Semiconductor Measurements & Instrumentation

SECOND EDITION

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Acknowledgments

Preface

Like the first edition, this one is devoted to material characterization and measurement, and does not discuss device measurements except when some material property can best be deduced by using a device structure. Also, like the first edition, this volume is designed primarily for the practicing engineer, although it should be quite useful to semiconductor manufacturing supervisors and to college or associates degree students whose interests lie in the area of semiconductor technology. In addition, those in general semiconductor management may find the chapters devoted to large analytical instruments (Chaps. 10–15) helpful when examining laboratory and wafer fab capital budgets.

In the 20 years since the first edition, two changes in the semiconductor industry have substantially increased our dependence on measuring techniques which are required to adequately characterize semiconductor materials. One of these changes was the shift in emphasis from bipolar to MOS technology, and the other was the continuing move to smaller and smaller geometries. Fortunately, there has also been a steady stream of new analytical instruments and measuring techniques introduced which greatly simplify the task of characterizing material for the newer and more stringent demands of ultra large scale integrated circuits (ULSI). The availability of inexpensive and compact computing power has led to the incorporation of very sophisticated mathematical analysis into most of the new instruments. While such capability can ease the engineer's interpretive tasks, it can also lead to serious misinterpretation of data if the machine is used for an application in which the computer algorithms do not apply. Therefore, an understanding of how an instrument is programmed, as well as a knowledge of the measurement principles involved is absolutely essential.

None of the newer analytical instrument developments have obviated the need for the older basic measuring techniques, so most of the contents of the first edition have been incorporated with updates into the first nine chapters of the second edition. The remaining six chapters are devoted to the more complicated analytical instruments which are used today as workhorse tools for semiconductor characterization, and include some not considered, or even invented, 20 years ago.

Two other technological changes have affected the content of this book in a major way. One has been the changing emphasis on specific semiconductors, like the fading of germanium as a major transistor material, the phenomenal rise in silicon usage, and the increasing emphasis on semiconductor optoelectronic devices and their required materials. The other change has been the exponential increase in semiconductor related articles and the widespread accessibility of computer based literature search data bases. The first change has led to the removal in this edition of most of the information specifically relating to germanium, and the inclusion of more gallium arsenide information. With the second change has come the realization that it is no longer practical to include all relevant references in a tutorial treatment such as this, since they could easily occupy a full volume of their own. With the data bases and search routines already available through library and World Wide Web resources, such an inclusion seems unnecessary.

Lists of symbols are included at the end of each chapter. Duplicate symbols, but with different meanings, will be found from chapter to chapter. The duplication arises because semiconductor technology has embraced parts of many fields, such as chemistry, electrochemistry, radiochemistry, physics, high-energy physics, electrical engineering, and mechanical engineering. Each of these has developed its own time-proven symbols, many of which overlap between disciplines, so it is not surprising that semiconductor characterization encounters the same redundancy. It appears that having a single table of symbols over such diverse subject matter would be extraordinarily confusing. Hence, we have grouped the symbols by technology field in individual lists at the end of each chapter.

Contents

Crystal Orientation

Introduction

The values obtained when many of the measurements discussed in later chapters are made may depend on the orientation of the crystallographic face on which the measurements are made, and on the direction in which the applied stress (e.g., voltage, force) is applied. Because of these dependencies, and because the outcome of many semiconductor processes is dependent on wafer crystal orientation, considerable em-

phasis must be placed on orientation. Some of the more common orientation-sensitive properties are given in Table 1.1. Table 1.2 summarizes orientation-dependent semiconductor processing steps that may be encountered. In general, if a property is anything other than a scalar, it will be orientation sensitive in most crystalline materials (1). However, those properties described by a second-rank tensor, and this includes almost all of the properties of common interest in the semiconductor industry (resistivity, thermal conductivity, and impurity diffusivity), are independent of direction in cubic crystals (which encompasses the majority of the present commercially important semiconductors).

There are, however, some problems in trying to predict behavior a priori. They arise when it is difficult to determine the defining equation of the property (e.g., hardness or etch rate) or because an apparently simple measurement of one property may in some subtle way involve additional phenomena. Further, there may be physical constraints such as very thin layers or very small diameter filaments under which a crystal can no longer be considered as three dimensional. Under such circumstances, properties normally isotropic may become orientation dependent. It is this phenomenon which causes orientation differences in the carrier mobility of silicon inversion layers.

Crystallography (2)

To help clarify the nomenclature used in discussing the orientation methods in this chapter and the crystallographic defects in chapter 2, a brief discussion of pertinent crystallography and crystallographic terminology is given in this section.

Crystalline material is distinguishable by its atoms being arranged in a periodic array. By repeatedly translating the unit cell, which may contain one or more atoms, the periodic array can be reproduced. The orientation of a crystal surface is described in terms of its relation to the faces of that unit cell or to the cell axes (the crystallographic axes). The determination of the cell size and shape and the location of atoms within the cell is done by x-ray methods, and will have been done long before any semiconducting material becomes commercially important. Such data can be found in standard references, but for convenience, the cell dimensions and crystal symmetry are given in Table 1.3 for some of the more common semiconductors. The cubic diamond lattice (which diamond, silicon, and germanium have) can be described as two interpenetrating face centered cubes displaced by $\frac{1}{4}$ the unit cell dimension a_o along the x, y, and z directions as shown in Figure 1.1a. Figure 1.1b shows an isometric view of the position of the atoms, while Figure 1.1c shows the direction of the atomic bonds. The III-V compounds (e.g.,

TABLE 1.1 Partial Listing of Directional Properties of Crystals

Tensor rank	Property	Symbol	Relates	Form of relation	Isotropic in
0	Density Heat capacity	δ C	Mass to volume Heat transferred to temperature changes	A scalar to a scalar	All classes
1	Pyroelectric co-efficient	P_i	Electrical polarization to temperature change	A vector to a scalar	None
2	Electrical conductivity Electrical mobility Thermal conductivity Diffusion coefficient	σ_{ik} μ_{ik} k_{ij} D_{ij}	Current density to applied field Current density to applied field and number of carriers Heat transferred to temperature gradient Current density to concentration gradient	A vector to a vector	All cubic
	Thermal expansion	α_{ij}	Elongation to temperature change	A scalar and 2d-rank tensor	
3	Piezoelectric coefficient	d_{ijk}	Polarization to applied stress	A vector to a 2d-rank tensor	None
4	Elastic constants Piezoresistance	C_{ijkl} π_{ijkl}	Stress to elongation Change of resistivity to applied stress	Two 2d-rank tensors	None
—	Hardness		Force to indention		
—	Breaking strength		Stress to fracture		
—	Chem etch rate (some etchants)		Amount of material removed to time		
—	Oxidation rate		Amount of material oxidized to time		
—	Ion implant depth		Ion penetration depth to energy		
—	Crystal growth rate		Amount of crystal grown to time		

TABLE 1.2   Some Orientation-Sensitive Semiconductor Processing Steps

Crystal growth from melt	Wafer polishing (mechanical)
Crystal growth from vapor	Ion implanting
Oxidation (for Si)	Diffusion
Alloy contact formation	Chemical etching
Scribe and break	

gallium arsenide, indium arsenide, indium antimonide, gallium phosphide) have a zinc blende structure, which looks like the diamond lattice except that the group III atoms occupy only the sites on one of the interpenetrating cubes, while the group V atoms occupy the sites of the other cube.

Plane indices

The various planes that pass through a crystal are described in terms of the reciprocals of intercepts of that plane with the crystallographic axes. In the case of cubic crystals the three axes are mutually perpendicular and oriented parallel with the edges of the unit cell. The intercept reciprocals are expressed as the smallest possible integers having the same ratio, and for crystal systems with three axes, the indices for a single plane are written as $(hk\ell)$. These are referred to as Miller indices, after William H. Miller, a nineteenth-century British mineralogist. Since the reciprocals of the intercepts of all planes are reduced to ratios of the smallest possible integers, all parallel planes have the same indices. For the hexagonal crystal system, in which there are three coplanar axes as well as one perpendicular to the plane of the first three, the indices are $(hki\ell)$; h, k, and i are related through $h + k = -i$, so that again, only three indices are actually needed. To indicate a hexagonal system, the terminology $hk{:}\ell$ is often used. A complete

TABLE 1.3   Crystal Symmetry of Some Common Semiconductors

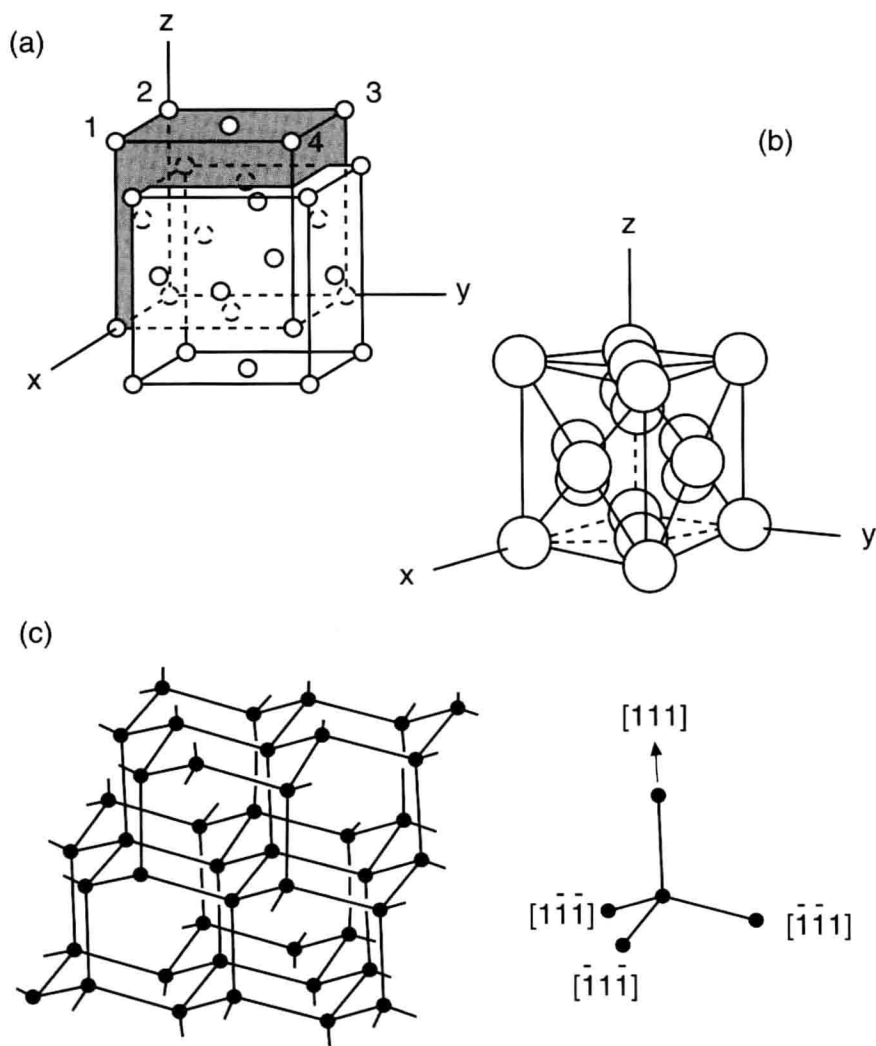|		
Cadmium sulfide	Hexagonal	a = 4.1368 Å, c = 6.7163 Å
Gallium arsenide	Cubic zinc blende	a = 5.6534 Å
Germanium	Diamond	a = 5.257 Å
Gray selenium	Hexagonal	a = 4.36 Å, c = 4.96 Å
Indium antimonide	Zinc blende	a = 6.48 Å
Lead sulfide	Cubic	a = 5.9 Å
Silicon	Diamond	a = 5.43073 Å
Silicon carbide	Diamond; hexagonal	a = 4.3596 Å; a = 3.0806 Å, c = multiples of 2.52 Å

(a)

(b)

(c)

Figure 1.1 (a) View of diamond lattice showing position of two interpenetrating face centered cubes. (b) Isometric view of diamond lattice. (c) Direction of atomic bonds in the diamond lattice. (b) Adapted from R. G. W. Wyckoff, 1960. *Crystal structures,* New York: Interscience Publishers. (c) Adapted from J. Hornstra, 1958. *J. Phys. Chem. Solids* 5: 129–141.

family of planes, resulting from permuting a given set of indices (including negative values) is denoted by braces; e.g., {111} represents the eight planes (111), ($\bar{1}$11), (1$\bar{1}$1), (11$\bar{1}$), ($\bar{1}\bar{1}$1), ($\bar{1}$1$\bar{1}$), (1$\bar{1}\bar{1}$), and ($\bar{1}\bar{1}\bar{1}$). The bar over an index number indicates a negative value.

Crystallographic directions

Directions are vectors, and if the vector goes from zero to the point $x = a$, $y = b$, $z = c$, then the direction coordinates are $[abc]$. The smallest set of integers $[hk\ell]$ having the ratio of $a:b:c$ are referred to as crystallographic directions, and like planes, all parallel directions have the same indices. For the cubic system, an $[hk\ell]$ direction is perpendicular to an $(hk\ell)$ plane. A complete family of directions is written as $\langle hk\ell \rangle$.

Relative position of planes

Examples of the position of various low-index planes in the cubic and hexagonal systems are shown in Figure 1.2. Probably the easiest way to visualize the positions of the various planes is by means of a model. Figure 1.3 is a photograph and a pattern for a very convenient paper model for cubic crystals. The pattern has been reduced for publication and should be enlarged to simplify actual model construction. The model shape is not a standard crystallographic form but rather is comprised solely of the complete sets of {100}, {110}, and {111} planes. Sometimes in older crystallographic literature a direction may be given, not

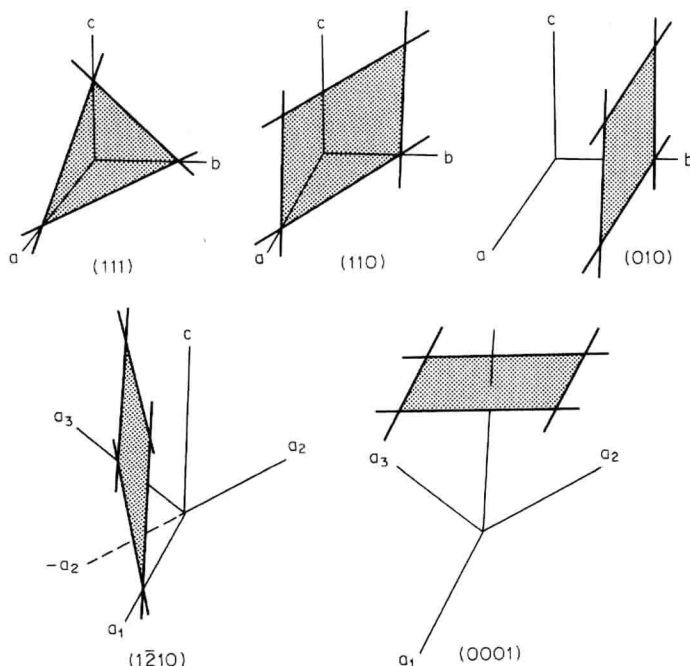**Figure 1.2** Examples of low-index planes.