CHAPTER 1

AN INTRODUCTION TO CLUSTER SECONDARY ION MASS SPECTROMETRY (CLUSTER SIMS)*†‡

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Cluster secondary ion mass spectrometry (SIMS) has had a significant impact on the mass spectrometry and surface analysis communities over the past two decades, with its newfound ability to characterize surface and in-depth compositions of molecular species with minimal damage, excellent spatial (100 nm or less) and depth (5 nm) resolutions, and increased sensitivities for bioimaging applications. With the continual development of new cluster ion beam technologies, we are breaking down barriers once thought to be unbreakable, and entering into new fields once labeled as out of reach. Instrument designs are now advancing to account for these new applications, allowing for further improvements in molecular sensitivities, selectivities, and even high throughput analysis. Although we are

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only at the beginning of the growth curve toward low damage molecular SIMS, we have come a long way over the past few years, and significant discoveries have been made. This book addresses these new discoveries and describes practical approaches to SIMS analysis of samples using cluster sources, with a focus on soft sample analysis.

1.1 SECONDARY ION MASS SPECTROMETRY IN A NUTSHELL

Before we discuss cluster beam technology, it is appropriate to first review the basics of SIMS. SIMS is a mass spectrometric-based analytical technique, which is used to obtain information about the molecular, elemental, and isotopic composition of a surface. In a conventional SIMS experiment, an energetic primary ion beam, such as Ga^+, Cs^+, or Ar^+ is focused onto a solid sample surface under ultra high vacuum conditions (Fig. 1.1). The interaction of the primary ion beam with the sample results in the sputtering and desorption of secondary ions from the surface of the material. These secondary ions are subsequently extracted into a mass analyzer, resulting in the creation of a mass spectrum that is characteristic of the analyzed surface (Fig. 1.2a), and yielding elemental, isotopic, and molecular information simultaneously, with sensitivities in the parts per million (ppm) to parts per billion (ppb) range. There are three basic types of SIMS instruments that are used most commonly in the field, each employing a different mass analyzer:

1. *Time-of-Flight Secondary Ion Mass Spectrometers (ToF-SIMS).* These spectrometers extract the secondary ions into a field-free drift tube, where the ions are allowed to travel along a known flight path to the detector. As the velocity of a given ion is inversely proportional to its mass, its flight time will vary accordingly, and heavier ions will arrive at the detector later than lighter ions. This type of mass spectrometer allows for simultaneous detection of all secondary ions of a given polarity and has excellent mass resolution. Moreover, because the design utilizes a pulsed ion beam operated at extremely low

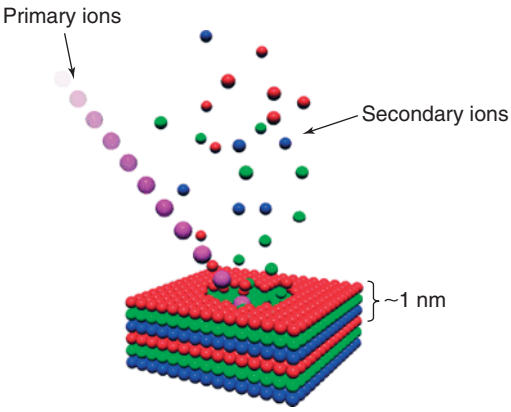

Figure 1.1 Illustration of the sputtering process in secondary ion mass spectrometry (SIMS).

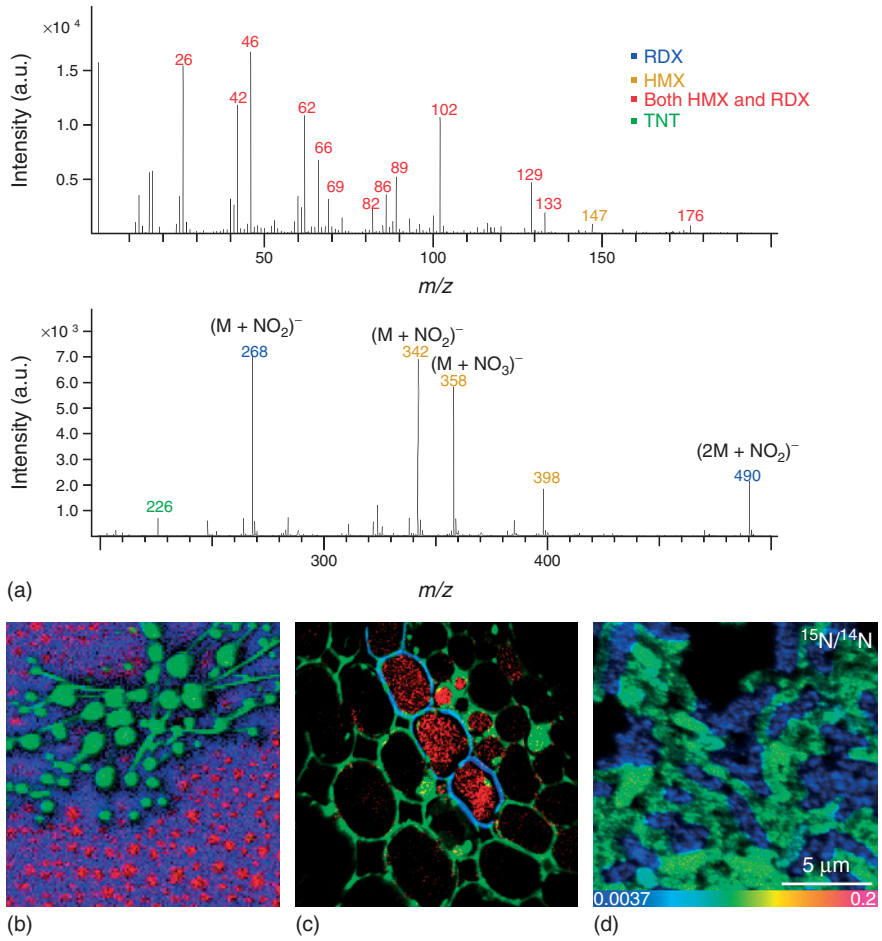

Figure 1.2 (a) Example of negative ion mass spectral data acquired from a sample of composition-4 (C-4) plastic explosive, comprised of poly(isobutylene), RDX explosives, di-isooctylsebacate, and other additives. (b) Example of negative ion molecular imaging (200 × 200 µm) in Semtex plastic explosive, based on RDX explosive, PETN explosive, poly(styrene-*co*-butadiene), and other additives; green = PETN explosive molecules (*m*/*z* 376), red = binder and oils (*m*/*z* 25), and blue = SiO_2^- (*m*/*z* 60) from the Si substrate. (c) Example of positive ion *elemental* mapping of trace elements in plant roots; green = CN^- (*m*/*z* 26), blue = Si_2^- (*m*/*z* 28), and red = As (*m*/*s* 75).[3] (d) Isotopic imaging of bacteria grown in ^{15}N culture medium. Green regions indicate ^{15}N-enriched bacteria, while blue regions indicate more natural isotopic abundances. Hence, the bacteria in the blue regions are not as metabolically active as the green regions.[4] Figure 1.2c and d recreated from Moore et al.[3] and Kilburn,[4] respectively, with permission from the American Society for Plant Biology and the University of Western Australia.

currents (picoampere range), this mass spectrometer is useful for analysis of surfaces, insulators, and soft materials, which may be prone to ion-induced chemical damage.

2. *Magnetic Sector SIMS instruments*. Magnetic sector SIMS instruments typically use a combination of electrostatic and magnetic sector analyzers for velocity and mass analysis of the sputtered secondary ions. The use of a magnetic field to deflect the ion beam causes lighter ions to be deflected more than the heavier ions, which have a greater momentum. Thus, the ions of differing mass will physically separate into distinct beams. An electrostatic field is also applied to the secondary beam in order to remove any chromatic aberrations. Because of the higher operating currents and continuous beams, these instruments are very useful for depth profiling. However, they are not as ideal for surface analysis and characterization of samples that will charge and/or damage readily.
3. *Quadrupole SIMS Instruments*. These instruments are becoming increasingly rare because of the relatively limited mass resolution attributed to them (unit mass resolution—unable to resolve more than one peak per nominal mass). The quadrupole utilizes a resonating electric field, where only ions with selected masses have stable trajectories through a given oscillating field. Similar to the magnetic sector instruments, these instruments are operated under high primary ion currents and are generally thought of as "dynamic SIMS" instruments (i.e., used for sputter depth profiling and/or bulk analysis of solid samples).

Although these designs are most commonly observed in the SIMS community at present, there are many new exciting designs emerging, which may play a more prominent role in the future.[1,2] These new designs include continuous ion beam designs with multiple mass spectrometers (e.g., quadrupole/ToF for MS-MS analysis) and even a Fourier transform ion cyclotron resonance (FT-ICR) instrument, with mass resolutions approaching 1 million or greater. These new designs will be briefly introduced in Chapters 4 and 8.

1.1.1 SIMS Imaging

In all SIMS instruments, mass spectrometric imaging can be achieved by focusing and rastering the ion beam over a selected area or by using secondary ion optical focusing elements (in the case of magnetic sector instruments), where the secondary ion intensity for a given mass-to-charge ratio (m/z) is monitored as a function of position on the sample. Examples of molecular, elemental, and isotopic mapping of components on surfaces are given in Figure 1.2b–d.[3,4]

1.1.2 SIMS Depth Profiling

SIMS can be utilized for both surface analysis (at low primary ion doses) and in-depth analysis (at high primary ion doses). An example of SIMS depth profiling is shown in Figure 1.3, which depicts the elemental intensities of Cr, Ni, and C,

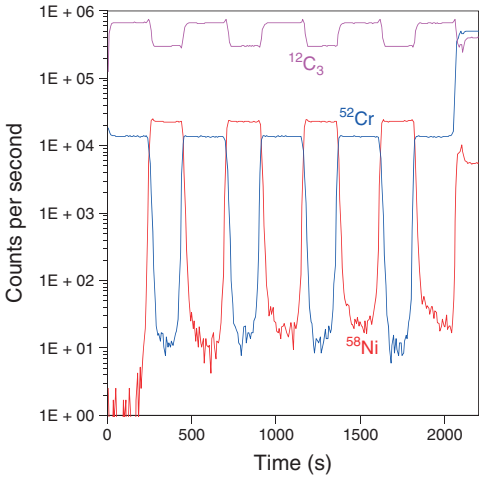

Figure 1.3 Example of SIMS depth profiling in Cr/Ni thin films. Data acquired from NIST SRM 2135a, containing nine alternating layers of Cr and Ni on silicon with nominal layer widths of 53 and 66 nm, respectively.

plotted as a function on increasing primary ion sputtering time in a sample containing Ni/Cr alternating layers. Each Ni and Cr layer is readily observed using SIMS depth profiling, as indicated by the inversely alternating Cr and Ni intensities.

Unlike inorganic samples, organic, polymeric, and biological materials have historically required the use of "static SIMS" analysis conditions, where the primary ion fluence is maintained at or below a critical dose in order to retain the surface in an undamaged state. This critical dose is defined as the "static limit," and is often reported to be at or less than 1×10^{13} ions/cm^2, depending on the sample and the ion beam employed. Unfortunately, this limitation results in decreased sensitivity and precludes compositional depth profiling in soft materials. One potential solution to this limitation is to use cluster or polyatomic primary ion beams (such as C_{60}^+, SF_5^+, or Ar_{700}^+) in place of atomic sources in order to extend the characterization of these samples beyond the static limit.

1.2 BASIC CLUSTER SIMS THEORY

When a cluster ion impacts a surface, the cluster breaks apart and each atom in the cluster retains only a fraction of the initial energy of the ion as described in the relationship shown below in Equation 1.1 (where E_c is the final energy of a constituent atom after collision with the surface, E_0 is the energy of the polyatomic ion before impact, M_c is the mass of the constituent, and M_t is the total mass of the polyatomic ion).[5]

$$E_c = E_0 \left(\frac{M_c}{M_t} \right) \tag{1.1}$$

Since the penetration depth of the ion is proportional to the impact energy of the ion, cluster ion bombardment results in a significant reduction in penetration depth of the ion. This causes surface-localized damage and consequently, preserves

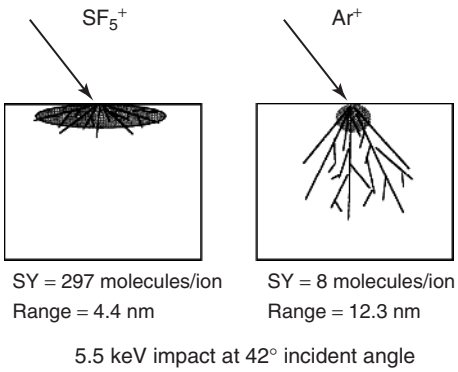

Figure 1.4 Graphic illustration suggesting how the high sputter yields and low penetration depths observed with polyatomic ion bombardment may reduce the accumulation of beam-induced damage in an organic thin film. The actual SRIM calculations are indicated below each illustration, where SY represents the calculated sputter yield in a PMMA sample, and the range represents the depth of the projectile into the PMMA sample. Reproduced from Gillen and Roberson[1] with permission from Wiley.

the chemical structure in the subsurface region (Fig. 1.4).[5] Similar energy atomic beams, however, will penetrate deeply, resulting in the breaking of molecular bonds deep into the sample and thus precluding the ability to depth profile in molecular samples. Furthermore, because there are more atoms bombarding the sample simultaneously with cluster ions, the sputtering yield can be significantly enhanced. This is in part because of the increased number of atoms per ion, but is also a result of the formation of a high energy density "collisional spike" regime that is formed with cluster ion bombardment, causing nonlinear sputtering yield enhancements (i.e., sputtering yield of $C_n^+ \gg nC^+$).[6]

1.3 CLUSTER SIMS: AN EARLY HISTORY

1.3.1 Nonlinear Sputter Yield Enhancements

The benefits of utilizing polyatomic ions for sputtering was shown as early as 1960, with the observation of nonlinear enhancements in sputtering yields when using polyatomic ions as opposed to atomic ions.[7–10] An example of this nonlinear sputtering effect can be seen in Figure 1.5, which compares the sputtering yield per incoming atom when employing Te^+ ions as compared to Te_2^+ ions under an identical E_c (Eq. 1.1).[9] It can be seen from Figure 1.5, that the sputtering yield resultant from one Te_2^+ diatomic ion is greater than the combined sputtering yield from two Te^+ atomic ions of similar E_c.

Although these nonlinear effects were observed much earlier, the benefits of cluster sources (where cluster is defined here as an ion with more than two atoms) for SIMS applications were not realized until the mid to late 1980s. One of the earliest works was published in 1982, in which the authors compared the performance

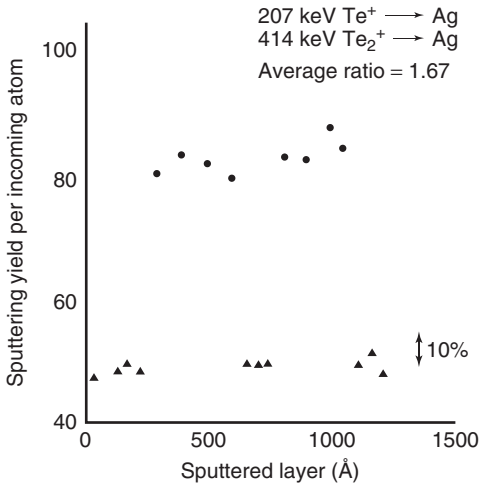

Figure 1.5 Sputtering yield per atom of a polycrystalline silver target using 207 keV Te^+ and 414 keV Te_2^+ ion bombardment as a function of sputtered layer thickness. Nonlinear effects are clearly observed. Reproduced from Anderson and Bay[9] with permission from the American Institute of Physics.

of siloxane molecular ions to Hg^+ ions for characterization of oligosaccharides in a glycerol matrix.[11] The results showed a large increase in the ionization of the organic molecules when employing the siloxane cluster source as compared to the atomic Hg^+ ion source.

Later, Appelhans et al. used SF_6 neutral beams to characterize electrically insulating polymer samples such as polytetrafluoroethylene (PTFE), poly(ethylene terephthalate) (PET), poly(methyl methacrylate) (PMMA), and polyphosphazene, where the authors found that the SF_6 cluster beam yielded 3–4 orders of magnitude more intense secondary ion yields from these polymer samples than equivalent energy atomic beams.[12–14] Similar findings were found in the mass spectra of pharmaceutical compounds.[13]

1.3.2 Molecular Depth Profiling

Another unique feature of cluster ion beams as compared to their atomic ion beam counterparts is their ability to retain molecular information as a function of depth in soft materials. The combination of increased sputter yields along with decreased subsurface damage has enabled the SIMS analyst to characterize compositions as a function of depth in organic materials for the first time; a process now referred to as *molecular depth profiling*. Cornett et al. were among the first to demonstrate the feasibility of molecular depth profiling with cluster ion beams, when they discovered that continued bombardment of protein samples with massive glycerol cluster ions yielded constant molecular secondary ion signals with increasing ion fluence, while the same samples irradiated with Xe^+ ions yielded the characteristic rapid signal decay that is commonly associated with atomic beams.[15]

An example of molecular depth profiling is demonstrated in Figure 1.6, which shows an early attempt at depth profiling in a thin glutamate film (180 nm) vapor

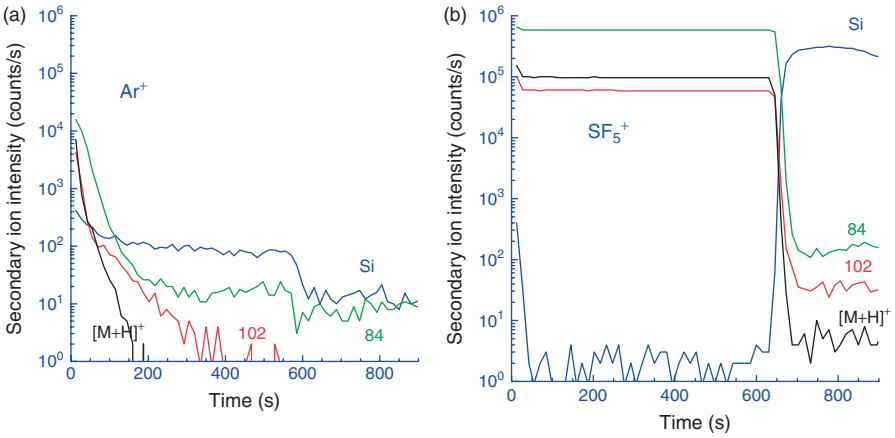

Figure 1.6 Comparison of depth profiles obtained from a 180 nm vapor-deposited glutamate film using (a) Ar^+ and (b) $SF_5{}^+$ primary ions under dynamic SIMS conditions. The $SF_5{}^+$ primary ion dose required to reach the silicon was 2.4×10^{15} ions/cm^2. Reproduced from Gillen and Roberson[1] with permission from Wiley.

deposited onto a Si substrate.[5] In this example, glutamate molecular ion signal intensities $[M + H]^+$, and fragment ion intensities (*m/z* 84 and *m/z* 102) are measured as a function of sputtering time, using both Ar^+ (Fig. 1.6a) and $SF_5{}^+$ polyatomic primary ions (Fig. 1.6b). Si^+ ion intensities (*m/z* 28) were also measured as a function of sputtering time in both examples. When employing the Ar^+ monatomic ions, the molecular signals decay rapidly, as is characteristic of atomic ion bombardment in molecular films. However, when employing polyatomic primary ion sources, the molecular ion and fragment ion intensities of the glutamate remain constant throughout the entire depth of the film. In addition, while the $SF_5{}^+$ source was able to profile through the entire film in the 900 s sputter time interval, as indicated by the decreasing molecular ion signal intensities with commensurate increases in the Si, the Ar^+ was unable to sputter through the material during the allotted time interval.

1.4 RECENT DEVELOPMENTS

Since the advent of cluster SIMS, there has been an abundance of work on surface and in-depth characterization of soft materials ranging from simple molecular films and polymers[16,17] to complex biological systems.[2] Cluster primary ion sources such as $C_{60}{}^+$, $Au_3{}^+$, $SF_5{}^+$, $Bi_3{}^+$, and $Ar_{(x>500)}{}^{n+1}$ have resulted in significant improvements (typically >1000-fold) in characteristic molecular secondary ion yields and decreased beam-induced damage. Furthermore, most of these sources have allowed for molecular depth profiling in samples; a feat that was unheard of with previously employed monatomic ion beam sources. With these new cluster sources, beam damage limitations have all but been removed for depth profiling in most organic

and polymeric materials. With the increased sensitivity, nanoscale depth resolution (<5 nm), and submicrometer lateral resolution, cluster SIMS is a promising new characterization tool enabling high resolution three-dimensional imaging capabilities for organic and polymeric-based materials (Fig. 1.7 and Fig. 1.8).[16,18]

1.5 ABOUT THIS BOOK

This book will serve as a compendium of knowledge on the topic of cluster SIMS. In this book, in-depth discussions on the various aspects of cluster SIMS and its applications will be presented—from the details of cluster SIMS theory and erosion dynamics, to experimental parameters for optimum depth profiling in molecular samples.

Theoretical discussions regarding cluster ion beam interactions with organic materials will be discussed in Chapter 2, where important aspects of molecular dynamics simulations will be reviewed. This chapter will review the current state of the literature in this field, as well as help one to obtain a better understanding of the physics of cluster ion bombardment in organic, polymeric, and biological samples.

Chapter 3 presents a detailed overview of the myriad of sources that are available, for SIMS, cluster ion beams, or otherwise. This chapter will provide

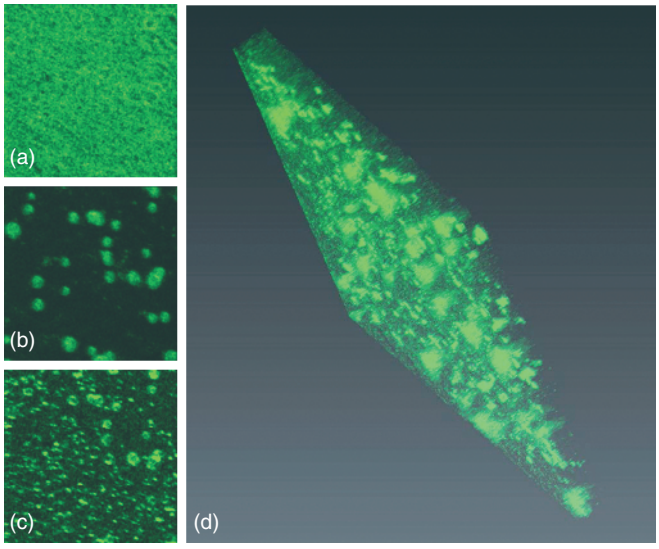

Figure 1.7 Positive secondary ion image maps (100 × 100 μm) of characteristic tetracycline signal (*m*/*z* 59) in a PLGA film, acquired using an SF_5^+ sputtering source in conjunction with a Bi_3^+ analysis source. (a) No sputtering, (b) 15 s sputtering with SF_5^+ (~75 nm depth), (c) 75 s sputtering with SF_5^+ (~375 nm depth), and (d) 3D volumetric representation of tetracycline signal (*m*/*z* 59) in PLGA film (acquired from approximately the top 2 μm) containing 15% tetracycline; 5 keV SF_5^+ beam energy, operated at 4 nA continuous current and a 500 × 500 μm raster.

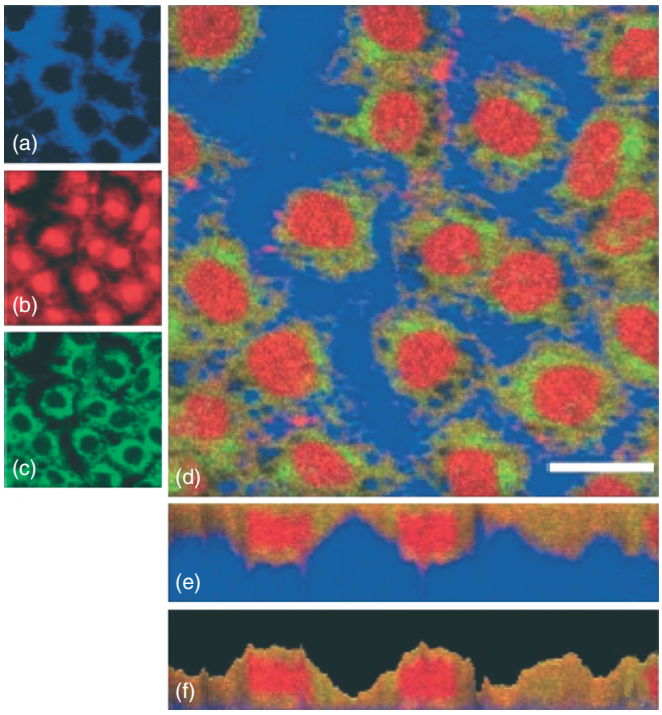

Figure 1.8 (a–d) Two-dimensional (2D) images of NRK cells after the forty-fifth sputter cycle. Summed signals of amino acid fragment ions are represented in red (b), those of phospholipids in green (c), and substrate-derived secondary ions are depicted in blue (a). (d) An overlay of the three images. The scale bar in (d) corresponds to 20 µm. (e) and (f) Vertical *xz* sections through the sample. Data acquired using C_{60}^+ sputtering in conjunction with Bi_3^+ analysis. Reproduced from Breitenstein et al.[18] with permission from Wiley.

information about how these various sources function, what they are used for, and the benefits and disadvantages of each.

Chapters 4 and 5 will provide a comprehensive review of the literature regarding the surface characterization and in-depth analysis of soft materials with cluster SIMS. Chapter 4 will describe the important aspects that need to be considered during any static SIMS experiment employing cluster sources (i.e., the best source, the experimental conditions, etc.). A similar approach will be taken in Chapter 5, which will provide a summary of molecular depth profiling. Both the physics and the chemistry of cluster ion bombardment will be discussed in detail, with the introduction of erosion dynamics theory and a brief description of ion beam irradiation chemistries.

Three-dimensional imaging in soft materials is the ultimate goal in molecular depth profiling. This topic will be introduced in Chapter 6, which will serve as both a review of the literature, and a tutorial for 3D imaging. There are, in particular, many important considerations and corrections that are required in order to obtain accurate representations of 3D SIMS image data. Many of these considerations

will be discussed here. Furthermore, this chapter serves as a guide for practical molecular depth profiling and analysis with cluster ion beams, discussing how one should make precise and accurate measurements of depth resolution, damage cross sections and efficiencies, beam conditions, and sputtering rates. The authors will discuss these measurements and more; defining the rules for different scenarios (i.e., organic/organic layers vs organic/inorganic layers), and identifying how and what should be reported in each of these scenarios.

Chapters 7 and 8 will discuss special applications of cluster SIMS for characterization of inorganic materials and biological materials, respectively. Chapter 8 will discuss in detail, the special case of biological samples. Biological materials and cells are particularly challenging and complex, and therefore need special consideration. This chapter will help the reader to better understand the successes and challenges for surface characterization and in-depth analysis of biological samples, and will serve as a detailed review of the field, displaying brilliant 3D molecular images in cells and other biological samples. Finally, all these discussions are wrapped up in Chapter 9, which briefly gives a perspective on what the future holds for the technique of cluster SIMS.

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