Laser-induced local activation of Mg-doped GaN with a high lateral resolution for high power vertical devices

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A method for laser-induced local p-type activation of an as-grown Mg-doped GaN sample with a high lateral resolution is developed for realizing high power vertical devices for the first time. As-grown Mg-doped GaN is converted to p-type GaN in a confined local area. The transition from an insulating to a p-type area is realized to take place within about 1–2 μm fine resolution. The results show that the technique can be applied in fabricating the devices such as vertical field effect transistors, vertical bipolar transistors and vertical Schottky diode so on with a current confinement region using a p-type carrier-blocking layer formed by this technique. © 2018 Author(s).

Many studies have been reported on the development of high-power devices using materials such as GaN/AlGaN, Ga2O3 and diamond.1–3 High-power vertical GaN devices, such as vertical field effect transistors (FETs), vertical bipolar transistors, and vertical Schottkey diode so on are the main applications of GaN-related materials. In case of vertical FETs the source–drain current should be confined to the gate region to control the current by the gate. To achieve this confinement, a local carrier-blocking layer of p-GaN has been proposed.4 Crystal regrowth5 or ion implantation6 into the n-type layer are commonly employed methods to achieve such a current-blocking layer.

Crystal regrowth is a complicated technique in which lithography needs to be performed during the interruption of crystal growth. In this process, the regrown crystal surface is exposed to air and contaminated by the lithography processes. Consequently, the quality of the regrown crystals is unsatisfactory.

Ion implantation needs a high-vacuum system, and spatial control of the implanted dopants is difficult. Furthermore, damage caused during the ion implantation is a serious problem. In order to reduce this damage, annealing processes are required.

In conventional p activation of Mg-doped as-grown GaN, a hot wall furnace or rapid thermal annealing processes are used for the annealing. However, the as-grown Mg-doped GaN is uniformly activated and locally confined activation is impossible. In contrast, the laser-induced local activation (LILA) process developed here for the first time allows the preparation of local p-activated regions without any damage or dopant migration. LILA is a technique for converting locally as-grown Mg-doped GaN or AlGaN epitaxial layers grown by metal organic chemical vapor deposition (MOCVD) to p-type GaN or AlGaN using excimer laser irradiation while conducting in situ monitoring of the surface during the process. It is demonstrated that it is possible to locally convert the as-grown n-type or insulating region to p-type in a conversion transition region of approximately 1–2 μm accuracy using LILA. Especially this LILA can control the areas to be activated as a fashion of area-by-area using a computer control system.
Here, local activation in Mg-doped GaN to p-type GaN from n-type as-grown GaN using LILA is reported. The sample used was a Mg-doped GaN layer epitaxially grown on a Si (111) substrate by MOCVD. On the Si substrate, a buffer layer (2 µm), a non-doped (4 µm) layer and a Mg-doped GaN (1 µm) layer were grown, successively. The Mg doping was $2.6 \times 10^{19}$ cm$^{-3}$.

Excimer laser light (193 nm, 10–500 Hz, 0.1–7 mJ/pulse, 10 ns pulse width) was collimated with a pin hole and lenses to a size of 1 mm × 0.2 mm on the sample surface. The profile of the laser intensity was observed using a knife edge method. The sample, on a stage, was scanned horizontally and vertically to obtain uniform and/or local irradiation. The optimum scanning speed for obtaining uniform irradiation was determined by simulation using the experimentally observed beam profile pattern. Photoluminescence (PL) and scattered light from the surface were observed in situ during the laser irradiation using an optical spectrum analyzer to control the irradiation condition as shown in Fig. 1.

The optical micrographs of the surface under laser irradiation at high and low power intensities are shown in Fig. 2. At an irradiation of 0.7 mJ laser power, the surface was mirror-like with p-type conversion (Fig. 2(a)). Under this condition, the in situ monitored PL and scattered light were identical to those of the unprocessed sample.

However, when the laser intensity was increased to 1.8 mJ, the scanning pattern of the laser can clearly be seen due to surface ablation and the surface is no longer mirror-like (Fig. 2(b)). A new spectrum appeared on the optical spectrum analyzer, which may have come from the surface modified by the laser. The details of the spectrum will be reported elsewhere.

The carrier types, the carrier density and mobility of the samples activated by LILA and the samples annealed using a conventional hot wall furnace were determined using Van der Pauw–Hall measurements. The experimental results are summarized in Table I. In the as-grown sample, the Hall effect could not be measured because of the high resistivity of the sample, but it was assigned as n-type from Seebeck effect measurements. The carrier type obtained by LILA processing was p-type; this was the same as that obtained by conventional heat treatment. The carrier density and mobility were comparable but the mobility obtained LILA method is higher than that obtained by
TABLE I. Carrier density and mobility of Mg-doped GaN activated by LILA and conventional hot wall furnace annealing determined by Van der Pauw–Hall effect measurements.

<table>
<thead>
<tr>
<th>Treatment Method</th>
<th>Carrier type</th>
<th>Carrier density ($\text{cm}^{-3}$)</th>
<th>Mobility ($\text{cm}^2/\text{V} \cdot \text{sec}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As grown</td>
<td>n-type</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Laser activation (1.1mJ, 150Hz in Air)</td>
<td>p-type</td>
<td>$3.3 \times 10^{16}$</td>
<td>4.7</td>
</tr>
<tr>
<td>Conventional Furnace activation (950°C, 20min in N$_2$)</td>
<td>p-type</td>
<td>$5.5 \times 10^{16}$</td>
<td>4.1</td>
</tr>
</tbody>
</table>

*aFrom Seebeck effect measurement.

conventional furnace activation method. In this region of carrier concentration of order of $10^{16}/\text{cm}^3$, phonon scattering may be a main scattering mechanism but not electron-ionized acceptor scattering. So, laser annealing phenomena to improve the crystal quality may happen.

In LILA process the process is confined in a small local area and the crystal quality may better than original one as discussed in previous paragraph. The spread of the heat generated by the laser is less than 1 to 2 micron meter as proved in Kelvin probe measurement shown in Fig. 4. So, this LILA process does not effect to other processes carried out for device fabrication such as ohmic contact formation and/or hetero structure interface.

For confirming local activation of as-grown Mg-doped GaN, LILA was conducted on a sample with a mask of 3-mm Si stripe patterns on the surface. As shown in Fig. 3(a), the laser irradiated the whole area of the sample with the mask, and the mask was then removed after irradiation to measure the conductance profile of the sample. The irradiated area changed to p-GaN and the non-irradiated area remained n-type as-grown GaN, which was confirmed by Seebeck effect measurements. Two microprobe measurements were carried out as shown in Fig. 3(b). Two microprobes separated at a distance of 0.3 mm were moved together to the perpendicular direction of the p–n$^-$ junction interface. The current between the two probes was measured after removing the mask.

FIG. 3. Two-probe conductance measurements on the LILA-treated surface using a mask. (a) Sample used for local activation by LILA with the mask. (b) Schematic view of the two-probe measurement of the local conductance. The two probes were moved on the surface in the direction perpendicular to the p–n$^-$ junction. (c) Current observed by the two-probe measurements as a function of distance.
The current observed as a function of the distance of the movement across the p–n\textsuperscript{-} junction is shown in Fig. 3(c). At the interfaces of the p–n\textsuperscript{-} junction (I) and (II), an abrupt conductance change was observed. The abrupt change was more than two orders of magnitude greater on conductance in the p-GaN compared to that in the n\textsuperscript{-} type as-grown GaN. The conduction transition width between the non-irradiated and the irradiated regions was determined to be less than the resolution limit of 70 \(\mu\text{m}\) in this two-probe method. This meant that the Mg did not diffuse under laser irradiation, the laser did not penetrate in the horizontal direction and local activation was enabled by LILA. The steepness of the interface was less than the resolution limit of 70 \(\mu\text{m}\) of this measurement.

To clarify the spatial resolution limit of LILA in the conversion region at a finer scale, Kelvin probe force microscopy (KFM) was performed, with which atomic force microscopy (AFM) could be performed simultaneously. Typical results are shown in Fig. 4.

The 4-\(\mu\text{m}\) Ti stripe metal masks at an interval of 8 \(\mu\text{m}\) were deposited on the as-grown surface using lithography for this experiment. After uniform irradiation on this sample, the Ti metal masks were removed. The Ti metal masked (non-irradiated) and unmasked (irradiated) regions can clearly be distinguished in the KFM image and line profile, where a potential difference of the laser-irradiated region and non-irradiated region of approximately 200 meV was observed (Fig. 4(a)).

This clear contact potential difference of about 200 meV arose from the work function difference between the p-type converted Mg-doped GaN by laser irradiation and the n\textsuperscript{-} type as-grown Mg-doped GaN. The value was smaller than that expected from the work function difference between ideal p- and n\textsuperscript{-} type GaN. The reason for the discrepancy is not clear at the moment, but the same phenomenon has been observed in other materials. In particular, the measurements on pure n- and p-type GaAs showed a work function difference of 260 meV.\textsuperscript{7} This was tentatively attributed to the surface states changing their degree of charging when the Kelvin force measurements were performed using AFM cantilevers, thereby inducing an uneven field at the surface.

The simultaneously observed AFM image is shown in Fig. 4(b). The surface was almost flat and the root mean square roughness of the surface was 9.5 nm. (The spikes observed in the KFM and AFM cross-sections were not noise, but were due to surface contamination during the processes.) This image confirms the boundaries of the masked and unmasked regions, agreeing well with the KFM results.
From these results, it can be concluded that the conversion transition from p- to n-GaN occurs over a distance of about 1–2 µm. The laser light was absorbed just on the surface because of the high optical absorption coefficient of GaN for 193 nm light (∼7×10⁵/cm)⁸ and the heat generated at the surface diffused isotropically. The observed transition region of about 1–2 µm suggests that the thermal diffusion length in which p-type conversion takes place from the as-grown sample is about 1–2 µm. As the thermal conductivity of GaN is 1.0 W/K·cm,⁹ the temperature at a depth of 1–2 µm below the surface is about 10–20°C lower than the temperature at the surface.

The carrier-blocking layer of p-GaN is underneath the GaN and AlGaN for vertical FETs. However, the thickness of AlGaN is about 10–20 nm and the thickness of the GaN is expected to be about 0.3 µm, depending on the device design. So, the Mg-doped GaN inside the device can be activated locally using this LILA method, and vertical FETs with a p-GaN carrier-blocking layer can be developed. When it is necessary for activation at deeper Mg-doped GaN layers locally, activation can be achieved using a multi-irradiation technique.

The present results show the strong potential for fabrication of vertical devices with p-GaN without using any regrowth or ion implantation techniques. In addition to this advantage LILA method makes possible to fabricate repeated and complicated small cells of devices using computer control system by positioning the local activating spots one by one and/or large area batch treatment for the activation.

In conclusion, a new technique, called LILA, has been established for the first time. This has achieved local activation of Mg-doped GaN using an excimer laser operating at 193 nm together with in situ observations of the surface during laser processing. Using this method, local activation of carriers with a lateral resolution of about 1–2 µm was possible, thus establishing the potential for fabricating vertical high-power devices without using any other fabrication techniques such as crystal regrowth, ion implantation or mesa structures.