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Research paper

Lithography-free microfabrication of AlGaN/GaN 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 (AlGaN)/GaN sensors. We microfabricated an AlGaN/GaN strain sensor through laser ablation of the underlying Si (111) substrate and direct bonding of aluminum wires to the sensor 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 approximately 106 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 AlGaN/GaN-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.

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1. Introduction

Microelectronics based on aluminum gallium nitride (AlGaN) and GaN heterostructures have gained interest for various sensing applications such as strain [1–3], pressure [4,5], inertial [6], chemical [7], and optical sensors [8–10] due to their 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 [11,12]. The majority of AlGaN/GaN mechanical sensors typically use suspended membranes [4,5,13] 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 [1,4,13]. In addition, fabricated devices need to be packaged separately on ceramic chip carriers. However, this multiple microfabrication steps and packaging process leads to high cost, large time commitment, and complexity of overall process. Consequentially, the 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 as reported in our former study [10,14] to create AlGaN/GaN strain sensors (suspended membrane type) in less than 5 min. 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) [10,14].

2. Experimental method

A schematic of our simple fabrication process is shown in Fig. 1. AlGaN/GaN-on-Si wafer (DOWA, 25% Al content in AlGaN, 2DEG mobility of ~1400 $\mathrm{cm}^2/\mathrm{V\cdot s}$) was singulated into 5 mm × 5 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 s. 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, Spectrum Semiconductor Materials Inc.) and directly wire-bonded (7476E, West Bond Inc., ultrasonic power of 460 mW for 30 ms) using aluminum bonding wire (25.4 μm diameter) [10] (Fig. 1c). The fabricated device

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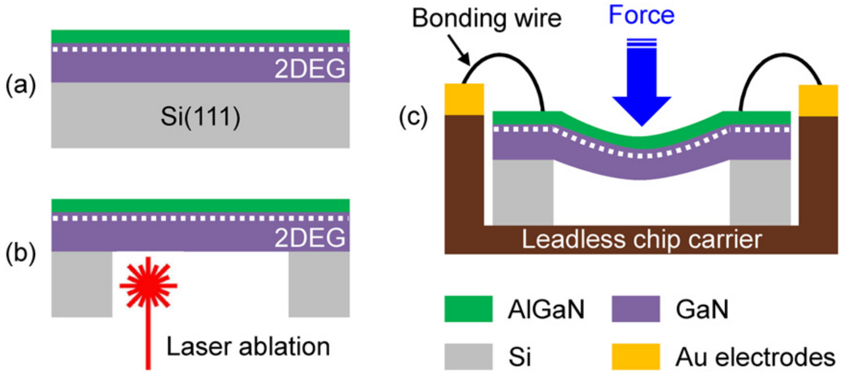

Fig. 1. Schematic of AlGaN/GaN strain sensors using a combination of laser ablation etching and direct wire bonding architectures. (a) Singulation of AlGaN/GaN-on-Si die, (b) membrane suspension using laser ablation, and (c) aluminum wire bonding between sensor surface and leadless chip carrier.

was tested under various displacements using a micromanipulator (Signatone S-M40 micropositioner) with a small tip, centered over the diaphragm. Force was applied through vertical displacements at 1/48th turn of the knob (~13.2 μm). Fig. 2a and b show the experimental testing setup and optical image of packaged AlGaN/GaN die on the LCC used in this study, respectively. A small tip on the end of the micromanipulator was centered over the packaged AlGaN/GaN strain sensor. The tip was slowly moved down towards the center of the membrane while measuring the current-voltage response in a range of voltage (V_{bias}) from 0 to 2 V. We added 1/48th of a turn and took sequential current-voltage measurements until the displacement reached approximately 106 μm. 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.

3. Results and discussion

Fig. 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 μm, as shown in Fig. 3b. Fig. 3c and d show a cross-sectional scanning electron microscope (SEM) image of suspended AlGaN/GaN diaphragm (thickness of ~190 μm) and Al wire directly bonded between the LCC and the GaN capping surface on top of the AlGaN barrier layer, respectively. The physically stable and electrically reliable metal contact was achieved using a direct wire bonding between the LCC and sensor surface [10,14]. This simultaneous fabrication and packaging process took only approximately 5 min (with 1 h of preparation time) whereas several hours and photolithography masks are needed in conventional microfabrication and packaging methods.

To characterize the fabricated strain sensors, we applied different displacements with a micromanipulator and measured the current-voltage response. Fig. 4 shows the change in current passing through the 2DEG with respect to applied displacement (i.e., strain). External tensile strain through applied displacement induces additional piezoelectric polarization of the 2DEG and increases the sheet carrier concentration [1,4,15–18]. Therefore, there was an increase in current when the membrane was gradually deflected from 13.2 μm to 105.8 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. Fig. 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 nA/μm unit) with the coefficient of determination (R^2) 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 has also been observed in other GaN based devices [19,20].

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

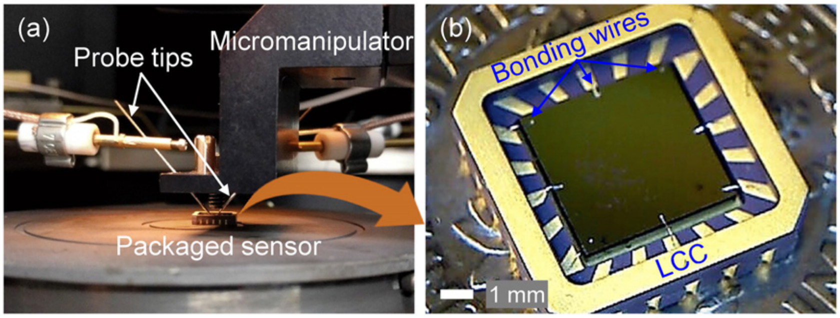

Fig. 2. (a) Image of experimental setup for strain transduction measurements and (b) optical image of packaged AlGaN/GaN die on ceramic leadless chip carrier (LCC).

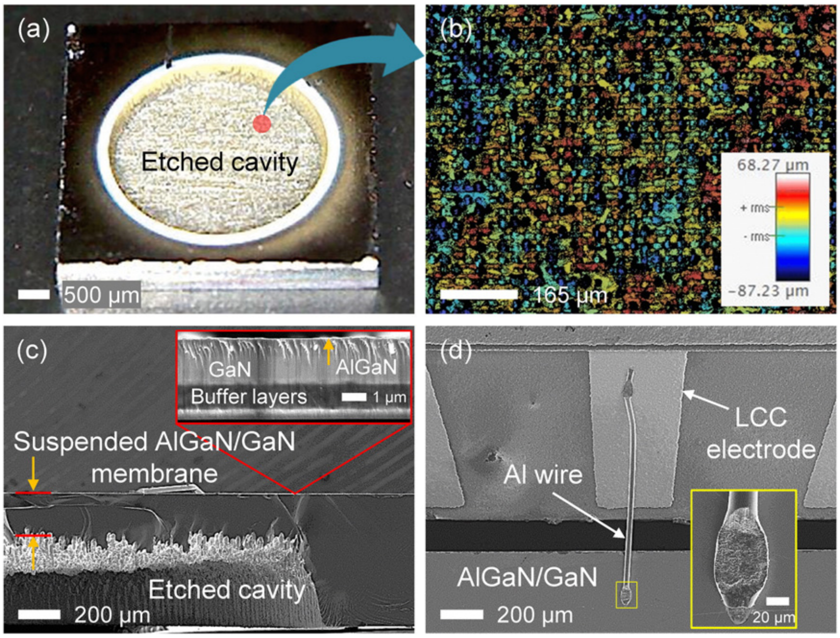

Fig. 3. (a) Optical image of a 3.5 mm diameter cavity etched by laser ablation of the underlying Si substrate, (b) confocal contour of etched surface indicating RMS surface roughness of ~21.34 μm, (c) cross-sectional SEM image of suspended AlGaN/GaN membrane after laser ablation etching, and (d) aluminum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

and reversible operation of the fabricated AlGaN/GaN strain sensor. There was some variation in the base current due to the manual placement of wire bonds [10] and AlGaN/GaN membrane thickness variation due to laser focus during the ablation etching process. 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.

4. Conclusions

In summary, this study reports the facile and rapid microfabrication technique for AlGaN/GaN strain sensors. The laser ablation was used for etching Si substrate and release AlGaN/GaN membrane within a short period time. The direct bonding of Al wires on sensors 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 microelectronic 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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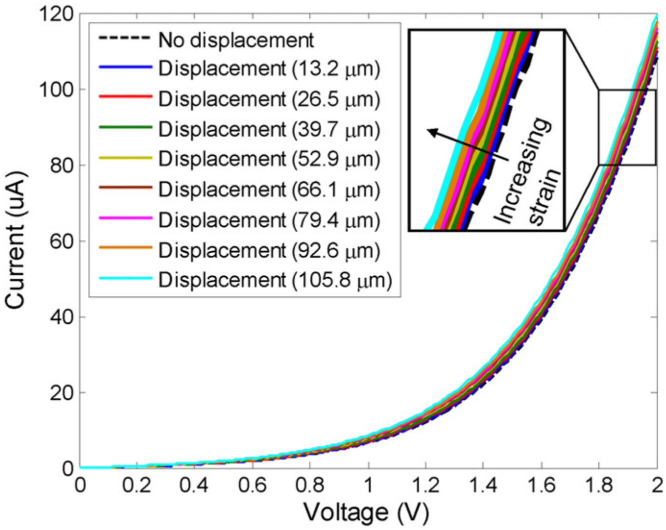

Fig. 4. Current change of the fabricated AlGaN/GaN strain sensor under different applied displacements.

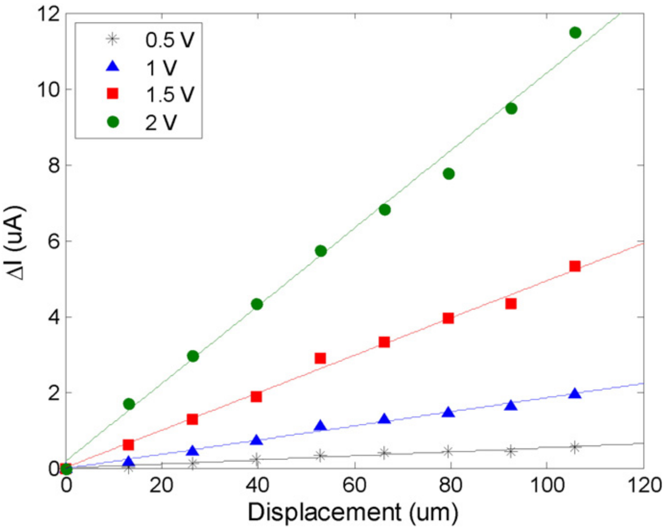

Fig. 5. Change of current and linear fitting curves with respect to various displacements under different operation voltages.

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	5.4	0.966
1	18.7	0.991
1.5	49.3	0.994
2	102.5	0.994

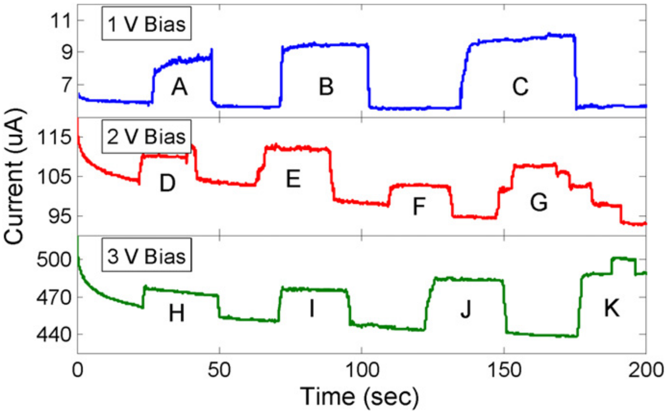

Fig. 6. Transient current response for the strain sensor under different bias voltages (1, 2, and 3 V) with different levels of displacement applied and released alternatively. Qualitative amplitude of applied displacements: A < B < C (at 1 V), D = F < E = G (at 2 V), and H < I < J < K (at 3 V).

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References

[1] B.S. Kang, S. Kim, J. Kim, F. Ren, K. Baik, S.J. Pearton, B.P. Gila, C.R. Abernathy, C.-C. Pan, G.-T. Chen, J.-I. Chyi, V. Chandrasekaran, M. Sheplak, T. Nishida, S.N.G. Chu, Effect of external strain on the conductivity of AlGaN/GaN high-electron-mobility transistors, Appl. Phys. Lett. 83 (2003) 4845–4847.

[2] M. Eickhoff, O. Ambacher, G. Krötz, M. Stutzmann, Piezoresistivity of $Al_xGa_{1-x}N$ layers and $Al_xGa_{1-x}N$/GaN heterostructures, J. Appl. Phys. 90 (2001) 3383–3386.

[3] K. Yao, S. Khandelwal, F. Sammoura, A. Kazama, C. Hu, L. Lin, Piezoelectricity-induced Schottky barrier height variations in AlGaN/GaN high electron mobility transistors, IEEE Electron Device Lett. 36 (2015) 902–904.

[4] B.S. Kang, S. Kim, F. Ren, J.W. Johnson, R.J. Therrien, P. Rajagopal, J.C. Roberts, E.L. Piner, K.J. Linthicum, S.N.G. Chu, K. Baik, B.P. Gila, C.R. Abernathy, S.J. Pearton, Pressure-induced changes in the conductivity of AlGaN / GaN high-electron mobility-transistor membranes, Appl. Phys. Lett. 85 (2004) 2962–2964.

[5] M.J. Edwards, E.D. Le Boulbar, S. Vittoz, G. Vanko, K. Brinkfeldt, L. Rufer, P. Johander, T. Lalinský, C.R. Bowen, D.W.E. Allsopp, Pressure and temperature dependence of GaN/AlGaN high electron mobility transistor based sensors on a sapphire membrane, Phys. Status Solidi C 9 (2012) 960–963.

[6] J. Tang, T. Liang, Q. Zhang, Y. Wang, W. Shi, J. Wang, J. Xiong, The research of piezoresistive effect in different temperature based on AlGaN/GaN HEFT-micro-accelerometer, 2010 10th IEEE Int. Conf. Solid-State Integr. Circuit Technol., IEEE, 2010, pp. 1542–1544.

[7] K. Matsuo, N. Negoro, J. Kotani, T. Hashizume, H. Hasegawa, Pt Schottky diode gas sensors formed on GaN and AlGaN/GaN heterostructure, Appl. Surf. Sci. 244 (2005) 273–276.

[8] M.A. Khan, M.S. Shur, Q. Chen, J.N. Kuznia, C.J. Sun, Gated photodetector based on GaN/AlGaN heterostructure field effect transistor, Electron. Lett. 31 (1995) 398–400.

[9] H. So, J. Lim, D.G. Senesky, Continuous v-grooved AlGaN/GaN surfaces for high-temperature ultraviolet photodetectors, IEEE Sensors J. 16 (2016) 3633–3639.

[10] H. So, D.G. Senesky, Rapid fabrication and packaging of AlGaN/GaN high-temperature ultraviolet photodetectors using direct wire bonding, J. Phys. D. Appl. Phys. 49 (2016) 285109.

[11] M. Eickhoff, J. Schalwig, G. Steinhoff, O. Weidemann, L. Görgens, R. Neuberger, M. Hermann, B. Baur, G. Müller, O. Ambacher, M. Stutzmann, Electronics and sensors based on pyroelectric AlGaN/GaN heterostructures - part B: sensor applications, Phys. Status Solidi C 0 (2003) 1908–1918.

[12] S.J. Pearton, B.S. Kang, S. Kim, F. Ren, B.P. Gila, C.R. Abernathy, J. Lin, S.N.G. Chu, GaN-based diodes and transistors for chemical, gas, biological and pressure sensing, J. Phys. Condens. Matter 16 (2004) R961–R994.

[13] T. Lalinský, P. Hudek, G. Vanko, J. Dzuba, V. Kutiš, R. Srnánek, P. Choleva, M. Vallo, M. Držík, L. Matay, I. Kostič, Micromachined membrane structures for pressure sensors based on AlGaN/GaN circular HEMT sensing device, Microelectron. Eng. 98 (2012) 578–581.

[14] H. So, D.G. Senesky, ZnO nanorod arrays and direct wire bonding on GaN surfaces for rapid fabrication of antireflective, high-temperature ultraviolet sensors, Appl. Surf. Sci. 387 (2016) 280–284.

[15] P.M. Asbeck, E.T. Yu, S.S. Lau, G.J. Sullivan, J. Van Hove, J. Redwing, Piezoelectric charge densities in AlGaN/GaN HFETs, Electron. Lett. 33 (1997) 1230–1231.

[16] S.N.G. Chu, F. Ren, S.J. Pearton, B.S. Kang, S. Kim, B.P. Gila, C.R. Abernathy, J.-I. Chyi, W.J. Johnson, J. Lin, Piezoelectric polarization-induced two dimensional electron gases in AlGaN/GaN heteroepitaxial structures: application for micro-pressure sensors, Mater. Sci. Eng. A 409 (2005) 340–347.

[17] O. Ambacher, M. Eickhoff, A. Link, M. Hermann, M. Stutzmann, F. Bernardini, V. Fiorentini, Y. Smorchkova, J. Speck, U. Mishra, W. Schaff, V. Tilak, L.F. Eastman, Electronics and sensors based on pyroelectric AlGaN/GaN heterostructures- part A: polarization and pyroelectronics, Phys. Status Solidi C 0 (2003) 1878–1907.

[18] A.S. Yalamarthy, D.G. Senesky, Strain- and temperature-induced effects in AlGaN/GaN high electron mobility transistors, Semicond. Sci. Technol. 31 (2016) 35024.

[19] O. Yilmazoglu, K. Mutamba, D. Pavlidis, M.R. Mbarga, Strain sensitivity of AlGaN/GaN HEMT structures for sensing applications, IEICE Trans. Electron. E89-C (2006) 1037–1041.

[20] E.D. Le Boulbar, M.J. Edwards, S. Vittoz, G. Vanko, K. Brinkfeldt, L. Rufer, P. Johander, T. Lalinský, C.R. Bowen, D.W.E. Allsopp, Effect of bias conditions on pressure sensors based on AlGaN/GaN High Electron Mobility Transistor, Sens. Actuators A 194 (2013) 247–251.