Preface

Microelectronic devices contain multiple layers of dissimilar materials, including metals, dielectrics, and semiconductors. When integrating these heterogeneous materials to create a device, the boundary that separates each pair of materials is called their interface. Examples are dielectric-semiconductor interfaces, metal-semiconductor interfaces, and metal-dielectric interfaces. As the device structures in gigascale electronics continue to shrink, their functionality is not only affected by the film quality of these dissimilar materials, but also is more and more determined by the stability of their interfaces. Interface stability has become an increasingly important issue that has a profound impact on the reliability of electronic devices during operation. For instance, the dielectric-semiconductor interface, such as the SiO_2–Si interface, was intensely studied for decades in order to understand its critical role on the operation of the metal-oxide-semiconductor field-effect transistor (MOSFET); meanwhile metal-semiconductor interfaces have been widely researched for years since they are the foundation for the operation of rectifying diodes, such as Schottky diodes. In this monograph, we focus on metal-dielectric interfaces, whose stability is key to understanding the reliability of multilevel interconnect structures in gigascale integrated circuits (IC), and more recently, of memristor devices.

In multilevel interconnect structures, metals are required to be very conductive, while dielectrics have to be highly resistive. But these requirements have become more and more challenging as the width of the dielectric layer between the metal lines gets very thin (tens of nm). Any disturbances at the metal–dielectric boundary can significantly modify their electrical properties. The typical disturbance we discuss in this monograph is the penetration of metal species into dielectric films. Such metal contamination is believed to be the main cause of early dielectric breakdown. There are two ways that metal can migrate into dielectrics: neutral metal atom diffusion and metal ion drift. The latter is exacerbated by the fact that the effective electric field across the dielectric film between metal lines has reached MV/cm range during device operation.

Research on metal-dielectric interfaces is receiving increasing attention, particularly after the introduction of Cu technology one and a half decades ago and the recent use of low dielectric constant (low-*k*) interlayer dielectric materials. There are many challenging fundamental questions that need to be answered, and some are very controversial and still under debate. Are conventional refractory metal barriers stable on low-*k* materials? What is the origin of metal-ion generation at the metal-dielectric interface? Why do some metals migrate mainly in ionic states inside dielectrics while others migrate only in atomic form? What role does moisture play in the instability of metal-dielectric interfaces? How is metal contamination affecting the lifetime of the dielectric? All these unknowns have become central research topics for the development of future IC technology. This monograph is an attempt to provide a unifying picture of the diverse but sometimes contradictory findings that are reported in the literature. This unifying picture is built upon fundamental physical and chemical principles and can provide readers with a clear account of the origins of the observed phenomena involving metal-dielectric interfaces.

The monograph consists of nine chapters. In Chap. 1, we introduce different types of materials of interest and their interfaces. We also introduce the types of instabilities that can occur at metal–dielectric interfaces, including thermally induced atomic diffusion and electric field-enhanced ion drift. In Chap. 2, we formulate the fundamental laws that govern thermal diffusion and field-enhanced ion drift. We discuss chemical interactions and the tendency toward oxide formation at the metal-dielectric interface, which is believed to be an important source of metal ion generation. The main test structures used to study interface stability, including metal–dielectric–metal (MIM) and metal–dielectric–semiconductor (MIS), are reviewed in Chap. 3. Electrical characterizations include I–V (current vs. voltage), C–V (capacitance vs. voltage), bias-temperature stress (BTS), and triangular voltage sweep (TVS). Elemental measurements include secondary ion mass spectroscopy (SIMS), Rutherford backscattering spectroscopy (RBS), and energy dispersive X-ray spectroscopy (EDX). Al–dielectric interfaces are discussed in Chap. 4. This chapter explains the origin of the stable Al–SiO_2 interface, which has served the IC industry for many decades. This chapter also discusses many Al/low-*k* interfaces, which, to the surprise of many researchers, fail badly under an electrical field. The stability of Cu–dielectric interfaces is presented in detail in Chap. 5. The origin of Cu ion generation and its relationship with interface Cu oxide formation are described. The impact of moisture and oxygen on interface stability is discussed. It is shown that, in the absence of oxidation agents, Cu ion generation and drift can be avoided. We demonstrate the severity of thermal diffusion of Cu in low-*k* dielectrics at low temperatures, even in the absence of an external electric field. In Chap. 6, we show that while refractory metal-dielectric interfaces could have excellent thermal stability, they may not be stable under an electric field, depending on the chemical nature of the dielectric surfaces. For most low-*k* dielectrics, contrary to common belief, refractory metal ions can be generated and can drift into the dielectrics under an external electric field due to the formation of metal sub-oxides at the refractory metal/low-*k* dielectric interfaces. In Chap. 7, advanced concepts of self-forming barrier strategies are explored. Processing challenges to the implementation of self-forming barrier strategies are reviewed. In Chap. 8, the mathematical formulations of the kinetics of metal ion drift in dielectrics are presented. We also discuss the methods of extracting ion diffusivity by experiments. The relevancy of metal migration inside dielectrics and the popular time-dependent dielectric breakdown (TDDB) reliability tests are discussed in Chap. 9. We also explore the possible future research directions in this chapter.

Although this monograph focuses on the metal-dielectric interfaces in the interconnect structure, the fundamental understanding gained here can be applied to the study of metal gate/high-*k* dielectric interfaces for future MOSFET applications. Also, the knowledge could be useful for memristor device research, whose operation relies on “unstable” metal-dielectric interfaces. Overall, this monograph can be used as a reference for university researchers and industrial scientists working in the areas of electronic materials processing, semiconductor manufacturing, memory chips, and IC design.

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