MOS Varactors with Ferroelectric Films

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***Abstract* — *Microwave* performance of MOS varactors with additional ferroelectric film (MFOS) is presented. The tunability of MFOS varactors above 20 GHz is more than 10%, higher than that of simple MOS varactor with sufficiently high Q factor. The proposed MFOS varactor has simple design and is compatible with standard CMOS processes. It may have symmetric C-V curves at rather high tuning voltages and superior performance at millimetre wave frequencies. In experiments varactors are based on $NaNbO_3$ films grown on high resistivity silicon substrates.**

I. Introduction

Recently attempts are made to fabricate cost effective RFICs using standard CMOS technology. In such RFICs MOS structures seem to be the most favourable devices for varactor applications. MOS varactors have already reported in a number of publications [1], [2]. However, it is well known that the tunability of MOS structures is very small at elevated microwave frequencies, and at millimeterwave frequencies their tunability is very small, i.e. they cannot be used as varactors. For millimeterwave applications ferroelectric varactors seem to be promising [3]. However, in most cases they are fabricated on substrates with a good crystalline structure. Nevertheless, ferroelectric varactors fabricated on silicon substrate [4] may have the advantage of integration with RFICs fabricated in standard silicon technology. Particularly, fabrication of ferroelectric films for memory applications integrated with CMOS transistors is a well-established process and no substantial difficulties may be expected in integration of MFOS varactors in CMOS RFICs. Widely used ferroelectrics, such as $SrTiO_3$ (STO), $BaTiO_3$ (BTO) and solid solutions of these materials, $BaSrTiO_3$ (BSTO) [5], [6] may be used in CMFOS varactors. Ferroelectric films in polar phase, such as PZT and NKN [7] also may be considered for varactor applications at millimeterwaves. Recent investigations show that at millimeterwave frequencies polar ferroelectrics may have rather low microwave losses, since domain wall motion or piezoelectric transformations do not contribute in the total losses [8].

In this work report on the performance of MOS varactors with additional ferroelectric layers (MFOS structure, Fig.1a) between SiO_2 and metal electrode. The proposed varactor has a simple structure and is compatible with standard CMOS process. A comparison of MOS and MFOS varactors is made to demonstrate the advantage of the former in terms of tunability and Q-factor at millimeterwave frequencies. It is believed that this is the frequency range where ferroelectric varactors may have competitive (in comparison with semiconductor varactors [3]) applications in microwave technology.

II. Varactor structure and measurement procedure

The interdigital electrodes, 0.5 μm thick, are photolithographically defined using ion etching, Fig.1. Each of them has 12.0 μm long five fingers. Slot- and stripwidths are 2.0 μm. The sizes of the contact pads in the horizontal plane are 125x125 μm^2. Planar design is simple in fabrication and integration. Both electrodes may be made thick, to reduce microwave losses. This design is suitable for small size and small capacitance high Q-factor varactors suitable for operation at frequencies above 20 GHz. It requires slightly larger tuning voltages in comparison with the sandwich type three layer structures and the tenability, T(V)=[C(0)-C(V)]/C(0), is not as large as in the case of "sandwich" type design . Ferroelectric films used in our experiments are about 0.5 μm thick and zero bias dielectric constant is ranging from 100 to 500 depending on frequency and fabrication technology.

On chip microwave characterisation of the varactors is made using HP 8510C vector network analyser at room temperature in the frequency band 0.045-50 GHz and a probe station (S-1160, Signatone). Estimated measurement accuracy is better than 5%. A simple equivalent circuit consisting of a capacitor and series resistor is assumed to compute the capacitance and effective loss tangent ($tan\delta$) from measured complex reflection coefficient, S_{11}, using relationship $Z=r-j/(\omega C)=Z_o(1+S_{11})/(1-S_{11})$, where Zo=50 Ohm is the impedance of the coaxial setup used in the experiment. The Q-factor of the capacitor is defined as $Q=1/(\omega Cr)$, and the effective loss tangent is defined as $tan\delta=1/Q$, which includes the losses in ferroelectric film, electrodes and silicon substrate.

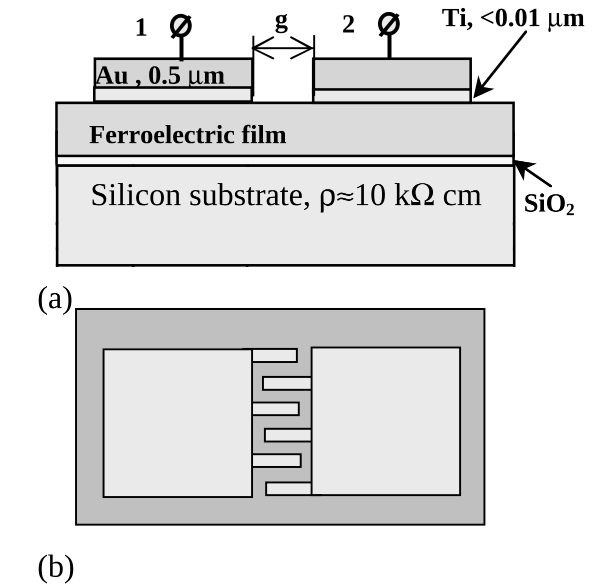


Fig.1. Cross-section (a) and layout of electrodes (b) of MOS varactor incorporating a ferroelectric layer.

III. COMPARATIVE PERFORMANCE OF MOS AND MFOS VARACTORS

The frequency dependencies of the capacitance and effective loss tangent of MOS and MFOS interdigital capacitors with similar electrode structures at different DC bias fields are shown in Fig.2. The absolute value of the capacitance in MFOS varactor is larger, as one expect from the presence of ferroelectric film. For the same reason the temperature dependence of MOS varactor is very weak in comparison with MFOS varactor.

The losses in the air above the capacitor and in the strips may be ignored as a first approximation and the effective loss tangent of the capacitors, Fig.1, may be presented as: $\tan\delta \cong G_1\tan\delta_{Fer}$, + $G_2\tan\delta_{Si}$ where $G_1<0.1$ and $G_2<0.5$ are geometrical factors. Since the geometry of the capacitor is involved the actual losses tangent in the bulk of ferroelectric film, $\tan\delta_{Fer}$, is expected to be larger than effective loss tangent given in Fig.3. As it follows from simple Drude model [9], in the given frequency range ($f>>f_{dr}$) the loss tangent in a high resistivity silicon may be given as $\tan\delta_{Si}=1/(2\pi f\varepsilon_o\rho_{Si}\varepsilon_{Si})=f_{dr}/f$. Thus, the reduction of losses above 25-30 GHz is related to high resistivity (r>10 kOhm cm) substrate. In these experiments the absolute value of Q factors for both varactors is low since the design, quality of ferroelectric film and the thickness of the electrodes are not optimised.

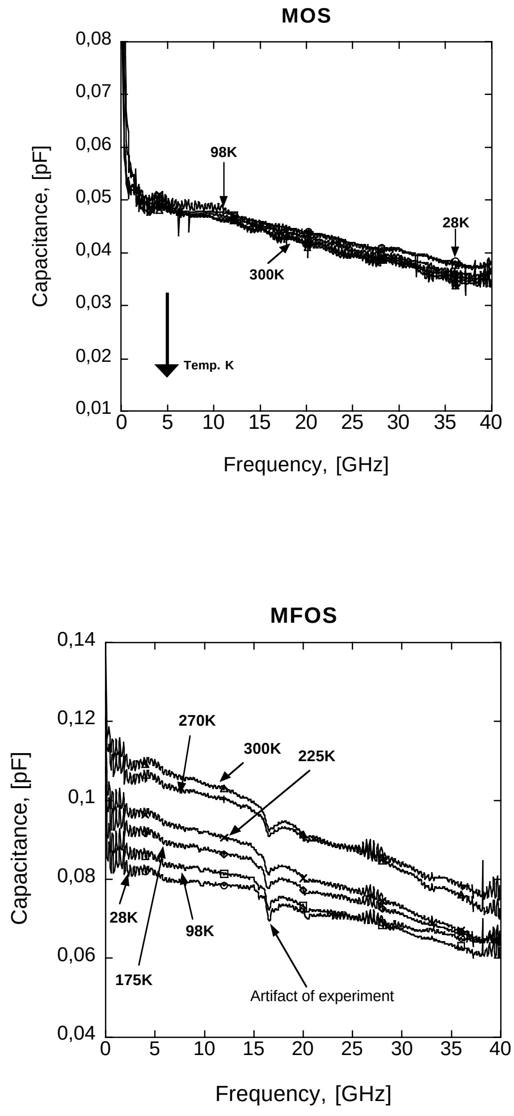
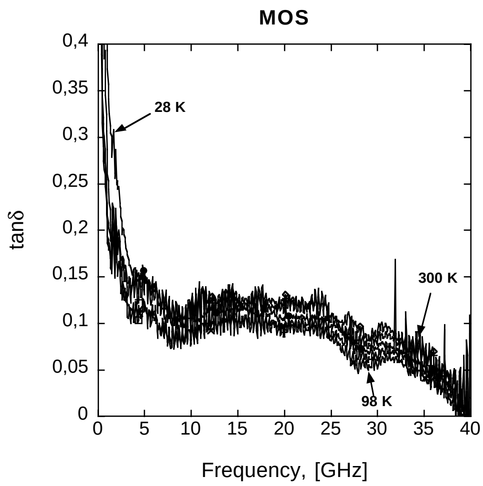
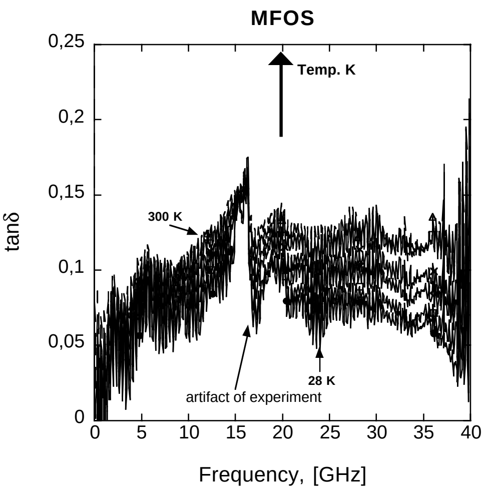


Fig.2. Frequency dependencies of the capacitances for MOS (a), and MFOS (b) varactors at different temperatures.

At frequencies above about 10.0 GHz the frequency dependence of the capacitance is predominantly due to the ferroelectric film for the following reasons. First, the thickness of the Au electrodes (about 0.5 μm) is of the order of skin depth (less than1.0 μm) at these frequencies, i.e. no substantial dispersion may be expected due to the skin effect. The dielectric (Maxwell) relaxation frequency, $f_{dr}=1/2\pi\tau_M=1/(2\pi\varepsilon_{Si}\varepsilon_o\rho_{Si})$, for the silicon substrate is about 15 MHz (τ_M is the relaxation time). Hence, there is no dielectric dispersion in silicon substrate [9]. Furthermore, since the resistivity and the dielectric permittivity of ferroelectric film are much larger than that of silicon the interfacial relaxation (Maxwell-Wagner) frequency [4] may be approximated by $f_{MW}=t/(2\pi g\sqrt{3}\rho_{Si}\varepsilon_o\varepsilon_{NKN})$, where t is the thickness of NKN film. For the given geometry and material parameter f_{MW}≈0.25 MHz and the interfacial relaxation also dose not contribute in the dispassion at frequencies above 10 GHz. This frequency dependence is quite significant below 10 GHz, especially below 1.0 GHz. The frequency dependencies of the dielectric permittivity and losses below 10 GHz are partly associated with the domain motion (especially below 1.0 GHz), and more importantly by SiO_2/Si interface. A comparison of tunabilities of MOS and MFOS varactors is shown in Fig.4. The tunabilities are given for highest voltages for each structure. Above these voltages the leakage currents and losses start increasing.



(a)



(b)

Fig.3. Dependencies of losses for MOS (a) and CMFOS (b) varactors on frequency at different bias voltages.

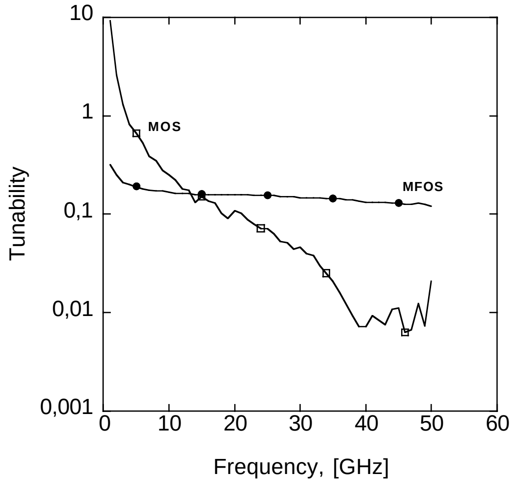


Fig.4. Frequency dependencies of tunabilities for MOS [T(30V)] and MFOS [T(40V)] varactors.

IV. Discussions and Conclusions

Fig.5 shows a simplified equivalent circuit of the MFOS varactor, where $C_{\perp 1}$ and $C_{\perp 2}$ represent the capacitances between the electrodes and SiO_2 layer, in the direction normal to the interface. C_{ox1} and C_{ox2} are the capacitances of the oxide film between the ferroelectric film and silicon substrate. C_{OS1} and C_{OS2} are the equivalent capacitances of oxide-silicon interface including the potential barrier at the silicon surface. The capacitance between the electrodes associated with the electric field parallel to the plane of ferroelectric film is denoted by $C_{||}$, and R_{si} represents the losses in the silicon substrate. The lines crossing the capacitor symbols and arrows in Fig.5 indicate that these capacitances are voltage dependent. In fact, we have two back-to-back connected metal-ferroelectric-oxide-semiconductor capacitors. Each of these capacitors should have C-V dependence typical for MOS capacitors [10]. It can be easily shown that the C-V performance of MFOS varactor has the shape shown in Fig.5b. Such a performance is observed in our experiments at frequencies as high as 30-40 GHz. The analysis of experiments also show that at low microwave frequencies (below about 10 GHz) the tunability of the capacitance is due to the surface barrier at the SiO_2/Si interface, while at millmeterwave frequencies the tunability is due to the ferroelectric film.

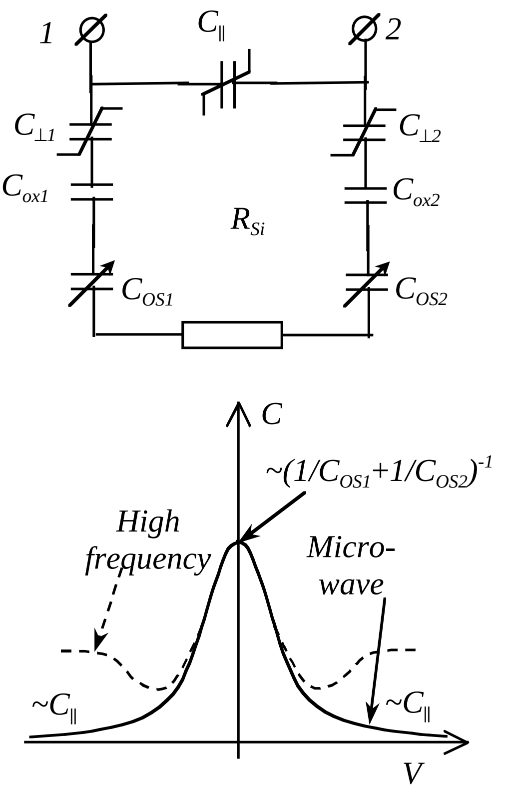


Fig.5. Equivalent circuit (a) and C-V (b) of MFOS varactor.

The results presented above show that MFOS structures have a number of advantages for applications in practical tunable microwave devices at f>10-20 GHz. The most distinguishing features for such applications is the high Q-factor (Q=15-80 at 40 GHz, depending on the NKN film quality), which increasing with frequency in contrast with the semiconductor analogues. Varactors based on *NKN/Si* films are also characterised by sufficient tunability, low dispersion, low frequency dependence of tunability, and possibilities of integration with silicon based microwave integrated circuits.

ACKNOWLEDGMENT

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