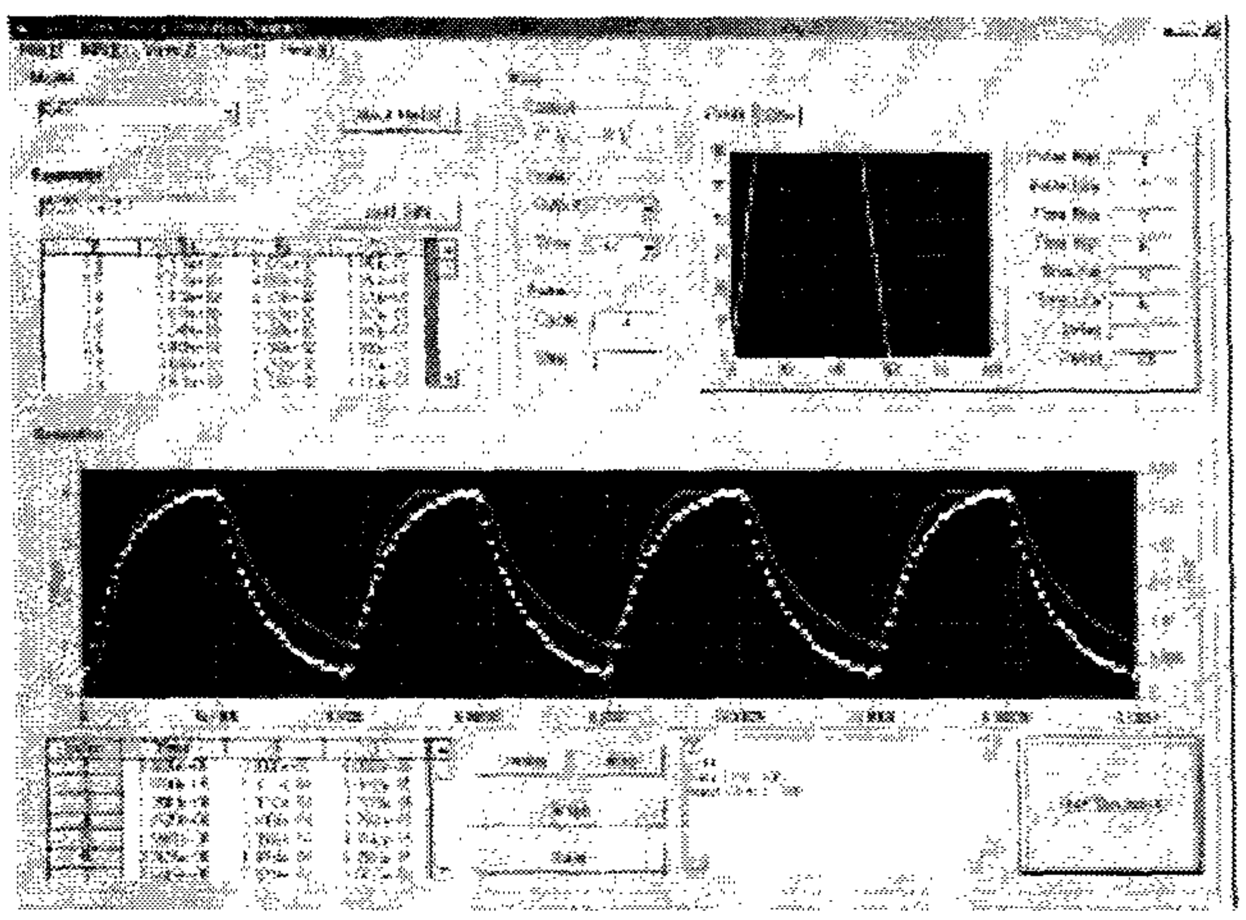

Figure 4 User interface of OLED power driving performance simulation program

Series of data shown in Fig. 5 are results of numerical simulation for OLED test cells using obtained parameter sets in Table 1 and 2. A square-like pulse of 100 μsec total period, 50 % duty, and 10 μsec rise/fall time is used for simulation. The pulse heights of 5 V and 130 μA are used in voltage control mode and current control mode, respectively. In voltage control mode, higher current is obviously required in presence of leakage current. In current control mode, we observe a longer current tail for normal test cell due to high impedance at low bias voltage. The simulation results are compared to be within 10 % error with experimental data measured by oscilloscope at the same operation condition, as shown in the last graph of Fig. 5.

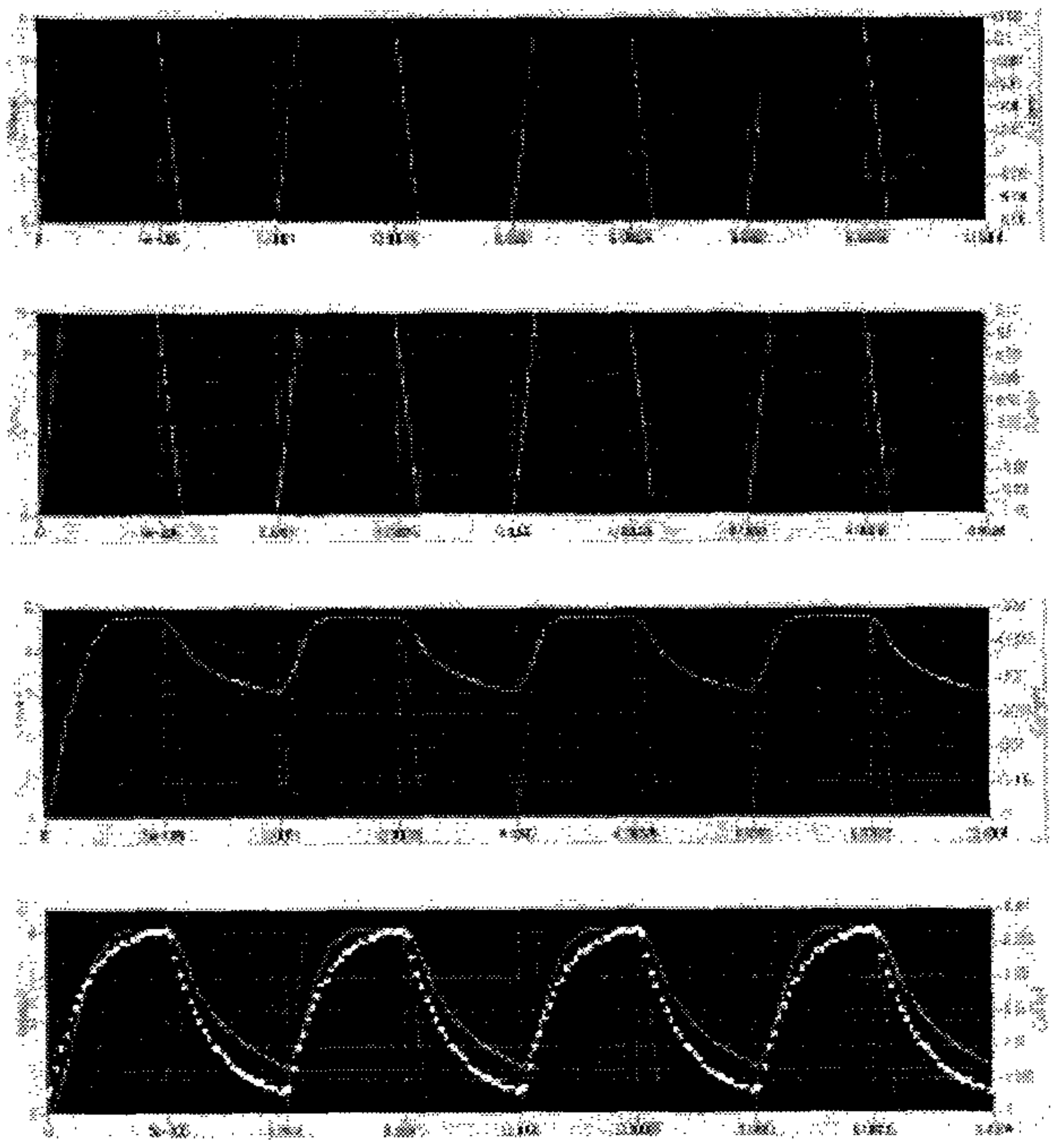

Figure 5 Numerical simulation of power driving of OLED test cells: from the top; voltage-controlled pulse for normal cell, voltage-controlled pulse for the cell with leakage current, current-controlled pulse for normal cell, current-controlled pulse for the cell with leakage current. The dotted plot in the bottom graph is experimental data from oscilloscope at the same device operation condition.

5. Conclusion

We demonstrated a systematic procedure to perform numerical simulation of OLED power driving operation using nonlinear parameter set obtained from measurements of bias dependence of complex impedance spectra and corresponding equivalent circuit model.

6. References

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