Current–voltage characteristics of light-emitting diodes under optical and electrical excitation*

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Abstract: The factors influencing the current–voltage (I–V) characteristics of light-emitting diodes (LEDs) are investigated to reveal the connection of I–V characteristics under optical excitation and those under electrical excitation. By inspecting the I–V curves under optical and electrical excitation at identical injection current, it has been found that the I–V curves exhibit apparent differences in voltage values. Furthermore, the differences are found to originate from the junction temperatures in diverse excitation ways. Experimental results indicate that if the thermal effect of illuminating spot is depressed to an ignorable extent by using pulsed light, the junction temperature will hardly deflect from that under optical excitation, and then the I–V characteristics under two diverse excitation ways will be the same.

Key words: current–voltage characteristics; light-emitting diodes; optical excitation; electrical excitation; junction temperature

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1. Introduction

Light-emitting diodes (LEDs) have long been adopted in numerous electronic systems[1–4]. LED devices are a kind of optoelectronic semiconductor device, designed and fabricated to generate optical signals by converting electrical power to optical power. The mechanism is called injection electroluminescence (EL). Hence, characterizing an LED device means evaluating the performance in EL. As electrical current injection is a prerequisite in producing EL in the characterization of LED chips or products, physical contact with the devices is inevitable when injecting current into them. However, in the case of wafer or chip detection, the physical contact can cause microscratches or metal contamination on the wafers or chips, especially in the manufacturing process of online applications. In optoelectronic devices, luminescence, either photoluminescence (PL) or EL, is the essential behavior of optoelectronic semiconductor devices, which results from the recombination of excess electrons and holes. Current injection is just one way of producing excess electrons and holes. Photo injection by optical illumination is another way. In PL, an LED device absorbs photos to produce light emission. Therefore a device that produces EL can also operate PL[5, 6], and either EL or PL can demonstrate the performance and characteristics of an LED device[7, 8]. This fact suggests that if LED devices are characterized through PL, there should be no need for physical contact with the devices and the disadvantages of contact characterization, such as microscratches, chip contamination and others, can be fundamentally avoided. Li *et al.*[9] studied the connection of PL and EL. They showed that for LED devices with band-to-band transitions, the emission spectra were primarily dependent on the energy distribution of carriers and not related to the injection ways of the carriers, and the differences in spectral characteristic values originated from the variable junction temperatures in two injection ways. In this paper, we will focus on the electrical characteristics of LEDs. To use PL instead of EL for nondestructively characterizing LED wafers or chips in contactless characterization, the connection of current–voltage characteristics under optical excitation and those under electrical excitation should be determined.

In this paper, we investigate the current–voltage (I–V) curves of LED chips under optical and electrical excitation at room temperature. To correlate I–V characteristics under optical excitation and those under electrical excitation, the similarities and differences between the voltage values under optical excitation and those under electrical excitation at identical injection intensities are analyzed, and the causes that generate the differences are explored.

2. Experimental section

2.1. Sample preparation

Red and green LED wafers are utilized in this work. The red one was made of an AlGaInP multiple quantum well structure grown from the metal-organic vapor-phase epitaxy (MOVPE) process, and the emission peak wavelength was nominally 632 nm. The green one was made from an InGaN multiple quantum well structure also grown from the MOVPE process, and the emission peak wavelength was nominally 520 nm. Chips made from these two kinds of wafers both had an area of 12 mil^2 with a thickness of 225 μm. AlGaInP and InGaN are the two main materials for the high-brightness LED chips today. The former is applicable for red, orange, yel-

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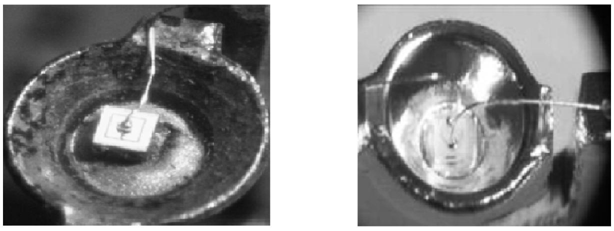

(a) (b)

Fig. 1. Top views of (a) a red AlGaInP and (b) a green InGaN LED chip bonded in a lead frame.

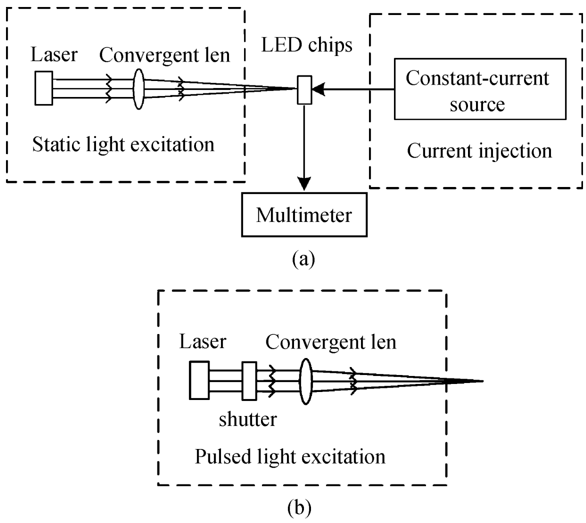

Fig. 2. Schematic of measurement of the current–voltage characteristics under (a) static light excitation, current injection and (b) pulsed light excitation.

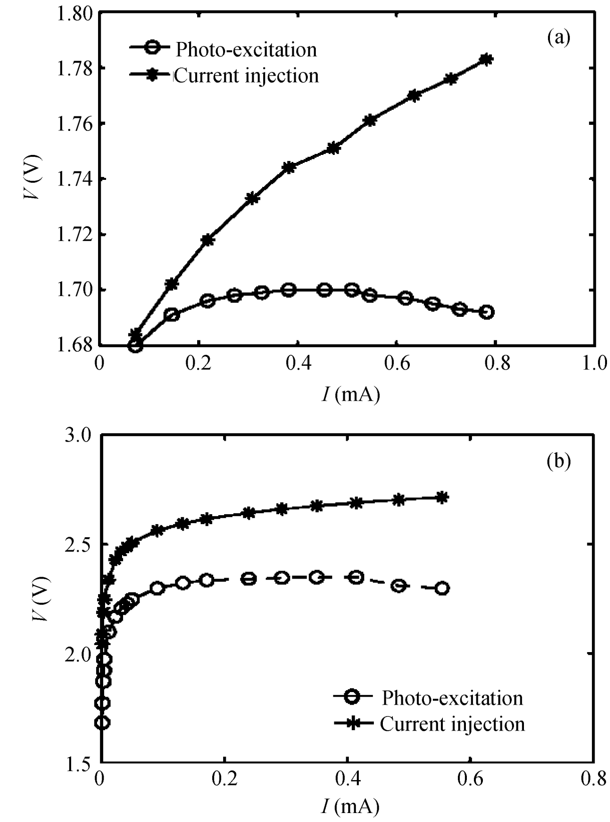

Fig. 3. I–V curves of (a) a red AlGaInP and (b) a green InGaN LED under photo-excitation and current injection. For photo-excitation, the horizontal axis indicates the photo-generated current and the vertical axis indicates the open-circuit voltage. For current injection, the horizontal axis indicates the forward drive current and the vertical axis indicates the forward-bias voltage.

low and yellowish-green LEDs and the latter is applicable for green, blue, violet and ultraviolet ones. The chips were bonded in lead frames without an epoxide resin wrap. Figure 1 illustrates the top view of an LED chip bonded in a lead frame.

2.2. Current–voltage characteristic measurement

Figure 2 shows the schematic of measurement of the current–voltage characteristics under optical and electrical excitation. Optical excitation was achieved by illuminating the chip from the top surface using a continuous laser beam from the Coherent Cube 405-100 violet laser with a wavelength of 305 nm. The laser intensity can be adjusted from 10 to 100 W/cm^2, and its spot can completely cover the top area of an LED chip. Electrical excitation was achieved by a constant current source flowing through the electrodes of the LED. The injection intensity was indicated by the photogenerated current under optical excitation and the forward-bias current under electrical excitation. The photogenerated current was monitored by measuring the reverse saturation current of an LED under illumination[10]. The same injection intensity refers to the photogenerated current under electrical excitation being equal to the forward-bias current under electrical excitation. The voltage and current were measured by a Keithley 2002 universal meter. In the used LED chip samples, illumination with 10 W/cm^2 can generate photogenerated current at about 1 mA, and the current increases linearly as the excitation density increases. The junction temperatures were measured by an infrared radiation thermometer with a resolution of 0.08 K with 320 × 240 pixels. The spatial resolution of the thermometer was set at about 0.08 × 0.1 mm^2 in our experiments. Pulsed light was produced by letting a continuous laser beam pass through a shutter, as shown in Fig. 2(b). The width of the pulse was varied by setting the switching period of the shutter to 2 s, 1/2 s, 1/125 s and 1/500 s.

The measurements were carried out as follows. First, while illuminating a chip using a continuous laser beam, measurements of the photogenerated current, the open-circuit voltage and the junction temperature were repeated at various excitation intensities. Second, under electrical excitation, the forward voltage and the junction temperature were measured at the forward current levels (provided by an adjustable constant current source) equal to the recorded photogenerated current under optical excitation. Third, the chip was separately illuminated using pulsed light with widths of 2 s, 1/2 s, 1/125 s and 1/500 s. For each width, the photogenerated current, open-circuit voltage and junction temperature were measured at the same excitation intensities as in the first step. All measurements were carried out at room temperature (288.4 K) under ambient atmosphere.

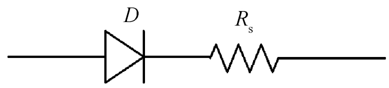

Fig. 4. Equivalent circuit of LEDs.

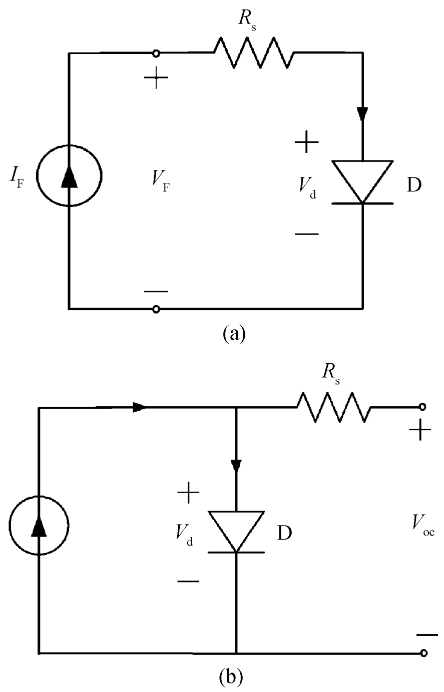

Fig. 5. Equivalent circuits when LED is (a) electrical injected and (b) photo-excited (open-circuit).

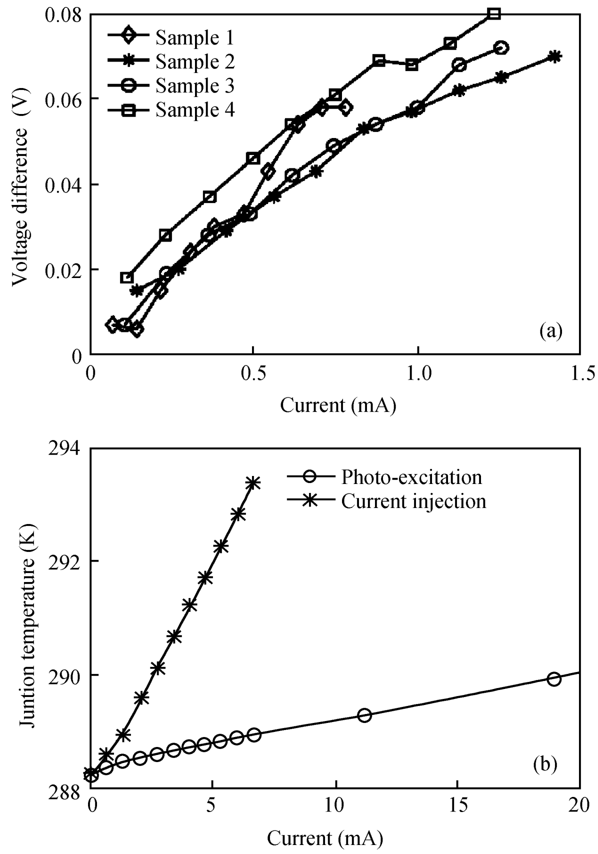

Fig. 6. (a) Dependences of the voltage differences between these two injection ways on the injection currents. (b) Dependences of the junction temperatures on the injection currents in a red AlGaInP LED.

3. Results and discussion

Figure 3 shows the measured I–V curves of the two LEDs. Under electrical excitation, the voltage increases linearly with the forward drive current. Under optical excitation, at current higher than 0.2 mA for the red LED and 0.4 mA for the green one, the curves show saturation. Another phenomenon is that, at the same current, the open-circuit voltage under optical excitation is always lower than the forward bias voltage under electrical excitation, and the voltage difference increases as the current increases.

The current of an ideal diode is often written as a function of the forward voltage $V_{\rm d}$ as

$$I = I_{\rm s} {\rm e}^{qV_{\rm d}/(nk_{\rm B}T)}, \tag{1}$$

where q is magnitude of electron charge (1.6×10^{-19} C), T is the junction temperature, $k_{\rm B}$ is Boltzmann's constant, $I_{\rm s}$ is the saturation current and n is the diode ideality factor. A real LED can be represented by the equivalent circuit of Fig. 4, consisting of an ideal diode D in series with resistance $R_{\rm s}$. When current $I_{\rm F}$ is injected to the device, the corresponding equivalent circuit is shown in Fig. 5(a). The device voltage $V_{\rm F}$ is

$$V_{\rm F} = V_{\rm d} + R_{\rm s} I_{\rm F}, \tag{2}$$

with series resistance Eq. (1) becoming

$$I_{\rm F} = I_{\rm s} {\rm e}^{q(V_{\rm F} - R_{\rm s} I_{\rm F})/(nk_{\rm B}T)}. \tag{3}$$

When an LED is excited with an optical source, a photocurrent is induced. The corresponding equivalent circuit is shown in Fig. 5(b). Under open-circuit conditions, the photocurrent does not flow through the series resistance $R_{\rm s}$, but only flows through the junction. Thus, the $I_{\rm ph}$–$V_{\rm oc}$ characteristic can be written as

$$I_{\rm ph} = I_{\rm s} {\rm e}^{qV_{\rm oc}/(nk_{\rm B}T)}, \tag{4}$$

where $I_{\rm ph}$ is the photocurrent and $V_{\rm oc}$ is the open-circuit voltage. Equations (3) and (4) imply that the existence of series resistance $R_{\rm s}$ makes the current–voltage characteristics under electrical and optical excitation distinct. However, when the forward current is lower than 20 mA, the voltage drop across the series resistance is far lower than that across the pn junction, and so it can be ignored. Thus, the $I_{\rm F}$–$V_{\rm F}$ and $I_{\rm ph}$–$V_{\rm oc}$ curves should be identical at current lower than approximately 20 mA. This does not agree with the result in Fig. 3. Equations (3) and (4) also show that the current–voltage characteristics are associated not only with the self nature but also with the junction temperature T. With this knowledge, it can be inferred that the junction temperatures T are different in two excitation ways at identical intensities.

In addressing the temperature dependence of the current–voltage characteristics, the voltage differences between these two excitation ways versus the injection current for different LED samples are presented in Fig. 6(a). We can see that the voltage differences grow approximately linearly with the

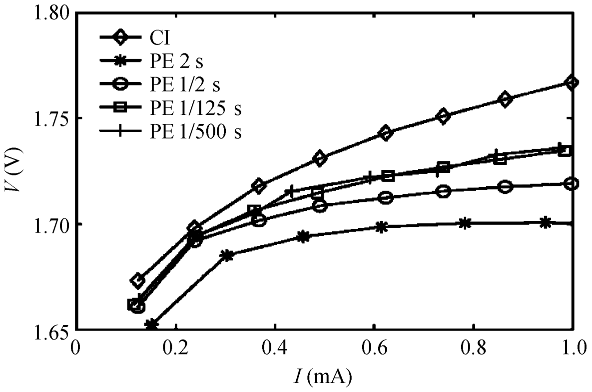

Fig. 7. I–V characteristics under pulsed light excitation, as well as those under current injection.

injection current. Figure 6(b) illustrates that the measured junction temperature T increases linearly with the injection current I and the increasing rate $\mathrm{d}T/\mathrm{d}I$ under optical excitation is higher than that under electrical excitation. This is because of the distinct thermal effects in two excitation ways. Ignoring the series resistance, in spite of the excitation way, the voltage V across the LED is

$$V = nk_{\mathrm{B}}T\ln(I/I_{\mathrm{s}})/q. \tag{5}$$

Under electrical excitation, V and I are respectively the forward voltage and the forward current; under optical excitation, they are respectively the open-circuit voltage and the photocurrent. The saturation current I_{s} is given by

$$I_{\mathrm{s}} = C_0\exp(-E_{\mathrm{g}}/k_{\mathrm{B}}T), \tag{6}$$

where C_0 is a parameter that is related to the materials, doping content, and size of the pn junction. E_{g} is the band-gap energy and it will decrease as the temperature increases. The temperature dependence of the energy gap of a semiconductor can be expressed by the formula[11]

$$E_{\mathrm{g}} = E_{\mathrm{g}}\big|_{T=0\,\mathrm{K}} - \alpha T^2/(\beta + T), \tag{7}$$

where α and β are fitting parameters. Therefore, when the injection current is the same, that is $I_{\mathrm{F}} = I_{\mathrm{ph}}$, the difference between the forward voltage and the open-circuit voltage is

$$\Delta V = V_{\mathrm{oc}} - V_{\mathrm{F}} \approx n[k_{\mathrm{B}}\ln(I/C_0) - a]\Delta T/q, \tag{8}$$

where ΔT is the junction temperature difference originate from the two excitation ways. Equation (8) shows that the voltage difference increases linearly with the temperature difference. Therefore, it can be concluded from Fig. 6 and Eq. (8) that the differences in I–V characteristics are basically derived from the variable junction temperatures in the two excitation ways. Figure 7 shows the I–V curves under pulsed light excitation (PE), as well as that under current injection (CI). Impulse durations of 2 s, 1/2 s, 1/125 s and 1/500 s were considered. The shorter the impulse duration, the smaller the heat generated in the pn junction, and then the lower the pn junction temperature. We can see from Fig. 7 that when the impulse duration of the excitation light decreases, the I–V curve under pulsed light excitation approaches the curve under current injection. As mentioned above, this is because of the decreasing pn junction temperature. Therefore, if the impulse duration is short enough so that the junction temperature hardly deflects from that under current injection, the I–V characteristics will agree with those under current injection.

4. Conclusion

In this paper, the I–V characteristics of light-emitting diodes under optical and electrical excitation are analyzed. The I–V characteristic of an LED device is primarily dependent on the energy distribution of the carriers and not related to the injection way of the carriers. The junction temperature T and the band-gap energy E_{g} are decisive parameters for influencing the electrical characteristics. We have experimentally observed that the I–V curves under optical and electrical excitation exhibit apparent differences in voltage values at identical injection current at room temperature. This shows that the differences in voltage values originate from the variable junction temperatures in two injection ways. It is considered that if the thermal effect of the illuminating spot is depressed to an ignorable extent by using pulsed light, the junction temperature will hardly deflect from that under current injection. This result provides a contactless method to measure the I–V characteristics.

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