Performance comparison of $Pb(Zr_{0.52}Ti_{0.48})O_3$-only and $Pb(Zr_{0.52}Ti_{0.48})O_3$-on-silicon resonators

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This paper provides a quantitative comparison and explores the design space of lead zirconium titanate (PZT)–only and PZT-on-silicon length-extensional mode resonators for incorporation into radio frequency microelectromechanical system filters and oscillators. We experimentally measured the correlation of motional impedance (R_X) and quality factor (Q) with the resonators' silicon layer thickness (t_{Si}). For identical lateral dimensions and PZT-layer thicknesses (t_{PZT}), the PZT-on-silicon resonator has higher resonant frequency (f_C), higher Q (5100 versus 140), lower R_X (51 Ω versus 205 Ω), and better linearity [third-order input intercept point (IIP_3) of +43.7 dBm versus +23.3 dBm]. In contrast, the PZT-only resonator demonstrated much wider frequency tuning range (5.1% versus 0.2%). © *2008 American Institute of Physics*. [DOI: 10.1063/1.3046717]

Multiband radios that have portable size and low power consumption are highly desirable in today's communication systems. Such radio architecture demands the existence of high performance intermediate frequency tunable filters to discern signals with dynamic waveforms and bandwidths. A length-extensional mode (LEM) resonator is an excellent constituent resonator to form these filter banks because it has a high Q, low R_X, and intermediate frequency of operation that can be defined lithographically.[1]

PZT has been previously shown to have up to 6% frequency tuning capabilities.[2] It also exhibits a large electromechanical coupling coefficient ($k_t^2=35\%$) in thickness-extensional mode.[3] However, PZT-only resonators are well known to have a low quality factor ($Q<300$).[3,4] In order to overcome the low quality factor of PZT-only resonators, we developed a fabrication technology to integrate LEM PZT transduction through transverse piezoelectric constant (e_{31}) with single-crystal silicon (SCS) resonators.

Previous results have shown that LEM vibrations can be excited by sandwiching a piezoelectric transducer, mostly aluminum nitride and zinc oxide, between metal electrodes.[5,6] However, due to the poor crystallinity of the piezoelectric thin films compared to SCS, several research groups have chosen to use the piezoelectric material for actuation and sensing while utilizing silicon as the resonating structure.[7,8] In this effort, PZT transduced resonators were fabricated with and without a 10 μm thick silicon device layer to explore the insertion loss, linearity, and Q trade-offs between the two types of resonators. The frequency independent motional impedances of the fundamental mode of PZT transduced LEM two-port resonators are[9]

$$R_{X\_PZT\text{-}on\text{-}Si} = \frac{\pi}{2} \cdot \frac{\sqrt{E_{eff} \cdot \rho_{eff}}}{Q} \cdot \left(\frac{t_{Si} + t_{PZT}}{E_{PZT}{}^2 \cdot W \cdot d_{31}{}^2} \right), \quad (1)$$

$$R_{X\_PZT\text{-}only} = \frac{\pi}{2} \cdot \frac{\sqrt{E_{PZT} \cdot \rho_{PZT}}}{Q} \cdot \left(\frac{t_{PZT}}{E_{PZT}{}^2 \cdot W \cdot d_{31}{}^2} \right), \quad (2)$$

where ρ_{eff} and E_{eff} are the effective (composite) density and Young's modulus, W is the resonator width, d_{31} is the trans-

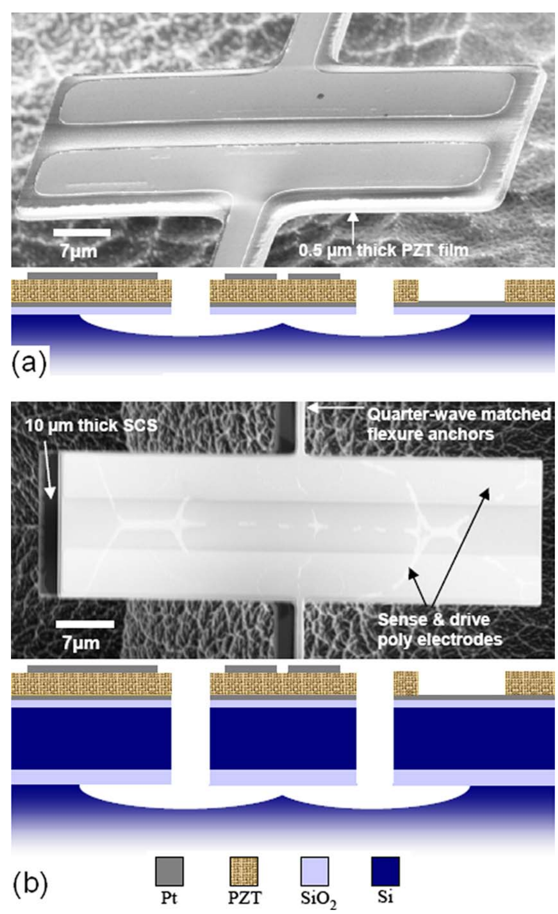

FIG. 1. (Color online) (a) Scanning electron microscopy (SEM) of a released PZT-only resonator. The cross-section diagram shows the resonator stack and illustrates the signal and ground pads. (b) SEM of released PZT-on-silicon resonator.

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TABLE I. Measured performance of PZT-only resonators.

	Res 1 PZT	Res 2 PZT	Res 3 PZT
Dimensions (μm $\times$ μm)	240 $\times$ 40	280 $\times$ 60	260 $\times$ 60
Q	202	91	241
f_C (MHz)	6.88	5.47	5.78
$\Delta f_{3\ \mathrm{dB}}/f$ (%)	0.50	1.10	0.41
R_X (Ω)	4078	8812	3628

verse piezoelectric coefficient, and ρ_{PZT} and E_{PZT} are the density and Young's modulus of the PZT thin film. PZT is an acoustically lossy material resulting in PZT-only resonators having low Q. Integrated PZT transduction with SCS resonators retains the mechanical energy within the high-Q silicon layer. Equation (1) indicates that there will be a net decrease in R_X if the improvement in Q outweighs the increase in t_{Si} for PZT-on-silicon resonators. However, the resonators have to perform extra work in order to overcome the inertia of the silicon. Hence the PZT-only resonators will exhibit higher pole-zero separation than PZT-on-silicon resonators in a one-port configuration.

The design approach for the resonators is strongly based on the previous work of Humad *et al.*[7] and Chandrahalim *et al.*[10] The device fabrication was largely based on the fabrication sequence outlined by Polcawich *et al.*[11] The PZT films were deposited using a chemical solution deposition method modified from Ref. 12 and using a crystallization temperature of 700 °C. An organic photodefinable layer was developed to provide protection of the resonator while allowing undercutting of the handle wafer silicon using a XeF_2 etch.[10] Finally, the PZT resonators were subjected to electric fields of 200 kV/cm for 10 min to align the ferroelectric domains. Figures 1(a) and 1(b) show PZT-only and PZT-on-silicon bar resonators fabricated in this process.

The dc bias is superimposed to the ac signal at both input and output ports using bias-T's for all measurements. Measured transmission responses of the fundamental mode PZT-only and PZT-on-silicon resonators with 0 V dc bias in air at room temperature are tabulated in Tables I and II. The PZT-on-silicon resonators exhibit higher Q and lower motional impedance compared to their PZT-only counterparts. PZT-on-silicon resonators also have higher resonant frequency because the thick silicon device layer that dominates the composite structures causes an increase in the ratio of E_{eff} to ρ_{eff}. These measurement results confirm that integrating PZT transduction with SCS retains the mechanical energy within the high quality silicon device layer. The improvement in Q (35$\times$) outweighs the increase in t_{Si} (10 μm), resulting in a net decrease in R_X.

TABLE II. Measured performance of PZT-on-silicon resonators.

	Res 1 PZT-on-silicon	Res 2 PZT-on-silicon	Res 3 PZT-on-silicon
Dimensions (μm $\times$ μm)	240 $\times$ 40	280 $\times$ 60	260 $\times$ 60
Q	5040	3820	4224
f_C (MHz)	15.94	13.65	14.72
$\Delta f_{3\ \mathrm{dB}}/f$ (%)	0.02	0.062	0.024
R_X (Ω)	167	319	290

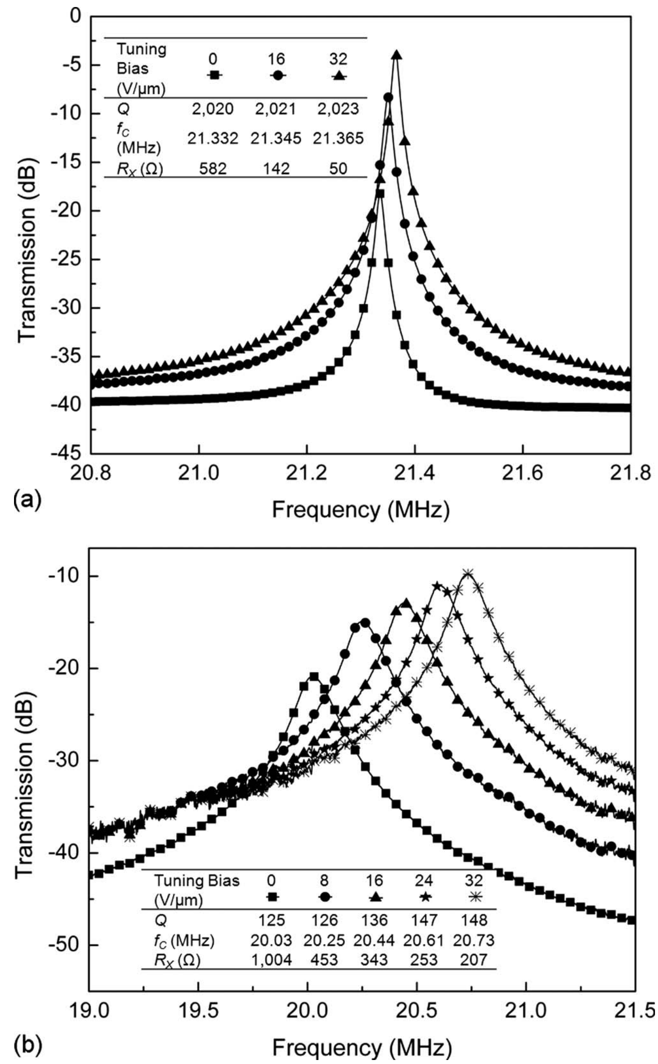

FIG. 2. (a) Measured transmission of a 190×40 μm^2 PZT transduced resonator on 10 μm silicon with different tuning electric fields in air at room temperature. (b) Measured transmission of a 90×20 μm^2 PZT-only resonator with different tuning electric fields in air at room temperature.

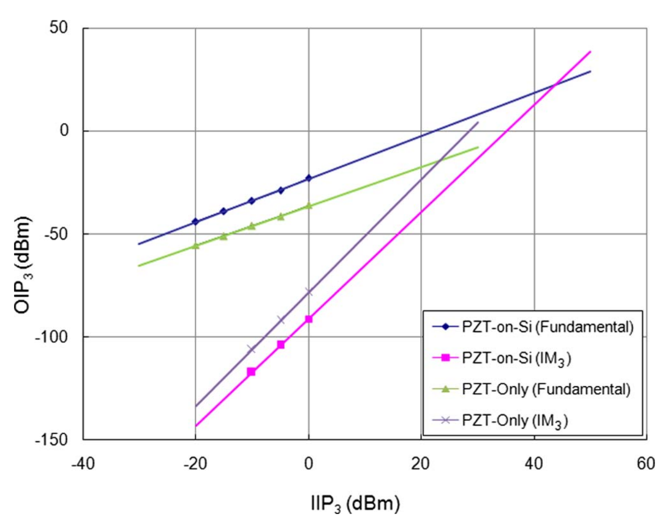

FIG. 3. (Color online) Measured IIP_3 of a 90×20 μm^2 PZT-only and 190×40 μm^2 PZT on 10 μm silicon resonators with 0 V dc bias in air at room temperature.

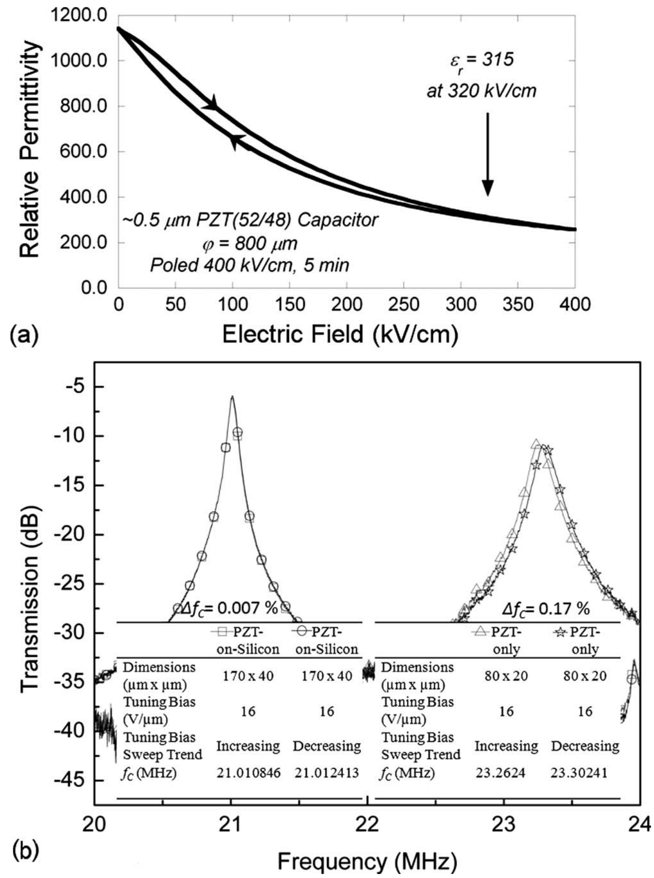

FIG. 4. (a) Measured hysteresis effect in the relative permittivity of a PZT thin film. (b) A PZT-on-silicon resonator shows imperceptible hysteresis, while a PZT-only resonator has Δf_C=0.17%.

PZT has an electric field dependent Young's modulus, permittivity, and electromechanical coupling coefficient ($k_{31}{}^2$).[2] As the dc bias increases, the transduction efficiency is improved. Therefore, by taking advantage of the electric field dependent $k_{31}{}^2$, we can reduce R_X and improve the insertion loss of the resonators. The frequency response around the fundamental mode of a PZT transduced resonator on 10 μm silicon with different tuning electric fields is shown in Fig. 2(a). A 0.2% frequency tuning capability is observed due to the electric field dependent Young's modulus, dielectric permittivity, and piezoelectric coefficient of the PZT thin film. Since the resonant frequency is dominated by the silicon device layer, there is very little resonant frequency tuning, whereas the improvement in electromechanical coupling leads to 11× improvement in motional impedance at 32 V/μm dc bias.

In contrast, the fundamental mode frequency response of a PZT-only resonator with different tuning electric fields is shown in Fig. 2(b). The PZT-only resonators demonstrate 5.1% electric field dependent frequency tuning capability, the highest tuning range reported by any piezoelectrically transduced contour mode resonators to date.

The immunity of the resonators to the third-order intermodulation distortion (IM_3) was characterized similar to the procedure outlined in Ref. 13. Two interferer signals f_1 and f_2 separated Δ_f away from each other are generated by the signal generators to excite the in-band IM_3 at $f_C=2f_1-f_2$. The PZT-only resonator exhibits the IIP_3 value of +23.3 dBm at Δ_f=100 kHz. By integrating PZT transduction with SCS, the nonlinear behavior of PZT can be strongly attenuated because the vibrating structure is dominated by silicon that has a superior acoustic linearity. This gives an improvement in IIP_3 to a value of +43.7 dBm, as shown in Fig. 3.

The hysteresis of PZT causes undesirable resonance frequency shifts in the resonator. Figure 4(a) shows the dynamically varying relative permittivity (ε_r) of the PZT film caused by the influence of increasing and decreasing electric fields. This hysteresis effect is translated into a minor frequency shift, as shown in Fig. 4(b). However, it can be simply compensated with the dc tuning.

In conclusion, the PZT-only resonators have shown the largest frequency tuning range for piezoelectrically transduced contour mode resonators reported to date. The composite resonator design approach is able to trade the lowered $k_{31}{}^2$ of the resonators for the increased intrinsic Q of the silicon resonator for a net improvement in device performance. By varying the silicon thickness and dc bias, we can define the desired Q and frequency tuning range of the resonators, trade-off between steep-walled narrow-bandwidth filters and low-Q wide-bandwidth filters, linearity, and center frequency agility.

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