Electrochemical etching - a way to enable transfer-printing of III-nitride devices

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Selective underetching of semiconductor devices for the purpose of heterointegration is highly desirable in the context of applications like displays and photonic integrated circuits. The separated thin structure should possess atomically smooth bottom surface to enable transfer-printing and keep high yield of the process. Nitride optoelectronic devices are highly regarded for their exceptional light emission properties at wavelengths from 450 nm to 550 nm, making them attractive for integrated light sources. However, III-nitrides, opposed to traditional III-Vs, lack a sacrificial layer that can be chemically etched.

In this paper we demonstrate a way to separate GaN-based layers using electrochemical etching (ECE). ECE is sensitive to the local conductivity of a given layer and to the bias voltage applied during etching. These relationships are presented on heavily doped (>10^{20} cm^{-3}) (In,Ga)N:Ge layers, which were investigated by scanning electron microscope and atomic force microscopy to choose optimal doping level and bias voltage to obtain electropolishing (complete removal of the etched layer).

Finally, we present a light-emitting diode structure with a sacrificial layer beneath, which was successfully transfer-printed to a foreign substrate after ECE. The measured optical spectrum of the light from a printed device is reported.

Introduction

Currently there is a huge demand for technologies enabling complex functionality of a single chip. For semiconductors this property can be achieved by using heterogenous integration, which includes designing and manufacturing devices separately to enable integration of processed chips into a higher-level assembly. Such platforms are aimed to possess enhanced system performance compared to standard monolithic systems and are very desirable for displays, photonic integrated circuits, visible light communication, etc. In micro-transfer-printing, a technology used for heterogenous integration, chips are manufactured on a host wafer and then separated from it. In the next step the devices are transferred to a foreign substrate using an elastomer stamp. One of the most important requirements for the separated thin structures is smoothness of their bottom surface, which ensures high yield of the process and good coupling to the foreign interposer.

Nitrides are ideal candidates for light sources in the visible spectral range from 450 nm to 550 nm and beyond [1]. The wide bandgap of GaN (3.4 eV) also opens the possibility of using it in high-power and high-frequency electronic devices. However, integration of nitride components on SiN or Si photonic platforms still remains a challenge due to lack of sacrificial layer that could be chemically etched, which would lead to separation of the device from the host substrate [2].

Electrochemical etching (ECE) has been demonstrated to be a powerful technique for porosification and electropolishing (complete removal) of GaN-based layers [3, 4]. ECE is conducted in a three-electrode setup in an acidic electrolyte. The sample is positively biased in order to deliver holes to the semiconductor/electrolyte interface, where material dissolution takes place following the equation: $GaN + 3h^{+} \rightarrow Ga^{3+} + \frac{1}{2} N_2\uparrow$. The morphology of the etched layer depends on its local conductivity and the bias voltage applied during the process. Thanks to these relationships, ECE can be used for selective removal of sacrificial layers in nitride structures enabling their transfer-printing.

Fabrication of the samples

The samples studied in this paper were grown by plasma-assisted molecular beam epitaxy (PAMBE) in a custom designed Veeco GEN20A reactor. For all structures bulk GaN substrates were used. Three series of samples were fabricated. First one (S1) was a stack of alternating 100-nm layers of undoped (In,Ga)N and (In,Ga)N:Ge with different Ge dopant concentrations from $6\cdot10^{19}$ cm^{-3} up to $5\cdot10^{20}$ cm^{-3}. InGaN:Ge instead of GaN:Ge was used to enable uniform dopant incorporation at the extremely high doping concentrations [5]. After ECE, the first series of the samples was investigated under scanning electron microscope (SEM) to investigate the obtained morphology and choose the range of Ge dopant concentration for further experiments. The second series of samples (S2) consisted of a 300-nm (In,Ga)N:Ge layer with graded Ge doping of $2.5\cdot10^{20}$ cm^{-3} in the first 260 nm and $7.5\cdot10^{20}$ cm^{-3} in the upper 40 nm. The Ge doped layer was capped with a 300-nm GaN:Si (Si concentration $2\cdot10^{18}$ cm^{-3}) layer. The separated layers were investigated using SEM to check the smoothness of the back side of the chips. As the last series of the samples an LED structure with a sacrificial layer was fabricated (S3). The S2 and S3 structures were covered with a thick dielectric encapsulation formed in tethers, so that the separated layers were suspended after etching of the sacrificial release layer, see Fig. 1. The separated LEDs were transfer-printed onto a silicon target sample. More details about the transfer printing technique can be found in [6]. All etching processes were conducted in a standard three-electrode set-up in 0.3M oxalic acid.

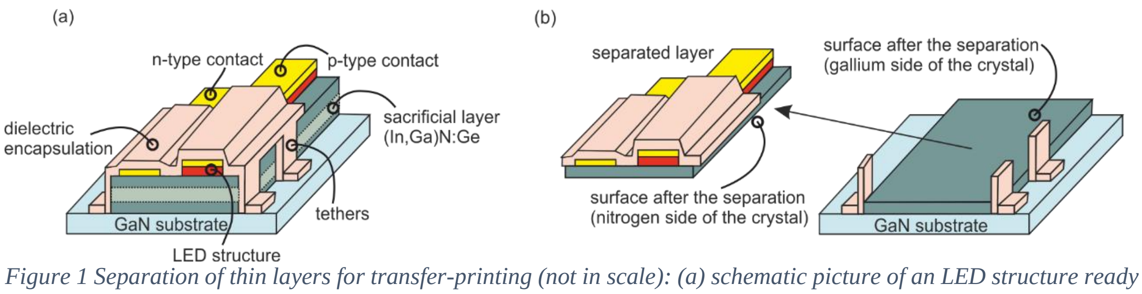

Figure 1 Separation of thin layers for transfer-printing (not in scale): (a) schematic picture of an LED structure ready to undergo electrochemical etching of the sacrificial layer, (b) picked coupon after removal of the sacrificial layer. Adapted from [7].

Electrochemical etching of (In,Ga)N:Ge layers

The structure with alternating undoped and doped layers (S1) was etched under 1.7, 1.9, 2 and 3 V [7]. The results of these experiments are presented in Fig. 2. Fig. 2a shows the dependence of morphology (no etching, porous layer, electropolishing) on bias voltage and Ge concentration. Two conclusions can be drawn: (1) the higher the voltage, the higher the porosity, and (2) the higher the Ge concentration, the lower the voltage needed for electropolishing. These statements are in line with the knowledge about ECE of GaN doped with silicon, another n-type dopant [3]. Basing on morphologies of the etched layers shown Fig. 2b we concluded that Ge doping on the level of 10^{20} cm^{-3} and bias voltage in the range of 2-3 V will be appropriate conditions for electropolishing.

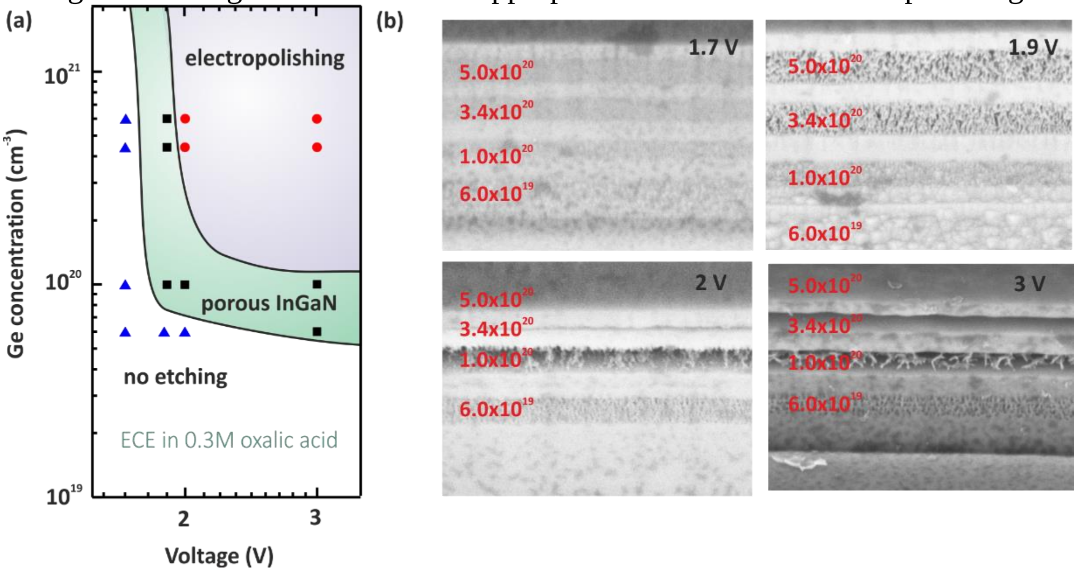

Figure 2 Electrochemical etching of (In,Ga)N:Ge: (a) dependence of morphology of the etched layer on Ge concentration and bias voltage, (b) SEM images if cross-section of the etched structures. Adapted from [7].

To ensure highest possible smoothness of the etched surface, the S2 samples possessed exceptionally high Ge doping ($7.5 \cdot 10^{20}$ cm^{-3}) in the upper part of the sacrificial layer. The etching bias voltage was set to 2.5 V. After ECE the samples were investigated under optical microscope. In top-view presented in Fig. 3a two neighboring fully underetched coupons can be seen – the left one is covered with the dielectric encapsulation formed in tethers, whereas the encapsulation and the cap layer from the right one delaminated during ECE. The left coupon was detached on a carbon tape and its back side was investigated under SEM, see Fig. 3b. High picking yield and very smooth surface were observed.

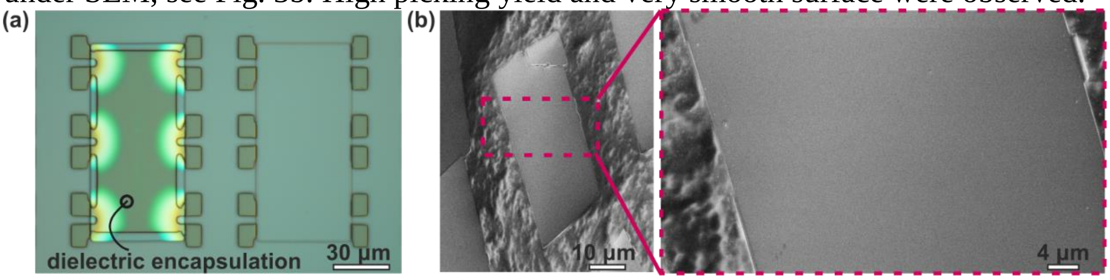

Figure 3 (In,Ga)N:Ge layers after ECE: (a) top-view optical microscope view of two neighboring coupons, (b) SEM image of the back side of a detached coupon.

Transfer-printing of GaN-based LEDs

An LED chip after etching is shown in Fig. 4a – the sacrificial layer is completely etched and the coupon is fully separated from the host substrate, therefore it was found to be ready for transfer-printing. The separated chips were successfully integrated onto Si wafer and tested electrically. Emission of blue light (Fig. 4b) was observed for fairly high voltages > 6 V. In Fig. 4c I-V characteristics of the transferred devices are presented with a considerable leakage current. Such a high opening voltage and leakage current are evidence of short circuit in the fabricated system. Further works will be focused on improvement of the chip design in order to enhance the picking yield and lower the opening voltage of the transferred optoelectronic devices.

Conclusions

Electrochemical etching has been demonstrated as a useful technique for separation of GaN-based devices from the host substrate. Thanks to its sensitivity to the local doping level, it was possible to selectively remove sacrificial (In,Ga)N:Ge layers with Ge dopant concentration ~10^{20} cm^{-3}. Moreover, the surface of the bottom part of the etched coupons was smooth, which feature is crucial for high yield of the transfer-printing process, as well as for good coupling between the interposer and the device. Last but not least, I-V characteristics of successfully transferred LEDs are presented. Presence of leakage paths in the manufactured devices was noted. The results shown in this work pave the way towards the integration of GaN-based optoelectronic devices into photonic integrated circuits.

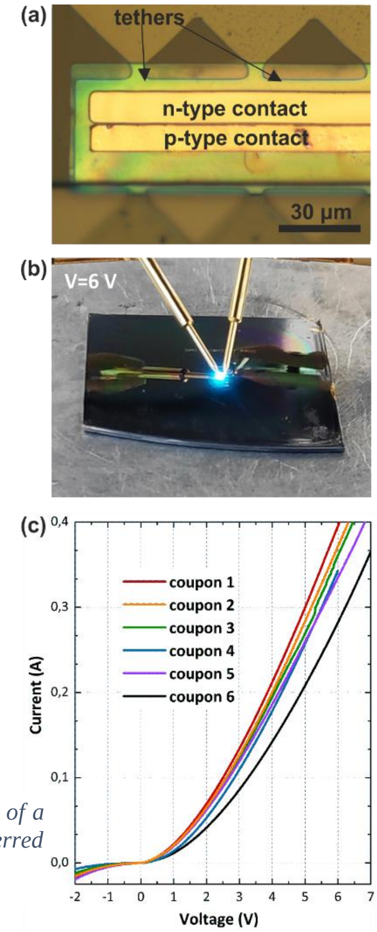

Figure 4 Transfer-printing of GaN-based LEDs:(a) optical microscope top-view of a separated LED coupon, (b) naked-eye view of blue light emission from a transferred device, (c) I-V characteristics of the transferred chips.

Acknowledgments

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