Hydrogen plasma passivation for blue laser diodes

Researchers claim the first use for a strategy resulting in enhanced power efficiency and thresholds.

Researchers based in China claim the first use of hydrogen (H) plasma treatment as a passivation strategy for blue ridge laser diodes [Lu Wang et al, Optics Express, v32, p34492, 2024]. The treatment enabled an increase in slope efficiency and reduction in threshold current, compared with conventional silicon

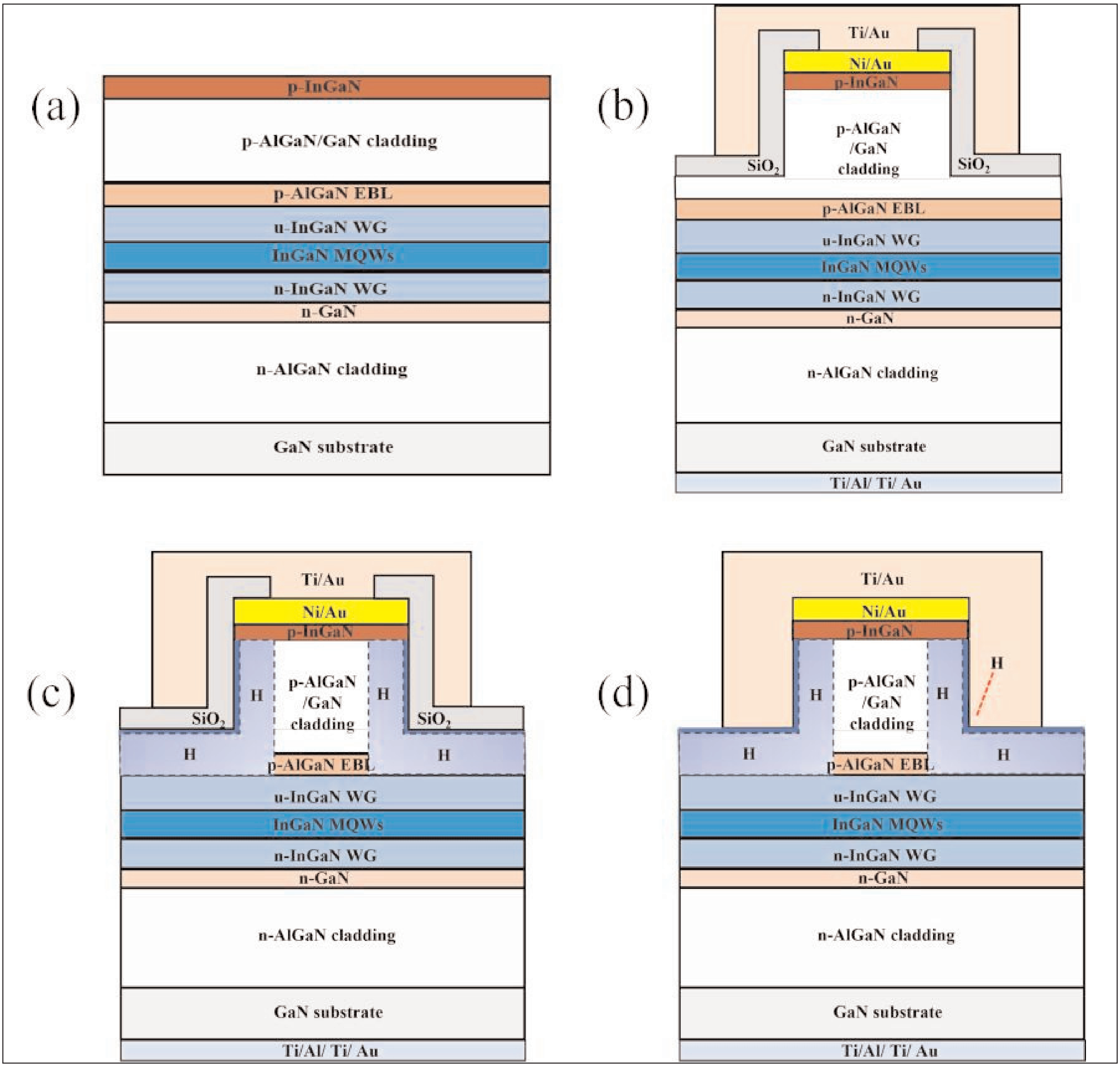

Figure 1. (a) GaN laser diode epitaxial structure. Further schematics of respective S_1–S_3 ridge laser diode passivation strategies: (b) conventional SiO_2; (c) double-layer; and, (d) pure H-plasma laser diode.

dioxide (SiO_2) passivation.

The H plasma treatment interacts with the magnesium (Mg)-doped p-type gallium nitride and aluminium gallium nitride (AlGaN) layers to produce neutral Mg–H complexes. These complexes reduce the conductivity of the p-type layers near the surface — a task usually given to insulating passivation materials such as SiO_2. Indeed, the activation anneal of p-type III–nitrides is designed to drive out H to enhance hole injection into light-emitting structures such as laser diodes.

The team included researchers from Suzhou Institute of Nano-Tech and Nano-Bionics, Changchun University of Science and Technology, University of Science and Technology of China. These researchers hope that the enhanced performance enabled by their H plasma treatment could lead to expanded commercial application of blue laser diodes in multiple fields such as communication, healthcare, military, industrial processing, and beyond.

The researchers comment on the effects of increased surface leakage currents caused by poor passivation: "The increase of the laser diode leakage current not only leads to energy wastage but also causes wavelength drift, reduction in output power, and potentially shortens the laser diode's lifetime."

The disadvantages of SiO_2 include "incomplete encapsulation, poor thermal dissipation, and performance degradation due to high interface state density," according to the authors.

The researchers studied three ridge laser diode passivation strategies: conventional silica/silicon dioxide (SiO_2); mixed H plasma treatment and SiO_2; and just the H plasma treatment (Figure 1). The SiO_2 layers were 200nm thick. The H plasma treatment was carried out in an Oxford Instruments' Plasmalab 100 ICP 180 system.

The RF power was set at 2W with the inductively coupled plasma power at 300W. The gas supply was hydrogen and argon at rates of 30 and 5 standard cubic centimeters per minute (sccm), respectively. The plasma treatment was followed by 350°C rapid thermal annealing for 10 minutes.

The epitaxial structure was grown on c-plane free-standing GaN with the usual AlGaN cladding, and InGaN waveguide (WG) and multiple quantum well (MQW), layers, along with a p-AlGaN electron-blocking layer (EBL) insertion below the p-cladding. The WG and cladding provide optical confinement, and the MQW generates and amplifies the photons via stimulated and spontaneous emission processes.

The ridge waveguide structure was 45μm wide and was created by etching down through the 130nm p-GaN contact layer and 440nm into the p-cladding.

The metal contact layers used nickel/gold (Ni/Au) for the p-electrode, and titanium/gold (Ti/Au) for the pad, applied after the passivation processes. The n-electrode/pad was a stack of Ti/Al/Ti/Au. The metal layers also provided reflectance of light back into the laser cavity.

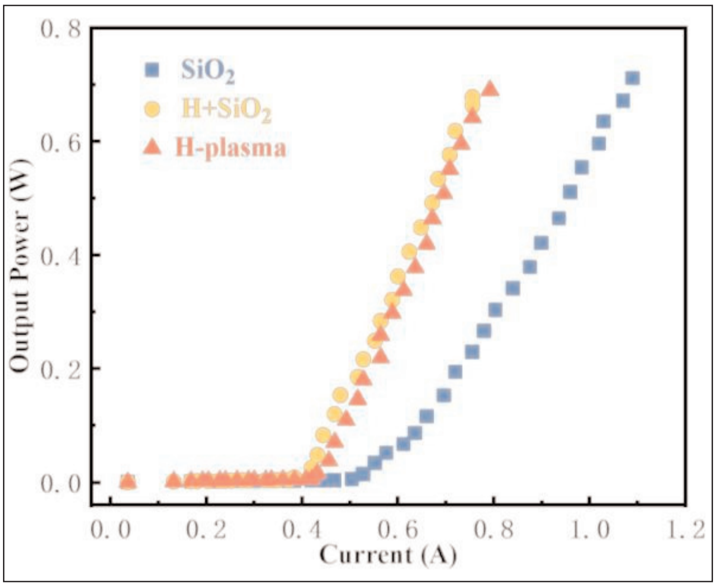

Figure 2. Light output power versus current for three device types.

The final laser diodes were separated into 1200μm-long cavities, and were treated to give 8%/98% reflectance for the front/rear facets, respectively.

In current-voltage measurements both H-plasma treated devices demonstrated a reverse-bias leakage current reduced by three orders of magnitude from ~10^{-5}kA/cm^2 for the conventional diodes to ~10^{-8}kA/cm^2 with H plasma treatment. The leakage with plasma treatment was close to the limit of the ability of the measurement equipment to register.

Under forward bias, the current injection at 6V was slightly lower in the pure plasma-treated diode, compared with the mixed passivation. The team suggests that this could be due to excessive hydrogen diffusion, adding: "In the future, the excess hydrogen entering the laser can be reduced by further optimizing the conditions (such as reducing the concentration of hydrogen gas, reducing the power of the ICP). In this way, only a small amount of hydrogen can form a complex reaction on the ridge, ensuring leakage and slope efficiency, and solving the voltage problem."

The light output power of the diodes (Figure 2) showed a slope efficiency of ~1.95W/A of the plasma-treated devices over 1.40W/A with just SiO_2 passivation. The pure H plasma diode (S_3) had a slightly higher slope efficiency, compared with the mixed passivation device.

The researchers comment: "During the deposition process of SiO_2 in S_2, some minor diffusion of Si and O atoms may occur. However, in S_3, no SiO_2 was introduced, resulting in a lack of Si and O atom diffusion. The above results indicate that, compared to traditional SiO_2 passivation layer, laser diodes treated with H plasma on the ridge exhibit significantly higher

Table 1. Summary of light output power-current behavior under three isolation/passivation conditions.

Sample	Isolation	Threshold current	Slope efficiency	Leakage
S_1	SiO_2	0.55A	1.40W/A	10^{-5}kA/cm^2
S_2	SiO_2 + H plasma	0.40A	1.93W/A	10^{-8}kA/cm^2
S_3	H plasma	0.42A	1.96W/A	10^{-8}kA/cm^2

Table 2. Benchmark of Suzhou et al’s results and other reports of blue laser diode performance.

Group	Country	Report	Slope efficiency	Light output power	Threshold
Nippon Chemical Industrial	Japan	2017	1.8W/A	5W	—
Sony Corp	Japan	2018	1.8W/A	5.2W	—
Osram Group	Germany	2014	1.6W/A	4.5W	—
Osram Group	Germany	2019	1.4W/A	—	0.01A
Hiya/Nichia Corp	Japan	2024	2W/A	—	0.28A
Suzhou et al	China	2024	1.96W/A	—	0.42A

slope efficiency, demonstrating superior treatment effectiveness.”

By analyzing the theoretical factors that can contribute to the slope efficiency, the researchers believe that the primary effect of the H plasma treatment is to reduce the absorption coefficient of the p-GaN layers, decreasing the internal optical losses of the laser diodes.

The threshold current for the H-plasma-treated devices was around 0.4A, compared with 0.55A for the conventional laser diode (Table c). The mixed device had a slightly lower threshold than the pure hydrogen plasma treatment of S3.

The emitted wavelengths of the devices were withing 1nm of each other: 450nm for S_1 and S_3, 449nm for S_2. The researchers also studied the H plasma layer by secondary-ion mass spectroscopy (SIMS), finding the thickness to be 238nm. This is negligible in comparison to the 45μm ridge width.

The Suzhou et al team also provides some comparison data/benchmarks from previous research reports (Table d). ■

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