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Capacitance measurements and *k*-value extractions of low-*k* films

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ABSTRACT

We review test vehicles and methods that are commonly used for capacitance measurements of low-*k* films and the general procedure for *k*-value extractions. We demonstrate that a considerable loss of accuracy may occur if metal–insulator–semiconductor (MIS) planar capacitors are used in high frequency (HF) capacitance–voltage (CV) measurements leading to significant underestimation of the *k*-value. We show that the lack of accuracy is due to parasitic impedance at the backside connection with the Si substrate and we provide a model. The effect of the parasitic impedance can be minimized by reducing the area of the gate electrode. Alternatively, samples can be provided with an ohmic back contact by means of one of the practical fabrication methods that are described. Quasi-static (Q-S) CV measurements did not exhibit any variation related to backside connection. However, we show that Q-S CV measurements loose accuracy for plasma-damaged low-*k* films because of increased dielectric leakage. Finally, issues related to capacitance measurements in dry atmosphere are addressed. We show that long (∼hours) transients can take place for plasma-damaged low-*k* films because of the slow release of water from the material underneath the metal gate, which acts as a cap. As a consequence, extracted *k*-value can significantly depend on sample resident time in the measurement chamber and on gate dimensions.

1. Introduction

In order to comply with the strict performance requirements for future technology nodes, insulating films with low relative dielectric constant (*k*-value) are being developed for reducing line-to-line capacitance and RC delay of Cu damascene interconnects [1]. In the development phase, the accurate determination of the *k*-value is fundamental. When different low-*k* films are compared, it is important that an accuracy of 0.1 or better is achieved in order to be able to benchmark the different materials against each other. Hence, errors in the evaluation of the *k*-value must be kept smaller than 0.1 for making differentiations possible. For 2.8 and 2.2 low-*k* films, errors of 0.1 translate into accuracies of 3.6% and 4.5%, respectively. Moreover, if the impact on *k*-value of different process steps, such as plasma etch or ash, chemical mechanical polishing (CMP), wet cleaning, needs to be estimated an even higher accuracy may be required. Achieving such levels of accuracy is not obvious when test vehicles have to be kept simple to allow fast characterizations and to prevent possible material modifications that complex fabrication processes could induce.

Metal–insulator–semiconductor (MIS) planar capacitors are commonly used as a test vehicle for capacitance measurements and *k*-value evaluations of low-*k* films. The investigated films are deposited on Si wafers and metal dots or Hg-probes are used to create top metal electrodes (gates) and form MIS capacitor structures. Backside metallization steps, that would be required for providing samples with ohmic back contacts, are generally skipped [2,3]. Wafers would need to be placed upside down on the chuck of the metallization chambers and scratches would be produced on the low-*k* film, deposited on the front side. The possibility to perform backside metallization steps before low-*k* film deposition could be an option but usually this is in conflict with contamination rules of deposition chambers. Moreover, metal on the backside would make blanket wafers not suitable for different characterization techniques, such as Fourier transform infrared spectroscopy (FTIR) measurements that are used to characterize material structure [4]. In practice, only a cleaning of the wafer backside is performed and connection to the Si substrate is simply realized by placing wafers (or wafer pieces) into contact with the metallic chuck of the probe station. Many investigations use low resistivity (highly doped) Si wafers without backside metallization [5]. Although the concerns with regard to backside connection may appear less stringent in those cases, our experiments show that the presence of an ohmic back contact still remains crucial. Metal dots are commonly evaporated or sputtered through metal shadow masks on the front side. Because of sputtering shadows, dot areas are not always well controlled and significant widening may occur. Conventional lithography, which provides a good control of the dot area, is generally avoided. Typical litho steps such as photoresist deposition and removal could degrade the investigated low-*k* films. In place of metal dots, Hg-probes can be used to form

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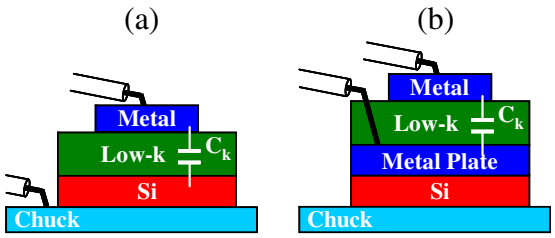

Fig. 1. For MIS capacitors (a), the Si substrate (bottom electrode) is contacted by connecting to the metallic chuck of the probe station. For MIM capacitors (b), the metal plate (bottom electrode) is contacted with a probe needle by scratching the low-k film.

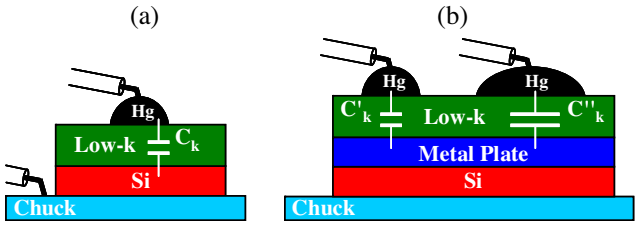

Fig. 2. MIS (a) and MIM (b) capacitors realized by using Hg-probes. MIM structures are formed by using two mercury droplets as two top electrodes: the measured capacitance (C) consists of the series of the two (film) capacitances (C'_k and C''_k) associated with the two electrodes.

capacitor structures. The top electrode is simply realized by a mercury droplet brought in contact with the low-k film. Hg-probes are often used to avoid time-consuming metallization and to further preserve the investigated films from possible damages that metal sputtering or evaporation could cause. The contact area is estimated by using reference samples with a dielectric film of a well-known thickness and k-value, e.g. thermal oxide ($k = 3.9$). However, the contact area of the mercury droplet may slightly change from material to material, which introduces errors. Finally, MIS structures are generally not hermetically sealed in order to avoid long and complex fabrication processes. Therefore, the film surface is exposed to the environment and water uptake and release can occur (capping layers are not deposited because they could damage the low-k film) [6]. As a consequence, the measured capacitance can increase or decrease depending on environmental conditions. This leads to poor accuracy because of poor reproducibility of the results. On one hand, by using simple test structures, the characterization is fast and low-k films are preserved from process-induced modifications. On the other hand, the achieved accuracy may be insufficient.

In this work, we inspect test vehicles and methods for capacitance measurements of low-k films in order to identify possible accuracy limitations. In particular, we investigate the impact on accuracy of backside connection, dielectric leakage and water uptake. Besides, we review the general procedure for k-value extraction and evaluate the effect of errors in film thickness, capacitor area and capacitance. The test vehicles and methods we inspected are presented in Section 2. In Section 3 we describe the samples we prepared for our study and the related fabrication processes. Problems of accuracy in k-value extractions and capacitance measurements are discussed in Section 4 and Section 5, respectively. In Section 6 we summarize and discuss the results of our study. Finally, the main conclusions are reported in Section 7.

2. Test vehicles and methods

2.1. Test vehicles for capacitance measurements

Fig. 1 shows a schematic representation of metal–insulator–semiconductor (MIS) and metal–insulator–metal (MIM) planar capacitors and the related measurement configurations. MIS structures are expected to provide the capacitance of the low-k film when the Si substrate is biased in accumulation. MIM structures are parallel plate capacitors and should provide the capacitance of the low-k film for any bias condition. For MIS structures, the fabrication process is very simple. Low-k films are deposited on n-type (6–24 Ω cm) or p-type (15–25 Ω cm) Si substrates, which represent the capacitor's bottom electrode, and metal dots are realized as the capacitor's top electrode (Fig. 1a). For MIM structures, an additional metallization step is required to form a metal plate to be used as the capacitor's bottom electrode (Fig. 1b). In both cases, top electrodes are contacted by using probe needles. As far as the bottom electrode is concerned, for MIM capacitors the metal plate is contacted with a second probe needle by scratching the low-k film on the top until contact is established. Therefore, the measured capacitance (C) only consists of the capacitance of the low-k film (C_k). For MIS capacitors, the Si substrate is contacted by connecting to the metallic chuck of the probe station. In this case, the measured capacitance (C) may differ from film capacitance (C_k) because of the effect of possible parasitic impedance at the contact between the Si substrate and the metallic chuck. Sometimes low resistivity (0.005–0.010 Ω cm) Si wafers are used as a substrate. In this case, MIS structures should in principle behave like MIM capacitors. However, this may not be the case because of possible parasitic impedance at the contact between the low resistivity Si substrate and the metallic chuck of the probe station. For capacitance measurements, MIM structures are, therefore, more ideal as a test vehicle when compared to MIS structures. However, MIM structures are not commonly used because of the more complicated and time-consuming fabrication process. As an alternative to metal dots, Hg-probes can be used to create the capacitor's top electrodes. Both types of structures can be implemented, as shown in Fig. 2. MIS capacitors are formed by using a mercury droplet as a top electrode (Fig. 2a). MIM capacitors are formed by using two mercury droplets as two top electrodes (Fig. 2b). In this case, the measured capacitance (C) consists of the series of two capacitances (C'_k and C''_k) associated with the two electrodes ($1/C = 1/C'_k + 1/C''_k$). For the tool we have used in our study, the second electrode consists of an annular mercury ring that surrounds the central mercury dot and that has larger area. The area ratio – ring contact to dot contact – is 48.6, for a central dot diameter of 768 μm. The actual contact area of the mercury droplets is calibrated by using reference samples.

2.2. Methods for capacitance measurements

Capacitance of low-k films is commonly evaluated by HF CV measurements at 100 kHz or 1 MHz, which are typical frequency values at which k-values are reported [7,8]. They are generally performed by means of an impedance analyzer that measures the total complex impedance with real and imaginary parts. The impedance analyzer we used for our study is the HP4284A precision LCR meter [9]. The result of impedance measurements is visualized with reference to a two-element equivalent circuit consisting of a capacitance in series (series operating mode) or in parallel (parallel operating mode) to a resistance. In the following, we will refer to the capacitance that is calculated and displayed by the instrument as measured capacitance (C). Of course, the measured capacitance will only correspond to the film capacitance (C_k) if the measured impedance can be represented by the selected two-element circuit. Fig. 3a shows double sweep (from accumulation towards inversion and return) HF CV measurements