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Evaluating k-values for low-k materials after damascene integration: Method and results

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ABSTRACT

This work discusses a method for measuring k-values of low-k films after integration in damascene structures. The experimental results are obtained from 90 nm ½ pitch single damascene structures on low-k materials with intrinsic k-values ranging between 2.2 and 3. The measurement technique is discussed in detail with a focus on the accuracy, limitation of the method, impact of low-k damage and applicability for smaller dimensions.

1. Introduction

The interconnect RC delay is an important performance parameter for the back-end of line. RC can be effectively reduced by reducing the capacitance C between parallel lines. To achieve this, low-k materials are used as dielectric material between the interconnect lines. During integration the low-k material is exposed to etch plasmas and processes that potentially impact the intrinsic k-value (k_{int}) of the pristine material and result in an effective k-value (k_{eff}) that is larger than k_{int} [1].

From a material properties perspective, not RC delay but k_{eff} is the relevant performance parameter for the low-k material under investigation. While the RC product can be measured by electrical tests, effective k-values must be derived by combining electrical measurements, material properties, geometrical information and simulations. The expected accuracy on k_{eff} is therefore less than accuracies obtained from direct electrical measurements.

2. Experimental technique

Fig. 1 shows the schematics of the damascene meander fork test structure used. The typical values for thickness and pristine k-values for the various layers in the stack are indicated. The effective k-value of a single damascene meander fork (MF) structure can be obtained by comparing the measured interline capacitance with simulations based on a geometrical model of the device. In order to model the experiment, an accurate description of the cross-sectional shape of the trenches and dielectric layers is needed. This information can be obtained from TEM cross-sectional images of the device. This cross-sectional view is then used in a 2D static field solver program to calculate electric fields and interline capacitance. The k-value used in the simulation is varied until the simulated capacitance matches the measured value. Fig. 2 presents an overview of the method. This technique described in [2] was further developed, refined and tested in order to better understand its accuracy.

Fig. 3 shows how the method can be applied. By making use of the linear dependence of C on k, k_{eff} can be determined by interpolation. At the same time all parasitic capacitances arising from the other layers can be determined by extrapolation to $k = 0$. This extrapolation has no physical meaning but is a computational technique to separate the contributions from the low-k layer from the other layer.

3. Results and discussion

3.1. Evaluation of measurement accuracy

The impact of various simulation parameters and measurement errors on the final accuracy of the k-value is described in the sections below.

3.1.1. Accuracy of capacitance measurement

The capacitance was measured by means of an impedance analyzer (HP4284A precision LCR meter [3]). Measurements were done at frequencies ranging between 10 kHz and 1 MHz. A gradual decrease in the measured value is seen with increasing frequency especially for the 10 cm long meander fork (Fig. 4).

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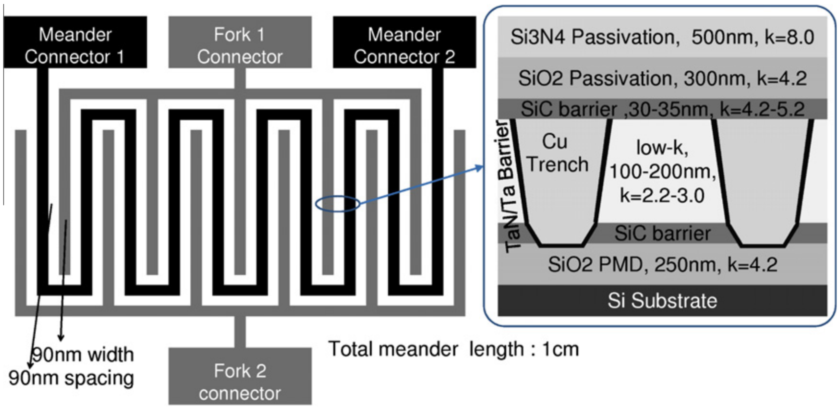

Fig. 1. Schematics of the test structure.

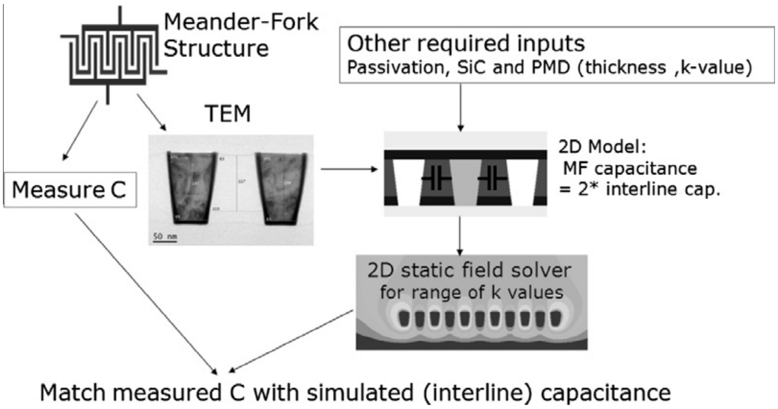

Fig. 2. Schematic overview of the measurement technique.

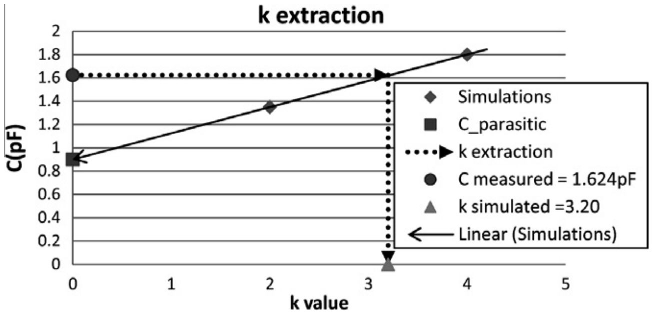

Fig. 3. *k*-Values can be extracted based on C and simulations for two arbitrary input values.

The drop in the measured value is caused by the MF that acts as an RC low-pass filter due to the resistance in the lines and the capacitance between the meander and fork. In order to measure the real *C* of the device, the measurement has to be done at a frequency well below the cut-off frequency f_C of the RC filter. For an order of magnitude of this frequency the formula $f_C = 1/2\pi RC$ for a classical low-pass filter was used. Accurate measurements of *C* can be obtained for 1 cm MF structures at a $f = 10$ kHz.

The typical measured values are around 2pF. Measuring such small *C* values accurately requires careful set-up and calibration of the measurement system. Calibration was done by measuring dummy devices on the wafer to take into account all parasitics arising from the measurement system, probe contacts, bonding pads and measurement chuck.

Note that for fork-fork structures much longer structures can be measured because the resistance *R* is determined by the length of each fork line, which is much shorter than the length of the meander line. However, the advantage of using MF structures is that structure integrity can be tested from continuity measurement which immediately yields a value for *R*.

3.1.2. Geometrical input for the simulation

The accuracy at which the trench shape can be measured from the TEM image is a limiting factor in the precision of the method. Initial simulations were performed with trapezoidal trench shape. The model was later adjusted to polygons with up to 12 vertices. The difference between results obtained with both model was in some cases up to 0.3 on k_{eff}. The trapezoid model cannot describe the trench shape sufficiently accurate to extract *k*-values. However, due to the limited number of parameters, it remains a useful model to do theoretical predictions based on simulations only.

An experiment was conducted in which the same device was analyzed 10 times using the 12 vertex polygon model. TEM image taken at 10 different places in the same device were used for each analysis. In Fig. 5 the variations on the extracted *k*-value can be seen for a representative 90 nm ½ pitch structure with intrinsic *k*-value of 3.0. The variation on the results was used to determine the error induced by the geometrical modeling based on TEM. For 90 nm ½ pitch structures, the error arising from the TEM is about 0.15 on k_{eff}. For smaller pitch, the error becomes larger.

3.1.3. Parasitic capacitances of layers in the stack

The extrapolation towards $k = 0$ in Fig. 3 indicates that the contributions from the low-*k* material to the total capacitance is small.