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Resonant MEMS based on cubic GaN layers

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In this work, we report the fabrication of GaN microelectromechanical structures (MEMS) based on cubic GaN grown by molecular beam epitaxy on 3C-SiC(100)/Si(100) pseudosubstrates. Free-standing beam resonators with a width of 5 µm and lengths from 250 to 1000 µm were patterned and characterized. Magnetomotively and electrostatically actuated resonators were analyzed under ambient and vacuum conditions resulting in quality factors of up to 250 under ambient conditions up to 40.000 under vacuum (1.9×10^{-5} mbar) and resonant frequencies from 97 to 406 kHz for the fundamental resonant mode. These results allow for the determination of the Young's modulus and the residual strain of the free standing structures. The measured GaN resonators exhibited Young's moduli from 235 to 260 GPa and high residual axial strains from 1.0×10^{-3} to 1.25×10^{-3}. For the cubic GaN layers from which the resonators were fabricated, residual strains between 3.3×10^{-3} and 5.8×10^{-3} have been extracted from XRD measurements. These values are on the same order of magnitude but a definite factor higher compared to the measurement results obtained for the fabricated GaN-beams, which indicates a partial layer relaxation caused by the influences of the MEMS fabrication processes.

1 Introduction Gallium nitride (GaN) and related group III–V nitrides are widely used in the field of light emitting devices [1, 2] and recently were demanded for high-frequency and high-power transistors [3, 4]. So far, most of these devices have been realized on the basis of hexagonal GaN. In recent years, however, cubic GaN layers have also been realized on GaAs [5], Si [6] and SiC [7] substrates using molecular beam epitaxy (MBE) [5, 7] and metal-organic chemical vapour deposition MOCVD [6].

Due to the quality of cubic GaN, which has continuously risen in the past years [8-10], the material of cubic GaN has also attracted interest for device applications. Therefore, cubic GaN, which exhibits a higher crystallographic symmetry over other materials with hexagonal phase, is expected to have many advantages in physical properties, including for example higher carrier mobility, simple cleavage, and higher p-type doping efficiency [11-13].

While the properties of hexagonal GaN are well known, the properties of cubic GaN - particularly the mechanical properties - have rarely been studied. For these investigations, cubic-GaN-based -MEMS resonators grown by MBE on 3C-SiC(100)/Si(100) pseudosubstrates [6] were fabricated and characterized under ambient and vacuum conditions.

We present the analysis of resonant frequencies and quality factors, which result in values for the Young's modulus and the residual strain of the free-standing struc-

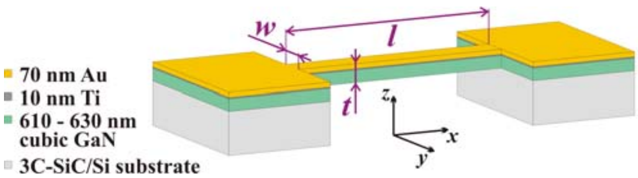

Figure 1 Schematic drawing of the basic resonator geometry.

Phys. Status Solidi C 7, No. 1 (2010)

tures. These results were then compared to measured and theoretically calculated values of cubic GaN-layers and consequently provide new insight into mechanical properties of cubic GaN.

2 Design and fabrication The basic resonator geometry is a doubly-clamped beam as displayed schematically in Fig.1. In the case of magnetomotive actuation, the beams consist of three layers, an active layer of 610 to 630 nm cubic GaN, a 10 nm Ti interlayer and a 70 nm Au top layer. The metal layers were omitted for the beams designated for electrostatic needle actuation. Beams for both actuation schemes were structured with dimensions of 5 µm in width *w* and lengths *l* from 250 to 1000 µm.

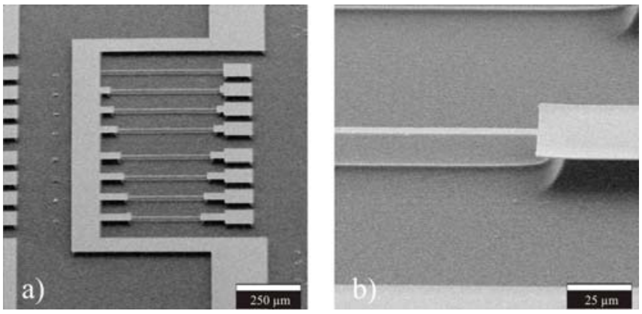

Figure 2 a) Bird's eye view of a processed GaN resonator array for electrostatic actuation and b) close up view of a GaN beam for magnetomotive actuation.

The cubic GaN layers were grown by MBE on 3C-SiC(100)/Si(100) pseudosubstrates, which were fabricated by a carbonization process in a rapid thermal vapour deposition or a chemical vapour deposition system described in [6]. E-beam lithography was used to pattern the top electrode (Ti/Au) and a 150 nm Ni mask was than patterned via lift off. This Ni layer served as mask material for the following chlorine based dry etching step, in which the cubic GaN was structured anisotropically to the Si substrate in an inductive coupled plasma etching system. Afterwards, the remaining Ni-mask was removed by a wet chemical etching step. A fluorine based dry etching step in an electron cyclotron resonance plasma etching system was utilized in order to isotropically etch the Si substrates, to obtain in free-standing resonators. In Fig. 2 processed cubic GaN resonators for electrostatic and magnetomotive actuation are displayed.

3 Theoretical techniques Based on the Euler-Bernoulli theory [14], the resonant frequency ω_n of a doubly-clamped beam containing a specific residual strain ε can be calculated as:

$$\omega_n = \frac{\kappa_n^2}{l^2}\sqrt{\frac{E \cdot I}{\rho \cdot A}} \cdot \sqrt{1+\gamma(\varepsilon)_n \frac{l^2}{t^2}\varepsilon}\ , \tag{1}$$

with the eigenvalues κ_n = 4.73, 7.85,…, $(n + 0.5)\pi$ and γ_n = 0.2949, 0.1453,…, $12(\kappa_n - 2)/\kappa_n^3$ [15], where n = 1, 2,… represents the mode number.

While the Young's modulus E and the density ρ characterize the beam material properties, the moment of inertia I (= $wt^3/12$ for a rectangular beam) and the cross sectional area A are defined by the beam geometry. For single layer beams, which were used for electrostatic actuation, the residual strain ε can be determined independently from any material parameters from the resonant frequency ratio of two different resonant modes of a selected beam by means of the equation [16]:

$$\varepsilon = \frac{1}{\gamma(\varepsilon)_1} \cdot \frac{t^2}{l^2} \cdot \frac{(\kappa_n/\kappa_1)^4 - (f_n/f_1)^2}{(f_n/f_1)^2 - (\gamma(\varepsilon)_n/\gamma(\varepsilon)_1)(\kappa_n/\kappa_1)^4}\ . \tag{2}$$

For precise calculation, the dependence of $\gamma(\varepsilon)_n$ on the residual strain ε cannot be neglected, which shows significance especially for highly strained beams. Taking the ε-value calculated by Eq. (2) and applying it with the measured resonant frequencies to equation (1) leads to the values for the Young's modulus E.

For multi-layer beams, which were used for magnetomotive actuation, the influence of the metallization has also to be taken into account [17]. In this case the terms EI and ρA in Eq. (1) have to be replaced by the sums of the flexural stiffness and mass loading per unit length of the individual layers [16, 18]:

$$EI \Leftrightarrow \overline{EI} = \sum_{j=1}^{s} E_j I_j \ \text{ and } \ \rho A \Leftrightarrow \overline{\rho A} = \sum_{j=1}^{s} \rho_j w t_j\ , \tag{3}$$

with j as the layer index and s as the number of layers. Due to the multi layer system, an effective thickness has to be determined using [16]

$$t^2 \Leftrightarrow t_{eff}^2 = \left(12\sum_{j=1}^{s} E_j I_j\right) / \left(\sum_{j=1}^{s} E_j \omega t_j\right) \tag{4}$$

and applied for t in equ. (1) and (2). Using equations (1) and (2) enhanced by equ. (3) and (4), allows to determine E and ε also for the multi-layer GaN resonators.

4 Measurement techniques The resonators were operated by magnetomotive actuation. The mechanical oscillation of the beams was caused by an oscillating Lorentz force, which was generated by an applied alternating current along the beams placed within a permanent magnetic field.

The resonant response of the beams was analyzed in the frequency domain by means of a differential measurement technique [16]. The investigations were carried out in a vacuum wafer prober system, which allows for the variation of pressure from 10^{-5} to 10^{3} mbar. To avoid the influence of the metal layers, caused by additional mass loading and residual strain, resonators without additional metallization layers were actuated by the electrostatic field caused by the voltage applied to a needle closely placed to the beam resonator. The read-out of the excited vibration was carried out optically using a laser-Doppler vibrometer (Fig. 3).

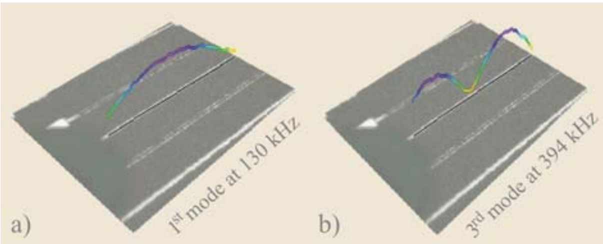

Figure 3 Exemplary mode shapes of a) the first and b) the third out-of-plane flexural resonance of a 800 µm long and 5 µm wide GaN-resonator under electrostatic actuation monitored by a laser-Doppler vibrometer.

5 Results Initially, measurements were carried out by laser-Doppler vibrometry to determine the residual strain and Young's modulus of single layer cubic GaN-beams. For this reason, resonant frequencies of the first three flexural out-of-plane modes were measured for beam lengths from 250 to 1000 µm.

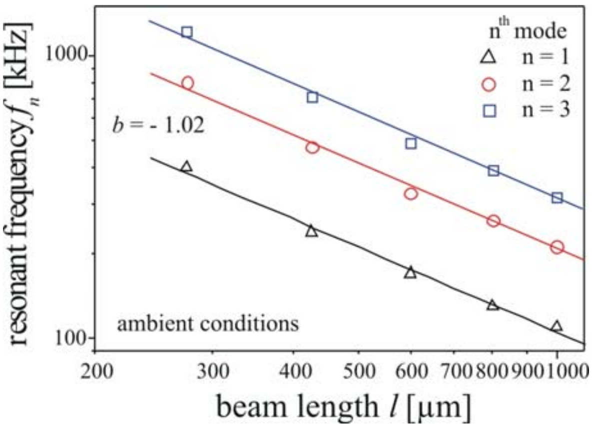

Figure 4 Resonant frequency f_n of the nth flexural mode versus beam length on double-logarithmic scales. Measurements were carried out for 5 µm wide single layer beams under ambient conditions.

According to Fig. 4, the slopes of the curves fell slightly below -1 (gradient *b*: -1.02), which indicates a high residual strain inside of the GaN beams yielding the highest possible f_n values with a dependence of $f(l)_n \sim 1/l$.

To confirm the values for the Young's modulus by another measurement method, the resonant frequencies of the first three flexural modes were also measured under vacuum conditions for multi-layer GaN beams with lengths from 250 to 1000 µm (Fig. 5). Vacuum conditions were chosen to avoid the influence of air damping on the frequency ratio of between different flexural modes. In these measurements, gradients *b* from slightly below -1 for the resonant frequencies versus beam length for multi-layer beams indicated a very high residual strain inside of the beams, too.

From Eqs. (1)-(4) the residual strain and the Young's modulus were determined based on the measured resonant frequencies of single- and multi-layer cubic GaN beams for several exemplary beam lengths (Tab. 1).

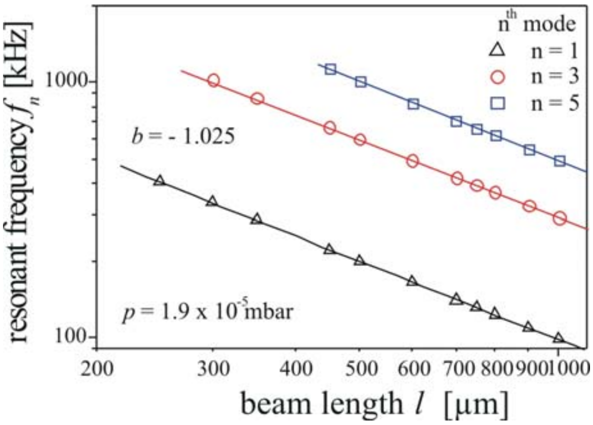

Figure 5 Resonant frequency f_n of the n^{th} flexural mode versus beam length on double-logarithmic scales. Measurements were carried out for 5 µm wide multi layer beams under vacuum conditions.

Young's moduli from 235 to 260 GPa and residual strains from $1.0\text{x}10^{-3}$ to $1.25\text{x}10^{-3}$ were demonstrated, which can be converted into stress values by means of Hooke's law.

Table 2 Examples of calculated strain, Young's modulus and stress from equ. (1)-(4) corresponding to measured resonant frequencies of a) single layer cubic GaN-beams and b) multi layer cubic GaN-beams.

Beam length [µm]	ε	E (100) [GPa]	σ [MPa]
a)			
275	$1.1\text{x}10^{-3}$	250	275
425	$1\text{x}10^{-3}$	235	235
b)			
350	$1.25\text{x}10^{-3}$	240	300
900	$1.19\text{x}10^{-3}$	250	297

Additionally, the quality factor Q of the cubic GaN beam resonators has been analyzed under different levels of ambient pressure between $1\text{x}10^{+3}$ and $1.9\text{x}10^{-5}$ mbar (Fig. 6). Thus, the high structural quality of the cubic GaN layers has been excellently confirmed by the high Q-values under

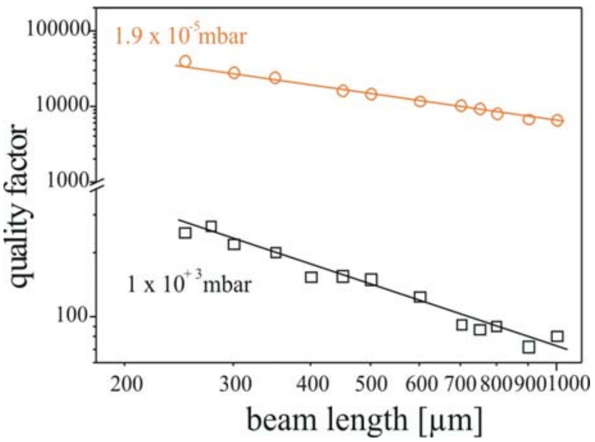

Figure 6 Quality factor Q at different levels of ambient pressure and resonant frequency f_n at a pressure of 0.01 mbar versus beam length. Measurements were carried out for 5 µm wide multi layer beams.

vacuum conditions which represent the intrinsic losses of the vibrating beam.

6 Conclusion Resonators based on cubic GaN grown on 3C-SiC(100)/Si(100) pseudosubstrates were fabricated and characterized. Measurements of electrostatic and magnetomotive actuated single- and multi-layer beams demonstrated Young's moduli from 235 to 260 GPa. These values are in good agreement with Young's moduli theoretically calculated by the use of the elastic constants (Tab. 2).

The residual strain of the cubic GaN layers, which were used for the fabrication of the resonators, was determined prior to the MEMS processing by means of XRD measurements in [10]. The values of the residual strain, between $3.3x10^{-3}$ and $5.8x10^{-3}$, extracted from these XRD measurements are of the same order of magnitude, but a certain factor higher when compared to the values of residual strain measured on the fabricated GaN resonators.

This behaviour was previously observed for highly strained 3C-SiC layers and beam resonators, too [23]. It can be assumed that the partial relaxation is caused by the processes carried out to fabricate the free-standing beam structures, which has to be accounted for in the resonator design.

The quality factors and resonant frequencies measured under ambient and vacuum conditions, as displayed in Fig. 6, are significantly higher in comparison to Q-values determined for highly strained 3C-SiC resonators [24].

Table 2 Theoretical calculated zinc-blende Young's moduli assuming a Poisson's ratio of unstrained cubic GaN of υ = 0.366 [22].

E (111) [GPa]	E (100) [GPa]	References
293	177	[19]
331	184	[20]
292	267	[21]

Therefore, resonant MEMS devices fabricated from cubic GaN promise an increased sensitivity in sensing applications.

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