The Design and Assessment of a Hypermedia Course on Semiconductor Manufacturing[1]

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Abstract

This article describes the design and evaluation of IC-HIP, a multimedia course on integrated circuit manufacturing (Schank & Rowe, 1992). Subjects browsed the course via standard hypermedia links or linear paths. Learning effects were assessed based on navigation method (hyperlinks vs. path), prior knowledge (low vs. high), and other factors (e.g., subjects' stated interests in semiconductors, and kinds and number of course nodes viewed). Effects of navigation method, prior knowledge, and pre-instruction interest on nodes viewed (by media type and topic area), were also assessed. Results suggest that subjects who browsed via hypermedia links tended to more often bridge topic areas rather than explore them in depth, but there were little or no learning differences by knowledge or navigation group, and neither prior interest nor nodes viewed (by number, topic area, or media type) were correlated with learning. These results and future work are discussed.

Keywords: Multimedia, hypermedia, navigation, integrated circuits (IC's), semiconductors.

Introduction

Students often have difficulty understanding and applying scientific principles. These problems are partly due to inconsistencies between the student's intuitions and the scientific models presented to them (e.g., diSessa, 1983; Gentner & Gentner, 1983; Ranney, 1987/1988; Schank & Ranney, 1992). Developing effective instruction on integrated circuit (IC), or semiconductor manufacturing (IC manufacturing) is particularly challenging because of the large number of complex electrical and chemical processes involved (e.g., current flow through a series of transistors, oxidation and etching processes used to realize circuits in silicon, etc.). Furthermore, many processes are not easily represented in traditional static media (e.g., text, graphics, and charts), because they involve time-varying dynamic change. They are more understandable when represented in continuous media (i.e., animation or video), or in multiple media representations. This paper will describe the design and assessment of an introductory, college-level, multimedia course on IC manufacturing developed using HIP (Hypermedia in PICASSO; Becker & Rowe, 1991). The system, called IC-HIP, is described in more detail below.

To accommodate exploratory as well as linear styles of learning, IC-HIP was organized with both hypermedia links (hyperlinks) and linear–paths. Studies suggest that some students learn better in hypermedia environments and others learn better in linear ones (e.g., Stanton & Baber, 1992; Recker & Pirolli, 1992; Smith & Weiss, 1988), but that when given an *option* between using either environment, subjects' navigation choices do not differ based on ability (e.g., Beasley & Vila, 1992). In this study, learning effects based on prior knowledge of IC's (high-knowledge vs. low-knowledge), method of navigation in IC-HIP (hyperlinks vs. paths), and other factors (e.g., media viewed) are examined. The remainder of the paper is organized as follows. First, IC-HIP is described. Second, the goals and methodology of the study are presented. Finally, the results and future work are discussed.

The HIP development environment

HIP is an extensible hypermedia framework fully integrated with PICASSO, a Lisp-based, object-oriented, graphical user interface development system developed at the University of California, Berkeley (Rowe, Konstan, Smith, Seitz, & Liu, 1991; Schank, Konstan, Liu, Rowe, Seitz, Ogle, & Smith, 1992). HIP allows users to integrate multimedia information into *hyperdocuments*. Each hyperdocument contains a set of nodes, in various media, connected by directional links. The development tools in HIP allow authors to easily incorporate both static media (e.g., text and graphics) and continuous media (e.g., video) into their hyperdocuments. HIP also allows authors to add new node types (e.g., animation) and create new links, paths, and "bookmarks" to organize node information. The navigation tools supplied allow users to browse a hyperdocument by: (1) following links from node to node, (2) selecting nodes from menus or a graphical map of the document, (3) creating and accessing bookmarks, and (4) following pre-defined paths. For instance, when HIP is in "hypermedia mode," links are indicated by boxed items (e.g., boxed words or pictures) on the screen (see Figure 1). The user can follow a link by clicking inside the relevant box, and then clicking the "Follow" button. In "path mode," the user can choose a path from the "Browse" menu, and follow it forward or backward via the "Next" and "Previous" buttons.

IC-HIP's design

The content and organization of IC-HIP was created and refined over a year of weekly research meetings and as a result of pilot work. The courseware authors (Schank and Rowe) began development by reviewing over thirty articles and books (e.g., Meindl, 1977, 1987; Oldham, 1977; Maly, 1987; Harrison, Holloway, & Patell, 1989; Longfellow, Troutman, & Borrus, 1991), and viewing several videos and taped lectures about semiconductor manufacturing, research, and markets (e.g., Rudell, 1989; Carranza, 1986; and 40 hours of lectures from an undergraduate course in IC fabrication; Oldham, 1991). Fabrication concepts were discussed with colleagues familiar with microelectronics technology and industries, including university faculty, members of the PICASSO and Computer Integrated Manufacturing (CIM) research groups, and an engineer designing an image-processing chip at Lockheed.

The explanations presented in the course were designed to clarify central, and non-transparent, concepts (e.g, how transistors work, why silicon is used to make ICs, and how circuit designs are transfered to silicon wafers). To dynamically illustrate relevant electrical and chemical processes (e.g., current flow, oxidation and etching processes), approximately 45 minutes of video material from video tapes of the Berkeley Microfabrication Facility (Rudell, 1989), and of lectures and demonstrations from an undergraduate IC fabrication course (Oldham, 1991) were incorporated into the course[1]. Although other excellent commercial quality tapes on semiconductor manufacturing are available (e.g., Carranza, 1986), the usage costs of these tapes (e.g., up to $20/second) discouraged us from using them.

To assess the usability of an early version of the system, six students were informally asked to use the system and to comment on it. The students indicated little preference regarding navigation method (hypermedia vs. paths), but they did request shorter, more concise (e.g., 2-4 minute) video segments[2] and less "jargon." As a result, some video clips were shortened, and some modifications were made to the explanations, nodes, and links in the courseware.

A sample screen from the current version of IC-HIP is shown in Figure 1. IC-HIP contains 96 nodes of information (45 text, 41 figure, and 10 video), organized into five topic areas: (1) basic IC technology, (2) the main stages of semiconductor manufacturing, (3)

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[1]Equipped with the appropriate hardware (e.g., a video overlay board and laserdisc player), HIP can play analog video in a window on the screen of the workstation. Since analog video equipment affords slower search and more tape wear, we plan to digitize the video clips in the course. This implementation would also allow us to distribute IC-HIP to a wider audience of users who may not have access to special video equipment.

[2]Video segment lengths originally ranged from 3-6 minutes, with one 11-minute segment. No subjects elected to view the 11-minute segment.

software systems used in IC manufacturing, (4) the Berkeley Microfabrication Facility (Microlab), and (5) world-wide semiconductor markets (see Figure 2). Related information (e.g., process–step parameters and pictures showing the results of processing) is cross-referenced in IC-HIP via 202 hypermedia links and five alternative linear paths (corresponding to the five topic areas), to accommodate both exploratory and linear learning. These paths are: (1) IC Elements, (2) IC Fabrication, (3) Software for IC Manufacturing, (4) The Berkeley Microlab, and (5) IC Markets. A sixth path, The Complete IC-HIP Tutorial, subsumes these five paths. Most of the material in IC-HIP, including node names, types, and links, is given in Schank and Rowe (1992). The topic areas covered in IC-HIP are summarized below.

—Insert Figures 1-2 about here—

Basic IC technology

This section of the courseware provides a review of microelectronic circuit elements and their evolution, including descriptions of basic circuit elements (e.g., resistors, capacitors, and transistors) and the historical discoveries that led to the miniaturization of these elements onto silicon. The functional roles of transistors, and how they work, are described in particular detail. Since the development of the transistor led to the silicon integrated circuit (and a revolution in electronics), it is useful to review the operation of the transistor here. Like a switch, a transistor can either allow or inhibit the flow of electric current in response to an external signal. Consider the transistor shown in Figure 3. When a positive voltage is applied to the gate, electrons are attracted to the area under the gate. These electrons establish a bridge between the source and drain that allows current to flow between them. When this happens, the transistor is "on"; otherwise, it is "off". By connecting together several transistors, large circuits that remember voltages (i.e., memories), or make complex switching decisions based on memories and other inputs, are created.

The properties and virtues of silicon and other circuit substrates (e.g., gallium arsenide) are also discussed in this section. Finally, bipolar and metal-oxide-silicon (MOS) digital logic technologies, and the speed, space, and power advantages of more recent technologies, including complementary MOS (CMOS) and combined bipolar and CMOS (biCMOS), are described.

—Insert Figure 3 about here—

IC manufacturing stages

The major stages of IC fabrication are outlined in this section of the course. The most important step is photolithography, which is the photoengraving process used to transfer a circuit pattern onto the surface of a silicon wafer. Photolithography is described in detail (see Figure 4; cf. Oldham, 1977). Also explained are the processes of oxidation to mask or insulate parts of the circuit, etching to dissolve away portions of the oxide surface, doping to selectively introduce impurity atoms (e.g., boron), which create active circuit elements (see Figure 5), and deposition of thin films of metal to form contacts between device elements. The post-fabrication stages of probing (i.e., functional testing), sectioning, sorting, packaging, and "burn-in" (i.e., final testing), and typical cycle times and yields at each stage, are also discussed here.

—Insert Figures 4-5 about here—

Computer integrated manufacturing (CIM)

The IC manufacturing process is complex, and design and fabrication are usually done independently. The fabrication process alone involves hundreds of steps, resulting in turnaround times of several months. This section introduces some recent computer-integrated manufacturing (CIM) systems that collect and monitor processing data to improve reliability and product consistency. Also described is how CIM systems integrate computer-aided circuit design (CAD) packages, computer-aided manufacturing tools (e.g., work-in-progress or WIP systems), process simulators, facility management systems, and production control and order entry systems, aided by shared integrated databases and formally specified fabrication process-flow representations (i.e., "recipes" that specify the steps needed to make a particular IC).

The Berkeley Microlab

In 1960, microelectronics research began at the Berkeley Microfabrication Facility, the first university IC lab in the world. This section discusses the history of the lab, as well as the kinds of equipment, software systems, and process-flow programming languages (e.g., the Berkeley Process Flow Language, BPFL; Rowe, Williams, & Hegarty, 1991) available in the lab. Software systems developed and used by students in the lab are described, and an example BPFL program is presented in detail (see Figure 6 for a program excerpt). Lab operation (e.g., via an on-line database, query interfaces, and sensor/monitor systems) and lab access are also discussed.

—Insert Figure 6 about here—

World-wide IC markets

Advances in IC technology are driven largely by economic desires for high yield and rapid turnaround time, mass fabrication at low cost, and large shares in the highly competitive, high-volume, electronic markets. One of the most striking characteristics that separates the semiconductor industry from other industries is the rapid change in products, manufacturing processes, and factories. For example, over the past 30 years, chip packages have remained fairly constant in size and price (about $5 per chip). Over the same period, the number of transistors per chip has doubled every year or two, to the point where today a typical chip can contain a million transistors. In the automotive industry, similar growth would have resulted in cars that today get a million miles to the gallon, yet stay the same price as the Model T in the 1920s (around $500)! This section discusses world-wide market economics (e.g., see Figure 7), compares Japanese and U.S. industries, and outlines causes of the declining market share of U.S. companies. Emerging high-volume markets (e.g., broadband communications, advanced display systems, intelligent vehicle and highway systems, and consumer electronics) are also discussed.

—Insert Figure 7 about here—

The empirical goals of the study

Our initial goal was to study performance effects based on prior knowledge of ICs (high- and low-knowledge), method of navigation in IC-HIP (hyperlinks vs. linear paths), and other factors (e.g., subjects' stated interests in ICs, types of media viewed, topic area nodes viewed, and the number of nodes viewed). Because our intention was to provide a foundation for using multimedia and hypermedia to help students learn about semiconductor manufacturing, learning was assessed within on-line conditions only, rather than between paper and computerized delivery media. We note that prior research has found little effect on learning due to instructional configuration (e.g., computer- versus textbook-based), beyond effects of resolution on reading speed (e.g., Clark & Salomon, 1986; Coleman, Koballa, & Crawley, 1992).

Since prior research suggests no main effect of navigation method on learning (e.g., Recker & Pirolli, 1992), we did not expect a significant difference in learning based on navigation method in the present study. Main effects of prior knowledge of ICs on performance seem less predictable (e.g., see Anderson, 1983): One might hypothesize that high-knowledge subjects have an advantage over low-knowledge subjects, since they have prior, organized knowledge about semiconductors into which new information may be easily incorporated, and old knowledge reaffirmed and skimmed. However, high-knowledge subjects also are more likely to see more familiar information and less novel material. They may thus face a greater "selection" problem than low-knowledge subjects, and hence be *dis*advantaged since they have to "filter out" this familiar information when trying to learn new material.

We also analyzed the interaction between prior knowledge and navigation mode. In their studies of LISP instruction, Recker & Pirolli (1992) found that high-ability subjects (by programming performance) learned better in hypermedia, while lower ability subjects learned better in a linear environment. Likewise, an interaction between knowledge[3] and environment is plausible here. Low-knowledge subjects might benefit more by using paths, since cognitive overload of having to decide what hyperlinks to follow may significantly detract a low-knowledge subject's attention from the content of the course. In contrast, high-knowledge subjects may benefit more by using the hypermedia environment, since it supports their learning by allowing them to follow the links most appropriate for them (cf. Schank, Linn, & Clancy, 1993). Finally, it was anticipated that across groups, the kinds and number of nodes viewed would not significantly differ, nor significantly effect learning (the null hypothesis). We turn now to the experimental design.

Method

Subjects

Twenty paid subjects, seven women and thirteen men, were selected from the University of California, Berkeley student population from responses to an advertisement. Subjects ranged in age from 18 to 39, and had various academic backgrounds including engineering/computer science (9 subjects), science education (3 subjects), business/economics

[3]Nb. Knowledge differs from (and can be orthogonal to) ability. That is, one could know a lot about a topic but be a poor learner, and similarly one could know little about a topic but be a good learner.

(2 subjects), and the humanities/social sciences (6 subjects). Subjects were pre-screened for their knowledge of semiconductors: Half reported prior knowledge of semiconductor technology, manufacturing, and markets. The other half reported no prior knowledge of these areas.

—Insert Figure 8 about here—

Procedure

A diagram of the procedure followed is shown in Figure 8. In the first session, which lasted about 30 minutes, each subject was asked to complete a short one-page questionnaire and a 25-question, short-essay pre-test (see Table 1). The questionnaire explicitly asked subjects about their background and interest in the topics covered in the course. In particular, subjects were asked to: (1) quantitatively rate their background and interest in the three main areas of the course (i.e., technology, manufacturing, and markets) on a scale from 1 ("very little") to 7 ("a lot") and (2) provide a written summary of this background. The questionnaires were used as measures of subjects' self-perceived levels of knowledge and interest in semiconductors and computers, primarily to pre-screen them as low- or high-knowledge subjects. The pre-test exam was used to measure subjects' prior knowledge of semiconductors. Subjects were asked to answer as many questions as possible on the pre-test, to keep their written explanations under 40 words, and to aim their explanations to "a hypothetical English-speaking undergraduate unfamiliar with microelectronics technology and industry."

—Insert Table 1 about here—

The next session was scheduled one to five days later, and lasted about 90 minutes per subject. Subjects were given a 5-10 minute introduction to the IC-HIP environment, and were then instructed to use the environment in either hypermedia or path mode for 50 minutes on their own. Half of the subjects (i.e., five high- and five low-knowledge subjects) explored in hypermedia mode, by selecting links indicated by boxed items on the screen and following them via the "Follow" button to whatever topics they desired. The other half selected paths via the "Browse" menu, and followed them via the "Next" and "Previous" buttons through the text, graphic, and video nodes. Subjects were informed that they would be tested on the material in the course, although they were not told how they would be tested.

The nodes viewed by each subject, and the time spent on each node, were recorded on-line as subjects browsed the course. Node-order and node-time measures, that is, what order subjects visit nodes and how much time they spend on each node, are collected automatically by the system. The interviewer sat a few feet away during each session so she could take notes and correct any software problems. She informed the subjects that she would be nearby, reading or doing other work, and the subject could ask for help if problems arose.

After browsing, subjects were asked to answer as many questions as possible on a post-test, and to complete an exit questionnaire. The post-test was identical to the pre-test (see Table 1). Answers to the test questions were explained in various parts of the IC course. The post-questionnaire asked for: (a) suggestions for changes in functionality and organization of the course, (b) suggestions about the helpfulness of various media, (c) the strong and weak points of the course from the user's perspective, (d) their post–instruction interest in microelectronics technology, manufacturing, and markets, and (e) other comments.

Explanations for the individual questions on the pre- and post-tests were "blindly" scored by the first author on a scale from 0 (blank or very poor) to 3 (excellent) based on the accuracy and completeness of the explanation. The maximum score possible on each test was 75 points. An "improvement score" (IS) for each subject was computed as the difference between their post- and pre-test score:

$$IS = \text{post-test score} - \text{pre-test score}$$

Since having more prior knowledge means that a subject is less likely to see (and hence learn) as much novel material in IC-HIP, another learning score, called the "learning rate" (or "proportion remaining learned"), was also calculated for each subject. This learning rate (LR) score takes into account the maximum amount of information unknown by a subject. Consequently, it corrects for the "selection" problem mentioned earlier. LR was computed as the ratio between the improvement score (IS), and the amount "left to learn" at pre-test time:

$$LR = IS / (75 - \text{pre-test score})$$

With any study, the methodology both enables and constrains the kinds of results observed. For example, in the present study, results may have varied with longer or unlimited periods of courseware use. Also, subjects may have remembered and maintained their answers from pre- to post-test, sometimes called "predictive intransigence" (Ranney, 1987/1988), and using an isomorphic rather than an identical post-test may have yielded different results. Increasing the number of subjects, and using multiple test-scorers (with acceptable inter-scorer agreement) may also have increased the power of the study. Further, the study does not examine "unlearning" effects (i.e., the reversal of incorrect prior knowledge), and hence may underestimate improvement (IS) and learning rate (LR) scores. Finally, correlations between other independent measures (e.g., natural ability, reading comprehension/speed, personality styles) and performance may be significant, but were not examined.

Researchers must weigh the importance of factors like these when designing studies. Balancing the usefulness of the results with the work required to achieve statistical significance can be difficult; for instance, narrow studies reporting significant results may have limited utility. The design of the present study was created and refined to satisfy both experimental reliability and resource constraints, the latter of which limited the number of participants, treatment time, and test scorers. Hence, the results should be interpreted cautiously. However, we note that the study is exploratory and part of an ongoing investigation, and welcome future effort (by ourselves and/or others) to replicate and expand the present study.

Results

Seventy-five points were possible on both the pre- and posts-tests, and the maximum score obtained by any subject was 51 (on a post-test), which suggests that there was no ceiling effect. Pre-test scores ranged from 0 to 40, post-test scores ranged from 7 to 51, and improvement scores ranged from 7 to 23. Tables 2 and 3 give the mean pre-test and improvement scores, respectively, by group. Subjects were divided into low- and high-knowledge groups based on the pre-test. As hoped, subjects' self-reported knowledge was predictive of their measured knowledge: the correlation between subjects' self-reported knowledge (e.g., knowledge of IC technology, IC manufacturing, IC markets, and computer technology) and pre-tests scores (by category) was significant (r=.52 to r=.7, p<.05). Correlations between subjects' knowledge (as measured by the pre-test) and their stated pre-instruction interest in IC fabrication (r=.52) and GUI interfaces (r=.53) also were significant (p<.05).

Knowledge, navigation, and other effects on performance

Neither pre-instruction interests, nor nodes viewed (by number, topic area, or media type), were significantly correlated with learning (either IS or LR). Two ANOVAs, with knowledge and navigation method as independent factors, were conducted. The improvement score (IS) was the dependent measure in the first analysis, and learning rate (LR) was the dependent measure in the second analysis. Each ANOVA had five subjects per cell. Tables 3-4 show mean improvement and learning rate scores by group.

—Insert Tables 2-4 about here—

The results in Table 3 suggest that low-knowledge subjects may have improved slightly more than high-knowledge subjects, particularly in the hypermedia mode. However, these apparent differences are not reliably different. The correlation between pre-test scores and improvement was not significant, and for improvement (IS), an ANOVA indicated no significant effects of knowledge ($F(1, 16) = 3.516$, $p = .079$) or navigation method ($F(1, 16) = .473$, $p = .502$), nor a significant interaction of knowledge by navigation method ($F(1, 16) = 2.0$, $p = .176$). Similarly, the results in Table 4 suggest that high-knowledge subjects (e.g., in the path condition) learned at a higher rate (LR) than low-knowledge subjects. Indeed, learning rate correlated significantly, and positively, with prior knowledge ($r=.46$, $p<.05$). However, an ANOVA indicated that these apparent learning rate differences are not reliably different: there were no significant effects of navigation ($F(1, 16) = .247$, $p = .626$) or knowledge ($F(1, 16) = .081$, $p = .778$), nor an interaction of knowledge by navigation method ($F(1, 16) = 2.164$, $p = .161$).

Media and topic area nodes viewed

During the 50 minute session with IC-HIP, subjects viewed 28 nodes on average. Path subjects tended to view at least the beginning of four of the five unique paths. (Recall that the sixth path subsumes the others.) Table 5 shows the mean number of nodes viewed by prior knowledge and navigation mode. The results suggest that high-knowledge subjects tended to view more material about IC fabrication and computer integrated manufacturing than did low-knowledge subjects. However, the correlations between prior knowledge and nodes viewed (by number, topic area, or media type) were not significant. Similarly, the results in Table 5 suggest that, compared to subjects in hypermedia mode, those who followed the linear-paths tended to view more material on basic IC technology and fabrication, and less on computer integrated manufacturing, the Berkeley Microlab, and IC markets. However, correlations between navigation mode, and nodes viewed (by number, topic area, or media type) were not significant. Also, there were no significant correlations between subjects' stated pre-instruction interests and the topic areas they actually visited. Neither were topic areas viewed correlated with post-instruction interest on the topic, except that subjects who viewed nodes on IC markets reported significantly more interest in markets on the post-questionnaire (r=.584, p<.05).

—Insert Table 5 about here—

Compared to subjects in the path condition, subjects in the hypermedia condition crossed over from one of the five major topic areas to another (i.e., followed a link that bridged two topic areas) *more* often, and changed between media types (e.g., went from reading text to viewing a video or figure) *less* often. In particular, hypermedia subjects changed topic-areas twice as often as subjects in the path condition (11.8 average topic changes for hypermedia subjects, vs. 5.0 average topic changes for path subjects), and explored different media types about half as often as subjects in the path condition (14.4 average changes for hypermedia subjects, vs. 24.7 average changes for path subjects). Average topic area and media type changes did not differ between low- and high-knowledge groups.

Discussion

Results suggested that navigation mode, interests, and number of nodes viewed were not correlated with learning. However, the significant positive correlation between pre-test scores and learning rate (LR) suggests that prior knowledge about semiconductors helped subjects learn from IC-HIP. That is, having prior knowledge may have helped subjects incorporate new information and reaffirm/skip old information. (Recall that the learning rate calculation somewhat corrects for the "selection" problem of having to filter out familiar information.) However, the ANOVAs indicated no significant main or interaction effects for either improvement (IS) or learning rate (LR). Taken together, these results suggest that advantages of prior knowledge for learning from IC-HIP may not be robust.

Audit trail analyses revealed that, compared to path subjects, subjects in the hypermedia condition changed topic areas more often, and changed media types less often. This suggests that the hyperlink subjects surveyed topic areas rather than explored them in depth. However, the total number of nodes visited (by number, topic area, or media type) did not significantly differ by knowledge or navigation group, suggesting that subjects (by group) attended to roughly the same amount of material in each topic area, and in each media format. Finally, prior knowledge and interests were not predictive of nodes actually visited. Post-instruction interest in IC markets was higher for subjects who viewed nodes in the world-wide markets section, perhaps because this material was new to most subjects and may have held more immediate import in their daily lives.

In sum, even though subjects in the hypermedia condition tended to change topic areas more often, there were little or no IS or LR learning differences by group. We have learned much in developing and assessing IC-HIP, and encourage further refinement and study of on-line hypermedia and multimedia instruction on semiconductor manufacturing.

Future Work

IC-HIP can be viewed as a "first-generation" multimedia system (e.g., one using analog video). Several graduate students and faculty have expressed considerable interest in IC-HIP, but currently the courseware is too expensive and cumbersome to deploy because it is a large Lisp system that requires special purpose hardware (e.g., video overlay boards and laserdisc players). However, we view these limitations as temporary. The eventual benefits of interactive multimedia environments with video seem promising, particularly for students who enjoy individualized, interactive, instruction (e.g., for students who have been out of school for a while and feel timid in a classroom environment, or who want to supplement their learning in a particular course, or who simply prefer an interactive multimedia environment to reading a book or waiting for the appropriate course to be offered). "Second generation" multimedia systems will be smaller and faster, and they will use digital video stored on-line using video compression/decompression chips (cf. Rowe & Smith, 1992). To advance in the direction of second generation multimedia systems, we are adopting a C-based multimedia toolkit and developing video playback utilities for digitized video.

Credits

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Table 1. Pre- and post-test questions.

1. What are transistors , and how do they work?
2. Why is silicon used to make IC's?
3. What is a semiconductor?
4. Who built the first IC chip, and what key inventions led to its development?
5. How are silicon wafers made?
6. What is photolithography?
7. What are photomasks, and how are they made?
8. What are the advantages and disadvantages of UV, X-ray, and electron-beam lithography?
9. Why are impurities added to a wafer during the fabrication process? How are they added?
10. How are circuit patterns generated and transferred to a wafer?
11. What are the major stages of IC manufacturing?
12. Why is the wafer surface usually oxidized before the circuit pattern is transferred to it?
13. Why are electron-beams used to write circuit patterns onto photomasks but not wafers?
14. How are microelectronic chips packaged?
15. After a circuit pattern is transferred to the surface of a wafer, how is it etched in??
16. How are metal contacts between circuit elements deposited on a wafer?
17. What is "computer integrated manufacturing"?
18. What is "work-in-progress" (WIP)?
19. What is the Berkeley Microfabrication lab, and how does it support UC students?
20. What software systems aid fabrication in the Berkeley Microlab, and how do they help?
21. What is a "process-flow" specification? How are process-flows specified in BPFL?
22. What are some distinctive characteristics of the IC industry, relative to other industries?
23. When (and why) did Japan surpass the US in IC chip production?
24. What are important, high-volume, future IC chip markets? Why are they important?
25. How (and why) have IC chip costs changed over the past 20 years?

Table 2. Mean pre-test scores by knowledge and navigation method.

Pre-test	Hyperlink	Path	Overall
Low Knowledge	3.2	4.4	3.8
High Knowledge	31.6	31.4	31.5
Overall	17.4	17.9	17.6

Table 3. Mean improvement scores (IS) by knowledge and navigation method.

Improvement score	Hyperlink	Path	Overall
Low Knowledge	16.0	13.8	14.9
High Knowledge	10.0	14.2	12.1
Overall	13.0	14.0	13.5

Table 4. Mean learning rate (LR) by knowledge and navigation method.

Learning Rate	Hyperlink	Path	Overall
Low Knowledge	.224	.197	.211
High Knowledge	.239	.323	.281
Overall	.231	.260	.246

Table 5. Mean number of nodes viewed by prior knowledge and navigation mode.

	Low-Knowledge		High-Knowledge		
Topic area	Hypertext	Path	Hypertext	Path	OVERALL
Technology	6.6	13.6	4.8	10.8	9.0
Fabrication	6.6	11.2	9.0	15.6	10.6
CIM	2.2	0.4	3.6	2.0	2.1
Microlab	4.2	1.4	3.2	1.6	2.6
Markets	5.4	1.0	4.8	2.6	3.5
Media type					
Text	17.2	16.0	16.4	17.6	16.8
Figure	6.4	9.0	7.2	9.8	8.1
Video	2.8	3.0	2.0	3.0	2.7
OVERALL	26.4	27.8	25.6	30.4	27.6

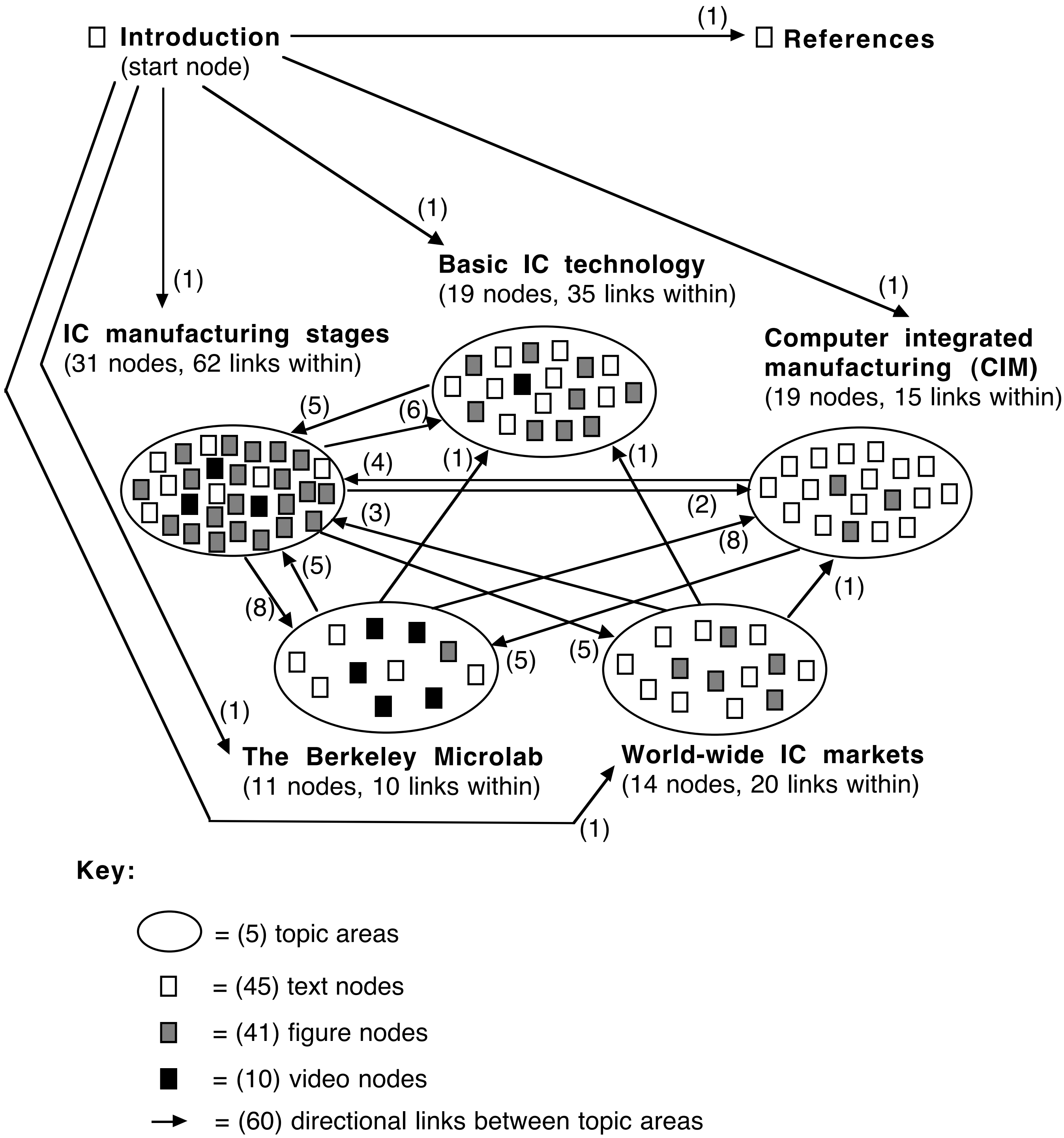

Figure 2. A diagram of IC-HIP. The (142) links between nodes within topic areas are not shown.

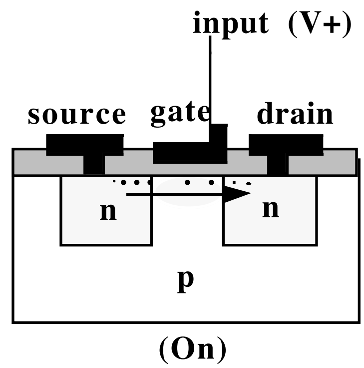

Figure 3. An negative metal-oxide-silicon (NMOS) transistor.

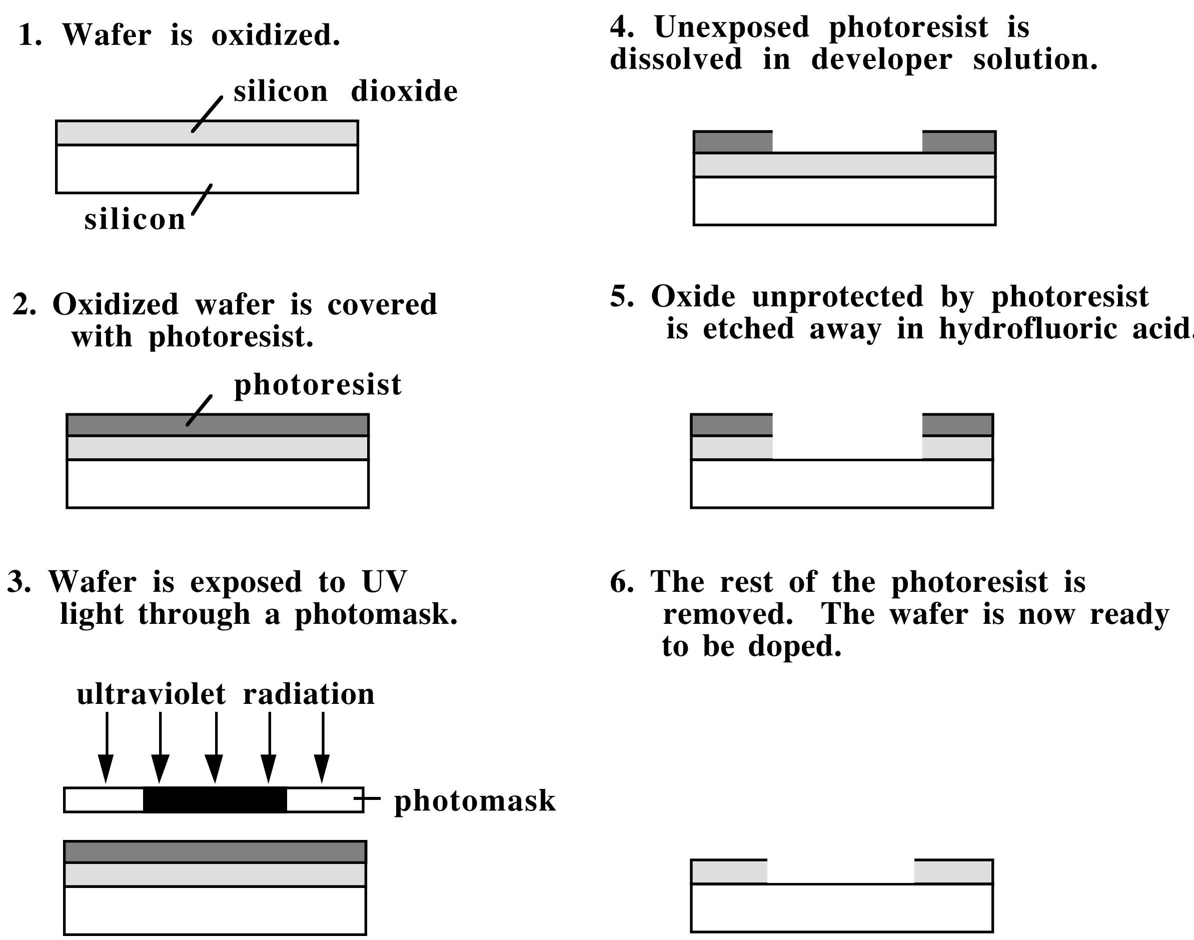

Figure 4. Typical stages of photolithography.

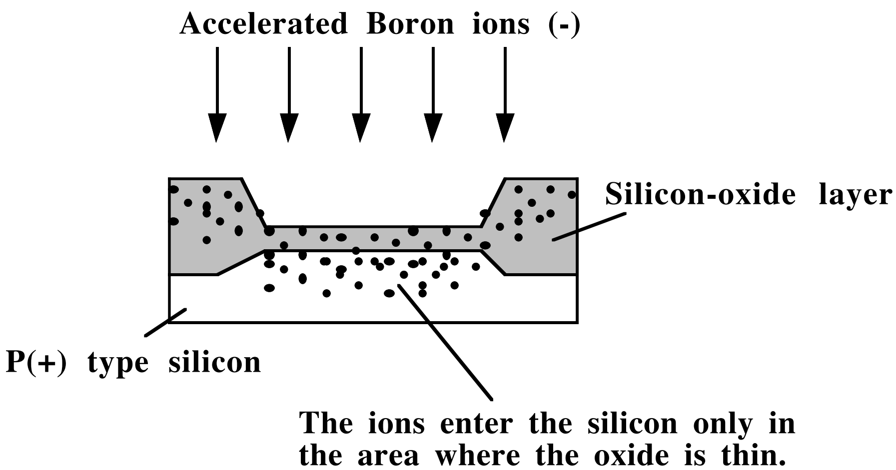

Figure 5. Doping (ion implantation) process to modify the electrical properties of the silicon.

```
step START-OXIDE begin /* oxidize wafer surface */
        std-dry-oxidation(thickness: {58 nm}, temperature: {900 degC});
end;
```

Figure 6. Excerpt from a CMOS fabrication process-flow (oxidation step), specified in BPFL.

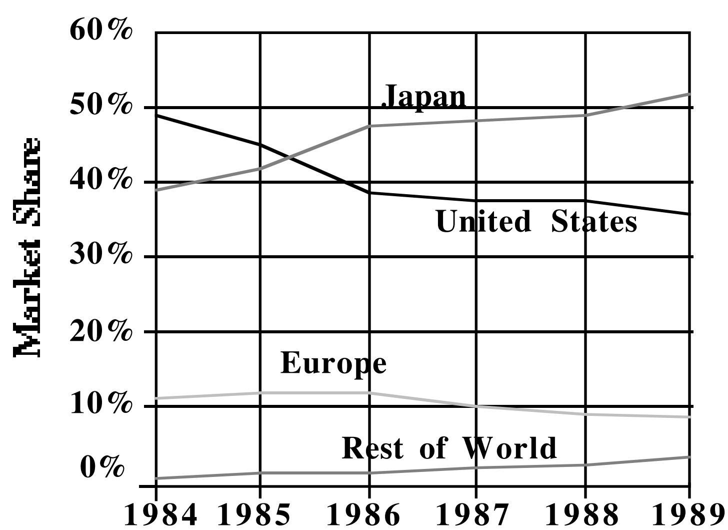

Figure 7. World IC production by region.

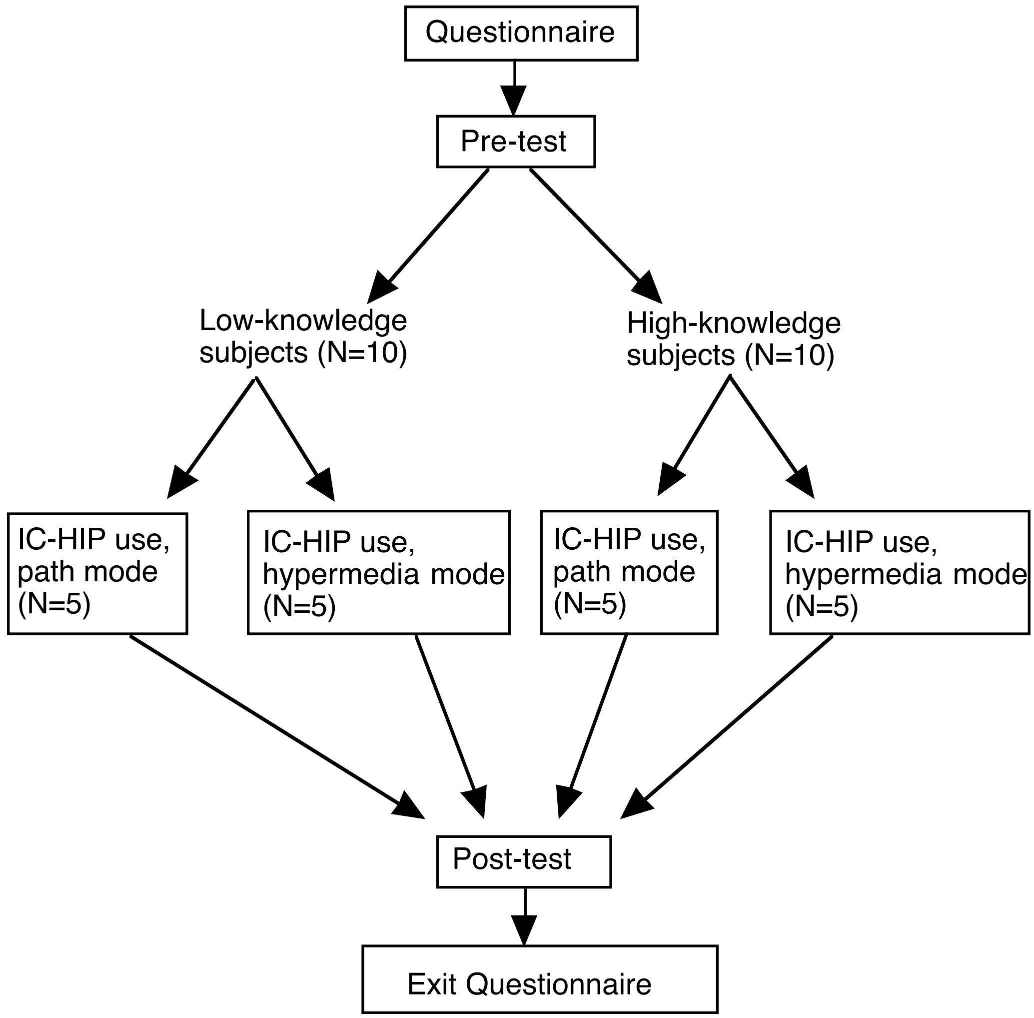

Figure 8. Diagram of methodology.