The Scanning Electron Microscope As An Accelerator For The Undergraduate Advanced Physics Laboratory

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Abstract. Few universities or colleges have an accelerator for use with advanced physics laboratories, but many of these institutions have a scanning electron microscope (SEM) on site, often in the biology department. As an accelerator for the undergraduate, advanced physics laboratory, the SEM is an excellent substitute for an ion accelerator. Although there are no nuclear physics experiments that can be performed with a typical 30 kV SEM, there is an opportunity for experimental work on accelerator physics, atomic physics, electron-solid interactions, and the basics of modern e-beam lithography.

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INTRODUCTION

An accelerator is a modern symbol of physics research and a glance through any modern physics textbook will yield a chapter or major section on accelerators and their use in fundamental research and for applications in medicine. In the 2009 conference on advanced undergraduate laboratories held at the University of Michigan[1], the use of accelerator experiments in advanced laboratories was mentioned in only a few of the more than fifty university programs discussed. Only a fraction of physics departments have local access to a traditional accelerator, yet many, if not most departments have access to a scanning electron microscope (SEM).

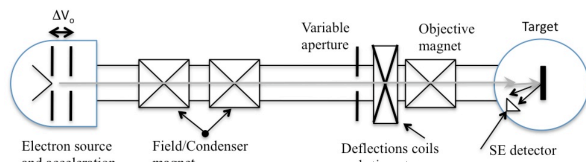

FIGURE 1. This is a schematic for a scanning electron microscope, but it could also represent a single-end accelerator if the first magnet is a bending magnet and the others are quadrupole-focusing magnets, instead of the dipole magnets of a SEM. The acceleration region of a 0-30 kV SEM is much smaller and less complex than higher energy accelerators.

Although accelerator experiments usually bring to mind nuclear and elementary particle themes, this accelerator can be integrated into the advanced laboratory course to study some very basic accelerator physics and technology. It can be used for a wide variety of advanced, non-nuclear experiments that can be open-ended, giving students an opportunity to use an instrument that they have invested time learning to use. Students can learn to operate a SEM in a couple of lab periods.

ACCELERATOR PHYSICS

A simple schematic drawing of a typical electron microscope, shown in Figure 1, looks similar to a single-ended accelerator of the 50 kV – 3 MV range of accelerating potentials. Many SEM accelerators are limited to a 30 kV maximum accelerating potential. With such a small potential there is no need for the complex accelerating column used in higher potential accelerators. A bending magnet to separate masses and charge states is not necessary on a SEM, so all magnets with a SEM are dipole (solenoidal) magnets for focusing the electron beam. Focusing magnets on higher potential accelerators are usually quadrupole magnets.

Accelerators, including SEMs, can be thought of as a source for producing and accelerating a beam of particles through beam-shaping magnets with instrumentation to study the beam-target interaction. There is also a Faraday cup to measure the beam current at the target. The beam of a SEM is scanned to produce an image, one pixel in the image for each position of the beam.

An analogy between an optical system, such as a microscope, and an accelerator is often used to help students understand the operation of the accelerator system. However, students rarely have more than cursory experience with optical systems and usually a shallow or even incorrect understanding of their operational principles. It is better to compare similar types of accelerators and mention the electromagnetic behaviors imbedded in the accelerator systems than to overuse the optical analogy.

Control labels on a SEM, such as contrast, focus, brightness, and magnification, shown in Figure 2, refer to imaging and not directly to the accelerator system operation. Relabeling a few of the controls on the SEM to reflect the devices they control, rather than the imaging effects that result, can help physics students make the connection between the operation of the SEM's accelerator system and the electromagnetism that the students have studied. An example of SEM controls is given in Figure 2 with some suggested name changes.

FIGURE 2. This is a selection of a few of the controls found on a typical SEM that uses a heated tungsten filament source. Terminology is often related to the control of the image rather than to the device in the accelerator being controlled. Changing some of the control names can help a student relate the control to the actual device and its operation in the accelerator system. For example, "Contrast & Brightness" (CON/BRT) can be "Detector Range & Gain"; "Magnification" (MAG) can be "Scanning Magnet Control"; "FOCUS" can be "Objective Magnet Control"; and "SPOT SIZE" can be "Condenser Magnet Control".

The magnetic fields of the SEM's field and objective magnets will always act as (positive) focusing lenses for a beam of electrons. This is not obvious to many students, but simple models can be used to explain the magnetic focusing[2] and can be used to predict an observable effect, the direction of the image rotation in a changing magnetic field. The objective lens (the final magnet as the electrons leave the SEM) is adjusted to bring the beam to a very small spot (between 0.5 nm and 10 µm, depending upon the SEM design). As an image is formed by deflecting (with scanning coils) the electron beam across an object, the image is rotated from the expected position by the interaction of the beam with the focusing magnetic field (-ev x B) of the objective magnet. The dependence of the rotation angle upon the magnetic field strength is shown in Figure 3. The two images of the silicon wafer in Figure 3 were made at constant beam energy but different magnetic field strengths, causing the electron beam to rotate through different angles for the two cases, and producing a rotated image. The two images were produced by physically moving the object closer to the objective magnet while simultaneously increasing the objective magnet's field strength. This effect can also be observed dynamically as the SEM beam energy is changed.

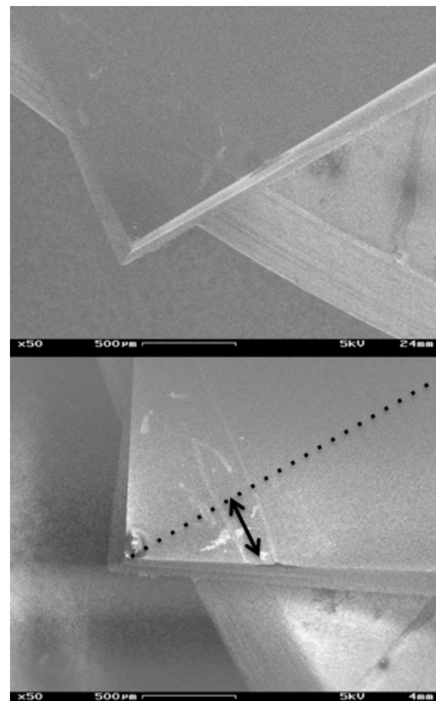

FIGURE 3. These two corner images of a silicon wafer were made at the same beam energy but with different objective magnetic field strengths. The lower image is rotated by about 25° from the upper image, and is an example of the spiral motion of the electrons due to the Lorentz force on them.

Each accelerator has a source with beam-shaping electric or magnetic fields, plus an acceleration region. Apertures are used to collimate and spatially filter the beam. A good image from the SEM requires that the cross sectional area of the beam is adjusted to be nearly circular, and good resolution requires a small spot size. The image resolution achieved by a SEM depends not only upon the beam diameter, but also on the precision of the electron beam scanning, and the interaction of the beam with the target. The beam diameter at the electron source, the chromatic aberrations, and the spherical aberrations of the focusing magnets are usually much more important contributions to the beam diameter than the increase from aperture diffraction of the electrons due to their deBroglie wavelength. These features and requirements are not usually found on a typical particle accelerator, and they add to the richness of using the SEM as an accelerator.

A biased Faraday cup is often used to measure the beam current in an accelerator system, and Faraday cups are also used on a SEM, usually without biasing[3]. In a SEM secondary electrons escaping the target are the source of electrons most often used for imaging in a SEM. By magnifying the image of the Faraday cup until only the inside of the hole is "visible" as a black image, few if any electrons are escaping and a good measurement of the beam current can be made. Drill bits from #65 to #115 can be used to make the holes in a metal target to use as the SEM Faraday cup (20:1 depth to diameter ratio makes for an effective Faraday cup). Beam currents usually range from picoamperes up to a few nanoamperes, depending upon the aperture size selected.

BEAM-TARGET INTERACTIONS

The beam electrons interact with the atoms of the target solid by scattering. Electrons come from the target solid as backscattered electrons, secondary electrons, or Auger electrons. Backscattered and Auger electrons provide information about the atomic composition of the solid, especially near the surface. Secondary electrons (SE) provide information about the surface topography. More secondary electrons are released from vertical edges than from level surfaces providing great image contrast. These electrons are accelerated to a scintillation detector biased positively to the target.

Photons with wavelengths ranging from x rays (characteristic and Bremsstrahlung) to the visible and infrared are emitted and provide information about the atomic composition and atomic structure of the solid. Any of these emissions can be used to create an image of the target. As an example in Figure 4, a SE image (4c) and two x-ray images (4a and 4b) are shown, along with the x-ray spectrum (4d). Each image provides a different perspective on the target. The secondary electron images require only a few seconds to acquire, while the x-ray images can require several hours, depending upon detector type, dead-time counting rates, and detector efficiency. The identification of elements from an x-ray spectrum produced with the SEM is often more convenient than using x-ray fluorescence or PIXE techniques, and is just as interesting.[4]

Only a few special types of ion-beam accelerators are capable of performing lithography, but all SEMs

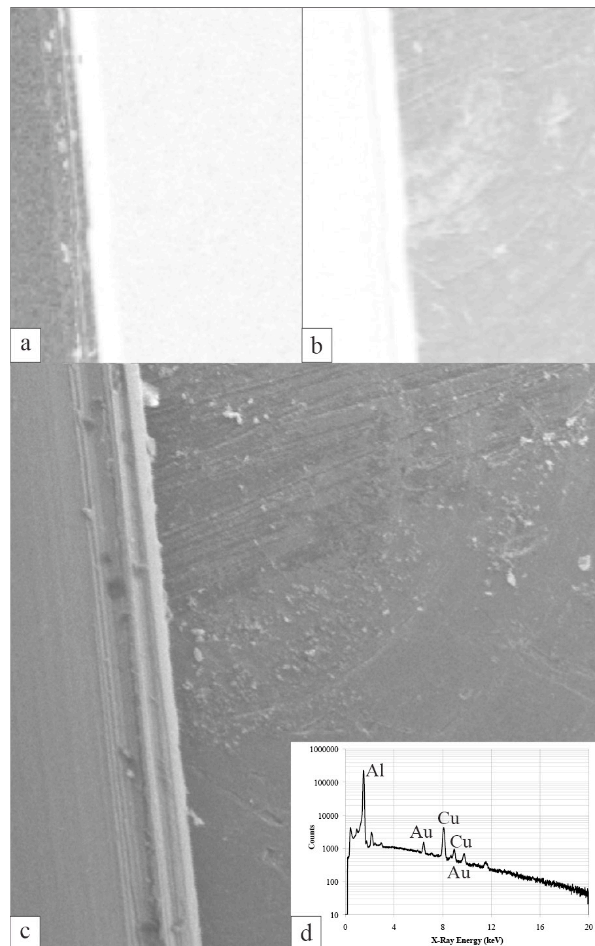

FIGURE 4. A piece of copper tape on a sanded aluminum stub, previously coated with a thin layer of gold, was imaged at 24 keV and 105x magnification. Images created with characteristic x rays from the copper and the aluminum are shown in (a) and (b) respectively, and the total x-ray spectrum for the region that was imaged is shown in (d). The darker areas represent the copper or the aluminum. The image created with secondary electrons is shown in (c). All three images cover the same area and are only displayed at different sizes in this Figure.

can be used for some elementary lithography, while others have features to perform more advanced lithography. Lithography with a SEM is very similar to optical photography. The "film" for SEM lithography is called the resist, which can be made of different polymers. Some polymers are very sensitive to electron (beam) interactions and their chain bonds are easily broken. A piece of a silicon wafer can be spin-coated[5] with a thin layer of the resist PMMA, poly(methyl methacrylate), a common polymer (Plexiglas) but one of the most commonly used for electron-beam lithography. A short exposure time with the electron beam scanning the field of view will decrease the average molecular weight of the PMMA. These molecules are easily removed by briefly immersing the wafer in a common solvent at room temperature. This will expose the underlying silicon and leave the high atomic-weight molecules of the PMMA nearly intact. Electrons at 10 keV and a

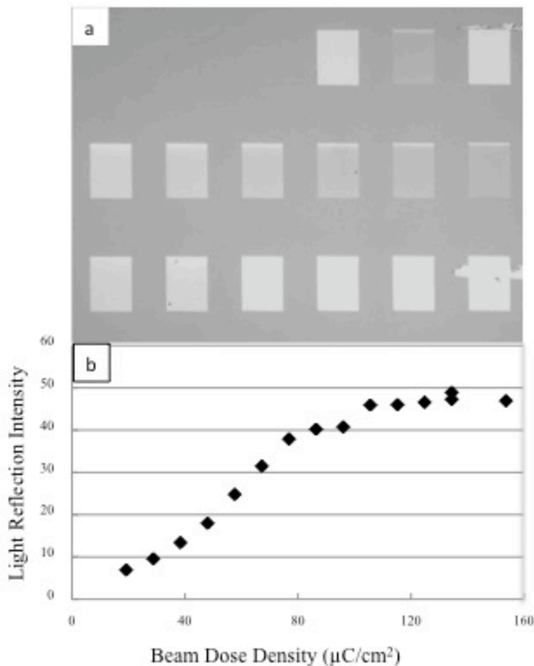

FIGURE 5. The upper image is an optical microscope image of rectangular regions created by electron-beam lithography. Each rectangle is the field-of-view of the SEM at a magnification of 620x, approximately 100 μm x 120 μm. Exposure times varied from 10 - 80 seconds for the 10 keV electrons incident upon the PMMA resist on a silicon wafer. After the resist was developed, the reflectivity of each exposed rectangle was measured using ImageJ software. The reflectivity of the silicon is much higher than the PMMA covered silicon and the graph of the reflectivity as a function of the beam dose density can be interpreted as doses above 100 $\mu C/cm^2$ will result in complete removal of the exposed PMMA.

magnification of 620x (100 μm x 100 μm field of view) were used to expose the pattern shown in Figure 5a.

Depending upon the size of the field of view (or the magnification used for the exposure), the exposed areas with some or all the PMMA removed during development can be viewed with an optical microscope (as shown in Figure 5) or viewed with the SEM. For the lithography shown in Figure 5a, the reflectivity of the exposed rectangular areas increases as remaining PMMA thins, until all the PMMA has been removed, exposing the highly reflective silicon substrate. An exposure-developing curve (bottom of Figure 5) is measured from the average observed brightness for each exposed area and the best dose density and developing time can be determined from this graph (Figure 5b). The exposure curve in Figure 5b is for 40 nm thick PMMA on silicon, developed in a 2:1 concentration of isopropyl alcohol and methyl isobutyl ketone for 90 seconds, rinsed in IPA for 60 seconds, and dried with N_2. Other developing techniques can also be used[6]. If a metal layer is deposited on the sample after developing the PMMA resist, all areas will be coated with the metal. Washing the wafer with acetone removes the remaining (metal-covered) PMMA. The silicon is left with a metalized pattern, that is, metal covering all the exposed regions.

Depending upon the SEM and its control software, complex lithography can be done by students at the micro-scale or the nanoscale. Without any special SEM features, rectangular exposures like those in Figure 5a can be made end-to-end to produce a single reflecting slit that can be tested optically. More complex arrays of slits can be made, though it is a time-consuming but rewarding endeavor. With better software, etch-a-sketch type lithographic images can be created and written into the PMMA resist with electron beams. Students who develop some skill with the basic lithography may continue to exploit the properties of the SEM to make lithographic patterns to create and test mechanical devices, electrical devices, and their combinations (MEMs and NEMs).

CONCLUSIONS

The SEM can be used as a tool in the advanced laboratory to provide a rich, new variety of experiments. Exploring the operation of the SEM as an accelerator provides students with a hands-on opportunity to operate an accelerator and to test the standard operating characteristics of an accelerator. Although nuclear experiments cannot be done with a SEM, the variety of photon and electron detectors that are standard with most SEMs opens up many other experiments, especially related to characterizing

solids. In addition, simple lithography can be performed with any SEM for the creation of micron-sized objects.

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