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Polar Ceramics in RF-MEMS and Microwave Reconfigurable Electronics: A Brief Review on Recent Issues

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Abstract. Properties and fabrication status of microdevices for microwaves based on polar ceramics are reviewed. We discuss bulk acoustic wave devices with AlN films, rf-MEMS capacitive switches with high permittivity materials, and tunable ferroelectrics. The relevant properties of ferroelectrics for microwave applications are summarized with emphasis on composites and thin films.

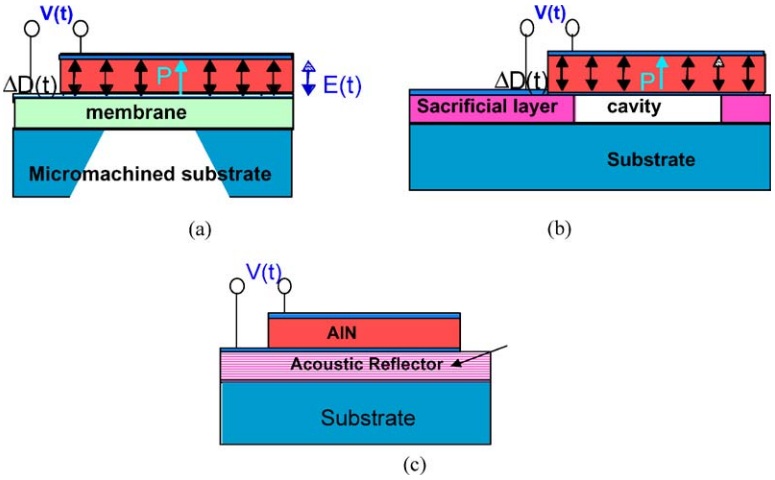
Keywords: ferroelectric, tunable, microwave, AlN, BST, piezoelectric, bulk acoustic waves, rf switch, rf-MEMS

1. Introduction

With the intensification of use of electronic communications, it becomes essential to produce high frequencies electronic systems that are miniaturized, reliable, and of low cost yet high performance. This is particularly true for integration of *passive* devices since passives occupy today nearly 60% of the total area of handheld devices. Due to their large size, and sometimes the need of special materials (e.g. $LiNbO_3$ crystals for surface acoustic wave devices) many microwave components such as filters and antennas are often placed outside the chip package, requiring inefficient connections, and introducing parasitic inductance into the system—miniaturization and integration of these components onto one substrate can be highly advantageous for cost and size reduction [1].

Miniaturized *tunable* capacitors open interesting perspectives for new *active* rf components: Miniaturized tunable filters, resonators, phase-shifters, antennas, etc. can potentially be manufactured with the desirable characteristics of very high Q (quality factor), narrow bandwidth, low power consumption, low insertion loss, high isolation, and high speed, replacing bulky, multi-component systems. The field of rf-MEMS (we refer to the wide definition of MEMS as microsystems not necessarily including moving parts) is being intensively developed for this end. The challenge in comparison of other MEMS containing devices is the making of high frequency circuitry that is compatible with MEMS technology. An area that received ample attention recently is that of rf-switches. These are either resistive or capacitive switches in which contacts are formed by actuation of a cantilever (usually a metallic cantilever actuated by electrostatic force) either with another metal (resistive switch) or with an insulator which is placed on top of a conductor (capacitive switch). An array of such elements, in which each element is individually addressed is often used. In parallel to the current development trends in IC technology, also MEMS developers realize that limiting the technology to that of standard materials such as Si, silicon oxide and silicon nitride does not necessarily provide the most efficient (performance to cost) and competitive solutions to miniaturization and integration components. Functional materials: piezoelectrics, ferroelectrics, magnetic, etc. are therefore being introduced. We limit this paper to polar ceramics.

Three groups of rf-MEMS components make use of polar ceramics: (1) acousto-electric components based on bulk acoustic waves [BAW] that control the transmission characteristics of a circuit utilizing the piezoelectric effect, (2) capacitive switches in which the dielectric layer is replaced by a high dielectric constant material, and (3) tunable capacitors in which tunability, namely the electric field dependence of the permittivity of ferroelectric materials is used to modify actively the capacitance of the circuit. The paper summarizes the



(a)

(b)

(c)

Fig. 1. Structure of BAW resonators: (a) Bulk micro-machined FBAR, (b) Surface micro-machined FBAR, and (c) SMR made of AlN film on an acoustic mirror [3].

state of art in polar materials for these three groups of components with emphasize on tunable ferroelectrics.

2. Polar Ceramics in Bulk Acoustic Wave Devices

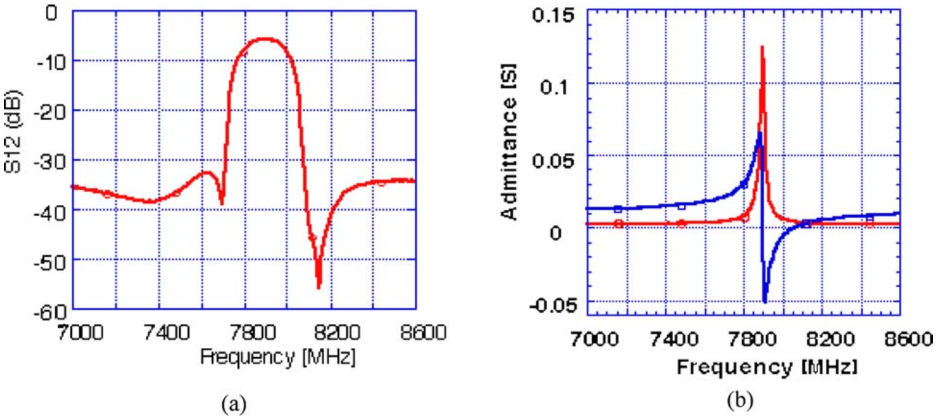
An important family of filters, resonators, and delay lines operates through the resonance of surface acoustic waves [SAW] that are generated in piezoelectric crystals, in particular $LiNbO_3$. The resonance frequency is inversely proportional in SAW devices to the distance between the interdigitated electrodes that are placed on the surface of the crystal, and the bandwidth is proportional to the coupling coefficient of the material. The increase in operation frequency of modern communication systems as well as the interest in miniaturization and integration motivates the replacement of the discrete SAW devices by BAW devices based on piezoelectric thin films. In the latter case the transmission frequency (f_o) is related to the thickness (t) of the film and the acoustic wave velocity in the material (vs) by $f_o = vs/(2t)$, placing the thickness, for devices operating at 2–10 GHz, in a convenient μm range.

BAW resonators are fabricated in 3 configurations: Bulk micromachined FBARs (Film Bulk Acoustic Resonators) offering excellent temperature stability (Fig. 1(a)), surface micromachined FBARs (Fig. 1(b)) offering flexibility of design, and SMR (Solidly Mounted Resonators) in which the suspended structure is replaced by an acoustic mirror built of alternating low and high acoustic impedance layers [2]. (Fig. 1(c)) thus offering additional robustness.

The material of choice for BAW devices is AlN [3], although devices based on other ceramic films, e.g. ZnO have been demonstrated too [4]. AlN is a polar material of the wurzite structure. It exhibits low leakage currents, low dielectric constant, and low dielectric and elastic losses with moderate piezoelectric coefficients. Due to its high elastic modulus, its sound velocity is high (5000–10000 m/s), and its limiting frequency is estimated to be above 100 GHz [5]. Its coupling coefficient ($k^2 = 6$–7%) is sufficient to obtain reasonable bandwidth. AlN based BAW devices feature a much higher Q factor than on-chip LC tanks which represent a competing downscaling technology [6]. An important advantage of BAW devices based on AlN films is the low temperature coefficient of the resonance frequency, 0–30 ppm/° depending on the device configuration [7]. As an example, Fig. 2 shows the performance of a BAW 7.9 GHz filter for microwave link in telephone network based on AlN thin film [8].

The best piezoelectric response is obtained when AlN films are grown with the [001] axis perpendicular to the surface of the substrate. Heteroepitaxial films sputtered on Pt electrodes in conditions that prevent formation of antipolar boundaries have shown excellent piezoelectric properties.

One of the attractive features of AlN is the possibility to process highly performing films at low processing temperature ($\approx 200^\circ$C). In this way standard silicon or GaAs substrates can be used as well as Al



(a) (b)

Fig. 2. Performance of 2 section π filter based on AlN SMR. The measured S12 scattering parameters in (a) give insertion loss of 7 db with bandwidth of 200 MHz for central frequency of 7.9 GHz. The resonance of a single resonator (30 μm^2) gave coupling coefficient of 5.9% and quality factor of 460 (b) [8].

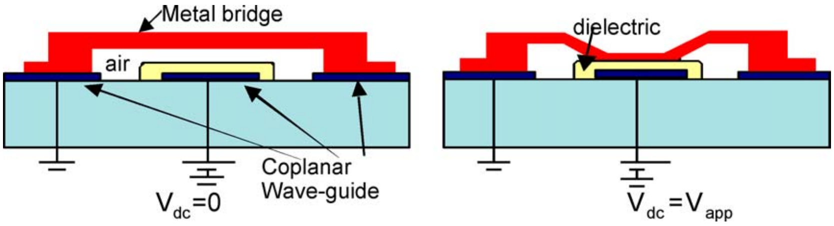


Fig. 3. MEMS capacitive switch in the up position, left, and in the down position (voltage applied), right.

bottom electrodes, and the resonators can be readily integrated with CMOS. Power handling capabilities are excellent [9].

3. Polar Ceramics in RF MEMS Switches

Activating passive devices by the introduction of tunability is of interest because one tunable element can replace a number of discrete components and reduce the volume and the weight of the device. Tunable high frequency capacitors made of mechanical MEMS switches are attractive because of their simplicity and are a subject of much development. The main advantage in comparison to PIN diodes is the lower power consumption. Another advantage is the lower losses. Switching speed is lower, but considered acceptable. Lifetime and reliability are still open issues. A typical capacitive switch is drawn in Fig. 3. Without tension the switch is in the up state, and a low capacitance is maintained between the bridge and the central conductor of the coplanar wave-guide line. Applying voltage between the two electrodes switches the bridge down, increasing the capacitance and short-circuiting the rf signal to the ground pads.

Typically SiO_2 or SiN_x are used as a dielectric layer. Replacement of the dielectric by a high permittivity material such as $(Ba,Sr)TiO_3$ [BST], increases the on/off ratio of the capacitance. BST MEMS switches have been reported recently by a number of groups [10, 11].

4. Tunable Ferroelectrics for Reconfigurable High Frequency Electronics

The permittivity of ferroelectrics, especially in temperatures not too far from the ferroelectric phase transition is strongly electric field dependent. Therefore a ferroelectric capacitor can in principle serve as a varactor, voltage dependent capacitor, fulfilling the same function as rf-MEMS switch or a semiconductor varactor. In comparison to rf-MEMS capacitor switches, tunable ferroelectric capacitors do not have mechanical parts and their response is faster. While the materials are not the standard IC materials and require development, the technology is rather simple albeit not yet worked in details. Tunable ferroelectrics are attractive for applications where the relatively high power consumption of pin diodes and the relatively slow response of MEMS switches make these solutions less attractive.

The most interesting materials for tunable ferroelectric applications are the displacive ferroelectrics in their paraelectric phase or incipient ferroelectrics such as $SrTiO_3$ [STO]. The high Curie-Weiss constant of these materials results in high values of dielectric permittivity and tunability even far above the Curie temperature, which also reduces the sensitivity of the permittivity to temperature changes. The absence of ferroelectric domains helps in keeping the loss level low.

The fundamental parameters that govern the functionality of ferroelectrics in tunable applications are summarized below. Critical review on the state of art is published elsewhere [12]. Much advancement has been achieved recently in the processing and fabrication technology [e.g. 13, 14]. Processing parameters, although of highest importance, are not discussed here due to space limitation.

4.1. On the Tunability and Losses of Ferroelectrics

The most important requirements from a ferroelectric for tunable applications are a high tunability and low dielectric losses. Tunability, n, is the ratio between the permittivity of the material at zero *dc* field $\varepsilon(0)$ and its permittivity under a given electric field $\varepsilon(E_o)$. Sometimes the relative tunability, n_r, is used: $n_r = 1 - 1/n$ (expressed usually in %). Starting from the usual expansion of the free energy with respect to the macroscopic polarization P of the material, it is possible to show that for low values of n the dependence of the tunability on the applied electric field and on $\varepsilon(0)$ is:

$$n = \frac{\varepsilon(0)}{\varepsilon(E_o)} = 1 + 3\beta\varepsilon(0)\varepsilon_0 P_{\mathrm{dc}}^2 \approx 1 + 3\beta(\varepsilon(0)\varepsilon_0)^3 E_0^2 \tag{1}$$

where β is the non-linear phenomenological coefficient, e.g. for BST typically $\beta \approx 8\ 10^9/\mathrm{JC^{-4}m^{-5}}$. Namely for low fields the tunability depends cubically on the permittivity. For large n (high fields):

$$\varepsilon(E_o) \approx \beta^{-1/3} E_o^{-2/3}/(3\varepsilon_0) \tag{2}$$

implying $n \propto \varepsilon(0)$. This is illustrated in Fig. 4, comparing materials with $\varepsilon_r(0)$ of 2000 and 1000. The *dc* field required to obtain tunability of the practical range of $n \approx 2$ depends on the permittivity with the relation $E_o \propto \varepsilon^{2/3}$. It is therefore obvious that a good tunable ferroelectric is high permittivity material. Detailed analysis is given in ref [12].

Good performance and low power loss is obtained with tunable materials of low dielectric losses. In high frequencies, dielectric losses arise from both fundamental phonon loss mechanisms and extrinsic mechanisms (due to the coupling of the microwave field with defects). Among the known extrinsic loss mechanisms those considered as significantly contributing to the loss in tunable microwave materials are losses due to interaction of the electromagnetic field with charged

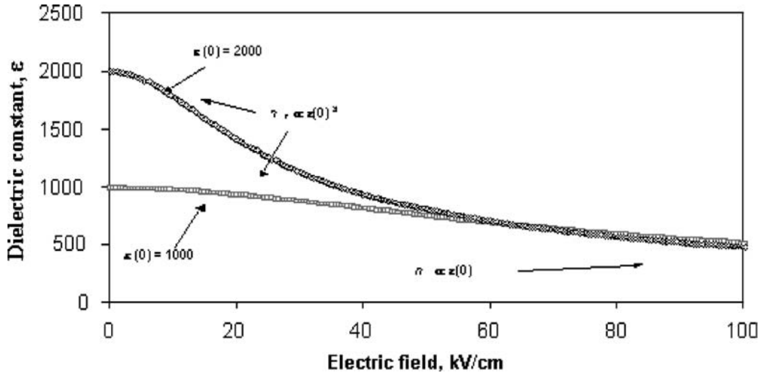


Fig. 4. Dielectric constant versus electrical field for hypothetical materials of various zero field permittivity. $\beta = 8 * 10^9/\mathrm{JC^{-4}m^{-5}}$ was used for the calculation of the field dependence.

defects, universal relaxation law mechanism, and quasi-Debye contribution induced by random-field defects. The intrinsic loss mechanisms correspond mainly to absorption of energy quanta of the electromagnetic field $\hbar\omega(\omega$ is the ac field frequency) during its collisions with thermal phonons, which have much higher energies.

In the ferroelectric state, an additional loss mechanism, the so-called quasi-Debye loss mechanism contributes to the losses. Quasi-Debye loss arises from modulation of the phonon spectrum off its equilibrium value due to the oscillation of the ac field, followed by a relaxation. *Quasi-Debye loss is allowed only in non-centrosymmetric crystals* where the phonon frequencies are linear function of the small electric field applied to the crystal. The oscillations of the ac field result in time modulation of the phonon frequencies that in turn induces a deviation of the phonon distribution function from its equilibrium value. A relaxation of the phonon distribution function gives rise to dielectric loss in a similar way as a relaxation of the distribution function of the dipoles gives rise to the loss in the Debye theory, hence the name 'quasi-Debye loss'. An important feature of the quasi-Debye mechanism is that, once allowed by the symmetry, it may introduce losses that are few orders of magnitude larger than losses due to other intrinsic mechanisms and comparable is magnitude to losses due to intrinsic mechanisms.

In microwave materials for tunable applications, which are typically centrosymmetric, the quasi-Debye mechanism does not contribute to the loss in the absence of the tuning bias. However, under a dc bias field, due to the breaking of the central symmetry, a *dc-field-induced quasi-Debye mechanism* occurs. For dc fields corresponding to small relative tunability the loss tangent depends quadratically on the applied field. For higher fields, the quadratic dependence does not hold, and appears to be different for different materials. This implies that the contribution of the field-induced quasi-Debye loss can dominate the total balance of the loss of a material, especially in the case of thin films where high dc fields are readily achievable.

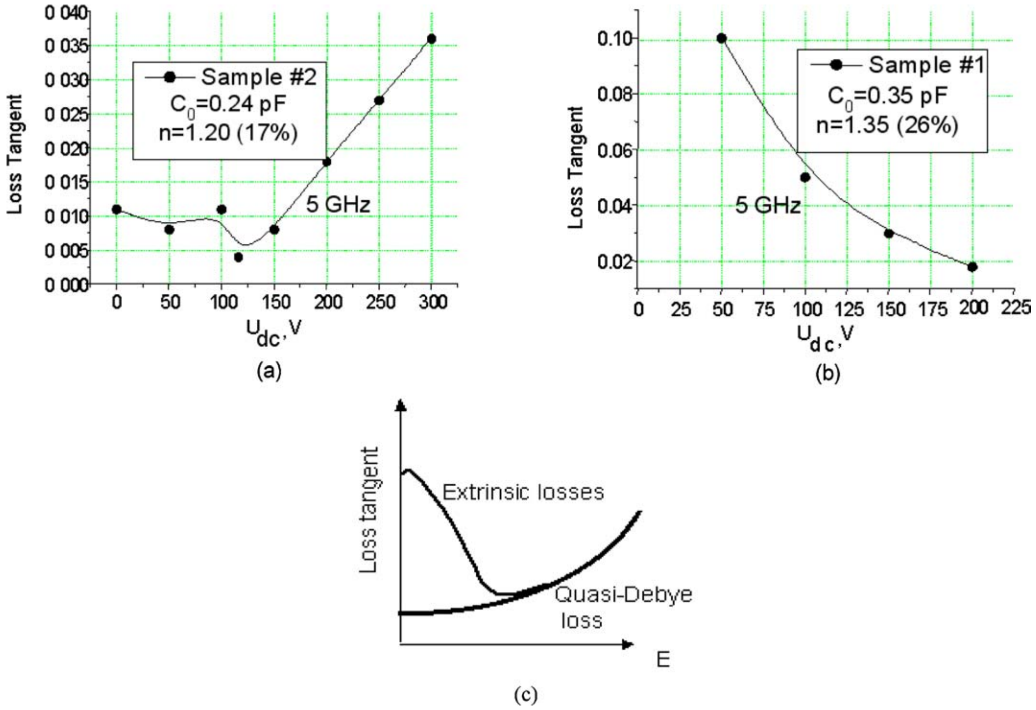
The role of the intrinsic mechanisms in the total balance of the dielectric loss of a material is strongly dependent on the dielectric permittivity of the material and the measuring frequency: typically, the higher the frequency and permittivity, the more important is the intrinsic loss. In the case of tunable ferroelectric materials at microwave frequencies, the intrinsic and extrinsic contributions are comparable so that the dominating contribution to the loss may be extrinsic or intrinsic depending on the quality of the material. An extrinsic/intrinsic crossover in loss may also take place under the action of a dc bias field, i.e. without the field, the extrinsic contribution dominates the loss, whereas under the field the intrinsic one does. This is shown in Fig. 5.

Altogether, for the materials of interest, the quasi-Debye mechanism is the only mechanism that leads to a higher loss under field, while the other mechanisms, intrinsic and extrinsic alike are more severe in the zero field situation where the permittivity is at maximum. In this way, the quasi-Debye mechanism imposes an upper limit on the tunable performance as a function of dc field. However, it should be kept in mind that the importance of Quasi-Debye loss varies from material to material, depending on the damping of the soft mode phonons. In such a way the losses are some what less field dependent in BST than in pure STO [e.g. 12].

4.2. Tunability of Ferroelectric/Dielectric Composites

Ferroelectric elements for tunable applications may be, intentionally or unintentionally, multiphase elements consisting of a ferroelectric phase and a dielectric phase of lower permittivity and losses. Addition of an 'inert' phase such as MgO to BST was reported recently to have positive effects (improved tunability and reduced losses) [15]. Thin film capacitors are known to have a 'passive layer' at the interface with the electrode and this makes them composites too: If the dielectric permittivity is measured in plane, the capacitor is a parallel composite, while if the dielectric permittivity is measured thickness wise, the capacitor can be modeled as an in-series composite (Fig. 6).

Taking into account the redistribution of the electric field in the composite, its overall permittivity, tunability and loss can be derived as a function of the relative volume of the two phases. It can be shown that in the parallel model and in the spherical inclusions model the tunability stays unchanged or only weakly volume dependent, while the permittivity is reduced. This can be useful in some applications such as dielectric lenses. For the in-series model, it can be shown that the tunability is equivalent to that of a pure ferroelectric in which the transition temperature has been shifted to a lower temperature relative to the initial ferroelectric transition. The often used 'brick model' of ferroelectric



(a) (b) (c)

Fig. 5. The influence of the quality of the ferroelectric capacitor on the field dependence of the dielectric loss: (a) High quality STO thin film capacitor manifesting quasi-Debye loss, (b) STO thin film capacitor of a lower quality manifesting extrinsic losses with reduction in the loss under field, and (c) schematic description of expected behavior of ferroelectric material with and without extrinsic losses under field, showing also the cross-over.

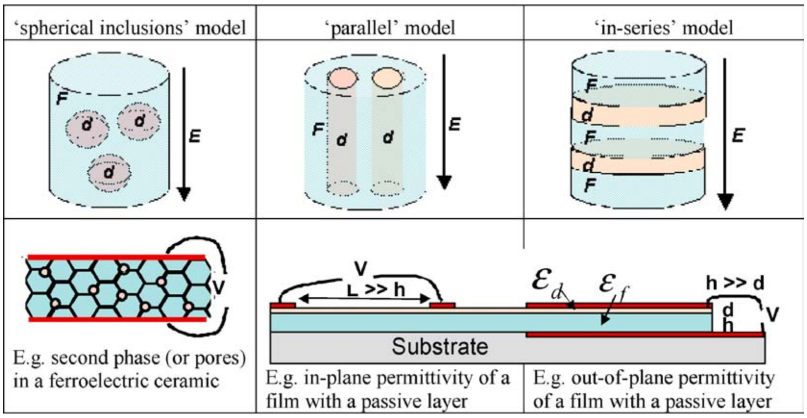


Fig. 6. Illustration of the 3 model composites, 'spherical inclusions', 'parallel' and 'in-series' and the corresponding capacitor structures. F-ferroelectric phase, d-dielectric phase ($\varepsilon_f \gg \varepsilon_d$).

bricks separated by a low concentration low dielectric constant inert phase behaves like the in-series model. All this is shown in Fig. 7. In both the composite models of spherical inclusions and of parallel configuration the losses are not reduced upon the increase of the passive phase. This means that the reports on reduction in loss in composites with dispersed inert dielectric phase are not related to the formal composite effect but rather to a chemical, microstructural or interfacial effect of the added phase.

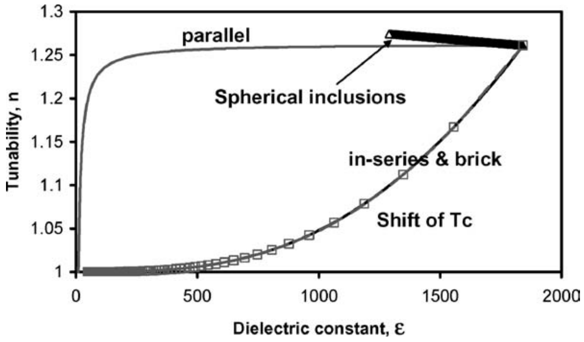


Fig. 7. Modeling of the change in tunability as a function of the dielectric constant for parallel model, in-series model, and spherical inclusions model. The in-series composite model is the same as an identical pure ferroelectric material of a lower transition temperature. The parameter used here are $\beta = 8.2 * 10^9\ \mathrm{JC^{-4}m^{-5}}$, $E = 17\ \mathrm{kV/cm}$, $\varepsilon(0) = 1840$. Spherical inclusions after Ref. [15, 16].

4.3. *Tunable Thin Films*

The use of thin films for tunable applications means substantial voltage reduction, and lower cost of production. *Microwave ferroelectric phase shifters* are of highest interest: A phase array antenna consists of numerous of radiating elements served by as many phase shifters. The phase shifters are used to modify and control the width and angle of the scanned radar beam. The use of ferroelectric films enables the integration of the phase shifters with the microwave circuits on one substrate, reducing the size, mass, and cost of the antennas in comparison to today's microwave semiconductor modules.

The dielectric response of tunable ferroelectric thin films differs from that of bulk materials: their permittivity is often lower and the loss is higher. Size effects are responsible for a part of the differences: The ferroelectric lattice is harder near the surface in comparison to the bulk. The ferroelectric film can be therefore considered as a composite of a ferroelectric layer sandwiched between two dielectric layers of a very small thickness. The hardness is a result of extrinsic and intrinsic reasons. The first is a processing related effect: The interface often has a higher concentration of lattice defects (vacancies, dislocations) and this weakens the dielectric response. Precise processing can reduce this effect. The intrinsic reasons for the dielectric hardness at the surface of the ferroelectric film are surface blocking of the polarization and depletion effect (built-in depletion charge due to depletion of carriers from the region adjacent to the electrodes). In addition, in the case of plate capacitor, the response is affected by the fact that the free charges in the electrode form a finite thickness layer that behaves as a capacitor connected in-series with the dielectric film. Effectively, this electrode effect is similar to a passive layer.

Detailed experimental investigations to differentiate the various size effects are not reported so far. However, the thickness effect has been reported by several authors [17–19]. The thickness dependence of in-plane permittivity has rarely been reported although it is of importance for applications as well as for the differentiation between the various physical mechanisms that contribute to this effect.

Misfit strain may substantially shift the Curie temperature and modify the permittivity. This has been shown theoretically [20]. The effect can be as strong as to make the normally insipient ferroelectric STO to be ferroelectric at room temperature [21].

The dielectric loss in thin films is roughly one order of magnitude higher than in bulk materials. The excessive loss in the films compared to single crystals clearly attests to their mainly extrinsic origin. A more detailed investigation revealed that, in well-prepared films (that have low loss at zero dc field), an increase of loss under dc field is observed, compatible with the Debye-loss mechanism (Fig. 5 above). The influence of strain on losses and on the tunability is expected to be limited to that obtained indirectly through the modification in the dielectric permittivity.

In spite of the many open questions, various group have demonstrated tunable devices with excellent performance: York and coworkers have shown recently [22] low voltage (20 V) phase shifters using parallel plate capacitor configuration having figures of merit of 93°/dB at 6.3 GHz and 87°/dB at 8.5 GHz.

5. Conclusions

The paper reviewed applications, fabrication and properties of polar ceramics in rf-MEMS and in microwave reconfigurable electronics. Integrated acousto-electric BAW devices based on polar thin films, mainly AlN, entered recently the market, after a rather short development period. They are likely to replace existing technologies on the basis of performance, ease of miniaturization, integration, and cost reduction. In the second application, rf-MEMS capacitive switches, polar ceramics such as BST are of interest due to their high permittivity. Thirdly, tunable ferroelectrics were discussed in view of their potential applications in tunable microwave devices. These applications put high demands on the material performance: Although further studies are needed, e.g. with regards to reliability and long term performance, ferroelectric thin film are attractive because tunability can be achieved with low voltage, as has been demonstrated in the last years by a number of groups.

Acknowledgments

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