3D Silicon Micromachined RF Resonators

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Abstract — **Passive components with high quality factor are required for many applications, e.g., filters. In the field of micromachining, this is commonly achieved by using multiple-wafer structures. An alternative technique is presented here together with design and measurement data, which is based on MEMS technology and yields single-wafer resonators thus reducing costs. Cavity resonators with the Si being partly removed show quality factors Q beyond 360.**

I. Introduction

Common on-wafer passive components such as inductors or the various line systems usually reach quality factors in the order of 5...50. For narrowband filter applications these Q factor values are not sufficient in most cases. Hence, there is a demand for passive components with higher Q values [1-5]. Furthermore, it would advantageous to monolithically integrate these elements applying an inexpensive wafer process as used for the other elements in the circuit and on the wafer.

This paper shows basic steps how to achieve high Q factors in the framework of a common Si process. First results for different types of resonators are discussed and compared to each other.

II. Fabrication Process

The fabrication process presented here involves the following technological challenges: the realization of 500 µm deep via-holes and, for air-filled cavity resonators, the removal of silicon by isotropic etching. Fabrication is done on 4 inch high-resistivity silicon (ρ >5000 Ωcm) wafers with a thickness of 500 µm and polished surfaces on both sides. The fabrication process is schematically shown in Fig. 1. After a cleaning step, the wafers are thermally oxidized to an oxide thickness of 1000 nm. Next, the oxide is removed where the via holes have to contact the resonator metalization top layer (using mask level 1).

Then, the metalization layers (20 nm Ti, 2200 nm Au) are defined using a lift-off process and mask level 2. This process yields very smooth surfaces of the gold metalization and very steep edges of the metalization layer. With a backside-to-front-side alignment process the via holes are defined in thick photo resist (using mask level 3).

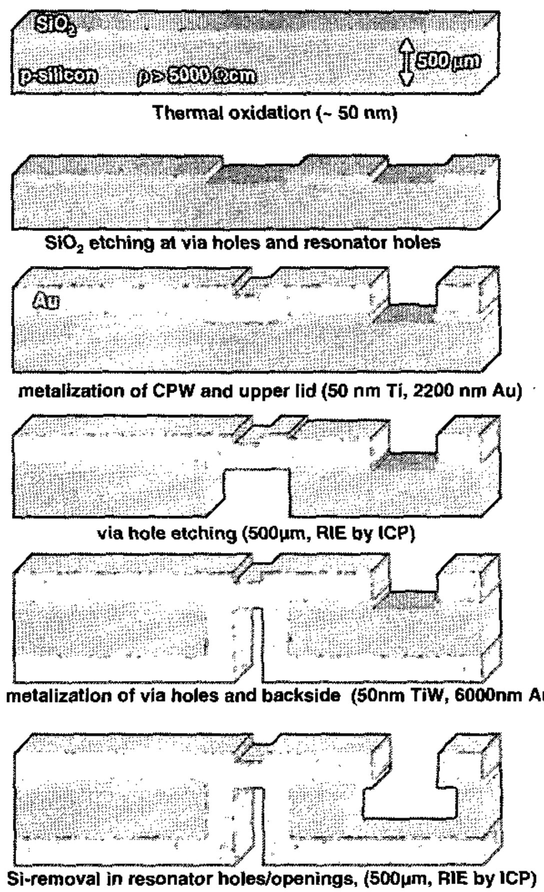

Fig. 1: Schematic description of fabrication process

The via holes are etched using an anisotropic deep silicon etch process as described in [6]. Vertical sidewalls are achieved with this dry-etching process (see Fig. 2). After removal of the residual photo resist in an oxygen plasma the via holes and the backside of the wafer are metalized by sputtering 100 nm TiW as adhesion and interdiffusion layer and 2000 nm Au as metalization layer. Additionally, the metalization layer on the backside is electroplated to 6 µm final thickness in order to improve the metal cover-

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age of the 500 μm deep via holes (Fig. 2). This completes the fabrication process of the substrate-filled type of 3D micromachined resonators.

For the air-filled resonators, on the other hand, the substrate material in the resonator cavity has yet to be removed. For this purpose, an 18 μm thick photo resist is defined on the top side of the wafer and patterned with a photolithographic process to open the windows for the Silicon etch process. Etching is performed in an ICP (inductively coupled plasma) etcher using the ASE (advanced silicon etch) process [6].

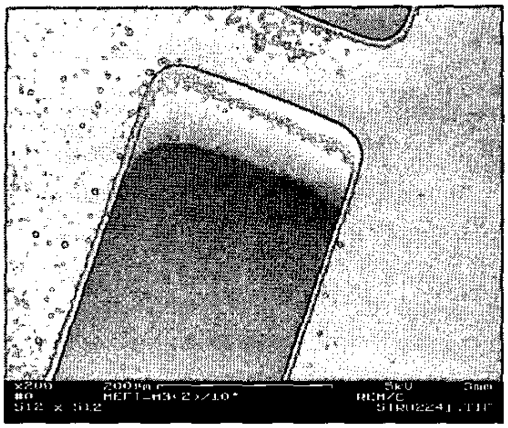
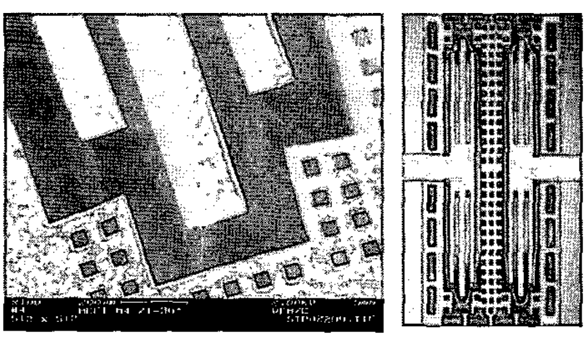


Fig 2.: SEM of metalized, 500 μm deep via hole chain, which forms the sidewall of the 3D resonators (backside of wafer).



(a) (b)

Fig. 3.: SEM (a) and photo (b) of the 500 μm cavity resonator with etched silicon substrate (top side of wafer).

First, an anisotropic process is used to etch down to a depth of 400 μm. Subsequently, we apply an isotropic process for the final etching down to the bottom of the resonator. The isotropic etch process leads to a lateral undercut *of the resonator patterns (up to 100 μm per edge).* Thus, as much silicon as possible is removed from the cavity. Figs. 3 (a) and (b) show an SEM picture of the 500 μm deep air-filled cavity resonator together with a photo. Using these fabrication process monolithic 3D micromachined cavity resonators in silicon can be realized *using a single-wafer process.*

III. Design and Measurements

Several types of resonators were realized, which can be distinguished by the type of excitation. Examples of the patch resonators are depicted in Fig. 4. The type in Fig. 4 (b) *is similar* to the structure presented by Cassivi et. al. [7].

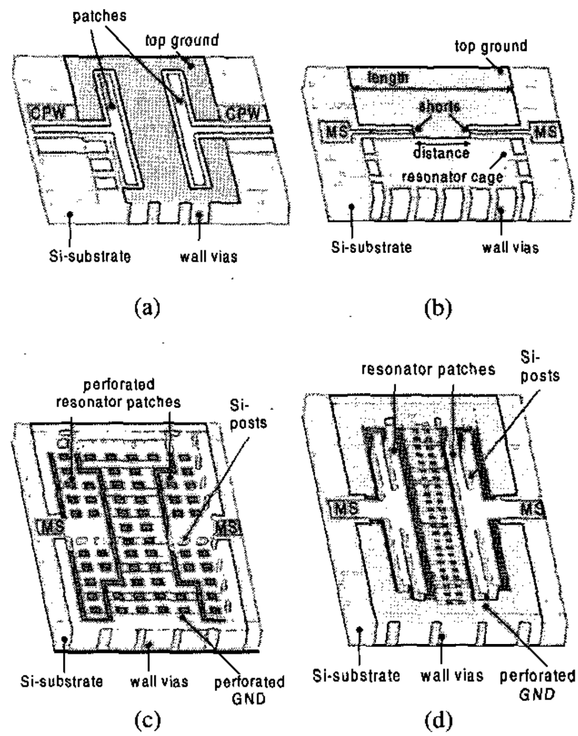


Fig. 4: Cavity resonators with Si-filled interior (a,b) and with Si removed by etching (c,d)

For design, the 3D Finite-Difference simulation method *is employed. The goal is to achieve a high-Q resonator for* application as a band-pass filter with a center frequency in the 20 GHz range and narrow bandwidth. In a first step, the patch resonator of Fig. 4(a) was realized. The version with Si-filled patch cavity showed relatively high losses. The measured unloaded quality factor of this element was about 80...90 [8]. Ohmic and dielectric losses as well as *surface conductivity deteriorated the electrical behavior.*

To improve the quality factor we decided to remove the Si in the cavity by etching. This increases the quality factor in a twofold way: First, for a given resonant frequency, the cavity increases in size due to the reduced effective permittivity, which in turn lowers ohmic loss. Second, dielectric and conductive losses in the Si substrate are avoided.

This was verified by both simulation and measurement results for the structures in Fig. 4(c) and (d), where unloaded quality factors Q > 130 are reached. Measurements are performed in a microstrip environment and the Q-factor value refers to the entire system of prober pad, microstrip line, and resonator. Deembedding of the microstrip line sections and extracting Q from the resulting data is critical since unavoidable uncertainties in microstrip and prober-pad loss may lead to significant overestimation of Q. This becomes critical the higher the unloaded Q factors are.

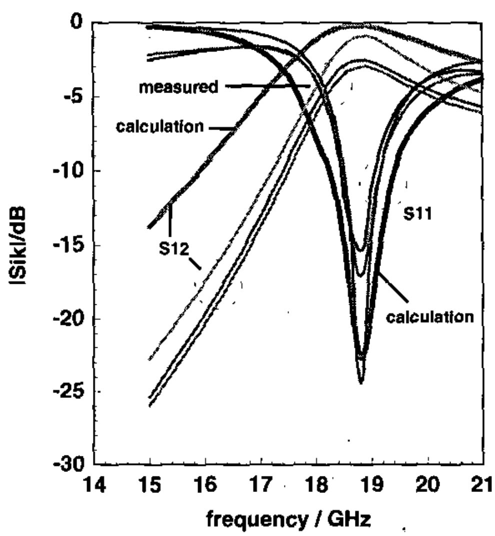


Fig. 5 Calculated and measured S parameters of cavity resonators with Si removed form the interior.

In Fig. 5, simulated and measured S parameters for some resonators of the type in Fig. 4(d) are plotted. The calculated quality factors of these structures reach about 400 if one assumes the Si to be almost entirely removed in the cavity. Accordingly, simulation results considering ohmic and dielectric losses show S_{12} values of close to 0 dB (-0.22 dB, see Fig. 5). Measurements of the fabricated resonators, on the other hand, yield transmission coefficients from –0.9 dB to –3.0 dB. This means that the losses are still higher than expected, thus reducing Q and affecting the bandwidth of the (unloaded) Z parameters plotted in Fig. 6. Beside surface effects in the Si substrate this is due to the fact that the Si was removed to a smaller degree than assumed for simulation.

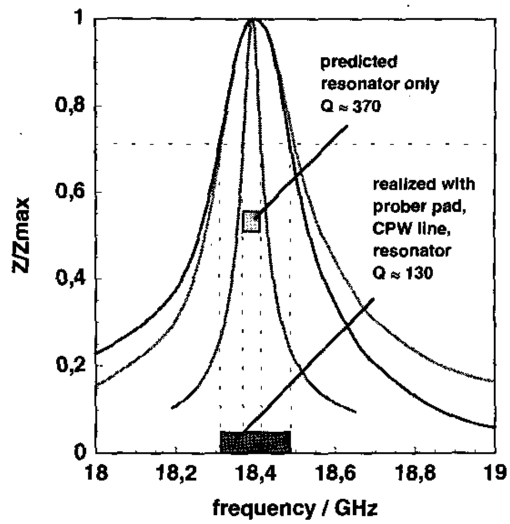


Fig. 6 Bandwidth and quality factor Q of the predicted and measured resonators with Si removed.

To achieve a band-pass filter function with these types of resonators additional transformations, e.g. by transmission lines, are necessary (see Fig. 7). The characteristic impedance of the transmission lines in Fig. 7 is relatively large and corresponds to a strip width of 16 μm. The open-ended stubs help to suppress transmission in the frequency range beyond center frequency. Measurements show that the transformation resulted in a bandpass filter function as designed, but with a low transmission due to losses in the transformation lines.

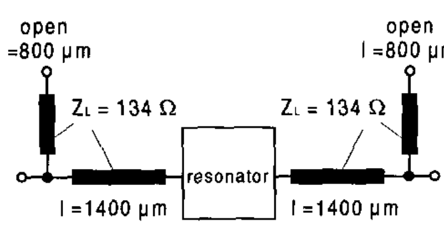


Fig. 7 Line transformation applied to achieve band pass behavior.

Finally, the resonator type in Fig. 4(b) was fabricated with the Si removed (Fig. 8). The size of this resonator is approximately 10 mm x 10 mm. Bandwidth and insertion loss of this resonator are related to the length L of the shorted microstrip stubs. Four different lengths were processed.

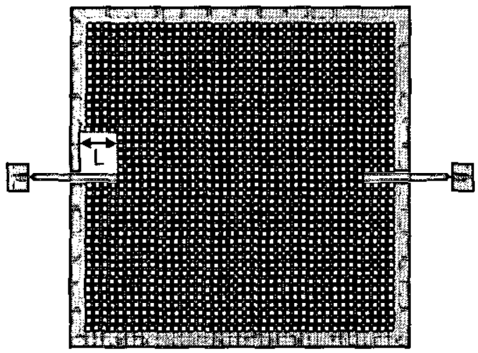


Fig. 8 Resonator with Si removed from the interior and feeding by short stubs (see also Fig. 4(b)).

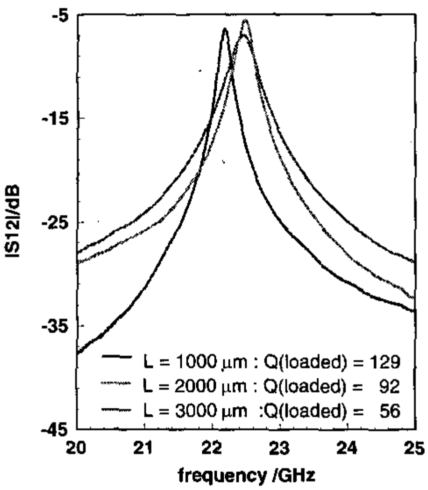


Fig. 9 Measured S parameters for the resonator with shorted microstrip lines according to Fig. 8.

In Fig. 9, transmission S_{12} is plotted (result for length L = 4000 μm not shown; Q(loaded) = 22 in this case). Clearly, bandwidth and quality factor depend on the length of the shorted microstrip stubs. A loaded quality factor of about 129 is reached for the best resonator. Unexpectedly, one finds an almost constant value of -6...-8 dB for insertion loss. Here, coupling should be better for the longer lines on top of the resonator as it is for the entirely closed top ground metalization. However, due to the perforation of the top ground layer, current flow is different from that in resonators with entirely filled metalization (see Fig. 4b). This may be one reason that the differences in S_{12} are only minor.

From the measurements the unloaded quality factors were calculated (Tab. 1). Both quality factors (loaded and unloaded) refer to the complete structure including prober pads and connecting lines.

length L of line	quality factor
1000 μm	366
2000 μm	197
3000 μm	110

Table 1 : Unloaded quality factors of resonator in Fig. 8.

IV. Conclusions

Silicon micromachined 3D resonators for K-band are realized using a single-wafer fabrication process derived from MEMS technology. High-resistivity Si substrates are used. Several types of resonators are investigated. Cavity resonators with the Si being partly removed by etching show quality factors Q beyond 360. Generally, however, the measured values fall short off the predicted ones. This indicates that Si-related losses, presumably particularly surface effects, degrade performance and have to be reduced further.

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