Microwave power dependent properties of ferroelectric varactors

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I Introduction

Ferroelectrics, especially in paraelectric phase, are widely considered for microwave applications. The main feature, that's makes them attractive for tuneable microwave applications, is the DC field non-linear dependent dielectric permittivity. A large number of tuneable microwave devices and systems have been demonstrated in the past [1], In general, the microwave power dependence of film parameters is an undesirable effect [2], however when properly designed, ferroelectric components may be used in harmonic generators and mixers. In this work we report preliminary results of nonlinearity measurements of parallel-plate ferroelectric varactors integrated on Si wafers.

The first reports on experimental investigation of nonlinearities in $Ba_xSr_{1-x}TiO_3$ based ceramics date back to 1950s and early 1960s. DiDomenico et al [3] report the first successful demonstration of a 3rd harmonic generator in 1962. Recently 2nd harmonic generation was demonstrated [4], by applying DC bias. Samoilova et al. [5] reported frequency conversion (harmonic generation) experiment in a Coplanar Waveguide (CPW) with a ferroelectric film. Where as Booth et al [6] uses a CPW with $Ba_{0.3}Sr_{0.7}TiO_3$ film, the non-linear capacitance C by using two approaches: i) third harmonic generation, and ii) $C(V_{DC})$ measurements at microwave frequencies. It was shown that the non-linear capacitance C determined from $C(V_{DC})$ measurements is in excellent agreement with the one found from third harmonic generation experiment, this leads to the conclusion that ferroelectric devices might be tuned with nanosecond speeds.

To study nonlinearities Kozyrev et al [2] designed a resonator loaded by a ferroelectric capacitor, using both a single signal as well as intermediation distortion, which confirmed previous results [3]. Kozyrev et al also gives a simple theory for estimation of overheating of the ferroelectrics films at high power levels, and it was shown that the power handling capability of a ferroelectric tuneable filter may be as high as 3.5 W. Experiments and more detailed analysis of the microwave heating on nonlinearities are given elsewhere [7].

In this work, we used simple, on-chip microprobe reflection measurements to determine microwave power dependence of the capacitance of parallel-plate ferroelectric varactors. It is shown that the nonlinear parameters estimated from this experiment are in good agreement with the nonlinear parameters found from $C(V_{DC})$ measurements at low frequencies. Hence, nonlinear parameters found from simple $C(V_{DC})$ measurements may be used in the development of microwave devices, such as harmonic generators and mixers.

II The structure of ferroelectric capacitor and measurement procedure

The capacitor has parallel-plate structure where the ferroelectric film is sandwiched between two Pt/Au plates, Fig.1a. $Ba_{0.25}Sr_{0.75}TiO_3$ films, 300 nm thick, are grown epitaxially by laser ablation. One-port reflection measurements are performed using a vector network analyser in the frequency range 1 to 30 GHz (limited by the measurement set-up), Fig.1b. The measurement, and the data processing procedures are given in [8]. The microwave power delivered to the test structure (probe tips) is varied from 8 dBm to –7 dBm. It is assumed in this measurement set-up that the microwave power is well controlled/monitored. The microwave power, P, delivered from the VNA to the DUT is measured at the input plane of the microprobe using a power meter. Ignoring the losses in the microprobe, the microwave voltage amplitude applied to the probes is computed using $V=(2PZ_o)^{1/2}$, where Z_o=50 Ω is the system impedance. The microwave field developed between the plates of ferroelectric capacitor is: $E=V/t$, where t is the thickness of the ferroelectric film.

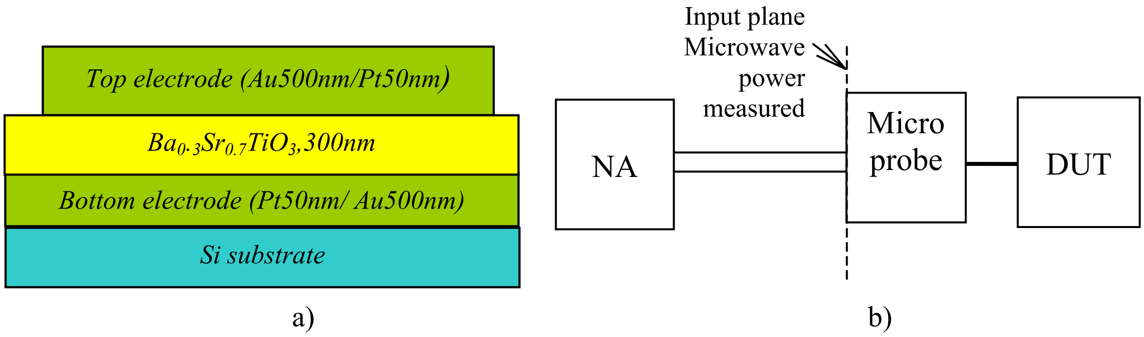

Fig.1 *Simplified cross section of capacitor (a), and measurement set-up (b).*

III Results and discussions

DC field dependent capacitance $C(V_{DC})$ and $\tan\delta$ is shown in Fig.2. These measurements are performed at 1.0 MHz, where the amplitude of the RF voltage is 1 V, which is smaller than the applied max DC voltage (+/- 25 V). As it follows from Fig.2 there is no noticeable hysteresis in either C or $\tan\delta$ upon reversal of the DC bias, indicating that the films are in predominantly paraelectric phase. In order to determine the non-linearities the C(V) and tanδ(V) dependence or rather ε(E) and tanδ(E), is calculated. Due to the symmetry of Fig 2, all odd terms are neglected and the series is limited to the second and forth order respectively.

$$\varepsilon(E) = \varepsilon(0) + \varepsilon_2 E^2 \tag{1}$$

$$\tan\delta(E) = \tan\delta_0 + \tan\delta_2 E^2 + \tan\delta_4 E^4 \tag{2}$$

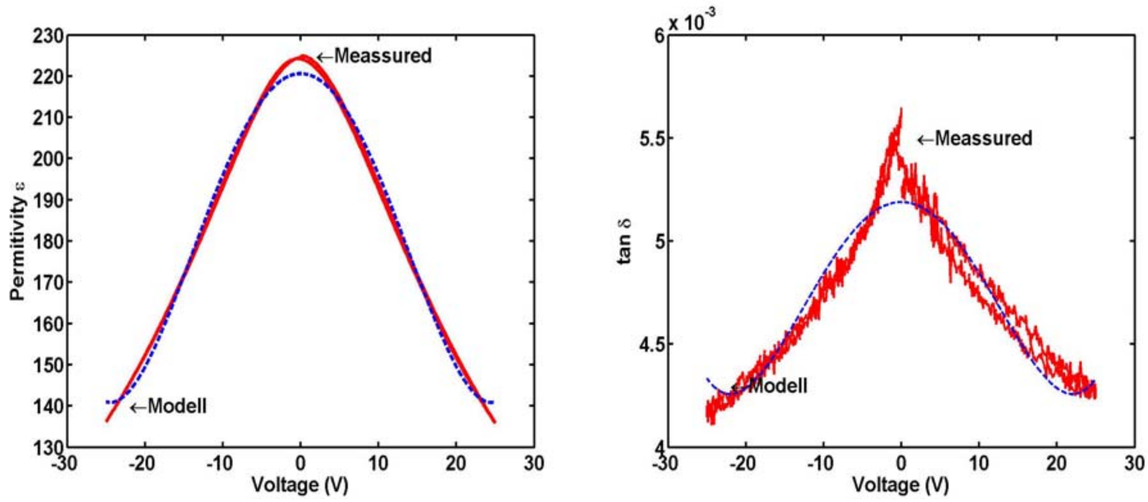

Fig.2 *DC voltage dependent permittivity $\varepsilon(V_{DC})$ and $\tan\delta(V_{DC})$ with the curves extracted from curve fitted data of a capacitor.*

Fig 3 shows that tanδ is increasing linearly with frequency and the permittivity is almost constant. The reduction of permittivity is due to parasitic inductance in the measurement set up [8]. The microwave power dependence of loss tangent shown in Fig.4 and Fig. 3b might be associated with three basic effects: heating of the film, charged defects loss mechanism [9] and non-linear field dependences of the losses. In general, to distinguish between these two effects, special experiments need to be carried out. But it follows from Fig.3b, that with increased microwave power, the losses decrease. On the other hand, it is known [7], that the heating increases the losses linearly. Hence, it seems that in our experiments, the effect of the heating has a minor effect, and following [3] the dependences given in Fig.2 and 4 may be approximated by (1) and (2).

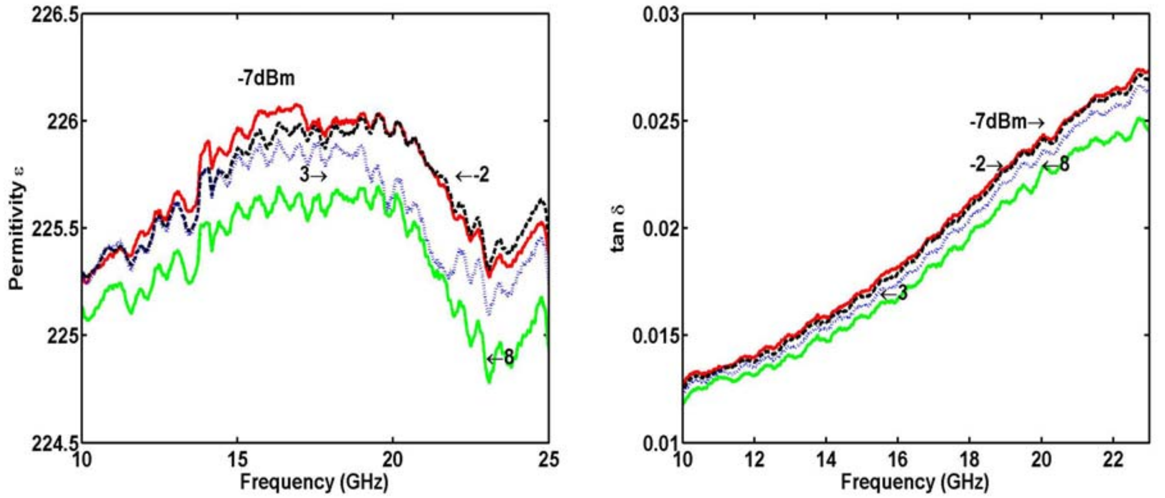

Fig.3 *Frequency dependencies of the permittivity (a) and loss tangent (b) of the capacitor at different microwave power levels.*

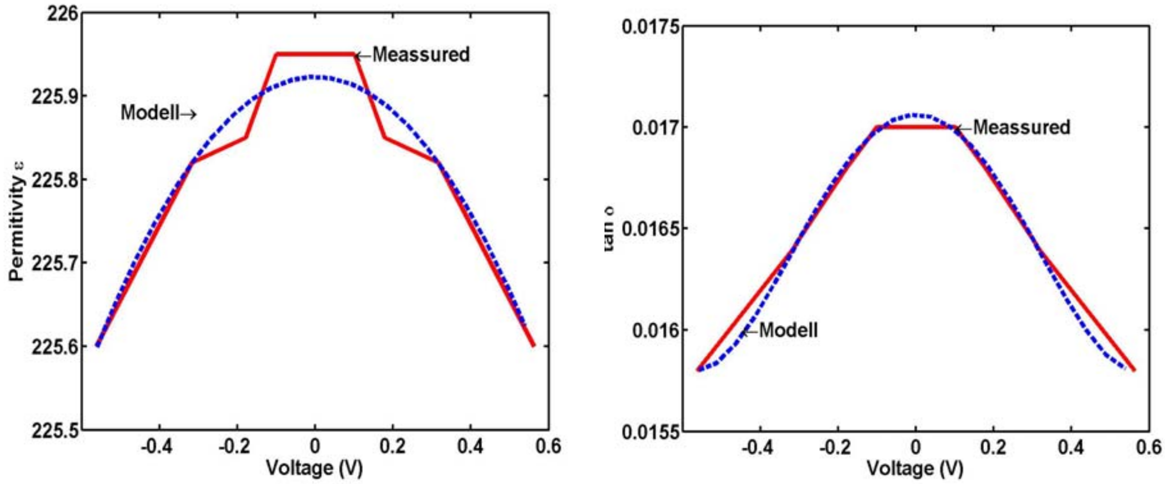

Fig.4 *Dependences of permittivity (a) and loss tangent (b) on microwave field at 15 GHz.*

In further discussions, we assume that the changes in the permittivity and losses follow the changes in the microwave field. This assumption is base on the results reported in [6], and needs to be approved for our capacitors, since the tanδ of our capacitors is rather low, and a time averaging procedure may be required. At this instance, the assumption for our case is based on the fact that the power dependent reduction of the permittivity, Fig.2a, is not frequency dependent. It also needs to be pointed out that the measurement uncertainty is larger than difference in amplitude in Fig. 3 especially for permittivity.

In order to be able to compare DC and RF measurements the different terms are shown in Table I. In Table II the results are compared to those published by others. At present there are very limited reports on the nonlinear coefficients of STO and BSTO film, and some of them are given in terms of capacitances and voltages, which make it difficult to compare with our results, since they include unknown geometrical factors. Table II summarizes the results of our measurements with results of some works, which we could present in a comparable format. As it can be seen there is a substantial dispersion between the reported results, which may be partly due to the accuracy (non of the reports give details about the accuracy), and mostly due to the differences in the quality and structure of the ferroelectrics used.

***Table I** Nonlinear parameters found from curve fitting at 15 GHz and DC respectively.*

Coefficient	ε_2	$\varepsilon_2/\varepsilon_{0V}$	$tan\delta_2$	$tan\delta_2/tan\delta_o$	$tan\delta_4/tan\delta_o$
From microwave	-2.31828e-14	-1.02579e-16	-9.23755e-5	-4.91274e-15	3.70881e-28
From DC	-2.56015e-14	- 1.13281e-16	-1.71351e-6	-6.65518e-17	6.16714e-33

***Table II** Comparison of nonlinear parameters.*

	$\varepsilon_2/\varepsilon_{0V}$ [1/V^2]	$\varepsilon_2/\varepsilon_{0V}$ [m^2/V^2]	$tan\delta_2/ tan\delta_o$ [m^2/V^2]
Booth [6]	$1.36*10^{-5}$	$2.17*10^{-18}$	-
DiDomenico [3]	-	$3.4*10^{-14}$	$1.8*10^{-13}$
Kozyrev [2]	$2.4*10^{-5}$	$6.11*10^{-14}$	-
This work	$2.8*10^{-3}$	$1*10^{-16}$	$0.5\text{-}67*10^{-16}$

IV Conclusions

A simple procedure for measurement of nonlinearities in ferroelectric capacitor is proposed. The method needs further improvement in terms of measurement of accuracy, the effect of temperature, involved time constants, electrostriction, and strains in the film. The results of the measurements are important for development of mixers and harmonic generators, and assessment of the undesirable nonlinear effects in tuneable microwave devices.

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