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Piezotronic Effect tuned AlGaN/GaN High Electron Mobility Transistor

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Abstract

The piezotronic effect is about utilizing strain-induced piezoelectric polarization charges to tune the carrier transportation across the interface/junction. We fabricated a high performance AlGaN/GaN High Electron Mobility Transistor (HEMT), and the transport property was proven to be enhanced by applying an external stress for the first time. The enhanced source-drain current was also observed at any gate voltage and the maximum enhancement of the saturation current was up to 21 % with 15 N applied stress (0.18 GPa at center) at -1 V gate voltage. The physical mechanism of HEMT with/without external compressive stress conditions was carefully illustrated and further confirmed by a self-consistent solution of the Schrödinger-Poisson equations. This study proves the cause-and-effect relationship between the piezoelectric polarization effect and two-dimensional electron gas formation, which provides a tunable solution to enhance the device performance. The strain tuned HEMT has potential applications in human-machine interface and the security control of the power system.

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Key words: high electron mobility transistor, AlGaN/GaN heterostructure, 2DEG, piezotronic effect

Introduction

Attributed to their superior carrier mobility and high power-handling capacities, AlGaN/GaN heterostructure based high electron mobility transistors (HEMTs) have demonstrated extremely promising prospects in the field of radio-frequency, high-temperature electronic components and microwave power amplifiers. [1-4] The two-dimensional electron gas (2DEG) in AlGaN/GaN interface is the major carrier for the high efficient electronic transport and was commonly assumed to be related to the piezoelectric polarization of the strained AlGaN layer and the spontaneous polarization. Understanding and controlling the transport behavior of carriers across the heterojunction interface is important for the optimization of their performance.

The piezotronic effect first proposed by Prof. Wang is about utilizing piezoelectric polarization potential induced by the external stress as the gate voltage to tune carriers' transportation across junction/contact interfaces. [5-12] Based on this effect, various novel electronic devices have been demonstrated, which possess significant fundamental science impact and technological applications. [13-16] Many reports have detailed the enhanced performance piezotronic devices tuned by external mechanical strain/stress, including piezotronic enhanced photodetector, [17] responsivity enhancement in chemical sensors, [18] output optimization of vibration sensors, [19] and piezotronic effect modulated heterostructure microwire. [20] Most of the previous researches focused on novel chemical synthesized nanostructures and seldom considered the complex and highly-integrated microelectronic devices.

With the coupling of piezoelectric polarization with semiconductor properties in III-nitride materials, it suggests that III-nitride HEMTs may become excellent candidates as strain-tunable transistors, and have potential applications in electromechanical sensing, actuating and mechanical energy harvesting. In previous reports, the current

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collapse by the structural design and relieving the self-heat are two effective efforts to tune/control the performance of AlGaN/GaN HEMTs. [21] However, very few reports investigated how the piezotronic effect affects physical properties of HEMTs.

In this work, we report the first piezotronic effect tuned AlGaN/GaN HEMT. We fabricated the high-performance AlGaN/GaN high electron mobility transistor. By applying various external compressive stress along the c-axis direction, the corresponding piezotronic effect was investigated by measuring the current-voltage characteristics of HEMT. Furthermore, theoretical simulations were performed via the finite element analysis (FEA) and self-consistent numerical calculation to systematically illustrate and confirm the proposed working mechanism. By taking into account the non linear piezoelectric effect, [22] the simulation I-V characteristics agree well with the experimental results. Such experimental design and theoretical modeling deepen our understanding on the fundamental physics of the piezotronic effect and provide effective guidance for device design and optimization. This study also provides a new approach to achieve human-machine interfacing.

Results and Discussions

AlGaN/GaN heterostructures were grown on 2-in. (0001) sapphire substrate by metal organic chemical vapor deposition (MOCVD). The wafer structure consisted of a GaN buffer (20 nm), a c-doped GaN (2 μm) and an unintentionally doped GaN (100 nm), followed by a 25 nm of $Al_{0.25}Ga_{0.75}N$, as is shown in Figure 1a. After cleaning the sample, a convex-character pattern (two rectangle) was fabricated using a negative photoresist SU-9I mold on the AlGaN surface with the ultraviolet lithography. And Ti/Al/Ti/Au (200/1000/450/550 Å) were deposited on the plate with the e-beam evaporation, and then annealed at 850 °C in N_2 environment for 30 s to form ohmic contacts. [23] To form schottky contact, metal stacks of Ni/Au (800/500 Å) were deposited by the e-beam evaporation as the gate electrode. This is a prevalent metallization scheme in the preparation of HEMT surface electrode. Figure 1b shows the source/drain and the gate contact of the device at the room temperature,

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experimental results proved the classical ohmic and schottky contact behavior. Figure 1c and 1d are the SEM images of the partial cross-sectional view of the ohmic contact and the schottky contact, respectively. The Ti/Al/Ti/Au alloy film is used as the source electrode with a total thickness of 220 nm, and Ni/Au layers are drain electrodes with a thickness of about 130 nm. Gate length L_g is 10 μm and the source–gate and source–drain spacing are 20 μm and 80 μm, respectively. The image of the HEMT in partial top view is shown in Figure 1e.

The DC $I_{DS} - V_{DS}$ characteristics were measured with Keithley 4200 Semiconductor Characterization System combined with the probe station. Figure 2a displays the $I_{DS} - V_{DS}$ characteristics curves at various gate voltages swepting from -4 V to 2 V, in steps of 1 V. At a low drain-source bias, the $I_{DS} - V_{DS}$ characteristics have a well-defined linear region, then the drain current approaches saturation as further increase in the bias. The measured results are similar to the pinch-off effect in classical depletion-mode MIS-HFET. [24, 25] The gate is a schottky contact, and the gate voltage is used to control the transmission of two-dimensional electron gas (2DEG) in the channel, thereby changing the source-drain current in the saturation regimes. HEMT was completely pinched off with a negative gate voltage of -3.5 V and the maximum transconductance of 19 mS at $V_{DS} = 5\ V$, as clearly demonstrated in the transfer curves shown in Figure 2b. When the gate voltage increases from -3.5 V to 2 V, the conduction channel in the GaN is broadened and the saturation drain current can be significantly increased from 4 mA to 67 mA with a quasi-linear relationship.

III-nitrides have excellent piezoelectric polarization properties and semiconductor properties and are excellent candidates as piezotronic devices. External mechanical strain are applied on the AlGaN/GaN heterostructure along -c-axis by vacuum locking the device on the sample stage, which is flat and horizontal. A 3D mechanical stages (moving resolution ~50 μm) combined with a stressometer is used to apply the external mechanical stress and measure the stress simultaneously. As the source–gate and source–drain spacing are 20 μm and 80 μm, the tip is exerted in the space near three

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electrodes. By moving the 3D stage, a compressive strain is applied on the devices and the value of stress applied on the device can be measured with a stressometer. When a certain compressive force is applied on the sample, most of the strain is produced in the AlGaN layers. Under the static mechanic equilibrium conditions, the forces are invariably cross the structure, and then the strain in GaN bulk is calculated with finite element method. Figure 3b shows the $I_{DS} - V_{DS}$ characteristics of the AlGaN/GaN HEMT at -1 V gate voltage under various external stress. A normal force was applied perpendicular to the AlGaN/GaN interface, which produces a compressive strain along the c-axis in the device. At a fixed applied bias above the turn-on voltage (-3.5 V), the source-drain current under external stress still exhibit a classic HFET transport properties combined with the quasi-linear transport region and non-linear saturation current region. However, the absolute value of the source-drain current was increased with the increasing the external stress from 0 N to 25 N (0.3GPa at center). It looks that the external strain can act as the "virtual gate" to control carrier transport. Commonly, current in linear region is attributed to the increased electron drift velocity with increasing the drain voltage. While in the saturation region, the electron drift velocity gradually reached to the electron saturation velocity and thus the current gradually saturated. Therefore, the saturated current is determined by the two-dimensional electron gas density.

Figure 3c plots the relative changes of saturation drain current at $\mathrm{V}_{DS} = 9\ \mathrm{V}$, $\mathrm{V}_{GS} = -1\ \mathrm{V}$ under room temperature condition as a function of external stresses. We define relative changes of current as $\Delta I/I_0 = (I_1 - I_0)/I_0$, where $I_0 = I_{stress\ w/o}$, $I_1 = I_{stress\ w/}$. From 0 N to 15 N, the relative change value rapidly increased with increasing external compressive stress, while the value gradually saturated and even slightly decreased as the external forces over 15 N. Due to the proportional relationship between the saturation current and 2DEG density, this result indicates that 2DEG density also increases as a logarithm function with external stress. And the slight decrease in saturation region should be related to more significant lattice scattering, such as

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interface roughness scattering which result from the shift of the 2DEG towards the AlGaN/GaN interface. [26] We plot the saturated current value at different gate voltages from -2 V to 2 V, depending on external stress in Figure 3d. The saturation source-drain current enhanced effect of the external stress also be observed at any gate bias. The maximum enhancement of saturated drain current was from 34.5 mA to 42 mA, nearly 21 %, obtained at $V_{DS} = 9\,V$, $V_{GS} = -1\,V$. This indicated that the "virtual gate' can be added to any bias.

The physical mechanism of the AlGaN/GaN heterostructure along *c*-axis with/without external compressive stress is proposed using energy diagrams shown in figure 4a and b. The group-III nitrides AlN, GaN are tetrahedrally coordinated semiconductors with a wurtzite crystal structure. Owing to the noncentrosymmetric crystal structure, two different types of intrinsic polarizations are presented in AlGaN/GaN heterojunctions: (i) the spontaneous polarization P_{sp}^{AlGaN} and P_{sp}^{GaN} existing in AlGaN and GaN, respectively; (ii) lattice-mismatch induced piezoelectric polarizations existing in AlGaN layer (P_{lm}^{AlGaN}). [27] In the HEMT structures with the Ga face at the surface, electric fields caused by P_{sp}^{AlGaN}, P_{lm}^{AlGaN} and P_{sp}^{GaN} will drive electrons towards a triangle-shape potential well in GaN close to AlGaN/GaN heterointerface. When compressive strain is applied in *c*-axis orientations in the device, piezotronic-induced polarization in AlGaN (P_{pz}^{AlGaN}) and GaN (P_{pz}^{GaN}) point from the Ga (or the Al atom) towards the nearest neighbor nitrogen along the -c axis. The total polarization in the direction orthogonal to the c-plane is given by the quadratic expression:

$$P_{Tot} = P_{sp} + P_{lm} + e_{33}\varepsilon_{\perp} + 2e_{31}\varepsilon_{\parallel} + e_{311}\varepsilon_{\parallel}^2 + e_{333}\varepsilon_{\perp}^2 + e_{313}\varepsilon_{\parallel}\varepsilon_{\perp} \qquad (1)$$

where P_{sp} is the spontaneous polarization, and P_{lm} is the lattice-mismatch induced piezoelectric polarizations. The e_{ij} and e_{ijk} are the non-linear piezoelectricity cofficients, taken from Pal et al. [22] The $\varepsilon_{\parallel}$ and $\varepsilon_{\perp}$ refer to external strain in c-plane and in the orthogonal direction, respectively.

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Under compressive stress, positive piezocharges are generated at the bottom of AlGaN layer while negative piezocharges at the top of GaN. Then the effective net fixed positive piezocharges accumulate at the interface can deepen the potential well, thereby increase interfacial 2DEG densities. Stress distribution and corresponding energy band and 2DEG concentration modulated by piezotronic effect were calculated by self-consistent coupling solutions of the Schrödinger-Poisson equations. Under compressive stress, the electric field established by the internal lattice polarization effect has been changed, result in carriers redistributing in GaN. According to the conventional theory of piezoelectricity and elasticity, the constitutive equations can be written as:

$$\begin{cases} \sigma = c_E S - e^T E \\ D = eS + kE \end{cases} \quad (2)$$

Where σ is the stress tensor, c_E is the elasticity tensor, S is the mechanical strain, e^T is the piezoelectric tensor, E is the electric field, D is the electric displacement, and k is the dielectric tensor. Quantitative strain distribution of the structure under different compressive stress was calculated using the COMSOL software package, shown in Figure 4c-f. From the stress field distribution, piezoelectric effect is concentrated in the point where the mechanical arm applied stress, and the maximum stress is nearly 0.18 GPa. Since the non-symmetry along *c*-axis of GaN material, piezoelectric charges are generated at the interface of AlGaN and GaN, and piezoelectric potential is created under the stress.

Our model obtains the stress modulated sheet charge density and the potential profile in AlGaN/GaN heterostructure by coupling the strain into the self-consistent Schrödinger equation and Poisson equation. [28, 29] The stress modulated Schrödinger equation yields the electronic wave function in the Poisson equation which, in return, generates the potential. This potential is fed back to the Schrödinger equation until the solution of Poisson equation tends to converge. The one-dimensional nonlinear Poisson equation can be written as:

$$\varepsilon\varepsilon_0\nabla^2 V(x) = -q\left(p - n + N_{piezo} + N_D^+ - N_A^-\right) \quad (3)$$

where ε is the relative permittivity of the material, ε_0 is the permittivity of

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vacuum, $V(x)$ is the potential field of wave function, q is the absolute value of the unit electronic charge, n and p are the concentrations of free electrons and free holes, N_{piezo} is the density of polarization charges (in units of electron charge), N_D^+ is the donor concentration, N_A^- is the acceptor concentration.

HEMT is a quantum device transporting charges with the 2DEG strongly localized at the interface. The stationary Schrödinger equation in the effective mass approximation is used to describe the energy band structure and carrier density:

$$-\frac{\hbar^2}{2}\frac{d}{dx}\left[\frac{1}{m^*}\frac{d\psi(x)}{dx}\right]+[V(x)-E]\psi(x)=0 \quad (4)$$

where, $\hbar$ is Planck constant, $m^*$is the electron effective mass along the quantum confinement direction, $\psi(x)$ is the electronic wave function, $V(x)$ is the potential energy field of electronic wave function in Eq.3, *E* is the electronic energy. With this partial differential Eq.2-4 solved by the finite difference method, the energy band, 2DEG concentration distribution, and the piezoelectric potential distributions in the device under a series of stress are derived.

Figure 4c display the distribution of energy band and carrier concentration along the c-direction without the external compressive stress. Due to the lack of the central symmetric in the wurtzite structure, the AlGaN film and GaN film induce a $13.1\times10^{-3}\,c/m^2$ spontaneous polarization along *c*-axis. More importantly, the lattice mismatch between AlGaN film and GaN film induce the piezoelectric polarization ($9.3\times10^{-3}\,c/m^2$ in our case) whose directions in AlGaN film and GaN film opposite to each other, which forms a triangle potential well at the interface. This triangle well captured free electrons and limited their movement along *c*-axis to form 2DEG. The 2DEG sheet density was deduced to be $0.92\times10^{13}\,cm^{-2}$ according to our device structure. When external compressive stresses were applied on the device, COMSOL physics simulation revealed an additional piezoelectric field was induced at the contact point and spread into the device, as shown in Figure 4d-f. The average sheet carrier density at the interface was put into the Poisson-Schrödinger solution. The

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calculation results revealed that the additional piezoelectric polarization deepen the triangle potential well, and the minimum energy value changed from -0.025 eV to -0.053 eV. It enhanced the confinement of free electrons to increase 2DEG concentration in the channel from $0.92 \times 10^{13}\ cm^{-2}$ at 0 N to $1.19 \times 10^{13}\ cm^{-2}$ at 15 N, increased by 29.3 %, which indicate a nearly logarithm function relationship between 2DEG concentration and the external stress. This would enhance the saturation source-drain current in HEMT, thereby improving conduction properties.

Further, the classic device equation was used to deduce the relationship between the external stress and transportation properties. In the linear regime, when derivingI_{DS}, we neglect the diffusion current in the channel and μ dependence on the built-in electric field. I_{DS} is obtained by integrating the current along the channel. The boundary conditions are:

$$V(x = 0) = R_S \cdot I_{DS},\ V(x = L) = V_{DS} - R_{DS} I_{DS} \tag{5}$$

where R_S and R_D are source series resistance and drain series resistance respectively, origin from access resistance in Gridless channel region between the gate-source and gate-drain. The voltage drops in the source and drain resistance could be neglected approximately. Therefore, the drain-source current in this regime is expressed as:

$$I_{DS} = \beta V_T [V_{DS} - (R_S + R_D) I_{DS}] \tag{6}$$

Where β is the transconductance coefficient and $\beta = W\mu\varepsilon/(dL)$, W is the channel width and μ is the mobility of carriers, ε is the dielectric constant, d is the thickness of the AlGaN layer, L is the gate length.

In the nonlinear region,

$$I_{DS} = \beta \left(V_{GS} - V_T - \frac{1}{2} V_{DS}\right) V_{DS} \tag{7}$$

where V_T is the threshold voltage of HEMT. The drain current changes as the square of the drain voltage, [30-32] which is in brilliant agreement with our experimental results. In the saturated zone, the channel current tends to be saturated and ceases to increase with the drain-source voltage. This means that the saturated drain current is no

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longer controlled by the drain voltage. Therefore, the drain-source current is expressed according to:

$$I_{DS} = \beta V_L \left[\sqrt{V_L^2 + (V_T - R_S I_{DS})^2} - V_L\right] \quad (8)$$

where $V_L = F_s L$, F_s represents the critical electric field for velocity saturation.

Based on the above theories, the deletion region underneath the gate can be broaden when a "virtual gate" bias is applied to the plate. With appropriate external stress applied, electrons tuned by the piezoelectric polarization effect can then flow from the source into the drain, through the channel. And then the drain current increased. As non-linear piezoelectric effect has been used to evaluate the impact of the strain induced piezoelectric polarization in wurtzite III-N materials and their alloys. When the non-linear piezoelectricity was taken into account, the simulated results showed better agreement with experimental data of the piezoelectric field in various structures. [33, 34] The I_{DS}-V_{DS} characteristics of HEMT with 15 N and 0 N stress at V_{GS} = -2 V were calculated and shown in Figure 5. Using the non-linear piezoelectricity model, the calculated results fitted with the experimental results well, especially in linear region and nonlinear region. Very minor differences exist in saturation region, it would be attributed to the kink effect, [35] which is an abnormal increase of the drain current in the saturation region. When 15 N compressive stress was applied, the calculated 2DEG density was increased to $1.19 \times 10^{13}\ cm^{-2}$, and the calculated current enhanced. Although the device equation was simple and omitted self-heating effect, the calculated source-drain current tendency was matched well with experimental results. It means that the piezotronic effect dominates the transport property in our devices. In AlGaN/GaN heterostructure field effect transistors, the origin of the 2DEG is still unclear. Although some theoretical researches predicted that may be related to spontaneous/piezoelectric polarization. And our researches offered a solid evidence that the piezoelectric polarization modulation effect on the current transportation. One of the important applications of HEMT are the power system, and this stress tuned technology provided a possibility application in human-machine interface.

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Conclusion

In summary, the piezotronic effect tuned electrical properties of HEMT devices have been experimentally and theoretically proved for the first time. When a compressive stress was applied on the sample, the source-drain current was enhanced and the increment of the saturation current was about 21 % at -1 V gate voltage under 15 N stress. The self-consistent coupling solutions of the Schrödinger and Poisson equations revealed that it was attributed the increased 2DEG density in the deepened triangle well under the compressive stress. Put the 2DEG density into the classic device equation, the calculated source-drain current plot fitted well with the experimental result. This study well reveals the cause-and-effect relationship between the piezoelectric polarization effect and 2DEG originated in, providing a feasible solution to performance enhancement of the device. This innovative way to enhance the performance of the device will play a significant role in many practical applications, such as the touch-sensitivity improved human-machine interfacing, HEMT based sensors and security-control power system.

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Notes

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References

[1] Pearton S J and Ren F 2000 GaN electronics *Advanced materials* **12** 1571-80

[2] TomášKa M, Lalinský T, Vanko G and Mišun M 2008 High Frequency Characterization and Properties of AlGaN/GaN HEMT Structures: IEEE) p 331-4

[3] Hwang Y-H, Li S, Hsieh Y-L, Ren F, Pearton S J, Patrick E, Law M E and Smith D J 2014 Effect of proton irradiation on AlGaN/GaN high electron mobility transistor off-state drain breakdown voltage *Applied Physics Letters* **104** 082106

[4] Fareed R S Q, Hu X, Tarakji A, Deng J, Gaska R, Shur M and Khan M A 2005 High-power AlGaN/InGaN/AlGaN/GaN recessed gate heterostructure field-effect transistors *Applied Physics Letters* **86** 143512

[5] Wang Z L and Song J 2006 Piezoelectric nanogenerators based on zinc oxide nanowire arrays *Science* **312** 242-6

[6] Wang Z L 2007 Nanopiezotronics *Advanced materials* **19** 889-92

[7] Zhang Y, Liu Y and Wang Z L 2011 Fundamental theory of piezotronics *Advanced materials* **23** 3004-13

[8] Wang Z L 2012 Progress in piezotronics and piezo-phototronics *Advanced materials* **24** 4632-46

[9] Huang X, Du C, Zhou Y, Jiang C, Pu X, Liu W, Hu W, Chen H and Wang Z L 2016 Piezo-Phototronic Effect in a Quantum Well Structure *ACS nano* **10** 5145-52

[10] Wu W and Wang Z L 2016 Piezotronics and piezo-phototronics for adaptive electronics and optoelectronics *Nature Reviews Materials* **1** 16031

[11] Zhao Z, Pu X, Han C, Du C, Li L, Jiang C, Hu W and Wang Z L 2015 Piezotronic effect in polarity-controlled GaN nanowires *ACS nano* **9** 8578-83

Accepted Manuscript

[12] Wang X, Yu R, Peng W, Wu W, Li S and Wang Z L 2015 Temperature Dependence of the Piezotronic and Piezophototronic Effects in a-axis GaN Nanobelts *Advanced materials* **27** 8067-74

[13] Liu Y, Niu S, Yang Q, Klein B D, Zhou Y S and Wang Z L 2014 Theoretical study of piezo-phototronic nano-LEDs *Advanced materials* **26** 7209-16

[14] Peng M, Li Z, Liu C, Zheng Q, Shi X, Song M, Zhang Y, Du S, Zhai J and Wang Z L 2015 High-Resolution Dynamic Pressure Sensor Array Based on Piezo-phototronic Effect Tuned Photoluminescence Imaging *ACS nano* **9** 3143-50

[15] Peng M, Liu Y, Yu A, Zhang Y, Liu C, Liu J, Wu W, Zhang K, Shi X, Kou J, Zhai J and Wang Z L 2016 Flexible Self-Powered GaN Ultraviolet Photoswitch with Piezo-Phototronic Effect Enhanced On/Off Ratio *ACS nano* **10** 1572-9

[16] Wang X, Yu R, Jiang C, Hu W, Wu W, Ding Y, Peng W, Li S and Wang Z L 2016 Piezotronic Effect Modulated Heterojunction Electron Gas in AlGaN/AlN/GaN Heterostructure Microwire *Advanced materials* **28** 7234-42

[17] Zhang Z, Liao Q, Yu Y, Wang X and Zhang Y 2014 Enhanced photoresponse of ZnO nanorods-based self-powered photodetector by piezotronic interface engineering *Nano Energy* **9** 237-44

[18] Niu S, Hu Y, Wen X, Zhou Y, Zhang F, Lin L, Wang S and Wang Z L 2013 Enhanced performance of flexible ZnO nanowire based room-temperature oxygen sensors by piezotronic effect *Advanced materials* **25** 3701-6

[19] Zhang Z, Liao Q, Yan X, Wang Z L, Wang W, Sun X, Lin P, Huang Y and Zhang Y 2013 Functional nanogenerators as vibration sensors enhanced by piezotronic effects *Nano Research* **7** 190-8

[20] Wang Z L 2010 Piezopotential gated nanowire devices: Piezotronics and piezo-phototronics *Nano Today* **5** 540-52

[21] Yuan S, Duan B, Yuan X, Cao Z, Guo H and Yang Y 2016 New Al0.25Ga0.75N/GaN high electron mobility transistor with partial etched AlGaN layer *Superlattices and Microstructures* **93** 303-7

[22] Pal J, Tse G, Haxha V, Migliorato M A and Tomić S 2011 Second-order piezoelectricity in wurtzite III-N semiconductors *Physical Review B* **84** 085211

Accepted Manuscript

[23] Gong R, Wang J, Liu S, Dong Z, Yu M, Wen C P, Cai Y and Zhang B 2010 Analysis of surface roughness in Ti/Al/Ni/Au Ohmic contact to AlGaN/GaN high electron mobility transistors *Applied Physics Letters* **97** 062115

[24] Gao T, Xu R, Kong Y, Zhou J, Zhang K, Kong C, Peng D and Chen T 2016 Integrated enhancement/depletion-mode GaN MIS-HEMTs for high-speed mixed-signal applications *physica status solidi (a)* **213** 1241-5

[25] Wang R, Cai Y, Tang W C W, Lau K M and Chen K J 2007 Integration of enhancement and depletion-mode AlGaN/GaN MIS-HFETs by fluoride-based plasma treatment *physica status solidi (a)* **204** 2023-7

[26] Antoszewski J, Gracey M, Dell J M, Faraone L, Fisher T A, Parish G, Wu Y F and Mishra U K 2000 Scattering mechanisms limiting two-dimensional electron gas mobility in Al[sub 0.25]Ga[sub 0.75]N/GaN modulation-doped field-effect transistors *Journal of Applied Physics* **87** 3900

[27] Ambacher O, Foutz B, Smart J, Shealy J R, Weimann N G, Chu K, Murphy M, Sierakowski A J, Schaff W J, Eastman L F, Dimitrov R, Mitchell A and Stutzmann M 2000 Two dimensional electron gases induced by spontaneous and piezoelectric polarization in undoped and doped AlGaN/GaN heterostructures *Journal of Applied Physics* **87** 334

[28] Hsiao T C, Kistler N A and Woo J C S 1994 Modeling the I-V characteristics of fully depleted submicrometer SOI MOSFET's *IEEE Electron Device Letters* **15** 45-7

[29] Kalafi M and Asgari A 2003 The behavior of two-dimensional electron gas in GaN/AlxGa1−xN/GaN heterostructures with very thin AlxGa1−xN barriers *Physica E: Low-dimensional Systems and Nanostructures* **19** 321-7

[30] Charfeddine M, Belmabrouk H, Zaidi M A and Maaref H 2012 2-D Theoretical Model for Current–Voltage Characteristics in AlGaN/GaN HEMT's *Journal of Modern Physics* **03** 881-6

[31] Faraclas E W and Anwar A F M 2006 AlGaN/GaN HEMTs: Experiment and simulation of DC characteristics *Solid-State Electronics* **50** 1051-6

[32] Kranti A, Haldar S and Gupta R 2002 An accurate charge control model for

Accepted Manuscript

spontaneous and piezoelectric polarization dependent two-dimensional electron gas sheet charge density of lattice-mismatched AlGaN/GaN HEMTs *Solid-State Electronics* **46** 621-30

[33] Pal J, Tse G, Haxha V, Migliorato M A and Tomić S 2011 Importance of non linear piezoelectric effect in Wurtzite III-N semiconductors *Optical and Quantum Electronics* **44** 195-203

[34] Pal J, Migliorato M A, Li C K, Wu Y R, Crutchley B G, Marko I P and Sweeney S J 2013 Enhancement of efficiency of InGaN-based light emitting diodes through strain and piezoelectric field management *Journal of Applied Physics* **114** 073104

[35] Zimmer T, Bodi D O, Dumas J, Labat N, Touboul A and Danto Y 1992 Kink effect in HEMT structures: a trap-related semi-quantitative model and an empirical approach for SPICE simulation *Solid-state electronics* **35** 1543-8

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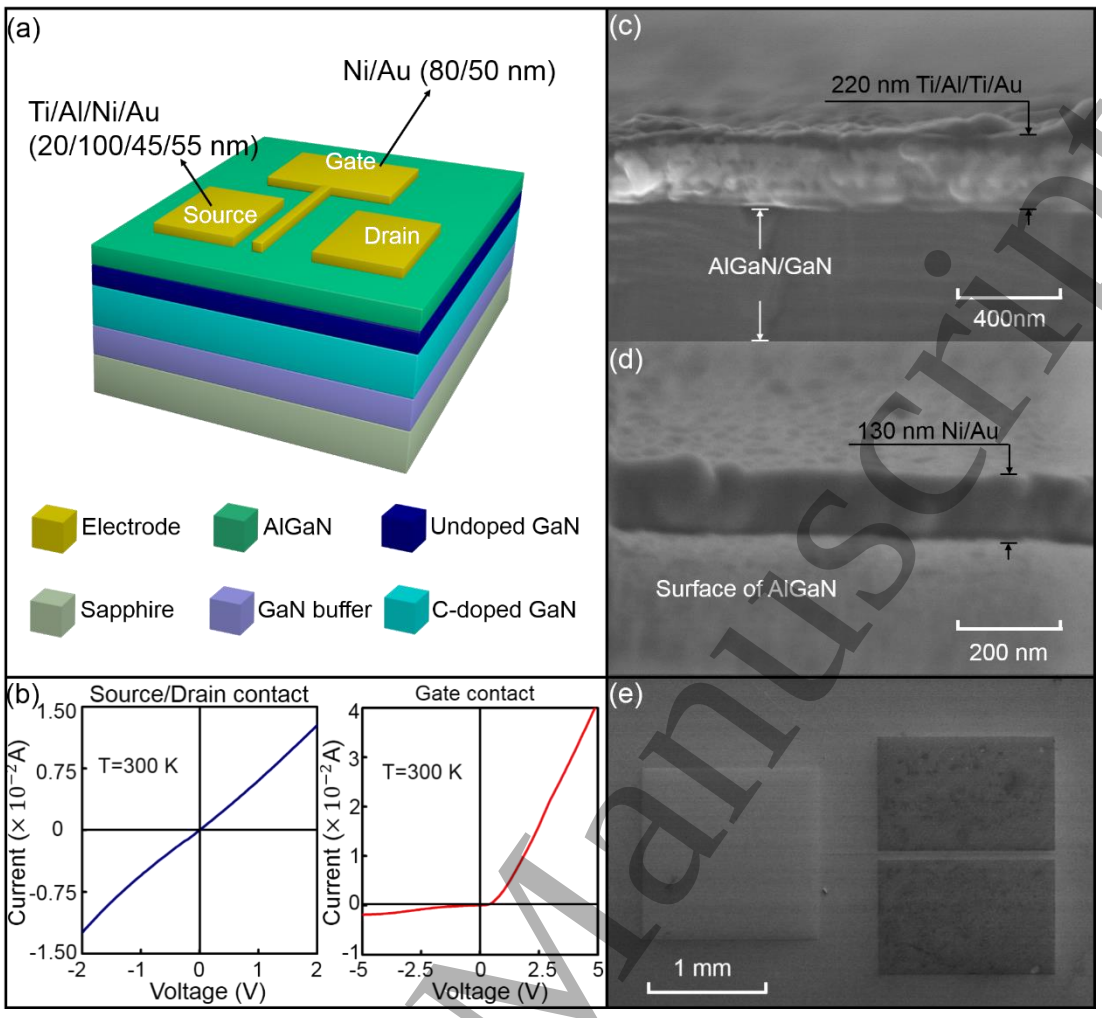

Figure 1. Schematic illustration of the AlGaN/GaN high electron mobility transistor (HEMT). (a) Structure of the HEMT based on (0001) sapphire substrate. (b) Ohmic contact curve and schottky contact curve of the device based on AlGaN/GaN heterostructure at room temperature. (c) Partial cross-sectional view of the ohmic contact (Ti/Al/Ti/Au) and HEMT. (d) Partial cross-sectional view of the schottky contact (Ni/Au) and the surface of AlGaN. (e) Partial top view of the HEMT.

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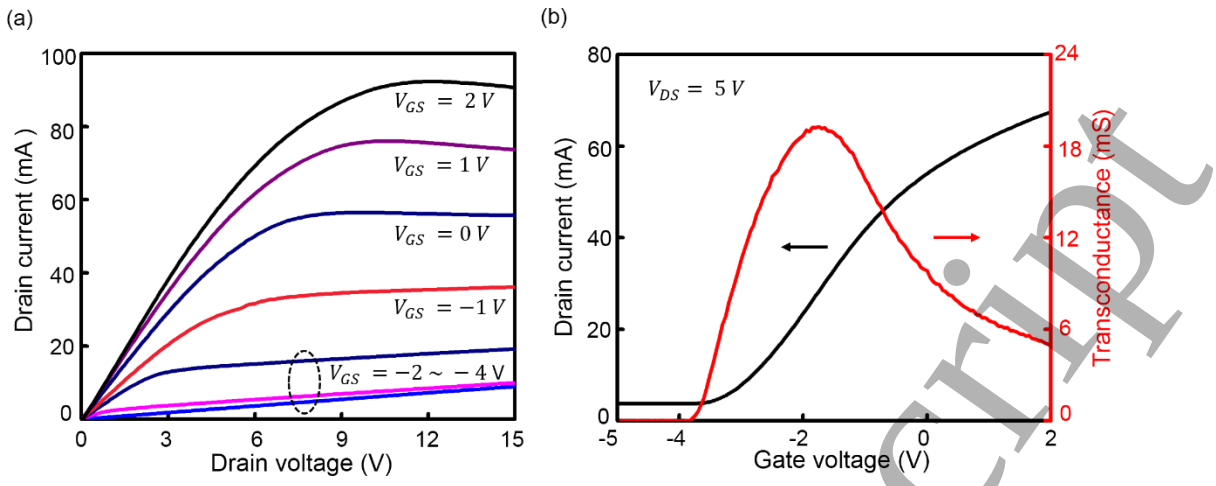

Figure 2. (a) Measured $I_{DS} - V_{DS}$ characteristics of the AlGaN/GaN HEMT. Curves from bottom to top correspond V_{GS} from -4 V to 2 V, step by 1 V. (b) DC characteristics for HEMT on sapphire, transfer characteristic at $V_{DS} = 5\ V$.

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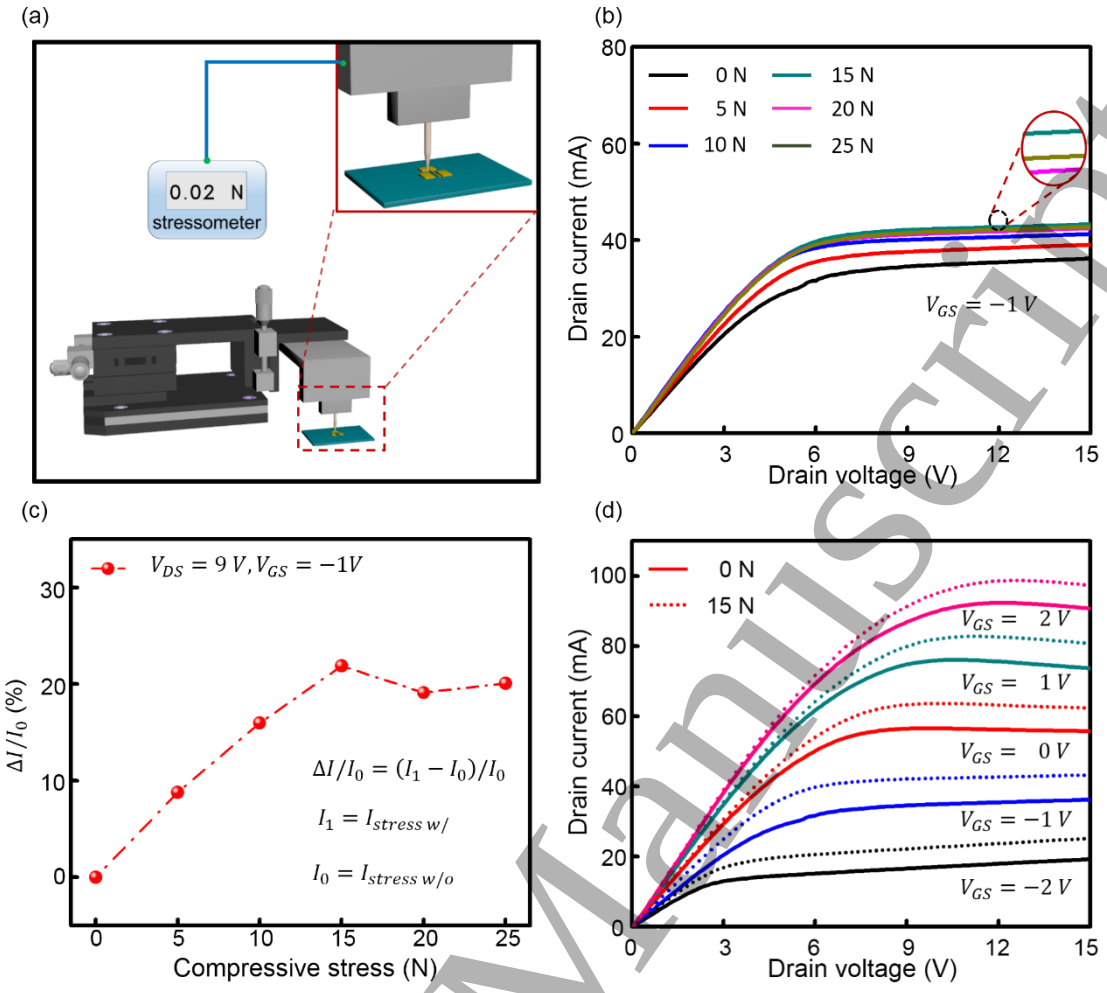

Figure 3. $I_{DS} - V_{DS}$ characteristics of the AlGaN/GaN HEMT at different stress along *c*-axis. (a) Experimental setup (lower) and the enlarged schematics (upper) of the HEMT. (b) $I_{DS} - V_{DS}$ characteristics of the HEMT when gate voltage is -1 V under applied stress from 0 N to 25 N along *c*-axis. (c) $I_{DS} - V_{DS}$ characteristics of saturation drain current at $V_{DS} = 9\ V$, $V_{GS} = -1\ V$ under room temperature condition as a function of external stresses. (d) $I_{DS} - V_{DS}$ characteristics of the AlGaN/GaN HEMT with 15 N stress (dot line) and without stress (solid line) at different gate voltages.

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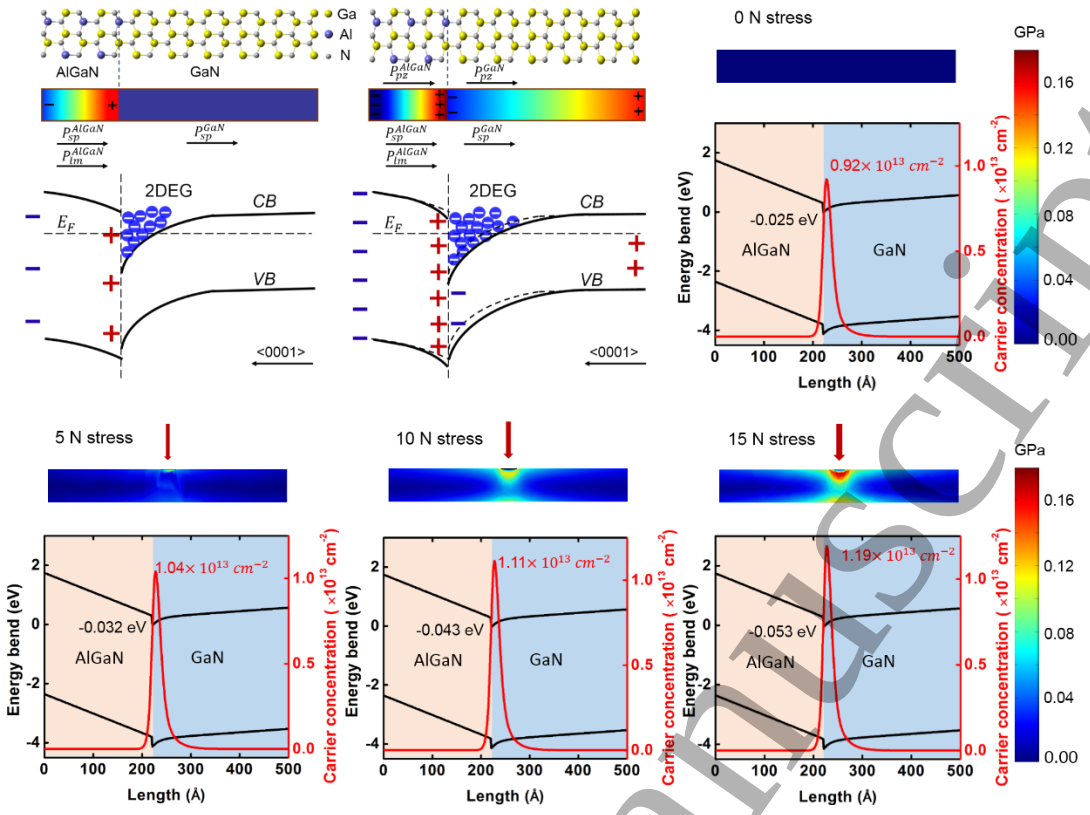

Figure 4. (a,b) Schematic energy band diagram of AlGaN/GaN heterostructure (a) before and (b) after applying compressive stress along c-axis, where the bending at the interface is created by the piezoelectric polarization. Calculated strain distribution (upper) and corresponding energy band structure and carrier concentration (lower) for the different applied strains in the sample: (c) 0 N; (d) 5 N; (e) 10 N; (f) 15 N. The dark lines refer to the valence band and conduction band energy in the AlGaN/GaN heterostructure. The red lines show the 2DEG distribution in the heterostructure.

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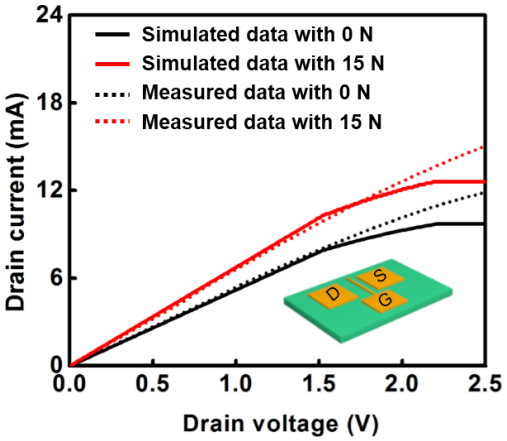

Figure 5. Simulated I_{DS}-V_{DS} characteristics of the AlGaN/GaN HEMT with 15 N stress (red solid line) and without stress (dark solid line) at V_{GS} = -2 V. The scattered points are the experimental results shown in Figure 3d. The inset is the schematic illustration of the HEMT.

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