Optical and Thermal Performances of (Ga,In)N/GaN Light Emitting Diodes Transferred on a Flexible Tape

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***Abstract*—Blue (Ga,In)N-based light-emitting diodes (LEDs) grown on a Si(111) substrate by metal–organic vapor phase epitaxy are transferred on a flexible tape after the Si substrate removal. Their optical and thermal behaviors are measured and compared to those of regular LEDs on Si. The light output power of the flexible LEDs is increased due to a higher light extraction efficiency related to the removal of the absorbing Si substrate. However, the maximum output power is limited by thermal effects due to the lower thermal conductivity of the flexible tape. Monitoring the electroluminescence wavelength of the flexible LEDs allows determining their acceptable operating range. The maximum flexible LED luminance is 5×10^5 cd/m^2.**

***Keywords* - Light emitting diodes, flexible tape, GaN, InGaN.**

I. INTRODUCTION

III-NITRIDE wide bandgap semiconductors are efficient materials for the fabrication of a variety of optoelectronic devices such as light emitting diodes [1], laser diodes [2] and of electronic devices for high-frequency and high power applications [3]. The performances of these devices are now very high. Some research efforts are currently devoted in order to get these same devices on flexible substrates as it is already the case for organic electronics [4], [5]. The expected advantage of using inorganic LEDs in place of organic LEDs is a much stronger luminance which is a key parameter for applications such as high luminance micro-displays [6], [7]. Indeed, these nitride devices are epitaxially grown on thick and rigid crystalline substrates such as sapphire or Si [8] and it is very difficult to constrain them [9]. In order to obtain flexible devices, one solution consists in transferring the nitride layer from its original rigid substrate used for epitaxy to a flexible one. This was recently demonstrated for InGaN/GaN LEDs and for AlGaN/GaN high electron mobility transistors [10]–[12]. Several strategies can be applied to transfer the LED structure. LEDs can be grown on sapphire substrate and detached using a laser lift-off technique [13]–[20] or can be grown on an h-BN release layer [21]. Alternatively, structures grown on silicon can be transferred after the full etching of the silicon substrate [22]–[24]. More advanced realizations such as the transfer of arrays of μLEDs on flexible substrates have also been demonstrated [22], [25]. Most of these demonstrations are based on two-dimensional structures but 3-dimensional nanostructure such as nanowires [26], [27] or GaN microdisks [28], [29] can be used as well with the additional advantage of being stress-free and weakly affected when the flexible substrate is strongly bent. Different flexible substrates have been used such as thin metallic substrates [30], [31], plastic substrates [4]–[11], copper coated polyimide substrates [20], or ceramic substrates [32]. Metallic foils have the advantage of a good electrical and thermal conductivity but with less flexibility than plastic substrates. In this work we focus on the study of LEDs transferred on plastic substrate and especially on the assessment of their performances and their limitations related to thermal dissipation. We focus on the use of an adhesive tape with a relatively high thermal conductivity and that is electrically insulating (for plastic films). The thermal conductivity is 3W/m.K and dielectric strength is 14.5 kV/mm.

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II. EXPERIMENTAL

The samples were grown by metal-organic chemical vapor deposition (MOCVD) on 6-inch Si(111) substrates in a showerhead-type Aixtron reactor with H_2 or N_2 carrier gases. Trimethylgallium (for GaN) or triethylgallium (for $In_xGa_{1-x}N$), trimethylindium, silane, bis(cyclopentadienyl) magnesium, and ammonia are used as precursors for gallium, indium, silicon, magnesium and nitrogen, respectively. At first, a 200-nm-thick AlN layer is deposited on the Si(111) substrate. Then, a stack constituted by layers of GaN (1700 nm), AlN (20 nm)/GaN (1000 nm)/AlN (20 nm)/GaN (500 nm) is grown to improve the crystalline quality and to compensate for the tensile strain coming from the thermal coefficient mismatch between the GaN and the Si(111) substrate. More details on this structure and its optimization can be found in [33]. These buffer layers are followed by 1 μm-thick Si:GaN n-type layer, a 5-periods $In_{0.16}Ga_{0.84}N$ (2.4 nm)/GaN (11.5 nm) multiple quantum well active region, and then a 20-nm-thick $Al_{0.2}Ga_{0.8}N$ electron blocking layer and a 130 nm- thick GaN layer are grown, these last two layers being p-type doped with Mg.

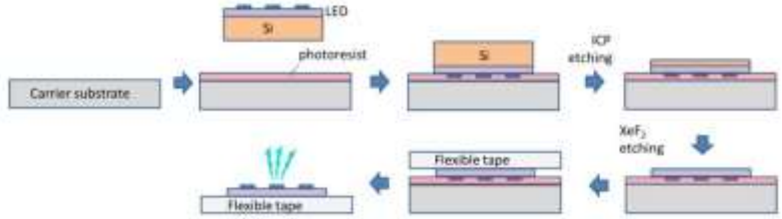

Fig. 1. Process flow for the transfer of the processed LED structure on Si substrate onto the flexible tape.

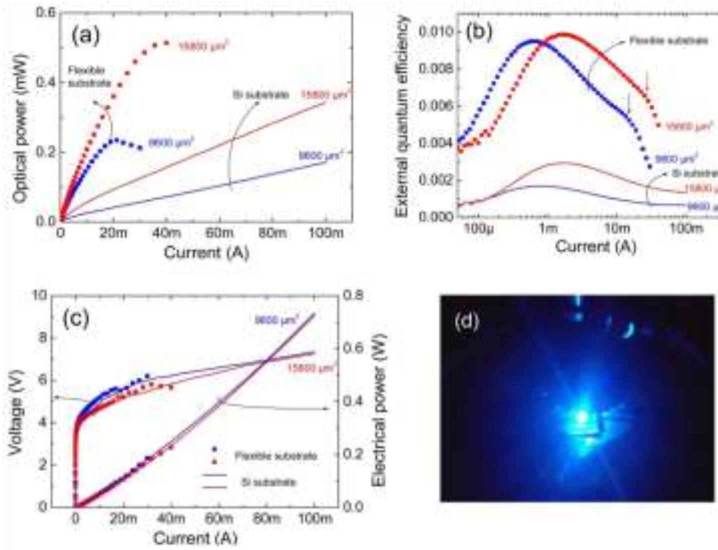

Fig. 2. Room temperature current dependence of the optical power (a), the external quantum efficiency (b), the voltage and the injected electrical power (c) of blue (Ga,In)N/GaN light emitting diodes on flexible substrates (squares) and on Si substrates (lines) for two different LED sizes: 9600 μm^2 and 15800 μm^2. (d) Photograph of a blue LED on a flexible substrate with an area of 15800 μm^2 driven at 10 mA.

LEDs are processed into rectangular mesas by reactive ion etching. The ohmic contacts are made of Ti/Al/Ni/Au (30/180/40/150 nm) metal stacks on n-GaN and Ni/Au (5/5 nm) semi-transparent current spreading layer plus a Ni/Au (10/100 nm) contact pad as top electrode to p-GaN. The semi-transparent area is 9600 or 15800 μm^2. The top p electrode area (contact pad) is 6000 μm^2. The LEDs are measured at room temperature under CW conditions. They are contacted using micro-manipulators with needle probes. The electroluminescence (EL) is detected using a BWTek spectrometer. The LED output powers are measured with a calibrated Si photodiode located at 30 mm above the devices. The current-voltage characteristics are measured using a Keithley 2400 source meter.

The procedure used to transfer the LEDs onto the flexible tape is shown in Fig. 1. The tape is an experimental version based on 3M 5515 Thermal pad from 3M Company. It consists of a thermally enhanced polymer carrier coated on one side with a silicone based adhesive. The key properties were slightly improved versus the commercial version to address the particular needs of this work and to provide an enhanced thermal conductivity of 3 W/mK. The Young's modulus is 110 N/mm^2. The process started with the spin coating of a photoresist onto the LEDs in order to protect them. Then, the sample was flipped and temporary bonded onto a sapphire carrier substrate. Deep RIE etching and then XeF_2 etching were used to gently remove the Si substrate without cracking the GaN layer. At this stage, the back side of the wafer was stuck onto the adhesive tape. Finally, the photoresist deposited on the front side was removed by immersion in acetone leading to the release of the LEDs from the carrier substrate. A similar process was previously used for the transfer of transistors based on (Al,Ga)N/GaN heterostructures or (Ga,In)N/GaN LEDs [10], [11], and [24].

III. Device Characteristics

The external quantum efficiency curves show a peak at a current (current density) of 0.7 mA (7 A/cm^2) and 1.7 mA (11 A/cm^2) for LEDs with an area of 9600 μm^2 and 15800 μm^2, respectively. We remark that this peak efficiency is obtained almost for the same current density in LEDs on Si and in transferred LEDs. For larger injection currents, the EQE decreases. This phenomenon known as "efficiency droop" is well documented for GaN-based LEDs [34]. One of the main origins of this droop is non-radiative Auger processes which become dominant at large current densities [35]. An additional feature can be seen on the EQE curves of LEDs on flexible substrate: at a current indicated by the arrow in Fig. 2(b) (~15 mA and ~30 mA for LED sizes of 9600 μm^2 and 15800 μm^2), there is an inflexion point followed by a strong decrease of the EQE. This drop in the EQE corresponds to the saturation of the output power as shown in Fig. 2(a). This phenomenon is absent for the LEDs on Si. According to the higher thermal conductivity of the Si substrate (150 W/m.K) compared to the flexible substrate (3 W/m.K) we can suspect that the output power saturation of the flexible LEDs is related to thermal effects that will be characterized in more details in the following. The maximum EQE (1%) is rather low compared to the best results published by OSRAM regarding LEDs grown on Si substrate [6] and can largely be improved using optimized buffer layers and LED structures, and adding surface texturation to improve the light extraction efficiency.

The maximum LED output power of the 9600 μm^2 LED is 2 times smaller than in [25]. Our LED output power saturates at an injected electrical power of 112 mW, i.e. 5 times larger compared to [25] due to the larger thermal conductivity of our flexible substrate. The similar LED electrical characteristics before and after transfer on the flexible substrate of Fig. 2(c) indicate that the LED transfer process does not lead to a strong change in the operating voltage. This voltage is relatively high compared to the state of the art due to non-optimized p-type doping. The injected electrical power of the LEDs on flexible substrate is very close to that of the LEDs on Si substrate. This shows that the thermal degradation observed is not linked to a strong increase of the operating voltage.

We study now the variation of the peak EL wavelength as a function of the current for LEDs with an area of 9600 μm^2. At low current, the emission wavelength λ_0 is respectively 480 nm and 479 nm for the LEDs on Si substrate and on flexible substrate. In this current range, the emission wavelength is almost constant. In the case of the LED on Si substrate, there is a blue shift of the EL peak for currents larger than 200 μA. At 100 mA, the emission wavelength is 465 nm corresponding to a blue-shift of 15 nm compared to the value at low current. This blue-shift has been attributed to band filling effects and to the progressive screening of the internal electric field in the (Ga,In)N/GaN quantum wells by the injected carriers [36], [37]. In the case of the LED on flexible substrate, there is a blue-shift of the EL wavelength up to a current of ~10 mA (104 A/cm^2) followed by a red-shift for larger currents Fig. 3(a). This red-shift is due to a strong increase of the LED temperature as shown by temperature measurement of the LED using an IR camera (Fig. 3(b)). No significant increase of the temperature can be detected for the LED on Si substrate. Therefore the wavelength emission difference (λ_{EL}) between the LED on flexible substrate and on Si substrate can give access to the red-shift due to the temperature increase. The variation of λ_{EL} as a function of the temperature measured by the IR camera is shown in Fig. 3(c). We calculate the expected $In_{0.16}Ga_{0.84}N$ bandgap energy variation as a function of the temperature T using the Varshni expression:

$$\Delta E(T) = -\frac{\alpha T^2}{\beta + T},$$

with $\alpha = 0.803 \times 10^{-3}$ eV/K^3 and $\beta = 797$K. These values for the $In_{0.16}Ga_{0.84}N$ alloy are linearly interpolated from the data for the binary compounds GaN and InN given in [38]. This calculation gives a good agreement with the experimental data showing that the simple measurement of the EL wavelength emission of the LED as a function of the current can reliably be converted in a temperature variation.

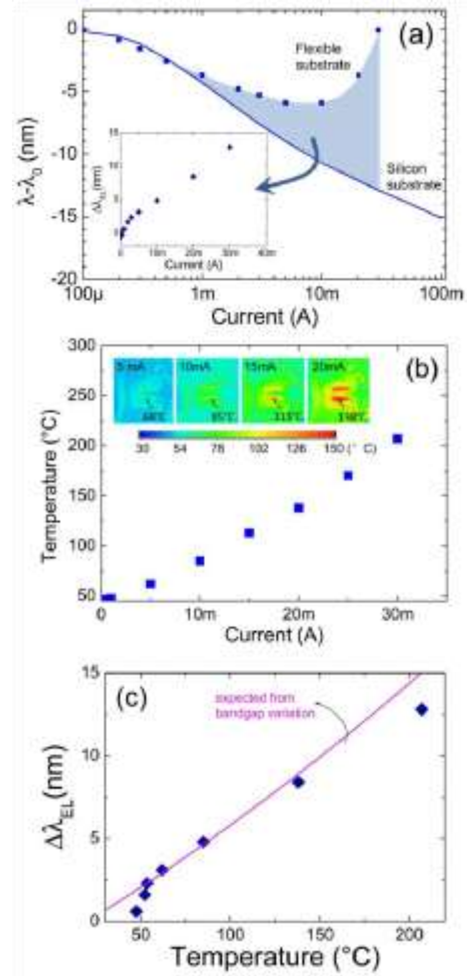

Fig. 3. (a) Electroluminescence wavelength difference $\lambda(I)-\lambda(I < 200\mu A)$ as a function of the current I for light emitting diodes (LEDs) with a surface area of 9600 μm^2 on Si substrate or reported on flexible substrate. The inset shows the wavelength difference λ_{EL} between the two different substrates. (b) Temperature variation measured with an IR camera as a function of the current for the LED reported on flexible substrate. (c) λ_{EL} as a function of the temperature of the flexible LED.

We applied this technique to assess the thermal behavior of flexible LEDs during bending. To do so the sample was mounted on a half-cylinder chuck with a curvature radius of 14 mm (see photograph in Fig. 4). As shown in Fig. 4, the EL variations of both the bent LED and the flat LED are very similar. This shows that there is no specific change in the thermal behavior of the flexible LEDs due to the bending.

IV. Conclusion

The large increase of the (Ga,In)N/GaN LED temperature during operation at large current limits the maximum output power which can be achieved with these flexible LEDs. However, we can point out that if lower light levels are acceptable, the flexible LEDs can be driven at the current corresponding to the maximum external quantum efficiency.

In this case no strong thermal effects are present. For the LED with an area of 15800 μm^2, at a current of 1.7 mA, an output power of 46 μW is obtained and a luminance of

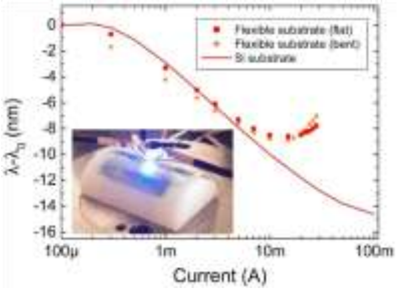

Fig. 4. Electroluminescence wavelength difference $\lambda(I)-\lambda(I < 200\mu A)$ as a function of the current I for light emitting diodes with an area of 15800 μm^2 on Si substrate or reported on flexible substrate. The flexible light emitting diode is measured under flat conditions or bent conditions with a curvature radius of 14 mm.

4×10^4 cd/cm^2 can be deduced (considering an isotropic emission). The maximum luminance is 5×10^5 cd/cm^2 at a

current of 40 mA. Even with a strong limitation of the injected current, the luminance that we obtained favorably compares with the one achievable in organic LEDs. If larger output powers are required, the LED series resistance has to be minimized to decrease the Joule heating for a given current.

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