

DAMPING MECHANISMS IN LIGHT AND HEAVY-DOPED DUAL-RING AND DOUBLE-ENDED TUNING FORK RESONATORS (DETF)

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ABSTRACT

We present models and measurements of lightly-doped and heavily-doped dual ring/dual-bar and double-ended tuning fork (DETF) resonators. Both models and measurements indicate that the Q of these resonators is only slightly impacted by the doping level, despite being dominated by thermoelastic dissipation (TED), which has a strong dependence on doping-dependent material properties. We compare experimental measurements of Q over a range of temperatures with models for TED, anchor damping and squeeze film damping. We found that the Q of light and heavily-doped resonators can be accounted for by a combination of TED and anchor or squeeze film damping. These results indicate that it is possible to fully account for the damping mechanisms in MEMS resonators if temperature-dependent measurements of Q are compared with models of the important mechanisms including the temperature-dependent materials properties.

KEYWORDS

Dual-ring, double-ended tuning fork (DETF), quality factor, lightly-doped, heavily-doped, damping, energy dissipation, thermoelastic dissipation.

INTRODUCTION

Microelectromechanical (MEMS) resonators are key components in timing and sensing applications ranging from electronics to communication technologies. Currently, MEMS resonators are highly reliable, with low-power consumption and low manufacturing cost [1,2]. Resonator properties are determined by geometry, materials, and ambient conditions. It has been seen that heavily doped silicon reduces frequency-temperature dependence [3,4,5]. Nevertheless, with the discovery of the impact of doping on the temperature dependence of frequency in silicon MEMS resonators [3,4,5], there is a corresponding need to study the impact of doping on the quality factor (Q) of resonators. We have heard concerns from some colleagues that heavily doping might significantly degrade Q in silicon MEMS due to the impact of the added free carriers on dissipation mechanisms, such as thermoelastic dissipation (TED) or ohmic loss mechanisms.

The dynamic response of a resonator may be characterized by the resonant frequency (f) and Q , both of which are dependent on the design of the resonator and on the materials properties. When heavy doping is introduced to provide temperature compensation, the properties of the materials are impacted – including both the elastic constants and other parameters such as heat capacity, thermal

conductivity, electrical conductivity [4,5]. Since, these materials properties can be strongly affected by the addition of doping, we naturally expect that f and Q will be changed as well. Further, since the temperature dependence of f is strongly impacted, it is natural to expect that the temperature dependence of Q may also be strongly impacted. In this paper, we present experimental observations and models of the Q of the dual ring extensional-mode resonators and double-ended tuning fork resonators, and compare the temperature dependence of the experimental results with our predictions to identify the damping mechanisms present in devices at all doping levels. By using complete numerical models for TED, and comparing these results with the experimental measurements, over a range of temperatures, it is possible to identify the presence and strength of other dissipation mechanisms, and to provide a complete model for all dissipation mechanisms present in the resonator [6].

FABRICATION AND DEVICE DESIGN

To better understand how dopants affect the Q , our group has designed two types of resonators, a dual-ring/dual-bar and a double-ended tuning fork (DETF) with four different doping levels. The schematic of a dual-ring/dual-bar and the DETF can be seen in Fig. 1 and Fig. 2, respectively. Both devices were built using the wafer encapsulation process (epi-seal [7]), which was proposed by researchers at the Robert Bosch Research and Technology Center in Palo Alto and then demonstrated in a close collaboration with Stanford University. The dual breathe-mode ring resonator and the DETF were designed to have an operating frequency around 19.7MHz and 1.3MHz respectively. A silicon-on-insulator (SOI) with a (100) 40 μ m device layer and a 2 μ m thick buried oxide layer were used. The doping levels of the device layer were Phosphorus (NP) 1.78m Ω -cm, Arsenic (NA) 3.1m Ω -cm, Antimony (NS) 17.1m Ω -cm, and Boron (PB) 15.8m Ω -cm [4].

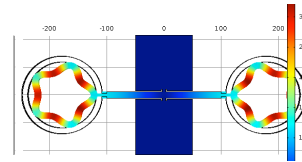


Figure 1: Top view of a breathe-mode ring resonator showing the shape of the mode and in particular the distortions in the ring extension from crystal anisotropy.

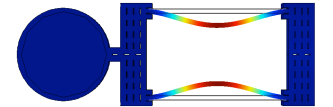


Figure 2: Top view of a flexural mode DETF resonator showing the shape of the mode.

METHOD

For this study, frequency-sweep measurements on over 40 different resonators were performed. To operate these devices, a 20V DC voltage was supplied to the resonant structure for both the DETF and dual-ring resonator. The Q was determined with an open-loop sweep using a Agilent 4395A network analyzer, with the resonators placed in a temperature-controlled oven, and operated from -20 to +80°C for dual-ring and from -40 to +80°C for DETF.

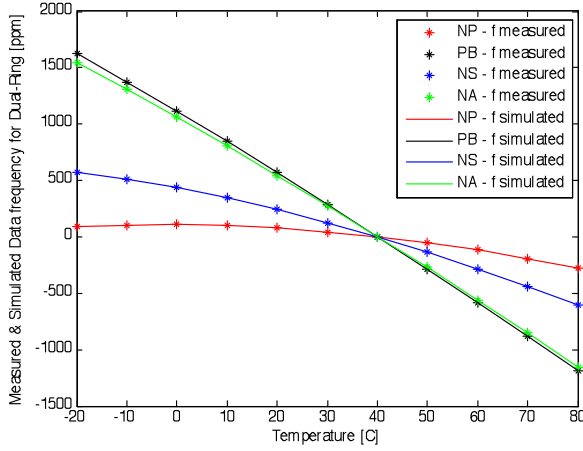


Figure 3: Measured (markers) vs. simulated (lines) for frequency-temperature curves for the dual-ring resonator.

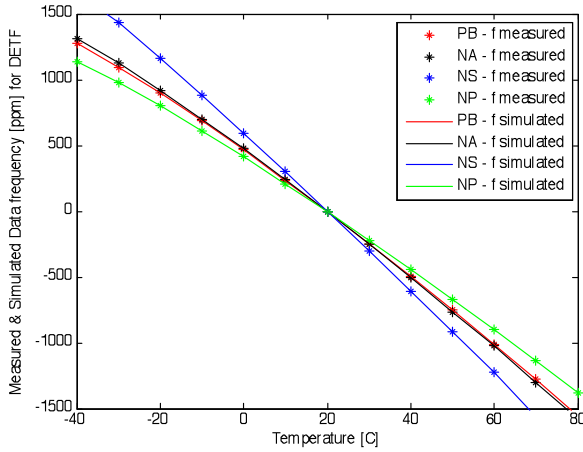


Figure 4: Measured (markers) vs. simulated (lines) for frequency-temperature curves for the DETF.

In all cases, the resonators exhibit a temperature dependence on the Q, and this temperature dependence is very helpful in determining the damping mechanisms present in these devices. We have complete quantitative models for the Q(T) from TED, and we expect that anchor damping should be independent of temperature and that squeeze film damping should have a specific temperature dependence[5]. Equation (1) shows that the total Q of a resonator can be represented as the reciprocal sum of independent energy

dissipation mechanisms.

$$\frac{1}{Q_{total}} = \frac{1}{Q_{TED}} + \frac{1}{Q_{AKE}} + \frac{1}{Q_{Anchor}} + \frac{1}{Q_{Air}} \quad (1)$$

The modeling of TED in both designs is performed in 3D using COMSOL FEM software [8]. In order to properly model the resonators, the model's coordinate system was aligned with the orientation of the resonators, and the appropriate temperature-dependent elastic constants were used [4]. The dimensions of the models for the dual-ring were R_{in} : 118 μ m, R_{out} : 140 μ m, t : 40 μ m, and for the double-ended tuning fork 200 x 6 x 40 μ m. We also included the temperature dependence of other materials properties, including the thermal conductivity [11], specific heat [9], and thermal expansion coefficient [10]. All of these parameters were incorporated from these references without tuning or fitting, and the dissipation associated with TED was extracted from simulations as a function of temperature and compared with experimental measurements [6,12].

RESULTS AND DISCUSSION

Surprisingly, our experimental results indicate that the dual ring and DETF resonators exhibit only a weak relationship between the Q-values and the doping type and concentration. Results for dual-ring resonators are shown in Fig. 5 and for tuning forks in Fig. 7. Our results from both measures and simulations show that the total variation of Q as a function of temperatures in our devices is less than 10%, even as the doping density varies by more than 10x.

For a detailed analysis of the dual-ring resonator, the measured values of Q displayed only a modest variation with temperature, which would normally indicate that the resonators are dominated by anchor damping, or the more fundamental Akheizer effect. For these devices, the f^*Q products are too low for us to expect Akheizer damping [8]. If these devices are dominated by anchor damping, it would also help explain the weak dependence of damping on the doping, as anchor damping does not depend on thermal conductivity, or heat capacity when temperature changes [9,10,11].

To fully understand the dissipation for these dual-ring resonators, we also designed computational models of the Q expected from TED, using the complete anisotropic representation of the silicon crystal mechanical properties for the doping densities of these devices, as well as the temperature dependence of these properties. TED can play an important role in the overall energy dissipation in these extensional-mode devices because significant strain gradients can arise in the ring as a result of the crystal anisotropy. In the case of the dual ring, surprisingly, the TED predictions for these resonators are all within 10% - 20% of each other, even for very different doping densities, as shown in Fig. 5.

We find that the measured Q of these dual-ring resonators is roughly half of the Q predicted from TED

simulations, indicating that TED is important, but not dominant in these devices, and therefore requires participation of at least one other dissipation mechanism.

Given that the experimental observations of Q are roughly temperature-independent, we need to consider an additional dissipation mechanism that is independent of temperature. Since we know that anchor damping should be independent of temperature, we attempted to fit the experiments with our TED simulations and an added constant anchor damping term. Fig. 6 shows the initial experimental measurements, as well as the TED simulation and our estimation for the anchor damping contribution, along with a total model for Q including TED and anchor damping

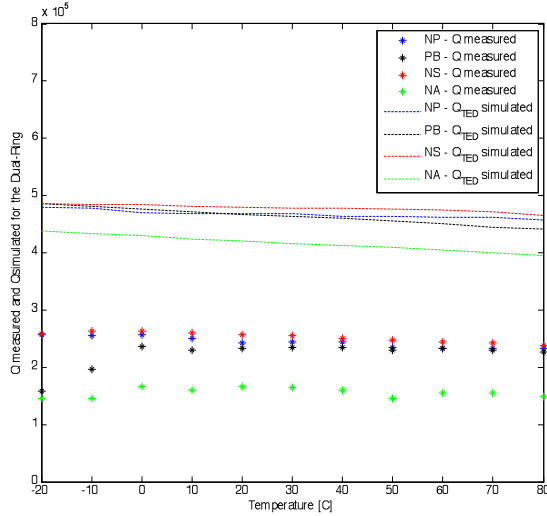


Figure 5: Measurements(markers) and TED simulations (curves) of the Quality Factor for light and heavily-doped dual-ring resonators

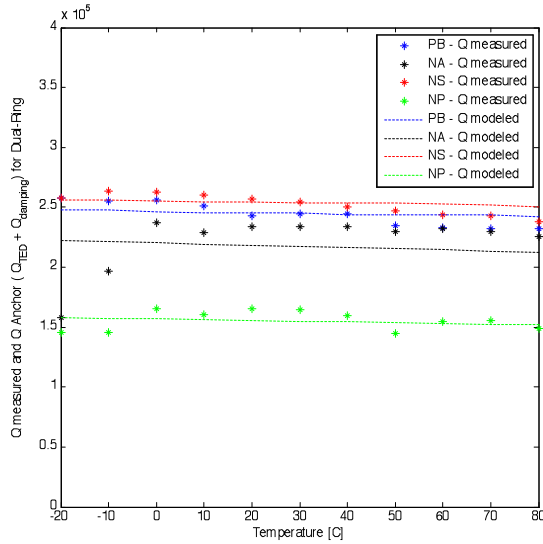


Figure 6: Measured Q (markers) vs. modeled Q (curves), which are a combination of TED and the pressure damping for the dual-ring resonators.

As shown in this figure, this combination of TED and anchor damping can completely account for the observed magnitude and the temperature dependence of the Q for this resonator. Based on these results, we have shown that the Q of these dual ring resonators arises from a combination of TED and anchor damping, and that the doping density has only a modest effect on the overall behavior.

Looking into the details for the DETF devices, we again see that the measurements of Q as a function of temperature are only slightly different for different doping types and levels. These data are shown in Figure 7. In the case of the DETF, we see a much stronger temperature dependence of the Q , so we expect that TED is a strong contribution to the dissipation in these devices.

As was the case for the dual-ring devices, we carried out complete simulations of the TED for these DETFs, incorporating the anisotropic and temperature-dependent materials properties into a 3D model in COMSOL. The resulting estimations for Q from TED over-estimate the experimentally-observed Q , and so we again seek to estimate an additional contribution from an additional damping mechanism.

The discrepancy between the TED model and experiment also seems to have a temperature dependence, and our attempts to model the total dissipation using a constant additional dissipation term, such as would be expected for anchor damping, were not successful. Another possible dissipation mechanism that might be expected to be more important for these lower-frequency resonators is squeeze film damping arising from the residual gas trapped in the encapsulation during the fabrication process. Because the remaining gas is nearly pure H_2 , an ideal gas model for the pressure-temperature relationship with fixed number of atoms is expected [12]. In this case, the expected Q associated with squeeze film damping would have a temperature dependence given by.

$$Q_{air} = C \frac{1}{\sqrt{T}} \quad (2)$$

where C is a fixed constant parameter associated with the pressure and the size of the gaps and other geometric parameters that should be similar for all DETF devices in this study. The C parameter is same across different temperatures. And for doping NA, NS, and NP the C parameter only varies 1% among those three doping, however for the PB doping the C parameter varies 15% as compared to the other three.

After selecting C values for each device, we were able to construct Q models based on the combination of our TED simulations and the added squeeze film damping contribution that are excellent fits to the experimentally-observed Q as a function of temperature.

For both the dual-ring devices and the DETFs, we were able to construct models based on a numerical estimation of TED based entirely on known materials properties and geometries, with only a single added dissipation mechanism in each case: anchor damping for the dual-ring devices and pressure-damping for the DETFs.

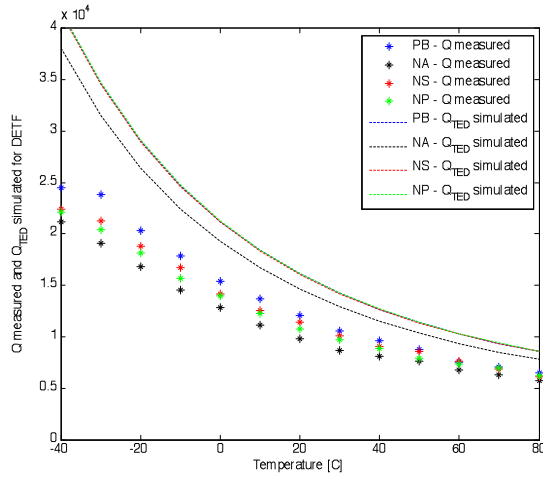


Figure 7: Measured Q (markers) vs. Simulated Q_{TED} (lines) for the double-ended tuning fork (DETF).

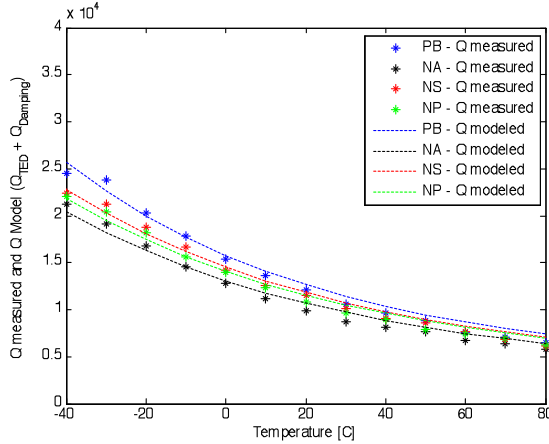


Figure 8: Measured Q (markers) vs. modeled Q (curves), which are a combination of TED and the pressure damping for DETF.

CONCLUSIONS

Our results show that the total Q of dual ring-bar resonators and double-ended tuning fork resonators is only very weakly impacted by the use of heavy doping to levels needed for temperature compensation of frequency. For the dual-ring resonators, the experimentally-observed $Q(T)$ can be fully accounted for with a combination of TED and anchor damping. For the DETF resonators, the experimentally-observed $Q(T)$ can be fully accounted for with a combination of TED and squeeze film damping. In all cases, the entire temperature dependence is fitted by models with only a single adjustable parameter – the amount of the anchor or squeeze film damping.

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