

Chapter 2

Lead Zirconate Titanate (PZT) for M/NEMS

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2.1 PZT Thin Films

This section concentrates on the leading ferroelectric material used in thin-film piezoelectric MEMS: lead zirconate titanate ($\text{PbZr}_x\text{Ti}_{1-x}\text{O}_3$) or PZT. PZT-based MEMS technology has been explored extensively for a variety of actuator applications [1] but has received less attention for RF MEMS resonator and filter applications. Despite the long and successful history of bulk PZT resonators [2], the process complexity/compatibility issues and high mechanical losses have discouraged the exploitation of this strong piezoelectric for these applications. However, for select MEMS resonator and filter applications, thin film PZT offers many unique advantages due to the high electromechanical coupling factors, permittivity, piezoelectric stress constants, and the DC-bias electric field dependence of these properties. Significant progress has also been made in developing materials deposition and processing technologies that address the fabrication challenges with PZT thin films. The goals of this section include an analysis of the deposition of these materials, patterning techniques, identification of device design and processing concerns, and finally a detailed subsection covering examples of how PZT thin films have been incorporated into resonant-based devices.

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2.1.1 Deposition

PZT thin films have been successfully deposited by a wide variety of processes with a majority of the early development done through various sputtering techniques with a strong focus on RF or ion-beam deposition using bulk ceramic targets [3–6]. Current research efforts primarily utilize sputtering [7, 8], metal-organic-chemical vapor deposition (MOCVD) [9–11], and chemical solution deposition (CSD) techniques [12–17] with many of the techniques summarized in Table 2.1. Each of these three techniques has and is used in commercial fabrication of PZT-based devices with ferroelectric random access memory (FRAM) initially using either CSD or sputtering and then migrating to MOCVD for ultrathin layers. For PZT-based MEMS devices, CSD and sputtering are both used in commercial production and foundry facilities. PZT deposition methods require strict control of the stoichiometry to prevent nucleation of non-ferroelectric fluorite and pyrochlore structures [18, 19]. Furthermore, lead oxide (PbO) becomes highly volatile above 500 °C, so one must take care to provide enough excess lead to compensate for lead loss through the release of PbO during any high-temperature processing and annealing [20].

A variety of substrates can be used for PZT deposition. However, there are requirements for both the substrate and metallization layers. Growth of PZT is strongly nucleation controlled, and with proper control of the nucleation, crystal orientation of the film can be manipulated [21, 22]. Single-crystal substrates (i.e., MgO, SrTiO₃) can be used to nucleate epitaxial, single-crystal PZT thin films [23].

For most MEMS applications, silicon is the substrate of choice. Furthermore, when it comes to resonant devices, PZT is often integrated with silicon-on-insulator (SOI) substrates to couple the high electromechanical coupling of the PZT with

Table 2.1 Deposition methods and parameters for PZT thin films

Deposition parameter	DC sputter (reactive)	RF sputter	MOCVD	CSD
Reference	[7]	[7, 39, 99]	[11]	[15]
Target stoichiometry	Pb, Zr, Ti (3 metal targets)	Pb _{1.20} (Zr _{0.53} Ti _{0.47})O ₃		
Excess Pb %		20		10 and 30
RF power (W)		100		
Bias (V or W)				
Pressure (Pa or T)		1–2	5 T	
Gas		O ₂ (1–3 sccm)	O ₂ (1 L/min)	O ₂
Deposition rate (nm/min)		10–20	12	
Temperature (°C)	570 Followed by post-dep RTA	550–700	550	RT → 350 → 650

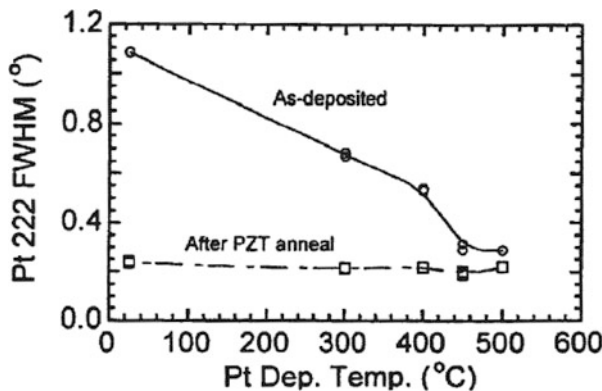


Fig. 2.1 Texture, FWHM of the sputtered Pt (222) peak, as a function deposition temperature and after thermal processing of a PZT film deposited atop the Pt film [24] (Reprinted with permission. Copyright 2004)

the high mechanical quality factor of the single-crystal silicon. When using Si, it is important to prevent the formation of lead silicide at the substrate interface by using buffer layers and/or metal layers. In most instances, a layer of silicon dioxide is used as a buffer layer in combination with a bilayer of TiO_2/Pt to serve as the base electrode for the PZT deposition. With the lattice constant of platinum being close to that of PZT (2–3 % mismatch for c-axis-oriented PZT), Pt can be an excellent template for (111) oriented PZT films as Pt tends to grow with a strong (111) texture. In order to maximize the texture within the Pt, the preferred material stack is $\text{SiO}_2/\text{TiO}_2/\text{Pt}$ [24]. The layer of TiO_2 serves as a buffer layer and template that allows higher degree of texture within the Pt. For detailed information on the method required for achieving highly textured (111) Pt, the readers are directed to Ref. [24] with one of the key figures reproduced in Fig. 2.1. It is noted that although Pt is great at seeding (111) PZT growth, the preferred orientation to maximize the piezoelectric properties of PZT is (001) orientation [22]. Methods of manipulating the texture of the PZT away from (111) orientation when using Pt layers will be discussed later within this section.

There are several metal and/or conducting oxides (i.e., Ru and RuO_2 and Ir and IrO_2) that can be used in place of Pt. These alternative electrodes can exhibit a higher resistance to Pb interdiffusion and thus provide a better barrier. Oxide electrodes are commonly used for the top electrode to reduce ferroelectric fatigue (reduction of switchable polarization with bipolar cycling, especially in excess of the coercive field of the PZT) [25]. Note, ferroelectric fatigue can be mitigated by simply using one of the electrodes as a conductive oxide (e.g., IrO_2 or RuO_2). An additional benefit of IrO_2 electrodes is it can serve as a barrier of hydrogen damage within PZT thin films [26].

Sputter deposition of PZT thin films has been completed through either reactive deposition using three metal targets (Pb, Zr, and Ti) or RF sputtering using ceramic targets. In either case, PZT thin films with excellent ferroelectric and piezoelectric

properties can be obtained. One challenge with sputter deposition is accurate control of the Pb and O content within the films. Lead has a higher sputter yield and higher volatility (i.e., PbO) compared to Zr and Ti. As a result, the lead loss must be compensated with either higher fluxes sputtered from pure Pb targets or excess Pb incorporated in ceramic targets. An additional item of note is the substrate temperature during deposition. The use of high temperatures during deposition results in higher Pb loss and typically requires higher excess lead content targets. If the substrate temperature can be maintained greater than 600 °C, pure perovskite phase PZT thin films can be achieved. Otherwise, a crystallization anneal is required on the sputtered film to convert the deposited layer into the desired perovskite phase.

MOCVD processes for PZT thin films have been researched as a key technology for mass production of ferroelectric random access memory (FeRAM) especially for device architectures requiring exceptional step coverage. For PiezoMEMS applications, there has been limited information reported on the piezoelectric properties of MOCVD-deposited thin films. For a summary of the MOCVD deposition process, readers are directed to Refs. [9] and [11] for more detail.

Chemical solution deposition (CSD) methods for ferroelectric thin films have been developed based on a variety of methods (i.e., sol-gel and metallorganic decomposition) and precursors [27]. The CSD techniques can be categorized into three main groups: sol-gel, chelating process, and metallorganic decomposition [15, 16]. The two most widely used approaches are based on a sol-gel approach using 2-methoxyethanol as a solvent and the inverted mixing order process using methanol as a solvent. Sol-gel methods have been primarily based on the research of Budd, Dey, and Payne in 1985 [12].

With the inverted mixing order (IMO) process, the lead, titanium, and zirconium precursors are combined in the opposite order from those developed in the original sequential addition process by Budd, Dey, and Payne [12, 28, 29]. In addition, the solvent used for the IMO process is primarily methanol with slight additions of acetic acid and deionized water for additional solution stability. The use of methanol instead of 2-MOE enables a less toxic solution preparation and the deposition process for the user [28]. Additionally, a commercial source of solutions is now available through Mitsubishi Materials using a proprietary solvent that is also less toxic than 2-MOE [30]. The PZT-N solution offered by Mitsubishi Materials is currently one of the most widely used solutions within the available foundries.

The most heavily researched processes for the deposition of PZT films use 2-MOE as a solvent and lead acetate trihydrate, titanium isopropoxide, and zirconium n-propoxide as the precursors [12, 31, 32]. This process has been used to produce PZT films with the highest piezoelectric coefficients to date. A general version of the 2-MOE-based solution process flow is highlighted in Fig. 2.2. To begin, the lead precursor (lead acetate trihydrate) is dissolved in 2-MOE followed by vacuum distillation to remove the water. The dehydrated lead acetate is allowed to redissolve in a portion of the 2-MOE solvent before being mixed with Zr and Ti precursors. Prior to being added to the lead precursor, Zr and Ti precursors are mixed in the desired stoichiometric ratio at room temperature with 2-MOE. The combined solution is refluxed for two to three hours at 120 °C

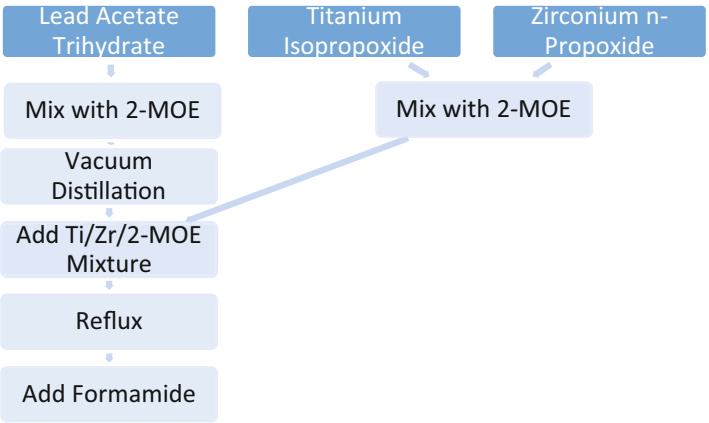
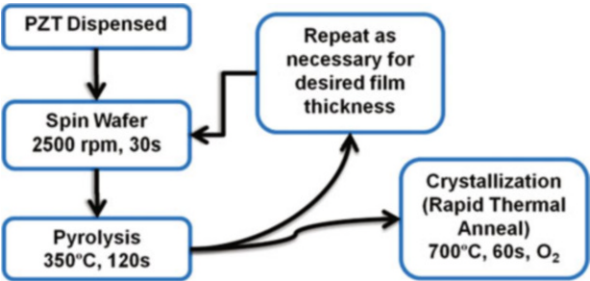


Fig. 2.2 Schematic process flow for creating a 2-MOE-based solution for PZT thin films

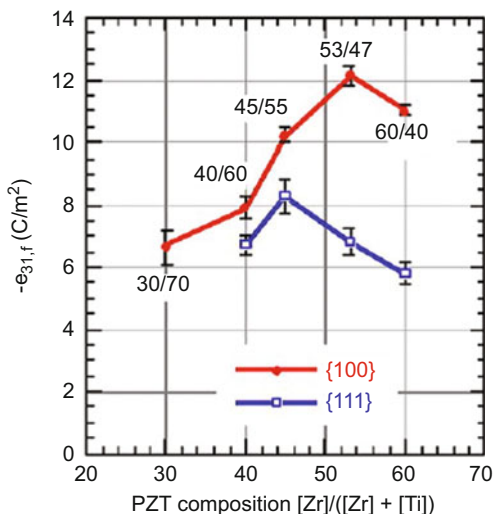
Fig. 2.3 Deposition and thermal treatment process flow for chemical solution deposition of PZT thin films based on a 2-methoxyethanol solvent system



using a rotary evaporator or comparable setup. Next, the solution undergoes a short vacuum distillation to remove a small amount of reaction by-products and adjust the concentration, typically 0.4 M. The final step is to add 4 volume percent of formamide, which serves as a drying control agent [33]. Additionally, a small percentage of acetylacetate may be added to the solution to assist in the long-term stability of the solution [34].

Regardless of the solution chemistry, the deposition processes are quite similar and graphically represented in Fig. 2.3. The only discrepancies are minor changes to the pyrolysis temperature or the crystallization temperature. Using automated solution coating machines (similar to those developed for photoresists), the deposition process usually begins by prefiltering the solution into the deposition canisters or syringes. The solution is statically dispensed onto the substrate and then spun to achieve a uniform film thickness across the substrate. Following the spin, the film is pyrolyzed on a hot plate to remove the volatile organics. The spin and pyrolysis steps are repeated as required (i.e., one to four layers) prior to the crystallization anneal in flowing oxygen. Using a 0.4 M solution, a four-layer spin process typically yields a final film thickness close to 0.25 μm . The process is continuously repeated until the desired film thickness is achieved.

Fig. 2.4 Transverse piezoelectric stress constant, $e_{31,f}$, of a 1 μm PZT thin film as a function of Zr/Ti ratio for both (100)/(001) and (111) oriented thin films [22, 23] (Reprinted with permission. Copyright 2003, Elsevier)



Regardless of deposition method, there are several key material parameters with which to judge the quality of the PZT thin film. The first is the crystalline quality of the film via X-ray diffraction (XRD). The best quality piezoelectric films will possess a high degree of texture in the (100)/(001) orientation (see Fig. 2.4). The easiest method of assuring a high degree of (100) texture is through templating the nucleation and growth with a PbTiO_3 seed layer and proper attention to the amount of excess lead present during any high-temperature annealing or crystallization processes [21, 33, 35]. An example XRD pattern of a highly textured CSD PZT thin film is shown in Fig. 2.5.

Optimizing material quality and properties requires controlling the stoichiometric gradients through the thickness of the PZT film. Figure 2.6 illustrates the importance of controlling these gradients, as these gradients represent deviations of the average properties of the film from the intended composition. As stated earlier, PZT films are strongly nucleation controlled. With heterogeneous nucleation occurring at the electrode interface, Ti-rich compositions nucleate first [21]. The end result is a sawtooth Zr/Ti gradient through the PZT thickness with a Ti-rich layer at the electrode interface and a Zr-rich layer at the film surface (see Fig. 2.6) [15]. To compensate for the gradient, Calame and Murali developed a process to reduce the gradient by manipulating the stoichiometry of each of the four CSD layers (63, 58, 48, and 43 % Zr content) deposited prior to the crystallization step [15]. As shown in Fig. 2.6, the average composition through the entire 2 μm thickness closely resembles the MPB desired composition of 53/47. Alternatively, recent work has demonstrated gradient-free films using process optimization with a ZnO buffer layer beneath a Pt electrode layer [36, 37].

For comparison, a list of the material properties achieved for each deposition method has been compiled in Table 2.2. Note, that quite often, the ferroelectric property, namely, the remnant polarization, is similar for the different techniques.

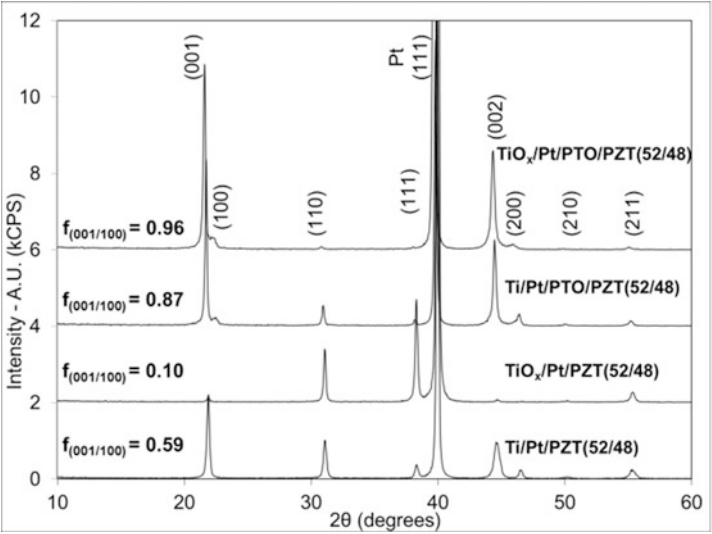


Fig. 2.5 Θ – 2Θ X-ray diffraction pattern for PZT (52/48) thin films ($\sim 0.5 \mu\text{m}$) using a PbTiO_3 seed layer to promote a highly textured (100) orientation [36] (Reprinted with permission. Copyright 2013 MRS).

Fig. 2.6 Zr content in two different PZT (53/47) films, one with a standard 2-MOE process using a crystallization anneal every four layers and the other using an optimized process to reduce the Zr/Ti gradient in the film [15] (Reprinted with permission. Copyright 2007 American Institute of Physics)

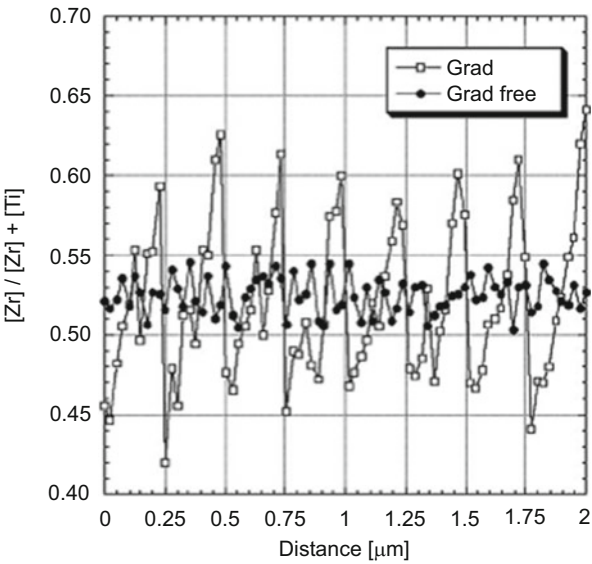


Table 2.2 Material properties as a function of deposition method

Technique	Stoichiometry (Zr/Ti)	P_r ($\mu\text{C}/\text{cm}^2$)	E_c (kV/cm)	$e_{31,f}$ (C/m ²)	d_{33} (pC/N)	ϵ_{33}	$\tan \delta$	Ref.
Sputter-RF magnetron	50/50	22–26	40–50	−25.1	100	800–1200	0.02	[7, 100]
CSD (N-PZT)	53/47	26.2	43.3					[29]
CSD (2-MOE)	53/47			−12.0	85	1180	0.029	[33]
				−17.7		1650	0.023	[15]

Table 2.3 Etch parameters for PZT thin films

Etching parameter	ECR-RIE	ICP-RIE	ICP-RIE	Wet	Ar ion mill
Reference	[46]	[48]	[49]	[43]	[101]
RF power (W)	10–200	400–800	500–800		150
Bias (V or W)	100–1000 V	100–400 V	200–350 V		36 V
Pressure (Pa or mT)	5e ^{−4} to 1 Pa	1–10 mT	0.1–2.0 Pa		0.7 mT
Gas(es)	CCl ₄ , CF ₄ , Ar	Cl ₂ /C ₂ F ₆ /Ar	BCl ₃ :Ar Cl ₂ :Ar	BOE:2HCl:4NH ₄ Cl: 4H ₂ O + 2HNO ₃ :H ₂ O	Ar
Etch rate (nm/min)	20–95	100–180	63–193	960	25
Resist selectivity (PR/PZT)	3:1–13:1	1.5–3:1	3–6 :1	1.5:1	1:1

However, the piezoelectric coefficients tend to be higher in the highly textured, gradient controlled CSD techniques.

2.1.2 Patterning Techniques

Patterning PZT thin films along with many other ferroelectrics remains one of the more challenging aspects of incorporating these compounds with MEMS. Not only are these compounds rather difficult to etch and pattern, but contamination from the heavy metal elements, especially lead, poses additional problems for most clean rooms. Specific to PZT, regardless of the Zr/Ti ratio, this material can be etched with all of the common etching techniques including wet processing, electron cyclotron resonance-based reactive ion etching (ECR-RIE), inductively coupled plasma (ICP)-based RIE, and ion milling as indicated in Table 2.3.

Wet etching techniques remain one of the easiest solutions to patterning PZT especially when selectively stopping the etch on a platinum electrode. However, this technique is limited to larger areas (several microns to tens of microns) because most etch chemistries are highly isotropic or can even have faster lateral etch rates.

Typical chemistries involve mixtures of hydrochloric (HCl) and hydrofluoric (HF) acids resulting in combinations of fluorine- and chlorine-containing by-products [38–40]. One of the most common chemistries with relatively high etch rate and excellent selectivity to platinum is a mixture of deionized $\text{H}_2\text{O}:\text{HCl}:\text{HF}$ (2:1:0.05). The HCl acid is used to remove lead and titanium, while the HF is used to remove titanium and zirconium. One problem that can occur with this etch combination occurs in films with excess lead where a white powdery lead residue remains on the wafer surface [42]. This lead-rich residue can be removed by adding small amounts of ammonium chloride and/or nitric acid to the solution [42]. Note that this etchant has a lateral etch rate nearly 2–3 times that of the film thickness.

Chemical and physical etching via reactive ion etching (RIE) and ion milling can provide the necessary dimensional control necessary for creating MEMS and NEMS structures. Similar to the wet etch chemistry, reactive ion etch techniques utilize combinations of fluorine- and chlorine-containing compounds (such as CF_4 and CCl_4) [19, 41–43]. A major challenge with a purely chemically based RIE is the extremely low volatility of the Zr and Ti by-products, namely, ZrF_4 , ZrCl_4 , TiF_4 , and TiCl_4 . To counter, the most successful etching techniques use combinations of RF-bias power in excess of 50 W, low pressures (<0.1 Pa), and elevated temperature. One leading technique is to etch the PZT in an electron cyclotron resonance/radio frequency (ECR/RF) reactor with 40 % CCl_4 , 40 % CF_4 , and 20 % Ar gases [19]. As shown in Fig. 2.7, this technique can achieve etching rates approaching 100 nm/min using 100 W_{RF} operating at a pressure of 1 mPa. Another chemistry for RIE is outlined by the ferroelectric random access memory (FRAM) community using

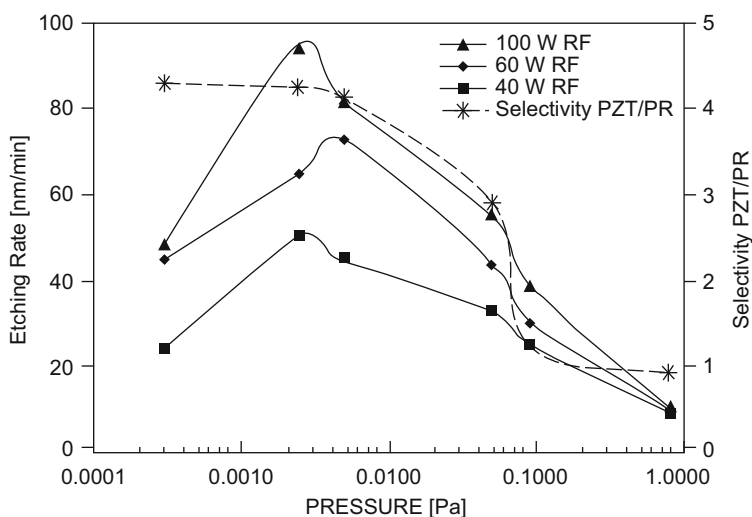


Fig. 2.7 Etching characteristics of PZT thin films as a function of processing pressure using an electron cyclotron resonance/radio frequency (ECR/RF) reactor [98] (Reprinted with permission. Copyright 2000)

inductively coupled plasma (ICP) RIE reactors with 70 % BCl_3 and 30 % Ar gas [44–46]. In addition to etching PZT layers, RIE can be used to etch the electrode layers such as Pt, RuO_2 , and IrO_2 . In general, the leading etch chemistries use chlorine-containing gases such as Cl_2 , CCl_4 , and BCl_3 with the etch mechanism being mostly physical in nature [19, 47–49].

The two biggest challenges with a chemical RIE approach to patterning PZT are controlling redeposition of the nonvolatile etch by-products and achieving the necessary resist selectivity. Processing at higher temperatures and using low pressures combined with high-throughput vacuum pumps increase the percentage of the by-products remaining in the gaseous phase. However, increasing the temperature causes severe resist degradation or even carbonization of the photoresist. As a result a hard mask needs to be employed. Further evidence of this is shown in Figs. 2.7 and 2.8 where resist selectivity dramatically decreases with increases in processing pressure or incident ion energy or RF bias. Resist degradation is yet another challenge with RIE etches of PZT. To preserve the resist integrity, any masking must be done with either hard-cured photoresist or hard masks to avoid degradation in soft-cured photoresist. Early work on hard masks included TiO_2 coatings with the FRAM community moving toward TiN or TiAlN coatings [49, 50]. The use of hard coatings enables a single mask layer etching process to etch the entire capacitor (electrode/PZT/electrode) (see Fig. 2.9). The same process can be used for MEMS actuators. However, care must be taken to account for the elevated voltages (electric fields) that the actuators require compared to that of FRAM. The gap separation between the two electrode layers is defined by the PZT thickness. Because this separation can be in the range of 0.25–2 μm , breakdown across the air gap becomes

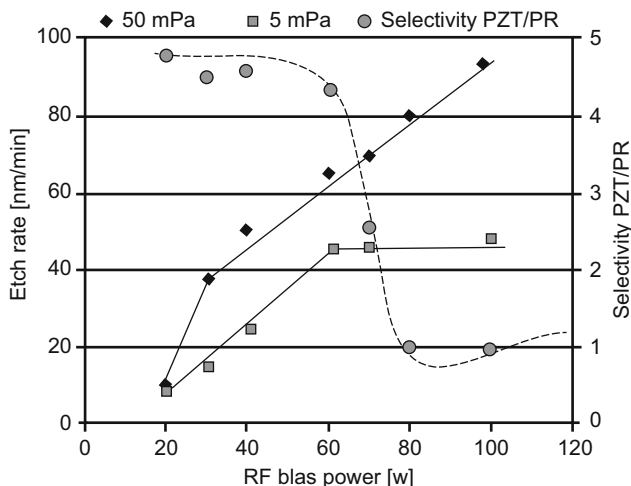


Fig. 2.8 Etching characteristics of PZT thin films as a function of RF-bias power using an electron cyclotron resonance/radio frequency (ECR/RF) reactor [54] (Reprinted with permission. Copyright 2000)

Fig. 2.9 Cross-sectional image/schematic of an FRAM capacitor (Ir/IrOx/PZT/IrOx/Ir) patterned using a single-layer hard-etch mask of TiAlN

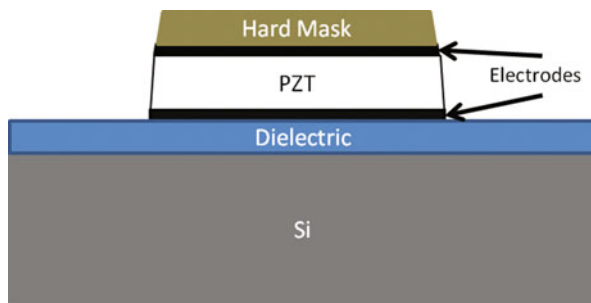
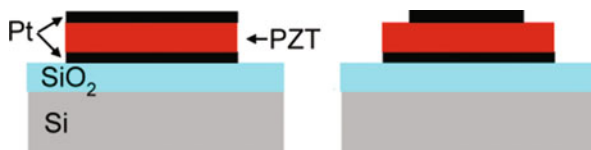


Fig. 2.10 Schematic cross section of PZT stack actuators patterned using (a) a single-etch process and (b) a multiple-step etch process.



a concern during device operation. For example, actuators comprised of a $0.5\ \mu\text{m}$ PZT film with Pt electrodes fabricated with a single-etch process have breakdown voltages on the order of $10\ \text{V}$ ($\sim 200\ \text{kV/cm}$). In contrast, employing a multiple-step etching (see Fig. 2.10) process to define the top electrode and the actuator separately increases the breakdown voltage for a $0.5\ \mu\text{m}$ thick PZT actuators to approximately $100\ \text{V}$ ($\sim 2000\ \text{kV/cm}$). This effect is primarily due to the fact that the PZT overlap required for the multistep etch/masking process increases the distance between the top and bottom electrodes. Alternatively, an interlayer dielectric coating such as an atomic layer deposited coating of alumina (Al_2O_3) can be employed to also mitigate breakdown across the air gap between the top and bottom exposed electrodes.

The final method of patterning PZT thin films is through a physical etch using Argon ion milling. Although this technique does not provide any significant selectivity to photoresist, PZT, or the electrode layers, it has several key advantages including the ability to etch the entire metal/PZT/metal stack and variable control of the angle of incidence [51]. For hard-to-etch compounds, especially materials with low volatility such as PZT and Pt, the accelerated Ar ions can be used to break the atomic bonds, while the variable angle control is used to push free atoms away from the wafer surface. Furthermore, the angle of incidence can be altered during the final stages of the etching to remove any redeposited materials. Similar to the chemical-based RIE procedures, the masking material for the ion mill must either be hardened photoresist or a hard mask as ion damage and redeposited heavy metal ions prevent clean removal of a soft photoresist. Although the ion mill generally has poor selectivity and a difficulty to accurately endpoint on the desired layer, an ion mill reactor can be configured with a secondary ion mass spectrometer (SIMS)

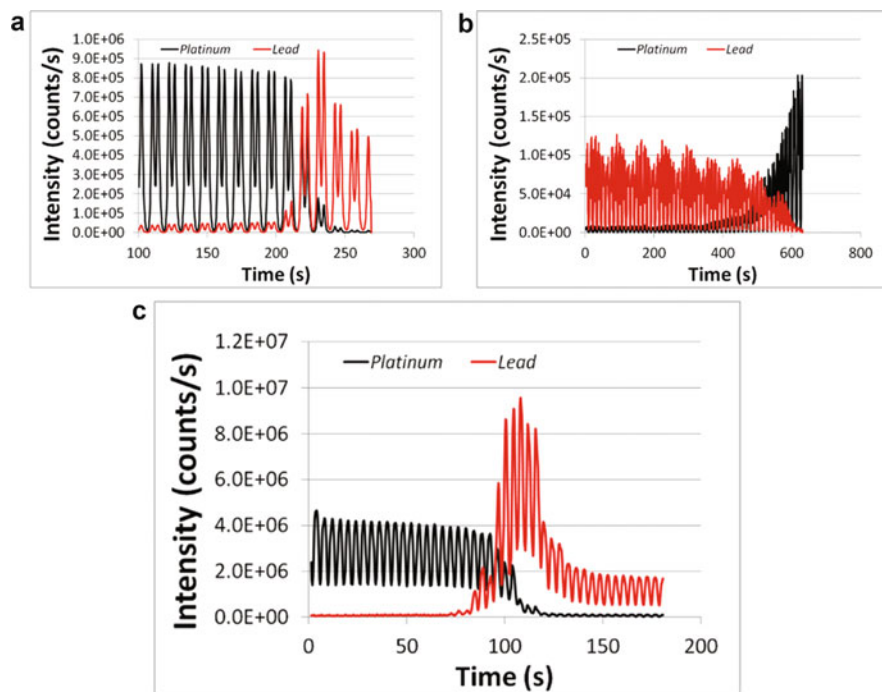


Fig. 2.11 Examples of using SIMS endpoint detection in conjunction with ion milling of (a) Pt etching and stopping on a PZT thin film using the falling edge of Pt, (b) etching PZT and stopping on a Pt thin film using the rising edge of Pt, and (c) etching PZT and Ti/Pt stopping on the underlying SiO₂ using the falling edge of Pt. Note the double peaks in the SIMS signal are the result from monitoring two substrates that are rotated under the beam during the etching process

endpoint detection system. The SIMS system analyzes the etched material as it is removed from the wafer surface and yields an accurate depiction of the depth of the current etch. An example of the endpoint detection is illustrated in Fig. 2.11 for a sample etching the top Pt electrode stopping on the PZT and for a sample etching the PZT and stopping on the bottom Pt electrode.

2.1.3 Device Design Concerns

An area of concern for PZT-based MEMS devices is degradation in the material properties during the device fabrication. The research on ferroelectric random access memory (FRAM) has advanced the understanding of the leading degradation mechanisms including ion damage, H₂ damage, and surface contaminants [52, 53, 55]. In many instances, the manifestation of damage in the PZT can be observed through characterization of the ferroelectric and dielectric properties. In cases where

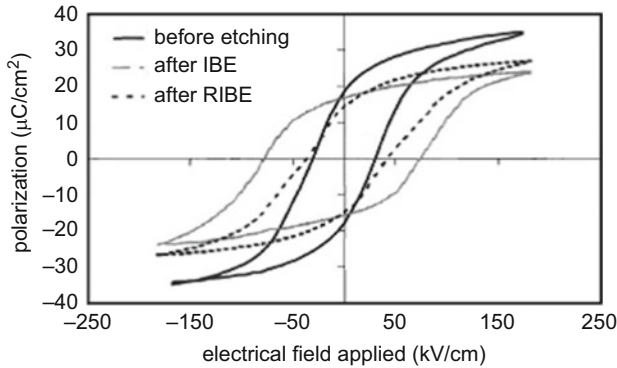


Fig. 2.12 Change in the polarization electric field hysteresis loop observed for virgin (before etching) PZT thin films, for a PZT film exposed to ion milling (after IBE), and for a PZT film exposed to a reactive ion etch (after RIBE). For both etched samples, the testing was done after depositing and annealing a top Pt electrode layer on the etched surface [56] (Reprinted with permission. Copyright 2005 American Institute of Physics)

the PZT surface is exposed to etch conditions and then electroded, reductions in the remnant polarization, increases in the coercive field, and decreases in the dielectric constant are observed resulting from the creation of a damaged surface layer lying beneath the top electrode (see Fig. 2.12) [55, 56]. The presence of the damaged surface layer is severely detrimental to the performance of the PZT, and consequently the preferred process deposits and patterns the top electrode onto the as-deposited, pristine surface of the PZT film.

For piezoelectric devices patterned after the top electrode has been deposited, degradation remains a potential problem. The PZT sidewalls are damaged during the patterning process and can introduce defects into the material. More importantly, exposure to H_2 through contact with the hydrocarbons in photoresist and forming gas anneals introduces protons in the PZT via diffusion, adversely affecting the ferroelectric and dielectric properties through domain pinning. Additionally, the feature size of the active device area can play a significant role in the degree of damage that exists in the PZT layer [54].

Regardless of the damage created by processing, in most instances the ferroelectric and dielectric properties can be recovered using a thermal anneal. To approach full recovery, the anneal must be done above the Curie temperature of the ferroelectric (e.g., T_c (PZT) $\sim 365^\circ\text{C}$). An example of how effective the recovery anneal can be is shown in Ref. [55]. In this example, the material properties are recovered to the initial conditions using a 500°C anneal (Fig. 2.13).

Another key aspect with PZT devices is the aligning of the ferroelectric domains or poling. Unlike the pure polar materials discussed previously (i.e., AlN and ZnO), the polarization in ferroelectric materials can be configured in a multitude of orientations. In order to optimize the piezoelectric coefficient of the PZT, the ferroelectric domains need to be aligned in a single preferred direction. For an

Fig. 2.13 Illustration of how high-temperature annealing can be used to recover the ferroelectric properties of PZT thin films after damage induced by the patterning process [55] (Reprinted with permission. Copyright 2002 American Institute of Physics)

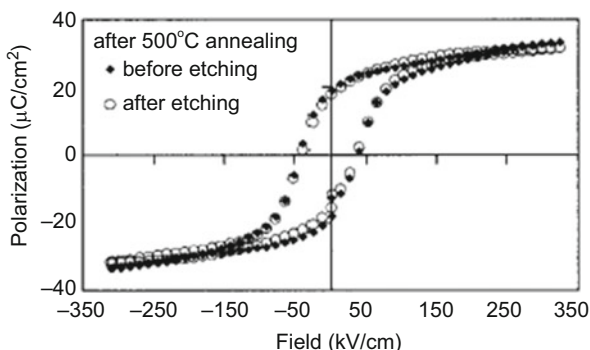
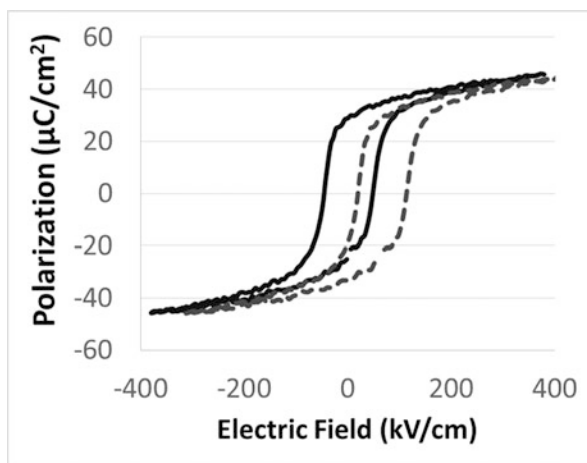


Fig. 2.14 Example of imprint in a ferroelectric illustrated by a shift in the polarization electric field response of the material



actuator in a parallel plate configuration (d_{31} mode), the poling direction is along the film thickness. The most direct method of poling is the application of an electric field nominally 3–4 times the coercive field for 10–15 min (i.e., 10–15 V for a 0.5 μm thick film). With respect to resonators and especially filters, the poling process post-fabrication can be a concern especially with very complicated device and circuit topologies. One possible approach that is of interest is to use heavily imprinted PZT films such that they are poled following the fabrication process. Imprint is defined as the presence of a strongly preferred polarization direction in a ferroelectric material such that the ferroelectric and piezoelectric hysteresis loops are shifted laterally along the electric field axis (see the example in Fig. 2.14). Essentially, the film has an internal bias field acting upon the polar domains resulting in a preferred orientation. If the imprint can be pushed toward extreme levels pushing toward and beyond the coercive field, the film will essentially always be in a preferred polarization state and achieving a near-optimal piezoelectric coefficient. An additional benefit especially for resonant devices is that the dielectric constant and dielectric loss are reduced under these internal biasing conditions enabling reduced parasitic capacitances and reduced loss in the devices.

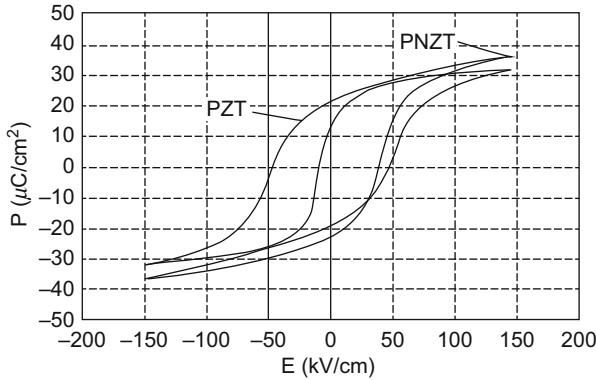


Fig. 2.15 Example of imprint in sputter deposited Nb-doped PZT (Reprinted with permission. Copyright FUJIFILM Corporation 2014) [25]

Imprint techniques fall essentially into two categories: in situ controlled and post-processed. In situ controlled are typically limited for use with sputtered films where the bombardment conditions can be refined to control the adatom mobility and manipulate the growth strains as well as the local defect chemistry (i.e., oxygen vacancies). An example of the imprint achieved in sputtered PZT is illustrated in Fig. 2.15. In contrast, post-processing imprint can be employed on films deposited by many methods and include thermal poling and exposure to ultraviolet radiation consisting of a wavelength smaller than the absorption bandgap of the material (i.e., approximately 365 nm for PZT [55]). With thermal poling, the electric field for poling is applied while the PZT is held at temperatures approaching half of the Curie temperature or higher, nominally 125–150 °C. Generally, thermal poling procedures have a longer duration and stability compared to the UV-assisted poling procedures.

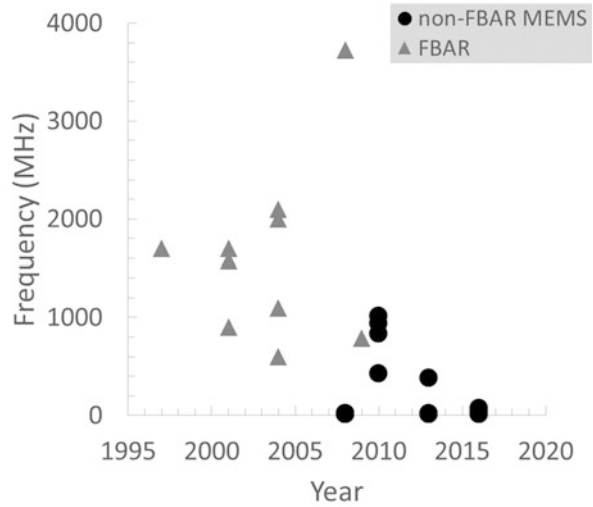
2.1.4 PZT-Based Resonant Devices

Table 2.4 includes select published results for PZT MEMS resonators since 1997 [56–71], and Fig. 2.16 plots the corresponding center frequencies versus the year the results were obtained. As highlighted in Fig. 2.16, PZT thin film for SAW and FBAR resonators was investigated during the late 1990s and early 2000s for cell phone RF filtering [70–75]. k_t^2 values as high as 35 % were demonstrated in PZT FBARs [71]; however, the poor quality factor performance of these devices (<237) resulted in inferior filter performance. PZT MEMS flexure-mode resonators [73] were also first investigated during this time. Since the late 2000s, several groups have explored PZT contour-mode resonators with much of the research motivated by certain defense applications at lower frequencies (<500 MHz).

Table 2.4 Representative published results for PZT MEMS resonators

Ref.	Year	Type	f_c (MHz)	k_{eff}^2 (%)	Max $ S_{21} $ (dB)	Q_m	R_m (Ω)	Method and composition	Material stack	FOM
[60, 61]	2016	Z-flexure	22	1.41 %	1.4	1856	3.3	Sol-gel 52/48	0.5 μm PZT/10 μm Si	26.5
[60, 61]	2016	Z-flexure	22	2.10 %	1	815	9	Sol-gel 52/48	0.5 μm PZT/10 μm Si	17.5
[60]	2016	Contour	56	8.15 %	2.7	289	8.5	Sol-gel 52/48	0.5 μm PZT on 1 μm SiO ₂	25.6
[60]	2016	Contour	10.7	0.05 %	8	6575	143	Sol-gel 52/48	0.5 μm PZT/10 μm Si	3.3
[62]	2016	Contour	10.7	0.48 %	1.7	3000	16	Sol-gel 52/48	0.5 μm PZT/10 μm Si	14.5
[63]	2013	Contour	15	3 %	2.1	541	11	Sol-gel 52/48	0.5 μm PZT/2 μm Si	16.7
[63]	2013	Contour	15.9	0.85 %	5.1	738	101	Sol-gel 52/48	0.5 μm PZT/4 μm Si	6.3
[63]	2013	Contour	18.9	0.38 %	3.7	2850	23	Sol-gel 52/48	0.5 μm PZT/10 μm Si	10.9
[64]	2013	Contour	382	–	–	–	542	Pulsed laser	0.5 μm PZT/3 μm Si	–
[65]	2010	Contour	834	–	12	314	296	Sol-gel 52/48	0.5 μm PZT/3 μm Si	–
[66]	2009	FBAR	790	10 % k_t^2	–	52	8.2	Sol-gel 53/47	2 μm PZT	4.0
[67]	2008	Contour	21	–	5	2023	50	Sol-gel 52/48	0.5 μm PZT/10 μm Si	–
[67]	2008	Contour	20	–	10	148	207	Sol-gel 52/48	0.5 μm PZT/0.5 μm SiO ₂	–
[68]	2008	FBAR	3724	52.7 % k_t^2	–	114	–	Sputtered 45/55	–	68.8
[69]	2008	Contour	15.9	–	–	5040	167	CSD: Sol-gel	0.5 μm PZT/10 μm Si	–
[70]	2004	FBAR	2000	9 % k_t^2	–	220	–	Sputtered 58/42	0.35–0.43 μm PZT	15.1
[71]	2004	FBAR	600	35 % k_t^2	–	45	–	Sol-gel 30/70	2.3 μm PZT	15.0
[71]	2004	FBAR	1100	17 % k_t^2	–	125	–	Sputtered 40/60	1.4 μm PZT	17.3
[71]	2004	FBAR	2100	22 % k_t^2	–	30	–	MOCVD 30/70	0.4 μm PZT	5.6
[72]	2001	FBAR	1581	19.1 % k_t^2	–	53	–	Sol-gel 30/70	0.8 μm PZT	8.4
[74]	2001	SMR	900	25 % k_t^2	–	67	–	Sol-gel 35/65	1.3 μm PZT	14.6
[75]	1997	FBAR	1700	9.6 % k_t^2	4	237	–	Sol-gel 52/48	0.8 μm PZT	17.4

Fig. 2.16 Select published results for PZT MEMS resonators since 1997; resonator center frequency versus the year the results were obtained



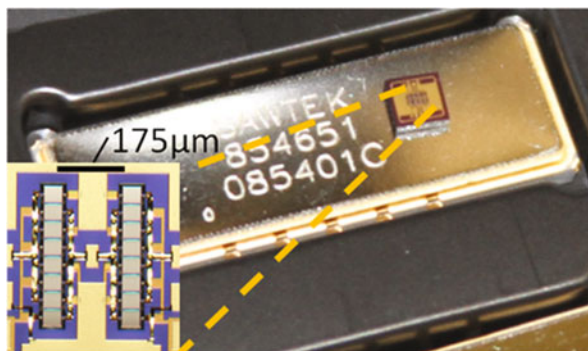
The unique capabilities of thin film PZT MEMS resonators arise from the high electromechanical coupling factors, permittivity, piezoelectric stress constants, and the DC-bias electric field dependence of these properties. The very high piezoelectric coefficients of thin film PZT enable strong electromechanical coupling despite the relatively large dielectric constants. PZT bulk ceramics vary in electromechanical coupling with composition, but typical quasi-static material values at low electric field are 48 % k_{33}^2 , 22 % k_t^2 , 12 % k_{31}^2 , and 39 % k_p^2 [74]. The subscripts for the electromechanical coupling are related to the directions of electrical and mechanical quantities. For k_{33} , the polarization and vibration are along the same direction (i.e., the 3 direction in this case) and as an example consider a ceramic rod polarized along its length and electrode at the ends. Related to k_{33} is k_t , which is used in cases where the surface area of device is substantially larger than its thickness. In cases where the polarization direction and vibration direction are orthogonal to one another, the k_{31} term is appropriate where the polarization is along the three directions. Finally, k_p is associated with discs with the polarization in thickness direction (i.e., 3 direction) and the mechanical vibration in the in-plane radial directions (i.e., 1 and 2). There are limited published results for thin film PZT quasi-static material coupling factors due to the difficulties in directly measuring these properties. However, k_{31}^2 values as high as 29.8 % [22] (based on permittivity and piezoelectric coefficient measurements and assuming s_{11}^E from [75]) and 27.9 % [79] (based on micro-tensile specimen testing of s_{11}^E and s_{11}^D) have been reported for low electric fields. The larger values for thin film PZT can be explained by the fact that thin-film piezoelectric properties have been shown to exceed those of bulk ceramic material [33], and the reported coupling factors for bulk material k_{ij}^2 are not identical to the effective film value. The film clamping effect [22] responsible for the discrepancy between e_{31} and the larger $e_{31,f}$

constants also influences the electromechanical coupling, resulting in an effective film coupling value that can exceed the bulk material k_{ij}^2 . The film clamping serves to enhance electromechanical coupling through the participation of additional piezoelectric coefficients in transduction. The largest electromechanical coupling factor reported with thin film PZT was achieved with a 3.7 GHz FBAR resonator with sputtered 45/55 PZT that exhibited a k_t^2 of 52.7 % and a $k_t^2 Q_m$ product of 57 [68]. For contour-mode MEMS resonators, a k_{eff}^2 of 8.2 % was achieved with a 0.5 μm PZT on 1 μm silicon dioxide/silicon nitride multilayer operating at 56 MHz with a Q_m of 289 [60] and motional resistance of 9 Ω .

The strong electromechanical coupling and high dielectric constants of PZT enable very compact filters, facilitating the design of resonators and filters for appropriate port impedances to avoid matching network losses, parasitic capacitance sensitivity, and large voltage swings [76]. High performance is also possible with direct 50 Ω termination without the need for any external matching networks [60]. The size of commercially available acoustic filters such as quartz and SAW at HF to low-UHF frequencies is rather large, and the performance of SAW filters is significantly degraded relative to higher frequencies. The size of impedance matching components at these low frequencies also presents a challenge to realize the benefits of small MEMS filters in large filter banks. PZT is particularly well suited to these low frequencies where high-performance low-loss filters can be directly interfaced with 50 Ω systems without the need for external matching. The size advantage of PZT MEMS filters over SAW filters is illustrated in Fig. 2.17 where a 70 MHz length-extensional 2-pole PZT MEMS filter [60] is seen atop a commercially available 70 MHz SAW filter.

The combination of strong electromechanical coupling and poor mechanical quality factor has led to the development of PZT-on-silicon resonator technology [60–62, 64, 65, 67, 69, 77–84]. PZT-on-silicon resonators (see Fig. 2.18) permit the tradeoff of resonator effective electromechanical coupling, k_{eff}^2 , and quality factor while nearly maintaining constant figure of merit (FOM) for similar resonator designs [82]. The largest FOM, non-FBAR PZT MEMS resonators published to date (FOM of 27) have utilized 0.5 μm PZT on 10 μm single-crystal silicon stacks [60, 61]. Trading electromechanical coupling for quality factor with comparable

Fig. 2.17 Size comparison between 70 MHz length-extensional 2-pole PZT MEMS filter atop a commercially available 70 MHz SAW filter [60] (Reprinted with permission. Copyright IEEE 2016)



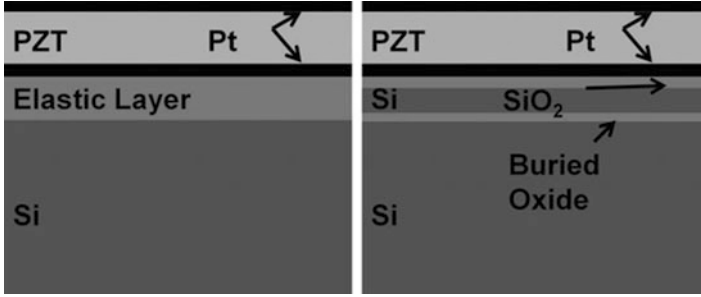


Fig. 2.18 Cross-sectional illustrations of typical PZT (*left*) and PZT-on-single-crystal silicon (*right*). PZT resonators are commonly implemented with various elastic layers, typically silicon dioxide or silicon nitride, and PZT-on-silicon resonators are realized with silicon-on-insulator substrates

figure of merit permits the development of resonators that would otherwise possess insufficient quality factors. Figures 2.19 and 2.20 plot the reported mechanical Q s of the resonators from Fig. 2.16 versus the year the results were obtained and center frequency, respectively. The apparent trend of decreasing Q versus frequency is interesting but is likely due to recently published high Q s at low frequencies with PZT-on-silicon devices. Furthermore, the largest reported FBAR Q results are not the lowest frequency devices. The significant improvements in resonator Q s since 2008 are largely due to the development of PZT-on-silicon MEMS resonator technology at lower frequencies (<1 GHz). The highest mechanical Q reported to date, 6575 in air, was achieved with a 10.7 MHz length-extensional mode and $0.5\ \mu\text{m}$ PZT on $10\ \mu\text{m}$ single-crystal silicon resonator with a k_{eff}^2 of 0.05 % (see Fig. 2.21) [60]. Moreover, PZT-on-silicon technology dramatically improves resonator power handling and linearity [61, 63]. Length-extensional [63] and disc Z-flexural [61] PZT-on-silicon resonators have demonstrated $>+10$ dBm and $>+15$ dBm 1 dB compression points at 16 and 22 MHz, respectively. These results compare very favorably to similar AlN MEMS resonators at these frequencies (-15.6 dBm) [85]. The addition of silicon to the resonator also significantly increases the average acoustic velocity that facilitates the design of higher-frequency contour-mode resonators [65].

The very high $e_{31,f}$ constants of PZT thin films enable the integration of RF MEMS acoustic filters with high-performance MEMS actuators such as RF MEMS switches, varactors, and tunable inductors. PZT resonators with and without single-crystal silicon (see Fig. 2.18) have been monolithically integrated with high-performance tunable RF MEMS passives that utilize the state-of-the-art actuation capabilities of PZT MEMS [86–89]. The low-loss and low-parasitic integration of piezoelectric MEMS acoustic filters with varactors and MEMS inductors could enable novel tunable filters via reconfigurable matching networks or facilitate the impedance matching and adjustment of rejection of filters in future complex RF system architectures [80].

Fig. 2.19 Select published results (see Fig. 2.16) for PZT MEMS resonators since 1997; reported mechanical quality factor versus the year the results were obtained (*semilog plot*)

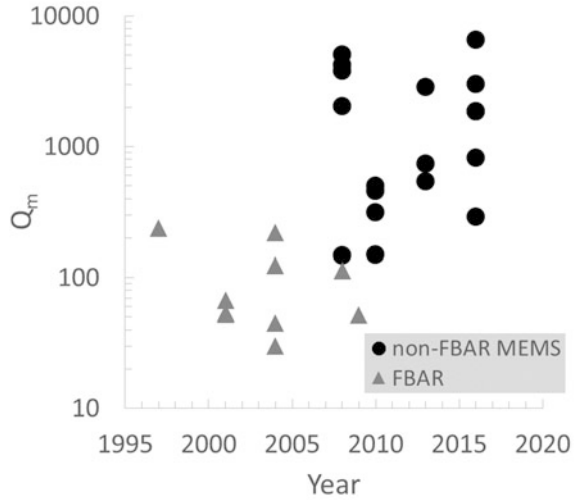
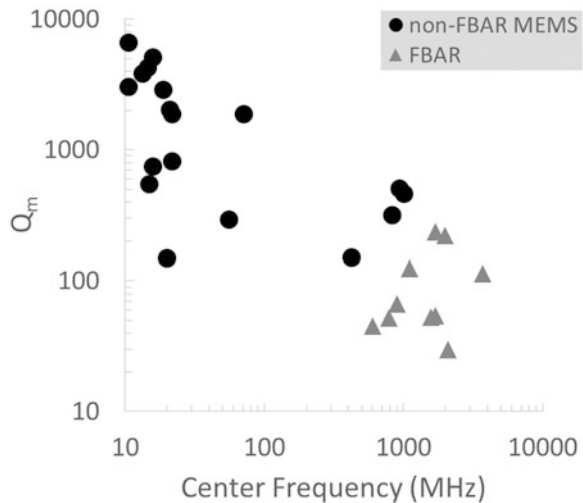
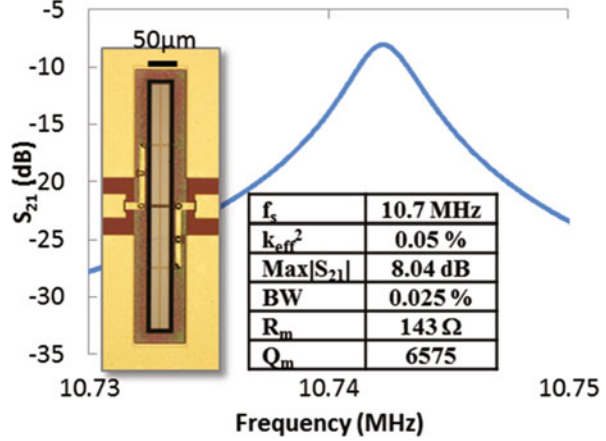


Fig. 2.20 Select published results (see Fig. 2.16) for PZT MEMS resonators since 1997; reported mechanical quality factor versus resonator center frequency (*log-log plot*)



The ferroelectric behavior of PZT induces both high electric field nonlinearity of the permittivity and piezoelectric properties [90]. These nonlinearities are only significant near or above the coercive field (high field) of PZT. High-quality PZT thin films tend to exhibit breakdown strengths that are far larger than those of similar composition bulk ceramic materials. This allows the application of bias electric fields that are many times the coercive field of the material to tune the dielectric constant, piezoelectric coefficients, and coupling factors. The significance is clear when considering the simple 2-port BVD model of a thin film PZT MEMS resonator as illustrated in Fig. 2.22. The DC-bias tuning of the permittivity enables

Fig. 2.21 Example result of high- Q PZT-on-silicon MEMS resonator from [60]. Measured frequency response of a 10.7 MHz gold-laced, length-extensional resonator when biased at 15 V. The device utilizes a 0.5 μm , 52/48, CSD sol-gel PZT film on 10 μm silicon (Reprinted with permission. Copyright IEEE 2016)



the static capacitances of the resonator to function as solid-state varactors. The tuning of the material electromechanical coupling factors result in tunable motional resistance, inductance, capacitance, and resonator effective coupling. The mobility and polarization switching of ferroelectric domains of the material, at high fields, lead to electric field dependence of the permittivity as illustrated in Fig. 2.23. Figure 2.23 plots the unipolar responses of the k_{33} dielectric constant and dielectric loss tangent for increasing and decreasing DC electric fields applied to a 0.5 μm , 52/48, CSD sol-gel deposited PZT film. The permittivity and loss tangent at high fields generally decreases as a result of a reduction in the number of domains not aligned with the applied field and the reduced movement of domain walls due to the bias electric field. It should be noted that while the dielectric loss of thin film PZT is commonly reported at low electric fields, significant improvements in the loss tangent, and hence the equivalent series resistance of resonator shunt capacitance, can be obtained with DC bias. The switching and wall mobility of non-180° domains (i.e., ferroelastic) result in both changes in polarization and strain. These processes tend to be nonlinear and hysteretic as well. At very large electric fields, electrostriction can also contribute to the strain response. All of these effects result in electric field dependence of the piezoelectric coefficients of PZT as illustrated in Fig. 2.24 for the same material plotted in Fig. 2.23. The tuning of both permittivity and piezoelectric coefficients leads to the tuning of the material electromechanical coupling factors. Figure 2.24 also plots the extracted k_{31}^2 from the e_{31f} and k_{33} results plotted in Figs. 2.23 and 2.24, assuming the measured dielectric constant is clamped and utilizing the s_{11}^E from [79]. The material coupling is seen to be highly dependent on the bias voltage. The particularly low coupling and piezoelectric constants in this example at low electric fields are not representative of most thin film PZT. Many groups have demonstrated the DC-bias tunability of PZT MEMS resonators. Center frequency tuning of 5.1 % was demonstrated in contour-mode resonators in [67] as shown in Fig. 2.25. The tuning of both series and parallel resonance frequencies of a PZT FBAR [66] is shown in Fig. 2.26. DC bias was used

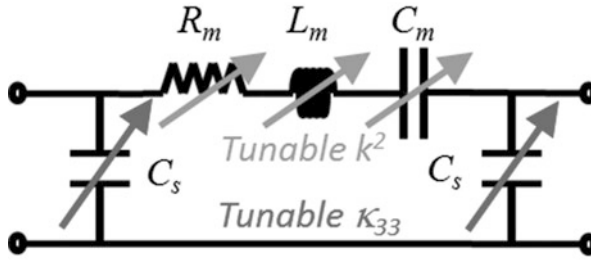
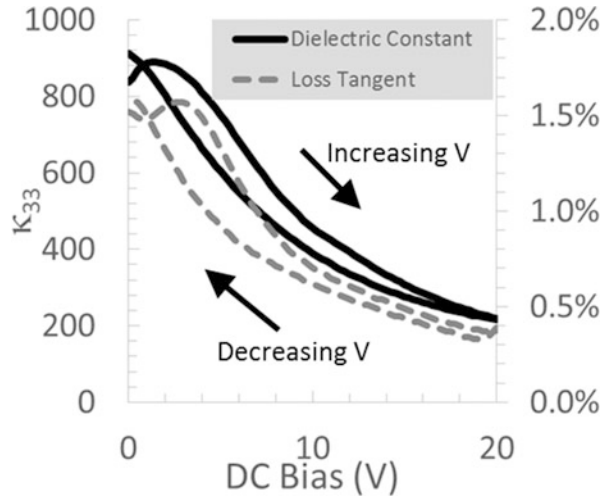


Fig. 2.22 Simplified equivalent circuit of thin film PZT MEMS two-port resonator highlighting effect of tunable material electromechanical coupling and permittivity. The static capacitances of the piezoelectric behave as varactors, and the motional R , L , and C also tune with DC-bias voltage

Fig. 2.23 Unipolar responses of the k_{33} dielectric constant and dielectric loss tangent for increasing and decreasing DC electric fields applied to a $0.5\ \mu\text{m}$, 52/48, CSD sol-gel PZT film



to tune the bandwidth of a low-loss 22 MHz out-of-plane disc flexure PZT-on-Si resonator array (see Figs. 2.27 and 2.28) [60, 61]. The bandwidth and maximum S_{21} vary from 24.3 kHz/16.8 dB at 1 V bias to 240 kHz/1.0 dB at 14 V bias. For bias voltages between 7 and 14 V, the bandwidth varies by a factor of $1.7\times$ for a variation of max S_{21} from 1.0 to 1.4 dB. Furthermore, ferroelectric-based MEMS resonators can be depoled by applying the coercive field that is the opposite of the current remnant polarization state resulting in an “off-state” for the resonator by tuning the material electromechanical coupling to zero.

Contour-mode and FBAR PZT MEMS resonators have been utilized to demonstrate filters [60, 64, 72, 90, 91]. An example result of a 10.8 MHz PZT-on-silicon 2-pole IF filter is shown in Figs. 2.29 and 2.30 [60]. Figures 2.29 and 2.30 display the wideband and narrowband measured S_{21} and S_{11} responses, respectively. The filter design is based on a self-coupled design [92] utilizing $0.5\ \mu\text{m}$ PZT (52/48 sol-gel) on $10\ \mu\text{m}$ silicon, higher-order length-extensional resonators. Table 2.5 lists

Fig. 2.24 Unipolar response under increasing applied voltage of the $e_{31,f}$ piezoelectric stress constant and extracted k_{31}^2 material electromechanical factor of the same film plotted in Fig. 2.23. The k_{31}^2 is extracted from $e_{31,f}$ and k_{33} assuming the measured dielectric constant is clamped (i.e., k_{33}^S) and utilizing the s_{11}^E from [79]

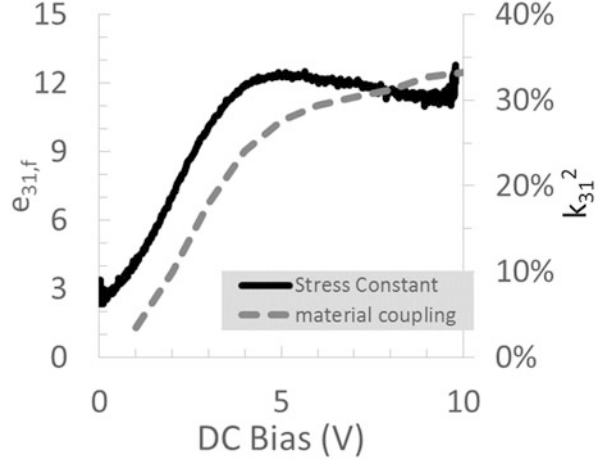
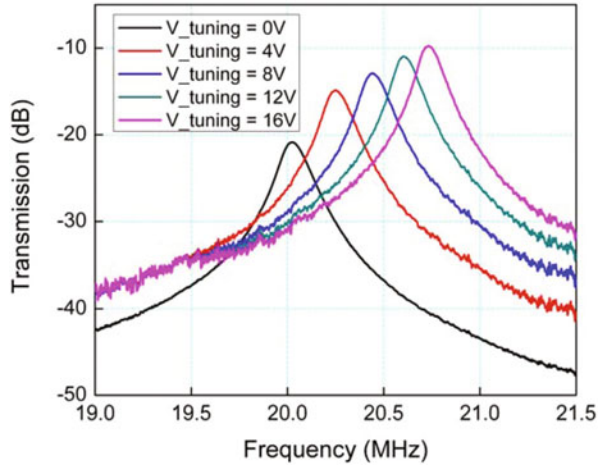


Fig. 2.25 Measured transmission of PZT MEMS resonator from [67], exhibiting 5.1 % center frequency voltage tunability (Reprinted with permission. Copyright IEEE 2008)



the performance of this filter as compared to similar low-frequency commercially available acoustic filters, including monolithic quartz, SAW, and ceramic technologies [93]. The PZT-on-silicon IF filter without external impedance matching outperforms the competing technologies in all categories except insertion loss (quartz for same number of poles) and power handling (SAW at a higher frequency). The performance listed for the commercially available filters is for the case of external impedance matching, while the PZT MEMS filter is directly terminated to 50Ω . The component size listed accounts for the size of the required discrete matching elements for the commercially available filters and the input and output bias tees for the PZT MEMS filter (assumes 0402 size components). Despite the relatively high insertion loss, the PZT MEMS filter performance was reported to meet the requirements of the intended IF filter application.

Fig. 2.26 Measured series (*fr*) and parallel (*fa*) resonance frequency tunability with applied DC-bias electric field for thin film PZT FBAR from [66]. The device utilized 2 μm 53/47 PZT deposited by CSD sol-gel technique and exhibited a maximum k_r^2 of 10 % with applied bias (Reprinted with permission. Copyright IEEE 2008)

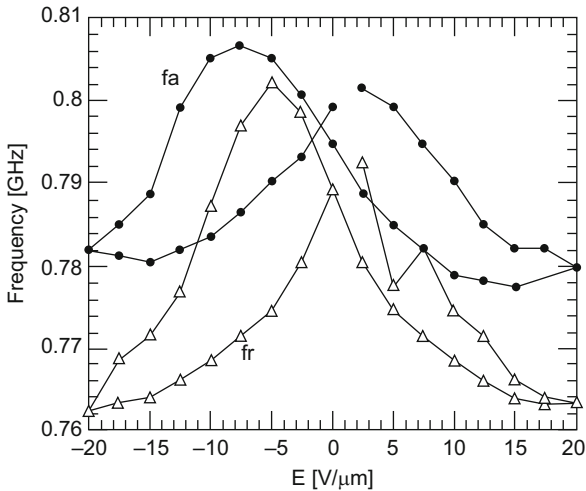
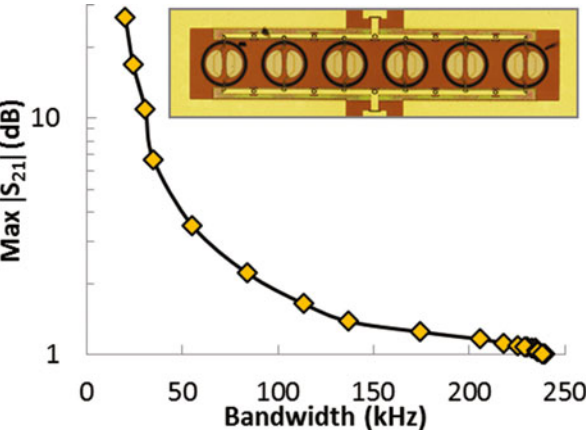


Fig. 2.27 Measured bandwidth tuning response of out-of-plane flexural disc array resonator from [60] with DC-bias voltages from 0 to 14 V. The maximum $|S_{21}|$ at 14 V bias is 1.0 dB (Reprinted with permission. Copyright IEEE 2016)



The primary limitations of PZT for resonator applications are the low mechanical (~ 200) and dielectric Q_s ($\sim 1\text{--}10\%$). In addition, the low acoustic velocity (~ 2800 m/s) and high dielectric constants ($\sim 300\text{--}1600$) and losses make it challenging to achieve high performance at high frequencies (>1 GHz). Furthermore, the need to provide DC bias for optimal material properties can provide unwanted complications. In light of these limitations and the aforementioned advantages, PZT resonators and filters are best suited to lower frequencies of operation (<500 MHz) where the small size and ease of design for $50\ \Omega$ termination provide unique benefits for acoustic filter applications and are well suited to applications that can leverage the integration of high-performance MEMS actuators. The figures of merit of PZT FBAR and MEMS resonators have been improving since the late 1990s, and PZT-on-silicon technology has provided resonator Q_s that are relevant for some filter applications (see Fig. 2.31). Promising efforts in recent

Fig. 2.28 Measured bandwidth tuning of S_{21} and S_{11} responses of an out-of-plane flexural disc array resonator (similar to Fig. 2.27) with bias voltages of 10, 3, and 2 V from [60]. (Reprinted with permission. Copyright IEEE 2016)

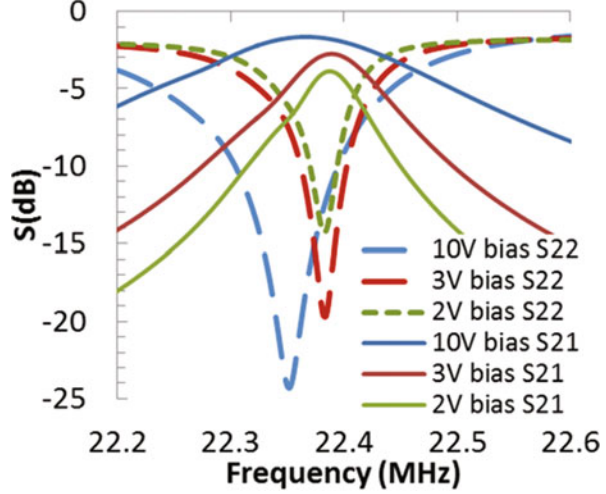
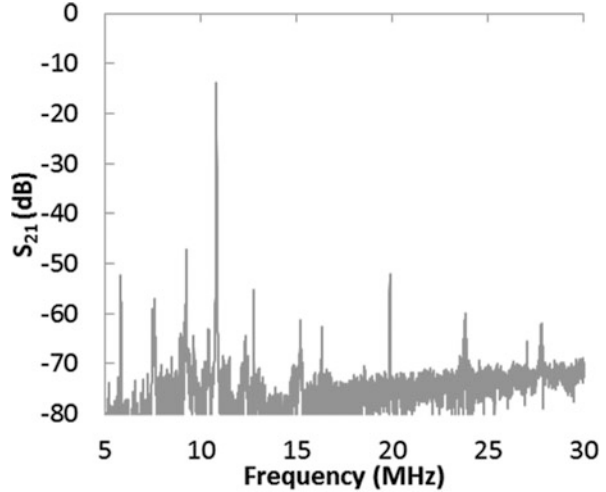
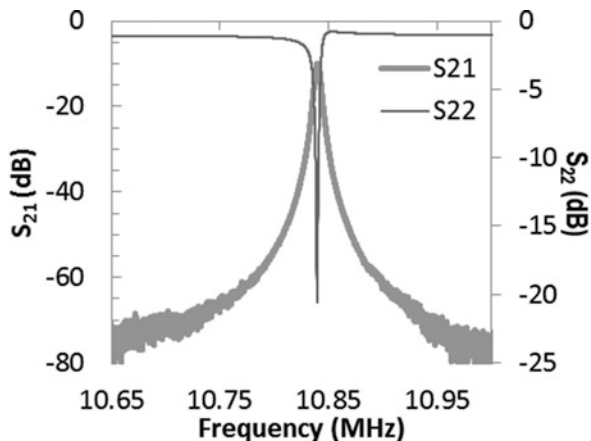


Fig. 2.29 Measured wideband S_{21} response of the 10.8 MHz PZT-on-Si filter from (Reprinted with permission. Copyright IEEE 2016) [60]



years with manganese/niobium doping [94–96] and ternary compounds based on thin film PZT and relaxor ferroelectrics [97] have demonstrated improvements in most material properties relevant to resonators including mechanical and dielectric loss, electromechanical coupling, and piezoelectric coefficients. FBAR resonators based on sputtered PMnN-PZT have demonstrated k_t^2 (49 %)- Q_m (185) products of 91 at 3.9 GHz with Curie temperatures that well exceed typical PZT [101]. Yet even this performance does not approach the best material k^2Q_m performance of commercially available bulk material PZTs. As stated earlier, thin film PZT has demonstrated piezoelectric coefficients and electromechanical coupling that are superior to similar bulk ceramic materials; however, thin films have yet to achieve the high-quality factors obtained with certain bulk PZT compositions. Figure 2.32

Fig. 2.30 Measured narrowband S_{21} and S_{22} responses of 10.8 MHz PZT-on-silicon 2-pole IF filter from [60]; response is from the same device in Fig. 2.29



plots the Q_m and material $k_p^2 - Q_m$ product versus the electrical Q (1/loss tangent) of commercially available bulk PZT compositions including modified PZTs [78]. The reported properties/results of the highest figure of merit thin film PZT resonator (FBAR from [68]) are plotted for comparison. It is evident that if similar Q_m and $k^2 Q_m$ performance can be achieved in thin films as in bulk material, that as much as an order of magnitude in improvement in PZT MEMS resonator FOM can be expected. Future improvements in the quality factor and figure of merit of PZT-based contour-mode MEMS resonators are expected to utilize such modified PZT materials.

2.1.5 Summary

This chapter has introduced the reader to the leading ferroelectric material used in thin-film piezoelectric MEMS: lead zirconate titanate ($\text{PbZr}_x\text{Ti}_{1-x}\text{O}_3$) or PZT. An overview of the material deposition and patterning techniques were provided as an introduction to the complex nature of processing PZT thin films. Additionally, device design considerations related to processing have also been addressed with respect to PZT-based resonant devices. With increasing interest in PZT-based PiezoMEMS technology from the major MEMS manufacturers, it is anticipated that PZT thin-film-based resonant devices could become a commercial product in the coming years.

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Table 2.5 Comparison of PZT MEMS filter [60] with commercially available acoustic filters

Filter technology	# Poles	f_c (MHz)	BW (%)	Insertion loss (dB)	Roll-off (dB/kHz)	Ultimate attenuation (dB) (± 1.5 MHz)	Term. Imp. (Ω)	Size (mm ³)	Max. power (dBm)
PZT MEMS	2	10.8	0.04	6.8	2.1	60	50	5.2	13
Monolithic quartz	2	10.7	0.07	1.5	1.1	35	1800	587.3	-10
Ceramic	-	10.7	1.03	9	0.2	30	330	339.0	-
SAW	-	43.8	6.86	14.8	0.04	42	2000	826.1	27

Fig. 2.31 Select published results for PZT MEMS resonators since 1997; resonator figure of merit ($k_{\text{eff}}^2/(1-k_{\text{eff}}^2)Q_m$) versus the year the results were obtained. For results where only k_t^2 was provided, k_{eff}^2 was approximated as $\sim 70\%$ of k_t^2 based on [101]

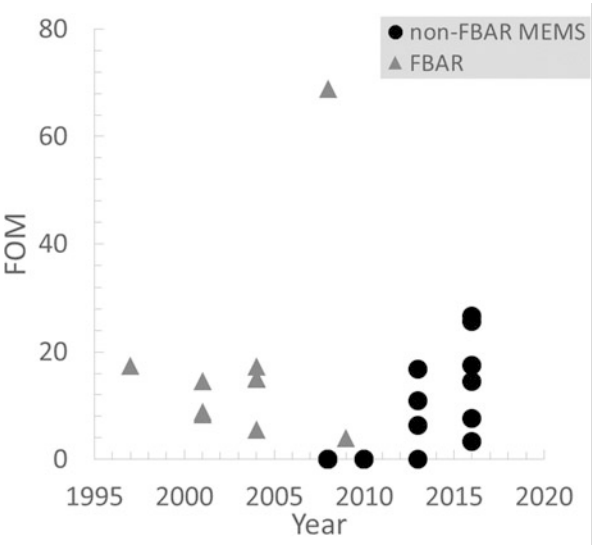
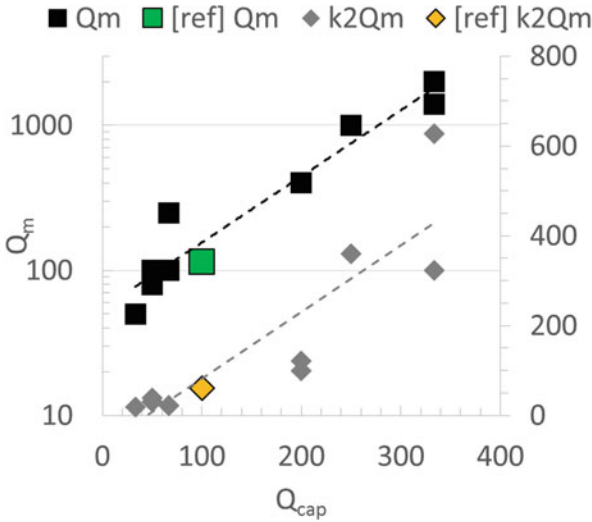


Fig. 2.32 Mechanical quality factor (Q_m) (logy axis) and material k^2-Q_m product versus capacitor electrical quality factor (1/loss tangent). The black and gray points are reported properties of commercially available bulk PZT compositions including modified PZTs [78] based on k_p^2 . The green and orange points are the properties reported for the highest figure of merit thin film PZT resonators to date from [68] for comparison. The lines are only intended to guide the eye



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