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Radio-Frequency Characteristics of Ge-doped Vanadium Dioxide Thin Films with Increased Transition Temperature

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ABSTRACT: This work investigates and reports on the radio-frequency (RF) behavior in the frequency range of 5 – 35 GHz of germanium-doped (Ge-doped VO$_2$) vanadium dioxide thin films, deposited on silicon substrates via sputtering and pulsed laser deposition (PLD) with estimated Ge concentrations of 5 % and 5.5 %. Both films exhibit critical transition temperatures ($T_c$) of 76.2 and 72 °C, respectively, which are higher compared to that of the undoped VO$_2$ which undergoes reversible insulator-to-metal phase transition at 68°C. Both types of Ge-doped films show low hysteresis ( < 5 °C) in their conductivity versus temperature characteristics and
preserve an high off-state DC-conductivities (corresponding to the insulating state of the phase change material) of 13 S/m, for the sputtered, and, 55 S/m, for the PLD deposited film, respectively. The DC on-state (corresponding to the conductive state of the phase change material) conductivity reaches 145,000 S/m in the case of the PLD film, which represents a significant increase compared to the state-of-the art values measured for undoped VO₂ thin films deposited on identical substrates. In order to further understand the off-state dissimilarities and RF behavior of the deposited Ge-doped VO₂ films, we propose an original methodology for the experimental extraction of the dielectric constant (ɛᵣ) in the GHz range of the films below 60 °C. This is achieved by exploiting the frequency shift of resonant filters. For this purpose we have fabricated coplanar waveguide (CPW) structures incorporating ultra-compact Peano space filling curves, each resonating at a different frequency between 5 and 35 GHz on two types of substrates, one with the Ge-doped VO₂ thin films and another one using only SiO₂ to serve as reference.

The reported results and analysis contribute to the advancement of the field of metal-insulator-transition material technology with high T_c for RF industrial applications.

**KEYWORDS:** phase change materials, radio frequency passive circuits, vanadium dioxide, dielectric constant, coplanar waveguide, CMOS, lossy dielectrics

**INTRODUCTION**

Recently, the applications of Mott insulators showing metal-to-insulator transitions have been actively explored¹⁻³, as the phase transitions could be triggered facts, practically in sub-nanosecond timescales and also because the device operation can be done purely electrically,
with technologies compatible with silicon CMOS. The key feature of feature of Mott insulators
is related to the fact that the energy of many other interactions is on the same order of magnitude
with electron–electron correlation and kinetic energy; as a consequence such interactions could
play a relevant role on the electronic properties of the material. The phase-change material
vanadium dioxide, VO$_2$, exhibits a monoclinic crystal structure and behaves like an insulator
below its insulating-to-metal transition temperature ($T_{ITM}$). Subject of many controversies, it is
currently agreed that the phase transition in VO$_2$ is probably a combined effect of lattice
distortion and Coulomb correlations. Due to its ease of integration, reversible insulator to metal
transition (IMT), fast switching time and device-size shrinking capabilities, the employment of
VO$_2$ as a reconfigurable radio frequency (RF) material has been recently investigated for a
variety of RF-reconfigurable devices on various substrates such as sapphire$^{4-8}$, or cheaper SiO$_2$$^{9-16}$
among others, in the frequency range of 1 – 35 GHz. The relatively low transition temperature
of VO$_2$ of $T_c = 68 \, ^\circ C$ when deposited on silicon (Si) CMOS compatible substrates hinders its
usability for developing RF switches since for most RF applications it is required to have a
switching temperature above 80 °C$^{17}$. On the other hand, the DC conductivity levels of VO$_2$ thin
films in their insulating off-state ($\sigma_{DC_{OFF}}$), and conductive on-state ($\sigma_{DC_{ON}}$) vary over a wide
range depending on the substrates used for deposition and hence the built-in lattice miss-
matches$^{18}$. Doping VO$_2$ proved to be a solution for changing the critical transition temperature $T_c$
(which is defined as the average between the $T_{ITM}$ and the metal-to-insulator transition
temperature $T_{MIT}$). This shift was downwards while doping with Co on Al$_2$O$_3$ substrates$^{19}$ or
upwards to $T_c = 93.6 \, ^\circ C$ using Ge on Si-substrates as shown in our previous work$^{20}$, however the
conductivity level $\sigma_{DC_{ON}}$ obtained above 93.6 °C was below 360 S/m (for Ge concentrations of
5.9 %), far lower than $\sigma_{DC_{-ON}}$ obtained for undoped VO$_2$ (which are higher than 10,000 S/m) when the latter was employed for RF research applications.$^{13-16}$

Unlike the range of optical frequencies, where ellipsometry (a far-field approach) is a powerful tool for the determination of the relative dielectric permittivity of the VO$_2$, given by

$$\varepsilon_{r,VO_2}(f,T) = \varepsilon'_{r,VO_2}(f,T) + j\varepsilon''_{r,VO_2}(f,T), \quad (1)$$

when thin films are deposited on different substrates$^{21-27}$, near field approach or conformal mapping$^7$ are used in RF engineering of electronic functions.

In the RF range, to the best of our best knowledge, no study is available in the literature about the dielectric constant, ($\varepsilon_{r,VO_2:Ge}(f,T)$), of Ge-doped VO$_2$ deposited on CMOS compatible substrates, or its relative dielectric permittivity:

$$\varepsilon_{r,VO_2:Ge}(f,T) = \varepsilon'_{r,VO_2:Ge}(f,T) + j\varepsilon''_{r,VO_2:Ge}(f,T). \quad (2)$$

Even for undoped VO$_2$, models used within 1 – 30 GHz for the relative dielectric function, are in their incipient stages of development, and exists only for the case of a VO$_2$ thin film on sapphire substrate obtained by using conformal mapping approximations.$^7$

In most cases, for the modelling of the off-state conductivity in RF VO$_2$ thin films used for switches, authors usually consider the material as a constant valued sheet resistance while seldom simulating it as a lossy dielectric, as depicted in Table 1. The conductivity $\sigma_{DC_{-OFF}}$ values measured at room temperature are then assumed as representative for the whole range of RF performances ($\sigma_{AC}(f) = \sigma_{DC_{-OFF}}$), and VO$_2$ is modelled as sheet resistance or a resistance.$^{4-7,8-12}$

On the other hand for thin VO$_2$ films deposited on SiO$_2$-Si CMOS compatible substrates these
films are simulated as a lossy dielectric\textsuperscript{13-16}, the $\sigma_{\text{DC, OFF}}$ being considered as the conductivity value at the central frequency ($f_0$) of the analyzed frequency band of the simulations ($\sigma_{\text{AC}}(f_0) = \sigma_{\text{DC, OFF}}$), while a fixed empirical value of 30 is used for the dielectric constant $\varepsilon'_r\text{VO}_2$ of VO\textsubscript{2} at room temperature.

The 3D electromagnetic field simulation software - Ansys HFSS (v. 17.2), used for modelling in RF applications\textsuperscript{13-16, 28-29}, has three predefined different models: two which are based on the Debye model and one other based on the Djordjevic-Sarkar frequency dispersion model\textsuperscript{30-31}. Their use avoids improper definition of the material\textsuperscript{32}, the latter one being used by default when losses exceed certain limits\textsuperscript{33} (unless de-activated by the user). When using one of these existing frequency dispersive models, the Kramers-Kronig relations followed by all real and imaginary parts of the dielectric functions of any causal material\textsuperscript{34} are obeyed, but only according to these particular models. Conversely, using the simplified models in\textsuperscript{13-16} (where authors use VO\textsubscript{2} only on a limited area of the devices) and assuming a constant $\varepsilon'_r\text{VO}_2(f, T = \text{25°C})$ and a non-constant $\varepsilon''_r\text{VO}_2(f, T = \text{25°C}) = \frac{\sigma_{\text{AC}}(f, T = \text{25°C})}{2nf\varepsilon_0}$ (where $\varepsilon_0$ denotes the vacuum permittivity), violates the Kramers-Kronig relations since a frequency-independent dielectric constant implies a constant imaginary part and this is obeyed only by vacuum\textsuperscript{34}.

In this work we first do a DC characterization of two germanium-doped VO\textsubscript{2} films with doping concentrations of 5 % and 5.5 %, prepared via sputtering and pulsed laser deposition (PLD), respectively, on CMOS compatible SiO\textsubscript{2}/high resistivity silicon substrates. We compare their temperature dependent DC conductivity levels $\sigma_{\text{DC}}(T)$ and temperature hysteresis (defined as $T_{\text{ITM}} - T_{\text{MIT}}$) with other undoped VO\textsubscript{2} depositions done in similar conditions by us\textsuperscript{16}. The PLD (243 nm) and sputtered (183 nm) Ge-doped VO\textsubscript{2} films exhibit $T_c$’s of 72 °C and 76.2 °C,
respectively, and present $\sigma_{DC,ON}$ values which are orders of magnitude higher than that of the 5.9 % Ge-doped VO$_2$ thin film from our previous work$^{20}$ with $T_c = 93.6$ °C.

Next we explore the $\varepsilon'_r{VO_2:Ge}(f,T)$, extract $\varepsilon'_r{VO_2:Ge}(f,25$ °C) and analyze the AC frequency and temperature dependent conductivity $\sigma_{AC}(f,T)$ behavior and modelling for both thin films within the 5 – 35 GHz frequency range below their $T_c$.

In our original procedure we rely on the design and fabrication of a set of space filling Peano-Hilbert curves$^{36}$, used as defected ground plane structures (DGS)$^{14,37-38}$ in multilayer coplanar waveguide technology (CPW). Each structure operates as a bandstop filter resonating at various frequencies within the 7 to 35 GHz range, depending on its (geometry and size), when on a reference substrate without the Ge-doped VO$_2$ thin film. The same filters fabricated on the multilayer CPW including the Ge-doped VO$_2$ films exhibit a relative frequency shift of their resonance frequencies ($f_r$) and lower bandstop attenuations. This allows us to extract $\varepsilon'_r{VO_2:Ge}(f,T)$ and the $\sigma_{AC}(f,T)$ below $T_c$. The same procedure is used for undoped VO$_2$ thin film depositions on the same substrate configuration from the fabrication run reported in$^{16}$.

Table 1. An overview of the dielectric loss modelling of VO$_2$ thin films in the off state at different frequency bands
### References

<table>
<thead>
<tr>
<th>References</th>
<th>Frequency spectrum</th>
<th>Dielectric constant $\varepsilon_{r,VO_2}(f)$</th>
<th>Conductivity $\sigma_{AC,OFF}(f)$</th>
<th>Model, simulation and assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3, 5-8</td>
<td>RF</td>
<td>-</td>
<td>$\sigma_{OFF}(f) = \sigma_{DC,OFF}$</td>
<td>Simulated as a resistive material. Area occupied by VO$_2$ is very small compared to the device area.</td>
</tr>
<tr>
<td>9</td>
<td>RF</td>
<td>-</td>
<td>$\sigma_{OFF}(f) = \sigma_{DC,OFF}$</td>
<td>Same as above.</td>
</tr>
<tr>
<td>10-13</td>
<td>RF</td>
<td>30</td>
<td>$\sigma(f_0) = \sigma_{DC,OFF}$</td>
<td>Simulated as a non-causal dielectric violating Kramers-Kronig relations, on SiO$_2$-Si substrates. Area occupied by VO$_2$ is very small compared to the device area.</td>
</tr>
<tr>
<td>4</td>
<td>RF</td>
<td>$\varepsilon_{r,VO_2}(f)$</td>
<td>Yes from $\varepsilon_{r,VO_2}(f)$</td>
<td>on Sapphire. Extracted via Conformal mapping, assuming infinite ground planes, simplified losses model$^{37}$.</td>
</tr>
<tr>
<td>18-24</td>
<td>Optical</td>
<td>$\varepsilon_{r,VO_2}(f)$</td>
<td>Yes from $\varepsilon_{r,VO_2}(f)$</td>
<td>Obeying Kramers-Kronig relations via different models (Lorentz, Tauc-Lorentz, etc.).</td>
</tr>
</tbody>
</table>

### EXPERIMENTAL SECTION

#### 2.1. Ge-doped VO$_2$ depositions

The 5% Ge-doped VO$_2$ film was deposited by reactive magnetron sputtering in high vacuum conditions with a base pressure in the chamber below $5\times 10^{-8}$ mbar and a process pressure of $\sim 7\times 10^{-3}$ mbar. The Ge is sputtered here from a V-Ge alloy target as sputtering of dopant from alloy targets is preferred over co-sputtering, as previously reported$^{20}$, due to easier process control. To deposit thermochromic VO$_2$ films (and avoid the formation of the oxygen poor V$_2$O$_3$ or the oxygen rich, thermodynamically stable V$_2$O$_5$), the oxygen partial pressure during the process must be precisely controlled. For that, a Proportional Integral Derivative (PID) feedback
control is employed which regulates the oxygen flow based on the pressure readings of a Zirox XS22 lambda-probe oxygen sensor. Hence, the oxygen partial pressure is strictly kept in the defined narrow range (5.8±0.2x10⁻⁴ mbar). For uniform film deposition (around 200 nm in our report), the substrate is rotated at 20 rpm. The deposition temperature is 450 °C.

The 5.5 % Ge-doped VO₂ was deposited with a PLD technique. The Ge-doped VO₂ film was deposited using a Solmates SMP 800 on a CMOS compatible wafer starting from a 5.5 % Ge: V₂O₅ target at a temperature of 400 °C and a laser pulse frequency of 20 Hz. The chamber was first pumped down to a base pressure of 10⁻⁶ mbar and then an O₂ flow of 5 sccm was employed to reach and keep the deposition pressure of 10⁻² mbar. After deposition, the temperature was raised to 470 °C for 15 minutes and then the wafer was let to cool down, still at the same pressure, until room temperature was reached.

2.2. Ge-doped VO₂ Characterization

The thicknesses of the Ge-doped VO₂ depositions were then determined via ellipsometry and cross-sectional SEM imaging:

The thickness of the PLD deposited Ge-doped VO₂ was determined via variable angle spectroscopic ellipsometry (VASE). The sample was measured at incidence angles of 65°, 70°, and 75° in the wavelength range from 240 to 1700 nm. The measured ellipsometric Ψ and Δ were fitted, together with the Ge-doped VO₂ layer thickness, using three independent Tauc-Lorentz oscillators. The substrate layers were measured separately on a series of reference samples to allow for an isolated measurement of the Ge-doped VO₂ properties. By this technique, the thickness of the Ge-doped VO₂ layer was determined to be 243 nm.
For the sputtered wafer, the ZEISS Supra 60VP SEM system with an electron high tension (EHT) voltage of 15 kV and a working distance (WD) of ~ 3 mm was used here to examine the sample cross section, resulting in Figure 1 (c) showing around 183 nm, on the sample margin where the cross-section was taken.

![Figure 1](image.png)

**Figure 1.** Cross sections of the substrate configurations used: Al depositions on (a) Ge-doped VO$_2$ VO$_2$/SiO$_2$/a-Si and (b) a reference SiO$_2$/a-Si, both on high resistivity silicon substrates. (c) SEM cross section of the PLD Ge-doped VO$_2$ sample, schematically shown in (a), towards the margin of the sample.

The electrical properties of the films were studied from room temperature up to 100 °C by determining their temperature dependent conductivity. This was done by standard four-point probe measurements using a semiconductor parameter analyzer (HP 4156C) and a control on the sample temperature up to 100 °C.

### 2.3. Filter design and electrical characterization

The proposed methodology relies on the design and fabrication of a set of *space filling Peano-Hilbert used as curves defected ground plane structures* (DGS) $^{37-38}$ in multilayer (CPW).
DGS represents a small area where the ground plane metallization is removed. These structures operate as bandstop filters\textsuperscript{37-38}, the form occupied by the DGS determining their \( f_r \) and bandstop rejection characteristics. Peano curves are space filling curves\textsuperscript{36,39,40}, whose lengths can be easily increased while occupying a small area. The \( f_r \) of the Peano DGS structure is dependent on their contour length, the bigger, the smaller the resonance frequency. On the other hand the size of the width of the generating curve, \( g \) (see please Figure 2 (a)) plays a more important role in the attenuation levels achieved. The proposed structures resonate at various frequencies within the 7 GHz to 35 GHz range when deposited on the substrate layer configuration in Figure 1. After depositing the above described Ge-doped VO\(_2\) layers, conventional photolithography followed by deposition of a 700 nm-thick Al layer are employed to form the CPW elements with low RF losses. The DGS are obtained by patterning the ground planes with the Peano curves. The increased length contour allows us to obtain resonances also in the lower frequency ranges of the RF spectrum and thus by changing their complexity and length we can obtain several resonators covering the C, X, Ku, K and partially the Ka bands where most wireless communications take place. The same resonators are then fabricated on the substrate layer configuration shown in Figure 1 (b) (without the Ge-doped VO\(_2\) thin films, while in (a) with it). Figure 2 presents the fabricated DGS space filling curve structures for various resonant frequencies on the reference substrate as indicated. The ground-signal-ground distances are 24-40-24 \( \mu \text{m} \) for all of them, while the width of their generating curve (\( g \)), (schematically described in Figure 2 for one of the structures) is 10 \( \mu \text{m} \) for the structures resonating at 7.2 and 9.4 GHz, 5 \( \mu \text{m} \) for the ones at 26 GHz and 35.2 GHz, while 21\( \mu \text{m} \) for the one resonating at 30 GHz.

The scattering parameters \( S \), (where \( S_{21} \) is insertion and \( S_{11} \) is the return loss)\textsuperscript{28-29} of the fabricated devices were measured with the Anritsu Vector Star Network Analyzer (VNA) in a
Cascade Summit prober with controllable chuck temperature which was set to 25 °C (RT), 40 °C, 50 °C and 60 °C.

![Cascade Summit prober with controllable chuck temperature](image)

Figure 2. (a) Peano-Hilbert-space filling curve type of DGS filters fabricated for a desired resonant frequency from 7 to around 35 GHz. The designed resonance frequency $f_r$ shifts on (b) Ge-doped VO$_2$/SiO$_2$/a-Si/HR-Si configuration with respect to the resonances obtained on the reference substrate in (c) SiO$_2$/a-Si/HR-Si.

**Results and discussions**

**3.1. DC behavior at various temperatures**

For the sputtered 5 % Ge-doped VO$_2$, we obtained a $T_c = 76.2$ °C. The conductivity level at this temperature is 20 times higher as compared to our previous 5.9% Ge-doped VO$_2$ film work$^{20}$, where we could report only 396 S/m at $T_c = 93.6$ °C. These levels are comparable with the ones obtained for VO$_2$ thin films with $T_c = 68$ °C$^{13-16}$ (Table 2), the transition temperature being slightly higher than for the other Ge-doped VO$_2$ films with Ge concentrations (0.1 %- 4.3 %) reported.$^{20}$
The PLD 5.5 % Ge-doped VO$_2$ film on the other hand shows excellent $\sigma_{DC,ON}$ levels of 145,000 S/m, with a $T_c$ of 72 °C (compared to 48,000 S/m and $T_c$ of 68 °C in undoped VO$_2$ films). The DC conductivity vs temperature measurements of all the films are presented in Figure 3 (a). In both the types of Ge-doped VO$_2$ films, we report an IMT-MIT (insulator to metal, metal to insulator transition) hysteresis with widths lower than 4.5 °C, far better than for undoped VO$_2$.

The crystallinity of the VO$_2$ and Ge-doped VO$_2$ films is confirmed by room temperature Θ-2Θ in Figure 3 (b) and in Figure 3 (c) by grazing incidence X-ray diffraction (GIXRD, Empyrean system equipped with PIxcel-1D detector, monochromatic Cu Kα radiation, grazing incidence GI angle 4°). The strongest peak at $2\Theta = 27.9^\circ$ in Figure 3 (c) is assigned to the (011) diffraction peak of the monoclinic VO$_2$ phase according to PDF 00-044-0252. The (011) diffraction peak positions for the PLD deposited films in Figure 3 (b) are slightly shifted to higher angles suggesting the presence of residual stresses the films.

The Figure 3 (d), (e) and (f) displays the SEM pictures of the continuous polycrystalline films, with larger grains (50-200 nm) in case of the sputtered Ge-doped VO$_2$ and the PLD undoped VO$_2$. 
Figure 3. (a) Measured MIT/IMT transitions of the fabricated Ge-doped VO$_2$ films showing transition temperatures $T_c$ at 76.2 °C for sputtered 5 % Ge-doped VO$_2$ (orange), and at 72 °C for the PLD deposited 5.5 % Ge-doped VO$_2$ (red) with improved high/low conductivities and low hysteresis, compared to our previously reported 5.9 % Ge-doped VO$_2$ (in green) and undoped PLD-deposited VO$_2$ (in blue$^{16}$). (b)-XRD spectra of the thin films done by PLD, (c), XRD spectra of the film by sputtering. (d)-(f) SEM images showing the grain structure of the: sputtered Ge-doped VO$_2$ (d), PLD Ge-doped VO$_2$ (e) and the PLD undoped VO$_2$ corresponding to ref$^{16}$ (f).

Table 2. Ge-doped VO$_2$ and VO$_2$ thin films DC behavior on RF CMOS compatible substrates

<table>
<thead>
<tr>
<th>References</th>
<th>Film type</th>
<th>Film conductivity at 25°C (S/m)</th>
<th>Film conductivity at 100°C (S/m)</th>
<th>IMT Transition temperature (°C)</th>
<th>Hysteresis width (°C)</th>
<th>$\sigma_{DC\text{ on}}/\sigma_{DC\text{ off}}$</th>
<th>Film thickness (nm)</th>
<th>Skin depth at 10 GHz (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>PLD VO$_2$</td>
<td>20</td>
<td>64,000</td>
<td>68</td>
<td>10</td>
<td>3200</td>
<td>170</td>
<td>20</td>
</tr>
<tr>
<td>13</td>
<td>PLD VO$_2$</td>
<td>22</td>
<td>48,000</td>
<td>68</td>
<td>10</td>
<td>2181</td>
<td>140</td>
<td>23</td>
</tr>
<tr>
<td>17</td>
<td>5.9 % Ge-doped VO$_2$</td>
<td>3.27</td>
<td>353</td>
<td>96.6</td>
<td>10</td>
<td>108</td>
<td>480</td>
<td>267</td>
</tr>
<tr>
<td>In this work</td>
<td>sputtered 5 % Ge-doped VO$_2$</td>
<td>12.18</td>
<td>7,633</td>
<td>78.2</td>
<td>&lt;4.5</td>
<td>627</td>
<td>200</td>
<td>58</td>
</tr>
<tr>
<td>In this work</td>
<td>PLD 5.5% Ge-doped VO$_2$</td>
<td>55.72</td>
<td>145,000</td>
<td>74.5</td>
<td>&lt;4.5</td>
<td>2603</td>
<td>243</td>
<td>13</td>
</tr>
</tbody>
</table>
An important feature of the PLD deposition, due to its increased $\sigma_{DC \_ON}$, is the skin depth at 10 GHz which is smaller than for all previous VO$_2$ depositions on the same substrate. This plays an important role in the on state conductivity of the Ge-doped VO$_2$, since ideally it is not desirable to operate far below the skin depth in RF-microwave design. The thin film thickness/skin depth ratio should be as big as possible, else the $\sigma_{DC \_ON}$ values measured in DC may not be obtained while working in AC, leading to potentially bigger conductive losses.

3.2. Room temperature RF behavior

The measured S21 parameters of the fabricated filters on Ge-doped VO$_2$ (done using the layer configuration displayed in Figure 1 (a)), and the S21 parameters for the reference filters (fabricated using the reference layer configuration displayed in Figure 1 (b)) are presented in Figure 4. The three filters presented in Figure 4 resonate at 7.4 (a), 26 (b) and 35.2 (c) GHz (please see Figure 2 for their DGS layout), when fabricated on the reference substrate. The presence of the Ge-doped VO$_2$ film shifts down the resonance frequency of the filters while attenuating their bandstop rejection performance with respect to the ones fabricated on the reference substrate. The same trend is observed also for the other two filters (whose layouts are presented too in Figure 2) and resonating at $f_r = 9.4$ GHz and at $f_r = 30$ GHz.
Figure 4. Room temperature measured S21 (dB) of fabricated Peano filters with 200 nm 5 % Ge-doped VO$_2$ deposited by sputtering (orange) and 243 nm 5.5 % Ge-doped VO$_2$ deposited by PLD (red). The black curve corresponds to the Peano filters on the reference substrate (on SiO$_2$) resonating at 7.2 GHz (a), 26 GHz (b) and 35.2 GHz (c).

In Figure 5 we show the S21 parameters obtained for the film used in$^{16}$, where undoped PLD VO$_2$ was used with 2400 nm-thick CPW lines (unlike the 700 nm one used here for the Ge-doped VO$_2$ film metallization and their reference substrates), together with the S21 parameters for their reference filters (with 2400 nm and 700 nm-thick CPW lines). Comparing these S21 parameters in Figure 5 with the ones obtained on the sputtered 5 % Ge-doped VO$_2$ thin film for the same three filters as in Figure 4 reveals a very alike behavior reflected in the very similar relative frequency shift and attenuation distortion.

Figure 5. Room temperature measured S21 (dB) of fabricated Peano filters with 200 nm 5 % Ge-doped VO$_2$ deposited by sputtering (orange) and VO$_2$ from the previous run (blue).$^{16}$ The black curves correspond to the Peano filters on the reference substrates (on SiO$_2$ with 2400 nm metallization, dashed, while continuous line with 700 nm metallization) resonating at 7.2 GHz (a), 26 GHz (b) and 35.2 GHz. (c).
3.3. Temperature and RF dependent behavior

To analyze the RF behavior of the Ge-doped VO$_2$ samples as a function of temperature, the measured transmission parameters S21 of the same filters have been measured at 40, 50 and 60°C, their performances being presented together with the S21 parameters of the reference filter, in Figure 6. As the temperature increases, the losses become more visible, decreasing the quality factor of the filters and their maximum bandstop attenuation around the resonance and bandpass performance elsewhere. The same trend is observed for the other fabricated structures resonating at 9.4 GHz and 30 GHz whose layouts are presented in Figure 2.

![Figure 6](image_url)  
**Figure 6.** Measured S21 (dB) of the fabricated Peano filters with 200 nm 5% Ge-doped VO$_2$ deposited by sputtering (orange) and 243 nm 5.5% Ge-doped VO$_2$ deposited by PLD (red) for various temperatures. The black curve corresponds to the Peano filters on the reference substrate (on SiO$_2$) resonating at (a) 7.2 GHz, (b) 26 GHz and (c) 35.2 GHz.

3.4. RF modelling and results on reference substrate

Ansys HFSS simulated S21 results together with the measured (at room temperature) are shown for the structures resonating at 7.4, 26 and 35.2 GHz (on the reference substrate). The S21
parameters are shown in Figure 7 (a). Their complementary S11 parameters can be seen in Figure 7(b)-Figure 7(d). (for the sake of simplicity only for these three structures, the same procedure being used for all). The results show a good agreement close to the resonance frequency between the simulated (designed) filters and fabricated ones for the reference layer configuration in Figure 1(b), showing the very accurate modelling capabilities of Ansys HFSS when the material parameters are known. In this work we have extracted the Ge-doped VO$_2$ dielectric parameters following a best fitting procedure of an analytical model with the S parameter experimental curves (displayed in Figure (4)).

![Figure 7](image.png)

**Figure 7.** Room temperature measured (black) and simulated (green) with Ansys HFSS (a) S21 (dB) of the fabricated Peano filters on the reference substrate for $f_r=7.2$ GHz one, $f_r=26$ GHz and $f_r=35.2$ GHz. (b) S11 on the frequency dependent 3D Smith chart$^{16}$ for $f_r=7.2$ GHz (c), $f_r=26$ GHz, (d), $f_r=35.2$ GHz plotted for the same frequency range as in (a).
3.5. RF Ge-doped VO\(_2\) modelling

The Ge-doped VO\(_2\) film RF material parameters were extracted by fitting the S parameters corresponding to the measured ones around their resonance frequencies: The thin film RF material parameters were tuned around each resonance frequency leading to the experimental extraction of the dielectric constant \((\varepsilon_r)\) and \(\tan\delta\) of the films below 60 °C, as already proposed in the beginning of this paper. The results are shown in Figure 8 for three of the five filters.

The de-embedding is performed around 5 resonance frequency points corresponding to the ones of the 5 Peano filters presented in Figure 2 fabricated on the two Ge-doped VO\(_2\) thin films. The thickness of the Ge-doped VO\(_2\) thin film is entered in the Ansys simulator according to the thin film thickness measurements on the different locations on the wafer where the filters were positioned. Additionally, this de-embedding is also done for filters fabricated on undoped VO\(_2\) (instead of the Ge-doped VO\(_2\)) in Figure 1(a) from the same run as in\(^{16}\), whose S21 parameters are presented in Figure 5, however using there 2400 nm metallization (instead of 700 nm, corresponding to their fabrication run).

Figure 8 presents the good matching of the de-embedded results and the measured ones for the fabricated filters on the reference substrates and the two thin films.
Figure 8. Room temperature measured and simulated S21 parameters of three families of filters. The filters fabricated on the reference substrate (black) fit well with the designed simulated ones (green). The filters fabricated on the Ge-doped VO$_2$ are de-embedded and fitted on a limited frequency band (green) around their resonance frequencies for both fabricated PLD (red dotted) and sputtered (orange dotted). The fitting is done by tuning the material parameters of the (newly defined) Ge-doped VO$_2$ material in the Ansys HFSS. The same procedure is used for all 5 families of filters.

In the extraction procedure $\varepsilon'_{r,VO_2:Ge}(f, T = 25^\circ C)$ and $\sigma_{AC}(f,T = 25^\circ C)$ are optimized around each resonance frequency of the Peano filters in order to match the measured responses obtained on the PLD and sputtered Ge-doped VO$_2$ substrates. This is done using extensive numerical simulations and optimizations in Ansys HFSS while extracting Ge-doped VO$_2$ material parameters for each deposition and frequency. The same extraction procedure is done for the undoped VO$_2$ thin film.

3.6. Dependence of Ge-doped VO$_2$ permittivity on frequency

The extracted parameters, using the methodology depicted in section 3.5, are summarized in Figure 9 and 10 at room temperature and correspond to the material parameters used in Figure 8 to fit the filter responses. The values extracted for the dielectric constant ($\varepsilon'_{r,VO_2:Ge}$) reflect the bigger relative
frequency shift in PLD depositions. As observable also from Figure 5, the filters fabricated on the undoped VO$_2$ and the ones on the 5 % sputtered Ge-doped VO$_2$ have a similar frequency shift in respect to their reference filters on SiO$_2$. The 5.5 % PLD Ge-doped VO$_2$ filters on the other hand in Figure 4 show a considerably larger relative frequency shift than all their counterparts. In respect to the losses, the filters on the 5.5 % PLD Ge-doped VO$_2$ film show decreased quality factors and bandstop performances (as already expected from the DC conductivity measurements where their measured conductivity was already 55 S/m, unlike 13S/m for the sputtered Ge-doped VO$_2$ or 20 S/m for the undoped VO$_2$ film—Figure 3 (a)).

On the other hand the extracted values for the conductivity ($\sigma_{AC,OFF}$) show slightly lower values in the low frequency range than in DC: this is partially because of the decreased room temperature when the S parameters were measured (lower than 25°C). Another cause is due to Joule heating while measuring the values in DC, and additionally at these frequency ranges we work far below skin depth and while a phenomenon of decreased AC conductivity was reported in thin metal layers$^{44}$, this may still occur for insulating thin films.

The AC conductivity values (Figure 10) are lower for the 5 % sputtered Ge-doped VO$_2$ thin film compared to the 5.5 % PLD one, while being similar to the values obtained for the undoped VO$_2$ film. This result is interesting and can be explained by comparing Figure 3, (b), (c), (d). The grain sizes of the undoped VO$_2$ and sputtered Ge-doped VO$_2$ are more similar (while dissimilar to the ones of the 5.5 % PLD deposited Ge-doped VO$_2$). A dependency of the THz dielectric and conductive parameters on the film’s morphology was already reported for undoped VO$_2$ films deposited under different pressure conditions.$^{44}$ A morphology change of the films, caused by the different growth conditions of the films, brings a significant dielectric and conductivity change, detected previously in the THz regions.
Here we observe that the undoped VO$_2$ and sputtered Ge-doped VO$_2$ have comparable grain sizes, similar DC conductivity levels and that their RF dielectric and AC conductivity levels stay similar within the 5-35 GHz frequency band too, while exhibiting a slight increase in respect to their DC values.

For the PLD Ge-doped VO$_2$ film we observe a significantly different morphology and very high conductivity levels already in DC. The extracted AC conductivity shows 81% increase within the analyzed frequency band, while the extracted dielectric constant proves to be around 3-4 times bigger than for the other two films for a large part of the frequency spectrum. The changes in the dielectric constant might be explained by the completely different film morphology$^{44}$ and by the Kramers-Kronig relations$^{34}$ which imply that a change in the imaginary part of the permittivity (different conductivity levels), will imply a change in the real part too.

The influence of film thickness on the dielectric constant and DC conductivity was studied in the vicinity of the analyzed spectrum on sapphire substrates at 38.5 GHz and has showed little impact on them below the transition temperature$^{22}$.

From an RF engineering perspective, Figures 3, 9 and 10 play an important role in the accurate and predictive design using VO$_2$ based films: Starting with a film with low DC conductivities (below 22 S/m) and the morphology in Figure 3 (d) and (f) we can expect the films AC conductivities to stay < 25 S/m below 35 GHz. Starting from a film with high conductivity levels in DC (55 S/m), we can expect 100 S/m losses at 35 GHz. This means that more care has to be taken into the design in order to face these high conductivity challenges or to be aware that the film itself may have an applicability only in the lower frequency ranges. Further, starting with a film with high conductivity values in DC, we may expect a larger dielectric constant. Knowing
these exact values plays an important role in estimating correctly the resonance frequencies of filters, self-resonance frequencies of RF inductors, OFF state switches performances, overall to adapt the designs to the thin films properties and focus on the frequency bands where the losses or dielectric changes do not critically affect the overall circuit performances.

The dielectric constant values obtained for the 5.5 % PLD deposited Ge-doped VO₂ are slightly lower than the ones reported for a VO₂ thin film on sapphire, where the values are decreasing from 110 to 90 within the 5 – 30 GHz frequency range. The conductivity levels of the 5.5 % PLD deposited Ge-doped VO₂ show a smaller increase with frequency in respect to the conductivity levels thin film studied on sapphire whose values increase with from ca. 32 S/m to 80 S/m within the 0-30 GHz range.

The extracted dielectric constant values with our structures and models for the 5 % sputtered Ge-doped VO₂ and the undoped PLD VO₂ thin film appear to be in accordance with the values reported below Tc in the W band (at 76.86 GHz), where these values do not exceed 20, for a 200 nm VO₂ thin film on Si.

However, the main question is about the large difference observed between the dielectric constant of Ge-doped films deposited by PLD and by sputtering. It is worth noting that some earlier ab-initio studies predicted an increase of the dielectric constant in binary oxides, driven by strain. Stresses occur between neighbouring grains and have been shown to affect the Tc of VO₂. Such strain is sensitive to the grain size and film microstructure, and both these properties are directly influenced by the growth condition. The high dielectric permittivity in PLD-deposited Ge-doped VO₂ has to be considered in conjunction with the DC conductivity, both parts of the complex dielectric response being interconnected through Kramers-Kronig relations. Within the studied
frequency range (7-35 GHz), the dielectric constant of the 5.5% Ge-doped VO$_2$ decreases from 100 to 70 concurrently with the steady increase of the conductivity. Under assumption of Debye-type relaxation these trends are consistent with the relaxation frequencies situated above the measurement range. Here we hypothesize that the physical origin of the high dielectric constant in Ge-doped PLD deposited films can be linked to a lattice softness associated with Ge-doping. VO$_2$ has a number of other phase transitions, e.g. M1 to metastable M2 monoclinic phases, which are likely to be affected by Ge-doping, and this may impact the dielectric response. It is also known that the energy of deposited particles in sputtering process could be an order of magnitude higher than in PLD. Consequently, sputtered films contain a higher concentration of defects contributing to the strain relaxation, which results in a different dielectric response. Obviously, this hypothetical scenario needs more validation through further experimental studies of pure and doped VO$_2$ layers, strain measurements and dielectric properties, which form a study beyond the scope of this paper.

Anomalously high dc conductivity has been another feature of the Ge-doped films deposited by PLD. This effect can be attributed to the charge transport through the grain boundaries. The SEM micrographs of the PLD films reveal much smaller grains (especially for the PLD 5.5% Ge-doped VO$_2$) and higher density of grain boundaries compared to the sputtered films, therefore a higher grain boundary conduction is expected. A more in-depth work on the density of states of Ge-doped VO$_2$ with various concentrations can be further foreseen to better understand this effect.
Figure 9. Room temperature extracted dielectric constants for the Ge-doped VO$_2$ and (undoped PLD) VO$_2$ films. $\varepsilon'_r$ by PLD in red. Sputtered $\varepsilon'_r$ in orange. $\varepsilon'_r$ in blue.

Figure 10. Room temperature DC and extracted AC conductivity for the Ge-doped VO$_2$ and VO$_2$ thin films. Ge-doped VO$_2$ by PLD in red. Sputtered Ge-doped VO$_2$ in orange. (Undoped, PLD) VO$_2$ thin film used in blue.
3.6. Temperature dependence of S-parameters of Ge-doped VO$_2$ filters

The results presented in Figure 6 for S21 show that as temperature increases the quality factors of the filters decrease, meaning more losses, while their resonance frequency exhibiting only a very slight change (due to the very slight increase of the dielectric constant).

As temperature increases the S11 parameter curves become more compact while represented on a Smith chart$^{49}$ basis, while (in the Figure 11 on the frequency dependent extension of the 3D Smith chart). This can be seen in Figure 11 for the S11 parameters for the three filters whose S21 parameters where presented in Figure 6. This is a result of increased losses. The position of the S11 parameter curves on the 3D Smith chart is determined also by a slight mismatch due to the increased dielectric constant of the thin films. The orientation of all of them is clockwise as frequency increases and can be seen directly in this representation, unlike on a classical Smith chart or simple 3D Smith chart.
5 % Ge-doped VO$_2$ by sputtering  5.5 % Ge-doped VO$_2$ PLD

(a)  
$f_r$=7 GHz

(b)  
$f_r$=26 GHz

(c)  
$f_r$=35 GHz

Figure 11. Reflection coefficients S11 on the frequency dependent 3D Smith chart$^{16}$. The temperature dependence of the Ge-doped VO$_2$ films is shown for 25 (blue), 40 (green), 50 (orange) and 60 °C (red) resonating at (a) 7.4 GHz, (b) 26 GHz and (c) 35 GHz.

CONCLUSIONS
We have reported and experimentally investigated the first of their kind Ge-doped VO$_2$ phase change materials deposited by sputtering and PLD, with high phase change transition temperature $T_{IMT}$, near 80 °C and preserving excellent off and on-state conductivities, electrically matching specifications of RF filtering. We have reported frequency (7-35 GHz) dependences of the dielectric constant and AC conductivities of thin VO$_2$ films via an original methodology using Peano-Hilbert filters; the extracted dielectric constant values decrease with the frequency and depend on the Ge-doping technique used. The reported dependences are extremely useful for accurately designing RF functions such as filtering. This work contributes to the field of RF reconfigurable functions with phase change materials, operating at high temperatures as per industrial requirements.

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