

PUSHKAR JAIN

Tantalum Oxide Thin Films for Embedded Capacitors

Using Pulsed DC Reactive Sputtering

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ABSTRACT

Embedded capacitor technology, where thin film capacitors are integrated at on-chip and/or off-chip levels, offers high packaging densities and improved electrical performance at potentially reduced costs of capacitor fabrication and integration. This research explores and establishes the leverages of using thin film embedded capacitors over currently used surface mount discrete capacitors. In particular, this thesis focuses on developing pulsed dc reactively sputtered tantalum oxide (Ta_2O_5) thin film capacitors to be integrated into established interconnect technologies of IC chips and packages.

A correlation between electrical breakdown field and dielectric constant, E_{BR} (MV/cm) = $(20/\sqrt{\epsilon_r})$ is empirically determined and used to establish a design space for breakdown voltage and capacitance density of planar capacitors, with film thickness and material dielectric constant as parameters. This design space sets the limits for “best one can achieve” (BOCA) breakdown voltages and capacitance densities using a particular dielectric. The validity of the developed design space is experimentally verified with Ta_2O_5 thin films over a wide range of film thickness (0.05 to 5.4 μm). Detractors causing the deviations from the BOCA breakdown voltages are identified and corrected experimentally. In particular, substrate cooling during deposition of “thicker” ($> \sim 1 \mu\text{m}$) films is required to deposit stoichiometric Ta_2O_5 exhibiting BOCA breakdown voltages, and “peak-to-valley” roughness at the metal/dielectric interfaces must be less than 10% of dielectric film thickness to avoid pre-mature breakdown of thin film capacitors.

An experimentally verified analytical model for pulsed dc reactive sputtering of Ta_2O_5 films is described and evaluated. The influences of important process variables, like oxygen flow rate and sputtering ion current, on the oxygen partial pressure in the chamber, deposition rate, film stoichiometry as well as film breakdown and leakage

characteristics are predicted using this model. The experimentally established existence of multiple oxygen partial pressures at a given oxygen flow rate (hysteresis loop) is theoretically explained using steady state analysis. The experimental results suggest that in order to ensure the electrical reliability of Ta₂O₅ films, deposition should be done at oxygen flow rates more than that required to go beyond the hysteresis region in oxygen partial pressure versus flow rate curve.

High frequency test vehicles were designed and fabricated to evaluate the electrical performance of Ta₂O₅, SiO₂, and Si₃N₄ thin film capacitors over a wide range of frequencies (dc to 20 GHz). Ta₂O₅, SiO₂, and Si₃N₄ show no dispersion at least up to 20 GHz. The total inductance of power connect vias is determined to be less than 50 pH/ μ m of via, which is at least two orders of magnitude lower than most discrete capacitors along with connection leads (> 4 nH). Providing several vias in parallel further reduces the overall inductance of the connection paths in thin film capacitors. The shorter connections and elimination of connection leads in thin film decoupling capacitors make them highly suitable for integration into 2D and 3D structures. Thin film capacitors based on SiO₂, Si₃N₄, and Ta₂O₅ can provide capacitance densities comparable to the state-of-the-art surface mount discrete decoupling capacitors (~ 30 nF/cm²). The leakage current densities below 10^{-6} A/cm² (at 0.5 MV/cm) are achieved with SiO₂, Si₃N₄ and Ta₂O₅ thin film dielectrics.

The extent of Cu diffusion/drift into Ta₂O₅ films is determined and compared with Al, Ta, and Ti at various biasing and temperature conditions using bias-temperature-stress (BTS) and triangular voltage sweep (TVS) techniques. No Cu diffusion was detected at 150 °C at least till 0.75 MV/cm. While, Cu diffuses/drifts into Ta₂O₅ at aggressive temperature conditions, i.e., at 300 °C was detected, a thin layer of Ti or Ta (~ 30 nm) acts as an excellent Cu diffusion barrier into Ta₂O₅.

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