Lithography-free microfabrication of AlGa_N/Ga_N 2DEG strain sensors using laser ablation and direct wire bonding

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Abstract

This work presents a simple and rapid lithography-free (i.e., maskless) microfabrication process for strain-sensitive aluminum gallium nitride (AlGa_N)/Ga_N sensors. We microfabricated an AlGa_N/Ga_N strain sensor through laser ablation of the underlying Si (111) substrate and direct bonding of aluminum wires to the AlGa_N surface, creating a Schottky contact to the two-dimensional electron gas (2DEG). We measured the sensor's current-voltage operation while displacing the center of the membrane up to 106.7 μm and characterized its sensitivity at from 0.5 to 2 V bias (i.e., 5 to 100 nA/ μm). This work advances the development of AlGa_N/Ga_N-on-Si microelectronics (e.g., pressure sensors, accelerometers, and gyroscopes) using the simplified fabrication process, which eliminates lithography, metallization, and etching, and reduces the manufacturing time (5 min) and cost, as well as the need for cleanroom environments.

Keywords: *Gallium nitride, Microfabrication, Strain sensor, Laser ablation, Direct wire bonding*

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Introduction

Microelectronics based on aluminum gallium nitride (AlGaN) and GaN heterostructures have gained interest for various sensing applications such as strain [1,2], pressure [3,4], inertial [5], chemical [6], and optical sensors [7,8] due to their higher sensitivity and extended operation temperature by wide bandgap properties. Among such devices, AlGaN/GaN-based mechanical sensors have particularly emerged because the conductive two-dimensional electron gas (2DEG) formed at the AlGaN/GaN interface is highly responsive to external stimuli [9,10]. The majority of AlGaN/GaN mechanical sensors typically use suspended membrane [2,3,11] or cantilever [1] elements with metal alloys for Ohmic and Schottky contacts. In general, such devices scheme requires multiple microfabrication steps including thin film deposition, lithography, dry/wet etching, metallization, and annealing. In addition, fabricated devices are needed to be packaged separately on ceramic chip carriers. However, this multiple microfabrication steps and packaging process lead to high cost, a lot of time, and complexity of overall process. Consequentially, a development of simple and rapid microfabrication/packaging techniques is required for the fabrication of various microelectronics. In this work, we demonstrate a facile, rapid, and reliable microfabrication technique using direct laser ablation and direct wire bonding [7,12] to create AlGaN/GaN strain sensors (suspended membrane type) in less than 5 minutes. The silicon (Si) substrate was quickly etched away using the laser ablation, which is much faster etching process compared to conventional Si dry/wet etching, to release membrane structure. The backside Si etching was achieved without any photolithography processes including photoresist coating, baking, photoresist development, and backside alignment. In addition, the direct bonding between suspended AlGaN/GaN membrane and chip carrier enables simultaneous metallization and packaging processes that eliminate tedious metallization process (i.e., lift-off).

Fig. 1. Schematic of AlGaIn/GaN strain sensors using a combination of laser ablation etching and direct wire bonding architectures. (a) Singulation of AlGaIn/GaN-on-Si die, (b) membrane suspension using laser ablation, and (c) aluminum wire bonding between AlGaIn surface and leadless chip carrier.

Experimental method

A schematic of our simple fabrication process is shown in Fig. 1. AlGaIn/GaN-on-Si wafer (DOWA, 2DEG mobility of $\sim 1400 \text{ cm}^2/\text{V}\cdot\text{s}$) was singulated into $5 \text{ mm} \times 5 \text{ mm}$ die (Fig. 1a). Then a circular diaphragm (3.5 mm diameter) of the underlying Si substrate was etched using laser ablation (DPSS Samurai UV Laser) (Fig. 1b). The laser was operated at 3 W at 30 kHz pulses, 30 passes, 200 mm/s scribe speed, 25 μm scribe spacing, and cross hatch cut path, completed in 200 seconds. The etched die was rinsed with acetone and isopropyl alcohol to remove chip debris. The die was then attached with polyimide tape to a ceramic leadless chip carrier (LCC) and directly wire-bonded (ultrasonic power of 460 mW for 30 ms) using aluminum bonding wire (25.4 μm diameter) [7] (Fig. 1c). The fabricated device was tested under various displacements using a micromanipulator (Signatone S-M40) with a small tip, centered over the diaphragm. Force was applied through vertical displacements at $1/48^{\text{th}}$ turn of the knob ($\sim 13.3 \mu\text{m}$). Figures 2a and 2b show the experimental testing setup and optical image of packaged AlGaIn/GaN die on the LCC used in this study, respectively. A small tip on the end of the micromanipulator was centered over the packaged AlGaIn/GaN strain sensor. The tip was slowly moved down toward the center of the membrane while measuring the current-voltage response in

Fig. 2. (a) Image of experimental setup for strain transduction measurements and (b) optical image of packaged AlGaIn/GaN die on ceramic leadless chip carrier (LCC).

a range of voltage (V_{bias}) from 0 to 2 V. We added $1/48^{\text{th}}$ of a turn and took sequential current-voltage measurements until the displacement reaches $107.6 \mu\text{m}$ over which the membrane was broken. To characterize the sensors transient and reliable response, the change of current with respect to time was also monitored with varied bias voltages. This measurement was conducted by alternatively applying and releasing displacement.

Results and discussion

Figure 3a shows an optical image of 3.5 mm diameter cavity etched by laser ablation of the underlying Si substrate. To characterize the surface roughness, etched surface was visually investigated using 3D non-contact confocal microscope (S-neox, Sensofar) and it showed RMS surface roughness of $21.34 \mu\text{m}$, as shown in Fig. 3b. Figures 3c and 3d show a cross-sectional scanning electron microscope (SEM) image of suspended AlGaIn/GaN diaphragm (thickness of $\sim 190 \mu\text{m}$) and Al wire directly bonded between the LCC and AlGaIn surface, respectively. The physically stable and electrically reliable metal contact was achieved using a direct wire bonding between the LCC and sensing surface. This simultaneous fabrication and packaging process took only approximately 5 min (with 1 hour of preparation time) whereas several hours and photolithography masks are needed in conventional microfabrication and packaging methods.

Fig. 3. (a) Optical image of a 3.5 mm diameter cavity etched by laser ablation of the underlying Si substrate, (b) confocal contour of etched surface indicating RMS surface roughness of 21.34 μm , (c) cross-sectional SEM image of suspended AlGaIn/GaN membrane after laser ablation etching, and (d) aluminum wires directly bonded between LCC and AlGaIn surface for electrical connection.

To characterize the fabricated strain sensors, we applied different displacements with a micromanipulator and measured the current-voltage response. Figure 4 shows the change in current passing through the 2DEG with respect to applied displacement (i.e., strain). External strain through applied displacement induces additional piezoelectric polarization of the 2DEG [13], changes in surface traps [14], and alters the Schottky barrier height [15]. Therefore, there was an increase in current when the membrane was gradually deflected from 13 μm to 106.7 μm . It should be noted that the current came back to the base current (i.e., dashed line in Fig. 4) when the strain was completely released, indicating a stable and reversible sensor's operation. Figure 5 shows the change of current (ΔI) with respect to applied strain under different operation voltages. To estimate the sensitivity of the sensor, a linear fitting curve was employed on each data. The measured data are in good agreement with linear fitting curves, as seen in Fig. 5. Table 1 summarizes the calculated sensitivity (in $\text{nA}/\mu\text{m}$ unit) with the coefficient of determination (R^2)

Fig. 4. Current change of the fabricated AlGaIn/GaN strain sensor under different applied displacement.

Fig. 5. Change of current and linear fitting curves with respect to various displacements under different operation voltages.

values of linear fitting curves. The R^2 values around 0.96 to 0.99 for four different linear fitting curves showed the proportional (linear) trend of current change with respect to the applied

displacements. In addition, the sensitivity increases with an increase in V_{bias} , which is a general trend of devices using a Schottky contact [16–18].

Table 1 Calculated sensor’s sensitivity and coefficient of determination values using linear curve fitting method.

Applied bias (V)	Sensitivity (nA/ μm)	R^2
0.5	5.3	0.966
1	18.5	0.991
1.5	48.9	0.994
2	101.6	0.994

To characterize transient response of the fabricated sensor, the real-time current change was monitored with different levels of displacement applied and released alternatively, as shown in Fig. 6. It should be noted that the base current at high V_{bias} (i.e., 2 and 3 V) was drifted at the beginning because of initial discharging from transients when device was first turned on. Once these transients were settled (stable), the current-voltage response was returned to the original base level upon release of the displacement, as shown in Fig. 6, demonstrating stable and reversible operation of the fabricated AlGaIn/GaN strain sensor. There was some variation in the base current due to the manual placement of wire bonds and AlGaIn/GaN membrane thickness variation due to laser focus during the ablation etching process. In addition, since this microfabrication technique relies on the fabrication of Schottky diodes, variations in surface states may have a larger impact on the device sensitivity than high-electron mobility transistors (HEMTs) architecture. Nevertheless, this prototyping method enables low cost testing for studying 2DEG transduction properties and rapid customization for GaN-on-Si microelectronics products without cleanroom infrastructure.

Fig. 6. Transient current response for the strain sensor under different bias voltages (1, 2, and 3 V) with different levels of displacement applied and released alternatively. 26.7 μm steps = A, D, F, H; 53.3 μm steps = B, E, G, I; 80 μm steps = C, J; 106.7 μm = K.

Conclusions

In summary, this study reports the facile and rapid microfabrication technique for AlGaIn/GaN strain sensors. The laser ablation was used for etching Si substrate and release AlGaIn/GaN membrane within a short period time. The direct bonding of Al wires on AlGaIn surface was achieved for simple electrical connection between the LCC and sensors. The overall fabrication process was completed within 5 min, which is significantly faster than conventional microfabrication processes. This prototyping method enables testing GaN-on-Si microelectronics devices before investing in a costly wafer-scale process, and studying GaN in laboratories without cleanroom facilities.

Conflict of Interest

The authors declare no competing financial interest.

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