Available online at www.sciencedirect.com
SCIENCE DIRECT®
Microelectronic Engineering 83 (2006) 528–535
MICROELECTRONIC ENGINEERING
www.elsevier.com/locate/mee

S-parameters-based high speed signal characterization of Al interconnect on low-k hydrogen silsesquioxane-Si substrate

Chia-Cheng Ho [a,1], Bi-Shiou Chiou [a,b,*]

[a] Department of Electronics Engineering and Institute of Electronics, P.O. Box 83, Engineering Building IV, 1001 Ta Hsueh Road, Hsinchu, Taiwan
[b] Innovative Packaging Research Center, National Chiao Tung University, Hsinchu, Taiwan

Received 19 August 2005; received in revised form 19 November 2005; accepted 12 December 2005
Available online 10 January 2006

Abstract

The International Technology Roadmap for Semiconductors (ITRS) predicts that by 2010 over one billion transistors will be integrated into one chip [Semiconductor Industry Associations, International Technology Roadmap for Semiconductors, 2004. Available from: <http://public.itrs.net/Files/2004UpdateFinal/2004Update.htm>]. The interconnect system of this one billion transistor chip will provide the required high-speed signal and power to transmit each transistor on the chip. This system will deliver high frequency signals to various circuits, and the parasitic effects associated with interconnect will become evident and cannot be ignored. Small parasitic capacitance (C) between interconnect are required to reduce the crosstalk, power consumption, and RC delay associated with the metal interconnect system. Therefore, interconnect with low dielectric constant (k) materials is required.

In this study, hydrogen silsesquioxane (HSQ) thin films prepared under various conditions are employed as the intermetal dielectric and the high frequency characteristics of Al–HSQ system are investigated and compared with those of Al–SiO_2 system. The S-parameters of the Al interconnect are measured for insertion loss and crosstalk noise. The interconnect transmission parameters are extracted from the S-parameters. A figure of merit (FOM) is employed to evaluate the characteristics of the Al–HSQ system at high frequencies (100 MHz–20 GHz). It is found that Al interconnect with HSQ films annealed at 400 °C has an insertion loss of 1.64 dB/mm, a coupling of −13.3 2 dB at 20 GHz, and a propagation delay of 0.121 ps/μm, while those of the PECVD SiO_2 films are 2.01 dB/mm (insertion loss), −13.40 dB (coupling), and 0.149 ps/μm (propagation delay). The Al-400 °C-annealed-HSQ system has better performance than the Al–SiO_2 system does from 100 MHz to 20 GHz. However, specimens with 350 °C-annealed HSQ films or plasma-treated HSQ films exhibit larger insertion losses and higher crosstalk noises than those with PECVD SiO_2 films do. Both annealing temperature and O_2 plasma treatment of the HSQ films affect the high frequency characteristics of the Al–HSQ system.

Keywords: S-parameters; High speed interconnect; Hydrogen silsesquioxane; Coupling effect; Attenuation noise; Insertion loss; Low-k dielectric; Crosstalk

1. Introduction

As the dimensions of ULSI circuits shrink, there is a need for faster performance and higher circuit density. Multilayer interconnect structures are the trend to produce high-density circuits and enhance device performance. However, at high operational frequencies (>1 GHz), the parasitic effects associated with the multilayer interconnect become a limiting factor for chip performance and can not be ignored [1–3].

The parasitic effects of the multilayer interconnect are comprised of resistance with variation due to the skin effect at high frequencies, the self- and mutual-inductance of interconnects, the shunt capacitances from signal lines to ground lines, the parasitic capacitance resulted from the intermetal dielectric, the leakage of the dielectric material and substrate, etc. All result in signal distortion, propagation delay,

* Corresponding author. Tel.: +886 3 5731927; fax: +886 3 5724361.
E-mail addresses: doubles.ee89g@nctu.edu.tw (C.-C. Ho), bschiou@mail.nctu.edu.tw (B.-S. Chiou).
1 Tel.: +886 3571212154203; fax: +886 35131590.

0167-9317/$ - see front matter
doi:10.1016/j.mee.2005.12.006

and crosstalk noise [3–9]. In order to retain signal integrity at high frequencies, the requirements for the intermetal dielectric include: a small dielectric constant, low leakage current, low moisture absorption, adequate mechanical strength, simplicity of process, and ease of integration [10–16].

Hydrogen silsesquioxane (HSQ) is a potential candidate of which the dielectric constant can be further reduced by forming a highly porous three-dimensional network structure [16]. The general formula for HSQ is $(HSiO_{1.5})_{2n}$, $n = 2$, 3, etc., which is an inorganic material that can be considered as a derivative of SiO_2 in which one of the four oxygen atoms bonded to every silicon atom is replaced by hydrogen. However, HSQ has many integration issues, such as: thermal dissociation of Si–H bonds, oxidation, plasma damage, formation of –OH bonds, absorption of water, etc. [11–13]. It was reported that with appropriate plasma treatments the thermal stability of HSQ could be enhanced [12]. Nevertheless, the plasma treatment may damage the surface and/or change the surface chemistry of HSQ and the reliability of the low-*k* dielectric HSQ may degrade [11–13].

In this work, HSQ films are prepared and O_2 plasma treatments are applied to some specimens. The electrical properties of Al interconnect on HSQ (Al/HSQ/thermal SiO_2/Si) and Al interconnect on SiO_2 (Al/PECVD SiO_2/thermal SiO_2/Si) are measured and compared. The electrical parameters (R, L, C, and G) are extracted from the measured *S*-parameters. The signal transient characteristics with signal delays and crosstalk noises between adjacent interconnect lines are evaluated by the inverse Fourier transform.

2. Experimental procedures

Four inch diameter p-type (1 0 0) Si wafers with nominal resistivity of 5–10 Ω cm were used as substrate. After standard RCA cleaning, a 100 nm SiO_2 film was grown on the Si substrate. Two dielectrics, hydrogen silsesquioxane (HSQ) and SiO_2, were deposited on top of the SiO_2/Si substrate. Hydrogen silsesquioxane (HSQ) was prepared by spin-coating Dow-Corning Flowable Oxide (FOX) on the wafer and then baked at 150, 250, and 350 °C for 1 min. Annealing was performed in N_2 furnace from 350 to 400 °C for 60 min as described previously [13]. The thickness of HSQ is about 500 nm after annealing. Some samples were subjected to plasma treatment. The O_2 plasma was operated at a pressure of 40 Pa for 5 min, a plasma power of 100 W and a chamber temperature of 250 °C. The amorphous SiO_2 films, deposited by the decomposition of tetraethyl orthosilicate, with 500 nm in thickness were deposited with PECVD (Multichamber PECVD, STS-MULTIPLEX CLUSTER SYSTEM, England) at 300 °C (substrate temperature) and 200 W. Then, 500 nm Al films were deposited by thermal evaporation onto the dielectric material to serve as interconnect.

The imizidation and chemical bonds structure of HSQ films were investigated by Fourier transform infrared reflection-absorption spectrometer (FT–IR–RAS). The FT–IR–RAS system used in this study (DA8.3, Bomen Inc., Canada) was a stand-alone measurement system. Its beam was P-polarized incident beam, and scan mode was 75° grazing incident angle reflectance because the samples were thin films. Two hundred scans were carried out, and the resolution was $\sim 1\ cm^{-1}$. A field emission scanning electron microscope (FESEM, S-4000, Hitachi Ltd., Japan) was used to examine the microstructure of the films. An LCR meter (HP-4285, Hewlett–Packard Co., USA) was employed to measure the capacitance and the dissipation factor of the dielectric from 75 kHz to 2.5 MHz. A Network Analyzer (HP-85122A, Hewlett–Packard Co., USA) which operates from 100 MHz to 20 GHz was used to measure the *S*-parameters of the interconnect on-wafer with the microwave probes. Before each measurement, the calibrations were carried out with SOLT pads (short, open, load, and through) purchased from Cascade Microtech (Cascade Microtech, USA). A de-embedding method proposed in [17] was employed to deduct the shunt parasitics of the probing pads. Then, the signal transient characteristics with signal delays and crosstalk noises between adjacent interconnect lines are evaluated by the inverse Fourier transform from *S*-parameters of the interconnect.

3. Results and discussion

3.1. Dielectric properties and microstructures of the HSQ films

A typical structure of HSQ is an Si–O cage containing Si–H bonds. The three-dimensional network structure of HSQ is obtained through annealing process. After annealing, some of the Si–H bonds dissociate and the cage is rearranged into network structure as shown schematically in Fig. 1(a) [13,18]. Fig. 1(b) shows the Fourier transform infrared (FT–IR) spectra before and after annealing with or without O_2 plasma treatment. The spectra exhibit a Si–H peak at $2250\ cm^{-1}$, Si–O stretching cage-like peak at $1130\ cm^{-1}$, Si–O stretching network peak at $1070\ cm^{-1}$, Si–O bending cage-like peak at $863\ cm^{-1}$ and Si–O bending network peak at $830\ cm^{-1}$ as listed in Fig. 1(a) [11]. Datum in the brackets in Fig. 1(b) is the relative Si–H peak area with respect to the Si–H peak area of the as-deposited HSQ films. The Si–H bond ($2250\ cm^{-1}$) absorbance decreases as annealing temperature increases especially after O_2 plasma treatment. The Si–O stretching cage-like bond ($1130\ cm^{-1}$) and Si–O bending cage-like bond ($863\ cm^{-1}$) break to form Si–O stretching network bond ($1070\ cm^{-1}$) and Si–O bending network bond ($830\ cm^{-1}$), respectively. Fig. 1(c) indicates that the absorbance peak ratios of Si–O network bonds (830 and $1070\ cm^{-1}$) to Si–O cage-like bonds (863 and $1130\ cm^{-1}$) are almost constant when specimens are annealed at temperatures less than or equal to 300 °C, while the increases in peak ratios are observed