Low-loss tunable capacitors fabricated directly on gold bottom electrodes

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At microwave frequencies, conductor losses due to the bottom electrode resistance severely limit the performance of metal-insulator-metal capacitors that employ tunable dielectric thin films. Here we demonstrate that a novel tunable dielectric, bismuth zinc niobate (BZN), can be integrated directly with low-resistivity Au bottom electrodes. The favorable crystallization kinetics allowed for a low thermal budget process compatible with Au electrodes. BZN thin films on Au bottom electrodes showed low dielectric loss tangents of ~0.0005 and high dielectric tunabilities of ~50%. The Au/BZN interface was abrupt and free of reaction phases. At high frequencies (>1 MHz) the total Au/BZN capacitor device loss was reduced compared to capacitors with Pt bottom electrodes. The low device losses of Au/BZN capacitors revealed a device geometry-dependent loss mechanism that contributed significantly to the device loss at high frequencies. © 2006 American Institute of Physics. [DOI: 10.1063/1.2186077]

Dielectric thin films that have an electric field tunable dielectric constant have been extensively studied for tunable circuits operating at microwave frequencies. High dielectric tunabilities are achieved by using metal-insulator-metal (MIM) structures. At microwave frequencies the conductor losses from the bottom electrode are believed to dominate the total device loss. Minimizing the conductor loss would not only improve device performance but also facilitate the interpretation of the measured device loss in terms of the dielectric loss, whose frequency dependence is often unknown.

To reduce the conductor losses, thick metal bottom electrodes with a low electrical resistivity are required. Pt bottom electrodes are used because of their chemical stability and ability to withstand the high-temperatures and oxidizing conditions during dielectric deposition. More recently, W and Cu electrodes were studied. However, these electrodes require processing of the dielectric under reducing conditions, which cause high leakage currents. Au would be the ideal electrode material. Au has a lower electrical resistivity (~2 μΩ cm) than Pt (~9.7 μΩ cm) (Ref. 14) and does not oxidize. However, the low melting temperature of Au (~1064 °C) makes integration difficult.

We recently demonstrated that thin films of nonferroelectric bismuth zinc niobate (Bi$_2$Zn$_{10}$Nb$_{12}$O$_{37}$ or BZN) have high dielectric tunabilities (~55%) and very low dielectric loss tangents (less than 0.0005). BZN has the pyrochlore structure and is a equilibrium phase in the Bi$_2$O$_3$-ZnO-Nb$_2$O$_5$ system. BZN thin film MIM capacitors with Pt bottom electrodes show high device quality factors (Q) of greater than 100 up to 10 GHz, comparable to the best reported BST devices. In this paper we show that BZN thin films with excellent dielectric properties can be integrated directly with Au bottom electrodes.

Au layers that were ~200 nm thick were deposited by electron beam evaporation on c-plane sapphire covered with ~3 nm thick Ti adhesion layers with no intentional heating of the substrate. X-ray diffraction (XRD) Φ scans showed that the Au films were mostly epitaxial (111) oriented (with some {100} oriented grains). BZN films were grown by radio-frequency (rf) magnetron sputtering from a stoichiometric target using an Ar/O$_2$ sputter gas mixture and a substrate temperature of ~300 °C. A post-deposition rapid thermal anneal (RTA) was performed for 5 min in ultra-high-purity N$_2$ at 750 °C to crystallize the films. The ramp-up time was about 10 s and it took ~5 min for the samples to reach room temperature after the RTA.

As-deposited BZN film were amorphous or nanocrystalline. XRD θ-2θ scans after the RTA showed that the BZN films crystallized in the cubic pyrochlore structure and were (111) textured [Fig. 1(a)]. No secondary phases were detected. Figure 1(b) shows a cross-section transmission electron microscopy (TEM) image of the BZN thin film on Au after the RTA. The interface with the Au electrode was smooth and free of reaction layers, as was confirmed by the high-resolution TEM [Fig. 1(c)]. The BZN film was fully crystallized, despite the very short annealing time, consistent with findings by others. The short crystallization times likely reflected the relatively low kinetic barrier against crystallization typical for pyrochlore oxides.

A schematic of the device structure for dielectric characterization is shown in Fig. 2(a). The device process was reported in detail elsewhere. The top contacts were 150 nm Au/100 nm Pt. Shorted devices with the same geometry but without the BZN film were fabricated on the same wafer. The dielectric properties were characterized with an impedance analyzer (Agilent model 4294A) connected to air coplanar probes (Cascade Microtech, Inc.) using a...
capacitor area was 1500 \( \text{m}^2 \) calculated from the capacitance \( C \), the distance between the top contacts was 50 \( \text{mm} \), and an abrupt interface free of reaction layers. The unlabeled peak at 2\( \theta \approx 26^\circ \) may be an artifact from the substrate. The Au bottom electrode was crystallized at 750 °C for 5 min in air, using a ramp rate of 10 °C/min so that the total annealing time was 180 s. The inset shows the dielectric tunability of an Au/BZN capacitor with an ~165 nm thick BZN film measured at 1 MHz at positive bias voltages. Figure 3(a) showed that the BZN film on Au had a permittivity of 180, similar to that of bulk BZN and BZN films on Pt electrodes. The inset shows the dielectric tunability for a ~165 nm thick BZN film at positive bias voltages, which was about 53%, similar to BZN films on Pt electrodes.

While the permittivity was independent of the measurement frequency [Fig. 3(a)], the \( Q \) factor was strongly frequency dependent. The equivalent circuit shown in Fig. 2(b) has been used to explain the frequency dependence, where \( R_s \), \( G_{dc} \), and \( G_{ac} \) represented the series resistance of the electrodes, the dc leakage through the film and the loss of the dielectric, respectively. The total device loss (1/\( Q_{\text{total}} \)) was then described by the following equations:

\[
\frac{1}{Q_{\text{total}}} = \frac{1}{Q_{\text{leakage}}} + \frac{1}{Q_{\text{BZN}}} + \frac{1}{Q_{\text{Electrode}}},
\]
fore, despite the low thermal budget the dielectric loss at electrode resistance to the high-frequency loss of the device. This showed that the capacitance between the Au and Pt capacitors decreased. This showed that an additional series resistance term was attributed to the third term in Eq. 2b. Figure 4 shows the data after removal of \( R_s \). The difference between the Au and Pt capacitors decreased. This showed that the model accounted for the contribution of the bottom electrode resistance to the high-frequency loss of the device.

The frequency dependence of the data in Fig. 3(b) showed, however, that an additional series resistance term not due to conductor losses contributed significantly to the device \( Q \) at high frequencies. This term was geometry-dependent, with smaller devices showing higher \( Q \) (Fig. 4). Therefore, this loss contribution was likely not a bulk dielectric effect. One possible explanation was a tunneling resistance between the metal and interface and surface states in the dielectric.28 Such a contribution would not be removed using shorted devices.

In summary, we showed that a novel, tunable, low-loss dielectric, pyrochlore bismuth zinc niobate, could be integrated directly on Au bottom electrodes. The process may also be of interest for other applications that require a low thermal budget and high-quality, high-permittivity dielectric films.

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