LSI/VLSI Testability Design

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PREFACE

Electronic systems, especially digital computers, have become so versatile and useful, that they are indispensable in modern society. Their rapid advances would not have been possible without the phenomenal progress toward LSI/VLSI (large-scale and very-large-scale integration) in the semiconductor circuit technologies achieved in recent years. With the electronic systems continually growing in the significance and pervasiveness of their application, their testing becomes increasingly important and, with LSI/VLSI, also more and more complex, difficult and costly.

Testing, as a professional activity, is probably as old as the art and techniques of design, fabrication and production. "Testability design" (or "design for testability") for LSI/VLSI circuits, on the other hand, is obviously much younger than circuit integration. Less than a decade ago, it was hardly known and seldom spoken of; today, most people agree that "something must be done to make the circuits more easily testable." This is an exciting, new field, full of interesting challenges; it is an important and fast-expanding field, in which many people are working and many more would like to take part.

With the advances in LSI/VLSI, it is basically the increasing *inaccessibility* of the circuits that makes testing more and more difficult and causes the testing costs to be an ever-growing portion of a product's total costs. Testability design means *adding* circuits within a test-object to make it easier to test. For systems using LSI/VLSI circuits, it has become an acute necessity that testability must be incorporated in the design. Nonetheless, one occasionally still hears expressions of bewilderment or skepticism about the practicality or usefulness of testability design, in questions like: *The many approaches reported, are they all different? — How do they fit together, so that I can understand and use them? — Where is all this going to lead us?*

This book will try to address such questions. It will aim to present and discuss the *basic concepts* of testability design, in simple language (yet without oversimplification, I hope) and in a coherent manner, so that they will be easily comprehensible to the newcomer. For those who are already knowledgeable in the field, the book may offer, as "food for thought," some new insights.

Working on the Josephson technology gave me the chance to look at the problems of testing rather in a new light. Two characteristics of the Josephson circuits, very high speeds and physical inaccessibility to external probing, accentuated the problems. Since very high speeds and inaccessibility to probing have long since become also the characteristics of LSI/VLSI semiconductor circuits, many of the thoughts and insights I have gathered are applicable to the semiconductor circuit technologies as well. The book comprises an attempt to present these thoughts and insights in an organized, correlated manner.

In recent years, test techniques and tools have no doubt been making great progress, contributing to advances in the art of automatic test equipment (ATE). But testability design, as an emerging discipline, is still at a stage needing much further development, in that it lags notably behind the LSI/VLSI technologies and — what is most acutely felt — it seems still to lack a *unifying concept*. That is, it lacks a concept which would handle the different types of testing (manufacturing tests, field tests, repair tests, etc.) with equal ease and validity, and unite them on a common simplifying basis — a concept which, in particular, would allow system-parts at various package-levels (chips, modules, cards, boards, etc.) to be tested not only on fixtures separately from the system, but also *within* the system while they are interconnected with one another.

Such an *in-system* testability for all system-parts will obviously be most useful in the testing, debugging and maintenance of systems (especially of large computer systems) comprising many high-density LSI/VLSI parts. Moreover, it is desirable that *at-speed* testing (i.e., testing at the test-object's operational speed), if feasible, should be practiced, since it will be more powerful than the low-speed (so-called "DC") testing, in that it will be able to detect many of the high-speed ("AC") faults.

It seems that there exist two barriers in LSI/VLSI testing: a cost and a speed barrier. Test-engineering — if it is to catch up and keep pace with the LSI/VLSI advances to be able to meet the present demands and the more critical challenges in the future — must overcome these barriers. It must make great strides and drastically diminish, within the next few years, its lag behind the LSI/VLSI technologies. But, can this be done?

This book will overview the evolution toward testability design hitherto, analyze what constitutes the cost and speed barriers, and indicate how they can be overcome. It will show that it should be feasible to overcome these barriers now, that most of the solutions needed are at hand, requiring only to be developed and utilized properly, and that the key to a unifying test concept as well as to achieving a breakthrough lies in the attainment of *in-system at-speed testability* for all system-parts.

The book will also look ahead to the future probable developments in test-engineering and in ATE. It is believed that, beyond attaining the in-system at-speed testing, test-engineering and ATE will advance and aim to achieve: the full automation of such testing, then of system diagnosis, debug and maintenance and, after that, the full automation of remote-controlled system testing and diagnosis. Obviously, only through in-system testing (i.e., without requiring the system-parts to be detached from the system), can these various stages of automation be developed and realized.

These will be the ultimate steps in the rationalization and optimization of test execution: they will relieve the human test-engineer of humdrum and tedious work, and free him or her for more creative and interesting tasks. By overcoming the barriers, the in-system at-speed testability design will open up whole new frontiers in test-engineering (in both hardware and software): it will offer boundless possibilities for further developments and make hitherto-infeasible capabilities realizable.

Many of the views presented here are unavoidably personal, and as such, they stand to be improved by future advances and better insights. If the book, as it is, can furnish useful information to some readers and help invite more people to understand LSI/VLSI testing and testability design to become active and innovative participants in the field, it will have fulfilled its intended purpose.

My thanks are due to many friends and colleagues and to my managers at the IBM Research Center for their encouragement, support and helpful discussions; and to my wife Kathy and our son Walter for their love, patient understanding and assistance.

F.T.

ABOUT THE AUTHOR

Dr. Frank F. Tsui is a Research Staff Member of the IBM Thomas J. Watson Research Center at Yorktown Heights, New York, where he has worked on the system aspects of Josephson circuit technology and on packaging technology and is at present working on parallel-processor systems. He has served on the faculty of the Technical University of Munich. Dr. Tsui holds some forty patents and patent applications, has published over seventy technical articles, and has received nine IBM Invention Achievement Awards.

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C OPERATION OF PATTERN GENERATORS AND COMPRESSORS

1 INTRODUCTION

test: a critical examination, observation, or evaluation,...as a means of analysis or diagnosis.

— From *Webster's Dictionary.*

If anything *can* go wrong, it *will.*

— *Murphy's Law.*

1.1 Importance of Testing

Importance of Electronics

Within only a few decades, electronic circuits and systems have become so eminently useful and diversely usable that they are practically indispensable in modern society. Especially with the rapid and copious advances in the *digital-computer* technology, many a long-dreamed-of and even undreamed-of extension to man's capabilities has become realizable.

In fact, in the whole history of technological developments, nothing else has ever had such a ubiquitous and pervasive influence on our daily life and on the future of our society. Electronic systems, capable of *storing* and *processing* vast amounts of data and information with speed, precision and reliability far exceeding what man can do, have entered and drastically changed almost every branch of human societal activity: information propagation and exchange, scientific measurements and instrumentation, systems modeling and control, industrial and agricultural production, government and business administration, education and research, medical and social services, transportation and environmental management, weaponry and warfare...even going on to what are envisaged to be knowledge processing and artificial intelligence.

To help us in seeing things more in their perspective, Fig. 1-1 shows the emergence and development of electronics and the computer, in relation to some major scientific and technical developments in the past two centuries (the time scale used is a logarithmic one counting backwards from year 2000). One cannot but be impressed by the multifarious genesis of new technologies and the tremendous accelerations of their growth in the last three or four decades. To think that the electron was discovered only 80-odd years ago, that the vacuum tube and transistor inven-

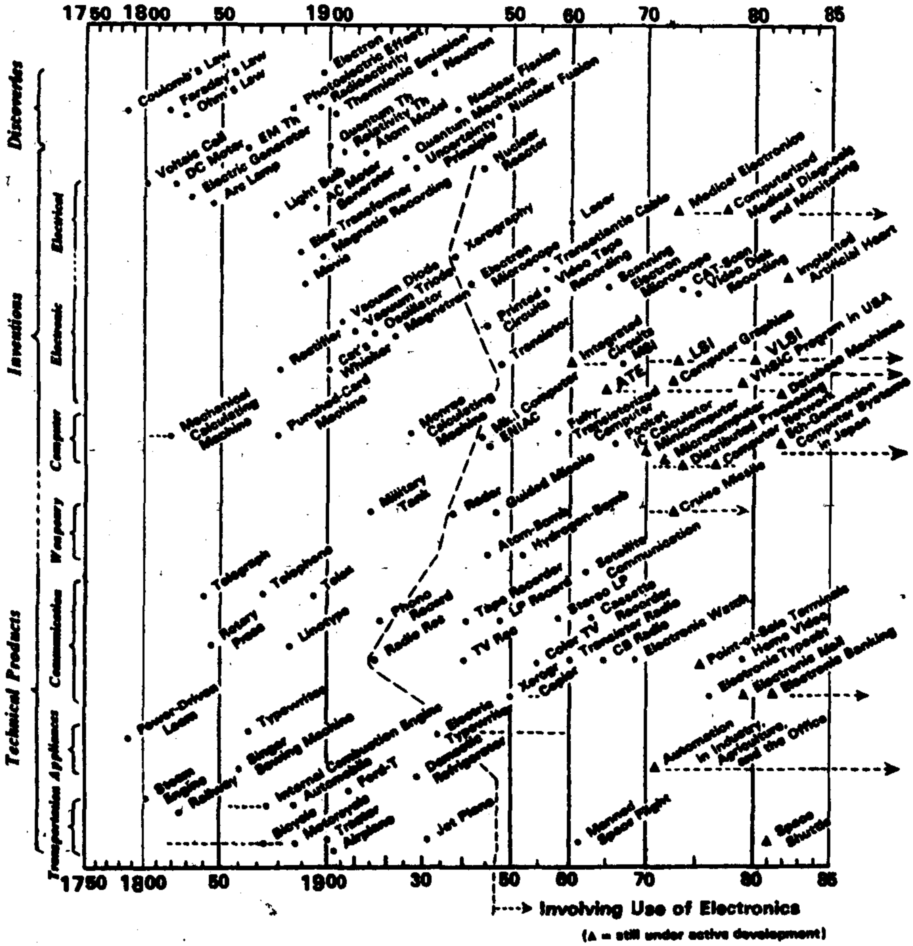

Fig. 1-1 Some Major Scientific and Technical Developments in the Past Two Centuries.

tions are barely 75 and 37 years old, how one must marvel at the bountiful fruits pouring out of the magic horn of electronics: radio and TV, audio and video recorders, electronic watches and pocket calculators, large and "personal" computers, radar and satellites, computer graphics and CAE, CAT- and NMR-scan[1], biosensors and computerized medical diagnosis, automation in the office, in the factory and on the farm. As is indicated

[1] CAE stands for "computer-aided engineering," a new expression combining the "computer-aided design" (CAD) and "computer-aided manufacturing" (CAM). CAT stands for "computerized axial tomography" or "computer-assisted tomography"; NMR, for "nuclear magnetic resonance."

in Fig. 1-1, since the late 1940's, practically *all* of the major scientific and technical developments have involved the use of electronic technologies.

Figs. 1-2(a) through (f) show some main aspects of advances in computer technology in the last 25 years:

¤ *Memory* in computer systems has developed from CRT (cathode-ray-tube) through ferrite-core to bipolar and MOS (metal-oxide-silicon) semiconductors, with a more than 40-fold increase in cycle-speed (Fig. 1-2(a)) and a nearly 20,000-fold reduction in power consumption (Fig. 1-2(b)).

¤ Effective computing speed, measured in "Megaflops" (million floating-point operations per second), has increased 10,000-fold, at an AACR (averaged annual compound rate) of 44.5% or more (ACRs ranging from 66.8% to 25.9%, Fig. 1-2(c)).

¤ The number of general-purpose computers in use in the U.S.A. has grown from about 1K in 1955, to 30K in 1965, 220K in 1975, and more than 500K in 1982, at an AACR of 25.9% (Fig. 1-2(d)).

¤ Total value of computers in use in the U.S.A. has grown from less than $1 billion in 1955, to over $8 billion in 1965, about $40 billion in 1975, and almost $60 billion in 1978 (Fig. 1-2(e)).

¤ Since the beginning of integrated-circuit developments in 1960, the annual utilization of electronic functions (transistors, logic gates and bits of memory) worldwide increased some 2,000 times by 1977. The utilization is expected to increase further by a factor of 100 in the decade 1977 to 1987 ([77Noyc$_2$][2]).

¤ After the 1981-82 recession, the data-processing equipment consumption worldwide was about $135 billion in 1982, $155 billion in 1983, and $180 billion in 1984; the consumption in the U.S.A. was about $53 billion in 1982, $63 billion in 1983, $78 billion in 1984, and is expected[3] to grow to more than $120 billion by 1987 (Fig. 1-2(f)). The computer production in the U.S.A. is estimated at about $61 billion in 1984, to become[3] $71.3 billion in 1985 and $82 billion in 1986.

¤ For the future, it is projected[3] that the available computing power in the U.S.A. will continue to grow at an AACR of about 40% (Fig. 1-2(d)). The recent upsurge in the popularity of "personal computers (PCs)" (exceeding all original projections) will probably augment this figure. The total PC (home and office microcomputers) sales in the U.S.A. grew from $4.7 billion in 1982 to $12.1 billion in 1984, and are expected[3] to reach $35.3 billion by 1989 (Fig. 1-2(g)). Continual growth in the use of "workstations" in design and engineering, of

[2] An explanation of the abbreviations used to denote papers and books for reference is given at the end of this book.

[3] Effects of the recent (1985) setback in worldwide semiconductor market are not taken into account in these estimations.

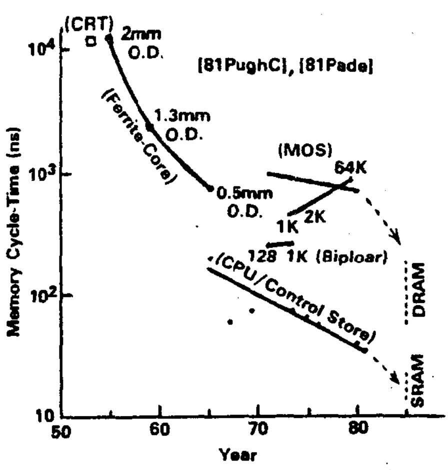

Fig. 1-2(a)
Advances in Computer Technology: Memory Speeds.

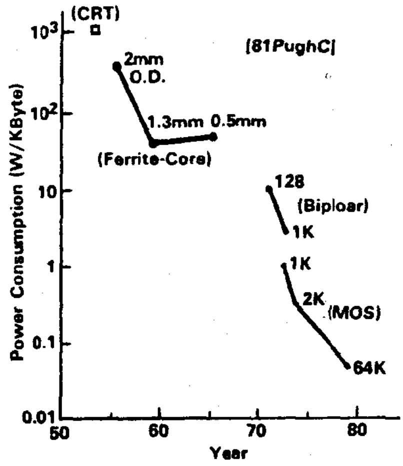

Fig. 1-2(b)
Advances in Computer Technology: Memory Power Consumption.

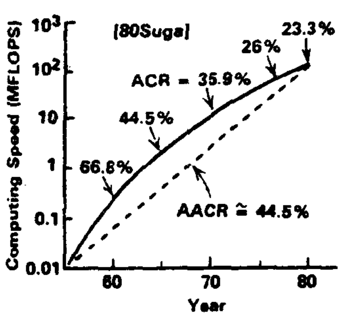

Fig. 1-2(c)
Advances in Computer Technology:
Effective Computing Speed.
(©1980 IEEE)

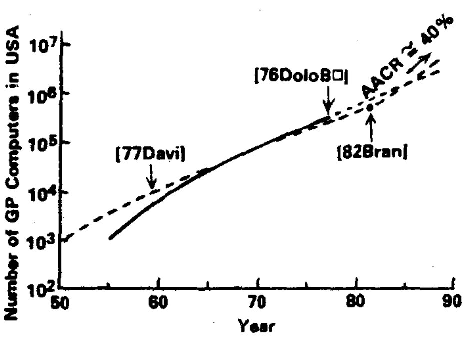

Fig. 1-2(d)
Advances in Computer Technology: General-Purpose Computers in USA.

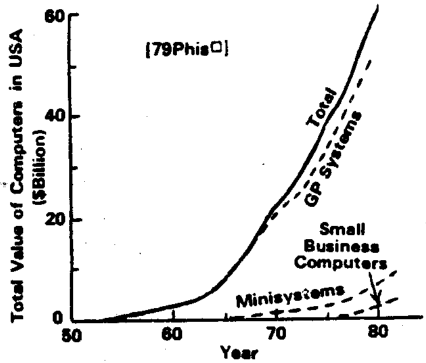

Fig. 1-2(e)
Advances in Computer Technology:
Total Value of Computers in Use
in USA. (©1979 Digital Press)

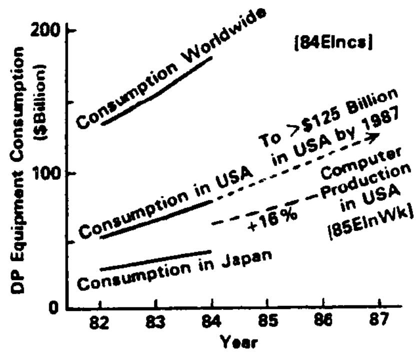

Fig. 1-2(f)
Advances in Computer Technology:
Data-Processing Equipment
Consumption.

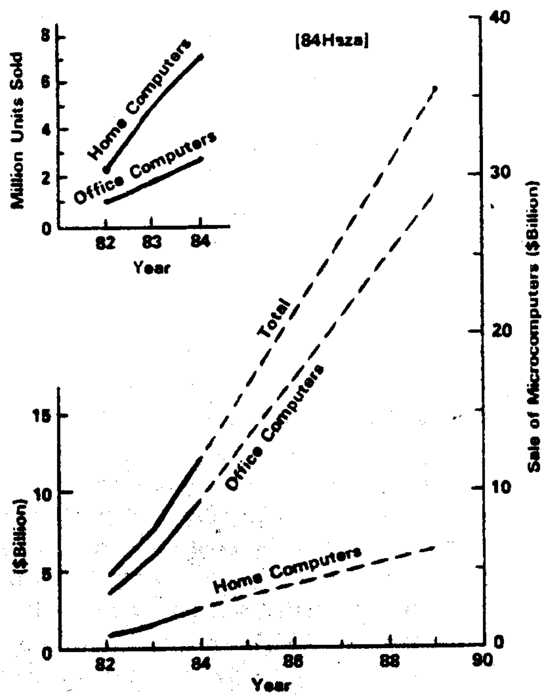

Fig. 1-2(g)
Advances in Computer Technology:
Sale of Home and Office Microcomputers in USA.