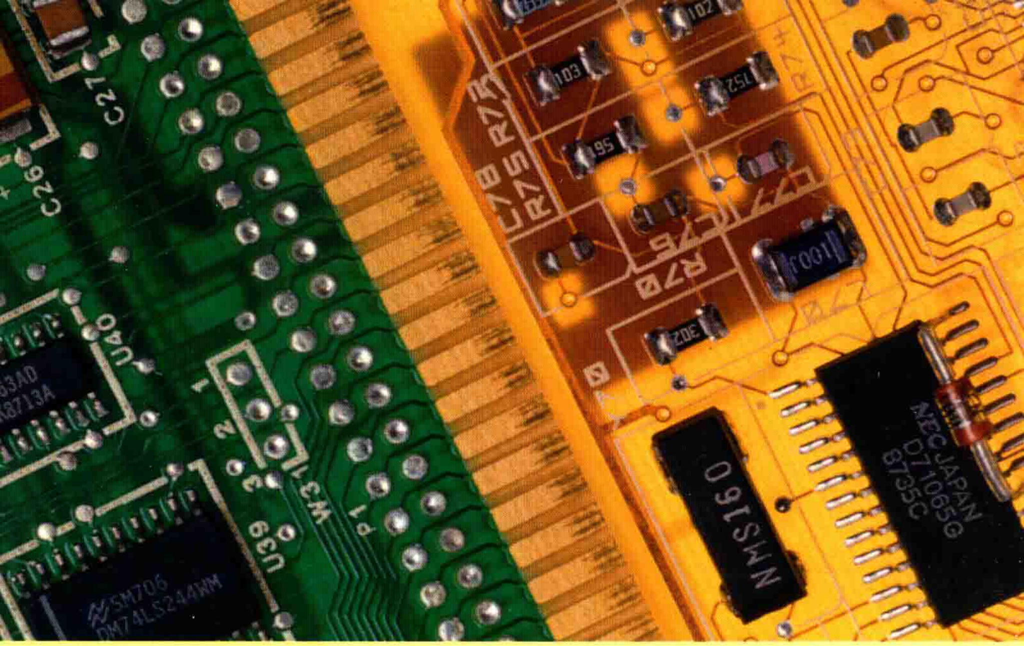

PUSHKAR JAIN

Tantalum Oxide Thin Films for Embedded Capacitors

Using Pulsed DC Reactive Sputtering

VDM
Verlag
Dr. Müller

PUSHKAR JAIN

Tantalum Oxide Thin Films for Embedded Capacitors

Using Pulsed DC Reactive Sputtering

VDM Verlag Dr. Müller

Impressum/Imprint (nur für Deutschland/ only for Germany)
Bibliografische Information der Deutschen Nationalbibliothek: Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über http://dnb.d-nb.de abrufbar.

Coverbild: www.purestockx.com

Verlag: VDM Verlag Dr. Müller Aktiengesellschaft & Co. KG
Dudweiler Landstr. 125 a, 66123 Saarbrücken, Deutschland
Telefon +49 681 9100-698, Telefax +49 681 9100-988, Email: info@vdm-verlag.de
Zugl.: New York, Rensselaer Polytechnic Institute, PhD Dissertation, 2003

Herstellung in Deutschland:
Schaltungsdienst Lange o.H.G., Zehrensdorfer Str. 11, D-12277 Berlin
Books on Demand GmbH, Gutenbergring 53, D-22848 Norderstedt
Reha GmbH, Dudweiler Landstr. 99, D- 66123 Saarbrücken
ISBN: 978-3-639-09662-0

Imprint (only for USA, GB)
Bibliographic information published by the Deutsche Nationalbibliothek: The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Cover image: www.purestockx.com

Publisher:
VDM Verlag Dr. Müller Aktiengesellschaft & Co. KG
Dudweiler Landstr. 125 a, 66123 Saarbrücken, Germany
Phone +49 681 9100-698, Fax +49 681 9100-988, Email: info@vdm-verlag.de

Produced in USA and UK by:
Lightning Source Inc., 1246 Heil Quaker Blvd., La Vergne, TN 37086, USA
Lightning Source UK Ltd., Chapter House, Pitfield, Kiln Farm, Milton Keynes, MK11 3LW, GB
BookSurge, 7290 B. Investment Drive, North Charleston, SC 29418, USA
ISBN: 978-3-639-09662-0

PUSHKAR JAIN

Tantalum Oxide Thin Films for Embedded Capacitors

ACKNOWLEDGMENT

First and foremost, I would like to acknowledge and thank my advisor Prof. E. J. Rymaszewski and Prof. T. S. Cale for their guidance and relentless support without which this thesis would not have been possible. Their knowledge, guidance, and support were crucial for the completion of this work. I would also like to acknowledge Prof. T. –M. Lu for guiding me like an advisor, and encouraging me to try out new ideas. I would like to thank my other committee members, Prof. R. J. Gutmann, and Prof. R. Kane for their guidance and valuable advice. The constructive criticism and guidance of my committee members helped me focus better on the thesis work.

I would also like to acknowledge Interconnect Focus Center and Center for Power Electronics Systems for providing me the financial support and research funding in various phases of this work.

Throughout this work, I have been helped by numerous other people in various capacities. I would like to thank Jasbir and Vinay, who helped me out tremendously throughout this work. Thanks are due to Anu and Tansel for sharing their immense experience in metal ion penetration and roughness evolution studies, respectively. I would also like thank Ravi and Jasbir for thoroughly reviewing this thesis, and providing valuable input in shaping this thesis manuscript. The clean room and the administrative staff at the Center for Integrated Electronics have been very helpful during my stay at RPI. I would like to thank Dana, Kelli, and Joelle for their help. My stay at Troy has been enjoyable because of the many great friends I made here. I would like to acknowledge Tuhin, Anju, Shom, Jasbir, Ravi, Amrit, Ashish, Rohit, Anu, Manisha, Tansel, Yongchai, Suchira, and Ed.

Last, but not the least, I would like to thank my family members for their love, support, and encouragement throughout the course of my academic career.

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) = $\left(20/\sqrt{\varepsilon_r}\right)$ 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" (> ~1 μm) 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 Ta_2O_5 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 Ta_2O_5, SiO_2, and Si_3N_4 thin film capacitors over a wide range of frequencies (dc to 20 GHz). Ta_2O_5, SiO_2, and Si_3N_4 show no dispersion at least up to 20 GHz. The total inductance of power connect vias is determined to be less than 50 pH/μm 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 SiO_2, Si_3N_4, and Ta_2O_5 can provide capacitance densities comparable to the state-of-the-art surface mount discrete decoupling capacitors (~ 30 nF/cm^2). The leakage current densities below 10^{-6} A/cm^2 (at 0.5 MV/cm) are achieved with SiO_2, Si_3N_4 and Ta_2O_5 thin film dielectrics.

The extent of Cu diffusion/drift into Ta_2O_5 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 Ta_2O_5 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 Ta_2O_5.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES