Nanometer-scale mechanical imaging of aluminum damascene interconnect structures in a low-dielectric-constant polymer

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Ultrasonic-force microscopy (UFM) has been employed to carry out nanometer-scale mechanical imaging of integrated circuit (IC) test structures comprised of 0.32-μm-wide aluminum interconnect lines inlaid in a low-dielectric-constant (low-*k*) polymer film. Such inlaid metal interconnects are typically referred to as damascene structures. UFM clearly differentiates the metal and polymer regions within this damascene IC test structure on the basis of elastic modulus with a spatial resolution$\leqslant$10 nm. In addition, this technique reveals an increase in the polymer elastic modulus at the metal/polymer interface. This nanometer-scale hardening corresponds to compositional modification of the polymer from the reactive ion etch (RIE) process used to form trenches in the polymer film prior to metal deposition. The reported direct, nondestructive nanometer-scale mechanical imaging of RIE-process-induced modifications of low-*k* polymers in IC test structures offers expanded opportunities for mechanical metrology and reliability evaluation of such materials.
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INTRODUCTION

Until recently, the performance of complementary metal–oxide–semiconductor integrated circuits (ICs) has been driven by the length scale of the transistor. Reductions in transistor gate length have led to increased transistor switching speed. However, this downward scaling of the gate length increases the density of metal lines used for transistor interconnects which, in turn, increases interline capacitive coupling (*C*) and average interconnect resistance (*R*). As the interconnect spacing moves below 0.13 μm, the *RC* latency of the interconnect lines has emerged as a primary IC performance driver.[1] This has hastened the replacement of aluminum and SiO_2 as the interconnect metal and insulator of choice for silicon-based ICs with copper and so-called low-*k* dielectric materials to reduce the effective *RC* constant of the circuit.[1] Materials possessing low-dielectric constants that are chemically compatible with IC processing are typically organic polymers or porous silicates.[2,3] The former materials possess inherently low molecular polarizability, while the latter exhibit low mass density. One of the greatest challenges in incorporating these materials into microelectronic devices concerns the mechanical properties (bulk modulus, shear modulus, and Poisson's ratio) of these materials, which are typically far inferior to SiO_2. For example, several porous silicates ($k\sim2.2$) being considered as candidate low-*k* materials possess Young's moduli as low as 2.5 GPa (compared to ~78 GPa for SiO_2).[4] Promising organic low-*k* thermoset polymers, such as Dow Chemical's SiLK®, possess similar moduli in the range 2.7–3.0 GPa.[5]

The need for such materials will only increase in the near future. For the so-called 100 nm IC device node the 2000 International Technology Roadmap for Semiconductors calls for a dielectric constant for interlevel dielectrics between 1.6 and 2.2.[1] But, the degraded elastic performance of low-*k* materials compared to SiO_2 raises the risk of mechanical failure within the interconnect structure due to externally applied stresses in interconnect planarization processing, and/or due to thermally induced internal stresses from the thermal-expansion coefficient mismatch of the dielectric and metallic components. To effectively integrate low-*k* materials in IC devices within these constraints, it is necessary to develop corresponding analytical and metrology techniques to directly image the mechanical properties of IC interconnect structures at the nanometer length scale. In this manner, the fundamental material properties governing stress-induced defect generation in nanometer-scale device structures can be directly investigated. In addition, so-called nanometer-scale mechanical imaging can be used as a unique tool for materials development for ICs and emerging nanotechnologies.[6]

In this article, we report the application of ultrasonic-force microscopy (UFM) to the nanometer-scale mechanical imaging of low-*k* interconnect structures; namely, single-level damascene Al/divinylsiloxane-bis-benzocyclobutene (BCB) IC test structures. The observed image contrast from UFM scans of these test structures scaled with sample mechanical rigidity, clearly differentiating metal and dielectric regions. The UFM mechanical image contrast was also inde-

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