THIN-FILM PIEZOELECTRIC-ON-SUBSTRATE RESONATORS WITH Q ENHANCEMENT AND TCF REDUCTION

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ABSTRACT

In this paper we report on lateral mode thin-film piezoelectric-on-substrate (TPoS) resonators with techniques to enhance the quality factor (Q) and reduce the temperature coefficient of frequency (TCF). Such techniques utilize a highly or degenerately doped Si substrate layer as the ground electrode, and reduce the thickness and volume ratio between the AlN piezoelectric layer and the Si substrate. By patterning the AlN and eliminating the bottom metal electrode, a record quality factor of over 30,000 is observed in air at 27MHz (>66,000 in vacuum). The highly-doped Si brings the resonator average TCF to around –12ppm/°C.

INTRODUCTION

The thin-film piezoelectric-on-substrate platform has been investigated for both high-Q resonators and low-loss filters [1, 2]. Such a platform in essence consists of a thin transduction layer of piezoelectric material such as AlN or ZnO on top of a substrate layer of low mechanical loss such as silicon or nanocrystalline diamond, as illustrated in Fig. 1. Both lateral and thickness mode of vibration can be excited for such a structure. This combination takes advantage of the high electromechanical coupling of the piezoelectric material and the low damping coefficient of the substrate layer. Thus TPoS resonators are expected to have higher quality factor than piezoelectric-only resonators and lower insertion loss than their capacitively transduced counterparts such as Si-only resonators. The temperature coefficient of frequency (TCF) of such a resonator is jointly determined by all the layers in the stack and as such can be engineered by their composition and ratio.

In this work, we demonstrate designs to optimize the quality factor of lateral mode AlN-on-Si resonators by reducing losses from various sources. The resonance frequency of resonators working at this mode is mainly determined by the lateral dimension and is usually in the range of a few megahertz to a few gigahertz. The dissipation factors of such a resonator have been discussed, and methods to reduce such losses are proposed in our design. The TCF of the resonator is reduced by a high doping level in the substrate Si layer and by a large substrate-to-piezoelectric layer thickness ratio. Multiple resonators are fabricated and compared. In one of our designs, quality factor in excess of 30,000 is achieved in air at 27MHz (>66,000 in vacuum) for a resonator operating at the fundamental width-extensional mode. Such a resonator shows a small TCF value of about –12ppm/°C, more than 50% reduction compared to resonators with lightly doped Si substrate.

RESONATOR DESIGN

Resonators reported in this work are based on a thin layer of AlN (<1µm) on the Si device layer of an SOI wafer. Such materials are chosen based on the large piezoelectric coupling coefficient of AlN, small mechanical damping factor of Si, and on their established fabrication techniques and CMOS compatibility. Dissipations in a TPoS resonator mainly come from the mechanical damping of each layer, the interfacial loss due to mismatch between the different layers, such as between the AlN and the electrode, between the metal layer and Si, and the electrical resistance of the electrodes.

Intrinsically, single-crystal Si has a smaller mechanical damping coefficient compared to AlN and common metals used for electrodes. A large ratio between Si and other layers is thus preferred to reduce the mechanical loss and achieve a high quality factor. To further minimize the acoustic loss, AlN is etched away in areas that the top metal electrode is removed. The Si layer is highly doped to a resistivity level of less than 0.001Ω·cm and is directly used as the ground electrode, eliminating the need for an extra metal layer. The elimination of the ground metal also reduces the interface mismatch between the different layers and further enhances the quality factor.
The TCF of a composite resonator is roughly determined by the temperature coefficient of elastic modulus (TCE) of each layer. Assuming that the layers have the same area and the contribution of thermal expansion to TCF is negligible, it can be shown that:

\[
TCF = \left( 1 + \frac{(1 + TCE_1)E_1t_1 + (1 + TCE_2)E_2t_2 + \cdots}{E_1t_1 + E_2t_2 + \cdots} - 1 \right)
\]

where \(E\) and \(t\) are the elastic modulus and thickness of each layer, respectively. Both AlN and Si have negative TCE values. A conventional way to achieve temperature compensation is to introduce another layer of opposite TCE value, such as SiO\(_2\). The growth or deposition of a high quality thick SiO\(_2\) is however not always easy when the overall resonator thickness is more than a few microns. Thus a more practical approach is to reduce the materials’ TCE values. It is seen from Eq. 1 that if the thickness of Si is an order of magnitude or more larger than that of the other layers, changing the TCE of Si will have the most pronounced effect on the overall TCF. A high level of doping reduces the temperature coefficient of elastic modulus in Si [3, 4], and will in turn reduce the TCF of the resonator. Thus, increasing the ratio of highly-doped Si in the stack not only helps to increase the quality factor, but will also reduce the temperature sensitivity of frequency.

**FABRICATION**

A comparative study is carried out to demonstrate the design principle. Two SOI wafers, with the device layer being 20\(\mu\)m and 60\(\mu\)m, respectively, are used as the starting substrate. The 20\(\mu\)m SOI wafer’s device layer has a resistivity of 0.001-0.004 \(\Omega\cdot\)cm and uses a thin Mo layer as the ground electrode. In comparison, the 60\(\mu\)m one has its device layer doped to below 0.001 \(\Omega\cdot\)cm and used directly as the ground electrode. The fabrication process is similar to that reported in [1] with some revisions, as illustrated in Fig. 2. A stack of Mo/AlN/Mo is deposited on the 20\(\mu\)m SOI wafer, and AlN/Mo is deposited on the 60\(\mu\)m SOI wafer without Mo between AlN and Si. Both batches have the same AlN and top Mo thickness. After patterning the top electrodes, AlN is patterned to reach the ground electrode (Si or metal) and remove AlN between top electrodes. 

**Figure 2. Fabrication process flow of an AlN-on-Si resonator, with AlN patterned between top electrodes.**

After etching trench to define resonator dimensions, AlN is etched between electrode fingers. Figure 3. The SEM image of a TPoS resonator with five interdigitated fingers working at the fundamental width-extensional mode.

Resonators with various electrode configurations are fabricated. The SEM image of a released resonator is shown in Fig. 3. The resonator has five interdigitated top electrode fingers separated by
areas from which AlN is etched. For each wafer, resonators with the same silicon dimensions but variable electrode finger width (from 15.2µm to 27.2µm) are fabricated to investigate the influence from AlN and top electrode dimensions.

MEASUREMENT AND ANALYSIS

The design with five interdigitated top electrodes, as shown in Fig. 3, is studied in this work. Such a resonator works at the fundamental lateral width-extensional mode, and the resonance frequency is determined by the resonator width W.

Fig. 4 shows the frequency responses of a resonator

![Image of frequency response plots]

(a) $|S_{21}|$ plot of a resonator with 20µm Si layer, measured with 100kHz span.

(b) $|S_{21}|$ plot of a resonator with 60 µm Si layer, measured with 20 kHz span.

(c) $|S_{21}|$ plot of a resonator with 60 µm Si layer, measured in the range of 20-40 MHz. The lower Q displayed is due to reduced resolution in measurement.

Figure 4. $|S_{21}|$ plots of resonators with the same AlN thickness and finger width (15.2µm), measured in air with 50Ω termination and on-wafer probing.

with 20µm Si and one with 60µm Si. Both resonators have the same resonator body lateral dimensions and top electrode width of 15.2µm, and work at the fundamental resonance at around 27MHz. The one with 20µm Si has a loaded quality factor of 14,844 and an insertion loss of 21.7dB in air (Fig. 4(a)). The Q of the resonator doubles on the 60µm substrate, as shown in Fig.4(b). Since Si has a lower acoustic velocity than AlN, the resonator with 60µm Si shows slightly lower resonance frequency than the 20µm one. This design shows very clean frequency response and there are no prominent spurious modes in the wider span of 20-40MHz (Fig. 4(c)). Multiple such resonators are measured, and the Q variation is measured to be small (between 29,000 and 31,500). However, the resonators with 60µm of Si have higher insertion loss due to reduced effective electromechanical coupling. Resonators on the same 60µm Si substrate but with wider electrode finger width of 22.2µm and 27.2µm are measured as well. With the increase of electrode width, both lower Q and lower IL are observed, as shown in Fig. 5. Such a trend indicates better electromechanical coupling but larger damping coming from the increased transduction area and AlN volume. With the increase of AlN-to-Si ratio, the resonance frequency also increases slightly.

Figure 5. $|S_{21}|$ plots of resonators with 60µm Si and (a) 22.2µm-wide and (b) 27.2µm-wide electrode fingers, measured in air.
Temperature measurement

The TCF of a resonator with 60µm Si is measured. The measurement is performed in a vacuum chamber, in which the resonator is wire-bonded to an evaluation board. The resonator has Q of 30,719 and IL of 27.7dB in air at room temperature, corresponding to an equivalent input-to-output series resistance (motional resistance transformed to the electrical domain) of ~2300 Ω. The Q increases to 66,592 and the IL drops to 19.9dB under vacuum (Fig. 6). Such values correspond to a series resistance of less than 900 Ω and an unloaded Q of ~74,000. The evaluation board also introduces extra feedthrough between the input and the output, resulting in the parallel resonance valley in the frequency spectrum. In the TCF measurement, the chamber is first heated up to 100°C then cooled down to -60°C. A linear fitting of the frequency-temperature plot gives the TCF value of about –12.0 ppm/°C (Fig. 7). This value is significantly lower than that of resonators fabricated on thinner Si with lower doping level. For comparison, the TCF is measured on resonators with different electrode layouts and working at the fundamental mode of lateral vibration, but having AlN on 20µm of 0.01–0.02 Ω⋅cm Si. Such resonators typically have TCF values of close to –30ppm/°C, such as the –28.5ppm/°C one shown in Fig. 7, demonstrating significant TCF reduction in our approach. However, the frequency-temperature relationship of the 60µm device shows some nonlinearity. The relative residuals of the measurement data compared to the linear fitting vary in the range of between –174ppm and +105ppm, or a total of 280ppm over the temperature range of –60°C to 100°C.

CONCLUSIONS

We propose and demonstrate techniques to build resonators of high quality factor and reduced temperature coefficient of frequency. A record high Q of >30,000 is achieved in air, while the TCF is as small as –12ppm/°C. Such characteristics are achieved on the AlN-on-Si platform, in which the Q is enhanced by the large ratio between Si and AlN and the elimination of a metal electrode layer, while the doping of the Si layer reduces the TCF significantly by more than 50%.

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REFERENCES


