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Plasma processing of materials at the atomic scale

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Plasma etching is finding new applications beyond the microelectronics industry. There are new challenges in the devising and controlling of plasma-surface interactions.

1. Introduction

A new generation of electromechanical devices is emerging that indirectly interface the processing power of microelectronics with the macroscopic world of human life. These are micro-electromechanical systems (MEMS) and their close relatives, micro-opto-electromechanical systems (MOEMS) and nano-electromechanical systems (NEMS); for brevity the single acronym MST will be used to imply the whole family of micro and nano systems technologies.

Conventional process technologies that have evolved for the manufacture of microelectronics to a very large scale of integration (VLSI) are amenable to adaptation for the fabrication of MST devices [1]. As a result, silicon is widely used as the base material for MST and plasma enhanced chemical vapour deposition and plasma etching are mandatory tools for shaping it. However, specifications of the manufacturing processes required for MST can be different by orders-of-magnitude from those in VLSI processes because of the contrasting quantity of material involved: microelectronics is still predominantly based on a planar geometry whereas MST devices are more often than not fully three dimensional. Nevertheless, the principal characteristics of processes based on low pressure, electrical discharge plasmas are still advantageous. For instance, plasmas exploit electrical energy to stimulate enhanced chemical reactivity to provide an etching medium. Furthermore, space charge sheaths at plasma boundaries introduce directionality in the rates of surface reactions through the bombardment by high energy ions. In addition, plasma processes are 'dry' – a fact that allows most of the fabrication sequence to be done without the repeated washing and drying necessary if wet chemical routes are used.

Tailoring processes for the plasma etching of silicon is of particular importance for a wide variety of MST demands. Key developments include robust and reliable control of atomic-order surface adsorption, surface diffusion and surface reactions in plasma etch processes. These surface mechanisms control the vertical and lateral etch rates as well as the etch-selectivity, all of which must be optimized in order to fabricate functional structures. Most of the previous work on etching mechanisms concentrates on reactions that are enhanced by ion-bombardment, and there has been much less on surface diffusion or adsorption processes. Existing models deal only with a sub-set of the key parameters in

what is a multi-dimensional problem. Moreover, they generally deal with essentially planar silicon structures, whereas there is now a need to describe the significantly more complex 3D processes required for MST devices.

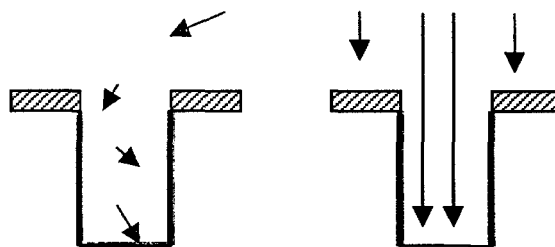
2. Plasma etching

In the plasma etching process, surface material is removed as volatile molecules formed in chemical combinations between the surface atoms and species originally activated in the plasma. The relatively hot electrons (1-10 eV) that predominate in low pressure gas discharges are particularly effective activators.

2.1 Vertical (anisotropic) etching

Of particular interest in etching features for MST devices is a process that cuts deep into the bulk silicon. The so-called 'switched etch process' achieves this in a succession of deposition and etch steps through which anisotropic etching is promoted. The sides of features are typically protected by a thin layer of fluorocarbon polymer deposited from radicals generated in a fluorocarbon plasma (Fig 1.). After only a few seconds of deposition, the plasma composition is switched to provide an etching medium based on SF_6 . Fluorine atoms, liberated by the inelastic collision processes in the plasma, etch those areas that are cleared of polymer by a strongly directed flux of energetic ions crossing the space-charge sheath at the interface between plasma and surface. The sidewall passivation is repaired by further cycles of deposition every few minutes. Though a very successful basis for fabricating MST devices this approach has a number of inherent limitations: sidewall passivation involves relatively thick complex hydrocarbon polymer films that are often difficult to remove; the sidewall profile has a characteristic scalloped edge linked to the multi-step procedure; chamber walls accumulate polymeric coatings that are a potential source of particulate contamination.

Fig 1 Plasma – source of active species and ions



2.2 Lateral (isotropic) etching

Etchant species can diffuse considerable distances across a silicon surface before becoming chemisorbed. This can fuel etching on sites not directly exposed to the plasma. Observations of etch profiles, particularly the persistence of sharp ridge shapes and of nature of undercut immediately beneath the mask, indicate that surface diffusion can be significant in the fluorine based etching of silicon [3]. Figure 2 shows heavily undercut features in silicon produced by an *isotropic* etching environment that nevertheless fails to 'polish' the sharp edges defined by the original mask.

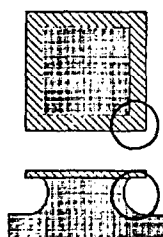


Fig. 2 Silicon etched under aluminium mask (10x10 μm) may show necking – sketches based on SEMs [3]

The rate of lateral etching of polycrystalline silicon exhibits strong aspect ratio effects on the submicron-scale, indicating different surface diffusion rates for different etchant species [4].

3. Controlling plasma etching

There are two approaches to controlling plasma-surface interactions in an etching environment. One uses chemistry; the other is based on control engineering.

The potential of atomic order control of adsorption and reaction has been demonstrated by studying the etching of silicon and related materials, atomic layer by atomic layer [5]. The etching proceeds in a succession of steps during which monolayers are chemisorbed and subsequently removed by ion bombardment. The growth of a monolayer is a self-limiting process that can be revealed through studies of etch rate. This then suggests a 'sharper' alternative to the switched etch process described above, with monolayer chemisorption replacing polymer passivation. Table 1 is a summary of adsorbent species and plasma gases used by Matsuura [5] for the etching of silicon using this approach. Sidewall passivation by these self-limiting processes exploits atomic scale phenomena and is accordingly simpler, faster and capable of achieving finer scale features.

MST devices require considerable quantities of silicon to be removed by plasma etching. The rate of etching is determined by the concentrations of the species involved (e.g. atomic fluorine and various bombarding ions). Thus there is a demand for denser plasma sources. At the same time the electron temperature in the plasma affects the relative amounts of the active species that are

created. Accordingly, a versatile source would have independent control over plasma density, the distribution of electron energies and the energy of ion bombardment. A way of coping with a multidimensional space for process parameters is to employ 'intelligent' optimization and control. Diagnostic data obtained *in-situ*, can be fed back to an Artificial Intelligence (AI) platform that controls the processing plasma. Recently this approach has been used to map the operational parameter space in terms of ion bombardment flux and energy [2]. The AI control has been mostly rule-based (including the application of fuzzy logic to achieve multi-variable control). More recently tuning and optimization has been done using the methods of genetic algorithms, simulated annealing, and differential evolution. These are all based on the idea of searching a parameter space to find an optimum or near-optimum, avoiding the local optima while not having to search exhaustively the whole parameter space.

4. References

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Adsorbant	Plasma	Remarks
Cl radical	Ar/Cl ₂	1/2ML etching for (100), depends on orientation
Cl ₂ molecule	Ar/Cl ₂	1/4ML etching for (100), depends on orientation
N radical	N ₂	~2ML nitridation
N ions	N ₂	~4ML nitridation

Table 1. Typical self-limiting conditions for plasma monolayer (ML) silicon etch processes established by Matsuura et al.