

Study of trenching formation during SF₆/O₂ reactive ion etching of 4H-SiC

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An accurate and reproducible SF₆/O₂ reactive ion etching process in 4H-SiC has been defined, to realise deep and vertical trenches with a high selectivity Ti/Ni mask, and tilted sidewalls with a controlled angle by etching using a SiO₂ mask. The trenching issues have been eliminated by increasing the plasma power. Smooth etched surfaces are obtained with a slightly tapered transition at the bottom of the sidewalls associated with a slight narrowing of the lower-end of the walls. Controlling the trench angle, very flat profiles are obtained for low pressure and plasma flow rates, and more vertical sidewalls by increasing these parameters.

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1. Introduction

Due to its excellent physical properties, the silicon carbide (SiC) has been and continues to be intensively studied and used as a wide-band gap semiconductor material for power devices, high temperature devices and MEMS (microsensors and microactuators in micro-electromechanical systems) operating in severe environments. Fabrication of these structures requires a locally controlled etching of SiC by dry etching techniques, due to the strong inter-atomic Si-C bonds. A photolithographic process is applied by patterning an adequate mask at the SiC surface. The mask is locally opened to form the zones to be etched. The resulting devices have electrical and mechanical properties directly related to the geometry of the etched sidewalls. Improvements of their characteristics are expected only after an analysis of the trench formation mechanisms: identifying the dependence factors of the profile shapes, those generating undesired effects like bowing (extra lateral etching along the trench sidewall), mask faceting and the trenching on sharp bottom corners.

Trenching consists in a sharp groove near the foot of the etched sidewall and has been attributed in general to the reflection of the ions from the sidewalls that produces a localized enhanced etching at the foot of the sidewall [1]. This phenomenon was also related to the mask faceting by the incident plasma ions and reactants [2], by their angular dispersion due to the collisions within the plasma sheath [3, 4] and to the ion deflection by the charged sidewalls and the local electric field distribution formed in the presence of the trenches in the substrate [5]. A model excluding the ion flux, and based only on the diffusion of reactive species at the surface has been able to explain the sidewalls disturbances, in particular for the trenching and bowing [6].

It is well known that the trenching phenomenon limits the SiC devices performances (breakdown voltage) and

must be avoided. The device structures must be designed with a special care given to the electric field distribution. The electric field, even in the most stressed areas, must be kept at a sensible level to avoid premature breakdown of devices. The trenching corresponds to such high-electric stress zone. Different mechanisms have been proposed and/or tested to eliminate trenching formation on the foot of the sidewalls, e.g., controlling the substrate bias and the energy of incident ions [5, 7, 8], decreasing the substrate temperature [4, 9], growing an inhibitor film on the trench sidewalls (especially to avoid bowing) [4] or using high pressure to increase neutral scattering and become less directional [7,10] The choice of the appropriate technique depends on the physical properties (isolating or conducting) of the sample substrate and of the mask, and on the etching setup process.

In this work, the local etching process of monocrystalline wafers in silicon carbide 4H-SiC politype has been optimised in order to fabricate high temperature and power devices. Reactive ion etching (RIE) was performed using SF₆/O₂ plasma. The main aim of this study is to understand and analyze the factors of the trench formation during the etching process. Therefore, an accurate and reproducible RIE process has been defined as having two objectives: (1) the realisation of deep and vertical trenches, and (2) of tilted (with a controlled angle) sidewalls.

2. Experimental

4H-SiC samples with a surface area of 5 cm² have been cut from n⁺-type SiCrystal and Cree Research wafers. The samples were first cleaned in solvents in an ultrasonic bath followed by a standard "piranha" solution and finally dipped in a buffer oxide etch (BOE) commercial solution.

Then, masks were formed on the 4H-SiC sample surfaces. For the vertical deep etching trenches, Ti/Ni masks with high etching selectivity compared to SiC [11]

were patterned by lift-off process, using a reversible photoresist with an adjustable undercut and electron beam evaporation of metal layers. To produce a tilted sidewall during the 4H-SiC etching, masks are used with an etch rate close to the substrate material [8]. In this case we have utilized a SiO₂ mask deposited by Ar/O₂ plasma sputtering of a Si target in a MRC 822 sputtersphere reactor. The SiO₂ mask was wet-opened with a classical photolithographic process, using a patterned positive resist and a BOE solution that allows to obtain an inclined border of the mask with an angle of 30°. As the mask is consumed slowly during the etching process, and as its edges are tilted, this results in a progressive opening of the windows in the mask. This movement of the mask boundaries during the process etching creates tilted 4H-SiC sidewalls.

SiC dry etching was performed with an SF₆/O₂ plasma chemistry produced in an Alcatel Nextral NE110 reactor, a Reactive-Ion-Etching (RIE) reactor with a plasma source generated at 13.56 MHz and a cathode electrode of 4 inches diameter. A particular attention was paid in order to obtain accurate and reproducible processes, by cleaning and passivating the reactor before the SiC samples etching, by keeping the reflected power in the reactor at minimal values and by isolating the quartz cathode to avoid micromasking on the SiC substrate. In our study, the plasma parameters have been varied, the RF power from 100 to 250 W corresponding to a self-developed dc bias from ~110 to ~285V. The process pressure have been varied from 20 to 100 mTorr, process duration from 5 to 30 min and the total gas flow from 16 to 64 sccm. We have chosen a 20% O₂ fraction, this value being reported as being the optimum for SiC etching, especially in terms of etching rate [12-13]. With Si substrates, the O₂ presence reduces the silicon etch rate as a result of the competition of oxygen atoms with fluorine atoms for the chemisorbtion on the silicon surface [10]. Increasing O₂ fraction up to 20% in SiC facilitates the S-F bonds dissociation, producing more F atoms and thus enhancing the SiC etching rate [12].

The etching depth and mask thickness were measured using a Tencor Alpha Step 500 profilometer. The morphology of the etched patterns was characterized by scanning electron microscopy (SEM) observations at very low angle.

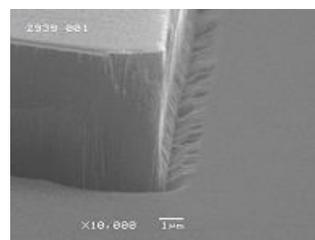
3. Results and discussion

3.1 Deep etching in SiC

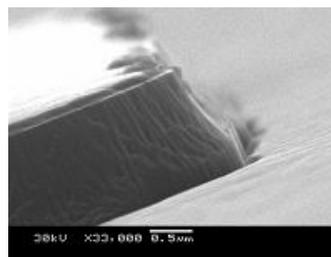
Fig. 1 presents examples of micrographs from 4H-SiC trenches obtained for an RF power of 100W. It is remarkable that in the obtained SiC etched surfaces, micromasking artifacts (also named "black silicon" zones in Si etching studies) are not present. On the Ni mask and SiC substrate surface, in the presence of fluorine-based plasma, desorption of weakly volatile species with negative boiling temperatures reported [14] occurs. Plasma ion bombardment enhances this phenomenon by physical sputtering and/or by chemical reactions, the volatile

species being eliminated through pumping, thus avoiding the formation of micromasking or thin films.

Despite the very smooth surface obtained at this low RF power applied, trenching systematically occurs at the foot of the sidewalls. Increasing the pressure in the chamber does not allow to eliminate this phenomenon as proposed in Refs. [7] and [10] where the ion-to-neutral flux ratio is changed. Mask faceting is also observed which could be responsible for the obtained jagged sidewalls.



(a)



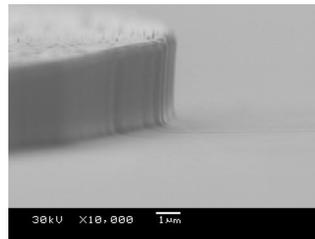
(b)

Fig. 1. SEM micrographs of 4H-SiC etched surfaces with a 25sccm SF₆ and 6.7sccm O₂ plasma at (a) 100W, 30 mTorr, 30min and (b) 100W, 60mTorr, 10 min.

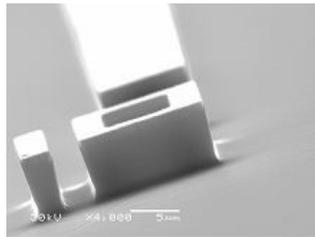
Nevertheless, we are able to eliminate trenching by increasing the RF power. In figure 2 examples of SEM micrographs obtained after a RIE performed at 250W are presented. Vertical trenches are obtained, with an etching depth of 3.2 μm and 6.6μm after 10 min and respectively 20 min of RIE realized at 60mTorr. Very high etching rates of 0.32-0.33 μm/min are thus deduced, specifying that for our reactor 250W corresponds to a RF power density of ~3.08 W.cm⁻². These results are somewhat in contradiction with those published in [8], where a low bias is applied to the substrate to avoid the trenching effect leading to a more tapered transition from the sidewall to the bottom surface. We note that these authors have obtained textured surfaces and jagged sidewalls. In our case, at the highest plasma RF power, which corresponds in our reactor to the higher substrate polarization, we obtain a well tapered transition from the sidewalls to the bottom surface. The surface remains smooth and the jagged sidewalls which were still presents at 100W cease to exist at 250W. Although the results from Ref. [8] are also obtained on hexagonal monocrystalline SiC, we notice that an ECR (electron cyclotron resonance) reactor

with a different plasma chamber configuration was utilized in this case.

Trenching elimination by applying higher bias power was also reported in Ref. [7] for chloride plasma etching of Si with an ICP (inductive coupled plasma) reactor. We note, however, that controlling the substrate bias is facilitated in the ICP. This gives the possibility to decorelate the energy of the generated plasma from the substrate bias



(a)



(b)

Fig. 2. SEM micrographs of 4H-SiC etched surfaces with a 25sccm SF_6 and 6.7sccm O_2 plasma at (a) 250W, 60mTorr, 10 min and (b) 250W, 60 mTorr, 20 min.

On our deep trench vertical sidewalls (Fig. 2 (b)), besides the slightly tapered transition at the bottom corners, we observe an extra lateral etching along the lower part of the trench sidewall, a narrowing of the wall thickness as can be clearly seen in the left feature of fig. 2b. Like the bowing shown in Refs. [4,6,10] and obtained in the upper part of the sidewalls, this phenomenon may be attributed to the incident ion deflection, combined with chemisorb of the formed reactants in these areas. Several authors have mentioned the role of the O_2 in the formation of a passivated (inhibitor) layer on the trench sidewall. This layer increases the plasma anisotropy [10, 15]. Angular dispersion of the incident plasma ions and reactants by collisions within the plasma sheath [4] and by the charged sidewalls [5] enhances the reactant transport toward the lower areas of the sidewall and produces a local desorption of the passivated layer.

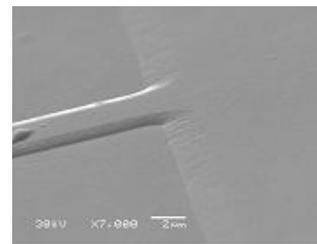
Removing the trenching effect by an increasing of the RF power may be also related to the extra lateral etching along the lower part of the trench sidewall. Instead, more energetic reactants are focusing in this area with a diminished mean free path.

3.2 Tilted sidewalls in SiC

This study was applied also to realise inclined sidewalls at a fixed RF power of 250W which preserve the etched surface from trenching. The profile of the etched 4H-SiC sidewall was controlled by the consumption of the SiO_2 mask, measured with interferometric analyses during the etching process. The SiC sidewall angle (β) is directly defined by the inclined border of the SiO_2 mask ($\alpha=30^\circ$) and SiC/mask etching selectivity (S) [16]:

$$\tan(\beta)=S\times\tan(\alpha) \quad (1)$$

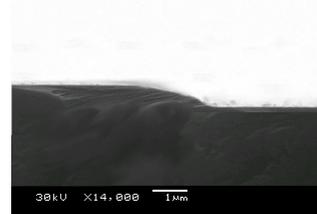
The etching depth is limited by the SiO_2 mask depth which is consumed.



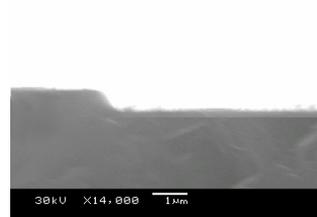
(a)



(b)



(c)



(d)

Fig. 3. SEM micrographs from tilted 4H-SiC sidewalls obtained by RIE etching: a) and b) 20 mTorr, 12.5 sccm SF_6 , 3.4 sccm O_2 , c) 60 mTorr, 25 sccm SF_6 , 6.7 sccm O_2 d) 100mTorr, 50 sccm SF_6 , 13.4 sccm O_2 .

No trenching is detected (Fig. 3 (a)) comforting our results presented above and a smooth etched 4H-SiC surface is obtained, volatile species being also formed from the etched SiO₂ mask.

From the results presented in figures 3a and 3b, we observe that using low pressure and low flow rates (20mTorr and respectively 16sccm total flow rate) leads to very flat angles. A SiC/SiO₂ mask selectivity in the 0.8 to 0.9 range is found from profilometer measurements of the etched layers. However, high pressure and high flow rate (60 to 100 mTorr and respectively 33 to 64sccm total flow rates) conduct to more vertical sidewalls (Fig. 3c and 3d) due to a higher SiC/SiO₂ mask selectivity in a range of 1.8 to 2.0. According to what we have mentioned above, the pressure regime affects the ion-to-reactive neutral species ratio, allowing control of the mask selectivity [7]. The selectivity values obtained follow the trend of the values extracted from eq. 1. By choosing a mask with a selectivity close to that of SiC allows us to obtain a significant range of sensibility for this parameter with the pressure and gas flow rates used. Thus, we can control the trench angle profile during the etching process.

4. Conclusions

During the fabrication process of the high power and high temperature SiC devices, the undesirable trenching effect obtained by dry etching drastically affects their performances. From the analysis of the results we have found a method of inhibiting this effect and controlling the trench angle profile.

Deep and vertical etched trenches have been obtained in 4H-SiC with a highly selective Ti/Ni mask.

The trenching in RIE 4H-SiC etched sidewalls can be eliminated by increasing the SF₆/O₂ RF plasma power up to 250 W. This increases the etching rate to values as high as 0.34 μm/min. Nevertheless, the mechanism behind the occurrence or the disappearance of trenching remains still unclear. In spite of the smooth surface and the slightly tapered transition obtained between the sidewall and bottom surface, we observe an inner sidewall curving due to an extra etching on their lower part. This can be related to deflections of the incident ions and reactants from the plasma sheath and/or from the sidewalls, but this process approach does not produce trenching at the foot of the sidewalls.

The control of the trench angle was realized by RIE with SiO₂ masks developed by wet etch. Very flat angles are obtained for low pressure and low SF₆/O₂ plasma flow rates and more vertical sidewalls by increasing these parameters. Nevertheless, in this case the etch depth is limited by the SiO₂ layer thickness which is consumed during the RIE process.

An interesting perspective of this work is to combine these two techniques by patterning a double masking (highly selective and consumable) in order to fabricate the tilted sidewalls in the 4H-SiC depth.

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