The Creation of Web-Based Interactive Virtual Experiments on Microelectronics and Nanoscience for Early Engineering Students

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Abstract

One of the greatest obstacles to attracting and retaining engineering students is the lack "hands-on" experiences early in the university curriculum. This paper describes a project that introduces early university students to the high tech fields of microelectronics and nanoscience though the use of web-based "Virtual Experiments." The website allows students to explore these fields at levels ranging from underlying science, to device physics, to processes and processing tools. New pages even recreate the layout and operation of an actual microelectronics factory site. Virtual reality is also used to support a real university lab in which a student can fabricate real devices in a few short lab sessions. The web material is presented in an intuitive and highly visual 3D form that is accessible to a diverse group of students. It has already been tested with high school science students, engineering students, and graduate business students. This paper describes the modules developed as well as the tools used.

I. Introduction

Microelectronics produces the transistors, computers and networks driving today's Information Age. However, to younger students (and the general public) the field remains mysterious and inaccessible because of its extreme complexity and miniscule scale. In most curricula, relevant concepts are developed over years of coursework. As a result only highly specialized Electrical Engineers may ever learn what goes on inside an integrated circuit. And yet, at their core, microelectronic devices operate on simple concepts of charges and fields that can be explained to a high school physics student. In this project, we sought to capitalize on the scientific intuition developed in high school science courses and to lead younger students to more advanced concepts through the use of self-paced 3D visualizations that would provide the hands-on experience so often lacking in early university curricula. These Virtual Experiments are dynamic, interactive visualizations of a microelectronic device, process or piece of equipment. A key point is that virtual reality is used to show the student *more* than he or she could see in reality. For instance, the visualization of a piece of hardware may fade away the shell of the instrument to show underlying mechanisms, unseen particles and fields, atomic scale views and other explanatory aids.

These modules offer students a perspective seldom possible in conventional lectures and blackboard diagrams. [1,2] For instance, in lieu of mathematical formulas, the student can see the time evolving, three dimensional state of an object. Further, the overview of a complex process, such as MOS transistor fabrication, can be presented as a 3D movie where the scale is easily changed from that of the complete circuit down to that of the atomic assembly processes. Throughout these presentations, every effort is made to explain the underlying science, thereby connecting with a base of material and experience with which the student is already experienced and confident. This virtual lab has already been tested by a large spectrum of users including high

school students looking for applications of the physics and mathematics they are being taught, early engineering students selecting majors, business students and would-be technology managers trying to understand the microelectronics industry, and visiting members of the general public. These free materials are web-based and accessible to all comers.

II. Software Tools

In part, this project grew out of an intense frustration with blackboards. One of us (Bean) had spent two decades as a researcher in microelectronics and nanoscience at Bell Laboratories. This background not only provided rich hands-on experiences, but it also gave time to develop "mind's eye" visualizations of many of the more mathematical concepts. In the classroom, it proved extremely difficult to communicate these visions on a blackboard. Further, the conventional "crutch" of mathematics was less effective with a generation of students who, studying a broader range of subjects, had a more poorly developed intuition for how differential equations mapped into real life behavior. A culminating experience came with a lecture that consisted of a sequence of drawings and diagrams depicting the dynamic behavior of a *single* microelectronic device. At the end of the lecture, a student's questions revealed that he had not made the connection between the figures and thought an array of *different* static devices was being depicted.

Frustration stimulated a search for alternatives. Inspiration was ultimately drawn from two sources: the tremendous impact of illustrated books such as David Macauley's "The Way Things Work" [3] and the explosion of dynamic 3D imagery beginning to appear in computer games. These suggested that it should be possible to develop web-based materials drawing on students' existing scientific experience and computer literacy, and to then expand that knowledge through the use of interactive, fully three dimensional visualizations. Further, it suggested that a basic, but nevertheless accurate, understanding could be conveyed in single web session or classroom/lab hour. Subsequent discussions with high school science teachers then suggested that the same materials could demonstrate to their students the utility of introductory science courses. With this expanded goal and team, supporting funds were successfully solicited from the National Science Foundation's program of "Course Curriculum and Laboratory Improvement" (CCLI).

We spent the first year of the project exploring various software platforms and content delivery mechanisms. We needed a tool powerful enough to create complicated three-dimensional objects and animations and yet still easy to use. Ease of use became a particular issue as we began to realize that undergraduate illustrators often came up with the most intriguing and imaginative presentation ideas. However, these students might stay with the project for no more than a single summer, and it was thus essential that the visualization authoring tool be intuitive and quickly mastered. We also sought to maximize ultimate access to our materials by producing animations that would be playable on all popular PC's, requiring few, if any, unusual players or browser plug-ins. Finally, we sought a web delivery platform compatible with the range of modems and DSL links common in high school science classrooms.

The first two options we explored were the Virtual Reality Markup Language (VRML) and the 3D API extension of the Java language. VRML is very easy to learn and use, but it is not really a programming language: mathematics and logical structures can only be provided through cumbersome interfacing with Java or JavaScript. VRML is thus best suited for a static world

through which the user simply moves. Sun Microsystem's evolving Java 3D API is, on the other hand, an extremely versatile language extension. However, at present, it performs only through complex low-level coding that can turn something as simple as "make a long brown box" into a half page of code. Further, it is an add-on to "Java 2" (actually version 1.2.2) which is not supported by many current web browsers.

We finally settled on two programs. "3D Studio MAX" from the Discreet Division of AutoDesk Inc. would be used for the offline creation of the 3D visualizations. MAX was first developed for authoring electronic games. It resembles a 3D CAD program but it emphasizes final appearance and ease of creation rather than numerical precision. Further, it incorporates a slider that allows one to depict objects at various times, and it then automatically interpolates color, visibility and shape between the specified time points. This information can then be "rendered" into movies (e.g. Apple Quick Time format) to be embedded in the final webpages. This rendering process can compute reflection and refraction of light, shadowing, and photographic textures with an accuracy that is difficult to distinguish from films of actual objects (see, for example, the full microelectronics factory visualization associated with figure 1). As important, MAX is a remarkably intuitive and easy to learn program. Various authors have published excellent tutorial books. One, the "3D Studio Max R3 Visual Quickstart Guide" by Michele Matossian, was so affordable and effective that we ultimately presented a personal copy to every new project member. [4]

The MAX movies formed the core of our webpages. However, early on we realized that even very dramatic and realistic visualizations would not hold a viewer's attention if viewed passively, in large blocks. We therefore divided movies into short scenes, each focusing on a single question or topic. The viewer could then pace the presentation and follow alternate lines of inquiry. A single "presentation" might then easily grow to several dozen MAX-generated 3D scenes. If these scenes were embedded in conventional HTML web pages, viewing would require either moving up and down long pages, or linking between dozens of different pages. Users would inevitably become "lost in hyperspace." [5] We found a solution in a second software package originally developed for interactive instructional CD's and since expanded for web page creation: "Director Shockwave Studio" from Macromedia Inc. The title of this program reveals two features. First, the program delivers interactive content through the ubiquitous Shockwave browser plug-in, one of the most widely used browser plug-ins in existence. It therefore met our criterion of cross-platform compatibility. Second, the program is based on the analogy of a director with a stage play, developing a detailed script describing the actions of his actors, musicians and sets and props. Following this analogy, the program imports movies, sound effects, graphics and text as players into the presentation. These elements are then pasted into a visual timeline complete with the alternative of loops, multiple branches, and a variety of built-in or programmable viewer interactions. Yet all of this can occur within a single HTML web page without the need for cross-linking or up and down movement on that page.

Software challenges remain. By attempting to capture reality, our presentations are intrinsically complex and rich in data. The transmission of these files is improved by their division into short scenes. However, current scene size (typically 0.5 - 2 MB) can still tax slower Internet connections. We will soon implement two improvements to this situation. First, newer video encoding algorithms (specifically Quick Time 6's incorporation of MPEG 4) will allow us to

compress scene file size by a factor of perhaps three.   Second, with the recent gift of a dedicated web server from IBM, we will soon implement "streaming video" where frame-by-frame on-demand movie delivery will remove the need for downloading a complete temporary copy of each scene before it can be played.

II. Website Content: Present and Future

Our project grew to include collaborations with two local high school science teachers, a regional magnet science high school, and our university's school of business. The common thread was that all of these audiences included students who had (or were in the process of acquiring) a basic scientific literacy at the level of high school physics. All knew (or could be reminded of) the ways electric charges attracted or repelled one another.   Most were inclined to avoid mathematics and yet were anxious to see how elements of their basic science knowledge could explain otherwise mysterious technological objects. As teachers, we realized that this was enough! Math and advanced coursework might be required to design devices and instrumentation but were frequently ***not*** required for a basic understanding of their operation, especially when explanations could take full advantage of virtual reality's ability to strip away layers, to move from human to atomic scales, and to depict the otherwise invisible mysteries of fields and forces through dynamic presentations. Thus, while our initial plan centered on microelectronics and nanoscience, it soon grew into a larger vision where these subjects were simply the most advanced illustrations of the application of high school electricity and magnetism. This development led to the name Virtual Lab, referring to a teaching and research laboratory *building* and the richness of experiences it can provide. Although the project is very much ongoing, below we provide a description of materials currently online or soon to appear. (Note that our entire focus is on building powerful alternatives to the type of static 2D images that illustrate this paper - we therefore urge the interested reader to view the full 3D animations on the website!)

The base URL of www.ee.virginia.edu/3d-science takes the user to a plain vanilla set-up page. As explained above, our site requires only Quick Time and Shockwave browser plug-ins. Both programs provide code that can be hidden in a web page to test for the presence of these players on the user's PC and, if necessary, divert the user to a website where the player can be downloaded. However, we found that this code occasionally fails by missing the presence of an already installed plug-in. Further, users (often the "more experienced") will override a rerouting in the belief that a plug-in or update is not required. Our entry page is thus simple HTML text explaining which plug-ins are required and how they can be tested.   The user then clicks a button linked to the true homepage of the website. Addition of this "set-up" page greatly reduced user problems, and it need only be visited the first time a user comes to the site.

On the second (but true homepage) of the site, we exploit the power of virtual reality to solve a university's chronic shortage of lab space. In virtual reality we seize the basement of the most prominent building on our campus: the Rotunda of Thomas Jeffferson's "Academical Village." As shown in figure 2, a supposed map of the basement appears, divided into rooms labeled Office (project information), Circuit Lab, E&M lab, Scientific Instruments, Semiconductor Science, Microelectronics Production, Microelectronics Teaching Lab, and Nanoscience (coming 2003). Clicking on any of these rooms reveals a listing of related webpages in a textbox at the right. In

addition, a helicopter on the lawn can be clicked to "fly" up to northern Virginia to visit the Micron Technologies integrated circuit plant.

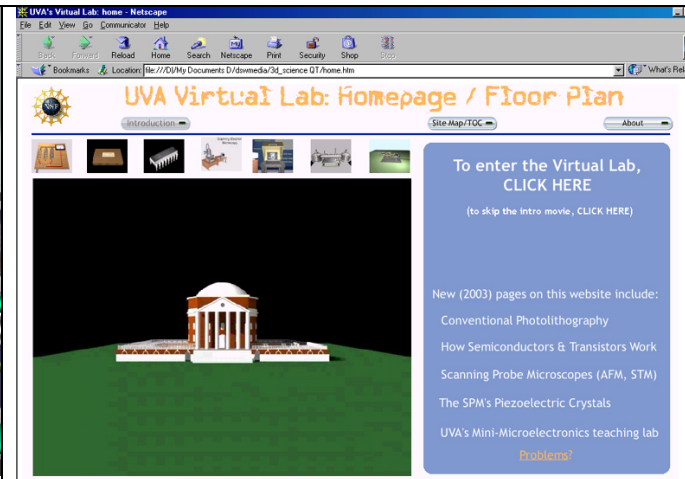| Figure 1. Snapshot from a photo-realistic virtual reality walking tour inside an integrated circuit manufacturing lab.	Figure 2: UVA Virtual Lab Homepage. Opening "splash" animation takes the viewer to the basement of UVA's Rotunda to see a map of Virtual Lab's rooms. A mouse click on a room then brings up full links to associated presentations.

A. Circuit Lab and E&M Lab

The Circuit and E&M labs were developed to address the needs of high school students and instructors, while providing a path upward toward more sophisticated content on the website. In both labs, presentations begin with objects as they appear in the classroom, but then exploit what we call "Superman X-ray Vision" to depict invisible phenomena such as fields, forces, energy and charges. The Circuit Lab is a suite of several dozen pages, each explaining components of basic electrical circuits. The pages were largely programmed by students and instructors from the Central Shenandoah Regional Governor's School for Science and Technology. [5] Virtual reality is exploited in two ways: the voltage of circuit elements is depicted as a changing height, and water flow analogies are presented for most elements (batteries become fully animated gerbil-powered water wheels). The E&M Lab opens with the depiction of a common high school experiment on magnetic induction (figure 3). The student can move a magnet through a sequence of more densely wound coils to see the induced current. This page is as classroom realistic as we could make it. Then, however, an "X-ray Vision" button takes the viewer to a parallel page where magnetic fields and charges become visible. There, the user is led gently through an explanation of exactly what the fields are and how the movement of the magnet leads to the observed current flow. The colors and conventions used in this depiction of magnetic fields and forces are adopted throughout the entire website. For instance, the student can ultimately view the virtual reality disassembly of a scanning electron microscope in which the same forces and symbols are used to explain how the e-beam is focused by a magnetic lens (figure 4). This explanation, divided into the same small steps

of analyzing magnetic field, relative velocity, force and charge movement ("Lentz's Law") is quite palatable, and yet it explains lenses that most graduate students (and many faculty) do not completely understand.
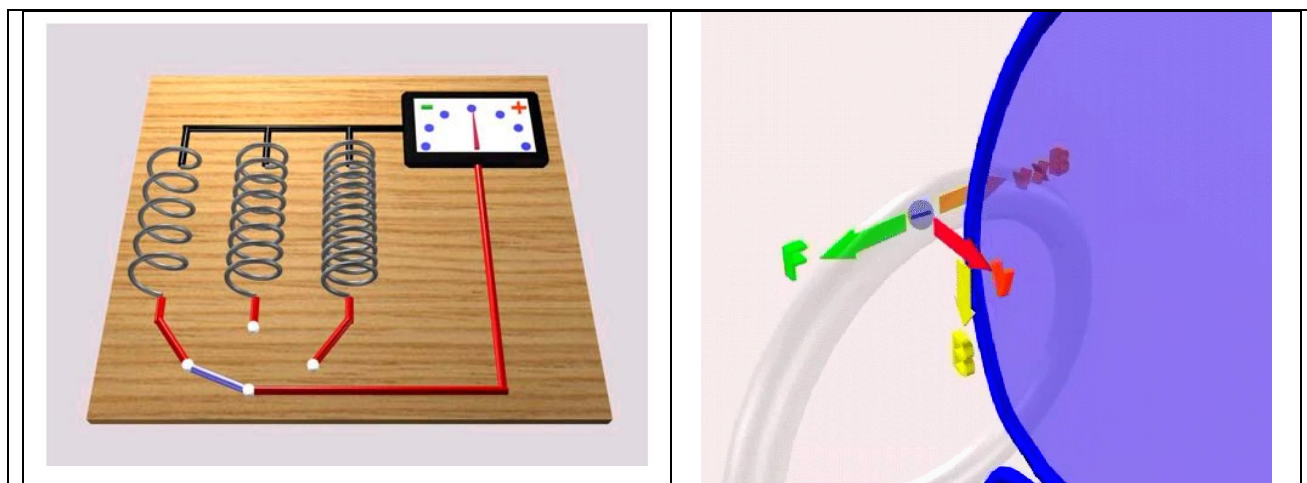

Figure 3: High school experiment on magnetic induction. Left: "real" version depicting apparatus as it appears in the classroom. Right: "X-ray Vision" version where charges, fields and forces become visible.

In addition to the above, the E&M Lab will soon be augmented by pages on electrostatics (from basic pith balls to Van de Graf generators) and by pages depicting applications of E&M. The latter include transformers, speakers, microphones, electric motors, guitar sound pick-ups and metal detectors. The basic MAX programs for these pages have been created by undergraduate interns and use the same methodology and symbols to explain the operation of these devices based on electrostatic and/or electromagnetic forces.

B. Virtual Scientific Instrument Lab

Images from scanning electron microscopes (SEMs) and atomic force microscopes (AFMs) are now sprinkled throughout textbooks and science articles of all levels.   These instruments are based on very understandable high school level physics, and yet few students have opportunities to see, much less operate and understand, how they work. We therefore chose these instruments as the next level of E&M application. Both pages begin by depicting the instruments as they appear on the UVA campus (although we took the opportunity to enlarge their rooms and improve the color schemes). However, the user is then taken deep inside the instruments to see how they work. For the SEM, particular highlights include animated explanations of how lenses focus and how images are generated from the sequentially scanned beam. For the AFM (or its cousin the STM), the viewer is shrunk down to the almost atomic scale of the probe tip and shown how an elegant optical system measures the tracking of the tip across test surfaces (figure 5).   The viewer is also offered a side trip for an animated tour of how piezoelectric crystals work and how they are shaped and assembled into the heart of the AFM.   An additional page describes the microelectronics research tool of molecular beam epitaxy. This instrument is less well known but is included because it *is* the PI's principle research tool! Further, at its heart it incorporates two evaporation sources that

provided yet another example on how magnetic forces can be used to direct electron beams toward useful ends.
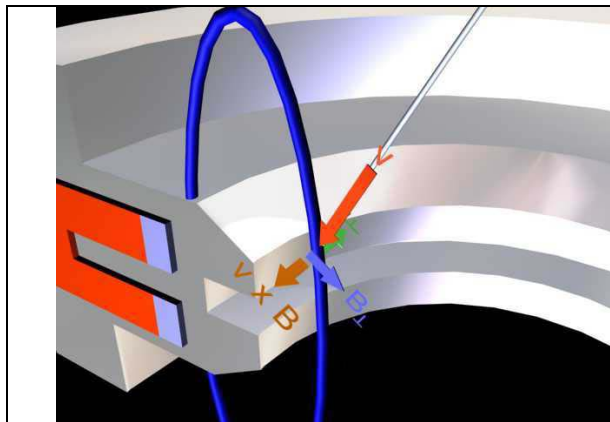

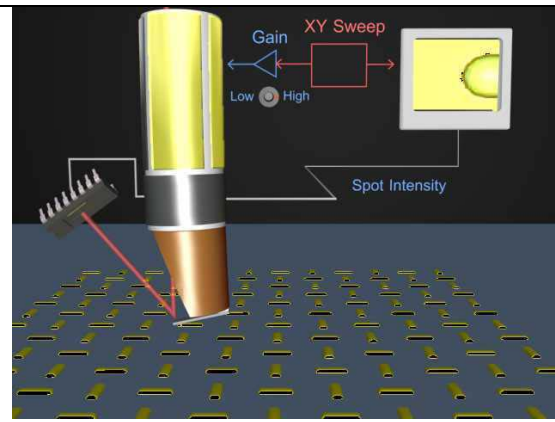| Figure 4. Snapshot from page depicting a virtual scanning electron microscope.   Shown here: action of a magnetic lens. | Figure 5. Snapshot from page depicting a virtual atomic force microscope. A companion page explains how the AFM's piezoelectric crystals work.   Shown here: explanation of how probe scan produces image. |

C. Semiconductor Science Lab

The first stop in the Semiconductor Science Lab is the page on "How Semiconductors & Transistors work" (figure 6). This page is one of the more exhaustive ones on the virtual lab site. The user is given a "do it yourself silicon crystal kit" complete with protons, electrons and neutrons. An intuitive explanation is provided for the shapes of atomic orbitals and how they influence chemical bonding to string the atoms together into a crystal. This fully bonded but non-conducting crystal is then augmented by the local introduction of impurities with one too many electrons, which quickly escape to roam the local crystal. Electrons are then sucked into the gap between two such domains by a negatively charged metal plate, completing the electrical path along the crystal bar. This visualization provides a basic, but entirely accurate, depiction of how the integrated circuit's MOS transistor works, based solely on concepts of charge attraction and repulsion. It not only avoids conventional blackboard mathematic formulas, but effectively shows things that cannot be depicted on the blackboard, such as the complex diamond-like structure of the silicon crystal.

This page is extended by another entitled "Semiconductor Crystals." It shows geometrical structures of popular semiconductors where the user can click and drag the structures to view different perspectives and crystal facets. There is also a link to a datasheet of crystal properties for the more serious student.   This page is, in fact, an indication of future directions for our website. All other pages consist of user-selected and paced movie segments that we created offline in 3D Studio MAX. On the other hand, the simpler crystals of this page are downloaded as 3D recipes to the user's own PC, where the user can arbitrarily manipulate them.   This technology is quite new

(and still contains bugs), but as it matures and allows for downloading of more complex objects and scenes, we will greatly expand the user interactivity of the web pages.
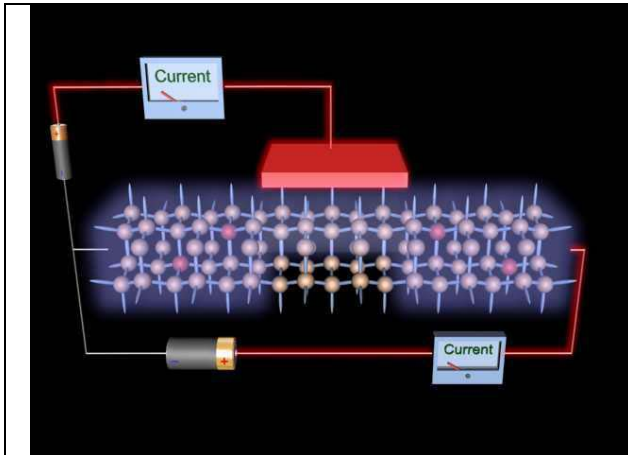

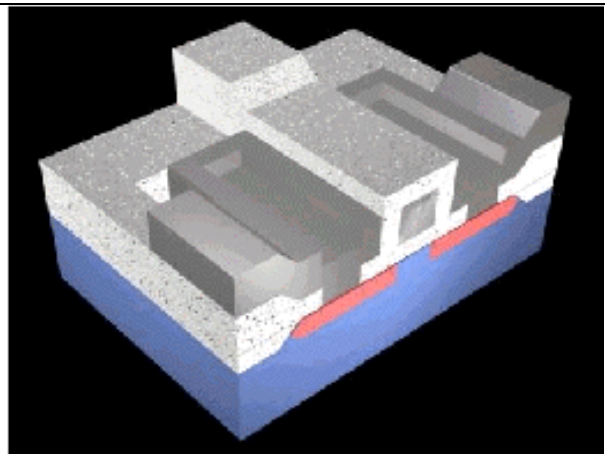| Figure 6. Page on "How Semiconductors and Transistors Work" which takes the viewer from the assembly of individual Si atoms through to a full explanation of a MOS transistor.	Figure 7. Companion page presenting the actual assembly sequence of a state-of-the-art MOS transistor.

These conceptual explanations of transistors are complemented by a page on transistor fabrication. "How an Integrated Circuit is Made" starts with a depiction of the original Intel 4004 Microprocessor. The page then "zooms into" the package, stripping away the network of switches, layers of metal, silicon, and silicon dioxide that make up the circuit, revealing an individual MOS transistor (figure 7). From there, the viewer is offered the opportunity to see how the transistor is made. This abstracted process consists of no fewer than fourteen steps. The sequence of masking and 3D growth is very difficult to depict in lecture notes or textbooks, even for the most artistically gifted of teachers. Further, when it is presented as a long series of static cross-sectional views, students often become confused. Virtual reality fills this gap and easily provides an evolving 3D perspective. To our gratification, during a university open house we found that even members of the general public insisted on going through the entire presentation so that they could finally say they knew how a transistor was made.

D. Microelectronics Production

Pages on "Semiconductor Science" segue into the website's room on "Microelectronic Production" and its helicopter field trip. The field trip evolved out of our collaboration with Micron Technology's integrated circuit manufacturing plant in Manassas, Virginia. Integrated circuit plants are not only off limits to members of the general public, they are off limits to all but selected employees. This restriction is necessary because the manufacturing environment must be kept so incredibly clean. A VIP tour thus consists of no more than the opportunity to peek through a series of small, carefully sealed, windows. Yet these *multi-billion dollar* plants are among the most complex and fascinating fabrication facilities on the face of the earth. Students Niladri Kansari and Coire Maranzano therefore worked with Micron to learn and depict the inner workings of their plant.

Three separate pages describe different aspects of the Micron plant. The first page provides a fly-by giving a bird's eye view to provide a sense of scale along with general descriptions of many of the site's dozens of buildings (figure 8). The next page disassembles the five-story main fabrication building, floor by floor, to show how the entire structure works together to provide a manufacturing zone containing less than one micron-size particle per cubic meter of air. The final page provides an employee's eye view of walking around within one zone of the ultra cleanroom. These pages include links to pages on device fabrication steps illustrated in the semiconductor science section so that the user can understand how laboratory fabrication steps map onto the actual industrial production flow. A sense of industrial engineering is also conveyed through depictions of how equipment is sited to permit service and supply while minimizing incursions into the critical cleanroom space and by descriptions of chemical supply and treatment systems.

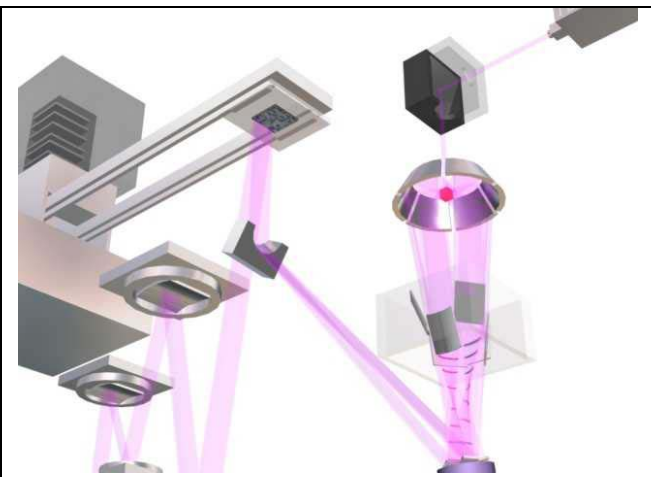|	
Figure 8. Snapshot from a suite of three pages animating a tour of the Micron Technologies integrated circuit manufacturing plant in Manassas, Virginia.	Figure 9. Part of a presentation on an alternative "next generation" lithography tool based on reflected extreme ultraviolet light.

The cleanliness of this plant's space only partially explains its multi-billion dollar factory cost. The balance comes from the incredibly expensive tools used within. The most complex of these is the micro-photographic pattern transfer process called "photolithography." Photolithography is the subject of three interactive, multi-scene webpages. The first depicts the current generation of ultraviolet light-based tools. Then, because this technology gating tool will soon lose effectiveness, Kansari developed companion pages on proposed "Next Generation" lithography techniques. One of these, "Extreme Ultraviolet Lithography" (EUV),[7] is being developed by an Intel-led international consortium (figure 9). The other, "Scattering with Angular Limitation Projection Electron-Beam Lithography" (SCALPEL), [8] has been driven by Bell Labs and IBM. Kansari and other team members visited both consortia and based webpages on these visits and on extensive research. These two pages may appear to go somewhat against the grain in their targeting of advanced students. However, the explanations are intuitive and similar in tone to the rest of the pages. They can be easily understood even by beginning students, and open the door to processes that are not yet described in current textbooks and courseware. They have even been used as the basis for an industry case study development within the University of Virginia's Darden School of Business.

E. Microelectronics Teaching Lab: Virtual Reality Meets Reality

The Virtual Lab provides an active means for young students far from our campus to explore electronics, microelectronics, and nanoscience.   However, on the grounds of the University of Virginia, we are coupling this website with a hands-on *real* microelectronics lab for freshman engineering students, students in non-technical majors, and students from neighboring high schools and community colleges. Not only will this lab make use of the "Virtual Experiments" above, but the lab itself has been recreated in virtual reality to provide an online lab manual that the student can visit before setting foot in the actual facility.

University microelectronics labs are typically assembled using equipment retired from industry. Even when new and completely reliable, these were units were meant to be operated by highly skilled professionals. They are expensive and, by the time we receive them, cranky and unforgiving to operate. Hence, most universities restrict their use to graduate students and advanced undergraduates. Our solution was to purchase prototypes of the "Modu-lab" semiconductor teaching modules being developed by Electro-Mechanical Services, Inc. [9] This equipment set consists of simple and affordable lab modules designed specifically for teaching and priced (for the full set) at less than 150k$. Because these units are much more robust, our intent is to open this lab to much younger and less experienced students. Further, rather than hiding its use in a specialized course, we plan to introduce it as a short lab segment in an introductory general engineering or electrical engineering class. We thus needed a viable process for fabricating a working device in three or four short afternoon sessions. We chose the simplest microelectronic device, the diode, as our target using an abstracted and simplified assembly sequence.

To prepare the student for the real EMS Mini-Fabrication Lab, we have developed a set of companion web pages. Again, these pages depict the lab as an actual room with virtual reality versions of each of the tools in that lab. We start with a visualization that reproduces, on the computer screen, what the student would actually see on entering the real brick and mortar lab at UVA (figure 10). Having anchored the viewer in the virtual world, the camera viewpoint becomes the user's viewpoint. The user can focus on various modules by simply moving the camera or branch off to related pages describing parallel science and technology. Used in this manner, the Virtual Lab module is somewhat adaptive to the user's individual learning style.

One of the most complex modules is again photolithography.   Its visualization captures the physical processes as faithfully as possible, but augments the scene with a dynamic "window-in-a-window" view that shows what a user will actually observe through the microscope as the sample is manipulated (figure 11). Because users are allowed to move step by step through the process, they can acquire a firm understanding of the process even before entering the real lab (and, indeed, we foresee adding online testing of this knowledge before students are allowed to use the real equipment).
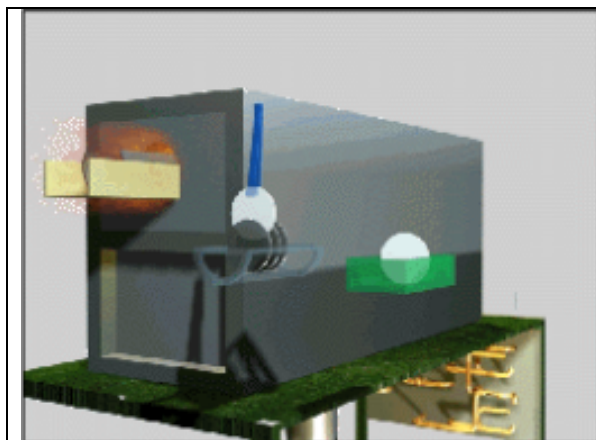
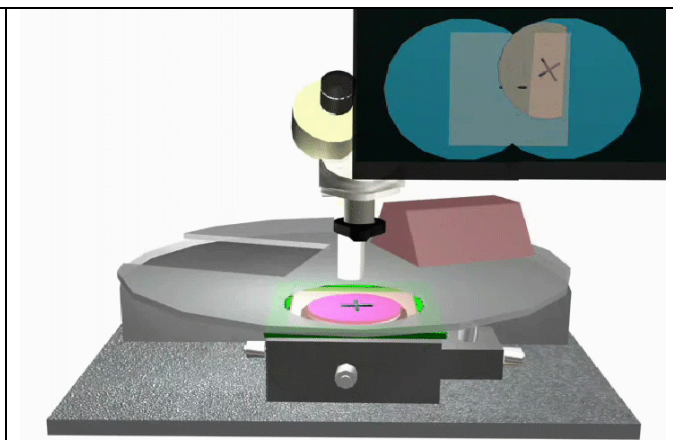|	
Figure 10: Virtual reality depiction of real doping furnace in new early undergraduate microelectronics/microscience lab.	Figure 11: Enhanced virtual reality depiction of part of the photolithography apparatus that superimposes a dynamic view of what the student will see through the attached microscope.

We plan to introduce this lab with a process recipe that involves lithography and oxidation on the first day, diffusion on the second day and metallization on the third. The student will be provided ample opportunities to personalize the process. For example, masks will be printed on transparent acetate sheets using a common laser printer. The student will have access to a template in the form of an AUTOCAD file, but will be able to modify the layout to experiment with different configurations. By simplifying the process down to three afternoons, the lab will serve as a "drop-in module" akin to the Virtual Lab pages, and we anticipate its use in a variety of circumstances and courses.

Conclusions

Microelectronics and nanoscience are generally hidden behind barriers of advanced prerequisite courses. Extreme small size and extraordinary complexity compound problems in these fields, but access is a problem throughout high-tech science and technology. The net result is that young would-be scientists and engineers now rarely have the personalized hands-on experiences once provided by tearing down the family car or assembling a Heathkit. Our goal is to breach this wall and replace these lost opportunities through the use of two tools: a suite of "Virtual Experiments" and a new set of laboratory teaching modules. "Virtual Experiments" build on this generation's literacy and passion for computer animations by providing an active means for young students *anywhere* to explore micro and nanoscience through layered stand-alone learning experiences. On our campus, these are coupled directly with a novel, greatly simplified, microelectronics/microscience lab that will be inserted into an early survey technical course in our curriculum.

Materials have been tested with students ranging from high school to business school and with members of the general public attending university open houses. We were particularly struck by the response from the non-technical adults and business students who frequently stayed for an hour or more, winding their way through 10 to 20 scene presentations repeatedly so they could finally

claim they understood how a transistor worked or how an integrated circuit was made. The frequent comment was "I've waited years to figure this out!"

Looking to the future, in the short term we will soon implement improvements in coding and web server delivery that will make presentations far snappier on conventional broadband links and even open the website to users of medium speed modems. In the longer term, we are tracking and testing recent software innovations that may allow us to replace the downloading of pre-recorded scenes with true transfer of 3D worlds object by object. Although this will require considerably more hidden coding, it will move us far closer to our ultimate vision of true virtual experiments where users are not limited by our anticipation of their lines of inquiry but can follow their own curiosity. Finally, despite these challenges, the bottom line message is clear: Effective 3D visualization software IS now available in a form and at a price that makes it ready to move out of the movie production houses onto universities campuses where, we believe, it has immense potential to enrich learning experiences.

Acknowledgments

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