Microwave Planar Capacitors Employing Low Loss, High-K, and Tunable BZN Thin Films

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Abstract **— Planar capacitors having high *Q* factor and tunability were implemented with cubic pyrochlore $Bi_{1.5}Zn_{1.0}Nb_{1.5}O_7$ (BZN) thin films deposited by RF magnetron sputtering. Device *Q* factors (Q_{DUT}) and capacitances (C_{DUT}) were measured using reflection coefficients based on vector network analyzers on Vycor glass and sapphire substrates, respectively. *Q* factors (Q_{int}) accounting for electrode and dielectric losses remained above 200 up to 20 GHz and around 1000 up to several GHz for the smaller devices on sapphire substrate and there was no sign of onset of dielectric relaxations. With the electric field dependent permittivity, the BZN thin films can be the alternative to conventional BST thin films.**

Index Terms **— Dielectric properties, Bismuth Zinc Niobate, Low-loss, Thin films**

I. INTRODUCTION

Metal-Insulator-Metal (MIM) capacitors employing high permittivity thin film technologies are one of the most extensively researched passive microwave components due to their relatively large fraction in the integrated circuits and the effort on increasing capacitance density and *Q* factors in CMOS technologies. Thin films exhibiting electric-field dependent permittivities are recently being explored for microwave frequency agile devices such as phase shifters and filters. In addition to a large tunability, these devices require dielectrics with low dielectric losses (tan δ) in the microwave frequency range. For room temperature applications, thin films of ferroelectrics such as $(Ba,Sr)TiO_3$ (BST) have been widely researched [1]. However, the synthesis of low loss BST thin films has proven to be challenging. In addition to intrinsic loss mechanisms, losses in BST films are determined by point defects, which are often difficult to control in thin film deposition. Lately, thin films of a non-ferroelectric material, $Bi_{1.5}Zn_{1.0}Nb_{1.5}O_7$ (BZN), having the cubic pyrochlore structure and high dielectric constant (170~200) have attracted interests for tunable applications due to very low losses (~5×10^{-4}) and large tunabilities (~55%) at low frequencies (~1 MHz) [2-6]. The field tunability $\Delta\varepsilon$ is defined as $(\varepsilon_{\max}-\varepsilon_{\min})/\varepsilon_{\max}$, where $\varepsilon_{\min}$ is the minimum measured permittivity at the maximum applied field, and $\varepsilon_{\max}$ is the dielectric constant at zero bias.

BZN ceramics exhibit a low temperature dielectric relaxation that is accompanied by a dielectric loss peak. This loss peak shifts to higher temperatures with higher frequencies, approaching room temperature in the microwave frequency region [7-9]. Therefore, bulk BZN is alleged inappropriate for low losses applications. Thin films, however, have different properties. For example, we have recently shown that tensile film stresses, on account of the thermal mismatch with substrates, reduce the activation energy of the dielectric relaxation and require higher frequencies to shift the dielectric relaxation into higher temperatures [10]. Thus BZN films can be presumably very promising for low loss and microwave frequency applications. Unfortunately, only single study has been reported on microwave dielectric measurements of BZN films at a single frequency so far [11].

The dielectric responses of BZN thin film capacitors are reported in this paper over a broad frequency range in the GHz region and very high *Q* factors can be obtained in tunable devices employing BZN films.

II. FABRICATION AND LOW FREQUENCY CHARACTERISTICS

BZN thin film capacitors were fabricated on Vycor glass (500 µm) and sapphire substrates (330 µm), respectively. The process details were as follows. The BZN film was deposited by RF magnetron sputtering after Ti/Pt (250/2000Å) bottom electrode deposition. Detailed sputter conditions are summarized in table 1 [3,14].

Table 1 BZN Sputter conditions

Sputter Parameters	Conditions
Base Pressure	1×10^{-8} Torr
Target-Substrate Distance	4 inch
Substrate Temperature	RT ~ 300 ºC
Substrate rotation	30 rpm
Overall gas pressure	50 mTorr
Ar/O2 flow rate ratio	85/15
Plasma power	150 Watts
Annealing atmosphere/Temperature	Air/750 ºC

The film thickness was ~3000Å and the capacitance density under this conditions leaded to ~5fF/μm^2. Films were patterned using 1:10 HF solution for 60 seconds. An ex-situ annealing at 750ºC in air for 5 minutes was carried out to crystallize the films. A 2000Å SiO$_2$ crossover layer was evaporated for passivation of the bottom electrode, and a 5000Å Au top electrode was patterned by a lift-off process. A rapid thermal annealing (RTA) at 700ºC for 30 seconds was performed and thick Au (1μm) metal contacts for probe measurements were evaporated to form the low-resistance interconnects and probe pads. Devices were separated by at least by 200 μm from each other to avoid cross-talk among them. The cross-sectional layout of the BZN capacitors is shown in the inset of Fig. 1.

Dielectric constant, *Q* factors, and tunabilities of the films at low frequencies (less than 100 MHz) can be obtained using relatively large area MIM capacitor structures. The maximum tunability was ~30% for the microwave devices as Fig. 1. This tunability was less than that of larger area devices on un-prepatterned bottom electrodes used for low-frequency measurements [3], shown for comparison in Fig. 1. The lower tunability of the films in the microwave devices was due to a lower dielectric strength that did not permit the application of large enough fields required for high tunabilities. The lower breakdown strength may be due to degradation of the air-exposed prepatterned electrode or due to field concentration at the edges.

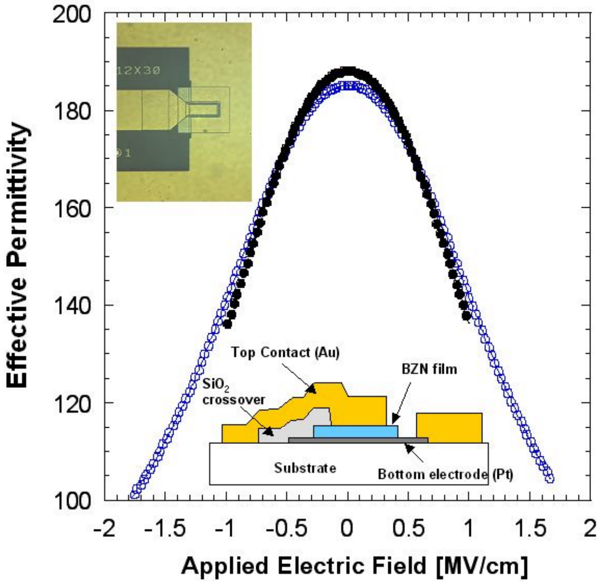


Fig. 1 Bias field dependence of the permittivity of 1500Å thick BZN film in a planar vycor/Pt/BZN/Pt capacitor structure (capacitor area: 2000 μm^2, open blue) and a 360 μm^2 microwave capacitor (solid black), both measured at 1 MHz. The insets show a schematic cross-section of the microwave capacitor (bottom) and a photograph of the device (upper left).

III. MICROWAVE FREQUENCY CHARACTERISTICS

At microwave frequencies, resistive and inductive parasitics in the capacitors strongly influence the measurements and data interpretation [12,13]. Devices with a small area are advantageous because they have a lower intrinsic capacitance, thus avoid self-resonance, and minimize extrinsic losses. However, small device areas lead to increased ohmic loss, and the high intrinsic capacitance densities of thin films of tunable dielectrics such as BZN and BST require electrode areas that are smaller than typical on-wafer probe tips, making measurements challenging. Relatively thick (~3000Å) BZN films were used for the microwave frequency characterization to alleviate these problems in this work. Rectangular MIM capacitors with areas between 50 and 900 μm^2 were fabricated that were subsequently interconnected to a larger metal contact or transmission-line that was probe-able. Depending on their size, the device capacitances ranged between 0.1 and 4 pF, which corresponds to values of nearly all microwave circuit applications.

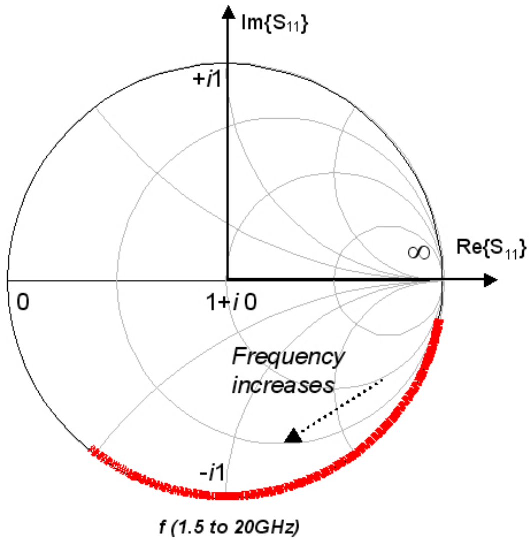
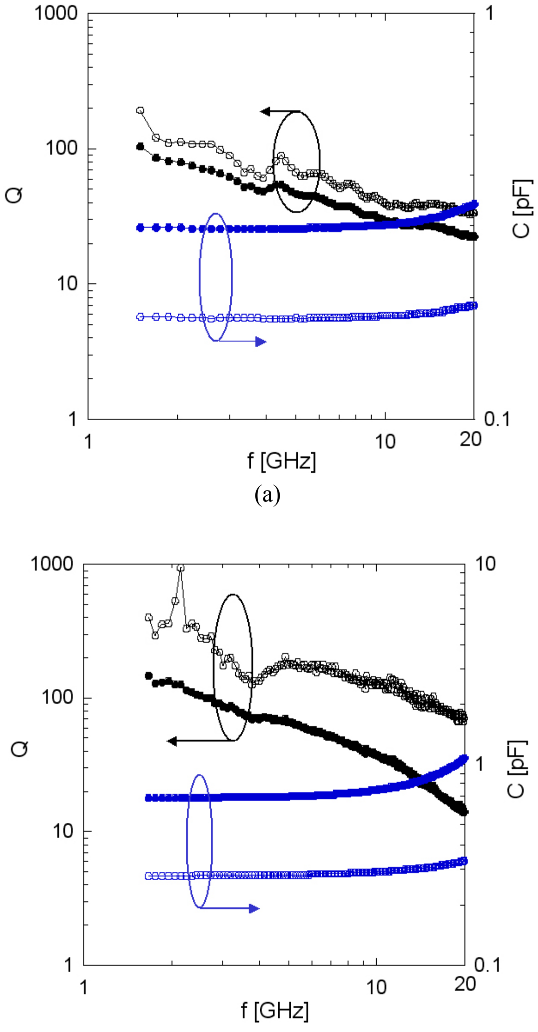


Fig. 2 Measured reflection coefficient (S$_{11}$) of BZN thin film capacitor on sapphire substrate for 100 μm^2 capacitor.

$$Z_{int} = \left.\frac{Z_{op}^2\left(Z_{DUT}-Z_{sh}\right)}{\left(Z_{op}-Z_{DUT}\right)\left(Z_{op}-Z_{sh}\right)}\right|_{Z_{op}\to\infty} \approx \left(Z_{DUT}-Z_{sh}\right) \quad (1a)$$

$$Q_{int} = \frac{\mathrm{Im}(Z_{int})}{\mathrm{Re}(Z_{int})} \quad (1b)$$

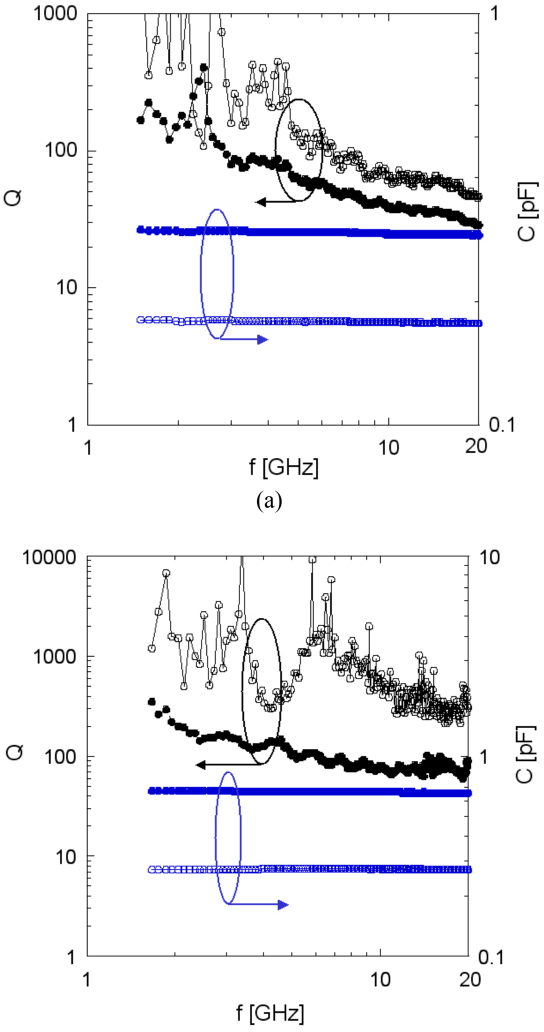
$$C_{int} = \frac{-1}{\omega \times \mathrm{Im}(Z_{int})} \quad (1c)$$



(a)

(b)

Fig. 3. Total device quality factor Q_{DUT} (black) and capacitance C_{DUT} (blue) on each substrate for two different area devices.
(a) Vycor glass substrates (○: 64 μm^2, ●: 100 μm^2)
(b) Sapphire substrates (○: 100 μm^2, ●: 225 μm^2)



(a)

(b)

Fig. 4. Intrinsic quality factor Q_{int} (black) and capacitance C_{int} (blue) for BZN capacitors after accounting for pad parasitics
(a) Vycor glass substrates (○: 64 μm^2, ●: 100 μm^2)
(b) Sapphire substrates (○: 100 μm^2, ●: 225 μm^2)

Fig. 3(a)~(b) displays the measured Q_{DUT} and C_{DUT} for vycor glass and sapphire substrates, respectively. Single port devices were designed and measured due to their simplified de-embedding processes. Using equations (1a)~(1c), the intrinsic Q factor Q_{int} and capacitance C_{int} were extracted after the test structure measurements. Open- and short-test devices, the identical devices without dielectric films, were fabricated for each size device separately on the same wafer and measured for accurate deembedding. Fig. 4(a)~(b) shows the intrinsic Q_{int} and C_{int} for vycor glass and sapphire substrates, respectively. The intrinsic capacitance C_{int} showed very little dispersion, only a slight decrease with frequency following a power-law with a small exponent, as would be expected for a nearly constant loss tangent. There was no indication of an onset of a dielectric relaxation, which would exhibit a much stronger frequency dependence [7]. The quality factor Q_{int} was frequency dependent but remained above 200 up for frequencies up to 20 GHz and around 1000 up to several GHz for the smaller device. The large scatter in the high Q-factor data is a limitation of network analyzer measurements as the device impedance moves away from 50 Ohms. The observed device area or periphery dependence of the quality factor Q_{int} is presently not understood but has also been observed for high-Q BST thin film capacitors [15]. The results suggest that the device performance at high frequencies is not limited by intrinsic BZN film losses, because such losses would be area (or periphery)-independent and would be accompanied by a stronger capacitive dispersion. The decrease in *Q* factor with increasing frequency is at least partially due to electrode conductor losses, which in the absence of other effects can easily dominate the device quality factor in small-area capacitors at high frequencies [3,16]. Low-frequency measurements of large-area capacitors showed that the contributions of electrode losses to the device quality factor became significant above 100 MHz [3]. The contributions of top and bottom electrodes may depend on device geometry [15]. It is also possible that an interfacial layer at the metal/dielectric interface that cannot be neglected at microwave frequencies contributes to the device quality factor [16]. The possible reason for obtaining higher *Q* factors with sapphire substrates may be the higher dielectric constant and lower loss of the substrates. Work is underway to reduce the contribution from the bottom electrode to the device *Q*-factor by using thicker electrodes with a higher conductivity and by optimizing the device design [16,18]. For bulk BZN, *Q* of ~33 at 1 GHz and ~8.3 at 10 GHz have been reported [9]. The Q-factors of the BZN thin film capacitors at microwave frequencies are much better than those of the best BST devices published so far [19]. Thus, despite significant contributions from the electrodes and other unaccounted parasitics to the device *Q*-factor, the much higher *Q*-factors of thin film devices showed that the BZN thin films investigated in this study had much lower intrinsic losses than bulk BZN at similar frequencies.

IV. CONCLUSION

High *Q* factor capacitors were realized using low loss, tunable, and high-permittivity BZN thin films. The dielectric properties were evaluated up to 20 GHz by measuring reflection coefficients. The intrinsic *Q* factors remained above 200 for entire frequency range and higher than 1000 up to several GHz range. The capacitors employing BZN thin films can be very promising to any of low loss microwave circuit applications due to high *Q* factors as well as the tunability.

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