MICRO STRUCTURING OF BULK SiC SUBSTRATES BY FEMTOSECOND LASER ABLATION

J. Zehetner[1], G. Vanko[2], J. Dzuba[2], T. Lalinsky[2], M. Lucki[3], S. Kraus[3]

[1]Research Centre for Microtechnology, University of Applied Sciences, Hochschulstrasse 1, 6850 Dornbirn, Austria

[2]Institute of Electrical Engineering, Slovak Academy of Sciences, Dubravskacest 9, 841 04 Bratislava, Slovakia

[3]Czech Technical University, Faculty of Electrical Engineering, Technicka 2, 16627 Prague 6, Czech Republic

E-mail: johann.zehetner@fhv.at

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Abstract

SiC is a material basis for pressure and strain sensors usedinharsh thermal environment conditions. For such sensor devices, piezoelectric III-N compounds, especially gallium nitride (GaN)-related heterostructures on appropriate tailored SiC diaphragms are often used. We demonstrated that diaphragms can be fabricated faster with laser ablation than by reactive ion etching. However, laser ablation frequently causes pinholes in SiC membranes provoking increased risk to damage the III-N heterostructure by the fabrication process.Our experiments confirmed that pinhole defects in the ablated membranes are initiated by ripple structures related to the polarization of the laser. We developed an ablation technique inhibiting the formation of pin holes caused by laser induced periodic surface structures (LIPSS). In addition we tested the hypothesis that LIPSS in SiCact like slot waveguides performing a numerical study of light propagation in LIPSS. The results showed that laser intensity is enhanced inside LIPSS which supportsthe experimental ablation findings in the formation of pinholes and led us to effective countermeasures.

1. Introduction

Motivated by the advantage of III-N compounds for pressure and strain sensors, we investigated AlGaN/GaN based electronic devices as sensing elements of such sensors and introduced an approach whereby the applied external force caused the accumulation of a piezoelectric charge induced between electrodes [1]. Published articles mention the possibilities to apply AlGaN/GaN membranes (grown on SiC substrate) and Pearton et al[2] introduced pressure sensors made of a circular membrane of AlGaN/GaN on a SiC substrate. Micromachining SiC is challenging in particular a common used reactive ion etching (RIE) process to produce micromechanical structures obtains low etch rates. The fabrication of membranes from bulk material would last tens of hours. Femtosecond pulsed laser ablation offers the opportunity to obtain higher etching rates but the ablation strategy has to be carefully adjusted to avoid structure damage of the SiC membrane and III-N heterostructure.

2. Fabrication of AlGaN/GaN membranes

The first laser we had available for the experiments delivered 380 mW average power at its second harmonic 518 nm wavelength, 100 kHz and 350 fs pulses. This specification was close to the lower limits of the possible parameterwindow, but we succeeded in producing our first membrane (Fig. 1, left and right picture) using laser ablation as a supporting technique in RIE [3, 4]. For thecomparison purposes, we also tested 193 nm excimer laser ablation to produce diaphragms, but bore diameters were limited to themaximum of ~ 200 µm due to thermal damage of the heterostructure (Fig. 1, second picture from the left). Our first results with the 380 mW fs laser (Fig. 1, second picture from the right) showed debris formation in the ablation area that limited the ablation depth to about 10 to 20 µm, which was more than ten times less than the required value to fabricate sufficient membranes. The idea was to compensate the lack of average power of our laser system by a scanning method avoiding the generation of v-grooves in the ablation area, as this reduces the limited fluence further below the ablation threshold. The results are depicted in Fig. 2;we achieved a clean bore bottom without any sintered debris on it. The clogging debris at the side wall was removed by frequent laser cleaning avoiding the hazardous HF-cleaning. Our prior approach was to remove the debris via a step structure or pyramid, which actually worked, but required excessive space [5].

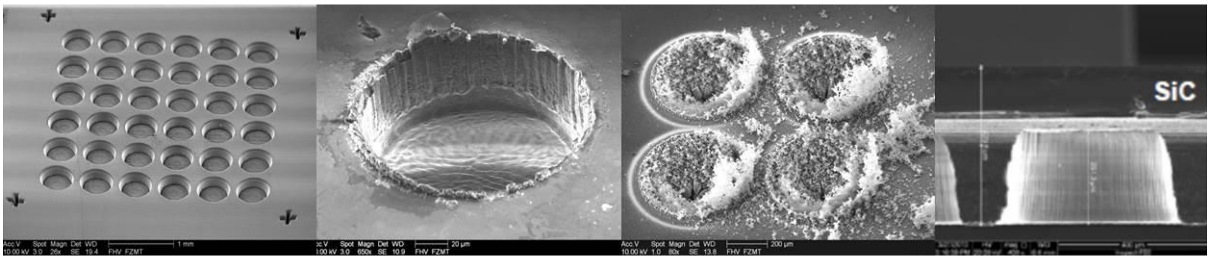

Fig.1:*First attempt and first results for membrane fabrication by laser ablation in SiC*

We tested two different scanning grid patterns, a standard xy grid with 5µm hatch in x and y direction (upper row of pictures Fig. 2) and a series of seven xy grids with a prime numbered hatch starting at 5 µm and ending at 23 µm, which was slightly smaller than thefocus diameter in the ablation area (lower row of pictures Fig. 2).

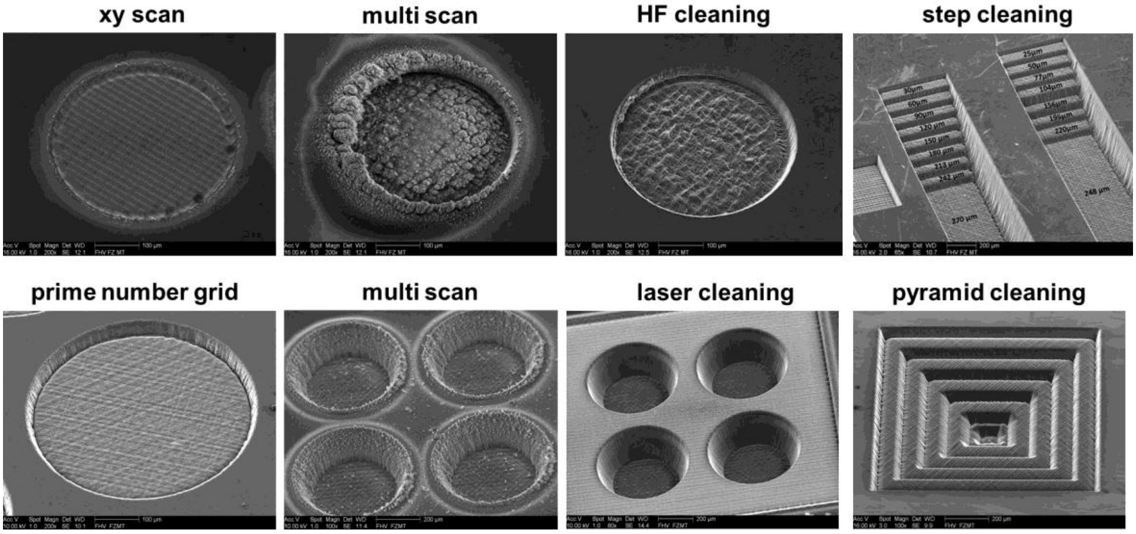

Fig.2:*Prime number scanning method and laser cleaning enlarged the possible ablation depth by more than 10 times*

The prime number method ensures that seven scans can be performed before the laser hits the same geometrical starting position again. However, after a run of seven scans, the original physical starting position does not exist anymore; it is part of the removed material. In a standard xy-scan at the same grid spacing every consecutive scan hits the same former position again and generates a v-groove pattern over time on the membrane surface. This transforms the circular focus spot to an elliptical shape with increased cross section area at the groove surface, reducing the fluence, and when the average power is low ablation stopsas threshold fluence cannot longer be provided. Remaining debris also contributes to the focus deformation, fluence reduction and consequently a significant amount of laser energy is absorbed in the bulk, and debris without ablation both are only heated andsinteredtogether at the interface area. Even HF-cleaning cannot remove such a debris “cake” entirely (Fig. 2 first row second and third picture from left). The portion of laser energy not consumed for the sintering process nor ablation process can pass through the bulk material and cause backside surface damage to the SiC or heterostructure III-N material (Fig. 3, left picture). Contrary, the prime number method in combination with laser cleaning avoided focus distortion and expanded the ablation depth (at the same minimum fluence laser parameter) from 10 to 20 µm to the required 250 to 300µm [6].As the bottom of the bore can be kept clean and is produced with better surface quality (no v-grooves, little debris),more of thelaser light is used for the ablation and a smaller amount coupled via the bulk to the backside surface.We observed reduction in tendency of surface damage leading to thinner possible membranes when using prime number scanning at low fluence values.

3. Backside damage

The backside damage was analysed in [7].We verified experimentally that theoretical simulations provided for glass in [8] apply well for laser induced damage in SiC (Fig. 3).A typical damage pattern is shown in Fig. 3, left picture, centered in a corona-like structure, and is a circular area with heavy damage caused from light leaking at the bottom of the bore. The second picture in Fig. 3 indicates that the corona is caused by light escaping the ablation area at the side wall of the bore and due to the Brewster angle the damage is slightly more severe parallel to the polarization of the linearly polarized laser. The second picture from the right shows the Brewster effect more clearly only in polarization direction (Y-direction). The strong short damage lines arising left and right from the square shaped hole are caused by the pinholes (Fig. 3 right picture) arising first in the corners of a bore in the direction perpendicular to the polarization. Laser induced periodic surface structures (LIPSS) are generated perpendicular to the polarization in SiC [9] and our simulations and experiments indicate that LIPSS can perform like slot waveguides and seed pinhole formation [10]. Via pinholes the intense laser light is channelled to the backside of the substrate causing surface damage.

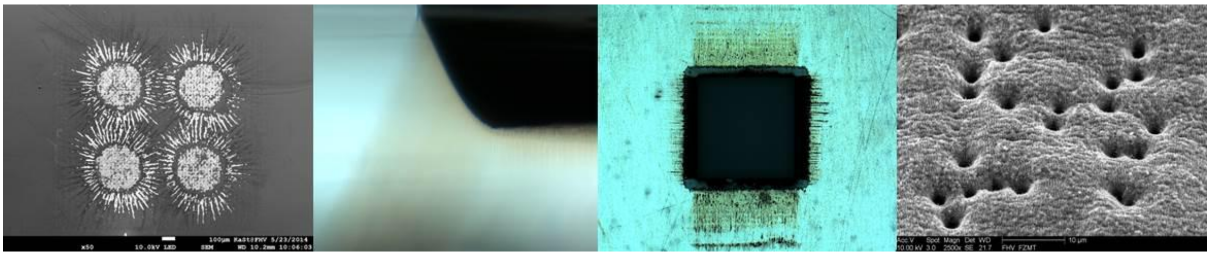

Fig.3:*Laser polarization dominates pinhole formation and backside damage*

Formation and performance of slot waveguides depends on the direction of the polarization. Rotating or flipping the polarization during the ablation process consequently terminates pinhole formation and reduces backside damage. Besides sub-µm LIPSS, we observed the formation of wave structures in the size of 100 µm on the membranes. When we rotated the sample to supress pinhole formation we realized that these wave structures changed in shape and flattened and we started to investigate the cause of their origin.

4. Sample Rotation

For the experiments we used the SPIRIT from HighQ Laser, 200kHz repetition rate at 350 fs pulse length, 520 nm wave length and maximum power about 1.4W after the 100mm focal length scanner optic.

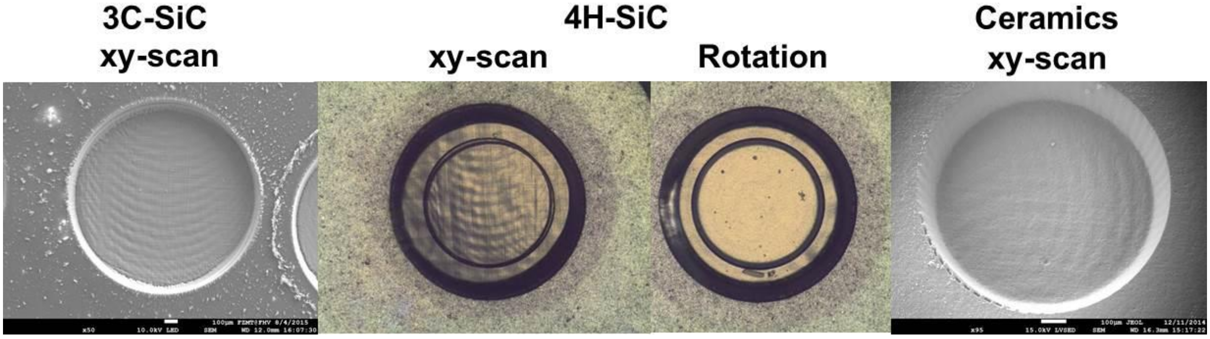

Fig.4:*Sample rotation or polarization flipping improve surface quality of the membranes*

Different to LIPSS, the waves in Fig. 4 had similar appearance independent ofthe type of material. They evolved after several hundred scans when a simple xy scanning pattern was used. When rotating the sample, the waves on the membrane vanished nearly and the shape of the side walls of the bores became much smoother (Fig. 4, second picture from the right).

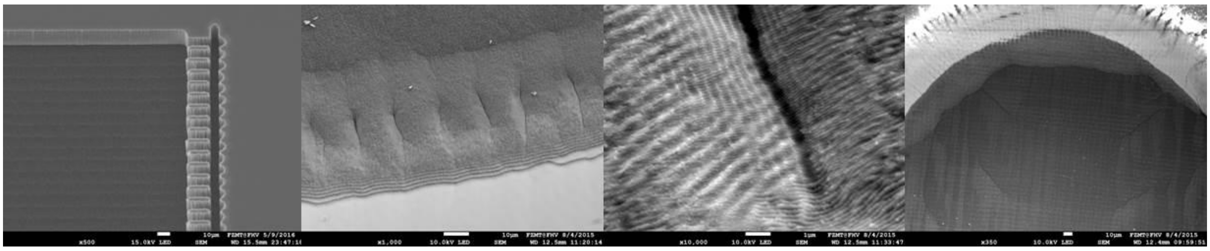

Fig.5:*Periodic structures on the edge of a bore can influence the whole surface quality of a membrane*

Taking a closer look to the corner of a square shaped structure produced by scanning in x direction,reveals that we created a several µm sized periodic structure due to animproper set delay timing of the laser/scanner interaction (Fig. 5 left picture). Similar structures are also created in round bores produced with xy scanning (Fig. 5 right picture) but these structures are not so striking to the human eye and can be overlooked. Such periodic structures create an interfering light distribution at the surface of the membranes corner area, which erodes the material and this pattern becomes more distinctive after every consecutive scan (Fig. 5 second picture from the left, enlarged second from the right). The enlarged picture shows periodic structures on the edge of the bore caused by the scanner, periodic structures created by interference in the corner area on the membrane and a certain field distribution by LIPSS. All together create complex field distribution causing distortion at the membrane surface especially distinctive in the corner area but after 500 to 1000 scans the interference pattern can spread and manifest itself in the membrane surface. Rotation destroys the periodic structures and smoothens the surface. We observed that a static xy-scanning method without rotation improves in surface quality of the membranes corner area when the polarization is frequently flipped or rotated. This is an additional indication that interference effects from wall distortions are involved in the surface quality of the whole membrane.

5. Conclusion

The laser polarization is involved in LIPSS formation, pinhole growth, membrane surface texture formation and backside damage. Understanding and controlling the polarization in the ablation process is essential for high quality membranes. The process simulation should include polarization effects especially when narrow, small or edged structures in SiC and other materials like Si or metals are to be structured by deep cavity ablation.

Acknowledgement

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