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Behaviour of CPW and TFMS lines at high temperature for RF applications in sub-45 nm nodes

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ABSTRACT

Coplanar waveguide (CPW) and thin film microstrip (TFMS) lines integrating porous ultra low-k as inter-metal dielectric layers ($k = 2.5$) and copper as metal, are for the first time experimentally measured up to 110 GHz and under different temperature conditions, up to 200 °C. The extracted attenuation and propagation coefficients of those transmission lines are compared to simulations performed with MAGWEL software, a frequency domain 3-D Maxwell solver. Based on the characterization results some guidelines related to interconnect design are presented for future applications.

1. Introduction

The performance of Silicon (Si) Integrated Circuits (ICs) has been growing exponentially thanks to the continuous downscaling of the transistor gate length and width. Reduction of the transistor dimensions has increased the reliability, speed, integration density, and has widely popularized the use and development of all kind of electronic devices. It has been recently proven [1] that the transistor is not any longer the limiting factor for the growing high speed performance and functionalities of ICs but the interconnections. Replacing the typically used silicon dioxide (SiO_2) as interconnect insulator with a low-k dielectric leads to a decrease of the distributed parasitic capacitances along the interconnects and thus the delay of signal propagation, or in other words an increase of the switching speed or cutoff frequency for digital and analog ICs, respectively.

On the other hand, due to the high integration level targeted for the sub-45 nm nodes, self-heating of the ICs is much more pronounced and then the ICs operate at higher temperatures. To analyze the performance, the limiting factors and the reliability of interconnections, characterization must not be limited to high frequencies but Radio Frequency (RF) measurements under high temperature conditions have to be performed.

In order to study the performance of transmission lines fabricated using low-k dielectric for 45 and sub-45 nm nodes, ultra-narrow coplanar waveguide (CPW) and thin film microstrip (TFMS) lines are investigated. For the first time such narrow lines are characterized and compared in terms of their propagation characteristics for frequencies up to 110 GHz and temperatures up to 200 °C.

2. Investigated CPW and TFMS lines

Both types of transmission lines, CPW and TFMS, are fabricated on a 300 mm wafer using a two-metal stack approach on top of a Silicon-on-Insulator (SOI) substrate. A Trench First Hard Mask (TFHM) dual damascene process with partial via etch patterning [2] is performed for the integration of the interconnection lines. TFHM is carried out with ultra low-k (ULK) SiOCH porous dielectric (porosity level of 26% and $k = 2.5$ as deposited) and SiCN capping layers ($k = 5$). E-beam lithography is performed to define lines and vias. To prevent copper (Cu) diffusion into the surrounding porous dielectric a Self Ionized Plasma (SIP) TaN/Ta metal barrier is deposited (~6 nm-thick). After the Cu deposition a chemical-mechanical polishing (CMP) step is performed, stopping at the SiO_2 hard mask. To reduce any possible changes in the structure and properties of Cu when it is exposed to high temperatures

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($T < 250$ °C) a rapid post metallization annealing (PMA) is also done [3]. The cross sections of the CPW and TFMS are presented in Fig. 1.

In regards to the lateral dimensions of the studied transmission lines, several CPW and TFMS dimensions are fabricated in order to investigate two different approaches in the design of transmission lines for 45 and sub-45 nm technologies: (i) a first approach which takes advantage of the low-k properties of the inter-metal dielectric by encouraging size downscaling, and (ii) a second one which considers a relaxation in the line dimensions. The dimensions of the different CPW and TFMS lines are presented in Table 1. For each of them five different lengths (L = 1000, 800, 600, 400, 200 μm) are designed.

3. Resistivity and temperature coefficient of resistance for Cu interconnections

Due to the dimensions of the interconnections investigated in this paper, it is expected that the insertion loss of these ultra-narrow transmission lines will be dominated by the metallic losses, which are directly related to the line equivalent resistance. Therefore, an accurate extraction of the copper resistivity as a function of the line dimensions is of first importance.

It has been demonstrated in [4] that interconnections with dimensions (width and height) smaller than 300 nm present a significant increase of their resistivity. In the case of copper and considering the technological node specifications, the Cu resistivity increases by a factor of 1.75, 1.9 and 2.15 for the 65, 45 and 32-nm node, respectively, related to its bulk resistivity (ρ = 1.67 μΩ cm). Such an increase of the line resistance will impact the time delay (RC constant) of the interconnections and will dramatically increase the attenuation of the RF signals.

The resistivity of the central conductor of the lines under study, as a function of the line length, is presented in Fig. 2a. We can observe that the resistivity is constant for all the line lengths, which proves the uniformity of the line dimensions even for the longest one. Only a maximum deviation of 10% of the central conductor resistance is measured from structures located at different places over the wafer. Both results prove the good uniformity of the TFHM process for the fabrication of these ultra-narrow lines.

In addition to the resistivity increase due to downscaling, it has been recently pointed out that for sub-micron interconnections the temperature coefficient of resistance (TCR) decreases when the dimensions (width and height) of the line scale down [5]. The TCR is calculated using the following formula:

$$TCR = \frac{R(T) - R_0}{(T - T_0) \cdot R_0} \quad (1)$$

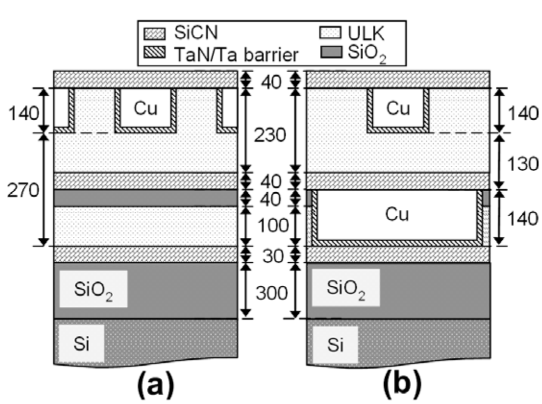

Fig. 1. Cross sections of studied (a) CPW and (b) TFMS lines. All dimensions are in nm.

Table 1
Transmission line dimensions and maximum frequency of operation (*fo*). For the CPW: *W* is the central conductor width, *S* the slot width and *Wg* the coplanar ground width. For the TFMS: *W* is the conductor width (metal 2) and *Wg* the planar ground width (metal 1).

	W [nm]	*S* [μm]	*Wg* [μm]	*fo* [GHz]
CPW1	80	3.5	14	20
CPW2	120	3.5	14	50
CPW3	150	0.15	1.5	52
TFMS1	80	–	11	15
TFMS2	120	–	11	25

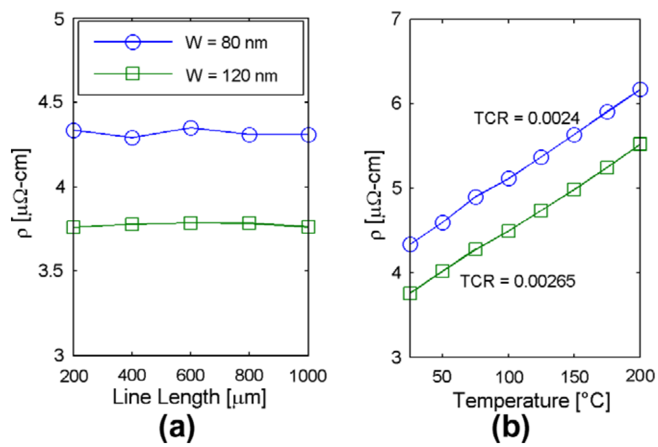

Fig. 2. Resistivity of the central Cu conductor for two different line widths, (a) as a function of the line length (at 25 °C), and (b) as a function of the temperature. In both cases the conductor height is H = 140 nm.

where R_0 and $R(T)$ are, respectively, the resistance at temperature T_0 and T. As illustrated in Fig. 2b for the lines investigated in this work, the Cu resistivity linearly increases with the temperature. TCR is in our case a constant value and can be also calculated as the slope of the resistivity *vs.* the line length curve. We obtain a TCR = 0.0024 and 0.00265 K^{-1} for the lines of 80 and 120 nm-width, respectively. Compared to the TCR of bulk copper (TCR = 0.004 K^{-1}) it means a reduction by a factor of more than 1.5 for both line widths.

4. Propagation performance of ultra-narrow CPW and TFMS lines

On-wafer high-frequency measurements are performed for a wide frequency range using a Vectorial Network Analyzer (VNA) and coplanar Ground-Signal-Ground (GSG) RF probes. Prior to the line characterization, on-wafer calibration using an Impedance Standard Substrate (ISS) is made. As mentioned before, the equivalent resistance of the lines is extremely high, $R \sim 5$ kΩ/mm for a line width of 80 nm, giving highly unmatched lines with high conductor losses. As a result, the raw S-parameters present a strong reflection ($S11 > -10$ dB) and low transmission ($S21 < -10$ dB) over the whole frequency range, even for the line with the more relaxed dimensions named CPW3. In order to compare the RF performance of the different lines the propagation constant of each line is extracted using the Line-Line calibration method [6], which is a particular case of the Through-Reflection-Line calibration method (TRL), for symmetrical and reciprocal thru and line standards. The reference impedance of the de-embedded S-parameters corresponds to the characteristic impedance of the line, and the de-embedded scattering parameters of the line can be expressed as

$$S11 = S22 = 0 \quad S12 = S12 = e^{-\gamma \cdot \Delta L} = e^{-(\alpha + j\beta)\Delta L}. \quad (2)$$

where γ is the propagation constant, ΔL the length difference between the de-embedded line and the thru standard, and α and β the attenuation and phase constants, respectively.

Before analyzing the experimental results, some general considerations in terms of propagation modes along lossy transmission lines must be given. In his fundamental work, Hasegawa et al. [7] identified three possible modes of signal propagation in metal–insulator–semiconductor (MIS) microstrip lines: (i) the slow-wave mode, (ii) the quasi-Transverse Electro Magnetic (TEM) mode, and (iii) the skin-effect mode. For a given transmission line, each of these modes can be considered dominant for a certain frequency range. To simplify our analysis we will not consider the skin-effect mode since in our case it occurs at frequencies far above our measurement frequency range. Thus, we identify only two frequency limits, *fs* and *fe*, which correspond to the high and low cut-off frequencies of the slow-wave and quasi-TEM zones, respectively. As explained in [7], a transition zone exists between both propagation modes. That transition can be easily detected since for both modes the normalized wavelength converges to a constant value.

The normalized wavelength corresponds to the result of dividing the product $2\pi f$ by βc_0, where f is the frequency of the propagated signal, and c_0 is the light velocity in vacuum. Thus, we will be able to identify the lower cutoff frequency *fe* of the quasi-TEM zone, as the frequency at which the phase constant starts being linear with the frequency and the effective permittivity of the transmission line is constant, assuming all dielectrics have no frequency dependent permittivity.

4.1. Propagation along CPW and TFMS at ambient temperature up to 110 GHz

The attenuation and phase constants of CPW2 line for different line lengths are shown in Fig. 3. As shown in Eq. (2), the propagation is independent on the line length, regardless of the propagation mode. However, above 50 GHz, a parasitic effect appears, and the extracted attenuation for the different line lengths diverges. The phase constant seems to be less sensitive to this parasitic effect, although small variations, which become larger at 90 GHz, can be already observed above 50 GHz. The variation of α is too large to be related to the 10% site-to-site deviation in the line dimensions. Moreover, the frequency above which this parasitic effect appears depends on the transmission line geometry. We define a high cut-off frequency (*fo*) below which the lines do not present parasitic effects and can be considered to properly operate. We estimate this frequency as the one at which the attenuation of the different length lines differs more than 10% from its mean value. The values of that maximum frequency of operation are shown in the last column of Table 1. The line with relaxed dimensions (CPW3) is the one with the highest range of operation and the narrowest TFMS line the one with the worst performance. This unexpected frequency limit, which is here for the first time observed, is a major drawback in the performance of interconnections as it considerably reduces the maximum operation frequency.

Although the origin of this parasitic effect is unknown, it is clearly related to the line dimensions and to the type of line. TFMS lines seem to be more sensitive than CPW ones, and a decrease in the line dimensions implies a reduction of the operation frequency range (lower *fo*). A possible explanation is the proximity of metal dummies to the narrow lines. The metal dummies are requested for improving the CMP step operated after each deposition of metal level. It has already been experimentally proven that for sub-65 nm node specifications, dummies increase the attenuation and phase constant, depending on their size and spacing [8]. Those metal dummies could have a bigger impact on the propagation mode of small dimension lines, as their size will be comparable to the cross-section line dimensions. The simulations performed with MAGWEL software considering the various transmission line geometries and without including the metal dummies agree pretty well with the measurements up to the frequency *fo* and do not present the parasitic effects.

Regardless of the performance at high frequencies we can compare the propagation parameters of CPW and TFMS lines for the frequency range of valid operation, lower than *fo*. The attenuation and phase constants of the different CPW and TFMS transmission lines are shown in Fig. 4. As expected, all of them present high levels of attenuation, being the metallic losses the main attenuation mechanisms. Hence narrower lines, TFMS1 and CPW1, present

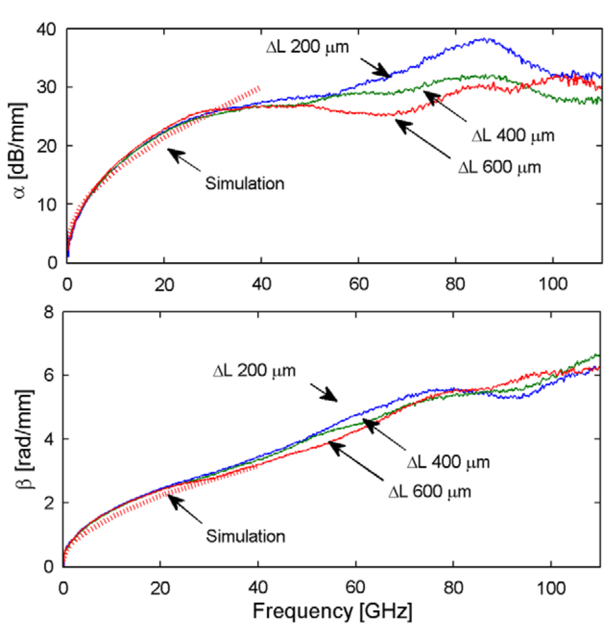

Fig. 3. Extracted and simulated (dashed lines) attenuation and phase constants of CPW2 for several ΔL. All measurements are made at ambient temperature.

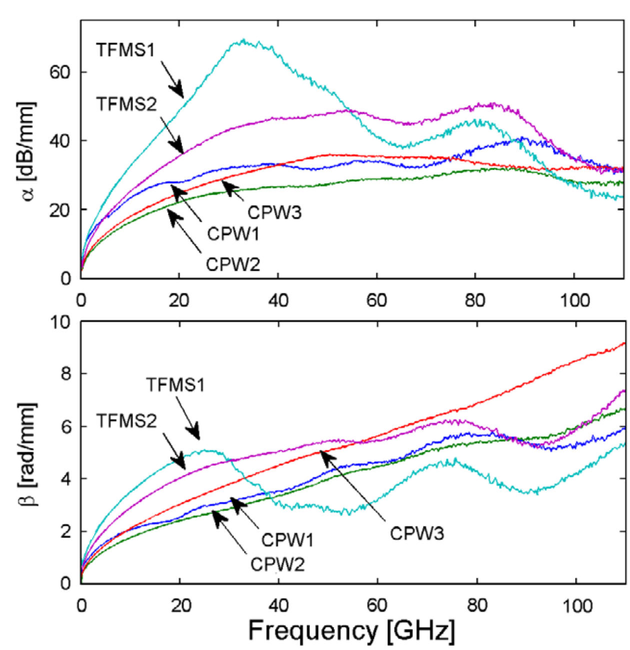

Fig. 4. Extracted attenuation and phase constants of the studied CPW and TFMS up to 110 GHz. Measurements are done at ambient temperature (25 °C) and for all lines ΔL = 600 μm.

higher losses than bigger ones, TFMS2 and CPW2. A closer look to the phase constant shows that only CPW2 and CPW3 reach quasi-TEM propagation in its operation range, while the rest operate in the transition zone between slow-wave and quasi-TEM mode [7]. High conductor losses enlarge such transition zone. In the case of CPW2, for which the slot width is larger than the thickness of the ULK dielectric, its attenuation and phase constants at quasi-TEM frequencies correspond to those of a CPW line lying on a lossy Si substrate. For such a large slot the electromagnetic fields penetrate deeply into the handle silicon substrate, then reducing the relative impact of the thin ULK properties on the waves propagation. On the contrary the narrow slot width of CPW3 should make the line to behave as a CPW with an effective permittivity close to that of the ULK. However, this is not the case as the surrounding SiCN and SiO_2 layers are thick enough to affect its behaviour. The remaining moisture inside the porous SiOCH and its dielectric losses [9,10] can also increase their attenuation and phase constants. These two last considerations are the most likely reasons to explain the higher attenuation for CPW3 than in CPW2 even if the first one has wider lines, hence reduced metallic losses. The higher attenuation level of the TFMS lines can be explained by their higher characteristic impedance compared to that of the CPW with similar line width.

4.2. Propagation under different temperature conditions

In the 45 and sub-45 nodes, an important portion of the heat originated from the various parts of the IC it is expected to be dissipated through the metal stack layers of the interconnections. The raising of their operation temperature should lead to an increase of the copper resistivity and thus RF losses. Moreover, the properties of the ULK dielectric could be affected by an increase of the temperature, for instance the remaining moisture could be removed, and hence the permittivity and dielectric losses decrease [9].

Extraction of the propagation constants for TFMS2 and CPW3 are shown in Figs. 5 and 6, respectively, under different temperature conditions. Measurements are done up to 40 GHz, which almost covers the total valid frequency range of operation for these lines. In both cases the attenuation and phase constants increase with temperature. For the TFMS2 the attenuation increases by a factor of 1.25 when the temperature changes from 25 to 200 °C, which corresponds approximately to the increase of Cu resistivity (~1.4) in that temperature range, considering the maximum 10% resistance error from site to site. Similar observation and explanation can be drawn for the measurement results of CPW3.

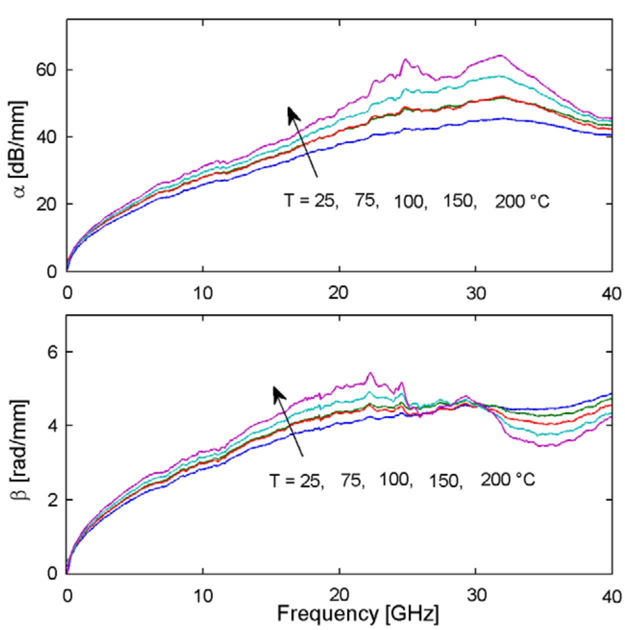

Fig. 5. Extracted attenuation and phase constants of TFMS2 under different temperature conditions.

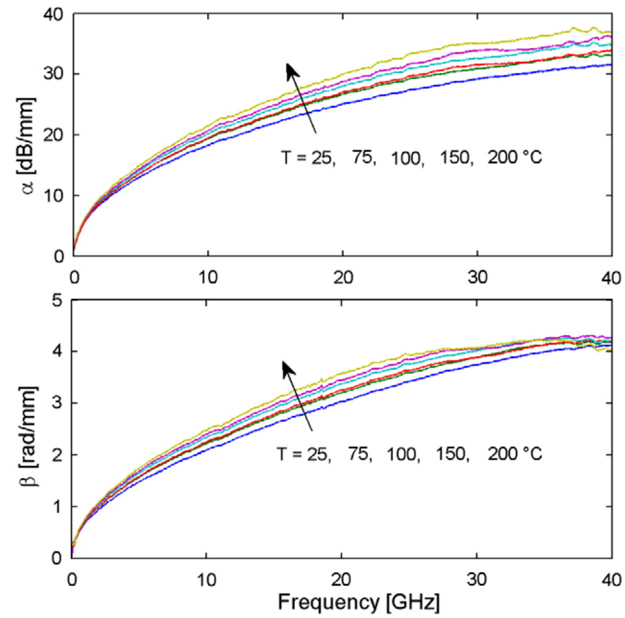

Fig. 6. Extracted attenuation and phase constants of CPW3 under different temperature conditions.

For a transmission line, assuming quasi-TEM mode, an increase in the phase constant cannot be explained based to an increase in the metal resistivity. The phase constant is only related to the effective permittivity which does not change with temperature. Nevertheless, as explained before, only CPW2 and CPW3 present quasi-TEM propagation at high frequencies. At frequencies in the transition zone the phase constant increases with resistivity, as it can be seen for TFMS2, and tends to converge to the same value when we approach the quasi-TEM propagation, CPW3 for frequencies above 35 GHz. It could also be supposed that the increase in temperature would reduce the moisture concentration in the porous ULK and will reduce its permittivity and losses [9]. However, the increase of the phase constant is similar to that of the Cu resistivity, and any possible variation due to changes of the ULK properties remains hidden.

The increase of attenuation and phase constants with temperature confirms again the high influence that conductor losses have in the reduction of the high frequency performance of ultra-narrow interconnections, making them even more sensitive to temperature variations.

5. Conclusion

For the first time the propagation performance of TFMS and CPW for the 45 and sub-45 nm node technologies are experimentally characterized up to 110 GHz and under different temperature conditions. Results show that both types of lines have a maximum frequency of operation, above which the lines present unknown parasitic effects. Those parasitic effects reduce the operation frequency range of the interconnections, hence their use for high-frequency and high-speed applications. The maximum operation frequency depends on the line cross-section dimensions but is independent on the line length. Further analysis must be done to elucidate the origin of these parasitic effects.

Due to the small dimensions imposed by the 45 and sub-45 nm nodes, the conductor losses and the characteristic impedance mismatch are the most limiting factors of the lines for their use in RF applications. It leads to high attenuation levels and strong reflections even for short interconnection distances.

The degradation of the interconnection performance with temperature is directly related to the resistivity increase of the metallic lines. Moreover, a decrease in the temperature coefficient of the resistance (TCR) due to line dimension reduction is confirmed for the 45 nm node.

Some general guidelines can be inferred by the simulation and experimental results.

- In all cases, relaxed dimensions must be used to reduce conductor losses, sensitivity to temperature variations, and the low cut-off frequency ot quasi TEM propagation. Line dimensions that correspond to a $\rho_{Cu} < 3\ \mu\Omega$ cm should be used;
- CPW structures should be preferred as they present a larger frequency range of operation, better performance compared to parasitic effects, and less attenuation levels than their TFMS counterparts. Moreover, CPW are better suited to obtain lines with better impedance matching, hence less power reflection and higher available power. The characteristic impedance of CPW partly depends on the conductor and slot widths, and not on the inter-metal dielectric thickness as it is the case for the TFMS;
- In order to reduce the impact of inhomogeneous inter-metal dielectrics CPW with wide slots can be used. The line performance will then mostly depend on the handle substrate properties. High-Resistivity (HR) substrates can be used for low loss RF applications, and HRSOI for hybrid integration.

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