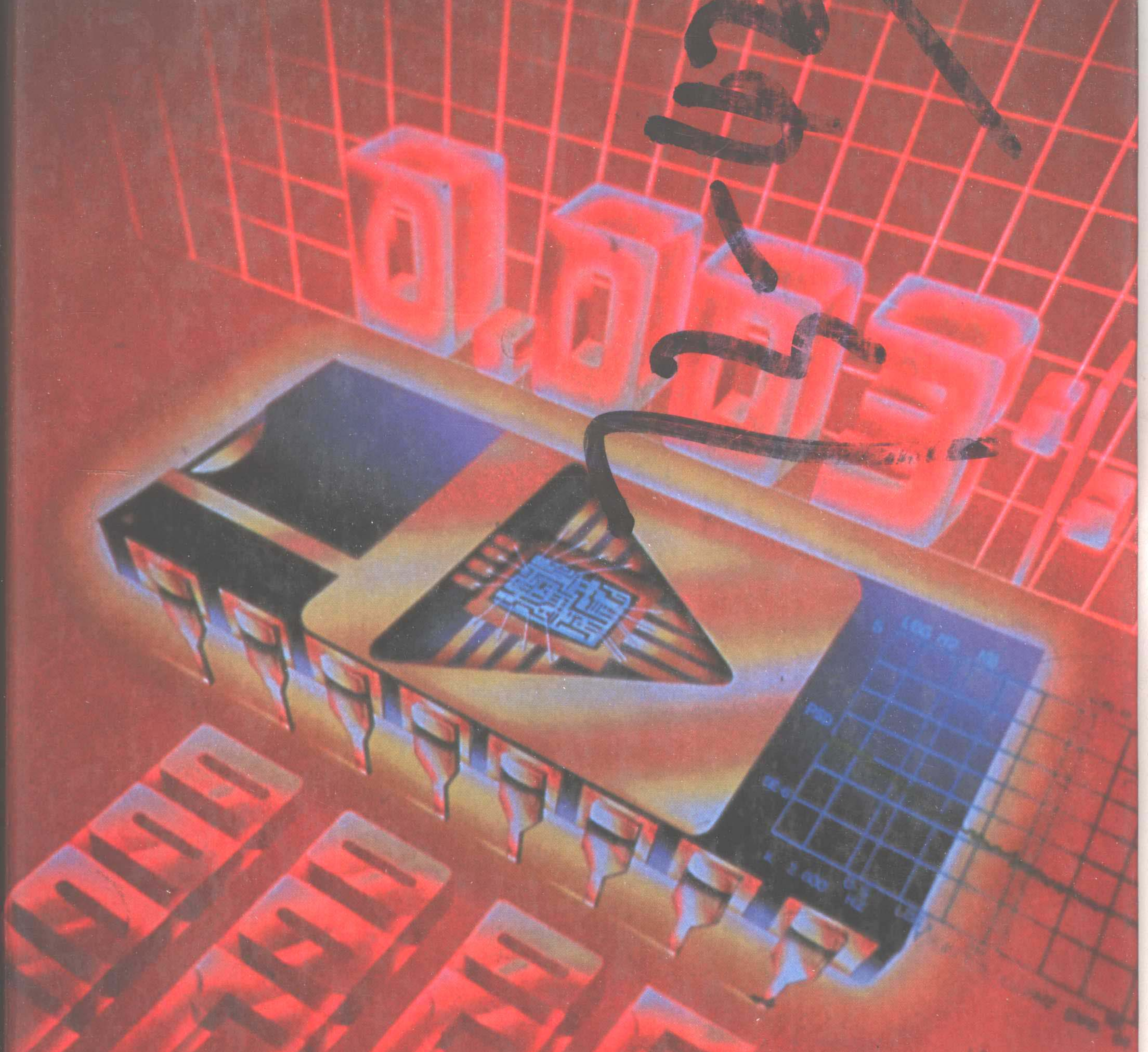
OP AMPS AND LINEAR INTEGRATED CIRCUITS



Richard A. Honeycutt

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Preface

PURPOSE OF THE BOOK

The introduction of the integrated circuit (IC) has revolutionized both the practice and the teaching of electronics. In the past, block-diagram approaches to circuitry were usually relegated to survey courses; now one can often buy a "block" in the form of an IC and simply insert it into the circuit. In the past, the study of feedback was an integral part of amplifier design. The analysis of a feedback loop was inseparable from the analysis of the circuit in which it was contained. Now, the unique characteristics of linear ICs usually make feedback analysis independent of the circuit around which the loop is connected.

This change in the field of electronics has spawned many new books. The first of these books were directed toward updating the training of practicing engineers. Often these books went into great detail concerning the design and construction of the ICs themselves. Later, textbooks began to be introduced. For good or ill, many of these books included the same material as the earlier ones. For the future engineer who would be designing ICs, this material was valuable, but for the other, more numerous, readership, this material was superfluous and unnecessarily burdensome.

This book was written to provide students, technicians, and engineers a practical understanding of linear integrated circuits. These three groups share five common needs. These are:

1. To understand basically how linear ICs work. Black boxes have an unnecessary aura of mystery.
2. To know the most common circuit configurations in which ICs will be used.
3. To understand manufacturers' specification sheets, and thereby to have access to reliable application data and the most current information on new devices.
4. To be able to simply design—from one's understanding and without memorizing a great number of formulae—most of the commonly-needed circuits that use ICs.
5. To be able to troubleshoot existing circuits that incorporate ICs.

This book attempts to fulfill these needs. It does it without much derivation of formulae and with no math beyond algebra, except for the unavoidable calculus involved in the discussion of differentiators and integrators. The approach throughout is basically intuitive. Theoretical material is given in sufficient depth to provide a firm foundation for understanding the principles involved. However, the emphasis is on information that is useful, and therefore easy to learn and retain. Because of the inclusion of specific sections on design and troubleshooting, the book will be useful long after a specific course of study is completed. It will also be helpful as a memory-jogger to the practicing technician or engineer.

PREREQUISITES

In order to gain the most benefit from this book, the reader should have a good understanding of high-school algebra and trigonometry. No calculus background is required. The reader should also be familiar with electric circuit analysis, including the application of Norton's and Thevenin's theorems. Finally, a familiarity with bipolar transistor and FET small-signal amplifiers is assumed. Readers who lack some of these prerequisites will still find the book useful, but may have to refer to appropriate reference books in order to fully understand some sections.

MAJOR FEATURES

- *Objectives:* Each chapter begins with objectives to help the student focus on the essential ideas to be gained from the chapter.
- *Examples:* The text includes numerous worked-out examples to illustrate all important design methods and many of the theoretical concepts.
- *Design Notes:* Most chapters include a *Design Notes* section that summarizes the approach to designing the specific circuits with which the chapter deals.
- *Summary:* Each chapter concludes with a summary of the important ideas presented in the chapter.
- *Problems:* At the end of each chapter, there is a set of problems designed to give the student practical experience and reinforce his understanding.
- *Laboratory Experiments:* After each chapter, there is a set of laboratory experiments to give the opportunity to see important concepts at work.
- *Appendices:* Four appendices are included in this book. Appendix A is the most extensive, and includes data sheets from representative linear ICs of all the types discussed in the text. Appendix B summarizes the techniques of calculating with decibel notation. Appendix C contains a wealth of application information on current-differencing amplifiers. Appendix D presents answers to the even-numbered problems presented in the text.

APPLICATIONS

The integrated circuits used as examples in this textbook have been chosen after consultation with the marketing department of a major IC manufacturer. With few exceptions, the specific units chosen are the most popular ICs of their type at the time of writing. It may surprise some readers to see such "old" devices as the 709 op amp and the 723 voltage regulator included in a modern text. However, according to current sales figures, these devices are still important in both replacement use and new designs. Several of the data sheets included in Appendix A are of the "long-form" type rather than the "short-form" variety more commonly included in textbooks. These complete data sheets include much valuable application information, design techniques, and circuits specific to the particular IC. This helps to familiarize the student with one of the important working resources of the professional engineer, as well as making available a sampling of that resource for use in the student's own projects. It is the hope of the author that after finishing this book, the reader will feel comfortable designing, using, and troubleshooting the vast majority of linear IC circuits.

COURSE PLAN

This book contains sufficient material for a full two-quarter or one-semester course on linear integrated circuits. If the text must be adapted to a shorter time frame, specific chapters can be omitted, depending upon the particular needs as perceived by the instructor. In any case, Chapters 1 through 4 are fundamental, and should be covered thoroughly. Chapters 6 and 7 also present material that is very important for the technician or engineer in today's work environment. With these basics covered, the remaining chapters can be used in any combination. It is recommended that the sequence of chapters not be modified, as each chapter is written with the assumption that earlier material has been assimilated.

INSTRUCTOR'S GUIDE

An instructor's guide is available as a companion to this text. It includes suggested lecture outlines, test objectives, and solutions to the problems.

A PERSONAL NOTE TO THE STUDENT, FROM THE AUTHOR

In any endeavor, there are certain techniques that make one's use of time more efficient and productive. The study of electronics is no exception. In order to make the most of the time you spend studying this book, I offer the following suggestions.

1. Read the text thoroughly, and with a notebook and pencil at hand. Our schools go to a great deal of effort to teach people how to read fiction. Unfortunately, the difference between reading fiction and reading technical material is seldom discussed. Fiction is approached with a view toward appreciation of the overall story line. It is usually read rapidly and with a great deal of emotional involvement on the part of the reader. Technical material must be read more slowly and with more attention to detail. Important sections should be marked in the text. One of my college professors once said, "A textbook is never truly yours until it is illuminated with your own notes." Some concepts will need to be reworded in your own fashion and written in your notebook, since learning is a highly individualized process. Rather than identifying with the exhilaration and despair of a fictional hero, you can ex-

perience for yourself the excitement of new discovery as you add to your own tree of knowledge in your chosen field.

2. Be very sure that you understand each example in the text. Work the examples out for yourself with the book closed, if necessary.

3. Do not approach this book as a series of facts that people have discovered and that you now have to memorize. This approach may have gotten you good grades in some history courses in the past, but it will not succeed in your study of electronics. Worse, it robs the study of the joy of understanding that should properly accompany your efforts. Instead, make sure that you understand the *why* behind every fact and equation. A student who knows where an equation came from has little need to memorize it. Spend a little time at the end of each section asking how the concepts of that section could be applied to some application of particular interest to you. Go beyond the examples and applications described in the book.

4. Use the objectives at the beginning of each chapter to set up mental file drawers in which to store the knowledge presented in the chapter. Knowing what a chapter is going to cover is a significant part of being ready to learn.

5. Use the summaries at the end of each chapter, not as a list of everything you need to know from that chapter, but as a checklist of important topics under which your knowledge from that chapter should be organized. Make absolutely sure that you understand the material in each chapter before going to the next. The study of electronics is cumulative in the sense that tomorrow's learning must be built upon today's understanding.

6. The *Design Notes* sections included in most chapters summarize design techniques. After you have mastered the material in the chapter, and for years to come, these sections will serve as a refresher on details of specific designs. Attempting to use the *Design Notes* sections as a substitute for learning the background material in the body of the chapter almost guarantees frustration. These sections are your quick-reference handbook to details of the design process.

7. Work all the practice problems at the end of each chapter. In my teaching experience, the most successful students have always been those who took the time to work through all the problems, even if their instructor only assigned some of them. Besides, these problems are chosen to simulate actual situations that you will encounter on the job. Since you have chosen electronics, you should find solving electronics problems stimulating.

8. If you do not have facilities at home for building and testing your own circuits, you should arrange immediately to get them. Design and/or build some projects. Successful engineers and technicians invariably have a hobby interest in electronics that motivates their professional interest. One of my best students of AC circuits routinely took problems home and implemented their solutions on his computer. I still use a drawing he gave me that was generated from a computer summation of the first five component frequencies of a square wave. Another of my best students had taught himself to redesign guitar amplifiers before ever enrolling in an electronics program. These students will be very successful—and, more importantly, very happy—in their careers. If you immerse yourself in the challenge of working with electronics, you will experience the thrill of discovery, of making the science and art of electronics your own. Success will follow.

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chapter one

Building Blocks of the Linear Integrated Circuit

OBJECTIVES

Upon completing this chapter, you will be able to:

- Give a brief account of the historical development of the linear integrated circuit.
- Describe the difference between linear and digital integrated circuits.
- Describe the operation of each of the three major building-block circuits that make up most linear integrated circuits.
- Discuss the variations that are possible in the design of the building-block circuits, and the effect of these variations upon the performance of the complete integrated circuit.

INTRODUCTION

Interesting, isn't it? Lee De Forest invented the vacuum triode in 1907, and an enormous electronics industry was spawned. Shockley, Brattain, and Bardeen invented the transistor in 1947, and we were told that Mr. De Forest's venerable baby was on its way out. The first reasonably priced linear integrated circuits (ICs) appeared in the late 1960s, and the death of the discrete transistor was announced. Yet here we are a couple of decades later with very large numbers of vacuum tubes still being sold (and a small amount of new tube-based equipment still being designed!), discrete transistor circuitry still being essential to our technology, *and* an ever-increasing number of ICs appearing to simplify the technician's life. So what's the moral of this little story? Don't believe everything you read in the newspaper (or in textbooks, for that matter!).

What has really occurred in electronics since 1907 is the continual *addition* of new technology. It is possible that transistors may someday completely replace vacuum tubes. But it is not conceivable that ICs will *ever* replace transistors, because of the flexibility of discrete parts in building one-of-a-kind circuits. Nevertheless, ICs do offer convenience, cost savings, reduced size, easier design, and, in some cases, improved performance when compared to discrete circuitry. For these reasons, an understanding of ICs is essential for any competent electronics engineer or technician.

For study purposes, ICs are customarily separated into two groups: digital and linear. ***A linear circuit** is one whose output signal bears a linear relationship to its input signal.* For example, the output of an amplifier is just its input multiplied by a constant gain. Multiplication by a constant is a linear function. A summing circuit's output is just the sum of its inputs. Addition is a linear function. The input and output signals of a linear circuit can have *any* value, within certain limits; they form a bounded continuum. Another name for linear circuits is *analog* circuits, because the signals with which they deal are analogous to some quantity in nature. For example, the electrical wave that corresponds to a sound wave (its analog) is processed in an analog circuit. The same is true for an electrical analog of video information, an electrical analog of the pH of a chemical solution, and an electrical analog of the temperature in a fiberglass oven. As an engineer friend of mine once truly said, "Mother Nature is analog!"

*A **digital circuit** is one whose output signal can have only certain specific values, corresponding to the digits of a number system.* Most often, the number system is binary, so there are only two possible values of input and output, corresponding to the digits 0 and 1. The output signal thus bears a logical/mathematical relationship to the input, not usually a linear one.

Number systems are a result of our attempts to quantify natural events. Most of those events being analog, they must be artificially assigned numerical values, or *digitized,* before they can be analyzed mathematically. This gives rise to a "half-breed" class of ICs that are part linear and part digital. These include primarily those circuits that interface between computing circuits and the outside world—analog-to-digital converters and digital-to-analog converters.

This book is primarily concerned with the first class of ICs, the linear ones. The first linear ICs were plug-in amplifiers made with vacuum tubes. (See Fig. 1–1A, page 7). Although not exactly today's idea of an IC, these were complete circuits that were integrated into a single package. With the introduction of transistors, ICs took the form of plug-in circuit boards full of parts (Fig. 1–1B, page 8). It occurred to some engineers that most of the "acreage" required for a circuit board was used up by spacing between components and by the individual cases of the components themselves. Hence, the *hybrid* IC (Fig. 1–1C, page 8, and 1–1D, page 9) was developed. This device is a small slab of ceramic onto which resistors have been built and other components have been mounted. Finally came the last step (so far, that is!), the monolithic IC. This is a complete circuit fabricated from a single tiny piece of silicon (Fig. 1–1E, page 10). When engineers today speak of ICs, they are talking about hybrids or monolithics. Plug-in circuit boards are now called *modules*.

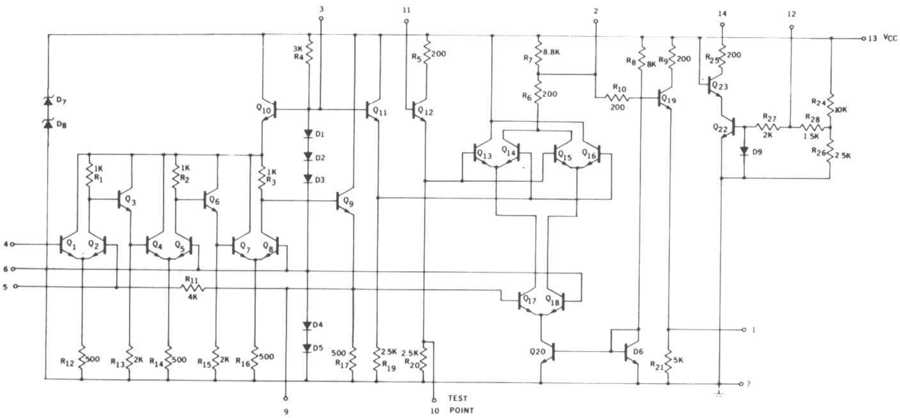
DIFFERENTIAL AMPLIFIERS

Basic Circuit

Most linear ICs are constructed largely of a versatile building-block circuit called the differential amplifier. Understanding the way diff amps (as they are often called) operate is important to understanding the operation of the ICs that use them. Figure

Sidebar

FOUR STEPS IN MONOLITHIC IC PRODUCTION



Schematic diagram of the IC, showing the components and interconnections to be formed on the silicon wafer. Numbered circles represent terminals of the finished IC. (Photos courtesy of Sprague Electric Co.)

(continued)

Sidebar

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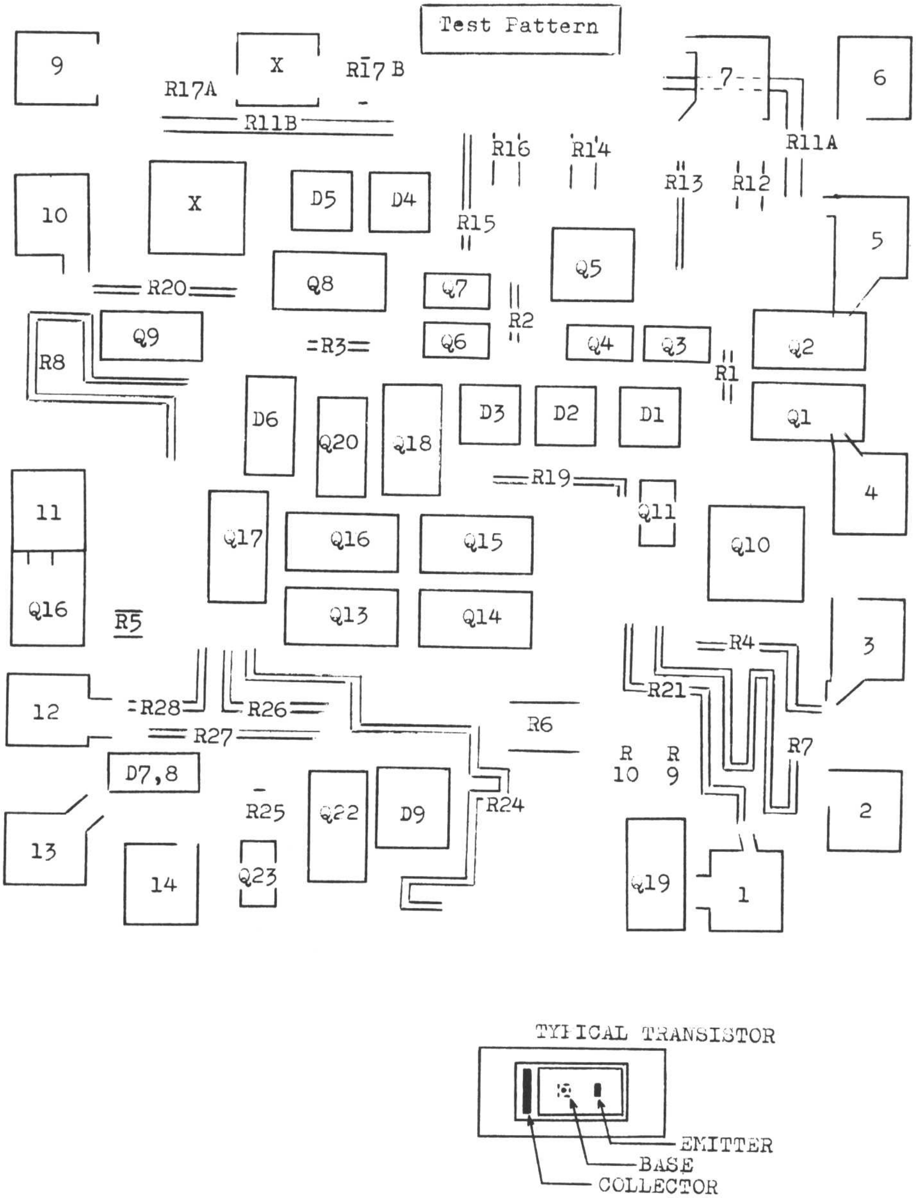

Parts layout, showing which component will be formed where on the silicon wafer.

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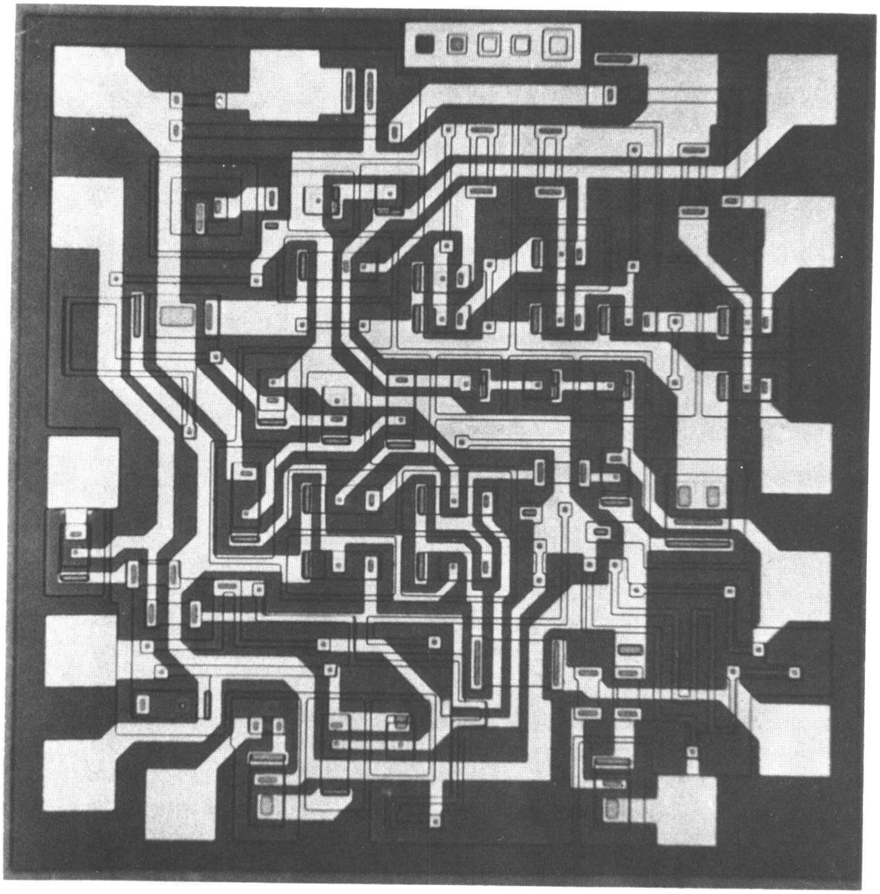
Sidebar



Photograph of the die, or circuit, that has been formed on the silicon wafer.