Negative Terminal Capacitance of Light Emitting Diodes at Alternating Current (AC) Biases

L. F. Feng, Y. Li, C. Y. Zhu, H. X. Cong, and C. D. Wang

***Abstract*—Measurement of obvious negative capacitance (NC) at large forward bias of light-emitting diodes (LEDs), using an alternating current (AC) small signal, together with direct current (DC) $I-V$ plot, has shown that the NC grows exponentially with the forward applied voltage. The experimental results are unexpected and are in conflict with Shockley's p-n junction theory which only includes increasing diffusion capacitance and certainly no negative capacitance. The experiment also shows that the ideal factor of LEDs is about 4, which far exceeds the traditional theory value. However, these results support the comprehensive p-n junction theory presented by Hess. Using the framework of his theory, the NC could be interpreted distinctly.**

***Index Terms*—Capacitance measurement, current density, light-emitting diodes, p-n junction.**

I. Introduction

HIGH-POWER light-emitting diodes (LEDs) have received great attention recently owing to their applications in energy-saving lights, display items and many other fields; therefore, the optical and electrical characteristics of LEDs at forward bias hold significant potential for research [1], [2]. However, for a new kind of light emission device, the general research on its performance focuses on the light emission and direct current (DC) current-voltage characteristics. The alternate current (AC) characteristics are seldom investigated. Although electrical characterization of a diode has been an important subject for over half a century [3], no attempt has been made so far to devise an accurate method for determining the parameters of a diode at forward bias voltage from AC analysis, which involves both real and imaginary parts. This greatly influences the research in this field; for instance, the theoretical research of diffusion capacitance [4], [5] and negative capacitance (NC) [6], [7] could not progress for want of reliable experimental confirmation. In fact, the study of forward AC characteristics is very important in the application of devices and in understanding their microscopic mechanisms [8], [9].

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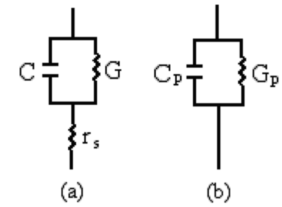

Fig. 1. (a) Actual equivalent circuit for a diode; (b) parallel measurement circuit.

In this paper, the obvious negative capacitance at large forward bias in light emitting diodes was measured using alternating current small signal together with direct current $I-V$ plot. It was observed that the NC grows exponentially with the forward DC voltage. The experimental results are in conflict with Shockley's p-n junction theory which only includes increasing diffusion capacitance and certainly no NC. However, these results are in agreement with the predictions of a comprehensive p-n junction theory presented by Hess [7], [14], which includes all contributions to the diode current. Using the framework of this theory, the NC could be interpreted distinctly. Furthermore, the measurements also show that the ideal factor of LEDs is about 4, which far exceeds the traditional p-n theory value.

II. Experiment

The measuring principle, which was discussed in detail in previous papers [8], [9], is only briefly explained here. The equivalent circuit of a real diode and the parallel equivalent circuit used in measurement are shown in Fig. 1(a) and (b), where C and G are the junction capacitance and conductance respectively, r_s is the series resistance, C_p and G_p are the apparent capacitance and conductance, respectively.

Comparing Fig. 1(a) with 1(b), one gets

$$G_p = \frac{G(1+r_sG)+r_s(\omega C)^2}{(1+r_sG)^2+(\omega r_sC)^2} \tag{1}$$

$$C_p = \frac{C}{(1+r_sG)^2+(\omega r_sC)^2} \tag{2}$$

At reverse or small forward bias voltages, the junction conductance is often determined by the leaked current. However, at larger forward voltages, it is displayed mainly by the differential conductance which is often greater than the DC conductance. At large forward bias, $G \gg \omega C$ is held; therefore, (1) and (2) can be simplified to

$$r_s = \frac{1}{G_p} - \frac{1}{G} \tag{3}$$

$$C = (1 + r_s G)^2 G_p \tag{4}$$

where the apparent conductance G_p and the apparent capacitance C_p can be obtained from experiments directly. The $I - V$ characteristic of diodes is

$$I = I_s \left(e^{\frac{qV_j}{nkT}} - 1 \right) \tag{5}$$

where the junction voltage is given by

$$V_j = V - r_s I. \tag{6}$$

When $V_j \gg nkT/q$. the junction conductance G consists mainly of differential conductance and is given by

$$G = \frac{\mathrm{d}I}{\mathrm{d}V_j} = \frac{qI}{nkT} \left(1 - \frac{V_j}{n} \cdot \frac{\mathrm{d}n}{\mathrm{d}V_j} \right). \tag{7}$$

Thus, one can accurately determine the dependences of C of LEDs on the forward bias voltages by combining (3)–(7).

Using the above method, many LEDs were measured. All the measured LEDs obviously displayed NC at large forward voltages, and the dependences of NC on forward voltage and frequencies are similar. The results presented here are only of two commercial blue LEDs from different manufacturers, named 1# and 2#.

The $I - V$ curves were measured using an Agilent 4155C parameter analyzer. Apparent conductance G_p and apparent capacitance C_p were measured directly using a HP4285A LCR meter and a TH2819 precision LCR meter respectively. The results of using both the LCR meters for the same sample are almost the same. All measurements were performed at room temperature.

Fig. 2 shows the forward $C_p - V$ profiles for 1# sample at frequencies of 100, 1 k, 10 k, and 100 kHz. The NC effect is more noticeable at lower frequencies and higher forward bias voltages, which is in good agreement with the NC behavior reported previously [8], [9]. Fig. 3 shows the $\ln|C_p| - V$ profiles for the same LED at different frequencies. At large bias, $\ln|C_p| - V$ curves at different frequencies are parallel, and $\ln|C_p|$ increases linearly with voltages, i.e. $|C_p| \propto e^{mV}$. Fitting $\ln|C_p| - V$ plots, the slope of fitting linear is about 9.5, namely $m \approx 9.5$.

From theoretical point of view, the relation of capacitance or conductor with voltage is $|C|$ or $|G| \propto e^{qV/nkT}$, where q is the electron charge, n the ideality factor, k Boltzmann's constant, T temperature, and V_j the voltage across the junction. At room temperature, $kT \approx 0.0259qV$, using $m \approx 9.5$ one gets the ideality factor as about 4, which is quite close to the experimental results [9]–[11]. Similar results were obtained for 2# sample as shown in Figs. 4 and 5. Furthermore, before the NC appearance, the terminal capacitance increases to a positive maximum. From the above experimental data one can conclude that the dependence of NC on voltage is

$$C_p = -C_0 \cdot e^{mV}. \tag{8}$$

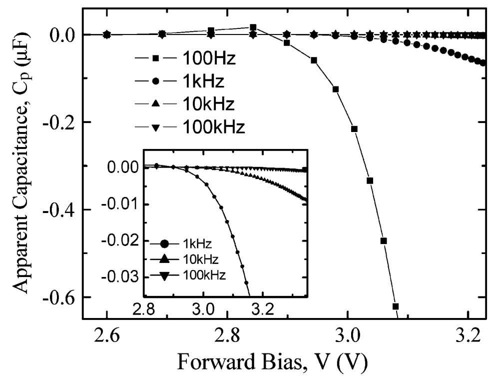

Fig. 2. Dependence of apparent capacitance C_p of 1# sample on forward bias voltages at 100, 1 k, 10 k, and 100 kHz. The inset graph shows the dependence of C_p on large voltages at 1 k, 10 k, and 100 kHz.

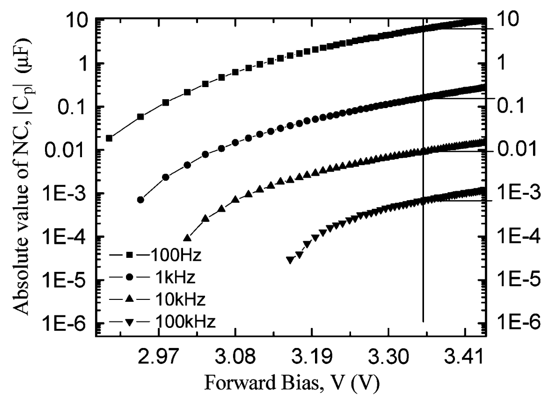

Fig. 3. Dependence of $\ln|C_p|$ of 1# sample on the forward voltage V. At larger bias, the curves are parallel. Ideality factor n calculated from slopes is about 4.

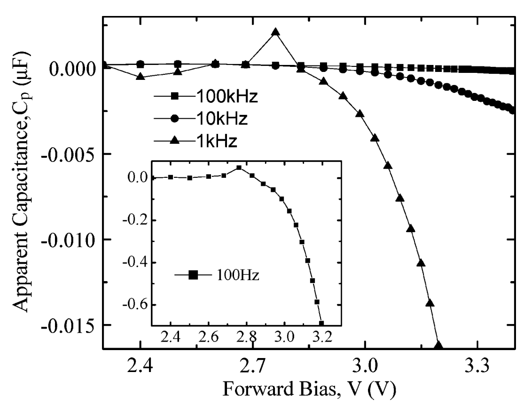

Fig. 4. Dependence of apparent capacitance C_p of 2# sample on forward bias voltages at 1 k, 10 k, and 100 kHz. Inset graph shows the dependence of C_p on higher voltages at 100 Hz.

where C_0 is a constant for a given LED.

The above experimental results are unexpected because they are in conflict with Shockley's p-n junction theory which only includes increasing positive diffusion capacitance and certainly no negative capacitance.

III. Analysis

To include all contributions to the diode current, Laux and Hess proposed an equivalent circuit and derived an expression

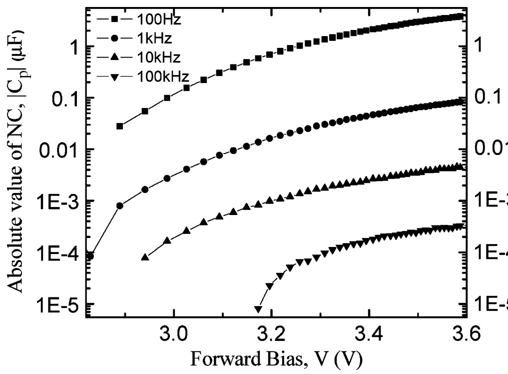

Fig. 5. Dependence of $\ln|C_p|$ of 2# sample on the forward voltage V. At larger bias, the curves are parallel.

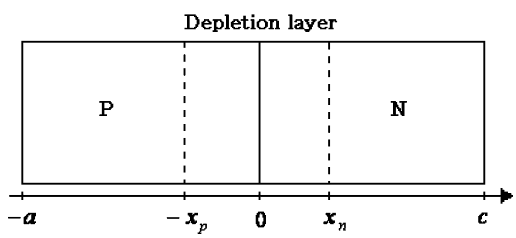

Fig. 6. Schematic diagram of the one-dimensional p-n junction. The metallurgical junction at $x = 0$ separates regions of constant acceptor doping N_A and donor doping N_D. Ohmic contacts are at each end of the diode, where $x_n = WN_A/(N_A + N_D)$, $x_p = WN_A/(N_A + N_D)$ and W is the width of depletion region. For detailed information, refer to [7, Fig. 1].

for each component of current in a one-dimensional p-n junction [7]. In their mode, the total current density is

$$\begin{aligned} J_t &= J_n(b)+J_p(b)+J_d(b) \\ &= \underbrace{e\int_{-a}^{-x_p} U_s \mathrm{d}x + e\int_{-x_p}^{b} U_s \mathrm{d}x + e\int_{b}^{x_n} U_s \mathrm{d}x + e\int_{x_n}^{c} U_s \mathrm{d}x}_{1} \\ &\quad \underbrace{+e\int_{-a}^{-x_p} \frac{\partial p}{\partial t}\mathrm{d}x + e\int_{-x_p}^{b} \frac{\partial p}{\partial t}\mathrm{d}x + e\int_{b}^{x_n} \frac{\partial n}{\partial t}\mathrm{d}x + e\int_{x_n}^{c} \frac{\partial n}{\partial t}\mathrm{d}x}_{2} \\ &\quad \underbrace{+e\int_{b}^{c} \frac{\partial(n-p)}{\partial t}\mathrm{d}x}_{3} + \underbrace{J_n(-a)+J_p(c)}_{4} + \underbrace{J_d(c)}_{5}. \end{aligned} \tag{9}$$

For a symmetrical p-n junction, $b = 0$. This choice for b is motivated by two reasons: 1) term 3 in (9) is maximized by this choice, making it equal at low forward bias to the value of the depletion capacitance $\varepsilon\varepsilon_0/W$, and 2) the integrations in (9), excepting term 3, can be well approximated by knowing only the local minority concentration [7]. Terms 2 and 5 of (9) always yield positive contributions to the sum, and terms 1 and 4 negative contributions.

Following is a brief review of the contribution of the recombination [term 1 in (9)] in the n-base to NC using the traditional assumption that $V_n = V_p = V_j$.

If the DC bias voltage is V_1, the AC small signal is $V_2 e^{i\omega t}$, and $V_2 \ll V_1$, where ω is the frequency of the AC small signal, then the total voltage of the p-n junction is

$$V = V_1 + \Delta V = V_1 + V_2 e^{i\omega t}. \tag{10}$$

The minority concentration in N-base is

$$p(x,t) = p_1(x) + p_2(x)e^{i\omega t}. \tag{11}$$

At low injection level, the drift current can be neglected. Substituting the diffusion current density equation and (11) into the carriers' continuity equation at AC modulating bias [12], [13], and ignoring the generation, one has

$$\begin{aligned} i\omega p_2(x)e^{i\omega t} = &-\frac{p_1(x)+p_2(x)e^{i\omega t}-p_0}{\tau_p} \\ &+D_p \frac{\partial^2\left[p_1(x)+p_2(x)e^{i\omega t}\right]}{\partial x^2} \end{aligned} \tag{12}$$

At the boundary of depletion layer, using quasi-equilibrium and $qV \gg kT$, one can get the total hole concentration

$$\begin{aligned} p(x,t) = p_0 + p_0(x_n)\left[e^{\frac{qV_1}{kT}}-1\right]e^{-\frac{x-x_n}{L_p}} + p_0(x_n)e^{\frac{qV_1}{kT}} \\ \cdot\left(\frac{qV_2}{kT}\right)e^{-\frac{x-x_n}{L_p}\sqrt{1+i\omega\tau_p}}\cdot e^{i\omega t}. \end{aligned} \tag{13}$$

where $L_p = \sqrt{D_p\tau_p}$, and L_p are the diffusion lengths of the holes in N type region. Using (13), the recombination current density of p-n junction in N-base is

$$\begin{aligned} j_{pr} &= \int_{x_n}^{\infty} q\left[\frac{p(x,t)-p_0}{\tau_p}\right]\mathrm{d}x \\ &= \frac{qp_0}{\tau_p}\left[e^{\frac{qV_1}{kT}}-1\right]\cdot L_p + \frac{q^2 p_0 L_p V_2}{\tau_p kT\sqrt{1+i\omega\tau_p}} e^{\frac{qV_1}{kT}}\cdot e^{i\omega t} \end{aligned} \tag{14}$$

Generally, τ_p is so small that $\omega\tau_p \ll 1$. Using series expansion, the AC admittance caused by recombination is

$$Y_{pr} = \frac{q^2 p_0 L_p}{kT} e^{\frac{qV_1}{kT}}\left(\frac{1}{\tau_p} - \frac{1}{2}i\omega\right). \tag{15}$$

In (15) the "−" sign confirms that the recombination current displays an inductance effect, that is, recombination leads to NC. In using carrier concentration [(13)], one can observe in the N-region that only the recombination of minority contributes to the total capacitance a value that is −1/2 times the value contributed by the diffusion; therefore, the negative terminal capacitance could not appear.

The foregoing calculation shows that the first term of (9) causes NC, but by using Shockley's theory framework the negative terminal capacitance could not be obtained. In traditional theory, the universal assumption that $V_n = V_p = V_j$ is often used to set the minority concentration at the edge of the depletion region. In fact, for the true physical picture in a p-n junction diode, this assumption could be too simplified. In solving (9), Laux and Hess presented a new DC and AC boundary condition for the injected minority concentration at the edge of the depletion region [7]

$$\begin{aligned} V_p = V_t - [\phi_i(x_n) - \phi_i(c)] - [\phi_p(-a) - \phi_p(-x_p)] \\ - [\phi_p(-x_p) - \phi_p(x_n)] \end{aligned} \tag{16}$$

where V_t is the applied bias, $[\phi_i(x_n) - \phi_i(c)]$ the electrostatic potential drop across the n-base, $[\phi_p(-a) - \phi_p(-x_p)]$ the hole quasi-Fermi drop across the p-base, and $[\phi_p(-x_p) - \phi_p(x_n)]$ the hole quasi-Fermi drop across the depletion region [7]. This condition correctly differentiates the role of the electrostatic and quasi-Fermi potentials in establishing the value of minority concentration at boundary. The negative terminal capacitance could be obtained from (9) [7], [14].

IV. Summary

NC in LEDs was studied using an AC small signal modulating measurement. Experimental data indicate that the NC grows exponentially with applied bias voltage, which is unexpected because it is in conflict with Shockley's p-n junction theory which only includes increasing diffusion capacitance and certainly no NC. Furthermore, negative terminal capacitance confirms the prediction of Laux and Hess' theory [7]. This paper is, therefore, not only of research value for application of High-power LEDs in energy-saving lighting systems but also of basic value on p-n junctions.

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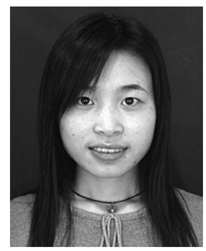

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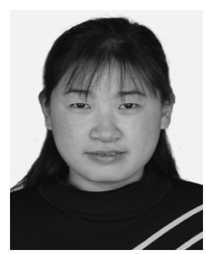

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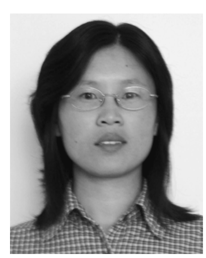

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