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Electrical Leakage Levels Estimated from Luminescence and Photovoltaic Properties under Photoexcitation for GaN-based Light-emitting Diodes

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The electrical leakage levels of GaN-based light-emitting diodes (LEDs) containing leakage paths are estimated using photoluminescence (PL) and photovoltaic properties under photoexcitation conditions. The PL intensity and open-circuit voltage (V_{OC}) decrease because of carrier leakages depending on photoexcitation conditions when compared with reference values for typical LED chips without leakage paths. Changes of photovoltage-photocurrent characteristics and PL intensity due to carrier leakage are employed to assess the leakage current levels of LEDs with leakage paths. The current corresponding to the reduced V_{OC} of an LED with leakage from the photovoltaic curve of a reference LED without leakage is matched with the leakage current calculated using the PL intensity reduction ratio and short-circuit current of the LED with leakage. The current needed to increase the voltage for an LED with a leakage under photoexcitation from V_{OC} of the LED up to V_{OC} of a reference LED without a leakage is identical to the additional current needed for optical turn-on of the LED with a leakage. The leakage current level estimated using the PL and photovoltaic properties under photoexcitation is consistent with the leakage level measured from the voltage-current characteristic obtained under current injection conditions.

Keywords : Light-emitting diodes, Photoluminescence, Electrical leakage, Photovoltaics, GaN
OCIS codes : (230.3670) Light-emitting diodes; (250.5230) Photoluminescence; (040.5350) Photovoltaic; (120.4630) Optical inspection

I. INTRODUCTION

Light-emitting diodes (LEDs) have been developed considerably for decades and applied in many areas, including the display and lighting industries [1-3]. In the LED industry, inspection processes to evaluate the quality and properties of the wafers and devices have been indispensable for the mass-production of LED chips. To examine their light-emitting properties, luminescence has been one of the key properties that shows the quality of the active structures. Photoluminescence (PL) measurements under photoexcitation have been employed as a primary inspection method for LED epiwafers before fabrication processes [4]. For evaluation of fabricated LED chips, probing the electrodes of the chips and measuring the optoelectronic properties by current injection have been the most reliable process, because the measurement condition is identical to that of typical LED operation.

However, occasionally, it can be quite difficult to probe the chips for several possible reasons, such as small electrodes, the fragility of the chips, or a huge number of chips on the wafers. For these cases, the electrical measurements under carrier injections by direct probing could damage the LED chips or be very difficult to apply for mass production. The alternative could be an optical measurement, which is mainly nondestructive, and PL measurement could be a candidate for the evaluation of LED chips, chip arrays, or chip wafers. The issue has been whether the PL results could provide any information on the electrical properties that is useful for the evaluation of

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LED chips, because there has been doubt resulting from conflicting results in early reports about the possibility of correlation between PL properties and the electroluminescence (EL) properties of the LED wafers and chips [5, 6].

For LED chips, correlation between PL and EL has been studied from the points of view of peak positions, half width, intensity, and efficiency [7-11]. However, not many studies have focused on electrical properties related to PL properties that could be applied for evaluation of LED chips. Previously, Drinker III *et al.* showed a linear correlation between the PL intensity of an InGaAs layer and the shunt resistance calculated from voltage-current (*V-I*) characteristics for InGaAs photodiodes [12]. For LEDs, it was found that the defective regions observed in epiwafers by a PL imaging method affected the *V-I* characteristics and EL properties of LED chips fabricated with epiwafers [13], and relations of PL intensities to electrical properties of LED chips with leakage paths have been studied [11] as the forward leakage level is one of the important electrical properties for evaluation of LED chip characteristics.

In the solar cell industry as well as the LED industry, inspection methods using PL and EL imaging have been developed intensively to evaluate wafers [14, 15]. It was found that the PL intensity is affected by leakage through the shunt resistance in a cell, and analytical processes including the diode voltage under photoexcitation were developed to understand the correlation between the PL properties and leakage currents in the cell [16]. The result implies that PL properties with the help of photovoltaic characteristics, which can be obtained during photoexcitation for PL, can reveal leakage properties of LED chips, because shunt resistance is one of the major leakage sources affecting the *V-I* characteristics of devices. The photovoltaics of LED chips, obtained during photoexcitation for PL measurements, were analyzed for the evaluation of the properties of the LED chips [17-19]. However, there was not much information on the evaluation of LED properties for sorting LEDs with electrical leakage paths as forms of shunt resistances or additional parallel junctions [20].

In this study, the PL properties and photovoltaic characteristics of an LED chip with a leakage path were analyzed to investigate the correlation between PL properties and electrical leakage at forward-bias conditions. Photoluminescence intensity reduction ratios and leakage current levels under different photoexcitation levels were correlated for an LED with leakage by mediation of photovoltaic properties.

II. EXPERIMENTAL

GaN-based LED chips with a 445-nm emission wavelength from a commercial 2-inch chip wafer were tested. The chip size was 160 × 90 μm^2. Three LED chips located nearest-neighbor, LED-L1 and LED-L2 with electrical leakages and LED-R without leakage, were selected, and their *V-I* characteristics and PL properties were compared. Photoluminescence measurements were performed using a micro-PL setup. During PL measurements, photovoltaic properties such as open-circuit voltage (V_{OC}) and short-circuit current (I_{SC}) were measured. For photovoltaic and *V-I* characterization, a source meter connected to probing modules attached to the wafer holder of the micro-PL was employed, and electrical contacts were made through the electrodes of LEDs. A 400-nm resonant excitation laser beam with a 30-μm diameter was focused near the center of the LED chip under test. The excitation power was in the range of 0.01-100 mW, which corresponds to a power density in the range of 1.4 W/cm^2-14 kW/cm^2. Luminescence intensities were acquired using a Si photodetector connected to a picoammeter. A schematic of the micro-PL setup employed in this study is shown in Fig. 1.

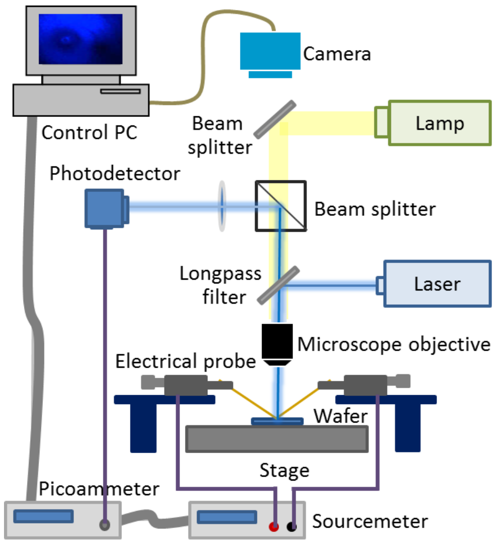

FIG. 1. A schematic of a micro-PL setup.

III. RESULTS AND DISCUSSION

The *V-I* characteristics of LED-L1 and LED-L2 are compared with that of LED-R in Fig. 2(a). Electrical leakages at the forward bias were observed. The leakage current level of LED-L2 was higher than that of LED-L1 at the forward bias region below 2.4 V. For the two LEDs, it was possible to observe decreases of PL intensity and V_{OC} compared with those of LED-R for a wide range of photoexcitation conditions, as shown in Figs. 2(b) and 2(c), respectively. The reduction of the PL intensity and V_{OC} appeared at the low-excitation region and diminished at almost identical excitation powers for each LED with leakage, as in Figs. 2(b) and 2(c). The decrements of both PL intensity and V_{OC} for LED-L2 were larger than those of LED-L1. The values of V_{OC} where the differences between properties of LEDs with leakage and without leakage disappeared were similar to the voltages where the

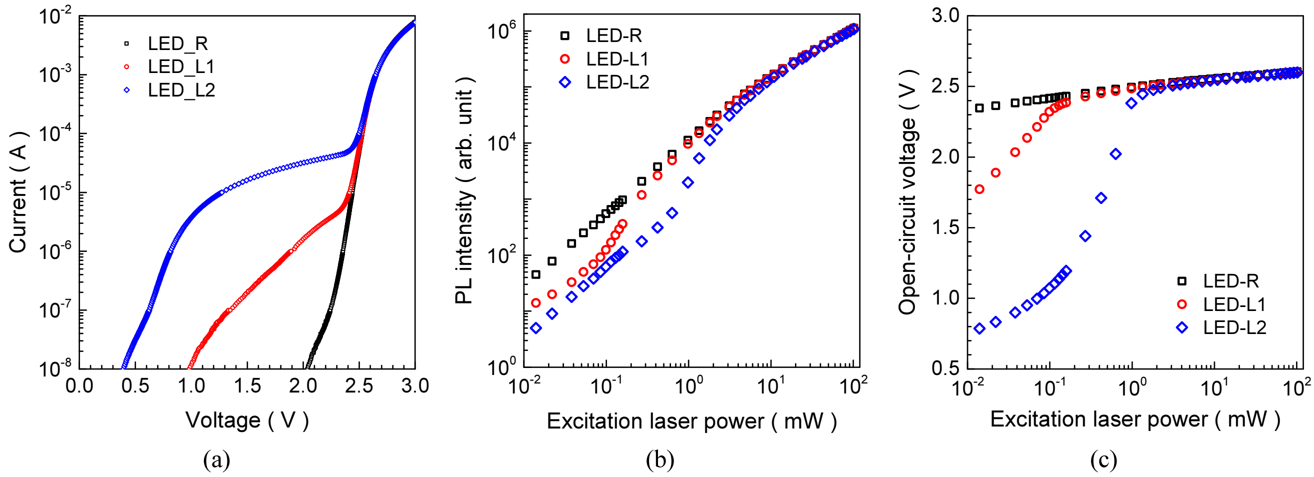

FIG. 2. *V-I* characteristics (a), PL intensities depending on excitation laser power (b), and open-circuit voltages depending on excitation power (c) for a typical LED without leakage (LED-R) and LEDs with leakages (LED-L1 and LED-L2).

currents of LEDs with leakages became consistent with that of LED-R at the *V-I* characteristic curves shown in Fig. 2(a). The results indicate that the reduction of PL intensity and V_{OC} for LED-L1 and LED-L2 is the effect of the forward leakage, and there is a possibility of correlations among the two parameters and electrical leakage.

The ratio of the leakage level to the I_{SC} under optical excitation could be correlated with the ratio of the PL intensity reduction to a reference value measured at the open-circuit condition [16]. The relation between the reduction of PL intensity and the leakage current level can be expressed for Si-based solar cells as Eq. (1) [16],

$$I_{leak} = I_{SC} \bullet \left\{ 1 - \left(\frac{I_{PL}}{I_{PL}^{0}} \right) \right\} \tag{1}$$

where I_{leak}, I_{SC}, I_{PL}, and I^{0}_{PL} are the leakage current, short-circuit current, reduced PL intensity, and PL intensity without leakage at a given photoexcitation condition, respectively. The equation was developed using the relations between PL intensity and voltage established during photoexcitation, and the diode equation with incorporation of a leakage current [16]. The PL intensity is proportional to the bimolecular radiative recombination rate [20], which can be described using the difference between quasi-Fermi levels for electrons and holes [21]. In the open-circuit condition, the PL intensity could be related to V_{OC} [22].

The I_{SC} increased with the excitation laser power under photoexcitation, which should have similar magnitudes for the neighboring LEDs, regardless of the existence of leakage paths if the epiwafer is uniform and there is no other surface contamination during fabrication processes. For the excitation power range applied in this study, the I_{SC} increased linearly up to 1 mA near 20 mW of excitation, and it showed a slightly sublinear increase at higher excitation levels, as shown in Fig. 3.

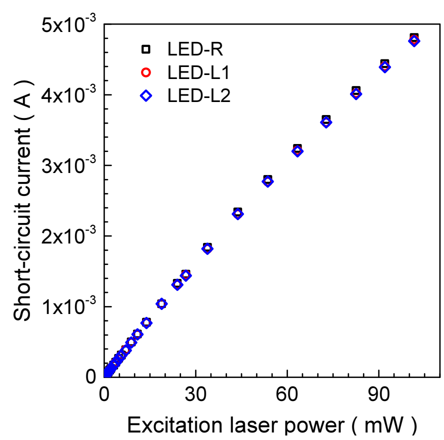

FIG. 3. Short-circuit currents of LEDs with respect to the excitation laser power.

To verify the leakage current calculated by Eq. (1) using the PL intensity reduction ratio due to leakage paths, the values were compared with a leakage current obtained by other methods. Photoluminescence is measured mostly under open-circuit conditions without electrical probing. The open-circuit conditions of the LEDs with leakage could be located between the open-circuit and short-circuit conditions of the LED without leakage, depending on the degree of the leakage. The V_{OC} could be formed because of the carriers that moved to the n- and p-layers under photoexcitation [23]. When there are leakage paths, carrier loss from the active region caused by the leakage paths, which resulted in the reduced V_{OC}, depended on the degree of the leakage. It has been reported that the leakage current was reduced, and V_{OC} could be raised by reducing the effects of leak paths [24, 25].

Two different approaches were investigated to estimate the leakage current levels of LED-L1 and LED-L2 using the reduced V_{OC} due to the carrier leakage from the V_{OC} of

LED-R at a given photoexcitation condition. The leakage current levels determined by the methods using photo-voltage-photocurrent relations of LEDs with or without leakages are illustrated in Fig. 4. The first method (method I) was to measure the reverse current corresponding to the V_{OC_leak} at the photovoltaic curve of an LED without leakage, which is leak_1 in Fig. 4. It was demonstrated that, when the voltage was reduced from V_{OC_ref} to V_{OC_leak} by injecting a reverse current, the PL spectrum of an LED chip without leakage was changed to the PL spectrum of an LED with leakage whose V_{OC} was V_{OC_leak} [11]. In this case, the direction of the current was identical to that of the carrier transport during photoexcitation. The second method (method II) was to measure the forward current for V_{OC_leak} of an LED with a leakage up to V_{OC_ref}, which is the V_{OC} of an LED without leakage obtained under the identical photoexcitation. The current was identical to the current value corresponding to V_{OC_ref} from the photocurrent-photovoltage relation of the LED with leakage, which is illustrated as leak_2 in Fig. 4. Leak_1 and leak_2 were measured with respect to the laser excitation power. The excitation power dependencies differed from each other for two leakage currents, as shown in Fig. 5.

Leak_1 obtained using method I increased with the excitation power, while leak_2 obtained using method II kept similar values, which were in the ranges of approximately 4.8×10^{-6} to 5.8×10^{-6} A and 4.5×10^{-5} to 5.3×10^{-5} A for LED-L1 and LED-L2, respectively, for the excitation conditions below 2 mW, where V_{OC} reduction was observed. The leakage levels obtained by method I and the leakage calculated using Eq. (1) with the PL intensity reduction were compared for the range of laser excitation powers, and the relation is plotted in Fig. 6. The values were well-matched until the leakage currents reached approximately 5.5×10^{-6} A and 5×10^{-5} A for LED-L1 and LED-L2, respectively. The values, 5.5×10^{-6} A and 5×10^{-5} A, were very close to the leakage currents obtained using method II. The two current values were similar to the currents of

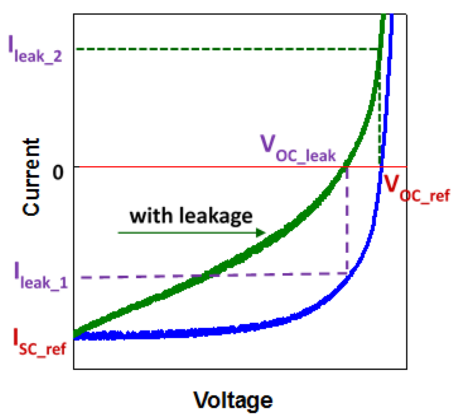

FIG. 4. Simplified photovoltaic characteristics of LEDs with leakage paths (green) and without leakage (blue) under photoexcitation.

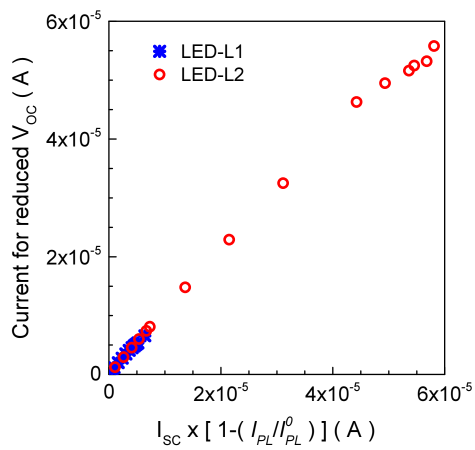

FIG. 6. Correlation of the leakage currents obtained using reduced V_{OC} with the leakage currents calculated using PL intensity reduction ratio and I_{SC}.

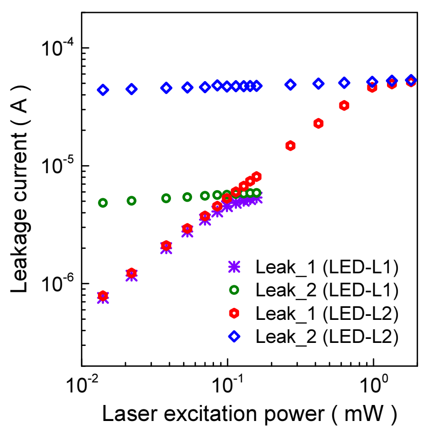

FIG. 5. Leakage currents obtained by two different methods using reduced V_{OC} resulting from the electrical leakage for LED with leakage (LED-L1 and LED-L2).

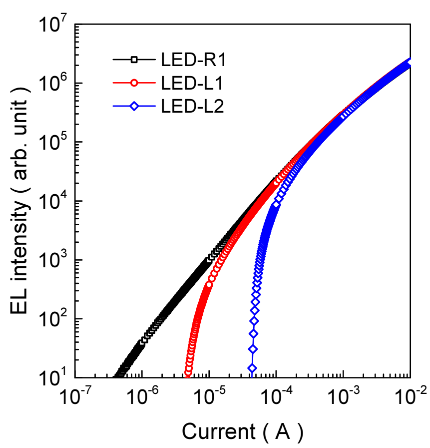

FIG. 7. EL intensities with respect to injection currents for an LED without leakage (LED-R) and LEDs with leakage (LED-L1 and LED-L2).

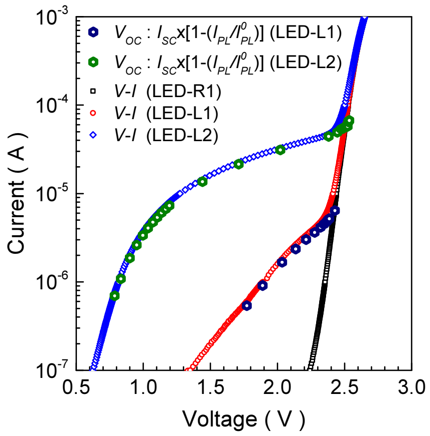

FIG. 8. Leakage current obtained using PL intensity reduction ratio depending on V_{OC} for LEDs with leakage (LED-L1, LED-L2) plotted together with *V-I* characteristics of LED-L1, LED-L2 and an LED without leakage (LED-R).

the optical turn-on where the EL begins to be detected for LED-L1 and LED-L2 under electrical excitation. The current value seems to be the current needed to overcome the carrier leakage through the leakage path to achieve radiative recombination at the active region. Figure 7 shows EL intensities for LED-R, LED-L1 and LED-L2 under current injection. Current values of optical turn-on for LED-R, LED-L1 and LED-L2 were approximately 4.5×10^{-7}, 4.8×10^{-6}, and 4.4×10^{-5} A, respectively. The optical turn-on voltages corresponding to each turn-on current were 2.322, 2.322 and 2.323 V, which were almost identical values to each other. This means that the current difference obtained from the *V-I* characteristics between an LED with leakage and LED-R near the optical turn-on voltage was around the leakage current value obtained using method II, and an additional current corresponding to the amount of leakage current is needed for an LED with leakage paths to emit light. The results shown in Figs. 6 and 7 indicate that the leakage of the LED chip at a low-forward-bias region below and near the optical turn-on voltage can be determined by PL and photovoltaic measurements.

When the V_{OC} dependence of the leakage current obtained using the PL intensity ratio and I_{SC} were plotted together with the *V-I* curve measured under electrical excitation, the tendency of the leakage current plot was consistent with the *V-I* curve at the forward-bias region below the EL threshold as shown in Fig. 8. The leakage current depending on the voltage obtained using parameters under photoexcitation was consistent with the *V-I* characteristic measured by current injection for LEDs with electrical leakages, even though the directions of carrier transport were different from each other for the two excitation conditions [18].

IV. SUMMARY

The relation between PL intensity and electrical leakage for GaN-based LED chips was investigated. For LEDs showing leakage at a forward bias, a decrease of PL intensity and open-circuit voltage under given photoexcitation conditions was observed. The reduction of PL intensity could be correlated with the electrical leakage that resulted from leakage paths in the LED chips. The leakage current depending on the voltage could be plotted using the PL intensity reduction ratio and PV properties, such as V_{OC} and I_{SC}, which were measured during photoexcitation for PL. The characteristic curves of the relation between the leakage current and V_{OC} were well-matched with the *V-I* characteristics of LEDs at the region below the voltage for the EL threshold. The results imply that PL measurements could be an alternative method to electrical probing for evaluation of electrical leakage for LED chips.

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