A Simple and Reliable Wafer-Level Electrical Probing Technique for III-Nitride Light-Emitting Epitaxial Structures

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***Abstract*—We report an easy-to-implement wafer-level electroluminescence characterization technique for InGaN/GaN light-emitting diodes (LED's) epi-wafers by means of multiple electrical probes. By first damaging the p-n junctions of the LED epilayer at localized spots, diode-like current versus voltage characteristics and emission spectra can be obtained at injection currents as high as 100 mA. This allows a relative but reliable comparison of device-related parameters such as differential quantum efficiency, leakage current, and series resistance among LED epi-wafers.**

***Index Terms*—current, electroluminescence, GaN, LED, III-nitride, probe technique, Schottky barrier, voltage.**

I. INTRODUCTION

III-NITRIDE based wide bandgap semiconductors have become increasingly attractive for optical emitters such as light emitting diodes (LED's), laser diodes (LD's) in the blue/UV spectral range, and high temperature electronic devices because of their superior performance and commercial potential [1], [2]. As III-nitride based light emitting devices (LED's and LD's) are commercialized in large quantities, reliable wafer-level evaluation techniques for these epi-wafers become increasingly important. The optical properties of InGaN/GaN quantum wells are usually evaluated by photoluminescence (PL). However, PL measurements only provide qualitative information on the radiative recombination efficiency of the active layer. Furthermore, PL measurements are sensitive to the p-type GaN cladding layer thickness, which is not the case for the probing technique presented. Often, pertinent device-related parameters such as light intensity, emission efficiency, breakdown voltage and leakage current are obtained only after the epi-wafer is processed into a device. It is highly desirable that a wafer-level characterization method be developed where these parameters can be extracted more *directly* with minimum intrusion to the sample. Such a characterization technique will not only reduce processing expenditures for poor quality wafers but also shorten the development cycle for growth recipes. In this article, we describe a simple and reliable electrical probing method to obtain the electroluminescence on the LED epi-wafers. The technique is then used for comparing the device-related parameters of LED epi-wafers grown under different conditions.

II. DESCRIPTION OF THE METHOD

III-Nitride LED epi-wafers are typically grown on insulating sapphire substrates. The probing technique we describe here is based on the fact that the sheet resistance of the top p-type GaN cladding layer is much higher ($>10^3$ times) than that of the n-type GaN layer for a typical LED structure [3]. This is a unique feature of the III-nitride material system due to the relatively low hole concentration ($<10^{18}/\mathrm{cm}^3$) achievable in these materials [2]. The schematics of the probing measurement are shown in Fig. 1(a)–(c). An array of three spring-loaded probes with 1 mm spacing is used for the measurement, where R_p, R_n, and R_c (or R_c') represent the resistance for the p-layer, n-layer, and the probe contacts, respectively. No specific surface treatment is applied to the wafer prior to probing. When a dc current is passed between probes 2 and 3, a high electrical potential is developed between the two probes due to the high resistance of the p-GaN layer. For typical LED epi-wafers, the terminal voltage is about ± 15 V at a current level of ± 150 μA. When the terminal voltage exceeds the sum of the turn on and the breakdown voltages of the two p–n junctions directly below probes 2 and 3, current will flow through the back-to-back p–n junctions via the low-resistance n-GaN layer. When this occurs, electroluminescence is generated by the injected current flowing through the forward biased p–n junction underneath the probe. Although electroluminescence can be generated in this way, it results in a high terminal voltage between the probe 2 and 3 which limits the maximum allowable current and can result in measurement instability. Further increase in the current leads to irreversible damage to both p-n junctions under the probes. We observed that such damage always occurred to both p-n junctions but is confined to localized spots near the probes. The damage near probe 3 (reverse biased) is caused by high voltage discharge, while the damage near probe 2 (forward bias), is caused by a sudden surge in current immediately following the diode breakdown at probe 3. After both junctions are damaged, the current–voltage (*I–V*) between the probes exhibits a resistor-like behavior, as represented by R_{d2} and R_{d3} in Fig. 1(c). The *I–V* characteristics before and after junctions damage are shown in Fig. 2. This provides a convenient way to electrically contact the n-GaN layer. Electroluminescence can be generated on a single p-n junction by passing current between probes 2 (or 3) and probe 1. The

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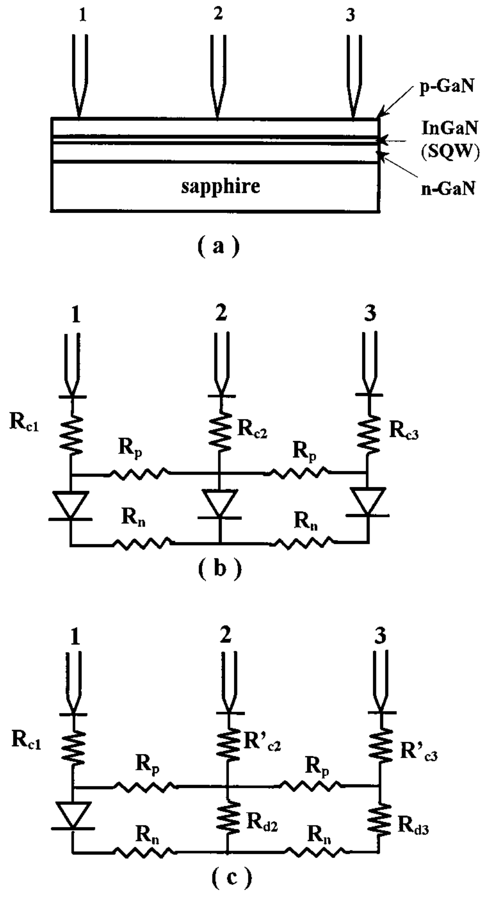

Fig. 1. Schematic diagram of the three-probe method: (a) InGaN/GaN SQW LED epi-structure with three probes and (b) and (c) show the equivalent circuit models of the wafer before and after the p–n junctions were damaged, respectively.

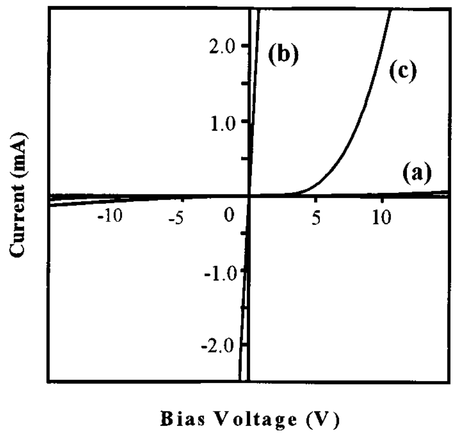

Fig. 2. *I–V* characteristics of the SQW LED epi-structure at different stages of the probe measurement: (a) before the diodes were damaged (between probes 2 and 3), (b) after both diodes were damaged (between probes 2 and 3), and (c) on a single p–n junction structure between probe 1 (anode) on a fresh spot of the wafer and probe 2 (cathode) on a damaged spot of the wafer.

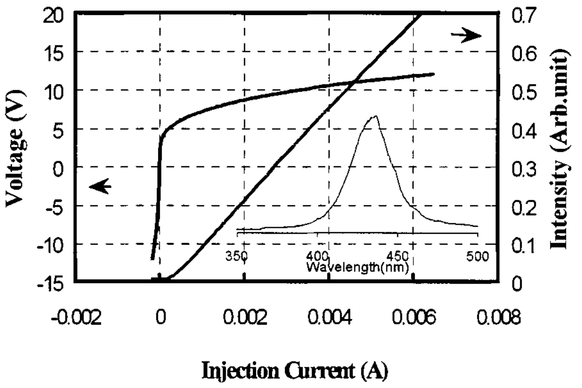

Fig. 3. Typical *I–V*, *L–I* and emission spectrum of InGaN/GaN SQW LED epi-structure obtained using the probing technique on a single p-n junction.

high resistance p-GaN cap layer effectively confines the injected current to an area directly underneath probe 1, thus avoiding the need for electrical isolation. Except for leakage current through the p-GaN layer, the probe measurement on a single p-n junction is identical to LED operation. From the *I–V* measurements between probes 1 and 2, 1 and 3, as well as 2 and 3, we can also extract the contact resistance, R_{c1} between the Cu probe and p-GaN cap layer.

In selecting the materials used for the probe, we have found copper (Cu) to be a superior choice compared to Tungsten. Not only does Cu form a reasonably low barrier height with p-type GaN [4], [5], it also provides a stable mechanical contact with GaN due to the larger probe diameter. The actual diameter of the Cu probe is estimated to be 130–140 μm, based on zero-biased capacitance measured (at 10 MHz) relative to an evaporated contact metal of known area.

III. RESULTS AND DISCUSSIONS

Fig. 3 illustrates typical *I–V*, *L–I* (light versus current) characteristics and the corresponding spectrum of the electroluminescence measurement of a single p–n junction. The structure of the single quantum well (SQW) LED epi-wafer (bottom to top) consists of a 1.5 μm n-GaN layer (Si-doped, 3×10^{19} cm^{-3}), a 4–8 nm thick InGaN well and a 0.2–0.5 μm p-GaN cladding layer (Mg-doped, $1–5 \times 10^{17}$ cm^{-3}) grown on insulating (1000)-oriented sapphire substrate. Close examination of the *L–I* curve indicates that the light intensity starts to increase only when the injection current exceeds a certain threshold, which we refer to as dead current. The dead current is related to quality and structure of the quantum well. The reproducibility of the probing technique is established by comparing *L–I* and zero-biased capacitance (at 10 MHz) measurements on various spots of a SQW LED epi-wafer. The variations of the capacitance and differential quantum efficiency, η_d (measured at 5 mA) are less than 5.7 and 10%, respectively, based on five separate measurements over a small uniform portion of the wafer. This indicates that the contact area of the Cu probe is very reproducible from round-to-round measurements. Stable and reproducible *I–V* and *L–I* characteristics were observed even at an injection current as high as 100 mA.

Next, we applied the probing method for evaluation of SQW LED epi-wafers grown under different conditions. The comparisons were made in terms of the leakage current, series resistance, dead current, η_d (at 5 mA), and breakdown voltage. The results are summarized in Table I. Careful comparison shows that samples with low η_d (samples A and B) tend to be associated with large dead current, large leakage current and low

TABLE I
SUMMARY OF DEVICE-RELATED PARAMETERS EXTRACTED FROM PROBE MEASUREMENTS ON InGaN/GaN SQW LED EPI-STRUCTURES GROWN UNDER DIFFERENT CONDITIONS

Run No.	Relative Differential Quantum Efficiency (η_d)	Dead Current (mA)	Leakage Current (mA)	Breakdown Voltage (V)	Series Resistance (Ω)
A	12%	2.7	0.64	20	164
B	9%	1.7	0.15	22	166
C	37%	0.11	0.10	50	175
D	46%	0.30	0.11	35	178
E(Ref.)	100%	0.08	0.10	45	27

breakdown voltage. This points to nonradiative defects in the active SQW region as the cause for the recombination and generation currents under forward and reverse bias, respectively. However, as the material quality of the SQW improves, as indicated by the higher η_d (samples C, D, and E), not only was the dead current reduced, the leakage through the p-n junction was also reduced to a level below the intrinsic leakage current of the probe measurement through the p-GaN cladding layer. For these samples, the difference in the dead current can be attributed to the intrinsic carrier transport across the SQW region, including possible thermionic emission through the SQW which dose not contribute to light emission. We also note from Hall measurements that samples with low R_{c1} exhibit higher hole concentrations. This is expected since a higher hole concentration will lead to lower contact resistance between the probe and the p-GaN cap layer. The fully processed LED's [6] are also measured on the same epi-wafers. Good qualitative agreement between the probe measurement results and LED results are obtained.

In some samples during the probe measurement, however, we observed electrical shorting when the applied probe current exceeds a critical value. The magnitude of the critical current becomes smaller for samples with either lower p-type doping concentration, or thinner p-type cladding layers. We believe this is caused by high-level injection of electrons in the p-GaN layer, which may reach a concentration comparable to the hole concentration in the p-GaN layer. We speculate that when the excess electrons extend all the way to the Cu probe, the contact resistance is suddenly lowered. This triggers a surge in current that in turn damages the p-n junction. We have demonstrated that this problem can be alleviated by using probes with larger contact area.

IV. CONCLUSION

We have demonstrated a reliable and easy-to-implement wafer-level probing technique in which the electroluminescence from the active p-n junction can be obtained with minimum intrusion to the wafer. This allows a relative comparison of device-related parameters such as differential quantum efficiency, leakage current, and series resistance from one wafer to the next. The method should find wide application for the evaluation and screening of III-nitrides epi-wafers prior to complete device processing.

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