Klaus Wetzig and
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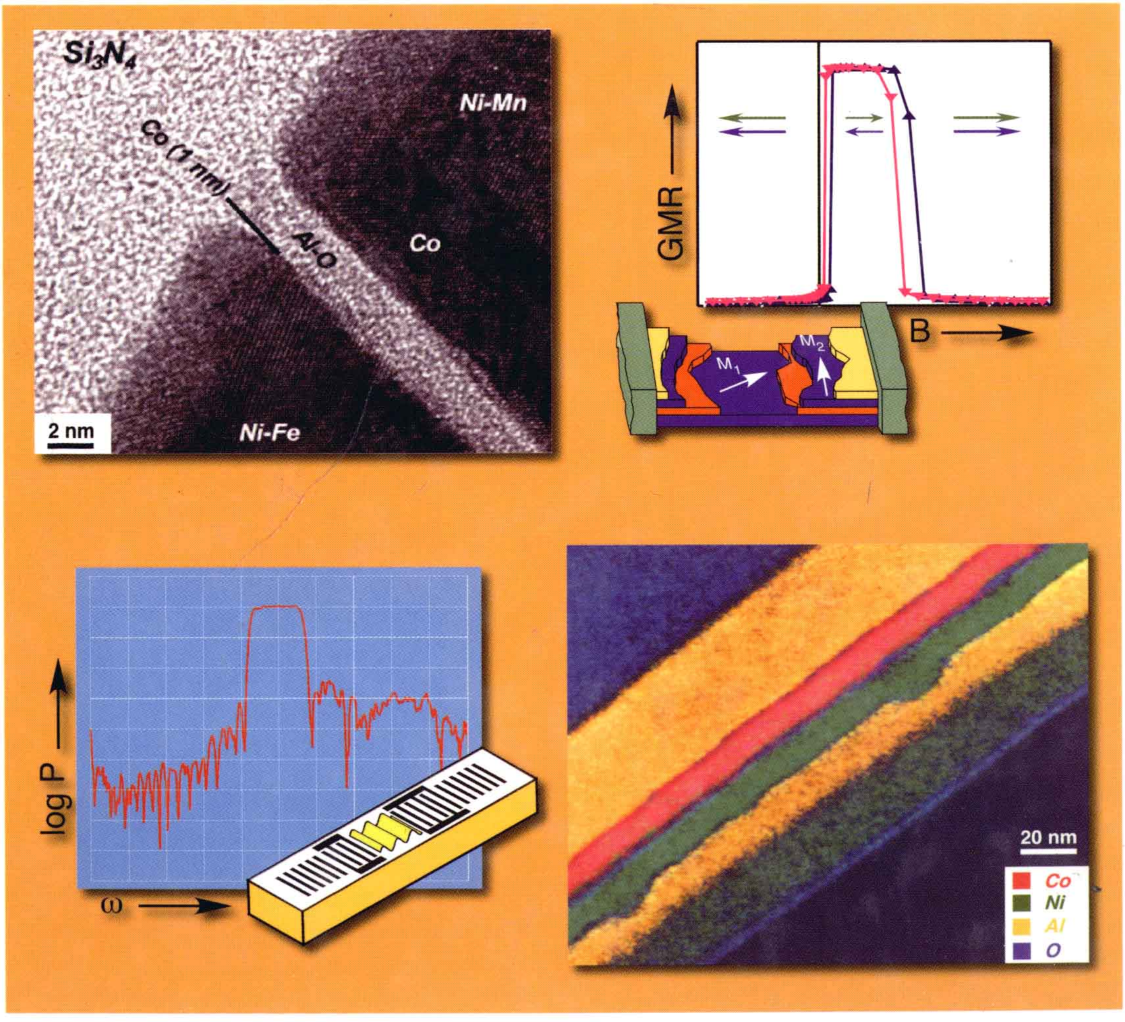
Metal Based Thin Films for Electronics



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Contents

1 Introduction

Prologue

Electronic devices have found widespread use in our everyday lives. The applications cover many areas such as consumer electronics, information technology, engineering, automotive application, transportation, medical diagnostics and treatments, etc. The construction of these devices and their building blocks involves elaborate fabrication processes which are based on a thorough understanding of materials science and solid state physics. The device functionality may involve conventional microelectronic, acoustoelectronic, optoelectronic, or future spinelectronic elements, or a combination of these (Figure 1.1). The functionality is achieved by a carefully engineered and complex combination of metallic, semiconducting, and insulating layers. These layers are often micro- and nanostructured by sophisticated lithography techniques in order to achieve the desired properties. Sometimes, as in the case of microprocessors, the structuring involves several levels. The individual feature sizes created by the structuring processes may be as small as 100 nm and are expected to become even smaller in the future in leading edge applications.

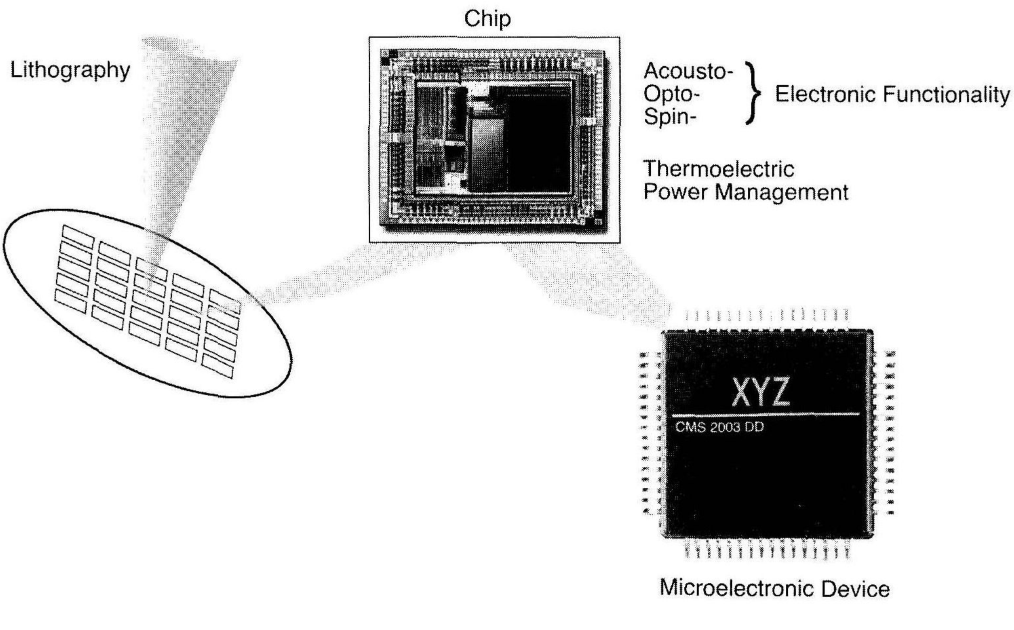

Figure 1.1: The application regimes of metal-based thin films in the microelectronics area

The fabrication of these electronic devices requires a very good control of the materials properties. This concerns not only the physical material parameters, but also the film structure and morphology. The latter are largely determined by the details of the deposition process and postgrowth processing procedures. In addition, the interfaces between different materials and material classes are also becoming of crucial importance. In this situation, a wide variety of analysis tools must be used to ensure a reliable process control and – if necessary – a precise failure analysis. These tools include not only different real space (microscopy) and reciprocal space (diffraction) techniques, but also spectroscopic techniques, electrical transport measurements, stress and strain analyses, migration investigations, etc.

Novel device technologies are often closely linked to the use of new materials or material classes. One recent example is the replacement of the conventional Al interconnects in microprocessors by Cu ones. This step not only involves new fabrication procedures, such as the "damascene" technique, but also requires new barrier layers to avoid the mixing of Cu and Si. Another example is the emerging technology of magneto- or spinelectronics. In its present state it employs complex magnetic units composed of metal or metal/insulator layer stacks. In addition to the electrical properties, the layers must also provide a distinct magnetic functionality. Since all of the classical ferromagnets Fe, Co, Ni and many antiferromagnets used in magnetoelectronics are metals, this adds another and very exciting facet to the application of metal-based films in electronics.

From the above considerations follows quite clearly that metal-based thin films play a central role in the different steps of the fabrication and for the specific functionality of electronic devices. The most evident use concerns conducting lines and interconnects. Less obvious is their employment as barrier layers against interdiffusion and segregation. Also very important are metallization layers, for example, in acoustoelectronic devices. In chemically complex systems, the physical properties can be conveniently changed by the chemical composition. This is particularly true for the conductivity and is exploited in silicides for thermoelectric applications. Metal-based films are also very important for X-ray optical techniques used to fabricate (X-ray lithography) and analyze (X-ray diffraction and spectroscopy) electronic device structures.

Since metal-based films have such a widespread use in the different areas of microelectronics, knowledge of the respective properties and phenomena is distributed over various fields of physics and materials science. As a consequence, one usually has to consult many different sources in order to get the desired piece of information or a broader overview of a specific issue. Considering the importance of metal-based films in the field of electronics it is thus justified to describe and discuss these systems, the associated effects and phenomena, and their applications in one place.

Organization, Aim and Content of This Book

The main purpose of this book is two-fold. On the one hand, it is meant to serve as a compendium for metal-based thin film systems and their usage in electronics technology. As such, it addresses both the scientist and the research engineer. On the other hand, the book also includes a more tutorial part which is intended to bridge the gap between fundamental phenomena and their technological applications. It may therefore also serve as a textbook for advanced students in solid state physics, materials science, and electronics engineering.

The book is organized into several chapters covering the range from principal aspects and phenomena over contemporary challenges in materials science to actual device concepts and applications. We thereby mainly concentrate on the relevant fields of interconnects, acousto-electronics, thermoelectrics, magnetoelectronics, and X-ray optics.

In *Chapter 2* we review the various fundamental aspects of metal and metal-based films with respect to the individual fields and applications addressed in this book. This chapter is mainly intended to convey background information for the advanced student in a more tutorial form. It forms a basis for the discussion of the future challenges and the device-related topics in the subsequent chapters. The first section is devoted to a key aspect in microelectronics, namely the means to transfer and distribute information and power in a microelectronic device, for example, in a microprocessor. This is achieved by means of metallic interconnects which are usually arranged in very complicated and delicate three-dimensional networks. The contribution discusses both Al and Cu-based technologies for interconnects and highlights the specific implications and problems associated with each technology. A somewhat less familiar, though not less eminent area of microelectronics is acoustoelectronics. Acoustoelectronic devices are based on the exploitation of phenomena involving the generation, transport, and filtering of surface acoustic waves. Their functionality is largely determined by the interaction between a piezoelectric substrate and a metallic film serving as an electrode. Surface acoustic wave devices play a strategic role in telecommunication and other high frequency applications. A rather novel facet of microelectronics is called magnetoelectronics or "spintronics" which is the topic of the third section of Chapter 2. Spintronics is still an emerging technology which is based on the transport of spins and charges, rather than just charges. It thus combines magnetic functionalities and materials with established microelectronics concepts. Current spintronics applications concern read heads in hard disk drives, magnetocouplers, or nonvolatile magnetic random access memories (MRAM). In the long run, reprogrammable magnetic logic circuits or active magnetoelectronic devices, such as a spin transistor, may be expected. The section reviews the fundamental aspects of spin-dependent transport and magnetic coupling phenomena in thin films and layer stacks. It also discusses the basic thin film arrangements and their specific properties with respect to a particular device functionality. Thermoelectricity exploits the conversion of thermal energy into electrical energy and vice versa for power generators, cooling devices, and temperature or radiation sensors. The particular relevance of thermoelectrical systems for microelectronics arises – among other reasons – from the increasing need for efficient thermal and power management of chip devices. The implementation of Peltier elements in the chip architecture can provide on-chip cooling facilities. The recovery of excess heat and its conversion into electrical energy may help to reduce the overall power consumption and represents a step towards future self-sufficient systems. The different material systems and thermoelectric concepts which are currently under consideration are treated in the fourth section. Particular emphasis is put on the role of the various materials properties with respect to the thermoelectrical efficiency parameters and figure of merit. The final section of the chapter deals with the role of metallic layers and multilayer systems for X-ray optics. The connection of X-ray optics to microelectronics comes from the progress in optical lithography techniques which aim at feature sizes well below 100 nm. Because of the smaller wavelengths, the novel lithography approaches can no longer be based on transmission optics, but have to use reflective optics instead. Metal thin film systems are therefore needed to realize the appropriate optical elements (mirrors, gratings, etc.). The section discusses the fundamental aspects of X-ray optics with respect to thin film systems based on reflection and diffraction.

Chapter 3 is devoted to the deposition techniques used to prepare thin film systems and to the main analytical approaches employed to study their behavior. The analysis involves microscopy, spectroscopy, or diffraction techniques and gives access to different properties, such as the film morphology, chemical composition, crystallographic and electronic structure. Deposition techniques for thin metallic films exist in a wide variety and are described in Chapter 3.1. Today vacuum based physical and also chemical deposition techniques play the dominant role in the preparation of thin metallic films, but non-vacuum based deposition methods such as electroplating or the modified CVD technique ALD (atomic layer deposition) are also of growing interest and will therefore be discussed in this book. Both transmission electron microscopy (TEM) and electron diffraction are strong techniques for studying micro- and nanostructures in metal based thin films. Furthermore, with enhancement of an analytical TEM by spectroscopic attachments for such as energy dispersive X-ray spectroscopy (EDXS) and electron energy-loss spectroscopy (EELS) it is also possible to receive chemical information (element distribution and chemical binding) in the nanometer range of thin films. A powerful method for the immediate study of electrical thin film properties is in situ scanning electron microscopy (SEM). In situ SEM methods allow the investigation of potential contrast, ferroelectric domains, electron beam induced current (EBIC) and processes of electro- or acoustomigration respectively. X-ray scattering techniques are discussed as a widely-used tool for structural information on thin films. Both the possibilities and limitations of angle diffraction, reflectometry, soft X-rays and magnetic scattering are discussed. Spectroscopic techniques allow the element distribution and depth profile analysis of thin films. They can be carried out by electrons, X-rays or ions and are frequently used in connection with imaging techniques such as scanning or transmission electron microscopy. In contrast to bulk materials, thin films on substrates are usually under mechanical stress. Thus, stress measurement methods play an important role in the characterization of thin films for electronics. Different techniques such as the substrate curvature and the $\sin^2 \Psi$ method are discussed under application aspects.

As one of the core parts of this book *Chapter 4* addresses current challenges in the investigation and application of metal-based thin films. These include the aspects of thermal stability, acousto- and electromigration, barrier and nucleation layers, functional electric and magnetic layers and mulilayers for X-ray optical purposes. These topics represent the forefront of the current research in materials science and solid state physics. Because of the continuing downscaling in the architecture of integrated circuits electromigration is a life- limiting process in metallization layers. The damage analysis is discussed both for Al and Cu interconnects. The introduction of copper as the conducting material for interconnects requires effective diffusion barriers since copper readily diffuses into silicon oxide and silicon. The optimization of barriers and new barrier/ seed concepts are therefore the focus of attention. Migration effects are also observed in surface acoustic waves (SAW) structures, as a result of diminishing structure dimensions (< 1 μm) and increasing electrical input power values (> 1 W) which cause very high power density levels and therefore high stress loading of metallization. Thus, new metallization concepts have to be discussed in detail. Spintronic applications of functional magnetic layers, such as for sensors and MRAMs, may be realized by thin film systems which may be grouped into multilayers, spin valves and tunnel junctions. These systems excel in a precisely defined functionality which is strongly influenced by temperature. Therefore the thermal stability plays a dominant role in both the manufacture and operation of functional magnetic layers, as will be demonstrated for magnetoresistive layer stacks. A further group of thin film based components with growing importance are multilayers for X-ray optical purposes, e.g. as reflectors for X-rays. Finally, the last part of Chapter 4 is focused on functional electric layers with well–defined electronic and electrical transport properties. Such thin film materials are used as resistance layers, thermoelectric sensors and generator devices. The optimization of the electrical and thermoelectric film parameters will be discussed in depth.

The application of metal-based thin film systems in electronic and microelectronics-related devices is the focus of *Chapter 5*. The diversity of the devices treated in this chapter highlights the widespread application areas of metal film systems. The first section deals with interconnect technologies for memory and logic products. Of particular interest are the combination of Cu interconnects and low-*k* dielectrics. The subsequent section on surface acoustic wave devices gives examples of high frequency filters, resonators and delay lines. The device concepts range from relatively simple transversal bandpass filters to programmable phase shift keying filters. The magnetic and magnetoelectronic sensor devices are mainly related to automotive applications and thus emphasize one of the growing future markets for microelectronics products. There, magnetic sensors are employed to measure positions, angles, rotational speeds, or torques with the aim of improving fuel economy, vehicle and passenger safety, and driving comfort in the present and new generations of automobiles. Reducing the energy consumption and improving the energy efficiency is also the driving force in the development of thermoelectric sensors and transducers. The devices discussed range from thermal converters for high precision AC measurements to low power thermoelectric generators and microcoolers for applications in microelectronics. The chapter closes with a section describing several examples of X-ray optical elements based on metal thin film systems. The applications cover not only X-ray telescopes and microscopes, but also recent developments in the area of extreme ultraviolet lithography (EUVL) instrumentation. The latter will be the fundamental tool for a future downscaling in microelectronics.

The final *Chapter 6* of the book gives an overview of the developments to be expected in the field of metal-based thin films and their implementation into microelectronic circuits and devices. The future will not only see the use of new materials and device concepts, but also the fusion of distinct areas to achieve improved or novel functionalities. This concerns, for example, the possible implementation of optical interconnects which may be seen as a combination of standard microelectronics and optoelectronics. Another example is the incorporation of nonvolatile functions on the basis of magnetic components, i.e., the synthesis of conventional microelectronics and spinelectronics. The major driving forces behind these activities are not only the expected revenue, but also the opportunity for new discoveries and developments which may completely change our current picture of microelectronics in the future.

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2 Thin Film Systems: Basic Aspects

2.1 Interconnects for Microelectronics

2.1.1 Introduction

Interconnects are the means of transportation of information within a microelectronic circuit. When one takes apart an old radio, one finds that all the active components are connected by single wires, each of which has been soldered to transistors, resistances, capacities etc. Nowadays this apparent chaos of wires is replaced by printed circuit boards where a polymeric substrate is covered with copper and channels are etched to create wires. A three-dimensional wire structure has been converted into a planar structure and only now and then has an additional wire to be added to form a bridge. The aspect ratio of the copper wires is small i.e. they are much wider than high. Low cost wet etch techniques can be employed.

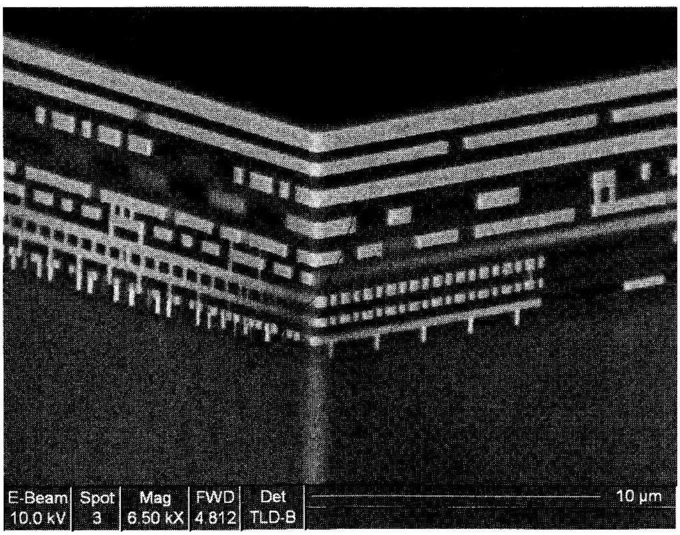

Figure 2.1: SEM cross-section of AMD's eighth generation microprocessor with eight levels of copper interconnects [2.1]

When one takes apart a modern microelectronic chip one will find a completely different scenario. Unlike the printed circuit board there are several up to ten different metal layers in an integrated circuit. The active components are all situated in the substrate, which is usually made of silicon. The aspect ratios are higher, in extreme cases even significantly greater than one (i.e. the lines are higher than wide). In addition to the conductor lines made out of copper or aluminum, one introduces several other layers, such as dielectrics, etch stops, anti-reflective coatings, diffusion barriers and vertical connections (so-called plugs). The barriers will be discussed at the end of this chapter. All of these layers have special functions and properties. Figure 2.1 shows a cross-section of a state of the art microprocessor revealing the complicated layers of wiring that will be described in detail later in this chapter.

In order to create a working circuit the engineer has to overcome two basic challenges: manufacturability and reliability. The first, even if sometimes very complicated, is usually straightforward. It is apparent whether a circuit works or not. However, sometimes the search for the reason for failure can be tedious. In the case of reliability, on the other hand, it is difficult to predict whether a circuit will work ten years from now. This task is usually addressed by a combination of the following concepts. Lifetime tests have to be accelerated by increasing temperature and the current densities that the wires have to carry. Obviously these conditions are not realistic and thus have to be extrapolated to service conditions. Empirical models that are based on variations in temperature and current density are relatively easily to formulate, however, they bear the risk of being too aggressive or too conservative when the extrapolation is made. It is now the task of materials science to promote understanding of the mechanisms responsible for failure, investigate their temperature and current density dependence and formulate mechanistic models that can be employed for lifetime prediction.

The next sections will focus on the fabrication of interconnect lines, their dimensionality and function, the materials science applicable to them and finally will elucidate future perspectives. The last section will focus on function and materials choice of diffusion barriers.

2.1.2 Metallization Layers

Function of On-Chip Interconnects and Materials Selection

The function of an interconnect system is to distribute clock and other signals and to provide power/ground, by connecting the various circuit/systems functions of a chip. The fundamental development requirement for the on-chip interconnects is to meet the high-speed needs of chips to transmit clocks and signals despite further down-scaling of feature sizes. In particular, the so-called RC (resistance x capacitance) time delay has to be minimized using a smart interconnect design and new technologies and materials. This task includes the development and the implementation of conducting material with low resistivity for interconnects and of dielectric material with low permittivity as the isolating material between them. Additionally, numerous other, mostly ultrathin films of the back-end-of-line layer stack have to be considered since they all contribute to the overall performance and reliability of the interconnect system: barriers, capping layers, etch stop layers, hard masks, etc.

The following requirements for the conductor material have been derived from the performance and reliability requirements of the on-chip interconnect system:

– low resistivity (high electrical conductivity)
– high thermal conductivity
– high melting point (and thus low diffusivities)
– materials compatibility to the isolating dielectric material and to barrier and capping layers