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Extraordinary tunability of high-frequency devices using $Hf_{0.3}Zr_{0.7}O_2$ ferroelectric at very low applied voltages

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This paper presents the applications of the $Hf_{0.3}Zr_{0.7}O_2$ ferroelectric with a thickness of 10 nm for tuning high-frequency devices such as filters, phase shifters, and phased antenna arrays in the X band when the low bias voltages in the range −3 V–+3 V are applied. In this respect, we show that a bandpass filter shifts its central frequency located at 10 GHz with 3 GHz, a phase shifter produces a phase difference of about 60 degrees in the X band, while the antenna array formed by two patched antennas is steering its lobe with ±32° at 10 GHz. These results open the way for the tunability of high frequency devices for very low power applications, which represent one of the most challenging issues in applied physics. *Published by AIP Publishing.*
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The initial report on the ferroelectric behavior of doped hafnium oxide (HfO_2) has used as doping material less than 4% mol. SiO_2. The ferroelectric HfO_2 has a 10 nm thickness, the ferroelectric phase being attributed to an orthorhombic crystalline structure.[1] The physical mechanisms for occurrence of the ferroelectric phase in HfO_2, as well as in ZrO_2, are detailed in several papers.[2,3]

The discovery of ferroelectric HfO_2 is of tremendous importance since, although ferroelectric materials are involved in many applications, only perovskite ferroelectrics such as $Pb(Zr,Ti)O_3$ or PZT have been used up to now. In micro- or nanoelectronics, perovskite ferroelectrics are not fully compatible with CMOS technology and suffer from limited scalability. Therefore, ferroelectric random access memories,[4] ferroelectric transistors for low-power applications,[5,6] or high-mobility graphene transistors on ferroelectric substrates[7] show moderate developments or are in infancy. In deep contrast, HfO_2 deposited via the atomic-layer-deposition (ALD) method is fully compatible with CMOS technologies and is commonly used as a high-*k* dielectric in widespread devices based on the CMOS technology, such as i-phones, laptops, computers, and TV-sets. So, ferroelectric HfO_2 could enable various applications working at low DC voltages.

In the case of high-frequency applications, the tunability of devices and circuits is a prerequisite for further development of radars, wireless communications, internet, and internet of things. All these high-frequency systems require a precise control of the parameters of devices and circuits, which must quickly adapt to sudden changes in the communication environment. The electrical tunability of high-frequency devices implying specific materials such as ferroelectrics, polymers, and liquid crystals is a mature domain, recently reviewed in Ref. 8. In principle, all future spatial or terrestrial communications will require Si-, GaAs-, or GaN-based circuits with controllable parameters, which will integrate electrically tunable materials working at high frequencies.

In addition, high-frequency devices based on perovskite ferroelectrics have another serious drawback, besides the integration issues with semiconductor technologies. Namely, the required DC voltage for tuning the frequency or the phase of such devices attains values of tens or even hundreds of volts, depending on the ferroelectric material.[9]

It is thus the role of this paper to show that high-frequency devices such as filters, phase shifters, and antennas can be tuned with only few volts when ferroelectric HfO_2 is used. The results presented in this paper are based on two major advantages of the hafnium oxide ferroelectric, pointed out in Ref. 4: (i) HfO_2 has a remanent polarization in the 1–45 $\mu C/cm^2$ range, depending on doping, still present up to 5 nm thickness, while in films of perovskite ferroelectrics thinner than tens of nm the remanent polarization is lost and (ii) ferroelectric HfO_2 has a giant critical electric field of 1–2 MV/cm, which is one order of magnitude higher than in perovskite ferroelectrics.

Using the available data in Refs. 2 and 4 for the ferroelectric $Hf_{0.3}Zr_{0.7}O_2$, we present first in the following the design and simulations of a tunable filter in the X band. The ferroelectric properties of $Hf_{0.3}Zr_{0.7}O_2$ originate in the replacement of Hf atoms in HfO_2 doped with Zr, which has a similar size and chemical valence to Hf.

The dielectric permittivity $Hf_{0.3}Zr_{0.7}O_2$ as a function of the applied voltage, extracted from experimental data in Refs. 2 and 4, is represented in Fig. 1(a), while the T-like filter configuration is displayed in Fig. 1(b).

In this filter, the capacitors are metal-insulator-metal (MIM) capacitors, consisting of 10 nm of $Hf_{0.3}Zr_{0.7}O_2$ in a coplanar waveguide (CPW) configuration fabricated on high-resistivity Si, which is covered with $Hf_{0.3}Zr_{0.7}O_2$. Each MIM capacitor has an area of $9.171 \times 9.171\ \mu m^2$, while the inductors have the following values: $L_1 = 2$ nH and $L_2 = 0.1$ nH. By changing the MIM capacitance via an applied

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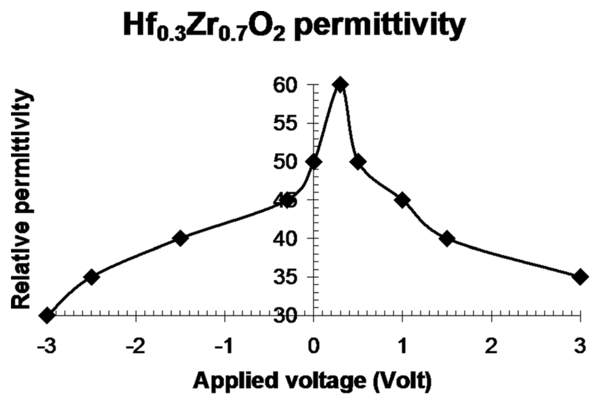
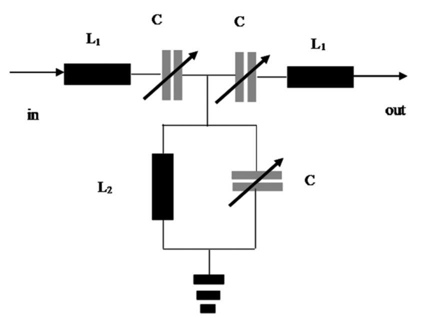


(a)



(b)

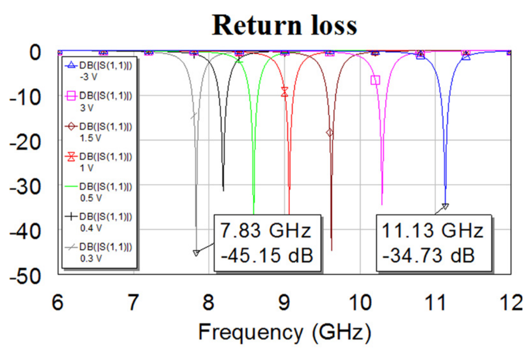
FIG. 1. (a) Dependence on the applied voltage of the dielectric permittivity of $Hf_{0.3}Zr_{0.7}O_2$ and (b) the T-like filter configuration.

voltage in the range -3 V to $+3$ V, the filter characteristics, i.e., the return loss (S_{11}) and the transmission (S_{22}), change significantly, as can be seen from Figs. 2(a) and 2(b), respectively. In particular, the filter is tuned from 7.83 GHz up to 11.13 GHz, i.e., by 3.3 GHz, as the DC voltage is tuned in the narrow range -3 V to 3 V. The filter has a bandwidth of 400 MHz and shows low losses. Low losses are expected since the measurements of the microwave behaviour of hafnium oxide on high-resistive Si indicate in the X band $\tan\delta = 0.05$.[10]

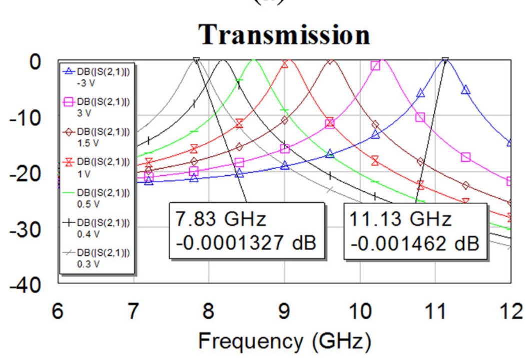
Further, we have developed a phase shifter cell consisting of a gold interdigitated (IDT) capacitor integrated in a CPW configuration, as shown in Fig. 3(a). The CPW is composed of three gold electrodes (the yellow regions in Fig. 3(a)) with a thickness of 200 nm deposited over 10 nm $Hf_{0.3}Zr_{0.7}O_2$ grown on 100 μm-thick high resistive Si. The central (signal) electrode of the CPW has a width of 100 μm, being separated from the ground electrodes by a gap of 50 μm. The IDT capacitor digit width is 5 μm, while the gap between two consecutive digits is 10 μm. The transition between the IDT capacitor and the CPW line is made by a taper.

The simulation results (not shown) indicate that the phase of S_{21} of the IDT capacitor based on the $Hf_{0.3}Zr_{0.7}O_2$ ferroelectric changes with 3.55° at 10 GHz when the voltage is tuned from -3 V up to $+3$ V. At the same time, the IDT capacitance changes in the range 1.714 pF up to 2.192 pF at 10 GHz showing a resonance between 11 GHz and 12 GHz. The IDT capacitance was calculated using the formula $C = \mathrm{Im}(Y_{11})/\omega$.

These data are then used to design a phase shifter having 14 IDT capacitors connected in series, the distance between two consecutive capacitors being 1 mm. The phase shifts of the CPW coplanar phase shifter, having a total length of 15 mm, are represented in Fig. 3(b) at three voltages -3 V, 0.3 V, and

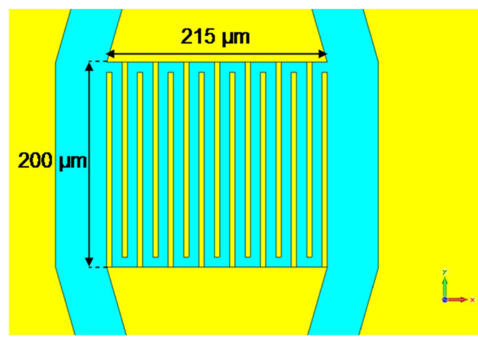


(a)

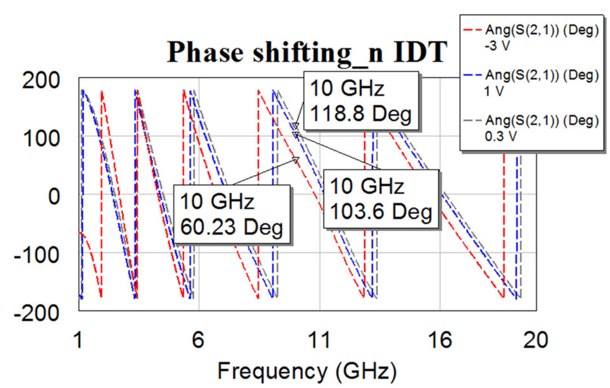


(b)

FIG. 2. (a) Frequency dependence of the return loss and (b) transmission of the filter based on $Hf_{0.3}Zr_{0.7}O_2$ ferroelectric at various applied voltages.



(a)



(b)

FIG. 3. (a) Phase shift cell and (b) phase shift of the CPW phase shifter formed from 14 IDT capacitors connected in series.

1 V. From these results, obtained with a CST simulator, it can be seen that the phase shift at 10 GHz between the phases at +0.3 V and −3 V is about 58.57 degrees. In addition, from Fig. 3(b) it follows that there are certain frequencies at which a phase shift of even 360° is possible. Such a very large phase shift can be used for electronic scanning of the beam of an antenna array.

In this respect, we consider further an antenna array composed of two patch antennas on 10 nm $Hf_{0.3}Zr_{0.7}O_2$ ferroelectric deposited on top of 100 μm-thick high resistive Si, all dimensions being indicated in Fig. 4(a). Numerical simulations of this array performed using CST confirmed that the isolation between the two antennas at 10 GHz is −44.72 dB, which is a very good value. Both antennas display $|S_{11}| = |S_{22}| = -16.52$ dB at 10 GHz, i.e., a voltage standing wave ratio (VSWR) = 1.352, which indicates a good matching.

If the previously studied phase shifter with 14 IDT capacitors is introduced now between antennas 1 and 2, the phase varies continuously between 60.23° and 118.8° with a total phase shift of $\Delta\phi = 58.57°$ as the bias is swept from −3 V to +0.3 V. As a result, the radiation pattern at 10 GHz is steered with ±32°, as can be seen from Fig. 4(b). The radiation efficiency is 15% due to the fact that the substrate thickness, of about $\lambda_0/300$, is very thin compared with the corresponding wavelength at 10 GHz.

The experimental data we have used are the most accurate and among few available to date extracted from a MIM capacitor TiN/HfO_2/TiN with the thickness of the TiN layer of 10 nm grown on Si (the conception of tunability of HfO_2 ferroelectric MIM for RF applications is suggested also in Ref. 11). The choice of TiN as the electrode is justified by the fact that this *n*-type wide band gap semiconductor, with a resistivity of 0.4 Ω cm and bandgap of 3.4 eV, induces a mechanical stress in HfO_2 preserving its ferroelectric state and suppressing the phase transition to the paraelectric phase. The workfunction of TiN is 4.6 eV, which is close to the corresponding value (4.7 eV) in polycrystalline Au in ambient conditions. Since the thickness of Au is twenty times larger than that of TiN and the free-space wavelength involved in this paper is of order of few cm, the TiN capping layer plays practically no role in the electromagnetic simulation. In addition, it was already shown that[12] the electrical and physical characteristics of TiN/HfO_2/TiN and Si/HfO_2/TiN capacitors are very similar, which suggests that the dielectric values obtained from Refs. 2 and 4 can be used for simulating HfO_2-based ferroelectric compounds on Si. This result is strengthened by another study (Ref. 13 and the references therein), which shows that Si has a similar role to TiN, namely, it prevents HfO_2 to switch from the ferroelectric to the paraelectric phase due to thermal expansion mismatch

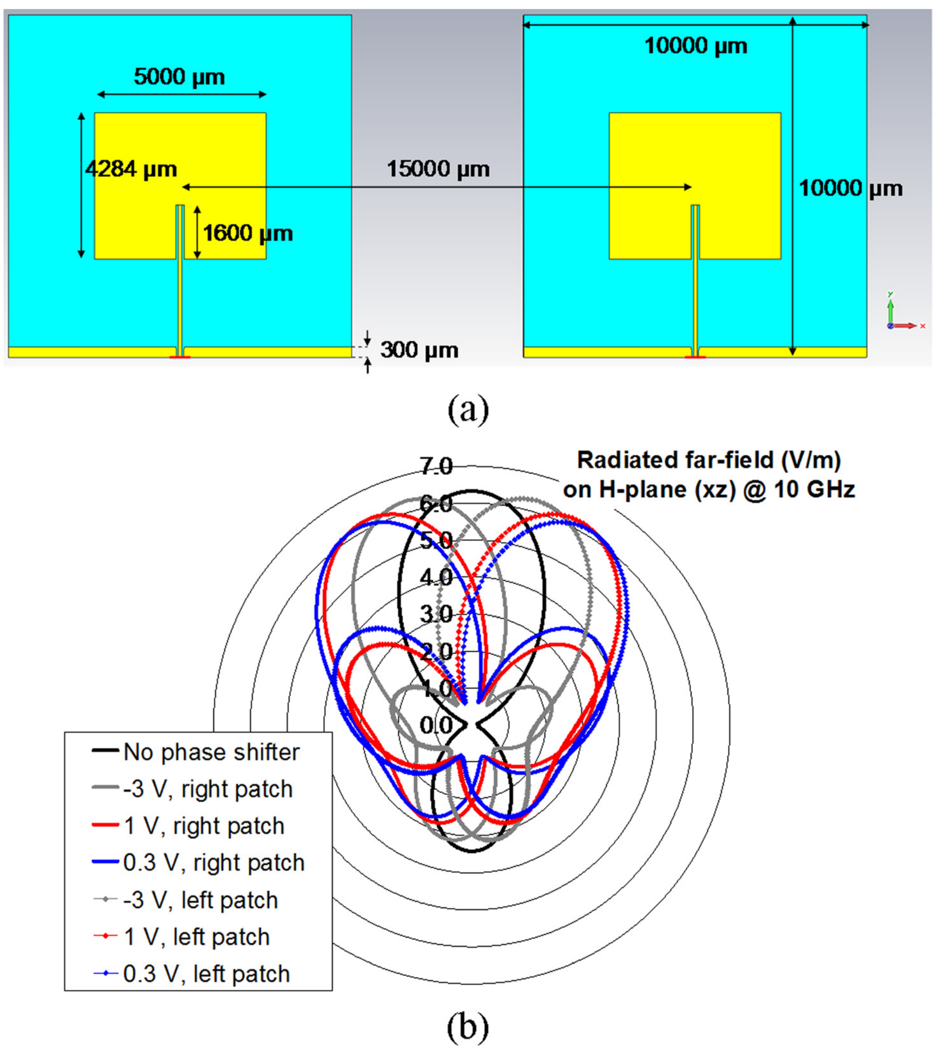


FIG. 4. (a) Array consisting of two patch antennas and (b) beam steering of the antenna array as a function of the applied voltage.

between Si and HfO_2, which produces a mechanical stress in the latter material.

In conclusion, the $Hf_{0.3}Zr_{0.7}O_2$ ferroelectric is able to tune significantly high-frequency devices such as filters, phase shifters, and antenna arrays. If the applied voltage is swept in the range -3 V to 3 V at 10 GHz, the filter changes its central frequency with 3 GHz, the phase shifter produce a phase difference of about 60 degrees, while the antenna array is steering its lobe with $\pm 32^\circ$. Since a lot of space and terrestrial communications have the frequency bandwidth in the X band, the above results show that low-power devices with a high degree of tunability can be used to enhance the capabilities of important communication systems.

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