High Q, Tunable Thin Film Capacitors and Geometrical Effects on Device Performance at Microwave Frequencies

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Abstract
Low loss, tunable capacitors were fabricated by rf magnetron sputtered high-k Bi$_{1.5}$Zn$_{1.0}$Nb$_{1.5}$O$_7$ (BZN) thin films. The dielectric properties were extracted by de-embedding procedure up to 20 GHz by means of reflection coefficients measurements. The extracted dielectric properties of BZN thin films were that permittivity was ~180 and tunability was ~30%. On vycor glass substrates, the Q factor including dielectric- and electrode-loss was more than 200 up to several GHz for 64 µm² device. There was no indication of onset of dielectric relaxation for the measurement frequency ranges. Q factor dependency on device geometry was also analyzed. The series resistance of the electrodes dominated the device Q factor at microwave frequencies. The electrode resistances were modeled by the sum of area-, periphery-, and conductor-dependent terms. The periphery-dependent series resistance was the most affected by the changes of device changes. Based on the analysis, improved device performance at microwave could be expected by increasing device perimeter. The BZN thin film capacitors with the high Q factor, electric field dependent permittivity, and refined device layout can be the alternative microwave passive components.

1. Introduction
Due to the miniaturization, the volume of state-of-the-art system can be realized smaller than ever before. Tunable applications such as phase shifters, matching network, and tunable filters demand the higher Q of LC resonant tank. The effects on improving inductors’ performance so far have been conducted and partially successful. However, prominent results have emerged with high-k material such as ferroelectric thin films. Those films exhibiting tunable permittivity are being extensively studied for microwave frequency agile devices. For room temperature applications, thin films of (Ba,Sr)TiO$_3$ (BST) have been most widely studied [1,2]. However, the synthesis of low loss BST thin films has shown 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. Recently, thin films of a non-ferroelectric material, Bi$_{1.5}$Zn$_{1.0}$Nb$_{1.5}$O$_7$ (BZN), the cubic pyrochlore structure and high permittivity (170~200), have attracted prominent condition [4]. The film sputtered was ~300 nm. Films were patterned using 1:10 HF solution for 60 seconds. An ex-situ annealing step at 750 ºC for 5 minutes was carried out to crystallize the films. A 200 nm SiO$_2$ crossover layer was evaporated to passivate the bottom electrode and the Au 500 nm top electrode was patterned by a lift-off process. A rapid thermal annealing (RTA) at 700 ºC was performed and Au 1 µm metal contacts for probe measurements were evaporated. The layout of the BZN capacitors is shown in Fig. 1.

Fig. 1. The top and cross-sectional layout of BZN thin film capacitors
The gap between top- and bottom-electrodes were 1~2 µm to improve the loss characteristics. To avoid cross-talk among devices, devices were separated by at least by 200 µm from each other. The device design was optimized to reduce series resistive components by tapering the access contact from the active area to the coplanar waveguide (CPW) contact pads, by depositing thicker electrodes, and by reducing the number of fabrication steps. The device areas ranged from 50 to 900 µm$^2$ and corresponding device capacitances covered those relevant for microwave circuit applications (0.1~4 pF).

2. Device Design and Fabrication
Devices were fabricated on 500 µm vycor glass substrates. Ti/Pt electrode was lifted off and followed by rf magnetron sputtered films under the optimized condition [4]. The film sputtered was ~300 nm. Films were patterned using 1:10 HF solution for 60 seconds. An ex-situ annealing step at 750 ºC for 5 minutes was carried out to crystallize the films. A 200 nm SiO$_2$ crossover layer was evaporated to passivate the bottom electrode and the Au 500 nm top electrode was patterned by a lift-off process. A rapid thermal annealing (RTA) at 700 ºC was performed and Au 1 µm metal contacts for probe measurements were evaporated. The layout of the BZN capacitors is shown in Fig. 1.

3. Device Performance at Microwave Frequencies
For low frequency range, devices were characterized by low frequency impedance measurements to evaluate the loss tangent and tunability. The typical area of the device under test (DUT) was 30x50 µm$^2$ and devices were measured from 100 Hz to 100 MHz. The tunability calculated was ~55% and the loss tangent was less than 0.0005 under zero bias at 1 MHz. Figure 2 shows the measured tunability and dielectric loss obtained from the low frequency measurements.

Small devices require additional transmission lines since direct probe contacting is impossible given the CPW probe size due to relatively high intrinsic capacitance density of BZN thin capacitors. This necessarily required de-embedding procedures to evaluate microwave frequency devices.

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occupying small electrode areas for RF capacitor realization. Microwave measurements were made using an Agilent 8362B PNA and an on-wafer probe station and analyzed using a software program.

The de-embedding procedure is summarized in Fig. 3. Single port devices were in this paper designed and measured due to their simplified de-embedding processes. The admittances of the DUT were measured in Fig. 3 and from Eqn. (1a). Quality factors and capacitances were extracted using Eqn. (1b) and (1c). Figure 4 shows the quality factors and capacitances of the DUTs after the deembedding procedure. As can be seen in Fig. 4, resonances were mostly due to parasitic components that were eliminated during the deembedding process. For the 64 µm² devices, the quality factor was more than 200 up to 5 GHz. No onset of a dielectric relaxation could be detected, i.e. the capacitance remained constant around the measurement frequency ranges. Bulk BZN shows dielectric relaxation in the microwave frequency ranges [5]. The Q factors of the BZN thin film capacitors at microwave frequencies are comparable to those of the best BST devices published so far [6] and further optimization of devices such as thicker bottom electrodes and sophisticated layout will further improve device quality factor.

4. Geometrical Effect on Microwave Frequency Performance

Around microwave frequency ranges, the layout of devices becomes significant for improving the Q factors as introducing microwave loss mechanism such as skin depth. The series resistance of the electrodes dominated the device quality factor at higher frequencies. The series resistance of both electrodes has been considered as constant value for most of the microwave device analysis. As the increase in the permittivity of dielectric materials makes the device smaller, this inevitably increases effect of contact electrodes and the design of electrodes become more important.

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\begin{align*}
R_{total} &= R_A + R_P + R_S = \alpha + \frac{\beta}{2L+L} + \gamma \frac{L}{W} \\
C &= \varepsilon \frac{WL}{t_f} \\
Q &= \frac{1}{\omega CR_{total}}
\end{align*}
\] (2a) ~ (2c)

where L: device length, W: device width, and \( t_f \): film thickness

Q factor dependency on device geometry was also analyzed in this paper. Q factors around microwave frequency can be defined as Eqn. (2a)~(2c). The top and bottom electrode should be considered for the conductor loss after deembedding procedure. In this case, the loss tangent for dielectric loss was assumed 0.002 for the analysis. Resistances were divided as the sum of area-, periphery-, and conductor-dependent terms and each coefficient obtained \( \alpha=3.9 \times 10^3 \) [Ω·μm²], \( \beta=11.7 \) [Ω·μm], and \( \gamma=0.75 \) [Ω]. Figure 5 shows the measurement and calculated Q factors with different device area. The resistances of periphery-related were the most affected by the change of device area. To
reduce the series resistance or improve quality factor in microwave frequency range, the perimeter should be increased. The resulting equivalent circuit around microwave frequencies including geometrical effects is displayed in fig. 6. The resistances can be the sum of 3 resistances which each expresses the area-, periphery-, and conductor-dependent terms instead of constant value. Refined device layout with the largest periphery could improve device characteristic tremendously. The BZN thin film capacitors with the high Q factor and electric field dependent permittivity can be the alternative microwave passive components.

Fig. 4. (a) Quality factors and (b) capacitances of DUTs after the de-embedding for 64, 100, 400, and 900 µm² devices

Fig. 5. Measured and simulated Q factors for different device area at 2 GHz (red dot : measurement, blue line : calculation)

Fig. 6. Equivalent circuits of BZN thin film capacitors around the microwave frequency including geometrical factors

Conclusions
Low loss microwave capacitors were realized using high-permittivity BZN thin films. The dielectric properties were evaluated up to 20 GHz. The Q factors remained more than 200 up to several GHz and there was no sign of dielectric relaxation. The devices were modeled by geometrical factors of electrodes and periphery-dependent resistances dominated in microwave frequency range. In addition to their extremely low losses, BZN thin film showed an electric field tunable dielectric constant, which makes these films interesting for tunable microwave applications.

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References