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Separation of the Metallic and Dielectric Losses of Tunable Ferroelectric Capacitors under Control dc Voltage

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Abstract—An approach to separate the metallic and dielectric losses in ferroelectric capacitors in all range of tuning under control dc voltages (U_{dc}) is considered. The procedure is based on measurements of the dc voltage dependencies of microwave losses ($\tan\delta_t(U_{dc})$) and capacitance ($C(U_{dc})$) for a set of capacitors with similar layout but with different nominals. Linear extrapolation of $\tan\delta_t(C)$ dependencies at different control dc voltages to $C = 0$ allows to evaluate the dielectric losses $\tan\delta_d$ as a function of the control dc voltage. The procedure of separation was performed for a set of sandwich metal/$(Ba_{0.5}Sr_{0.5})TiO_3$/metal capacitors. Capacitors parameters were measured at a frequency of 2 GHz in a range of electric field strength in ferroelectric of $E = (0 - 30)$ V/μm. The intrinsic commutation quality factor of BSTO film itself was estimated by the method proposed.

1. INTRODUCTION

Ferroelectrics (FE) such as $(Ba_xSr_{1-x})TiO_3$ (BSTO) in the paraelectric state are attractive for application in tunable microwave (MW) devices. Voltage-controlled passive (tunable filters, phase shifters, reconfigurable antenna arrays, etc.) and active (frequency multipliers and mixers) devices of MW microelectronics can be realized on the basis of FE films [1–4]. The devices based on FE films have high tuning speed, low power consumption, high power handling capability and low cost. The most often used FE nonlinear elements of the MW devices mentioned above are tunable capacitors (FE varactors).

The FE varactor can be represented at microwaves (for frequencies much less than a self-resonance frequency) by the equivalent circuit shown in Fig. 1. In accordance with the equivalent circuit the microwave loss is defined by two dissipation mechanisms: loss in dielectric ($\tan\delta_d$) and loss in electrodes ($\tan\delta_e = \omega C R_e$). R_e is a resistance of metallic electrodes, and R_d is an equivalent resistance of dielectric loss.

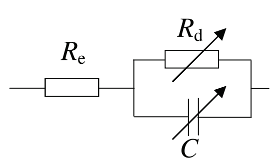

Figure 1. Equivalent representation of FE varactor at microwaves.

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Thus, the total microwave loss ($\tan\delta_t$) can be written as

$$\tan\delta_t = \tan\delta_d + \tan\delta_e = \tan\delta_d + \omega C R_e \quad (1)$$

The possibility to determine the nature of losses provides the information about "pain points" of dielectric and electrodes fabrication processes. This knowledge can be used to improve parameters of FE varactors in point of their design and technology.

The common approach to separate electrode and dielectric losses in linear dielectric capacitors is based on the measurements of the total microwave losses ($\tan\delta_t$) of a set of capacitors with similar construction, but different capacitance nominals (C). Extrapolation of linear dependence of $\tan\delta_t$ (C) to $C = 0$ allows to obtain the value of dielectric losses ($\tan\delta_d$) in accordance with Eq. (1).

Specific feature of nonlinear FE capacitors is the variation of both the capacitance (C) and the total loss ($\tan\delta_t$) under the control dc voltage (U_{dc}). The capacitance ($C(U_{dc})$) always decreases under U_{dc}, that results in the decrease of electrode loss ($\tan\delta_e$). However, the dependence of $\tan\delta_d$ on electric field strength E_{dc} has unpredictable behavior due to different natures of losses mechanisms [1, 5, 6]. Taking into account that the operating regime of ferroelectric varactors corresponds to the wide range of electric field strength in dielectric (up to $E \approx (30-40)$ V/µm), the information about the contribution of dielectric and electrode losses is required to characterize the MW parameters of capacitors over the entire tuning range.

For the first time the estimation of the relative contributions of BSTO and conductor losses to the total quality factor of the FE varactor as a function of frequency (45 MHz–1 GHz) at different thicknesses of Pt electrodes was presented in Ref. [7]. The separation of the losses was made by the calculation of the metallic loss in assumption of the invariable BSTO loss in frequency range considered. It was demonstrated, that the contribution of the metallic loss becomes predominant above 10 MHz.

In the resent paper, the procedure based on the same common approach represented by Eq. (1), but taking into account the experimental $C(U_{dc})$ and $\tan\delta_t(U_{dc})$ dependencies, is described. The method allows to derive the contribution of dielectric and electrode losses of FE varactors in all range of control voltages. Experimental dependencies of $\tan\delta_d$ and $\tan\delta_e$ on U_{dc} for a set of FE varactors are demonstrated.

2. EXPERIMENT AND DISCUSSION

The layout of the sandwich Ti/Pt/($Ba_{0.5}Sr_{0.5}$)TiO_3/Pt/Au varactor on MgO substrate is presented in Fig. 2. The different capacitance nominals $C(0) = 6.2$, 2 and 1.2 pF were defined by the electrode overlap of $a \times b = 22 \times 22$, 12×12 and 10×10 µm^2, respectively. Thicknesses of structure layers were Ti/Pt-layer $t \approx 1300$ nm, Pt/Au-layer 1500 nm and BSTO film $d \approx 700$ nm. The gap width between the Pt/Au top electrodes $w = 10$ µm. The estimated self-resonance frequencies of the varactors are more than 15 GHz.

The microwave parameters of the varactors were measured at a frequency of 2 GHz by HP 8719C vector network analyzer and the coaxial resonator test-fixture. The measuring resonator provides unloaded Q-factor ~ 2000, the decoupling between MW circuit and dc control voltage circuit more than 60 dB, and the accuracy of capacitance and quality factor measurements of 1% and 5% respectively [8,9].

Voltage-capacitance dependencies of the varactors C (U_{dc}) are presented in Fig. 3 for the range of the dc voltage variation of $U_{dc} = (0-22)$ V. The tunability of varactors is presented in Fig. 4 and can be estimated as $K = C(0)/C(U_{dc\,\max}) \approx 4$. All samples demonstrate the practically identical dependencies of K vs U_{dc} despite the difference in nominals. The dc voltage dependencies of total microwave losses $\tan\delta_t$ (U_{dc}) of the varactors are presented in Fig. 5.

On the basis of $C(U_{dc})$ and $\tan\delta_t(U_{dc})$ dependencies (Figs. 3 and 5), the correlation between $\tan\delta_t$ and C at each value of U_{dc} was established, and the corresponding dependencies $\tan\delta_t(C)$ are plotted (Fig. 6). The linear dependencies of $\tan\delta_t(C)$ at different values of control dc voltage correspond to the constant dielectric loss $\tan\delta_d$. Extrapolation of these dependencies to $C = 0$ in accordance with Eq. (1) allows to derive the dielectric loss versus control dc voltage ($\tan\delta_d(U_{dc})$) for the BSTO film. Fig. 7 demonstrates the result of separation of dielectric and electrode losses for three varactors with different nominals.

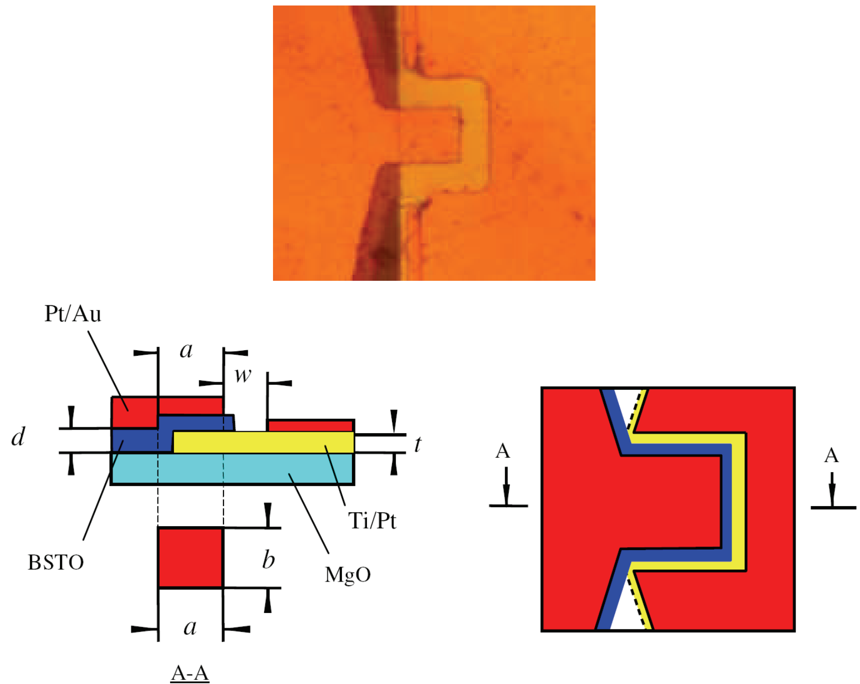

Figure 2. Photo and layout of the FE varactor.

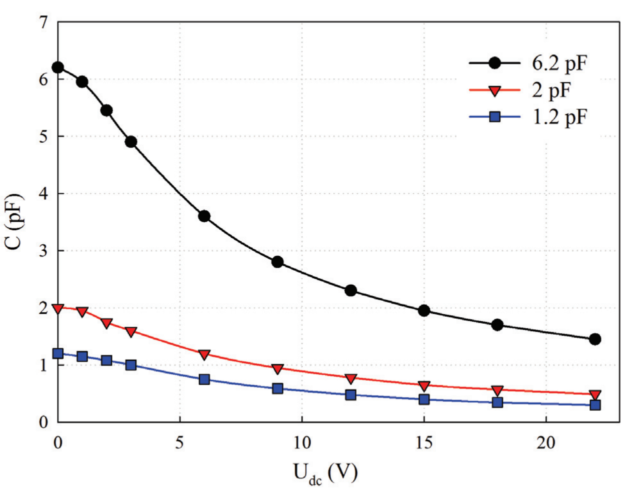

Figure 3. The capacitance versus control dc voltage for different FE varactors.

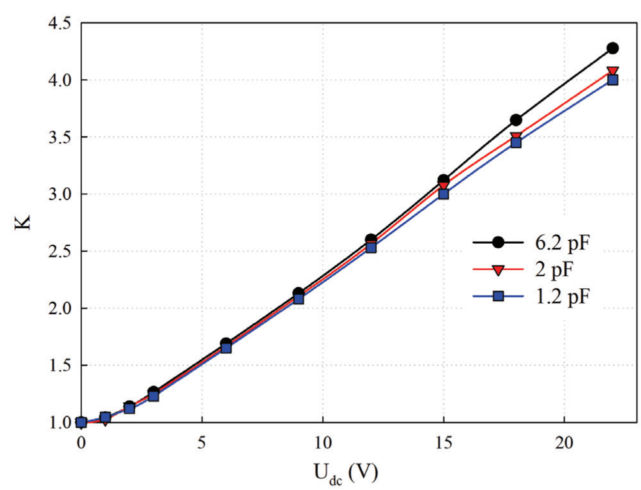

Figure 4. The tunability versus control dc voltage for different FE varactors.

Measurements show that the electrode part of the total losses for 6.2 pF varactors are varied in the range of (30–15)% in the entire range of U_{dc}. Obviously, the contribution of electrode losses decreases with the varactor nominal and amounts (15–16)% for 2.0 pF and (8–3)% for 1.2 pF capacitors.

The commutation quality factor (CQF) introduced by Vendik [10] can be used to characterize the ferroelectric materials and varactors on their base in point of MW application. This parameter takes into account the dc-field induced changes both in capacitance and in loss tangent.

$$CQF = \frac{(K-1)^2}{K \cdot \tan\delta\ (U_{dc}=0) \cdot \tan\delta\ (U_{dc}=U_{dc\,\max})} \tag{2}$$

Usually CQF is used to calculate the figure of merit of devices [2, 10], but not of a FE material

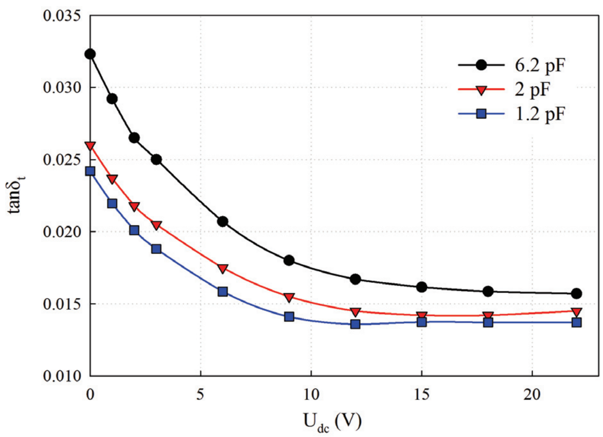

Figure 5. The total loss versus control dc voltage for different FE varactors.

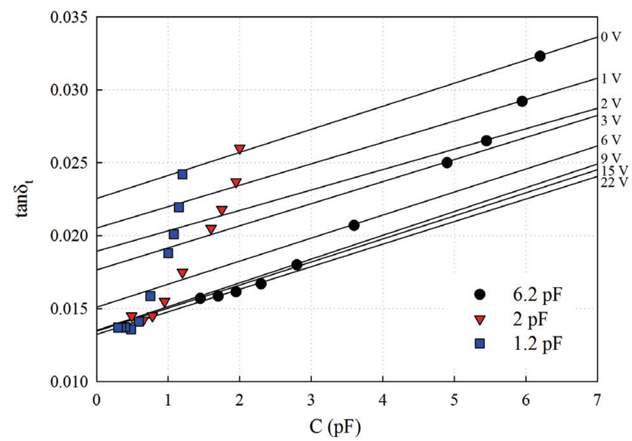

Figure 6. Extrapolation of $\tan\delta_t$ (C) dependencies to $C = 0$ for different FE varactors.

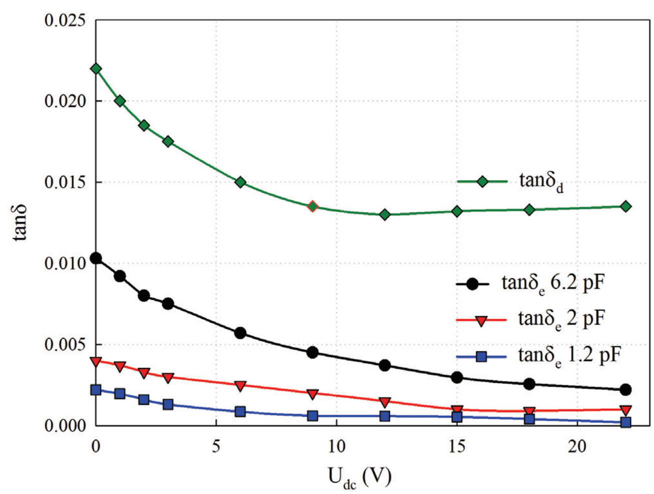

Figure 7. The result of separation of dielectric and electrode losses.

itself, because there is no correct information about $\tan\delta_d(U_{dc})$ dependence. The separation of loss mechanisms allows to derive the intrinsic CQF of the FE film in varactor after all manufacture stages. The variation of the dielectric loss under the control voltage is $\tan\delta_d = 0.022 - 0.014$ (Fig. 7). Taking into account the tunability $K = 4$ (Fig. 4), the figure of merit of the BSTO film itself can be estimated by Eq. (2) as $\text{CQF}_d \sim 7300$, while the CQF of the FE varactor is about 6400 for the 1.2 pF nominal and 4300 for the 6.2 pF nominal. Thus, the proposed procedure allows to estimate the quality of FE film and the quality of electrodes separately.

3. CONCLUSIONS

The proposed procedure to separate the metallic and dielectric losses in tunable FE capacitors provides a possibility to characterize the MW properties of FE film itself in varactor structures in an entire range of control dc voltages, and to derive the intrinsic commutation quality factor of FE films. It will be interesting to use the procedure for FE varactors with not commonly used metal/FE structures, but with actively developed nowadays semiconductor/FE structures [11].

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