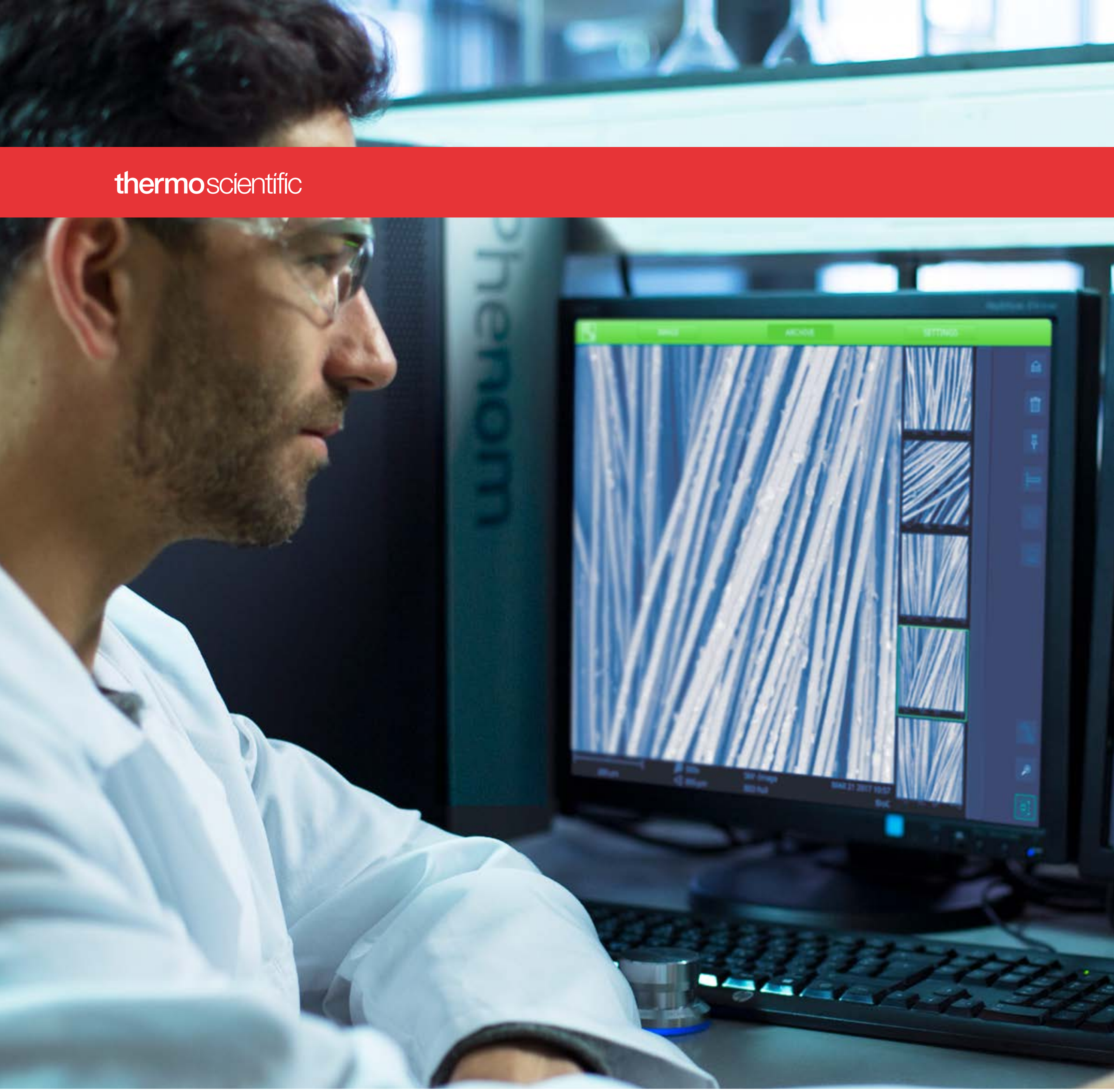

Scanning Electron Microscopy Working Principle

Nearly everything you need to know about SEM

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CHAPTER 1

The evolution of microscopic analysis: from light microscopes to electron microscopy

Biology, geology, physics, medicine, material science, etcetera—in almost every branch of science microscopes play a major role in a scientist's daily work. A large number of areas make use of different types of microscopes and related technology: from X-ray microscopy, optical microscopy, scanning probe microscopy to scanning acoustic microscopy.

Among these different techniques, electron microscopy is one of the most widely applied methods since it provides impressively high magnification and, at the same time, a relatively high throughput.

It is with an exploratory sense of curiosity that scientists from an earlier generation wondered about the micro-cosmos: the tiniest particles of the world, cells—the smallest units of life—and all the accompanying minute items inaccessible to the naked eye. Eventually, with the invention of light microscopy, scholars started exploring the world from a different resolution level. Hundreds of years afterward, researchers cannot imagine doing their job without devices that magnify objects many hundred and even many thousands of times.

In this whitepaper, you will be able to learn the essentials about microscopy with a focus on electron microscopy:

- What are the different types of microscopes available?
- What is electron microscopy?
- What is the difference between scanning electron microscopy (SEM) and transmission electron microscopy (TEM)?
- How can you choose a microscope that best fits your research process?

CHAPTER 2

Challenges in microscopic analysis

Although the use of microscopy has brought researchers many benefits, challenges persist in optimizing and enhancing their analyses in order to obtain a high-quality outcome.

1 **A large or multi-sample analysis**

Microscopes are often designed for the analysis of only one, small sample. Needless to say, this is a problem when many of them have to be examined. In some research fields, for example when performing a quality control on additive manufacturing powder, hundreds or even thousands of copies must be viewed. Obviously, in this case, the faster it happens the better for the user. Very often, analyzing one sample after another is not an option since it would simply take too much time.

Another challenge involves the viewing of large objects. The majority of the microscopes provide only a limited amount of space. Therefore, the ability to examine a specimen that exceeds a certain size is restricted.

2 **Quality management in imaging sciences**

In many cases, the primary goal of researchers is to acquire as much information about a sample as possible. Hence, a standard procedure is to obtain the sharpest and highest-resolution image possible. Scientists, therefore, continuously look for the next best thing that will provide them with more insights.

3 **Performing analyses more efficiently**

The capacity to draw the right conclusions from an analysis remains a primary goal. However, in addition to that researchers are often required to work as fast and as efficiently as possible. To do so, new and innovative equipment is needed, which takes over part of the researcher's work and optimizes the research process.

4 **Performing analyses in one's own working environment**

Not all scientists have a fully-equipped laboratory at their disposal. For that reason, many researchers seek the ability to perform analyses in common work environments.

CHAPTER 3

What microscope best suits your analysis? Different microscope types explained

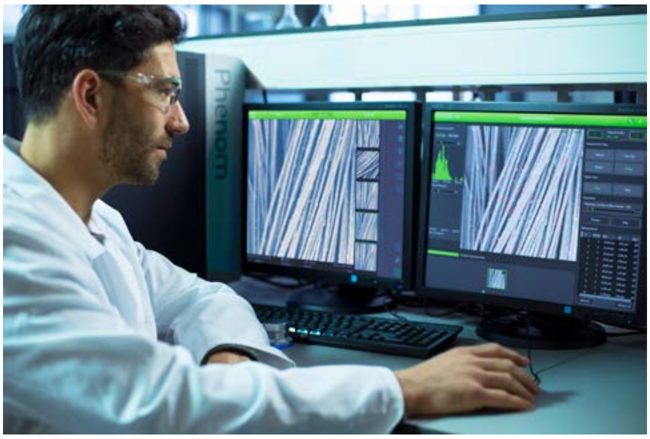
In general, almost all microscopes can be divided into three basic types: optical, charged particle or scanning probe. In order to understand which model best fits your research process, it is essential to understand the exact difference between them.

Optical microscopy

The optical microscope is the most popular and commonly seen type in use. In optical microscopy, visible light and transparent lenses are used to see objects down to a size of about half a micrometer. This makes it possible to examine, for example, tiny animals such as insects and even single cells.

Scanning probe microscopy

Scanning probe microscopy maps interactions that occur between the probe and the sample. For this, the method uses a very sharp needle, which scans the specimen. During the process, it comes into contact or near-contact with the sample surface. On the basis of interacting forces between tip and atoms on the surface, this technique creates atomic scale resolution images.



Electron microscopy

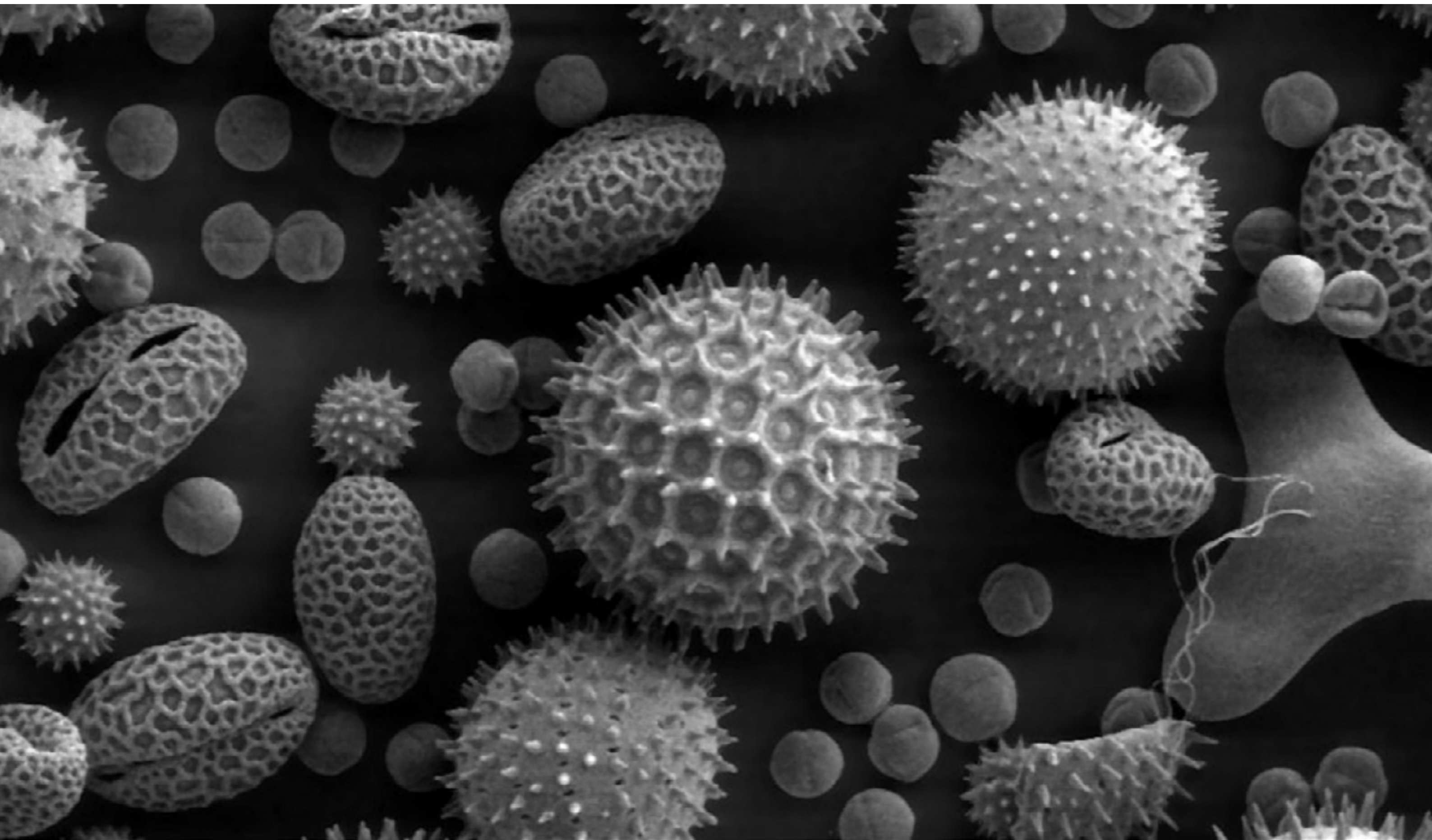
In the 1920s, researchers found out that an electron beam in vacuum behaves much like light does: electrons also exhibit wave-like properties—however, with a wavelength that is about 100,000 times shorter than that of visible light. The discovery led to the invention of electron microscopy. Electrostatic lenses are used to precisely focus either electrons or ions into a sharp beam, which scans the surface. An electron or ion microscope allows for displaying features as small as 0.05 nanometers, which is 4,000 times better than a typical light microscope.

CHAPTER 4

Electron microscopy

The first electron microscope was built in 1931 and has been improved ever since. The technique makes use of the interactions between electrons and the atoms composing the analyzed sample. An electrical voltage accelerates the electrons emitted by the source and magnetic lenses direct them towards the sample. Collisions with gas molecules disturb the signal, hence, the whole set-up, notably the electron source and the sample holder, are sealed inside a special chamber to preserve vacuum. Moreover, the chamber shields against contamination, vibration or noise.

Depending on the texture and composition of the sample, electrons interact differently with it. Using the information contained in the reflected, scattered, transmitted or even newly-generated electrons, high magnification images can be generated. The resolving power of modern electron microscopes can be significantly below one nanometer reaching the atomic level. Hence, the method is mainly applied for displaying objects or structures that cannot be viewed by classical light microscopes.



Transmission electron microscopy (TEM)

In TEM the accelerated electrons pass through the specimen. The transmitted ones then become focused as an enlarged image onto a fluorescent screen, which emits light when struck by these charged particles. TEM can show several characteristics of the sample, such as morphology, crystallization, stress or even magnetic domains. The resolution of state-of-the-art TEMs can be even below 0.05 nanometers. In order for electrons to travel through the specimen, it has to be very thin, often less than one hundred nanometers. In some cases, this means a major challenge that could completely prevent the application of the TEM.

Scanning electron microscopy (SEM)

In SEM, the electron beam scans the sample in a raster-pattern. Instead of passing through the specimen, electrons get reflected on the surface or even ionize atoms within the sample by liberating electrons. These so-called secondary electrons, as well as the backscattered electrons, can serve as signal to build up the final image. SEM images represent the morphology of a sample and can also reconstruct quasi-three-dimensional views of the sample surface. Therefore, the technique is basically used to obtain a high-resolution picture of surface features and allows conclusions about the distribution of different chemical elements within the sample. Modern SEMs can reach a resolving power better than one nanometer.

CHAPTER 5

Synopsis: the similarities and differences between SEM and TEM

Although both microscopes use electrons instead of light in order to acquire a higher image resolution, the techniques differ in detail.

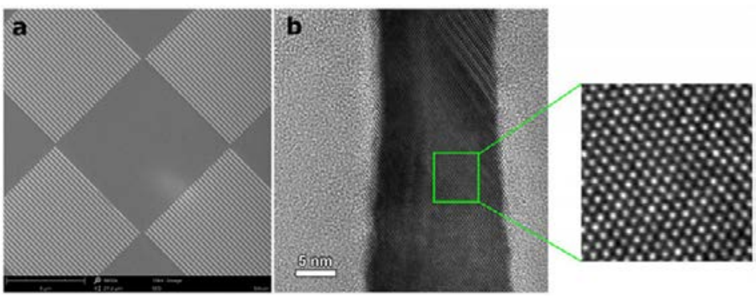
What are the similarities?

Both SEM and TEM have in common some major components:

- An electron source
- Several electromagnetic and electrostatic lenses to control the shape and trajectory of the electron beam
- Electron apertures
- A sample chamber which is put under high-vacuum

What are the differences?

- Whereas SEM gives information about the surface of the analyzed object, TEM allows information to be obtained about the inner structure of the sample.
- TEM exhibits a better resolution than SEM.
- Compared to SEM, TEM has tighter requirements in terms of sample preparation and analysis conditions.



Electron microscopy images of silicon. a) SEM image with SED offers information on the morphology of the surface, while b) TEM image reveals structural information about the inner sample.

CHAPTER 6

Overview: scanning electron microscopy (SEM)

Since the introduction of electron microscopes in the 1930s, SEM has developed into a very powerful tool within several different research fields—from material science to forensics, from industrial manufacturing to life sciences. The main reason for this growth in popularity can be attributed to the continuous shrinking of the dimension of materials used in many applications.

But how exactly does an SEM work and what do you need to know about this technology? Below, we answer the most commonly asked questions about SEM.

What is SEM?

An SEM is a type of electron microscope that uses an electron beam to scan the sample. The electrons that are backscattered, as well as the ones that are knocked off the near-surface region of the object, are detected and used to create high-resolution images.

How does it work?

An electron source—also referred to as an electron gun—emits electrons that get accelerated by an applied voltage. Magnetic lenses converge the stream of electrons into a focused beam, which then hits the sample surface in a fine, precise spot. The electron beam then scans the surface of the specimen in a rectangular raster.

The user can increase the magnification by reducing the size of the scanned area on the specimen. Detectors collect the backscattered and secondary electrons (SE). The corresponding signals are measured and the values are mapped as variations in brightness on the image display. The secondary electrons are more frequently used as read-out signal. They highlight the topography of the sample surface: bright areas represent edges while dark regions represent recesses.
light microscopes.

For what purposes and specimen can SEM be applied?

As soon as microscopic information about the surface or near-surface region of a certain specimen is needed, SEM becomes a necessary tool. For that reason, the method finds applications in nearly every branch of science, technology and industry. The only clear challenge is that the viewed object should withstand the vacuum within the chamber and the bombardment by the electrons.

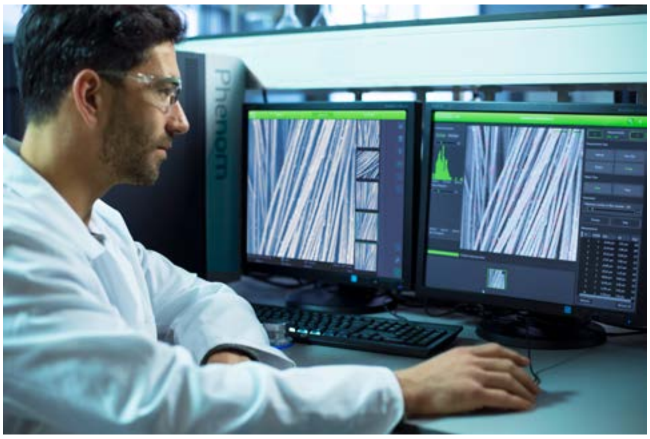
Sample preparation

Most specimens do not need any preparation and can be directly placed into the chamber. However, if a sample contains volatile components such as water, this has to be removed beforehand. Otherwise the water would evaporate very rapidly in the evacuated environment. This would change the appearance of the specimen or even damage it. That is why a drying process of the sample, commonly referred to as fixation, must be applied in order to exchange the liquid by a polymer. Prepared in this way, the specimen can now be imaged under vacuum.

Non-conducting specimens accumulate charge under electron bombardment. An electron beam though, cannot scan a charged object. On this account, samples need to be coated with a conducting layer before being analyzed with the SEM. Platinum gives a fine-grained coating and can easily be applied by a device called a sputter coater. By applying this procedure, non-conducting samples can also be imaged with SEM and good quality pictures of the surface can be obtained especially via the SE-detector.

Who can profit from scanning electron microscopes?

Generally, SEM technology can provide valuable benefits for research in various markets and industries.



Materials Science

The interdisciplinary field of material science focuses on the diverse properties of matter and their potential applications in sciences as well as in engineering. For that, a thorough analysis of the material is crucial. In so doing, engineers and material scientists are able to create novel materials with desired properties.

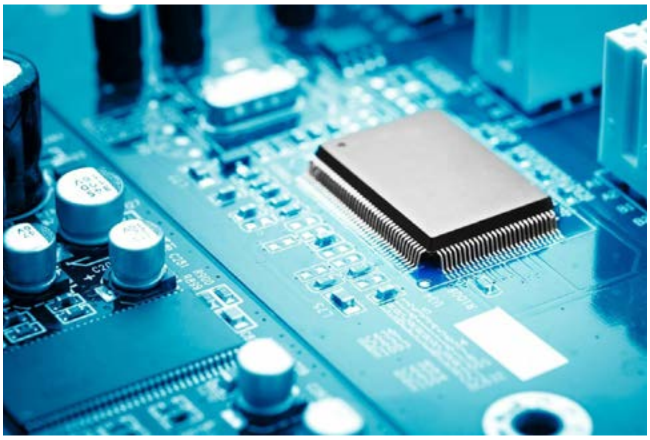
A scanning electron microscope can help them to observe and analyze material surfaces and interfaces, either for quality insurance purposes during production or for the analysis of compounds after processing. In short, the possibilities are almost endless.

Life Sciences

Life scientists, amongst others covering the fields of biotechnology and medical science, use many different microscopes to analyze cells, microbiology, food, cosmetics or blood. SEM is almost indispensable in their daily work since it combines high-resolution imaging with a high sample throughput. Additionally, new innovative SEM techniques have opened up a whole new range of opportunities to image biological samples with unprecedented accuracy.

Earth sciences

SEMs can help geologists and geophysicists to investigate the macro, micro, and nanostructure of our planet. Understanding the composition and texture of materials is a major component of studying the earth and its physical constitution.



Electronics

In electronics, it is all about innovation. In order to keep up with consumer demands and to keep ahead of competitors, electronic manufacturers have to produce ever-shrinking features. Finding the right balance between performance and time-to-market can be a challenge. Scanning electron microscopes can support manufacturers research and quality control departments, increase efficiency and stimulate innovation.

Industrial manufacturing

Consumer expectations are sky-high, and it is up to the industrial manufacturers to meet these. Therefore, engineers and scientists have to understand their products at all levels. SEM helps them to acquire microscopic details of the whole product. Having direct access to high-resolution imaging and analyses can, for example, support them to make their products safer, longer-lasting, stronger or in some cases lighter.

Forensics

Evidence is the crucial part in crime investigation. Microscopic clues can be obtained from materials such as particles, fabrics, metals, textiles or glass. In this context, an SEM can be of great value for forensic investigators—for example to identify scratches and indents on objects or gunshot residue particles.

CHAPTER 7

A summary of the important characteristics of SEM and tips on how to choose the right model

Finding the right type of SEM for your research can be difficult. There are many characteristics to which you need to pay attention. The majority of the factors depend on your specific research and the samples you want to image and analyze. In this context, several components, parameters and settings of the SEM influence the results of the analysis. In order to guide you in the process of choosing an SEM model, we highlight the important aspects to be considered:

Resolution

In physics, resolution is defined as the minimum distance between two objects that still allows the observer to distinguish them as separate entities. Therefore, this parameter is one of the main characteristics of microscopes in general. Users should remember the following rule of thumb: The resolution of the microscope should be 5 to 10 times lower than the size of the feature you want to resolve. That means for example: if you want to image structures with an average size of 50–100 nanometers an SEM with a resolution of 10 nanometers provides good results. Smaller features will look blurry and would require a more sophisticated device in order to be resolved. The resolution of modern SEMs can fall somewhere between less than 1 and 20 nanometers.

Magnification

The microscopic magnification describes the measure of the apparent increase in size of a viewed image or object. Even if this parameter seems kind of similar to the resolution, it is not the same. The statement “the microscope has a magnification of 1000 times” does not specify how sharp the image eventually is. Therefore, it is important to distinguish between magnification and resolution. Under ideal conditions high-end SEMs can magnify up to one million times.

When operating an SEM, the user increases the magnification by decreasing the scanned area. The required field of view for your sample imaging depends on the purpose of your analysis. For example: you image closely packed particles with an average size of one micrometer and you simply want to count them. Then you magnify only until that point at which you can distinguish single particles from each other. This means you can have several hundreds or even more particles in one image. On the other hand, if the purpose of your research lies in the analysis of the structure of a particle, you must, of course, zoom in further.

The electron source

The purpose of the electron source is to provide a stable beam of electrons. There are two groups of electron sources used in SEM, varying in the amount of current they produce into a small beam size, the stability of the beam and the lifetime of the source.

The acceleration voltage

The voltage is an indication of the electron’s energy content; the value of this parameter therefore determines what kind of interaction the beam has with the sample. As a general guideline, a high voltage corresponds with a higher penetration into the surface of the sample known as bigger interaction volume. Theoretically, an increase in accelerating voltage results in a stronger signal. However, there are also disadvantages such as charging effects and damage of the specimen that comes along with high voltages.

The current intensity

In modern SEMs, the user has the ability to control the size of the electron probe. This is mainly achieved by adjusting the condenser and the objective lenses of the system and by selecting different apertures. In general, the spot size should be kept as small as possible since this way the resolution is enhanced.

Customizability

In many cases SEMs can be equipped with several different detectors or accessories. Such additional components allow users to perform a variety of different analyses or to use samples, which can usually not be imaged with an SEM.

User experience and time to image

An SEM, which can be quickly loaded with the sample saves time. For this, an efficient evacuation of the chamber is crucial. To some extent also the user-friendliness defines how much time is needed to collect the results. A system that is easy to handle and has a short loading time can provide the user with results within 1–2 minutes.

What are the costs of an SEM?

When choosing an SEM, besides its imaging and analysis capabilities, the initial and operational costs play an important role in the purchase decision. Three different cost items make up the total SEM costs:

- **Initial investment**

  The initial investment is the largest cost item and depends heavily on the type of SEM you choose. A floor model SEM, for example, requires a significantly higher investment than a desktop SEM and provides you with extra research possibilities.

  The table on the next page offers a cost comparison between a desktop and floor model SEM plus the facilities required by each type.

- **Maintenance costs**

  Besides the initial investment, maintenance is necessary to keep the SEM in good condition. The costs for this can be split as follows:

  All desktop SEMs use a pumping system consisting of a pre-vacuum and turbo molecular pump. These components require a regular maintenance performed by a service engineer. Such service costs money.

  From time to time the electron source has to be replaced. During an SEMs, lifetime this is the most expensive part of maintenance. Electron sources with longer lifetimes are usually more expensive, but in turn, save costs in the long run. The Phenom desktop SEM is the only desktop scanning electron microscope with a long lifetime CeB6 source with an average of 1500 operating hours.

Operational costs

- **Power consumption**

  An SEM runs on electricity. Clearly, the amount of energy needed strongly depends on how long the instrument is in use. An SEM with low power consumption can help to reduce costs.

- **Robustness**

  Sometimes, users by themselves cause problems to the system. This especially happens, when there are multiple operators working with the SEM. Internal damages can for example emerge in case the sample is not loaded correctly into the chamber. Choosing an SEM with a secure and user-friendly loading system avoids repair costs.

- **Time-to-image**

  A high sample throughput accelerates the analysis, and saves valuable working time. In contrast, a relatively slow loading and unloading time, however, will slow down your research process and increase your operational costs.

Types of Thermo Scientific ™ Phenom Desktop SEMs

Thermo Scientific Phenom XL Desktop SEM

Light optical magnification	3–16×
Electron optical magnification range	80–100,000×
Vacuum modes	Charge reduction mode (low vacuum mode) High vacuum mode Medium vacuum mode
Detector	EDS (optional) SED (optional)
Resolution	<14 nm

Thermo Scientific Phenom Pro Desktop SEM

Light optical magnification	20–134×
Electron optical magnification range	80–100,000×
Vacuum modes	Charge reduction mode (low vacuum mode) High vacuum mode Medium vacuum mode
Detector	SED (optional)
Resolution	8 nm (SED) 10 nm (BSD)

Thermo Scientific Phenom ProX Desktop SEM

Light optical magnification	20–134×
Electron optical magnification range	80–100,000×
Vacuum modes	Charge reduction mode (low vacuum mode) High vacuum mode Medium vacuum mode
Detector	EDS (optional) SED (optional)
Resolution	8 nm (SED) 10 nm (BSD)

How to Choose a Scanning Electron Microscope

Providing guidance in the selection of the right microscope

This guide is intended to assist you in choosing the most suitable Scanning Electron Microscope (SEM) system for your research. It provides:

- An introduction to SEM technology
- An overview and explanation of primary SEM features
- Guidance throughout the microscope selection process

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