Planarization of high topography surfaces with deep holes and cavities using two-step polymer coating

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ABSTRACT

Pattern transfer on structured surfaces is still a technical challenge in MEMS fabrication due to the accumulation of photoresist at the structure base and the discontinuity at the structure opening. This paper reports a planarization method which employs a two-step polymer spin-coating to cap the structures to facilitate pattern transfer on structured surfaces. The first spin-coating uses heat-depolymerizable poly (propylene carbonate) (PPC) to either partially fill or completely intersect the structures, and the following spin-coating uses polyimide (PI) to form a complete capping film on the structured surfaces. The thermal decomposable feature of PPC allows it to decompose as a sacrificial layer during PI curing, leaving only PI films on the structured surfaces after the two-step coating. High topography surfaces with deep holes with diameter of 25 μm, long trenches with length of 500 μm, and large cavities with width of 100 μm, have been well planarized using the proposed method. Subsequent photolithography verifies that photoresist can be well applied onto the planarized surfaces, and the pattern transfer results are satisfactory. Silicon dioxide deposited using plasma enhanced chemical vapor deposition (PECVD) and aluminum deposited using sputtering are also demonstrated on planarized surfaces. The preliminary results demonstrate the feasibility of planarization of high topography surfaces using the two-step coating method.

1. Introduction

Fabrication of micro-electromechanical systems (MEMS) and microsensors with three-dimensional (3-D) structures depends on special microfabrication technologies such as deep reactive ion etching (DRIE), KOH or TMAH wet etching, wafer bonding. Pattern transfer in MEMS fabrication uses photolithography technology that is critical in integrated circuit (IC) fabrication, but sometimes it differs significantly from that in IC due to the high topography of the surfaces inherent to the 3-D features of MEMS and microsensors [1–4]. Since the surface topography ranges from several microns to hundreds of microns, deploying photoresist on the structured surfaces normally causes non-uniform photoresist thickness, i.e., accumulation at the structure base and discontinuity at the structure opening, which impose a great difficulty to obtain fine line width.

Normally, pattern transfer on high topography surfaces can be classified into two categories. One is lithography on the base and the sidewall of large cavities that are fabricated by KOH or TAMH

etching, and the other one is lithography on the top surfaces with deep structures. For either cases, the most challenging problem is to coat uniform photoresist on the wafer surface. Besides the non-uniformity of photoresist caused by the convex or the concave high topography structures, the slant surfaces etched by KOH or TMAH on (1 0 0) wafers may reflect the incident beam during photolithography, causing undesired multiple exposures and unpredicted "ghost images".

Since pattern transfer on structured surfaces is frequently used in MEMS fabrication, different methods have been developed to solve this problem. For cavities etched by KOH or TMAH, electroplating and spray coating of photoresist on the structured surfaces have been well developed as an alternative to conventional spin-coating. Electroplating of photoresist, which employs electroplating mechanism and special photoresist, is the most commonly used method to coat photoresist [5–8]. However, a conductive layer beneath the photoresist is a prerequisite. Spray coating, which uses a nozzle to spray photoresist on structured surfaces, enable a conformal photoresist layer on irregular surfaces, and is another powerful tool to coat photoresist on the base and the sidewall of cavities [9–12]. To get uniform coverage, the spray layer is rather thick [13]. Other methods, like coating in saturated solvent followed by rotation [14] and complete filling structures with

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photoresist followed by exposure [15], have also been developed to solve the problem. Recently, a dynamic surface tension (DST) coating technique has been reported to coat conformal and thin photoresist over high topography surfaces [13], but the surface roughness still need further improvement.

For substrates with deep holes or trenches, an effective approach is to use dry-film photoresist on the structured surface [16–18]. The dry-film photoresist can be placed easily onto the surface of structured wafers, providing a convenient way to form a flat photoresist film on top of the deep structures by lamination. However, the thickness of the dry film is usually over 10 μm, which likely imposes difficulty in obtaining high resolution and thus fine line width. Besides photoresist layers, dry-film can also be used as a cover layer to fabricate microchannels [17,19,20], which significantly facilitates the fabrication of microfluidic devices.

In this paper, we report a fabrication technique that can essentially planarize the substrate with high topography features, such as deep holes, long trenches, and large cavities. A heat-depolymerizable polymer is applied to the substrate surface to cover the opening of the deep structures, such that a relative flat and smooth surface is obtained after spin-coating a second polymer. The first polymer is removed by thermal decomposition during high temperature curing of the second polymer. The second polymer resembles a flat dry-film, but it is much thinner. Once a surface is obtained, normal lithography using spin-coating of photoresist, mechanical grinding, and plasma enhanced chemical vapor deposition (PECVD), can be applied.

This paper is arranged as follows. Section 2 introduces the principle of the method, the polymers and their properties, and the processing details. Section 3 reports the experimental results, including the PPC coating results, the properties of the polymer mixture, the planarization results of vertical holes and slant cavities. Section 4 reports SiO₂ deposition and lithography on planarized surfaces, and the last section is conclusion.

2. Materials and fabrication

The proposed technique uses two-step polymer spin-coating to cover the structures on the wafer surface, and then further deposition of photoresist, polymers, or PECVD SiO₂/SiN can be applied on the substrate surface.

2.1. Technological design

The proposed coating process for topography planarization is illustrated in Fig. 1 using deep holes as an example. The method includes two steps of spin-coating, i.e., first spin-coating of a sealing polymer to cover the opening of the deep holes, then spin-coating of a planarization polymer to obtain flat surfaces.

As shown in Fig. 1(a), deep holes with certain diameters are fabricated on a wafer using DRIE. Then, a sealing polymer A is spin-coated on the wafer surface to form diaphragms on the opening of the holes, as shown in Fig. 1(b). Although the thin film of polymer A is continuous over the substrate, the surface topography of the film is considerably beyond tolerance. To obtain a flat surface, polymer B is spin-coated on the surface of polymer A, as shown in Fig. 1(c). Since the polymer accumulated in the bottom of the holes may cause problems during the following processes, polymer A should be completely removed after polymer B is applied, as shown in Fig. 1(d). To remove polymer A, a heat-depolymerizable material is used as polymer A. By heated to high temperature, polymer A is decomposed and the products of decomposition escape by penetrating through polymer B. Therefore, polymer A acts as a sacrificial layer in this process.

To retain the integrity of polymer B after polymer A is removed, the solvent of polymer B is miscible with polymer A. Therefore, a polymer mixture composed of polymers A and B is formed on the top of the deep holes after spin-coating of polymer B, and the topography of the structured surfaces can be further reduced.

2.2. Reagents

Selection of polymer A and polymer B is critical to realize the proposed idea. The requirements for polymer A are ease of forming a capping or an intersecting diaphragm on deep structures and ease of removing even covered by polymer B. The requirements for polymer B are sufficient mechanical strength, good chemical and high temperature stability, ease of removing by RIE, and miscible with polymer A.

Heat-depolymerizable polymers, which decompose above a critical temperature, are commonly used sacrificial materials due to the ease of releasing. Typical heat-depolymerizable polymers include polynorbornene [21] and polycarbonate [22,23]. Based on the characteristics of polymers and the conditions for thermal decomposition, poly (propylene) carbonate (PPC) (Sigma–Aldrich, product No. 389021) with an averaged molecular weight of 50,000 is chosen as polymer A. The thermal decomposition of PPC can be achieved at low temperatures (250 °C), which is compatible with CMOS and MEMS processes. The capping capability of PPC can be adjusted to some extent by tailoring the concentration of the PPC solution.

Since PPC can be dissolved in cyclopentanone, low temperature-cured polyimide (PI) ZKPI-330I (POME Company, Beijing, China) in cyclopentanone solution is chosen as polymer B. The curing temperature of PI is in the range of 160–250 °C, and after curing it has sufficient mechanical and chemical stabilities up to 400 °C. PI can be removed using mechanical grinding or oxygen plasma etching. The combination of PPC and PI is a low temperature system, and for special purposes, other high temperature materials can be used.

2.3. Spin-coating of polymers

The PPC powder was dissolved in anisole to obtain PPC solution. As the viscosity and non-Newtonian flow behavior increase with solid concentration, the PPC concentration ranging from 10% to 20% (in weight ratio) was evaluated according to the applications and the structures. The PPC solution was spun at 700 rpm for 9 s for complete dispersion, followed by a main spinning at 2000 rpm for 60 s to form a uniform thin film. The PPC polymer film was then soft-baked at 120 °C for 30 min on a hotplate to completely eliminate the anisole solvent. After PPC curing, the openings of the deep holes are covered by the PPC films, and the original high topography is significantly reduced. Then, a second spin-coating was employed to deposit PI thin film. PI solution was applied onto the wafer surface that was coated with PPC films, and the wafer was spun at 3000 rpm for 60 s to form a film of PPC–PI polymer mixture.

As the cyclopentanone in PI solution also dissolves PPC, the cured PPC film is re-dissolved during spin-coating of PI, and PI–PPC mixture is formed after PI spin-coating. Then, the mixture was cured at 250 °C for 6 h in a vacuum environment (1–2 Pa) to solidify the PI, which simultaneously decomposes the PPC in the mixture. The byproducts of PPC decomposition escape from the capping polymer mixture, leaving the deep holes to be covered with only PI films. Without the assist of PPC, only PI is unable to form capping films on the structured surfaces. This is because that PPC has low viscosity and good fluidity to form a capping layer for deep structures, whereas PI tends to fill the structures partially, imposing a significant difficulty to remove the PI in the deep (high aspect-ratio) structures using RIE etching after the process.