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A surface micromachining process for suspended RF-MEMS applications using porous silicon

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Abstract A porous silicon (PS) surface micromachining technology for suspended RF-MEMS device fabrication is proposed. Using PS as sacrificial layer and SiO_2 film as support membrane, suspended metallic structure has been realized. The lateral size of the obtained suspended inductor is $450 \times 425\ \mu m^2$. Sputtered aluminum with 1 μm thickness is used as structural materials. To avoid any damage of the Al structure during the process, TMAH solution with Si powder and $(NH_4)_2S_2O_8$ is used to remove the PS layer through etching holes.

1 Introduction

With the high-speed development of modern communication systems, miniaturization of radio frequency (RF) wireless communication systems has received increased attention in research and development. The main purpose is to integrate the miniaturized passive devices, such as inductors/capacitors and switches, with IC circuits so that a "monolithic" RFIC can be obtained. The greatest challenge of this task is to fabricate the passive devices on lossy silicon substrate with high performance. Due to their silicon IC compatibility and capability to realize high performance, Micro-Electro-Mechanical Systems (MEMS) technologies have been widely used to make these devices. Many high quality (Q) passive devices such as RF filters, oscillators, switches, inductors and capacitors (so-called RF-MEMS devices) have been realized [1, 2]. Nevertheless, the existing fabrication processes for RF-MEMS devices are still too complex for practical applications. Complex process steps not only result in low device reliability but also augment the product cost. This will hinder the application of RF-MEMS. In this paper we propose a simple one-side technology with porous silicon (PS) as sacrificial layer to address such issues. The experimental result shows that it is a possible solution for future RFIC fabrication.

For silicon-process oriented RF-MEMS devices, the lossy silicon substrate underneath the structures has to be removed to minimize the substrate loss. This in general can be done by anisotropy etching, which starts from the backside of a wafer [3]. Another optional method is to fabricate the devices on silicon substrate beforehand and then attach them with glass or other materials [4]. The problems presented in these methods are time consumption, or low repeatability. Porous silicon as a sacrificial layer can reduce the process complexity. The formation process of PS has been well established for many years, its preparation and etching are simple and inexpensive. Further thin-layer processes can be performed on the PS layer and serve as support films. After the device's structure is manufactured on the support film, the sacrificial layer is removed via etching holes on the film, and suspended RF devices can be achieved. A suspended RF-MEMS device (planar spiral inductor, for example) is schematically shown in Fig. 1.

Usually, PS is etched by KOH solution, in which the K^+ ion is very harmful for CMOS circuits. In the case of RF-MEMS devices fabrication, due to the possible eroding to the metallic structure (such as Al) by KOH, an alternative releasing etchant is expected. The recently developed modified Tetramethyl Ammonium Hydroxide (TMAH) can be considered as a suitable candidate [5]. With the addition of $(NH_4)_2S_2O_8$ and silicon powder to TMAH, the solution can etch the PS quickly without attacking the uncovered Al. Without alkali metal ions, this etching process is safe for the CMOS circuit, and a possible IC compatible MEMS process can be further established.

2 Porous silicon preparation

PS is fabricated via electrochemical etching in a special receptacle, as shown in Fig. 2.

The receptacle is the main part of the experimental setup. Inside, there are a plank and a seal ring, which are both made of polytetrafluorethylene. After placing the Si wafer onto the plank and lock it with the seal ring, the receptacle was separated into two isolated parts. In each part there is a platinum electrode. HF solution is used as electrolyte to realize the anodic oxidation. During the electrochemical etching, the current will flow through the wafer. In this way, the wafer surface that opposite to the cathode platinum is the anode of electrochemical etching, and where PS formation was happened.

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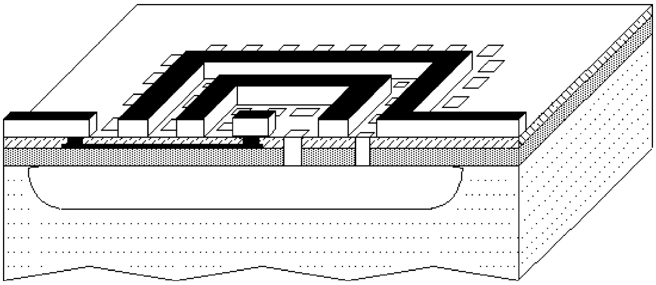


Fig. 1. Schematic of suspended spiral inductor

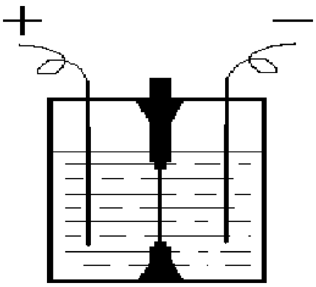


Fig. 2. Schematic of the setup and experimental arrangement for PS formation

To limit the treated area locally, certain mask layers are needed to serve as etch-resistant films. All films that are inert (or more stable in electrochemical etching than Si) in HF solution can serve as mask layer, such as SiC and noble metals. Si_3N_4 is a common mask layer since its reaction with HF is quite slow (<10 nm/min in 20% HF [6]). For the short time of anodization (<10 min), photoresist is also an effective mask layer [7]. In our experiment, 200 nm Si_3N_4 was chosen as a mask to obtain a correct sacrificial layer relief.

While used as sacrificial layers in RF-MEMS devices, a very smooth PS surface is expected so that support films like nitride, oxide, silicon carbide, and metal can be deposited onto it with high quality. The final PS quality will greatly depend on the operation conditions [8]. For our purpose, the following anodization parameters have been used:

Solution: HF (40%):$C_2H_5OH = 3:1$ (volume ratio)
Current density: $J = 40$ mA cm^{-2}.

During the electrochemical anodization, ethanol was added to the solution to reduce the surface tension of the liquid. This will help hydrogen go into the liquid instead of sticking to the surface of the wafer, and the surface appearance of the PS will be improved. After 10 min of anodization, a layer of 30 μm SP is formed, which will be used as sacrificial layer in the process hereafter.

3
Removing porous silicon

Many anisotropic silicon etchants can be used to remove the sacrificial layer of PS, including inorganic aqueous solutions of KOH, NaOH, CsOH, and NH_4OH, as well as organic aqueous solutions containing TMAH and ethylenediamine-pyrocatechol (EDP). Traditionally, 1% KOH solution is used to remove the PS for its high etching rate and low cost. Recent use of TMAH solution as etch agent is gaining popularity for its relative non-toxicity compared to EDP and its CMOS compatibility, as it contains no K^+ [9]. Further more, dissolving an appropriate amount of silicon particles in TMAH can decrease the aluminum etching rate. Researchers have reported a silicon etchant with zero aluminum etching rate. This etchant consists of 5 wt.% TMAH solution, 1.4 wt.% (or above) dissolve silicon, and 0.4–0.7 wt.% $(NH_4)_2S_2O_8$ oxidant additive [5]. Surely this process could be accepted as a CMOS process without big modification.

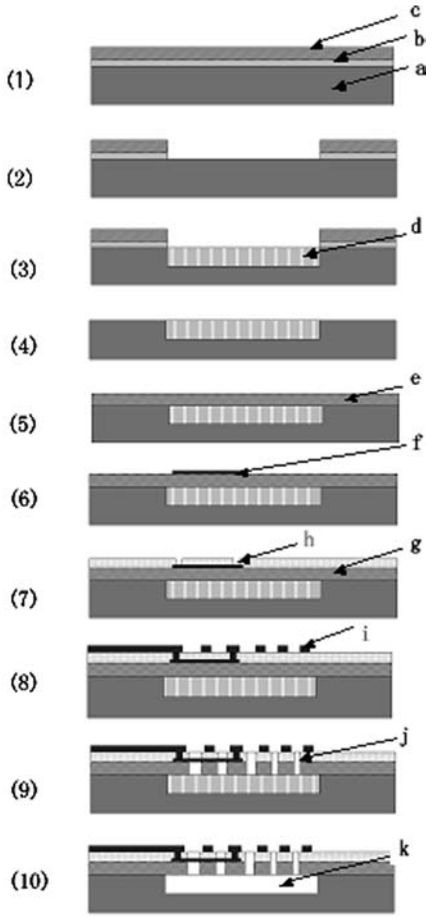
To get a suspended structure on a support membrane, the PS must be etched via etching holes in the membrane. The distribution of etching holes has to be considered carefully to assure the efficiency of PS removal, as well as the robust of the membrane. The releasing difficulty will be increased if the size of the holes is too small. On the other hand, the SiO_2 film will be damaged if the holes are too big. In our experiment, 4×8 μm^2 etching holes with 8 μm separations are punched into the support membrane.

After TMAH etching via etching holes, an air gap is achieved and therefore the suspended structure can be realized on the membrane. By this method, many kinds of structures can be prepared on the film before removing the PS layer, and the structures can then be suspended after the etching of PS.

4
Fabrication process

Based on the experiment with PS fabrication and removal, a new one-sided technology for fabricating Si substrate based suspended RF-MEMS devices has been obtained. The planar spiral inductor structure is used as suspended RF-MEMS structure to demonstrate the feasibility of this process. The major fabrication steps are illustrated in Fig. 3. It starts with a N-type (1 0 0) wafer with $\rho = 0.01$ Ω cm.

(1) 200 nm SiO_2 is formed by oxidization, and 200 nm Si_3N_4 is deposited on it by low-pressure chemical vapor deposition (LPCVD) at 700 °C as a mask layer.
(2) Anodization windows are etched by reaction ion etching (RIE).
(3) The PS is formed by the anodic electrochemical etching in Hydrofluoric acid.
(4) The Si_3N_4 and SiO_2 layer is removed by wet etching in HF solution.
(5) 1 μm SiO_2 is deposited using LPCVD as a support membrane.
(6) Metal 1 (300 nm aluminum) is sputtered and etched, and serves as the lower line in the inductor.
(7) 300 nm Si_3N_4 is deposited using plasma-enhance chemical vapor deposition (PECVD) at 280 °C as an insulating layer between metal 1 and metal 2. Via holes are etched by RIE.
(8) Metal 2 (1 μm aluminum) is sputtered and etched, and serves as the upper coil in the inductor.
(9) Etching holes in the Si_3N_4 and SiO_2 are formed using RIE.



a: Substrate b: SiO2
c: Si3N4 by LPCVD d: Porous Silicon
e: SiO2 by LPCVD f: Metal 1 (Al)
g: Si3N4 by PECVD h: Via Holes
i: Metal 2 (Al) j: Releasing holes

Fig. 3. Fabrication process of the MEMS inductor

(10) 5% TMAH solution (also consist of 1.6% dissolved silicon and 0.6% $(NH_4)_2S_2O_8$) is used to remove the PS via etching holes, and an air gap is achieved.

5 Results and discussion

A suspended spiral MEMS inductor structure has been achieved by using PS as sacrificial layer. Its SEM picture is shown in Fig. 4.

The total size of this inductor is $830 \times 500\ \mu m^2$, the structure size of the coil is $395 \times 380\ \mu m^2$, the size of the support film is $450 \times 425\ \mu m^2$ and the membrane thickness is 1 μm. The calculated inductance of the inductor is 4 nH. The thickness of the metal is 1 μm. For the reason that the side erodes during patterning the aluminum layer via wet phosphonic acid etching, the metal width is smaller than expected. This problem can be overcome by etching the aluminum with dry method, which can be easily realized in a standard CMOS pilot line.

Figure 5 shows a detail of the suspended inductor. No further etching is observed after the PS is released. This

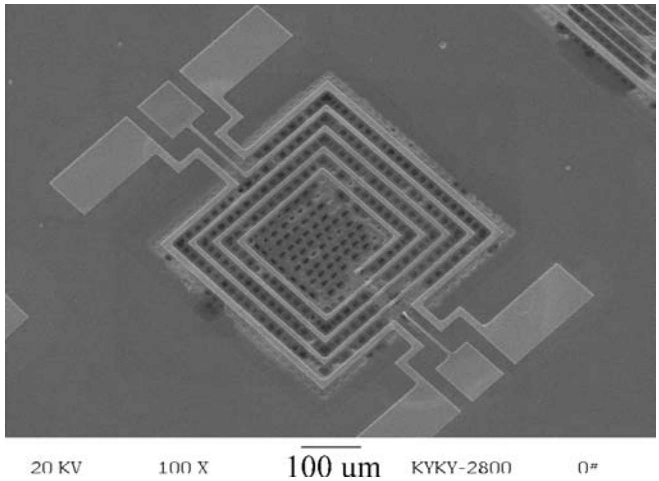


Fig. 4. Suspended spiral MEMS inductor

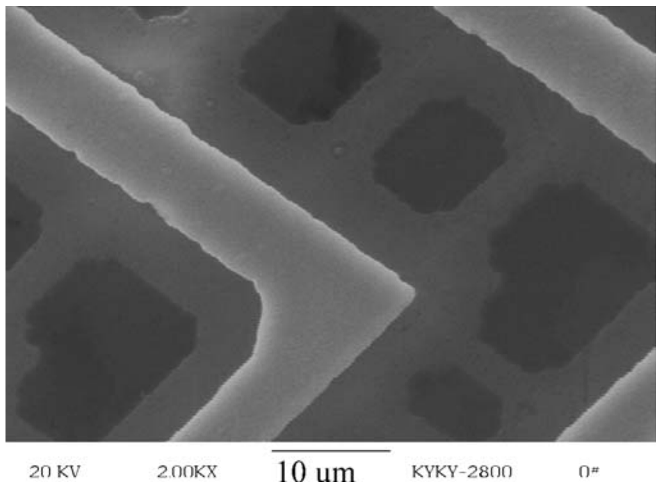


Fig. 5. Detail of the suspended inductor

shows that suspended structures stand well on a SiO_2 membrane.

Fabrication of the PS plays an important role in the process due to which the PS will affect the quality of the support membrane. If the size of the holes is too big, the membrane on PS will not be smooth enough to serve as support film and performance of the final devices will be affected. Normally, high concentration of HF is recommended to fabricate compact PS. But this kind of HF solution will etch the masking layer of Si_3N_4. The result of the inductor structure proved that the PS fabricated under the conditions used in our experiment (30% HF solution, current density is $J = 40$ mA cm^{-2}) could serve well as sacrificial layer in MEMS devices.

After the formation of PS, the Si_3N_4 layer must be removed before the deposition of support film. Normally, Si_3N_4 layer is removed by boiling in pure H_3PO_4. But H_3PO_4 can also etch silicon with a speed of 0.3 nm/min at 180 °C [6], and the large inner surface of PS makes etching by H_3PO_4 at this temperature quite easy. During our experiment, after seething H_3PO_4 for 15 min, the PS is destroyed completely. An alternative method to remove

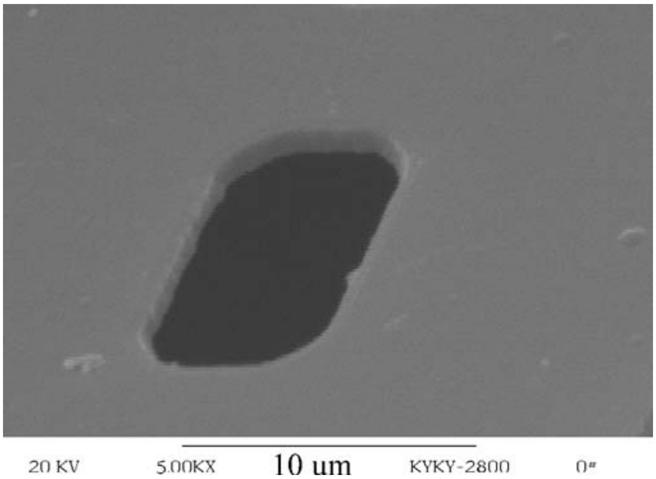


Fig. 6. SEM picture of the membrane and etching hole in detail

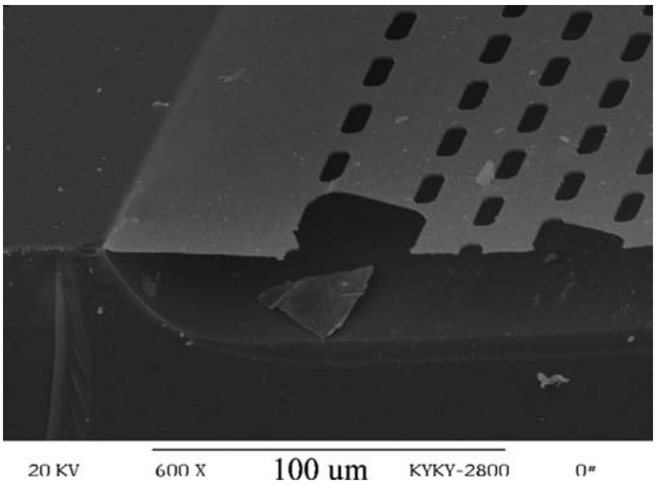


Fig. 7. Section view of the suspended structure

the Si_3N_4 layer without damaging PS, therefore, is to immerse the wafer in a low-concentration HF solution for quite a while. In our experiment, the Si_3N_4 on the sample is removed completely after immersion in the 10% HF solution for 2 hours, and the PS remained intact.

To support the whole device, the membrane must be rigid enough. The SiO_2 film with a thickness of up to 1 μm can serves this purpose well. Figure 6 shows the features of the membrane and the etching hole.

SiO_2 film as large as 2×2 mm^2 is successfully achieved. The maximum lateral distance between the etching holes is 540 μm, and the etching hole size is 4×8 μm^2. An air gap with the thickness of 30 μm can minimize the substrate losses beneath the RF-MEMS devices. Figure 7 shows the membrane and the air gap.

It can be seen that the membrane on PS is smooth. The etching of TMAH will not affect the performance of the membrane of SiO_2 or Si_3N_4, because the etch rate of SiO_2 and Si_3N_4 is significantly lower than that for silicon [10]. Careful observation shows that all the PS underneath the membrane is totally removed.

As anodization and TMAH solution both contain no alkali metal ions, they are harmless to CMOS circuits. All of these advantages make this process one that is low in cost and harmless to the IC circuit.

6 Conclusion

A porous silicon (PS) surface micromachining technology for suspended RF-MEMS device fabrication is discussed. PS formed in the conditions of HF (40%):C_2H_5OH = 3:1 (volume ratio) at a current density $J = 40$ mA cm^{-2} is suitable for MEMS devices. Using TMAH solution with Si powder and $(NH_4)_2S_2O_8$ as etchant, the process can be harmless to the IC circuits. A suspended spiral MEMS inductor structure has been designed and fabricated. The obtained result shows the reliability of this technology. Therefore, it is a possible fabrication process for suspended RF-MEMS.

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