Microstructuring of Ion-Implanted GaAs for High Temperature Sensor Applications

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Abstract

Results are presented using deep ion implantation to microstructure the GaAs for sensor applications at increased ambient temperatures. Three selective etching methods were used to micromachine ion-implanted GaAs with different implantation parameters and subsequent treatments. The corresponding membranes and cantilevers are fabricated.

Introduction

Microstructuring of semiconductors is an important issue in sensor fabrications. Because of the large bandgap integrated sensing systems based on GaAs can be expected to operate at high temperatures [1]. For sensor devices as pressure sensors and accelerometers, micromechanical structures such as membranes and cantilevers have to be fabricated, which should consist of the same materials or have similar thermal expansion coefficients as the bulk in order to reduce the thermal stress. On the other hand capacitive sensors are proposed to be used because of their reduced temperature dependence at the elevated temperature range. The fabrication of the large dimensional membranes and the narrow gap between two electrodes are required to increase the capacitances in order to increase the sensitivity. In order to reliably perform selective etching, etch-stop or sacrificial layers thus have to be introduced into the GaAs layer sequence.

It is well-known that GaAs-based heterostructure materials exhibit high etching selectivity against GaAs. In comparison with the epitaxial growth of heterostructure layers in GaAs, ion implantation represents a versatile technique: The local implantation can be selected by masking and the depth of such layers is controllable by varying the ion energy. The selective implantation is particularly attractive to realise capacitive sensors on single chips. The ion implantation is localized only in the areas to be microstructured. The required signal processing circuitry can be integrated on the same chip. The ion-implanted GaAs material represents different selective etching properties according to different implantaion parameters and subsequent treatments. In this paper three selective etching strategies will be presented which can be used to realise different sensor types.

Pure GaN is known to easily dissolve in alkaline solutions which do not attack GaAs. The high dose implantation of nitrogen into GaAs and subsequent annealing produces $GaAs_{1-x}N_y$ $(y < x < 1)$ which has similar selective etching properties to pure GaN [2]. The implanted atoms have a near Gaussion profile in targets. By using high ion energy, an implanted buried layer can be formed. Such buried $GaAs_{1-x}N_y$ layers can be used as sacrificial layers. Using the selective etching of $GaAs_{1-x}N_y$ against GaAs, the top GaAs layer acting as the membrane can be produced.

Ions which are propelled into the GaAs crystal collide with GaAs atoms and displace them from their lattice sites. At the same time, the cascade collision enormously increases the number of displaced atoms. One ion can leave behind over several thousands of vacancies produced over its projectile trace. The atoms sited at interstitial positions show less chemical stability than the original atoms. If a layer contains a sufficient density of displaced atoms it can be used as sacrificial layers. Defect-sensitive etchants can be used to remove this layer.

By the use of electrolytic etching techniques one can selectively etch *p*-GaAs to *n*-GaAs or *n*-GaAs to n^--GaAs. The pulse etching method [3] makes the etching highly controllable and reproducible. The ion implantation of nitrogen with low doses can compensate the *n*-doped GaAs to n^- [4]. This layer can be used as etch-stop layer. The corresponding mechanical stress induced by the ion implantation with low doses should be small. In this way, one can fabricate single crystaline GaAs mechanical structures.

In the following three fabrications of microstructures in nitrogen-implanted GaAs will be described using different selective etching methods. Experimental results will be presented and discussed.

Fabrication of GaAs cantilevers using selective etching of $GaAs_{1-x}N_y$

Nitrogen ions with a dose of 2×10^{17} cm^{-2} and at an energy of 630 keV were implanted into the bulk GaAs. Fig. 1 shows compositional profiles measured by XPS. The penetrating range of nitrogen was located at a depth of about 780 nm from the surface. The maximum concentration of nitrogen nearly amounted eight percent in GaAs. The samples were then annealed at 750^0C

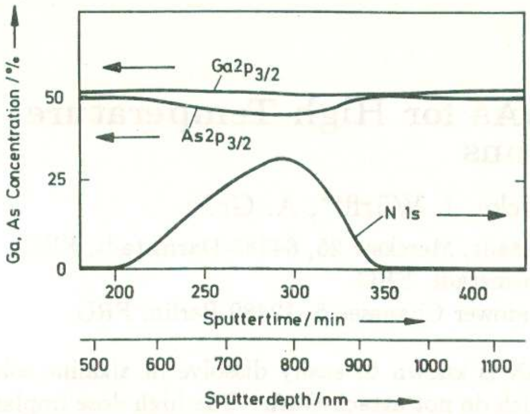

Fig.1 Compositional profiles of Ga $2p_{3/2}$, As $2p_{3/2}$ and N $1s$ measured by XPS.

for 30 min, capped with PECVD Si_3N_4. Using a 200 nm thick evaporated SiO_2 layer as the etch mask, the samples were first nonselectively eched up to 700 nm in NH_4OH:H_2O_2:H_2O (2:1:300), reaching the implanted layer. The selective etching of the $GaAs_{1-x}N_y$ buried layer was performed in $1N$ NaOH solution for 30 min. Fig.2 schematically describes the fabrication steps. The SEM photograph of a fabricated approx. 600 nm thick GaAs cantilever beam covered by SiO_2 with a width of 10 μm and a length of 50 μm is presented in Fig.3. The air gap between of the beam and substrate amounts about 300 to 400 nm.

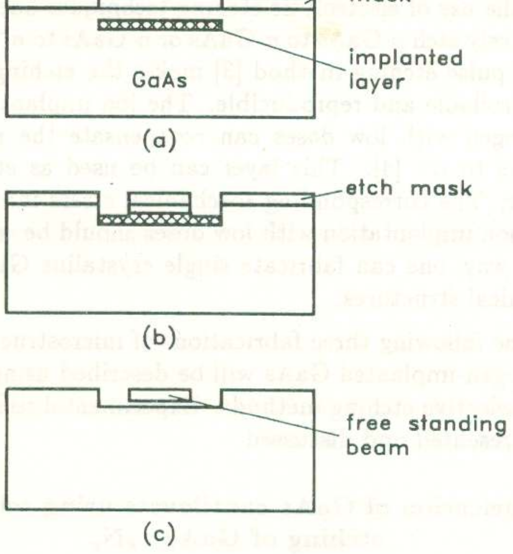

Fig.2 Fabrication of a GaAs cantilever beam using the selective etching of $GaAs_{1-x}N_y$ buried layer: (a) selective implantation; (b) annealing and nonselective etching; (c) selective etching.

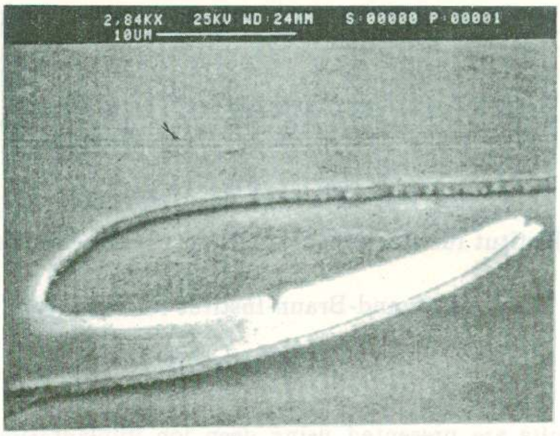

Fig.3 SEM photograph of an upward-bending GaAs cantilever beam covered with SiO_2.

This beam was bent upwards due to the stress at the SiO_2/GaAs interface, arising from the different coefficients of thermal expansion and the grading profile of nitrogen in GaAs (s. Fig.1). By means of measurement of gap in comparison of nitrogen profile as shown in Fig.1 it can estimated that a minimum amount of $y = 5\%$ in $GaAs_{1-x}N_y$ compound is required to achieve the etching selectivity. The reduced annealing temperature down to 650^0C showed the similar selective etching property. Ref. [4] reported that GaN can be formed at 640^0C. GaAs membranes with dimensions of some hundred micrometers are also fabricated. But they showed no mechanical stability. The electrical investigations showed also no possibility to completely restore the top GaAs layer due to the high implantation dose. One possibility to obtain mechanically stable membranes is to use high implantation energy up to the MeV range. The top layer will be then less damaged and the thickness of membranes will be raised because of the increasing of ion penetrating depth.

Fabrication of Si_3N_4 diaphragms using damage-selective etching

The ion implantaion parameters were the same as in the first case. The fabrication process is schematically shown in Fig.4. The 1 μm PECVD Si_3N_4 was deposited on the samples at 250^0C. No annealing was subsequently performed. Using a 70 nm thick evaporated Cr as the etch mask for 1 μm PECVD Si_3N_4, the samples were dipped in KI:I_2:H_2O selective etchant for 10 min at room temperature. The selective etching was successed via the etch holes through the narrow damaged layer. The underetching was complete. The gap between the Si_3N_4 and the GaAs substrate was approx. 2 μm. Fig.5 shows the suspending Si_3N_4 diaphragm with a diameter of 500

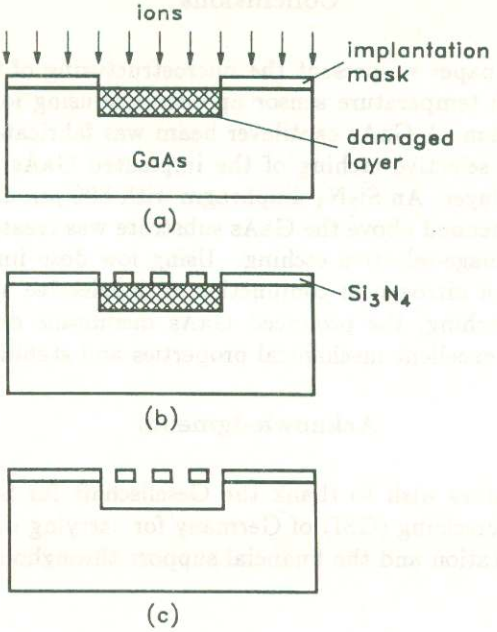

Fig.4 Fabrication of an Si_3N_4 suspending diaphragm: (a) selective implantation; (b) deposition of Si_3N_4; (c) selective etching.

μm, capped with the thin Cr-layer. The etch surface is flat. A close-up SEM photograph of Fig.5 would show the stiffness of the diaphragm suspended over the GaAs substrate.

The selective etching depth of as-implanted GaAs is 4 μm and reduces to 2 μm after the deposition of Si_3N_4 at 250^0C. The etching thickness is deeper than the estimated ion projected depth of approx. 780 nm from the surface [2]. This may result from cascade collisions of target atoms and the ion channeling effect. The implantation with lower doses down to 10^{16} cm^{-2} showed also selective etching property which disapeared after annealing from 600^0C. The PECVD Si_3N_4 used as the static electrode of capacitive sensors has a similar thermal expansion coefficient to GaAs and nearly four times higher Young's modulus than GaAs [5] making it of interest for high temperature applications. The compressive stress of such Si_3N_4 diaphragms should be avoided and the tensile stress has no impact on the properties of sensors. The multilayer diaphragm for such static electrodes is recommended to be used. The different thermal expansion coefficients of the multilayer will compensate the thermal stress.

Fabrication of single crystaline GaAs membranes using selective pulse anodic etching

Fig.6 presents the fabrication process. To compensate the n-doped GaAs, low dose nitrogen (2×10^{14} cm^{-2}) with an energy of 630 keV was deeply implanted into

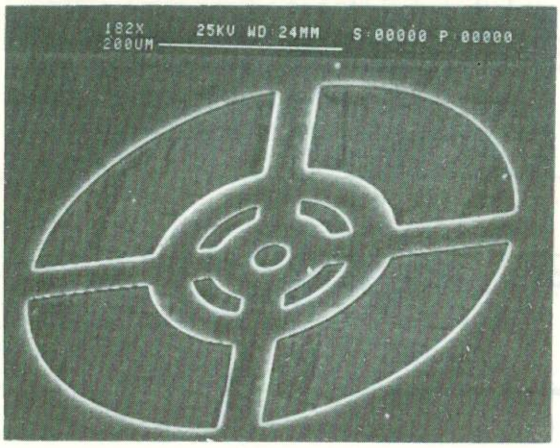

Fig.5 SEM photograph of an Si_3N_4 suspending diaphragm with etch holes.

n-bulk GaAs ($n = 3.3 \times 10^{17}$ cm^{-3}). The optimum annealing temperature for the selective etching was investigated to find the maximum breakdown voltage, measured by two tips directly contacted on the sample surface with the help of a semicondutor parameter analyzer. The maximum breakdown voltage was found after the annealing at 600 ^{0}C for 10 min, protected by PECVD Si_3N_4. An ohmic contact was formed on the sample backside. The samples were non-selectively etched, using the evaporated SiO_2 as etch mask. The electrolytic etchant used here was a commercial platinum solution. The anodic selective etching was performed using 4500 pulses with 15 V amplitude, 1 μs pulse width and 10 ms period. Fig.7 shows a GaAs cantilever membrane with a width of 40 μm and a length of 80 μm. The membrane thickness and gap between the membrane and substrate are 1.1 μm and 2.5 μm.

The thickness of cantilevers obviously is larger than this estimated ion penetrating depth. One reason is that the ion dose is relatively small and below the so-called amorphous dose. In this case, the ions could penetrate deeper as estimated due to the channeling effect. The fabricated GaAs cantilevers stiffly suspend over the substrate and show no noticeable bending. This exhibits excellent mechanical properties and stability. The selective etch mechanism is obviously different from the doping dependence. The pulse anodic etching is isotropic. For the n to n^- selective etch, the gap between the substrate and 40 μm wide cantilever should be at least 20 μm in case of a complete underetching. But in our experiments the gap is only 2.5 μm, which can be explained as follows. The profile of the ion implantation damage is nearly of a Gaussion form and similar to the ion profile. The top layer is less damaged than the implanted layer for the deep ion implantation. After the annealing the top layer is for the most part restored in contrast to the

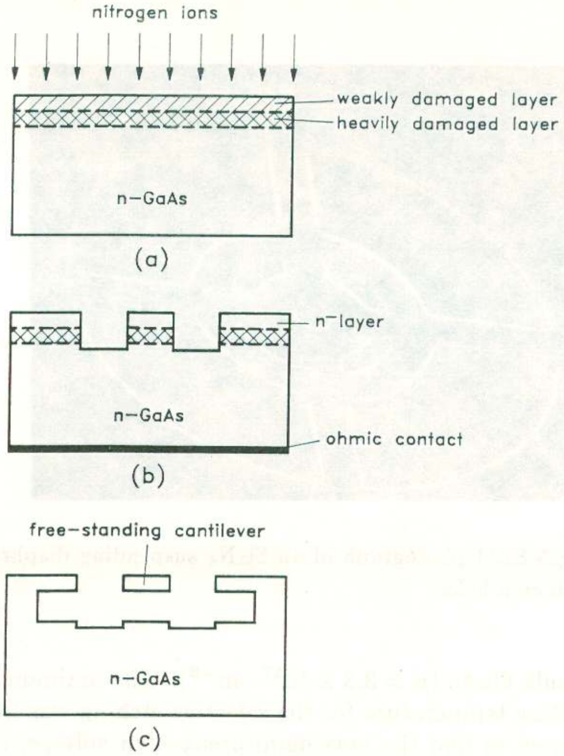

Fig.6 Fabrication of a single crystaline GaAs cantilever using selective pulse anodic etching: (a) nitrogen implantation; (b) annealing, ohmic contact forming and nonselective etching; (c) selective anodic pulse etching.

implanted buried layer. Therefore, the etch-stop and sacrificial layers were simultaniously introduced by one ion implantation step. The present damage, appearing as traps, will lower the breakdown voltage. The crystal damage leads to a preferred etching and higher etch rate in this region. Annealing investigations showed that the implanted samples can be completely recovered to the single crystaline GaAs after annealing of 10 min at 800^{0}C.

Fig.7 SEM photograph of a GaAs cantilever.

Conclusions

In this paper we present the microstructuring of GaAs for high temperature sensor applications using ion implantation. A GaAs cantilever beam was fabricated after the selective etching of the implanted $GaAs_{1-x}N_y$ buried layer. An Si_3N_4 diaphragm with 500 μm diameter suspended above the GaAs substrate was created by the damage-selective etching. Using low dose implantation of nitrogen in conjunction with selective anodic pulse etching, the produced GaAs membrane demonstrates excellent mechanical properties and stability.

Acknowledgments

The autors wish to thank the Gesellschaft für Schwerionenforschung (GSI) of Germany for carrying out ion implantation and the financial support throughout this work.

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