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An Investigation of the Uses of Scanning Electron Microscopy in the Analysis of the Substructure Morphology of Semiconducting Devices

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Abstract

The purpose of this study is to determine the technical requirements of SEM failure analysis in regard to its' inclusion in the Energy and Power curriculum of the Department of Industrial Technology, University of Northern Iowa.

AN INVESTIGATION OF THE USES OF SCANNING ELECTRON MICROSCOPY IN THE ANALYSIS OF THE SUBSTRUCTURE MORPHOLOGY OF SEMICONDUCTING DEVICES

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CHAPTER 1

INTRODUCTION

Background of the Problem

Recent discoveries in certain scientific and/or industrial facilities have major implications for the field of Industrial Technology. Caused by a need for lower costs and higher performance, new advanced materials are being used in novel applications for industrial manufacturing. Two prominent recent examples of this type of innovation, in the electronics field, are computer memory technology and superconductivity.

Technological innovation, of this sort, requires a basic understanding of the materials being utilized. Basic and applied research into the structure of any material requires familiarity with the tools and processes used in materials analysis. A principal tool used in material analysis is the electron microscope. Commercially available for about 40 years, thousands of electron microscopes have been sold as research or analysis devices. The introduction of the Scanning Electron Microscope (SEM), some 20 years ago, revolutionized the field of electron microscopy and broadened its scope (Watt, 1985, p. vii). Features such as high resolution, high useful magnification and an extraordinary depth of field make the SEM a very important analytical tool (Von Heimendahl, 1980, p. 36).

A major user of Scanning Electron Microscopy technology, in the last few years, has been the electronics industry, accounting for nearly half of all SEM sales (Newbury, Joy, Echlin, Fiori & Goldstein, 1986, p. 45). The SEM has become a integral tool of the design, manufacturing and service processes for all current and future semiconductor devices.

> The SEM offers modes which allow the operation of devices such as switches, transistors, and even complete integrated circuits, to be observed under conditions which approximate those of normal use. As the size of devices has been reduced to the micrometer scale, and as devices themselves become more complex, the fact that the SEM can combine imaging and chemical microanalysis with such facilities as the ability to identify electrically active defects, or measure voltages, make it in many cases the most versatile tool for characterization, diagnosis and failure analysis (Newbury, et al., 1986, p. 45).

An understanding of the capabilities and innovations possible of Scanning Electron Microscopy is dependent on a knowledge of the techniques used.

> Materials analysis laboratories that support manufacturing processes in many semiconductor facilities bring together a combination of techniques to support basic research, assist in process development, solve production problems, provide quality-control and quality-analysis programs, and perform failure analysis for products in the field (Kladnik, Schiefelbein & Gill, 1986, p. S22).

The need for the Industrial Technologist to be familiar with the capabilities of SEM technology is apparent, regardless of their particular field of emphasis. The capabilities and range of innovative application is equally meaningful for research and development, manufacturing, production and quality control (M. F. Fahmy, personal communication, June 15, 1987).

> As technological innovations produce changes in skill and knowledge requirements, the content of training will have to be modified accordingly. Training curricula may have to put the accent on the development of cognitive and analytical skills instead of manual skills. Curriculum planners will also have to consider altering the relative weight of various technical disciplines that prepare trainees for particular occupations or jobs. Thus curricula may increasingly stress the development of electronics and computer-related knowledge and skills at the expense of, say, mechanical engineering skills. In some cases minor, and therefore easily managed, additions to existing curricula may be the best response to changes in skill requirements (Alfthan, 1985, p. 526).

Statement of the Problem

The problem of this study was to determine the capabilities of Scanning Electron Microscopy technology on the surface analysis and substructure morphology of an Electrically Programmable Read Only Memory (EPROM) device, an integrated chip and a silicon wafer.

Purpose of the Study

The purpose of this study is to determine the technical requirements of SEM failure analysis in regard to its' inclusion in the Energy and Power curriculum of the Department of Industrial Technology, University of Northern Iowa.

Research Questions

This study will have the following research questions:

1. What are the capabilities of the SEM in regard to failure analysis of micro-electronic devices?
2. What procedures and/or specialized knowledge is required to conduct SEM failure analysis of micro-electronic devices?
3. Is the SEM a viable tool for failure analysis of micro-electronic devices?
4. What are the limitations of the SEM in regard to micro-electronic failure analysis?

Delimitations

This study was delimited as follows:

Service related micro-electronic failure analysis is difficult to conduct because failed components are usually discarded. This limitation on population was overcome by procurement of a silicon wafer containing a sample selection of over 100 integrated chips. The manufacturer had established that a portion of the chips contained on this wafer were operationally defective.

Limitations

This study was limited as follows:

1. This study was conducted using the Hitachi S-570 Scanning Electron Microscope. Techniques and

Procedures are, therefore, specific to that apparatus.

2. The micro-electronic devices analyzed were a limited sample. They were an EPROM device, an integrated chip and a silicon wafer,which contained over a 100 integrated circuits.
3. This study will not the address magnetic, voltage or Electron Beam Induced Current contrast capabilities of SEM technology, due to a lack of specialized equiptment necessary for that type of micro-electronic analysis.

Assumptions

This study has the following assumptions:

1. The techniques used in the failure analysis procedures of this study are applicable to any other available micro-electronic devices.
2. The reader of this paper will have knowledge of the basic characteristics and operational relationships of a Scanning Electron Microscope.
3. The technology used in the failure analysis of electronic semiconductor devices is applicable to other disciplines in the field of Industrial Technology.

Definition of Terms

The following terms were defined for the purpose of this study:

<u>EPROM</u> -- An 8192 word by 8 bit ultraviolet erasable and electrically programmable read-only memory integrated electronic semiconductor device.

<u>Integrated Chip</u> -- A type of circuit in which all the components are constructed on a single tiny chip of silicon.

<u>Silicon Wafer</u> -- A three inch circular disc containing over 100 integrated circuits. Made of silicon material, the wafer is the product on which integrated circuits are manufactured. Individual integrated circuits are then tested for operational performance and standard of quality before being mounted in individual devices.

<u>Scanning Electron Microscopy</u> -- A branch of electron microscopy utilizing the unique characteristics of the Scanning Electron Microscope.

<u>Morphology</u> -- A branch of materials analysis dealing with the form and structure of materials.

<u>Scanning Electron Microscope</u> -- A device made up four systems: illuminating/imaging, control, display and vacuum. Analogous to a light microscope, the SEM uses an electron beam to provide the required illumination for analysis of various items. SEM utilizes a set of electromagnetic lenses in contrast to the glass lenses used in light microscopy.

CHAPTER 2

REVIEW OF THE LITERATURE

Recent technological innovations have begun to influence the way industry is approaching the problems and opportunities of manufacturing, design, research and operational management. Capabilities exist in industry, unknown just a few years ago, and the pace of technical innovation is accelerating. Products are being researched, designed, produced, and marketed in a fraction of the time considered normal just a few years ago. The ability to innovate, in process, product or material, is becoming an important key to the success of every industrial endeavor. Nowhere is this more evident than in the semiconductor industry. The manufacture of new products or devices is requiring novel innovations in materials science. This is resulting in a increase in the importance of materials analysis.

The ability to understand surface and subsurface features of electronic materials is becoming a very crucial aspect of the electronic industry. Developmental changes and the application of new innovative analysis techniques have changed the capabilities of electron microscopy so that this technology has been the medium of electronic analysis.

Surface Analysis

The ability to use a material, for whatever application you have in mind, is linked to your understanding of the basic structure of that specific material. To see and understand is the first step required in the field of innovative materials usage. Gibson (1985) has stated:

> Instruments that can "see" the atom are becoming essential to fabricate and diagnose electron devices - integrated circuits as well as discrete devices ... Tools are needed to observe the devices ... but unfortunately the wavelength of light limits the resolution of the venerable optical microscope to typically several tenths of a micron (p. 38).

This limitation, imposed on the materials analyst, was a problem until recent technology transfers from the field of electronics. The electronics industry, requiring a better understanding of the intricate workings of their products, adopted certain procedures and tools from the science of biology.

> The new technology combines the power of computer analysis with an electron microscope specially built to magnify living tissue samples and display them in 3-D on a video screen. Originally developed to help biologists unravel the cellular structure of the human body, these techniques are also being used to determine the durability of ceramics and other materials and the quality of integrated circuits on a semiconductor chip (Bass, 1984, p. 66).

As the complexity has increased and size of the electronic devices has shrunk, the problem of failure analysis and quality control has become harder and harder to understand. The instrument of choice, for many electronic analysts, has become the Scanning Electron Microscope (SEM). Goldstein, Yakowitz and Newbury (1977) have declared:

> The scanning electron microscope (SEM) is one of the most versatile instruments available for the examination and analysis of the microstructural characteristics of solid objects. The primary reason for the SEM's usefulness is the high resolution which can be obtained when bulk objects are examined (p. 2).
>
> In the United States, instruments with relatively high resolution are used by many semiconductor companies, including IBM, AT&T, Hewlett-Packard, Xerox, Texas Instruments, Rockwell International, Monsanto, and Motorola.... Scanning electron microscopes are routinely used for line-width measurement in integrated circuits and for studies of circuit patterns. In addition a growing number of semiconductor research and development laboratories use electron microscopes for diagnostics and failure analysis (Gibson, 1985, p. 39).

The review of the literature indicates that the use of the SEM is crucial to the analysis of the certain surface features of micro-electronic devices. Techniques for pattern line-width measurement have been developed which are becoming increasingly important to device operation. Yamaji, Miyoshi, Kano and Okumura (1985) have stated that:

> Since the pattern linewidth becomes smaller and smaller, even a small change in pattern linewidth gives rise to remarkable

> change in the device characteristics. Therefore, it is extremely important to measure the pattern size with high accuracy and reliability (p. 97).

Substructure Morphology

The application of SEM procedures and techniques can be applied to other problems of electronic manufacture and fabrication distinctly different than surface analysis. The literature indicates that another important use of SEM technology is in the study of the surface and subsurface topography or morphology of microelectronic devices (Davidson, 1983, p. 672; Seiler, 1983, p. R1; & Sasov, 1985, p. 1109). According to Sasov (1985):

> The main aim of an overwhelming majority of microstructure investigations is the study of the inner structure of objects... 3-Dimensional reconstruction of microobjects in millimetre and micron ranges is necessary in defectoscopy, material sciences, in non-destructive tests of semiconductor devices and integrated circuits in particular, as well as in biology, geology, physics, chemistry, medicine etc... In all cases computerized microtomography in SEM obtains unique data, which cannot be obtained by any other method of investigation (p. 1109 -1110).

The ability of the SEM to obtain data about the structure and operation of microelectronic devices is possibly the area in which the greatest potential use exists for this technology. Certain uses of SEM techniques, procedures and processes are more important than others. As with all new technology, the questions raised via the use of these techniques and procedures greatly outnumber the questions answered. Gibson has stated (1985):

> Perhaps the most potent application of high-resolution electron microscopy in the semiconductor industry is the study of interfaces. These play a dominant role in the operation of most semiconductor devices, yet in many cases the atomic structure of the interfaces is poorly understood (p. 42).

The available literature has indicated that the field of electron microscopy, and especially the field of Scanning Electron Microscopy, are having a major impact on the electronics industry. The procedures and techniques of Scanning Electron Microscopy have, within the last few years, revolutionized the basic processes of research, design and fabrication of electronic devices. A major area of future research in the field of electronics will require a basic understanding and appreciation of the impact of electron microscopy.

CHAPTER 3

METHODOLOGY

The data for this study was obtained by application of a modified failure analysis procedures technique specified by the American Society for Metals (1975c). The procedures were modified only, in regard to deleting those procedures unsuitable for semiconductor analysis.

Failure Analysis Procedures

The failure analysis procedures utilized in this study are modified techniques, outlined by the American Society of Metals, and presented in SEM: A User's Manual for Materials Science, (Gabriel, 1985, p. 95). An outline of the modified failure analysis procedures is listed below:

1. Collection of background data and selection of samples.
   a. Determination of all details surrounding the failure.
   b. Determination of the history of the failed component.
   c. Preliminary reconstruction of the sequence of events leading to the failure.
2. Preliminary examination of the failed component. The specimens are visually examined with the

unaided eye and also using the 15X - 30X magnification on a stereo microscope.

3. Selection, identification, preservation and cleaning of specimens.
4. Macroscopic examination and analysis of surfaces.
5. Microscopic examination and analysis of surfaces.
6. Determination of failure mechanism.
7. Analysis of all evidence, formulation of conclusions and report writing.
   a. The results of steps 1-6 are compiled and their interrelationship interpreted.
   b. Recommendations for corrective actions to avoid future similar failures are presented.

Population

The population of this study consists of three different semiconductor devices. A commercially available 64K Ultraviolet EPROM device, a special non-insulated integrated chip and an exposed silicon wafer containing many semiconductor devices or chips.

Data Collection

Data collected for this study consist of a series of photographs, taken on two separate occasions, directly from the Cathode Ray Tube of the display system of the Hitachi S-570 Scanning Electron Microscope. Numbered and labeled photographs are used for examination and illustration of specific analysis procedures. Specified areas studied, via this analysis procedure, will be in the use of the SEM in regard to surface examination for contaminants, topographic contrast and subsurface morphology. Visual analysis of the photographs will reveal details of both surface and subsurface construction.

CHAPTER 4

PRESENTATION AND ANALYSIS OF THE DATA

The research data, for this study, was gathered during two separate visits to the SEM lab. Data was obtained by examination of several micro-electronic devices via SEM. Photographs were taken from the Cathode Ray Tube of the Hitachi S-570 SEM for visual analysis.

EPROM Analysis

The EPROM chip was analyzed during the first visit to the SEM lab. Because of the nature and physical construction of the EPROM chip, results were inconclusive. Prior to this laboratory visit, the EPROM device was subjected to a 400 volt charge. Initial attempts to examine this device were unsuccessful because of a unnoticed protective glass cover. Removal of this cover resulted in unwanted widespread contamination of the circuitry surface. This is vividly shown in photograph number 100, Figure 1. Removal of the EPROM device from the SEM examination chamber and cleaning of the specimen resulted in a better analysis pictures as shown in photograph 101, Figure 2.

Physical interaction between the electron beam and the insulating material of the chip housing resulted in poor resolution and was the cause of poor quality photographs. Additional interference, due to the physical location of the EPROM chip, resulted in distorted and fuzzy photographs. Increasing the magnification of the SEM did not significantly improve the quality of the resulting pictures. Additional details were observed but the quality of the resulting pictures still suffered from distortion and fuzziness. Photographs 102 and 103, Figures 3 and 4, provide visual confirmation of this event.

Figure 1. Contaminated EPROM surface taken with SEM at 25,000 volts SEM accelerating voltage, magnification 100X, magnification bar 0.30 mm.

__Figure 2__. EPROM surface after cleaning, 25,000 volt SEM accelerating voltage, magnification 100X,0.30 mm magnification bar.

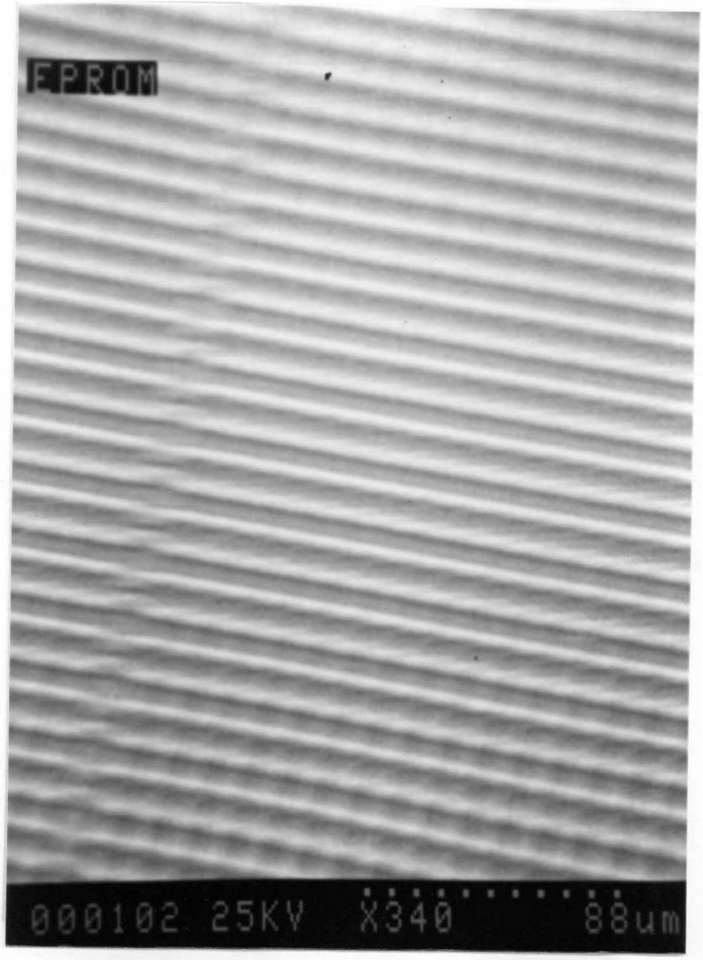


Figure 3. EPROM surface topography, 25,000 volt SEM accelerating voltage, magnification 340X, 88 μm magnification bar.

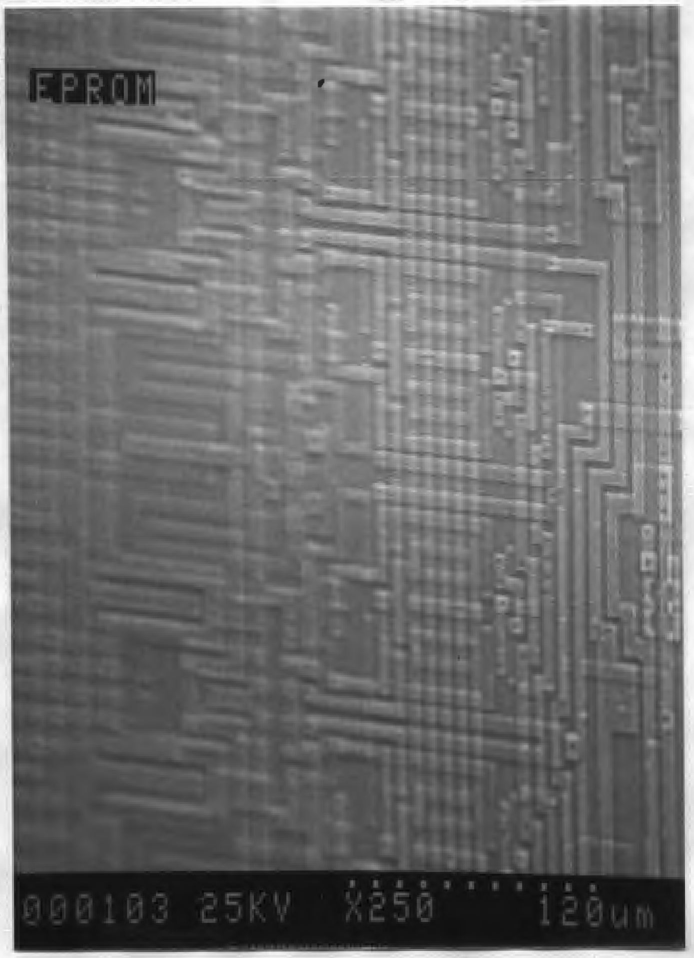
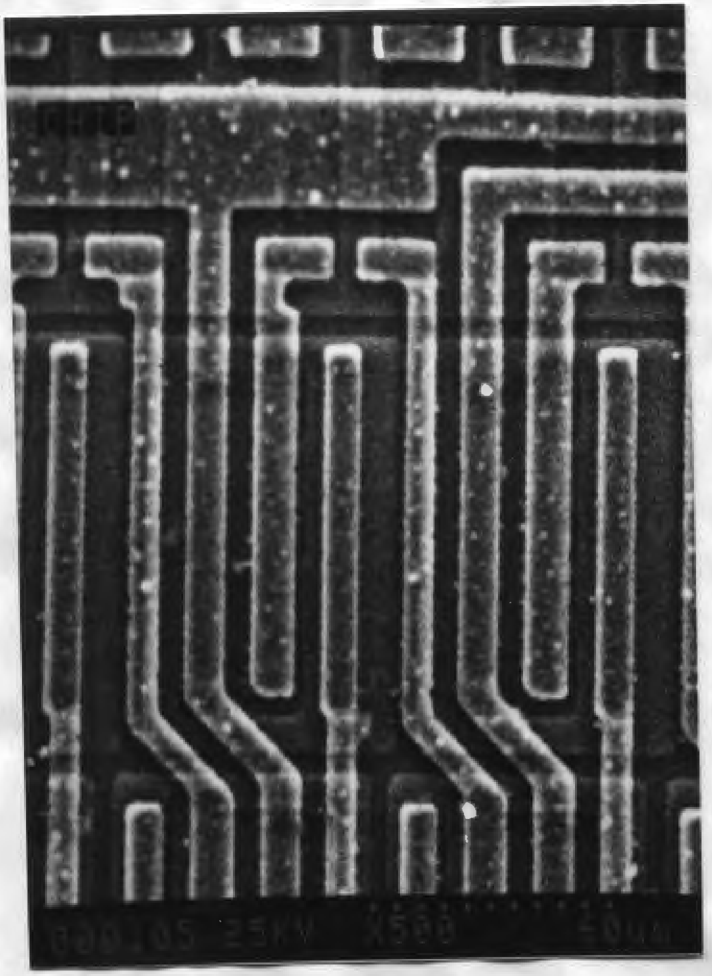


Figure 4. EPROM circuitry layout, 25,000 volt SEM accelerating voltage, magnification 250X, 120 μm magnification bar.

Integrated Chip/Silicon Wafer Analysis

The solution to this problem of poor resolution, inferior picture quality and insulating material interference required better sample selection techniques. Additional micro-electronic devices were obtained for analysis purposes. The devices obtained for analysis were an special non-insulated integrated chip and a silicon wafer. Noticeable improvements in both resolution clearity and picture quality resulted from this decision. With improved resolution, the capabilities of the SEM for surface examination, topographic contrast and substructure morphology were evident.

Examination of the surface structure and substructure of both the silicon wafer and the integrated chip revealed details of the quality required for the manufacture of multi-layered semiconductor devices. Proper magnification settings can allow an analyst to trace the surface and subsurface structure of an electronic device for comparison with design specifications. Quality control analysis of manufacturing processes can be traced, via this method, gathering specific information on the cause or mode of failure. Pictures 105 and 108, Figures 5 and 6, are illustrative of this technique. Specific details of the surface and subsurface arrangement of this electronic device are readily available during this procedure. Improper arrangement of gating, variable linewidth, and damaged or surface contaminated integrated circuitry can be readily identified using this technique of SEM surface analysis. Additional capabilities of SEM technology, unaddressed in this research project, exist for magnetic, voltage and current contrast. These special analysis techniques provide data about operational failures of micro-electronic devices.



<u>Figure 5</u>. Integrated chip with surface and subsurface details visible, 25,000 volt SEM accelerating voltage, magnification 500X, 60 μm magnification bar.

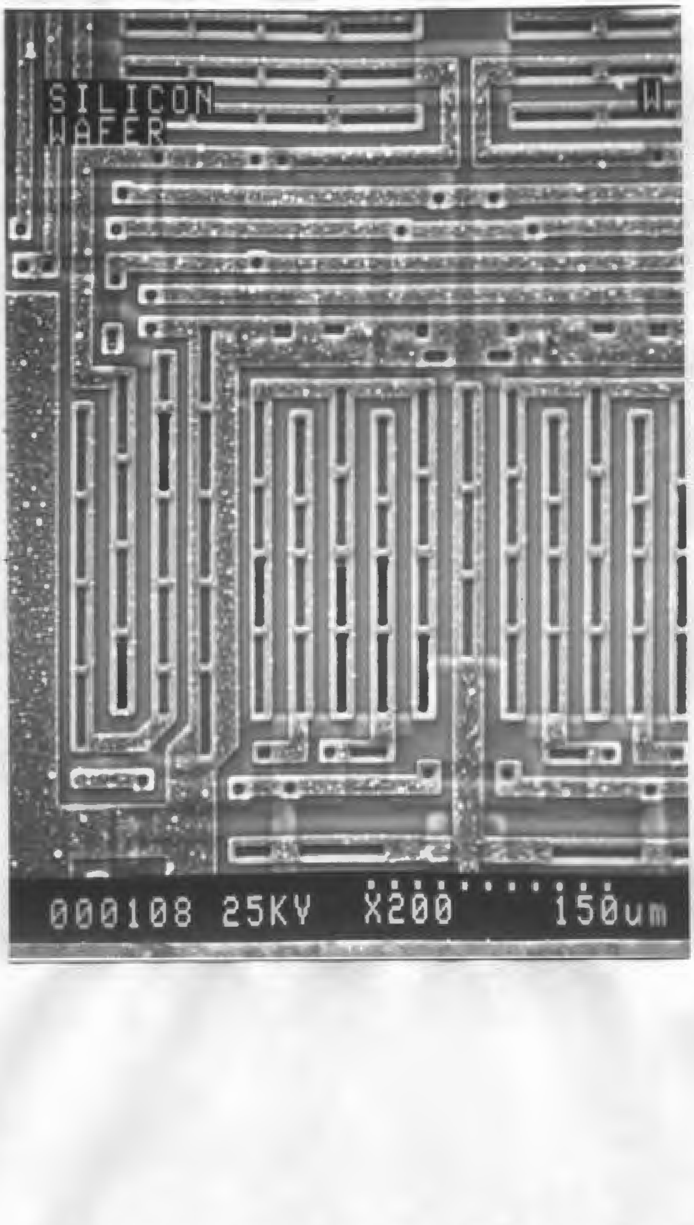


Figure 6. Silicon wafer with surface and subsurface details visible, 25,000 volt SEM accelerating voltage, magnification 200X, 150 μm magnification bar.

Surface analysis of an electronic device can reveal details about the condition of that device previously unknown. Photograph 106, Figure 7, is illustrative of this analysis technique. Details of surface contamination and a possible defective area (upper right edge of the photograph) are seen in this photograph. Closer inspection of the possible defective location shown in photograph 107, Figure 8 and identified by the letter C, revealed that the defect was of surface contamination rather than as the result of damage to chip gating or line width.

Additional details of the layered substructure of this integrated chip are also revealed in the photograph. Analysis of that layered arrangement is another procedure facilitated by the unique characteristics of SEM technology. The exact placement of layered devices, in relationship to each other, is crucial to the proper operation of multi-layered devices. Substructure placement can be observed using this capability of SEM technology. This is illustrated in photograph 106, Figure 7.

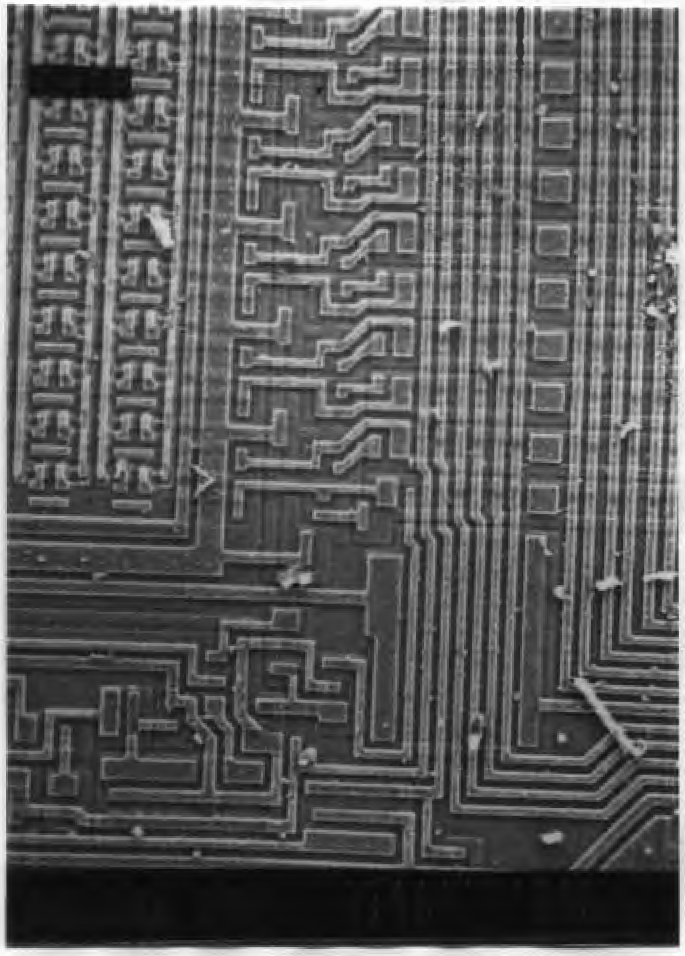


Figure 7. Chip surface and subsurface showing surface contamination and layered arrangements, 25,000 volt SEM accelerating voltage, magnification 150X, 200 μm magnification bar.

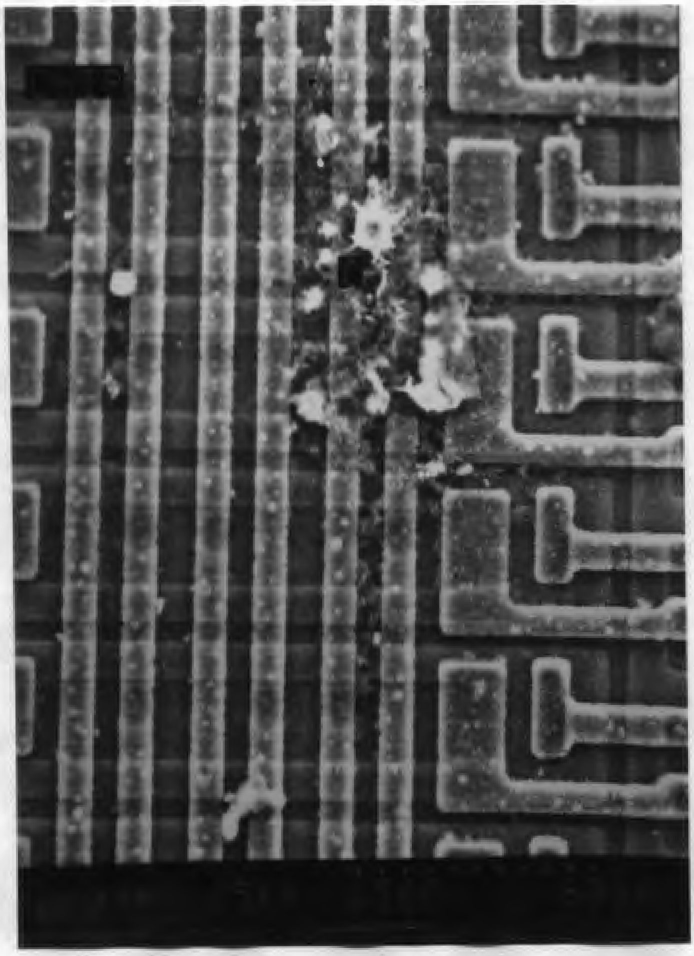


Figure 8. Closeup of chip contamination source (letter C),25,000 volt SEM accelerating voltage, magnification 500X, 60 μm magnification bar.

Substructure morphology can be further examined using increased SEM magnification which will allow detailed examination of the structure of the materials used in the manufacture of this micro-electronic device. To demonstrate this capability, a series of photographs were taken of a specific section of the silicon wafer. Increased magnification revealed the impurities in the silicon material used in the manufacturing process. Photographs 109, 110 and 111, Figures 9, 10 and 11 respectively, reveal with increasing detail the imperfections and impurities of the silicon material used in the manufacture of this device.

<u>Figure 9</u>. Silicon wafer substructure morphology, 25,000 volt SEM accelerating voltage, magnification 500X, 60 μm magnification bar.

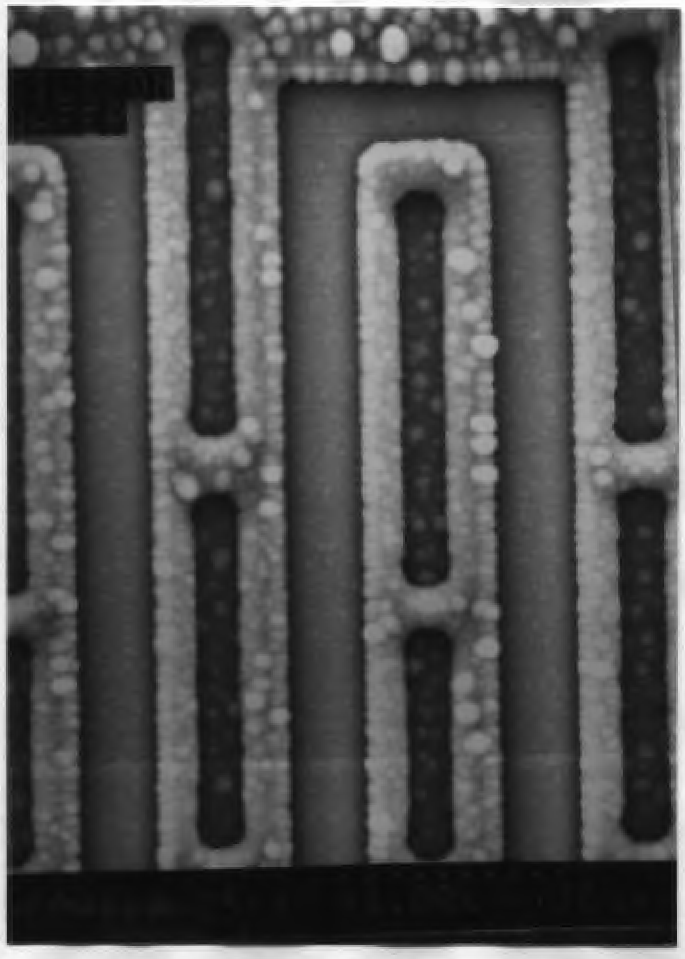


Figure 10. Silicon wafer substructure morphology, 25,000 volt SEM accelerating voltage, magnification 1000X, 30 μm magnification bar.

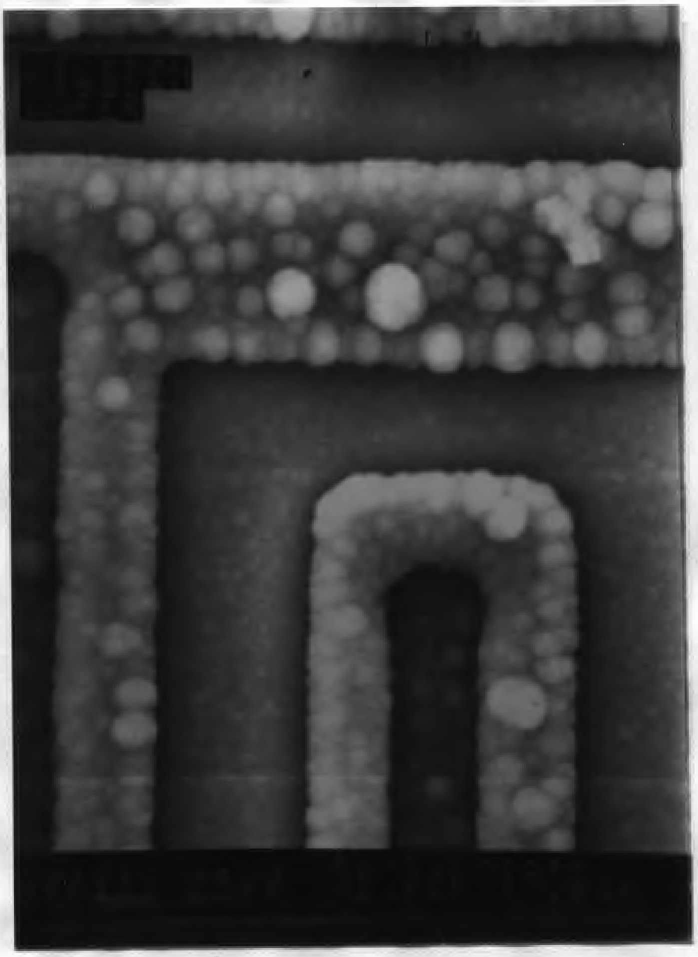


Figure 11. Silicon wafer substructure morphology, 25,000 volt SEM accelerating voltage, magnification 2000X, 15 μm magnification bar.

CHAPTER 5

SUMMARY, DISCUSSION, RECOMMENDATIONS

The results of this study provided the data necessary to describe the capabilities of an SEM in regard to surface contamination, topographic contrast and limited subsurface morphology. The sample photographs established that the SEM can differentiate between surface contamination and service related damage. Additional information was obtained which demonstrates the ability of the SEM to analyze and detect impurities in the substructure of electronic devices, as well as its' ability to show the multi-layered structure of some of the micro-electronic devices.

Summary

The capabilities of the SEM in regard to surface and subsurface examination are excellent. Resolution, depth of field and contrast were adequate in the first experiment but dramatically improved in the second experiment.

The necessity of understanding the basic operational requirements of the SEM was evident from the very first. Problems of sample preparation, inadequate recognition of the possible problems from interaction of the electron beam and the target electronic device were the cause of the problems in the first experiment.

Improved electronic samples and better preparation procedures resulted in a dramatic improvement in the quality of the information obtained from the second experiment. This indicates that a period of introductory training needs to be administered to everyone attempting to utilize the SEM. Proper training and familiarity can only improve the quality of information obtained from the SEM.

The limitations encountered in the operation of the SEM as an micro-electronic analytical device centered around the lack of specialized equipment designed to detect specific electronic failures. Many defects in electronic devices cannot be detected solely via surface analysis or substructure morphology testing. The devices examined exhibited surface contamination, impurities in silicon material used in the manufacturing processes and possible unwanted variations in line width or form. Because the micro-electronic devices had not been used extensively in service use, no service related defects were discovered.

Discussion

If the Department of Industrial Technology, University of Northern Iowa is to do as Douglas Pickles (1984) suggests is required of all such programs, " to expand their facilities to include more courses in high technology" (p. 3307-A), then it seems that electron microscopy is a strong candidate for consideration. In the authors opinion, this is an opportunity for the Department of Industrial Technology to better utilize present University high technology resources, expand Department curriculum into needed technological skills and properly prepare graduate and undergraduates for the industrial job market.

According to Alfthan (1985):

> Technological innovations are bound to have far-reaching repercussions not only on the number of jobs available on the labor market but also on the content and organization of work and hence on the skills, qualifications and attitudes required of the workforce ... If workers are to reap their share of the benefits, however, they must be given the sort of training and education that will equip them to meet the challenge posed by these new work demands (p. 517).

Electron microscopy is a relatively new field, affecting and being affected by changes in cutting edge industrial technology. The literature published in related journal and industry sources indicate that the applications of this field are widespread throughout the disciplines of industrial technology. This research project has revealed that the capabilities of the SEM, for failure analysis of micro-electronic devices, is substantial. Specific knowledge required to operate the SEM can be obtained via an addition to the present curriculum of the department. Content of this course should center on development of the diagnostic and analytical skills necessary for proper SEM operation. This research project has revealed that the SEM, in many cases, is the only viable analytical tool and is only limited by the experience, skill and equipment available to the user. Ignorance of the basic concepts, capabilities and techniques of electron microscopy can only be seen as a missed opportunity for the faculty and students of any Industrial Technology program.

Recommendations

Therefore these recommendations, suggested by this research project, are proposed:

1. That an addition to the curriculum of all programs of the Department of Industrial Technology be considered. This addition is to be a course in the analytical uses of the Electron Microscope. The subject matter of this course should include SEM theory of operation, procedures and techniques for preparation of materials for analysis, and specific techniques for analysis of the data collected.
2. That further research be done to establish the most effective and efficient way to train personnel and establish an energetic industry-university technology transfer program.
3. That funds be raised and allocated for the purchase of specialized equipment suitable for a

complete SEM analysis of micro-electronic devices and materials.

Dr. James P. Orr recently stated, at the 18th Annual Conference of the National Association of Industrial Technology, that "one of the most important responsibilities we have in an industrial technology program is to provide an adequate and current curriculum" (Orr, 1985, p. 58). The opportunity exists for the Department of Industrial Technology to properly prepare its' students in the techniques required to utilize this very important industrial tool. Minor changes in curriculum structure and program content have been suggested as a way to address this issue. Understanding the concepts and capabilities of this analytical device can only assist in the proper preparation of technologists better able to exist in the changing world of Industrial Technology.

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