Materials Science and Engineering B 169 (2010) 78–84

Contents lists available at ScienceDirect

Materials Science and Engineering B

journal homepage: www.elsevier.com/locate/mseb

Self-organized nanostructures in silicon and glass for MEMS, MOEMS and BioMEMS

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ARTICLE INFO

Article history:
Received 5 June 2009
Received in revised form 5 November 2009
Accepted 9 November 2009

Keywords:
Nanostructured Surfaces
Black Silicon
Glass
Silicon on Ceramics
Etching
Plasma processing

ABSTRACT

The utilization of self-organization in the process workflows for Micro-Electro-Mechanical-Systems (MEMS) and their derivatives is a smart way to get large areas of nanostructured surfaces for various applications. The generation of nano-masking spots by self-organizing residues in the plasma can lead to needle- or tube-like structures on the surface after (deep-) reactive ion etching. With lengths of 3 up to 25 μm and 150 up to 500 nm in diameter for silicon broad applications in the fields of micro fluidics with catalysts, micro-optical or mechanical mountings or carrier wafer bonding in microelectronics are possible. Now, we also developed dry etching processes for fused silica which shows analogue properties to 'Black Silicon' and investigated these glass nanostructures by a first parameter study to identify new usable structures and hybrids. This innovative starting point allows the transfer of 'Black Silicon' technologies and its applications to another important material class in micro- and nanotechnologies, fused silica.

1. Introduction

1.1. Motivation

Today's progress is mainly driven by miniaturization in almost all fields of research and technology. The structures of Micro-Electro-Mechanical-Systems (MEMS) as well as their enhancements such as MOEMS (Micro-Optical-Electro-Mechanical-Systems) and BioMEMS (Bio-related MEMS) are often generated using various lithography steps, which transfer design information from a computer via masks onto the substrate. The cost for these processes increases with increasing feature density and smaller structures, especially if nanometer dimensions or resolution is required.

The utilization of self-organization effects can generate a statistically distributed nanopattern on surfaces which can subsequently serve as lost masks for growth and etch processes. A classic additive technology including self-organization (or self-assembly) is the Vapor–Liquid–Solid (VLS) synthesis method for nanowires [1], self-organizing a thin gold film into gold clusters by dewetting during a thermal process.

Another important example of such a MEMS process with self-organizing effect is the generation of 'Black Silicon' during subtractive dry etching (see Fig. 1), named due to its impressive light absorption. This was first observed and described by research groups in the US [2] and the Netherlands [3] in the 1990s.

Examples of the first scientific applications, derived from the optical effects, are found in the field of light absorbers, antireflective coatings and enhancement of solar cells. Commercial implementations have been demonstrated by the US company SiOnyx Inc. [4].

In addition to its light absorbing effect, 'Black Silicon' can also be utilized for micro-fabricated cold cathodes [5], an electron emitting structure.

The fragile appearance of the silicon needles normally inhibits the search for mechanical applications. However, a closer look at the nanostructured surfaces in our lab under the electron microscope showed morphologies resembling surfaces of Velcro® textiles. This led to mechanical experiments to use 'Black Silicon' as interlocking surface for bonding of silicon to silicon and as catalyst carrier surfaces [6].

Now, based on the great success with silicon nanostructures, we expand the material spectrum towards glass, in particular fused silica. Our process research on nanostructured glass surfaces led to the formation of 'Glass Grass' and the possibility of transferring the known applications from 'Black Silicon' to another and special material. Fused silica is made from flame hydrolysis of silicon tetrachloride, resulting in the purest silicon dioxide with outstanding chemical resistance and mechanical properties, opti-

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doi:10.1016/j.mseb.2009.11.020

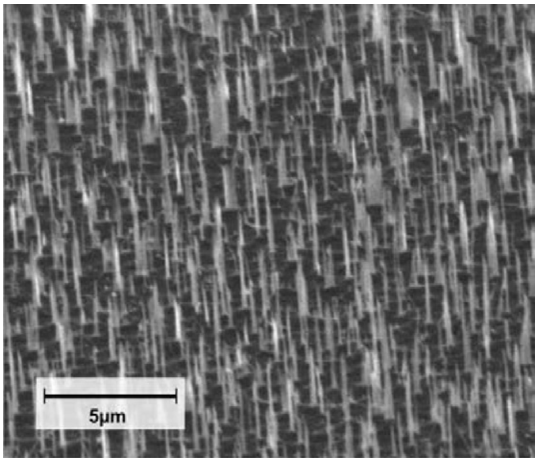

Fig. 1. Example of 'Black Silicon' with short needles, approx. 2 μm, density approx. 600,000 per mm^2.

cal transparency and very low thermal coefficient of expansion. This enables applications in micro fluidics and micro-optics, even in harsh environments. Due to the additional basic advantage of its biocompatibility it is also used in BioMEMS. However, a great challenge for a wider distribution of fused silica as a construction material for micro- and nanosystems is the combination with other materials and components. Resulting from its resistivity, fused silica is difficult to bond to other materials, e.g. silicon, and hard to process. Nanostructured surfaces in glass like 'Black Silicon' offer a smart solution for novel bonding techniques. Thus, the idea to transfer it to fused silica was obvious.

1.2. Mechanical applications of 'Black Silicon'

During intensive process variation studies and technology development for standard reactive ion etching (RIE) and deep reactive ion etching (DRIE) we observed different formations of 'Black Silicon' in both processes (see Section 2).

Microscopic analysis of 'Black Silicon' revealed very long needle-like structures for DRIE and extremely high needle densities for RIE. The geometrical parameters define different preferred applications for the two needle types. Deep reactive ion etched 'Black Silicon' is used for catalysts, silicon-to-silicon and silicon-to-polymer bonding, whereas shorter and modified self-organized needles by the RIE machine are used for silicon-to-ceramic bonding and catalysts as well.

All enlarged surfaces like porous materials, rough surfaces or needle-structures possess a high potential for catalyst carriers. The catalyst carrier is subsequently covered with the catalyst, primarily platinum, rhodium, gold, etc., using technologies like evaporation or dip coating. Chemical reactions then take place on the surface of the catalyst, serving as a condensation spot for the reactant molecules and mainly accelerating the reaction speed and lowering the activation energy. 'Black Silicon' as a carrier material has positive properties such as high thermal conductivity ensuring a homogenous temperature distribution (see Fig. 2) and can be easily integrated into micro fluidic process flows, if they include dry etching processes [6].

The silicon-to-silicon bonding process with nanostructures can be used as a kind of nano Velcro® for various assembly and packaging processes [6], see also Fig. 8, bottom left. It could even replace state of the art 'pick and place' steps which commonly use adhesives.

The combination of the silicon interlocking chips with a plastically deformable material (e.g. thermoplastic polymers) allows the bonding of heterogeneous compounds [7]. If the needles can indent the matrix of a material, a stable interlocking interface region is formed.

Bonding of silicon with LTCC (*l*ow *t*emperature *c*o-fired *c*eramics) is a further application using the penetration of nanostructured silicon surfaces into ductile materials [8]. LTCC is an established group of materials and at the same time a sophisticated technology field for fabrication of reliable ceramic wiring substrates/boards (System in Package). Fundamentally, LTCC tapes consist of glass and alumina powder linked with a polymer binder. Therefore, it has a ductile and polymer character in the unfired state and behaves almost like a normal polymer work piece.

2. Technology

2.1. Dry etching basics

The formation of the nanotextured surfaces on silicon and fused silica is done by self-organized, lithography-free reactive ion etching (RIE) or deep reactive ion etching (DRIE). Both plasma etching processes are working with the same abrasive principle – a selective passivation of explicit areas and a combination of chemical and physical attack to the non-protected material surface. In general, silicon based material systems react with fluorine based plasma chemistry like SF_6, CHF_3, CF_4, C_4F_8, etc., to volatile compounds like SiF_x, etc. A more or less vertical ion bombardment supports the selective abrasion. Depending on the assembly of plasma reactors passivation and etching operate at the same time (RIE) or can be controlled separately (DRIE).

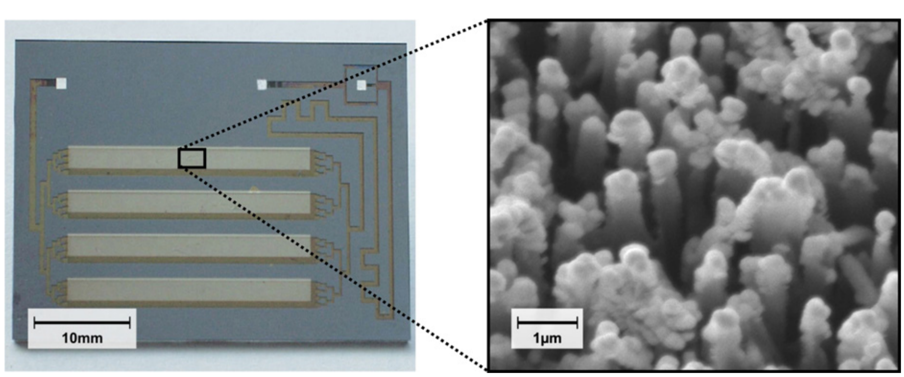

Fig. 2. 'Black Silicon' as a catalyst carrier, left: micro fluidic chip with approx. 100 nm platinum covered nanostructured silicon surface, right: SEM picture showing the platinum on the silicon needles of about 15 μm length and 200–500 nm diameter.