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Negative capacitance in light-emitting devices

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ABSTRACT

The negative capacitance behavior in light-emitting diodes and laser diodes has been observed and characterized by using ac admittance–voltage method. Experimental results proved that the strong negative capacitance behavior is always accompanied by remarkable light emission. We confirmed that the negative capacitance is an effect of the junction instead of other behavior or measurement error. We presented a numerical calculation by solving one dimension continuity equation based on a simple diode model. The results show that the negative capacitance behavior in light-emitting diodes has great relation to injected carriers recombination in the active region of luminescence.

1. Introduction

The forward electrical characteristics in LEDs and LDs are relevant important for analyzing their performance, microscopic mechanisms and practical applications, where the diodes are under dynamic regimes. In the forward admittance measurements, negative capacitance (NC) behavior has been observed in Schottky diodes [1–3], p–n junctions [4], quantum well infrared photodetectors (QWIPs) [5,6] and homojunction far-infrared detectors [7]. But in these reports only the measured apparent capacitance values of the devices were given without calculating forward junction capacitance [1–7]. In fact, the junction capacitance may be much larger than the measured apparent capacitance at high forward biases. And the calculation of junction capacitance is necessary in order to get the quantitative interpretation of the NC effect in various diodes convincingly.

Remarkable NC phenomenon was observed in LEDs and LDs in the ac admittance measurements which method we developed before [8]. Further experiments showed that remarkable NC was always accompanied by light emission and confirmed as the capacitance behavior of the diode but not other effect. And we believe the mechanism of NC in LEDs and LDs is very different from that in other devices.

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2. Our method

The parallel mode was adopted to measure the admittance in our experiments. Most capacitance meters suppose that a diode could be represented by the parallel circuit shown in Fig. 1a, where G_p and C_p are measured apparent conductance and measured apparent capacitance. It is known that the equivalent circuit of a p–n junction diode is always considered to consist of a junction capacitance C, a junction conductance G, and a series resistance r_s as shown in Fig. 1b. Generally, the differential conductance is regarded as the junction conductance G at forward bias, because it is much larger than the dc conductance caused by junction leakage current as long as the forward bias is slightly higher. Since the total impedance for circuit in Fig. 1a is equal to the total impedance for circuit in Fig. 1b, we could get the following equations:

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

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

where ω is the angle frequency of the small ac signal. At high forward bias, when $G \gg \omega C$, Eqs. (1) and (2) could be simplified as

$$G_p = G/(1+r_sG), \tag{3}$$

$$C_p = C/(1+r_sG)^2, \tag{4}$$

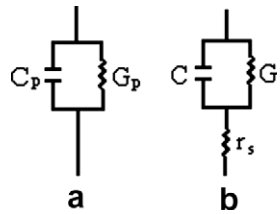

Fig. 1. (a) The equivalent measurement circuit for parallel mode. (b) The equivalent circuit of a p–n junction diode.

and we obtain

$$r_s = 1/G_p - 1/G, \quad (5)$$

$$C = (1 + r_s G)^2 C_p, \quad (6)$$

where G_p and C_p are measured directly and the differential conductance G can be derived from I–V plot [9].

3. Experiments and results

We tested many different samples including some commercial LEDs and LDs. Firstly, we presented the experimental results and analyses of typical GaN LEDs 1# and 2#. The tested wafers were grown by metal organic vapor phase epitaxy (MOVPE) with epilayers consisting of an 2.4 μm n-GaN layer ($\sim 2.5 \times 10^{18}$ cm^{-3}) and a 0.5 μm p-GaN layer ($\sim 2 \times 10^{17}$ cm^{-3}). The Ti/Au electrode of n layer was annealed at 550 °C for 10 s, and the Ni/Au electrode of p layer was annealed at 500 °C for 3 min. The mesa of the junction is 280 μm × 280 μm.

The forward admittance–voltage measurement was made with HP4284A LCR meter. The ac voltage v of 10 mV was superimposed on the forward dc voltage V at frequencies of 1 kHz–1 MHz. Care was taken to ensure that the parasitic elements do not influence the measurement data. Current–voltage (I–V) characteristic was measured with HP4140B. The electroluminescence (VMEL) intensity was measured at frequencies of 1–100 kHz. And a block diagram of the used experimental setup is shown in Fig. 2. The tested LEDs were driven by dc scanning voltage also together with ac voltage v of 10 mV. The optical signal of VMEL was transformed by a Si photodiode into the electrical signal, which was detected by a lock-in amplifier. All of the measurements were made at room temperature.

Fig. 3a shows the measured apparent capacitance C_p of the LED 1# at forward bias. It can be seen that the NC effect is stronger at lower frequencies. Higher frequency makes the effect appear at higher bias. In order to confirm the NC is the diode's own characteristic instead of other eternal effect or measurement mistake, we did further experiments. The larger known capacitance C_a was used in parallel with the tested diode. Thus the total measured capacitance value is $C' = C_p + C_a$. Fig. 3b shows the measured capacitance C' for LED 1# at frequency of 1 kHz and C_a = 13800 pF. Comparing Fig. 3a and b, we can find that the C'–V curve is equivalent to

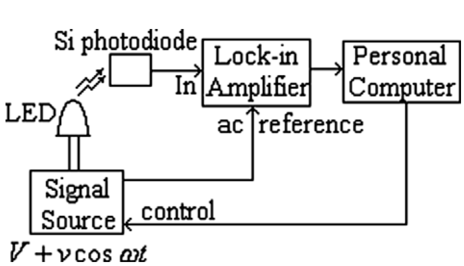

Fig. 2. Block diagram of experimental setup to measure VMEL intensity.

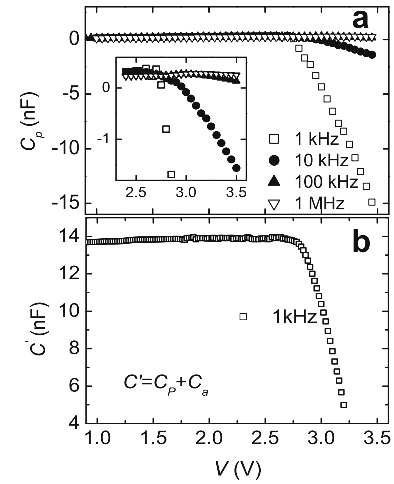

Fig. 3. (a) Dependence of apparent capacitance C_p on forward bias voltage V with different frequencies for GaN-based LED 1#, (b) total measured capacitance C' vs. forward bias voltage V curve at frequency of 1 kHz for GaN-based LED 1#.

translating the C_p–V curve at frequency of 1 kHz. Therefore, considering the validity of the measurement for positive capacitance, the negative capacitance of the diode can be confirmed.

The VMEL intensity of the LED 1# is shown in Fig. 4a. The intensity decreases while the frequency increases. And the VMEL intensity increases rapidly with the increasing forward bias. After reaching the maximum at about 3.45 V, it begins to decrease. For LED 1#, the decrease of VMEL intensity at high forward voltage means the reduction of the internal quantum efficiency that is defined as the proportion of the radiative recombination rate to the total recombination rate.

Fig. 4b shows the calculated junction capacitance of LED 1#. Comparing Figs. 4b and 3a, we can see that the junction capacitance may be much larger than the apparent capacitance at high forward bias. And in some cases, the magnitude of the negative junction capacitance at higher bias could exceed that of the positive capacitance, which mainly consists of diffusion and depletion components at lower bias [10], by several orders of magnitude [8]. Comparing Fig. 4a and b, we can find that the strong NC behavior is always coincident with the remarkable VMEL. For LED 1#, the mea-

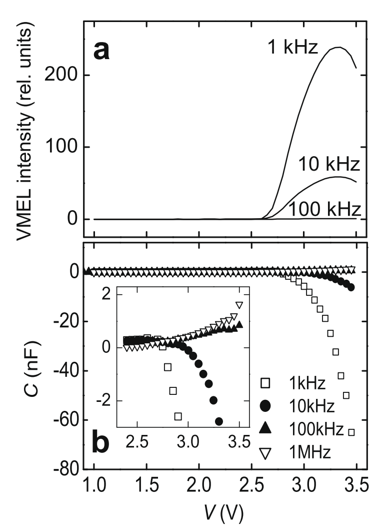

Fig. 4. (a) VMEL intensity vs. voltage characteristics at frequencies of 1–100 kHz for GaN-based LED 1#. (b) Dependence of junction capacitance C vs. forward bias voltage V characteristics at frequencies of 1kHz–1 MHz for GaN-based LED 1#.