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Investigation of P(VDF-TrFE) Ferroelectric Varactor for Tunable Radio Frequency Application

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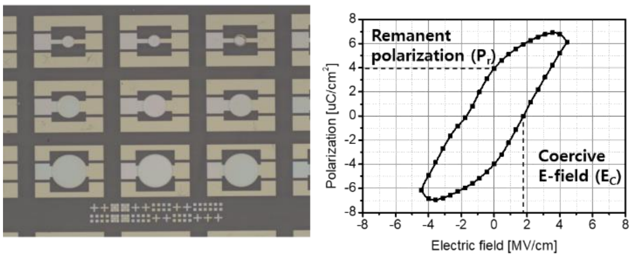
Abstract

In this work, we investigated the frequency tuning range (FTR) of P(VDF-TrFE) ferroelectric varactors. The tunable permittivity characteristics as a function of the bias voltage were maintained up to a microwave frequency range; FTR of ~2.5% was observed at 1 GHz proving the feasibility of P(VDF-TrFE) organic/ferroelectric material for use in a microwave frequency band.

1. Introduction

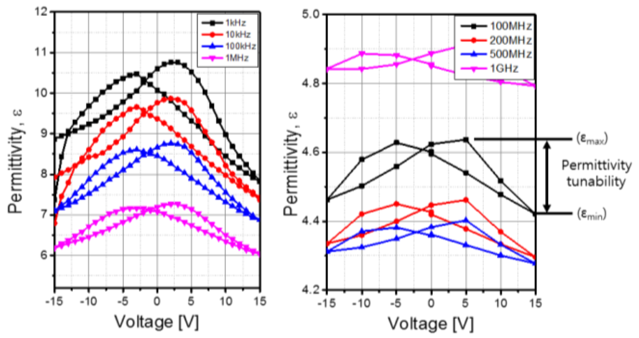
Tunable radio frequency (RF) devices have been demanded because of the enhanced usability with the tunable resonance frequency. Especially, a tunable metasurface or a frequency selective surface enables a transmit array or reflectarray antenna design that allows beamforming on the surface itself without changing the feeding [1]. Conventional tunable RF devices are designed with pin diode varactors which require a complex epitaxy and/or fabrication process and a special circuit operated under reverse bias conditions.

Ferroelectric varactors have tunable permittivity characteristics as a function of the applied electric field. Advantages of ferroelectric varactors in comparison with conventional pin diode varactors are the simple fabrication process and bi-directional voltage operation. A microstrip patch antenna based on a ferroelectric material was first proposed by Modelski, et al in 2000 since when various tunable RF devices with ferroelectric materials, such as $BaTiO_3$ [2], $Pb(Zr\text{-}Ti)O_3$ (PZT) [3], and BST [4], have been reported. Recently, P(VDF-TrFE) copolymer has been received attention for use in tunable RF devices due to their design versatility, wide permittivity tunability, high Curie temperature, and low cost [5].



(a) (b)

Fig. 1 (a) Microscope image of a fabricated MFM capacitor and (b) its corresponding polarization-electric field characteristics.



(a) (b)

Fig. 2 (a) Low frequency and (b) high-frequency dielectric constant versus applied voltage characteristics (ε-V) of P(VDF-TrFE) MFM capacitor.

The frequency tuning range (FTR) of ferroelectric materials decreases as the frequency increases due to the limited relaxation time of polarization dipole movement. Therefore, it is important to know the permittivity tunability of a given ferroelectric material as a function of frequency. A few studies have been reported on the frequency dependent ferroelectric characteristics but the frequency range was typically below 10 MHz [6],[7]. In this work, we investigated for the first time the frequency-dependent polarization switching characteristics of a metal-ferroelectric-metal (MFM) capacitor with P(VDF-TrFE) ferroelectric material up to the microwave frequency range.

2. Results and Discussion

A microscope image of the fabricated MFM capacitor and its corresponding polarization-electric field hysteresis loop characteristics are shown in Fig. 1(a) and 1(b), respectively. The fabricated 72-nm thick P(VDF-TrFE) MFM capacitor with a diameter of 200 μm exhibited a remanent polarization of ~ 4 μC/cm^2 and a coercive electric field of ~ 1.87 MV/cm.

In order to investigate the permittivity tunability of P (VDF-TrFE) MFM capacitor, capacitance-voltage measurements were carried out from 1 kHz to 5 MHz using a semiconductor parameter analyzer (B1500A) whereas s-parameter measurements were carried out from 100 MHz to 5 GHz using a network analyzer (E8361C). Since the MFM structure was a series capacitor, the s-parameters measured by the network analyzer was converted to ABCD parameters and the capacitance was extracted by

$$\text{Capacitance} = \frac{1}{j\omega \times imag(B)} \quad \text{where, } B = Z_0 \frac{(1+S_{11})(1+S_{22}) - S_{12}S_{21}}{2S_{21}}$$

The extracted dielectric constant-voltage (ε-V) characteristics are shown in Fig. 2. The dipole moments of the ferroelectric lattice structure were changed by the applied voltage, resulting in the butterfly-shaped ε-V characteristics. The maximum (ε_{Max}) and minimum (ε_{Min}) dielectric constant values are plotted as a function of frequency in Fig. 3(a) and the calculated permittivity tunability characteristics are plotted in logarithmic and linear frequency scales in Fig. 3(b) and 4(c), respectively. The tunability was calculated by (ε_{Max} - ε_{Min})/ε_{Min}. According to the measurement results, both permittivity and tunability decreased with frequency. It was observed that the tunability was maintained up to > 1 GHz. The tunability of 2 – 3 % above 500 MHz can still be utilized for tunable RF device applications [1], [5]. Decreased permittivity and tunability can be attributed to free dipoles oscillating in an alternating electric field. Dipoles can follow the electric field change at low frequencies but cannot follow the change at high frequencies ($f >> 1/\tau$ where τ is relaxation time); dipoles begin to lag behind the electric field change and lose their movements beyond the characteristic frequency ($f = 1/\tau$) [6], [7].

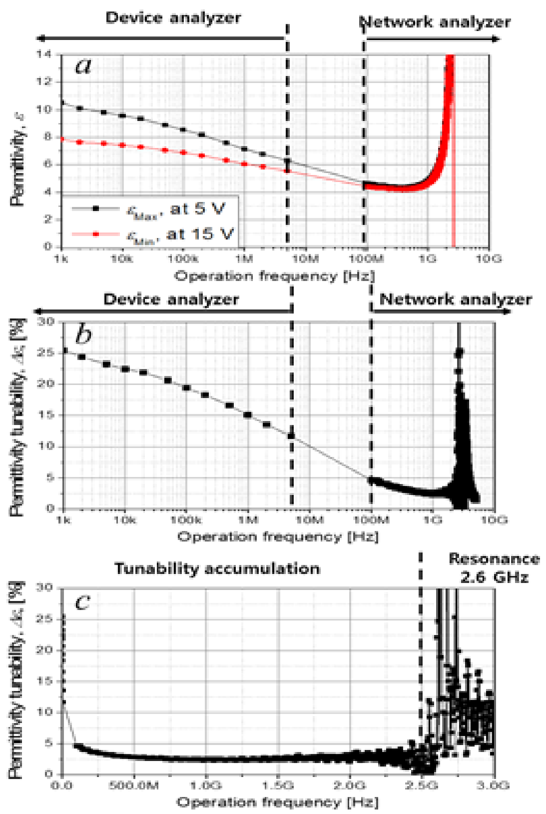


Fig. 3 (a) Maximum and minimum permittivities versus frequency. (b)The frequency tuning range (FTR) in a logarithmic frequency scale and (c) a linear frequency scale

3. Conclusions

The frequency dependent permittivity tunability of P(VDF-TrFE) MFM capacitor was reported for the first time up to a microwave frequency range. A permittivity tunability of ~2.5% was observed at 1 GHz, which proved the feasibility of P(VDF-TrFE) for use in tunable RF devices. When designing tunable RF devices, the permittivity tunability is very important because it determines the range of selectable frequency as well as the transmission and reflection coefficients of the device. Therefore, this work is an important finding for designing tunable RF devices based on P(VDF-TrFE) ferroelectric material.

Acknowledgments

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