BOSCH DEEP SILICON ETCHING: IMPROVING UNIFORMITY AND ETCH RATE FOR ADVANCED MEMS APPLICATIONS

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ABSTRACT

Bosch deep silicon etching [1] is nowadays widely used on inductive coupled plasma equipment. Most inductive plasma sources in the field consist of a coil of one or several turns wound around a dielectric vessel, which is powered by radio frequency to generate a high density plasma. Wafers are placed onto a substrate electrode downstream of the plasma source. RF self-biasing is applied to accelerate ions from the high density plasma towards the wafer. A major drawback of this kind of plasma source is its limited uniformity, which lowers the yield in critical MEMS applications. In this paper, we present an approach to improve etch uniformity by introducing an aperture construction between the plasma source and the wafer. In combination with balanced coil drive, excellent uniformity over 150 mm diameter wafers was achieved even at very high etch-rates.

INTRODUCTION

High aspect ratio microstructuring is one of the key processes in the MEMS field. The ability of flexible pattern transfer into silicon with vertical sidewalls and high accuracy is a crucial requirement in nowadays advanced MEMS devices. Wet etching technology based on the anisotropic etching behaviour of alkaline solutions, as it was used in the early days of micromechanics, is not capable of transfering complex geometries with accurate dimensional control into a silicon wafer. Plasma etching, as it is well established in semiconductor manufacturing is free from geometrical restrictions, however the semiconductor based processes are designed for only a few microns etch depths and are lacking etch-rate and mask selecitivity. For example, chlorine based plasma etching processes are capable of high accuracy silicon microstructuring, however at rates typically below 1 μm /min and with limited selectivity towards the masking material, typically in the range of 20-30:1 for SiO_2-hardmasks [2]. Photoresist masking cannot be used with chlorine based chemistries. The need to fabricate deeper structures requires both higher etch-rates and better mask selectivities. The latter requirement often involved metal masks like Ni or Cr which hardly fit into a semiconductor environment. Nevertheless, impressive results have been achieved with approaches combining chlorine based plasma etch technology with additional release, dielectrics and metal deposition steps, like the SCREAM process [3].

The need for higher etch-rates led people to look into fluorine based process chemistries. In contrast to chlorine, fluorine radicals readily etch silicon without any need for ion assistance. As a consequence, the etch is no longer directional, but isotropic by its nature. The way to achieve anisotropy in a fluorine based process is via sidewall passivation schemes: Ion impact onto the sidewalls is weak in reactive ion etching and a passivating film preventing isotropic etch attack can build up there, whilst the etch bottom is subject to strong ion impact breaking through any passivating film formation. Oxygen was used to achieve silicon sidewall passivation in SF_6/O_2-plasmas by oxidation of the surface and silicon oxide redeposition preferentially at the sidewalls of etched structures [4,5]. The passivation mechanism can be enhanced by cooling the wafer to cryogenic temperatures of below 173K during the etch [6]. Oxygen type passivation is difficult to control, and redeposition of compounds of low volatility tends to form etch bottom roughness especially at cryogenic temperatures. In combination with high density

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plasma excitation in an inductively coupled plasma source, very high etch-rates approaching 10 μm /min can be achieved.

Veneer type passivation using teflonlike sidewall films is an alternative to oxygen passivation, however recombination of fluorine radicals with unsaturated, film-forming monomers in the plasma leads to pairwise extinction of active species, thereby forming saturated molecules again which do no longer participate neither in etch nor in film-forming reactions. Etch rate and profile control in a process where etch and film-forming gases are mixed are generally poor.

BOSCH DEEP SILICON ETCHING

The Bosch approach [1] is based on a variation of the teflon-film sidewall passivation technique which avoids recombination of active species in the gas phase: deposition and etch steps are performed subsequently, as is indicated in Figure 1. During the etch steps, part of the sidewall polymer material deposited in the previous deposition step(s) is removed from the sidewall by off-vertical ion impact hitting the sidewalls, and redeposited deeper into the trenches. Driving forward the sidewall polymer film leads to a local anisotropy of the etch step, which would otherwise be nearly completely isotropic. As a result, only a small sidewall roughness remains as an indication of the discontinuous process. The process works at room temperature and shows a very high selectivity towards standard photoresist masks, reaching 200:1 under certain process conditions, and also towards a large variety of hardmasks (SiO_2, Si_3N_4,...), exceeding 300:1. Etch-rates of 6 μm /min can be achieved with good profile control. Surface Technology Systems Ltd., Plasmatherm Inc. and ALCATEL Comptech are offering this process technology on their high density Inductively Coupled Plasma tools [7,8,9]. The unique process capabilities were opening new advances in MEMS technology, for example in the application of thick SOI-wafers for a new generation of MEMS devices [10]. Many research groups are now working on process improvements and new applications [11,12].

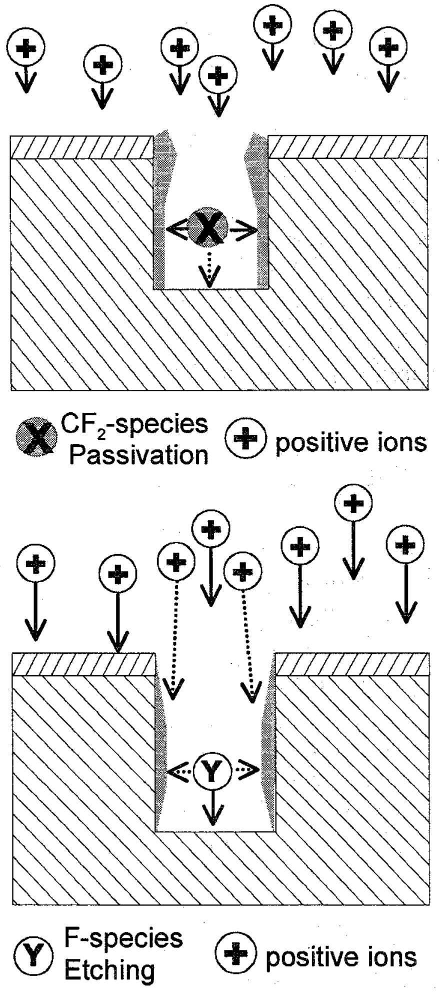

Figure 1: Sidewall passivation mechanism of the Bosch Deep Silicon Etching Process. The protecting film deposited in the passivation step is extending deeper into the trenches during the etch step to yield a smooth sidewall.

The high density ICP sources used for this process generally consist of a RF driven coil with a number of turns wound around a dielectric vessel. Due to the electromagnetic field distribution of the coil, the plasma excited closer to the coil area has a higher density than the plasma in the center area of the source. This plasma inhomogeneity is reflected in the etch process via a non-uniformity of rate, increasing from center to edge of a wafer. For a 150 mm diameter wafer, the etch-rate increase from center to edge is typically between 10-15 % (minimum to maximum). This non-uniformity may cause severe problems in the fabrication of MEMS devices, especially when a buried dielectric layer is used as an etch stop and as a sacrificial layer: to finish structures in the wafer center, an overetch inevitably occurs in the edge areas, which leads to profile distortions and notching at the dielectric interface especially for higher aspect ratio trenches. Since profile control is directly linked to etch uniformity, this parameter decides on the spread of device performance over a wafer.

EQUIPMENT MODIFICATIONS

Figure 2 shows a scheme of a typical ICP machine configuration, as is the STS Multiplex ICP. For better uniformity of the etch, the original ICP configuration was upgraded by two modifications:

A metal shield construction was developed for installation downstream from the plasma source. The metal shield consists of an aperture and a cylinder ring mounted on top of the aperture. The whole device is bolted to the machine core for thermal contact and electrical grounding. This construction adds an ion loss to the plasma propagating out of the source region downto the wafer. The ion loss mechanism by ion-electron recombination at the metal walls is supposed to reduce the enhancement of plasma density normally occuring from center to edge. In addition, eddy currents induced into the closed ring are expected to reduce and shield source fields from the wafer. Underneath the aperture, a nearly fieldless drift zone should allow homogenization of the flow of neutral radicals to the wafer.

From literature, it is well known that capacitive coupling leads to current flow through the dielectric chamber wall from the inductive coil to the plasma, which may significantly deform the plasma density distribution and affect etch results on a wafer. A balanced RF drive is suggested to compensate these currents and reduce the plasma potential [13]. Therefore, the inductive coil was driven in a way to allow adjustment of (a)symmetry of the RF drive by a suitable balanced/unbalanced transformer, as can be seen in the scheme of Figure 3. Thus, the influence of drive (a)symmetry on uniformity, with and without the aperture installed, can be studied.

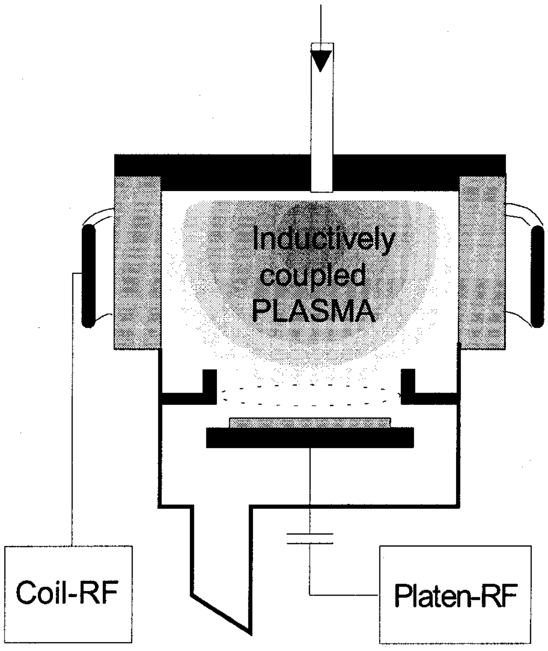

Figure 2: Scheme of an ICP machine, with uniformity aperture installed downstream from the source.

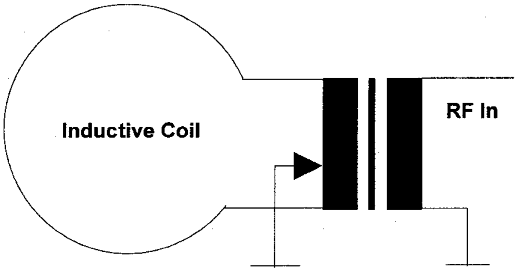

Figure 3: Balanced RF-Drive of Inductive Coil with Option for Symmetry Adjustment.

RESULTS

Typical *ASE* [7] process conditions were run in this configuration at a fixed RF coil power of 800 Watts and a fixed process time of 10 minutes. Etch depth reached after 10 minutes was 23-25 μm in wide gaps and 16-18 μm in 2 μm narrow gaps in all cases. Center to edge variation was measured for 150 mm diameter wafers containing a variety of test patterns with an open silicon area close to 15%. Etch-depth non-uniformity was calculated as (Max-Min)/Average from 5 measurements taken for each wafer. Figure 4 shows the uniformity results achieved for different symmetry adjustments, with and without the aperture installed, respectively.

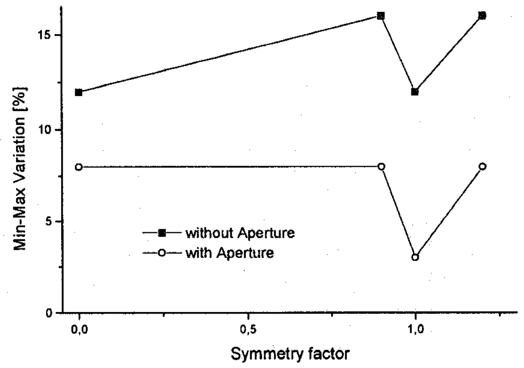

Figure 4: Etch depth variation over 150 mm diameter wafer for different symmetry adjustments, with and without the aperture installed. The lines are to guide the eye.

Without the aperture, the fully asymmetric situation (0.0), with one end of the coil grounded and the other powered by RF, yields an etch-rate increase from wafer center to edge of 12%. A nearly symmetric configuration – below and above perfect symmetry (0.9 and 1.2, respectively) – leads to even worse etch-rate variation of 16%. For exact symmetry (1.0), the original value of 12% is re-established.

With the aperture installed, etch-rate increase from center to edge is 8% in the fully asymmetric case, this value remaining constant also for nearly perfect symmetry (0.9 and 1.2). This represents an improvement of 40% compared to without using the aperture. However, for exact symmetry of the drive (1.0), non-uniformity drops to 3% which corresponds to +/-1.5%. This excellent value could be proven as long-term stable and was confirmed also for very high etch-rates of 6 μm/min achieved at 3 KWatts RF excitation.

CONCLUSIONS

Installation of an aperture in combination with a fully symmetric drive of the inductive coil leads to a dramatic improvement of etch uniformity by a factor of 4. Without an aperture, symmetric drive showed no uniformity benefit.

IMPORTANT APPLICATONS

The following figures show important MEMS applications which are manufactured or under development at Bosch. In figure 5, a surface-micromachined accelerometer structure is depicted which is fabricated by deep trench etching from thick polysilicon grown in an epitaxy reactor [14]. This device has been in production since 1997 for car safety systems, mainly the airbag. High aspect-ratio comb capacitors provide sufficient capacitance for off-chip electronic evaluation of the sensor devices.

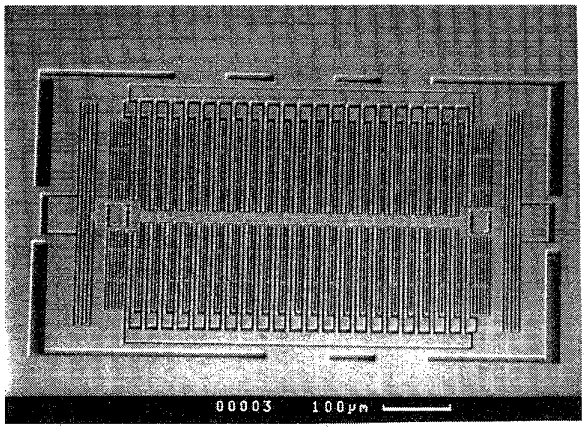

Figure 5: Surface Micromachined Accelerometer fabricated by Deep Polysilicon Etching.

Figure 6 shows a micromachined gyroscope for vehicle dynamic control which is manufactured in a combination of deep-trench etching a thick bulk silicon membrane and surface micromachining accelerometers on top of the membrane structures. The membrane is wet etched from the wafer backside in KOH solution. The accelerometers are fabricated in thick polysilicon micromachining technology, again using deep trench etching. This device incorporates electromagnetic drive by Lorentz forces and has been in production since mid-1998 [15]. The two masses are kept in a counterphase oscillation. Coriolis forces which appear in response to yaw rate are measured by the accelerometers on top of the vibrating masses.

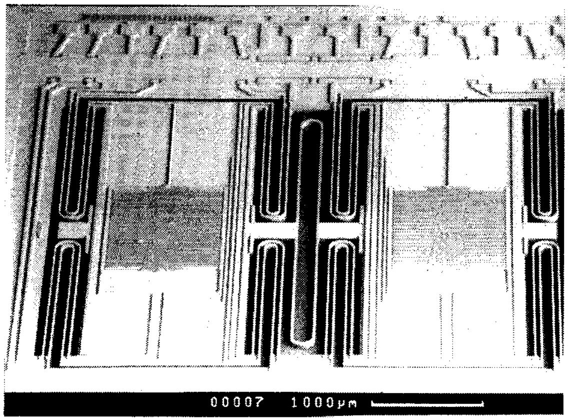

Figure 6: Yaw Rate Sensor by Combined Deep Etching of Bulk Silicon Membrane Structures and Thick Polysilicon Accelerometers.

Figures 7 and 8 show surface-micromachined gyroscope structures. These are developed for roll-over sensing in automotive safety systems. Both use integrated electrostatic drive via high aspect-ratio comb structures.

The device in Figure 7 is a rotational type in-plane vibrator with out-of-plane detection mode. The whole sensor element is anchored to the substrate only by the central tether beam in the middle of the structure. The gap between the moving mass and the underlying electrodes for capacitive detection is only 1.4 µm wide. In response to an angular velocity with its axis in plane, an out-of-plane torsion adds to the in-plane base rotational vibration.

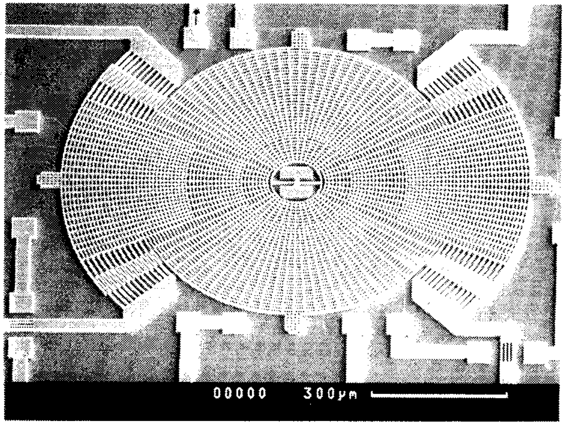

Figure 7: Surface Micromachined Gyroscope (rotational type resonator). Financial Support from the European Commission DGIII in the ESPRIT IV framework is gratefully acknowledged.

The device in Figure 8 is a linear type in-plane vibrator with in-plane rotational detection mode. The two vibrating masses are driven in counterphase. Coriolis forces in response to yaw rate around a perpendicular axis lead to an in-plane rotational vibration of the whole structure which is detected by two pairs of comb capacitors visible at the top and the bottom of the SEM picture.

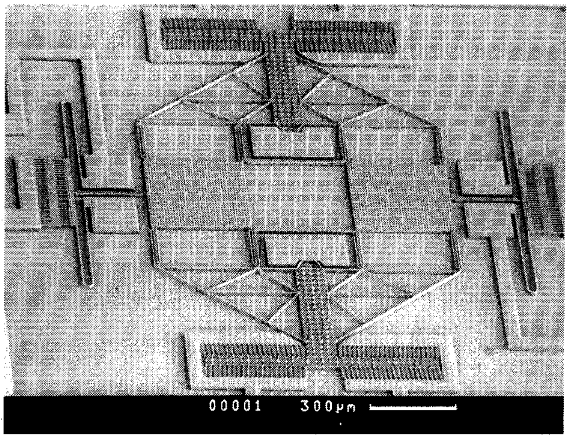

Figure 8: Surface Micromachined Gyroscope (linear type resonator). Feasibility Study.

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